Power Quality

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Lecture - 29
AC-DC Converters That Cause Power Quality

Welcome to the course on Power Quality, today I would like to cover AC-DC converters that cause the power quality problems. The outlines of the presentation will be introduction, state of the art, classifications of conventional AC-DC converter, single phase conventional AC-DC converters, analysis of single phase conventional AC-DC converters, three phase AC-DC converters, analysis of three phase conventional AC-DC converter, numerical examples, summary and then the references.

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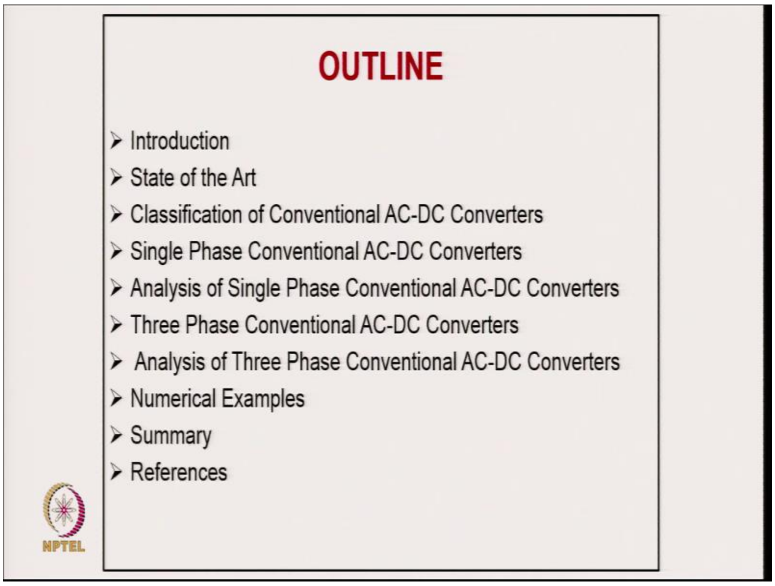

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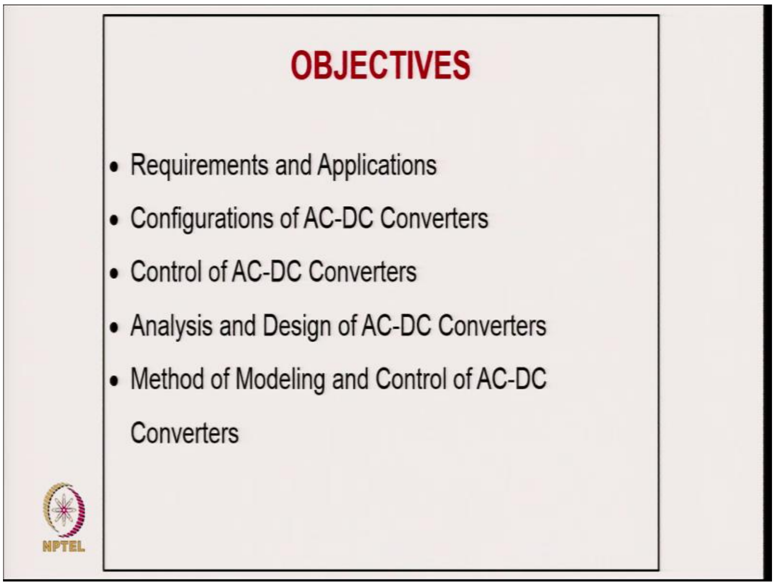

Well, the objective of this lecture is to discuss what are the requirements, applications, and the configurations of conventional AC-DC converters, control of AC-DC converters and then analysis and design of AC-DC converter, then the method of modeling and control of AC-DC converters.

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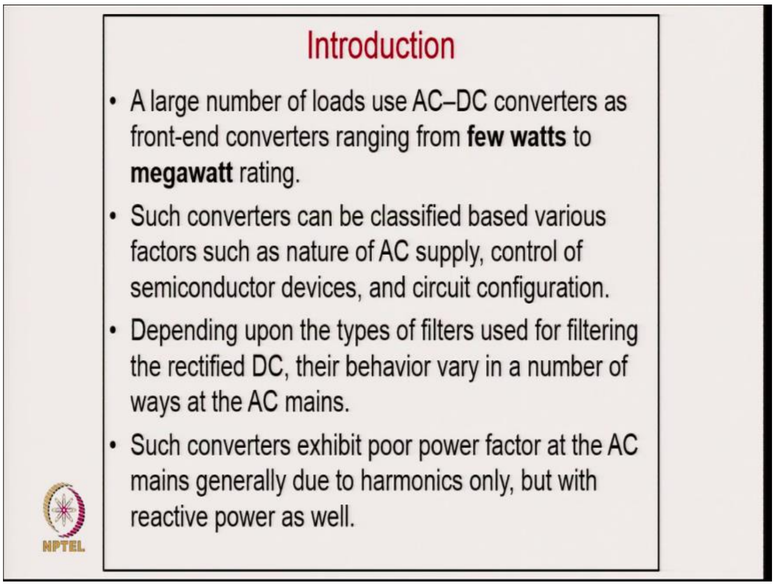

A large number of the loads use AC-DC converters as a front - end converter ranging from few watts to megawatt rating, and such converters can be classified based on various basis such as nature of AC supply, control of semiconductor devices and the circuit configuration. Depending upon the type of filter use for filtering the rectified DC, their behavior varies in the number of ways on AC mains. Such converters exhibit poor power factor at AC mains generally due to the harmonics distortions and reactive power demand from AC mains.

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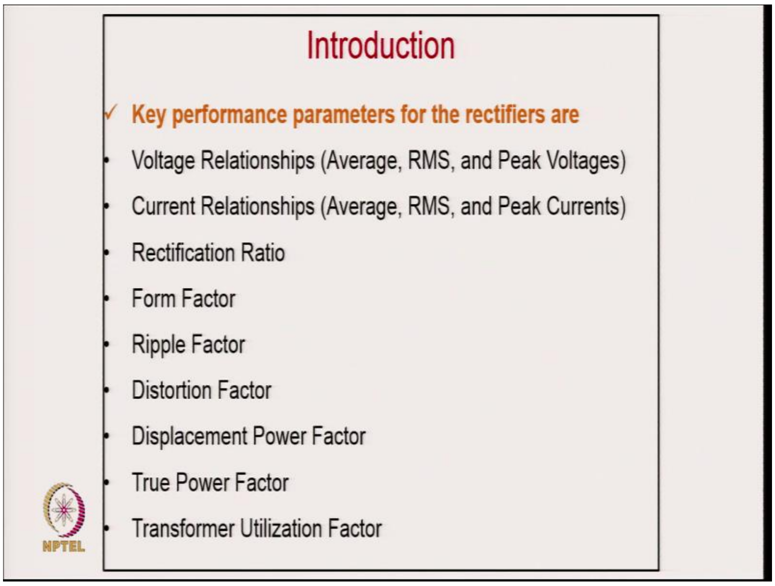

Well, the key performance parameters of the AC-DC converters or rectifiers are voltage relationship, current relationship, rectification ratio, form factor, ripple factor, distortion factor, displacement power factor, true power factor and transformer utilization factor (if they have transformer-based structure).

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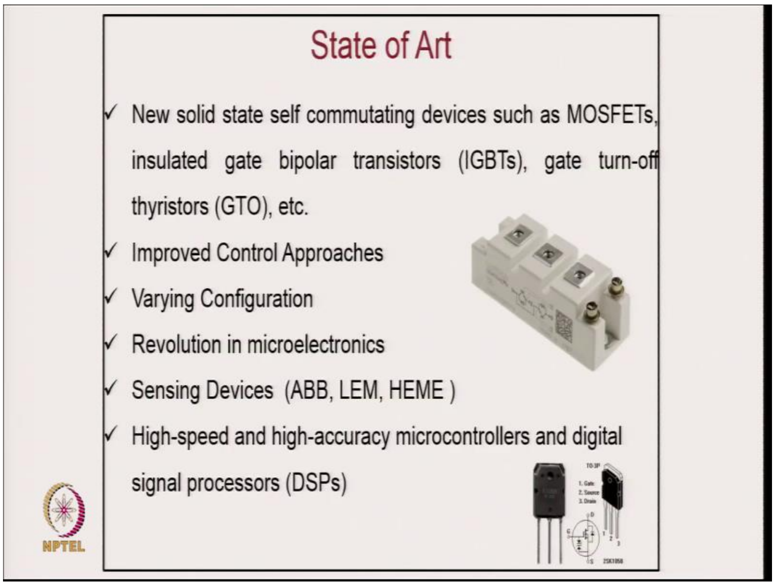

Now coming to the state of art of AC-DC converters. Such converters utilize new solid state self-commutating devices such as MOSFET, IGBT and gate turn off thyristors along with improved control approaches. Normally, the high-speed DSP or the micro controller, which have come from the revolution of microelectronic, are used to implement the control objectives of these AC-DC converters. Further, to sense the controllable quantities like voltages and currents, various sensing devices like hall effect current and voltage sensors which are manufactured by many like ABB, LEM, HEME, are generally utilized.

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Now coming to the application of conventional AC-DC converters, in many applications, they cause the power quality problems, if not designed properly. The typical examples of such applications are switch mode power supplies, the mobile chargers, electric vehicle chargers, (which are coming up in a big way due to government policies and support), and LED driver circuits (for the lighting purpose may be in different power level starting from few watts it goes to like a maybe even 12 to 18 watts).

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Further, the other major applications of AC-DC converters, include computer power supplies and motor drives. Most of the AC motors such as brushless motors, squirrel cage induction motor, permanent brushless motors, synchronous motors and synchronous reluctance motors; use solid state variable frequency drives, which has front end the AC-DC converter and back end DC-AC converter for driving the motors.

Furthermore, the AC-DC converters are extensively used in home inverters, to charge the battery from the home AC supply. In high frequency welding machine where the AC-DC converter employed for the rectification. Even in a ceiling fan, the AC is converted into DC, and then DC is converted into three phase AC for driving different motors like permanent brushless DC motor or switched reluctance motor.

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There are some other applications where aforesaid equipment's or AC-DC converters are used such as in a steel rolling mills, paper mills, printing presses, textile mills, traction system, home appliances, portable hand tool and HVDC transmission systems.

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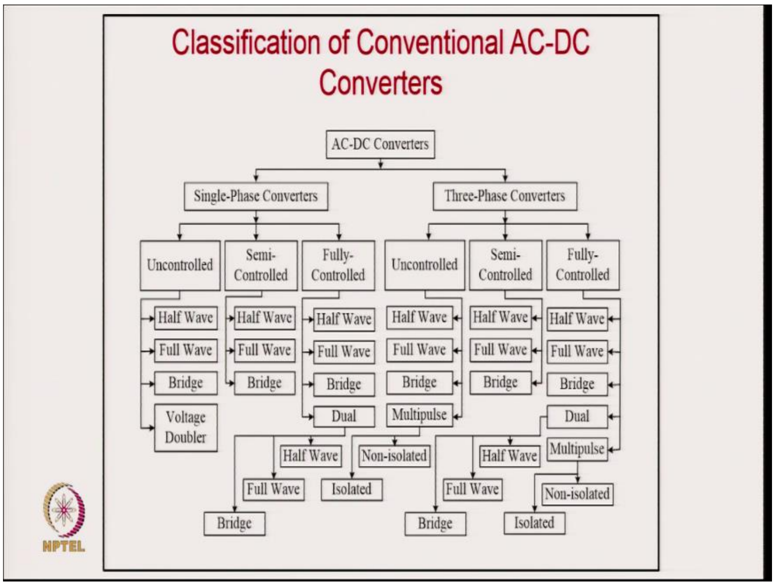

The conventional AC-DC converters are classified into two broad categories which include single phase and three phase AC-DC converters. The single phase AC-DC converters can further be classified into uncontrolled, semi controlled and fully controlled.

The single phase uncontrolled AC-DC converters can be classified into half wave, full wave, bridge and voltage doubler configurations. Similarly, the semi controlled and fully controlled single phase AC-DC converters are classified in to half wave, full wave and bridge categories. The fully controlled of course have a dual converter category, which is further categorized into half wave, full wave or bridge configurations.

The three phase conventional AC-DC converters have similar classifications. The uncontrolled three phase AC-DC converter can have half wave, full wave, bridge and multi pulse configuration. The multi pulse can be again isolated, non-isolated because you might be using transformer or you may not be using transformer. Similarly, the semi controlled have half wave, full wave, and bridge type configurations. Whereas, the fully control converters can be classified in to half wave, full wave, bridge and dual converter categories. The dual converters have half wave, full wave and bridge configuration, whereas a multi pulse can be of non-isolated or isolated.

If we talk about uncontrolled AC-DC converters, they have a very extreme kind of a harmonics injection into the supply system or they draw the harmonic current from the supply. Whereas, the semi controlled and fully controlled converters not only draw the harmonics, but also demand reactive power. Thus, most of these converters deteriorates the power quality at the AC side.

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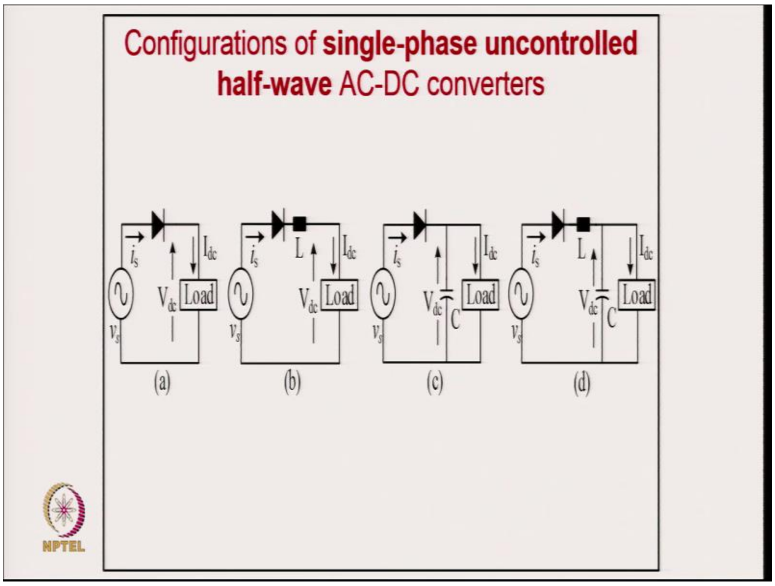

The first category is half wave, which might have different loads without filter or have inductive filter, capacitive filter or an LC filter at the load end. Generally, these converters are used in very low power rating applications like upto few watts.

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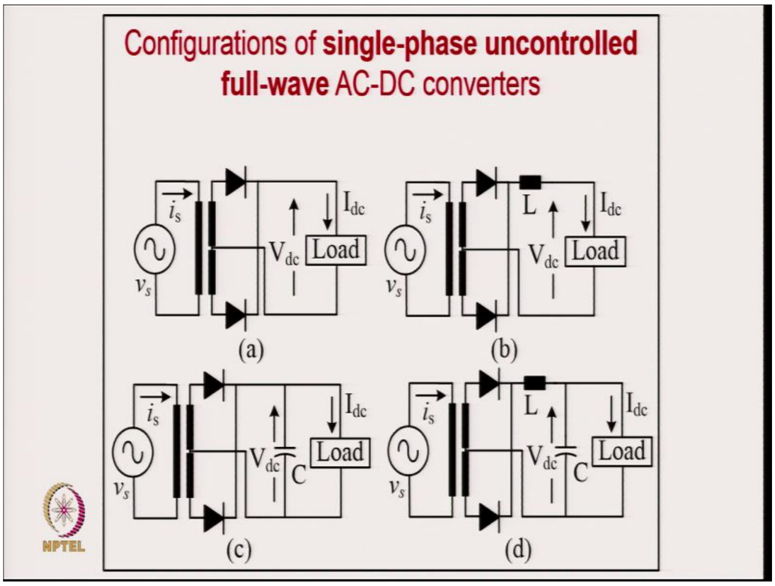

Further, the full wave with push pull configuration can have simple load without any filters or can have an inductive filter, capacitive filter or LC filter across the load. All these will have certainly power quality problem.

In case of a highly inductive load, the supply current will certainly have square wave shape, whereas for a capacitive load, the supply current will be peaky in nature. The crest factor for inductive load is 1, but for capacitive nature it goes up to 2 to 3. Typically, in that case, a small inductor certainly reduces the crest factor and shape the supply current in between two cases. Such configurations are extensively used to reduce the voltage at low level.

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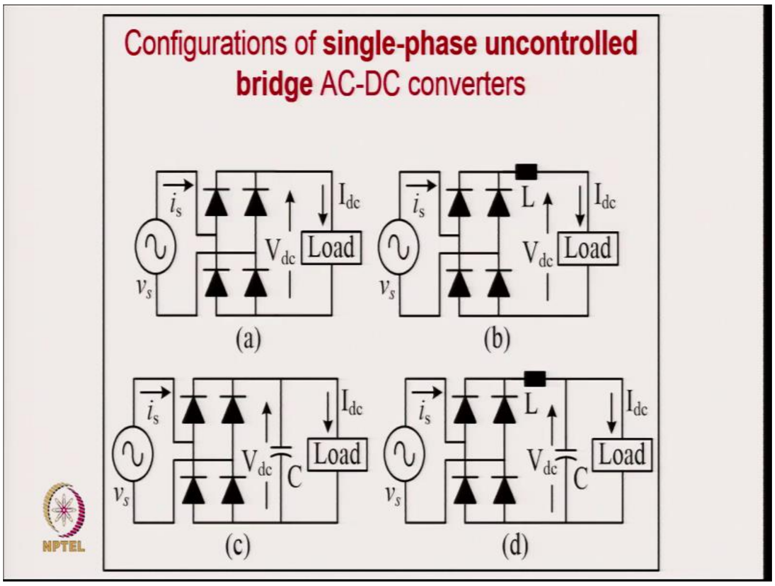

Further, the full wave with bridge type configuration, can have simple load without any filters or can have an inductive filter, capacitive filter or LC filter across the load. In case of a highly inductive filter, the converter will have a square wave current on the supply side that certainly injects the harmonics. However, due to diode rectifier such configurations do not put much reactive power burden on AC mains.

In case of a capacitive filter, the supply current will be peaky in nature and the AC-DC converter draws very large amount of harmonic from the AC mains. The harmonics content in case of inductive filters are not so high maybe the total harmonics distortions (THD) can go up 48%, however, in case of capacitive filters, the THD might as high 80 to 90 %. In which, the third harmonics remain quite dominating, which further cause excessive neutral current. Certainly, an inductor cascaded with capacitor will reduce the peak of supply current and ensure a good quality DC, but supply current THD still remain high somewhere in between 48 % to 90%.

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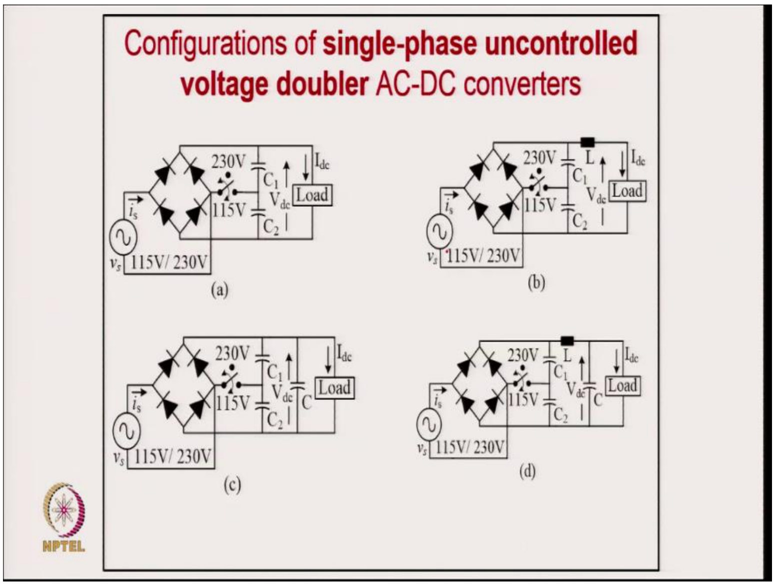

Further, the voltage doubler configurations have wide supply voltage range operation capability. In case, if the switch is down, all these circuits can operate with 115 V supply system, like in North America the supply system is around 110 to 120 V. Whereas, if the switch is up, all these circuits can operate with 230 V supply system like in Europe or India the single-phase supply is around 230 V. However, the output voltage will remain almost the same in both cases, thus loads will not be affected.

These configurations provide simple, light weight, and low-cost solution as compared to other topologies which generally use bulky, costly, noisy, and lossy transformers to achieve wide supply voltage range operational capability.

However, such configurations draw large amount of harmonics from the supply system because of the capacitive filter at their output end.

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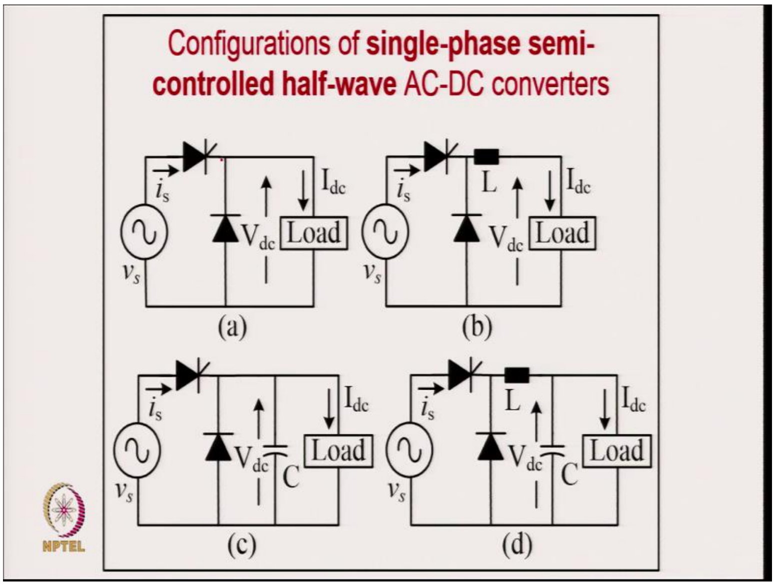

Well, the previously described AC-DC converters was uncontrolled, now coming to semi control AC-DC converters, the half wave semi control converter consists of one thyristor and one diode. When the thyristor conducts you have energy, after that, if you have an inductive load, the freewheeling diode will conduct. The other three configurations are with inductive, capacitive or LC filters. This is what we call it semi controlled half wave converter.

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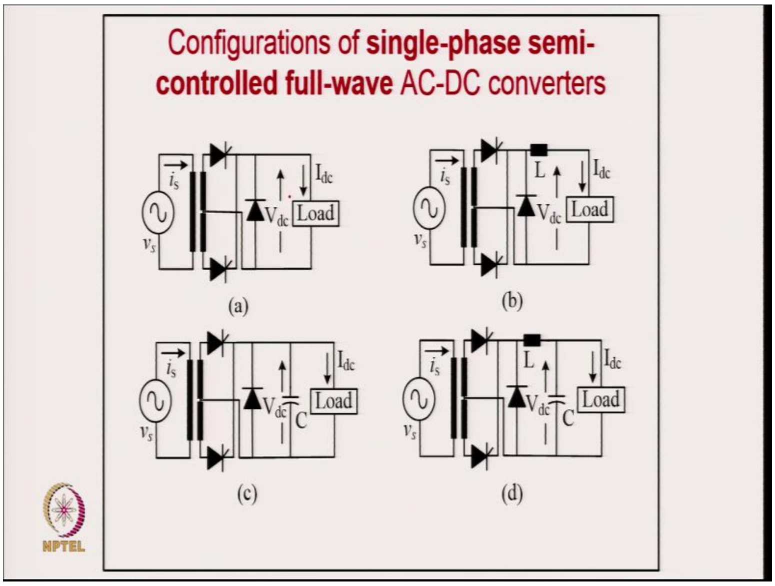

And these are the full wave semicontrolled AC-DC converters

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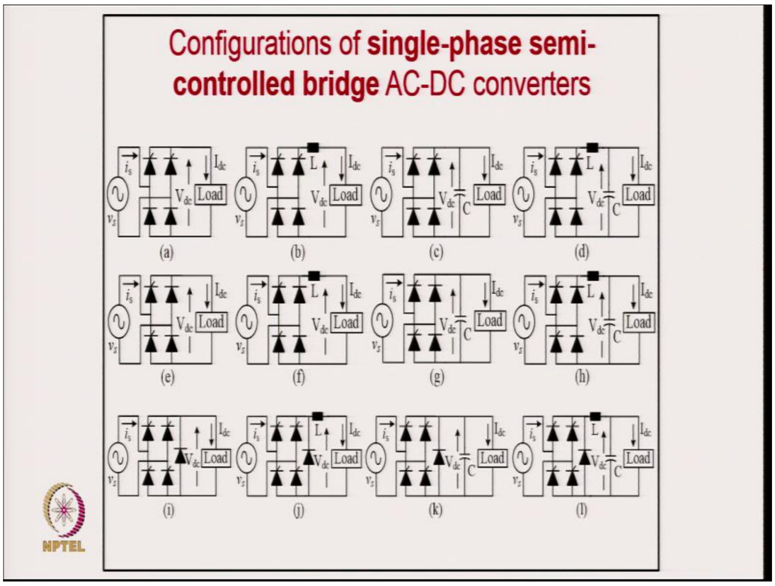

And then you have a bridge type semi-controlled AC-DC configuration with the different kind of filters. If you can look into the bridge semi control AC-DC converters might have 2 thyristor, 2 diodes and in some cases only 4 thyristors with 1 diode with different kind of filter arrangement.

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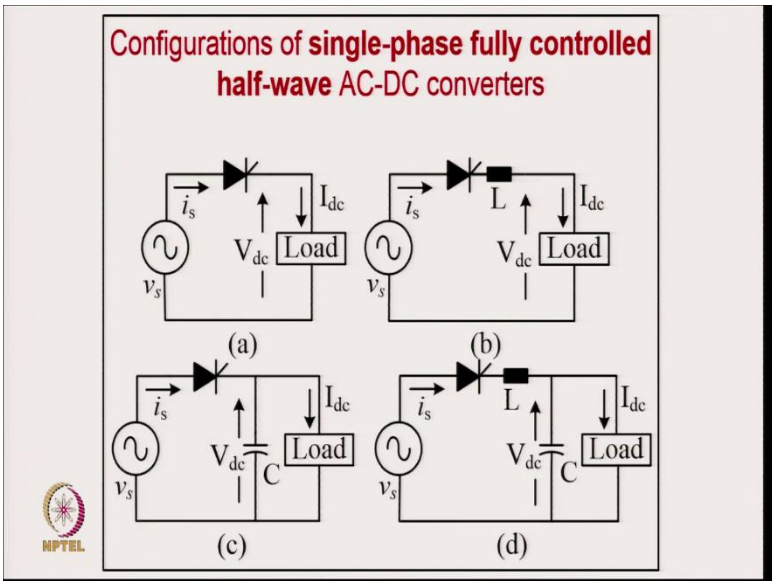

Then we have half wave fully control AC-DC converter with different kind of filter like with no filter, inductive, capacitive, and LC filter.

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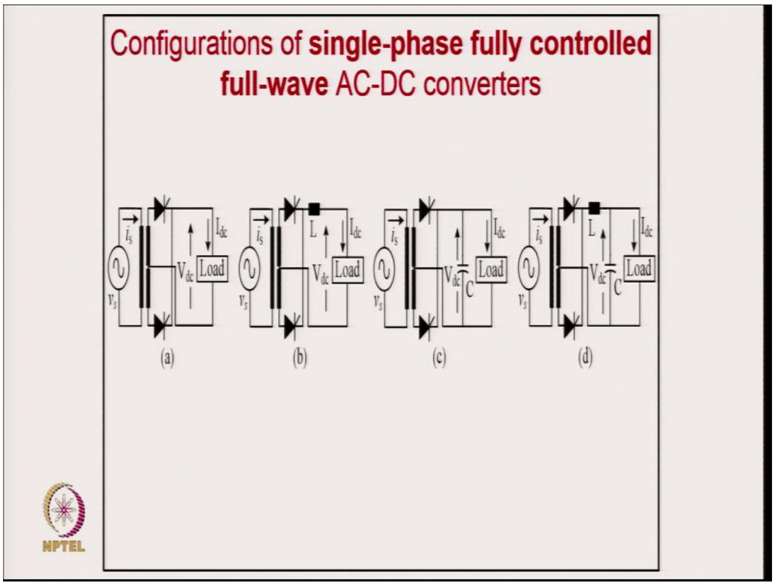

And then you have typically fully controlled full wave converters with no filter or inductive, capacitive, and LC filter combination.

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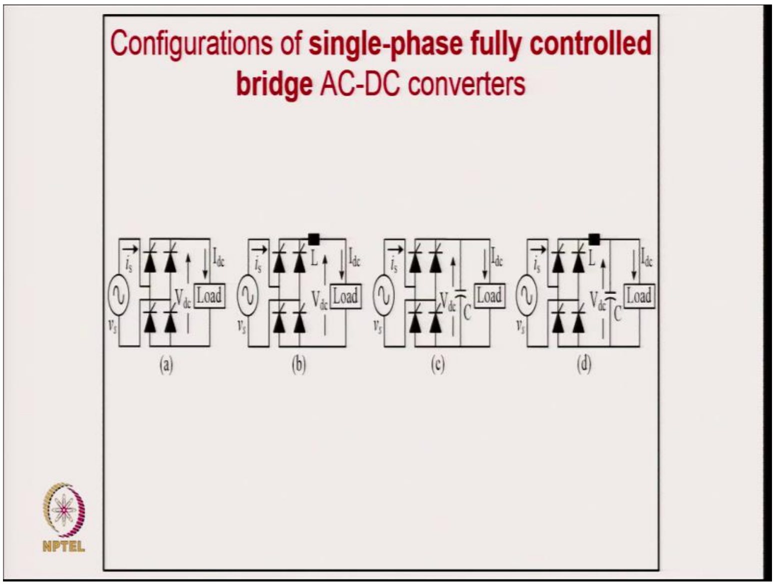

Then, we have bridge type fully controlled AC-DC converters with no filter or inductive filter or capacitive filter or LC filter.

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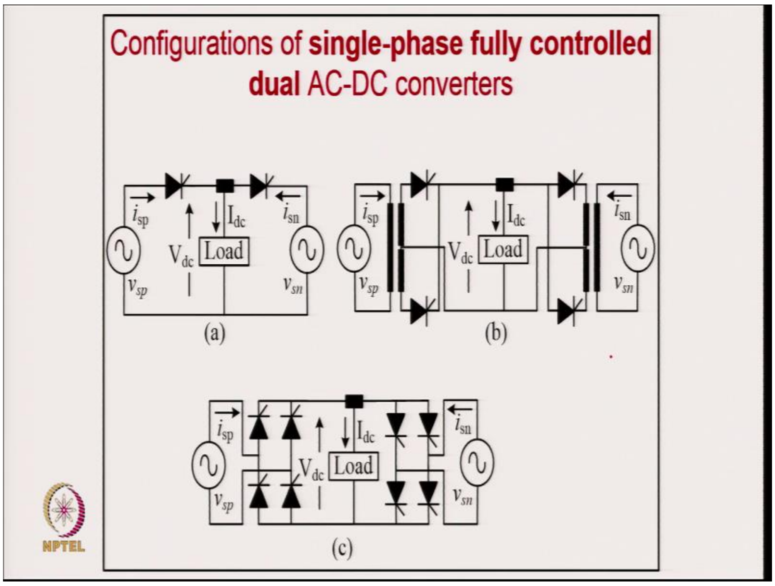

Or you have single phase dual converter with the half wave, full wave and bridge configurations. In a dual converter, it is possible to change the voltage and current direction at the output.

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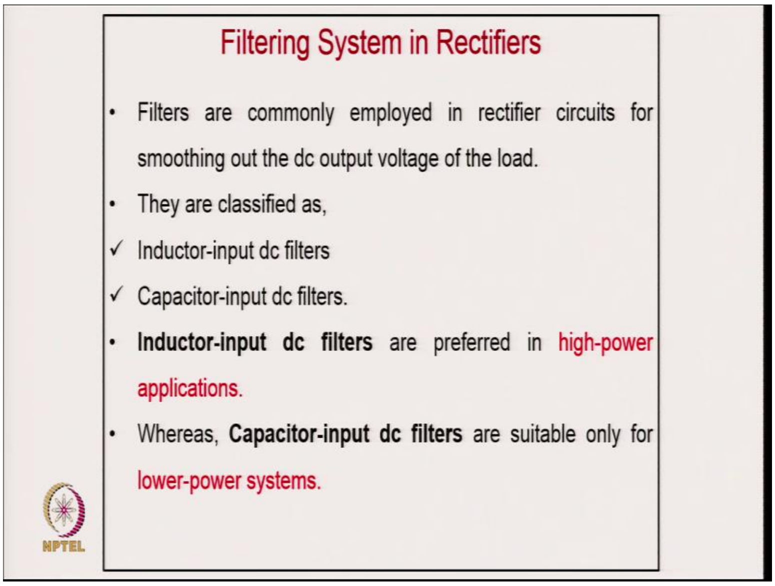

Of course, in case of these single phase AC-DC converters, the filters are commonly employed in rectifier circuit for smoothing out the dc output voltage of the load, but this affect certainly the power quality on the input side.

The filters are classified like inductor-input filter, and capacitive input filters. The inductor input filters are preferred in high power, whereas, the capacitive input filters are suitable for low power applications.

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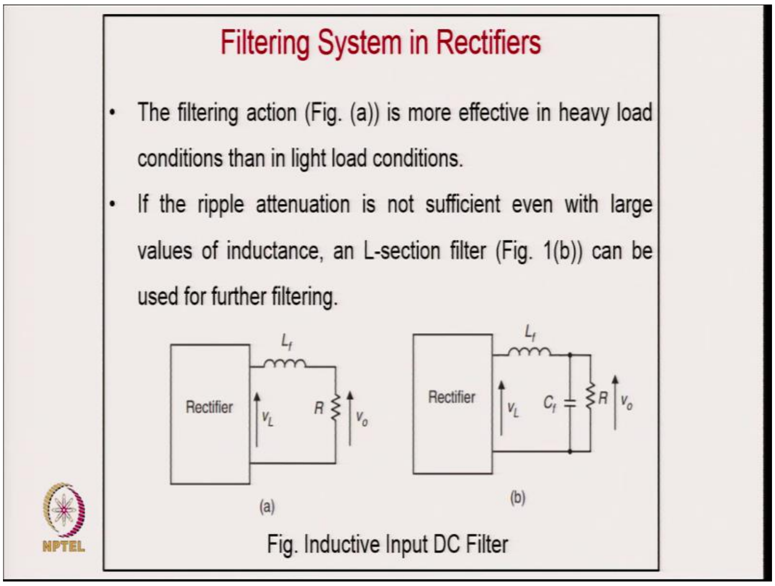

However, the performance changes with the filter, such as, in case of an inductive filter at the input supply, the supply current will be flat, and the crest factor would be less than sine wave. But, in case of an LC filter, it is in between L filter and sine wave.

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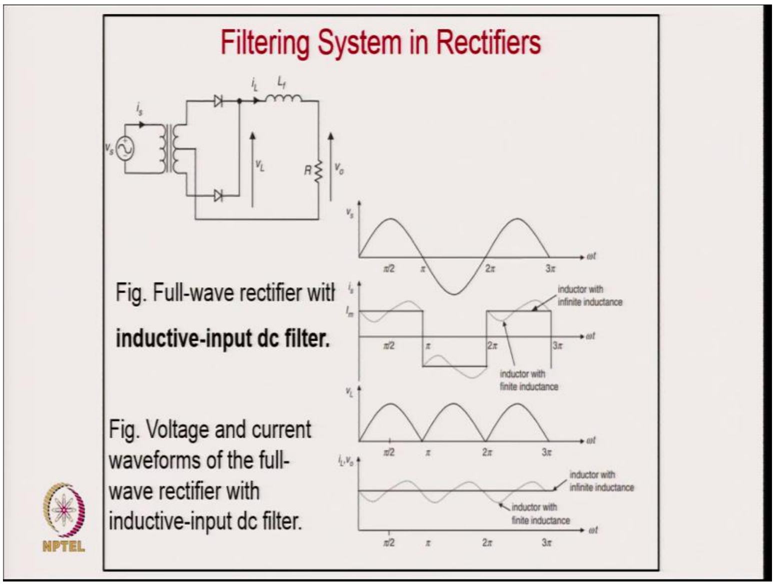

Considering a simple case, a full wave rectifier with an inductive filter, let’s say with an infinite inductance, then you will get a kind of square wave current at the supply end. But if certainly the inductor is not so high, then some ripples appear in the load current as well as in the supply current. In such cases, the supply current has a quite substantial total harmonic distortion.

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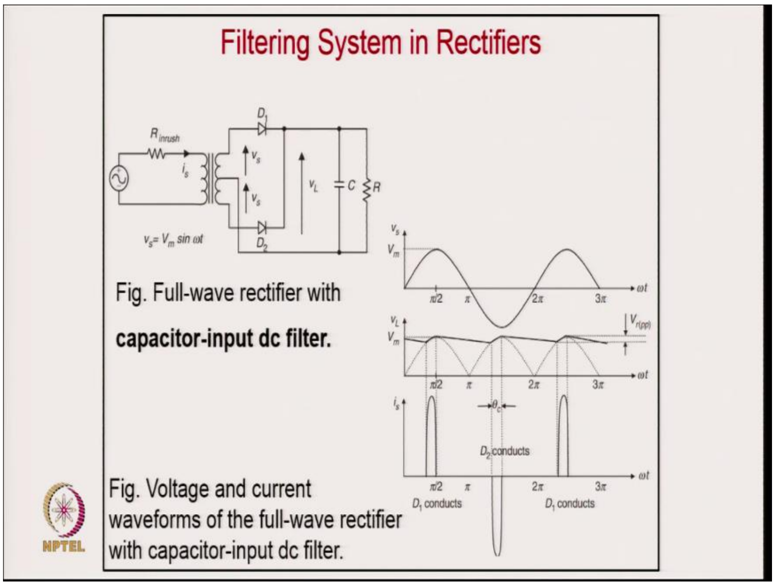

And in case of a capacitive filter, the circuit will certainly draw peaky current from the supply side. In such cases, the circuit will draw current only for the period when the supply voltage is more than the capacitor voltage. Therefore, the crest factor as well as the harmonics will be very high.

In some applications, this may not be the exactly the case, as the duration of diode conduction depends on the time constant of circuit filter and equivalent load resistance. The conduction period may go on changing like it might varies to 60 degrees, 90 degree or 120 degrees out of 180 degrees. Further, if the value of capacitor increases the duration go on reducing, but the ripples will be less in the output voltage. Similarly, if the capacitor is less duration will be more, but ripple in the output voltage will increase. So, it depends how you really design the circuit, but the crest factor of the supply current is quite substantially high. This kind of situation we have in many applications, about which, we will talk in subsequent chapters.

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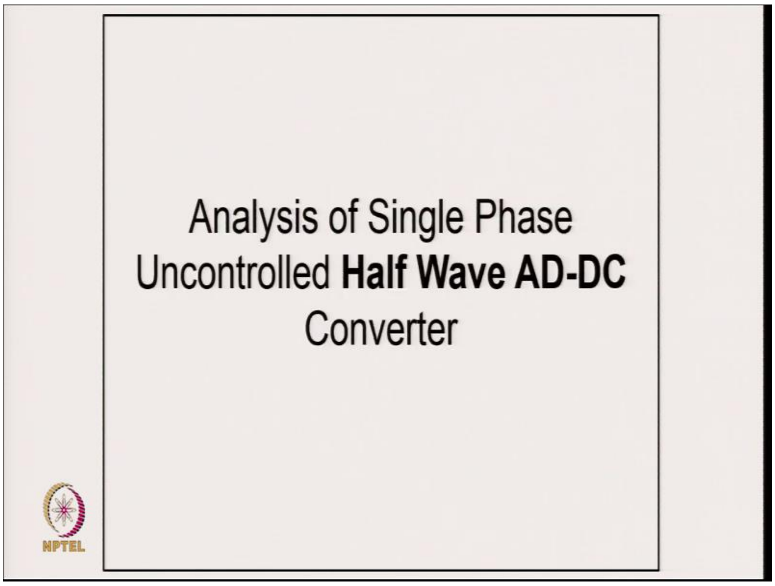

Coming to the Single Phase Uncontrolled Half Wave AC-DC Converters.

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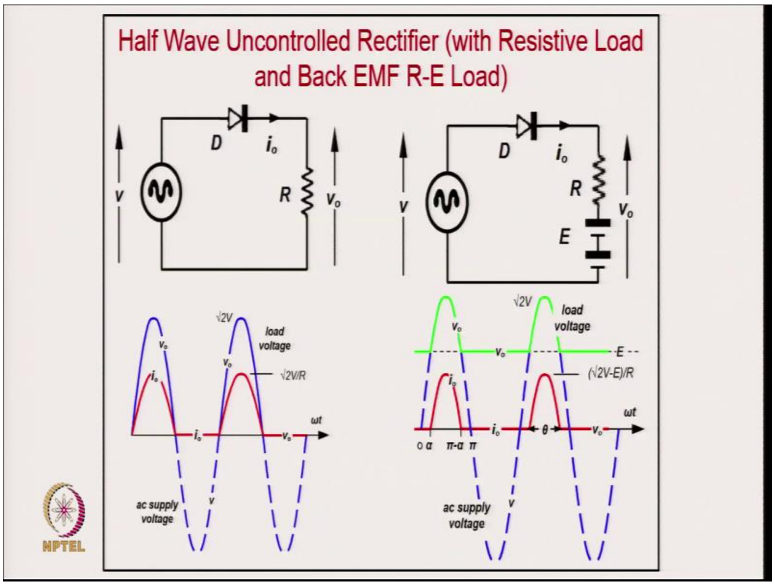

In the single phase uncontrolled half wave AC-DC converter, you will get the supply current only in the positive half cycle, where the voltage is in positive high. As you can see, this system injects DC component into the supply system and due to this, it is used for a small battery charging with very low power. However, such converters not only inject the harmonics in the supply system but also inject DC component into supply system which may cause transformer saturation.

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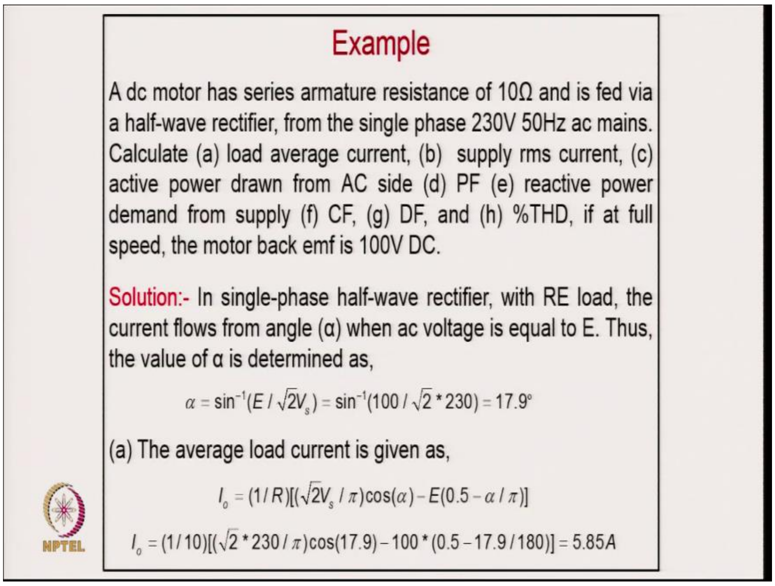

Considering an example of half wave uncontrolled AC-DC converter. A DC motor has a series armature resistance of 10 ohm fed via a half - wave rectifier, from a single phase 230 volt 50 hertz AC mains. Calculate the load average voltage, supply rms current, active power drawn, power factor, reactive power, crest factor, distortion factor, and THD, if at the fully speed, the motor back EMF is 100 volts.

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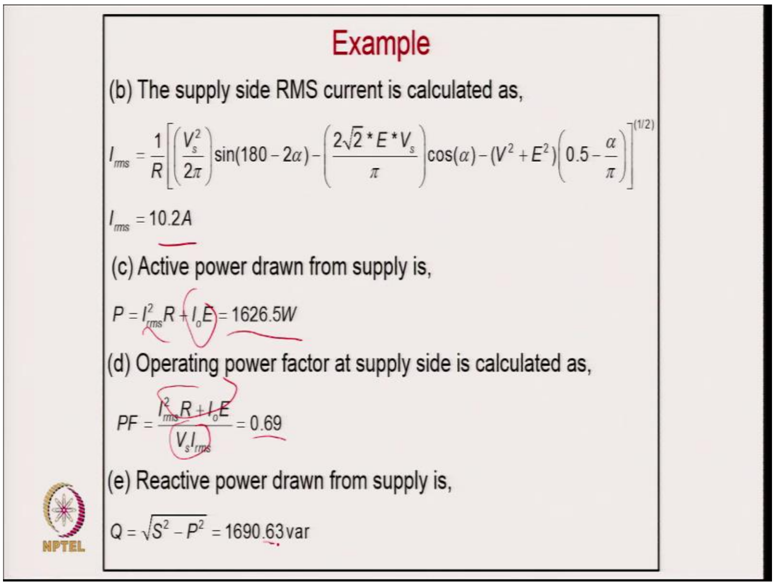

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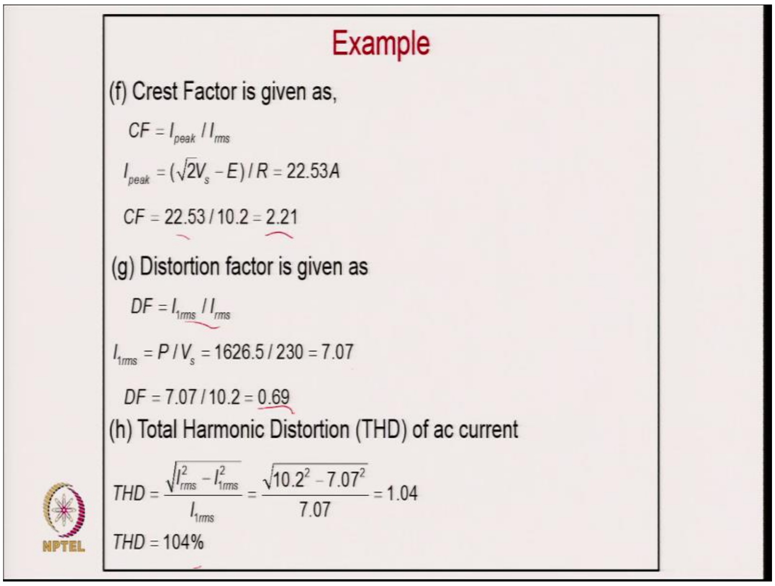

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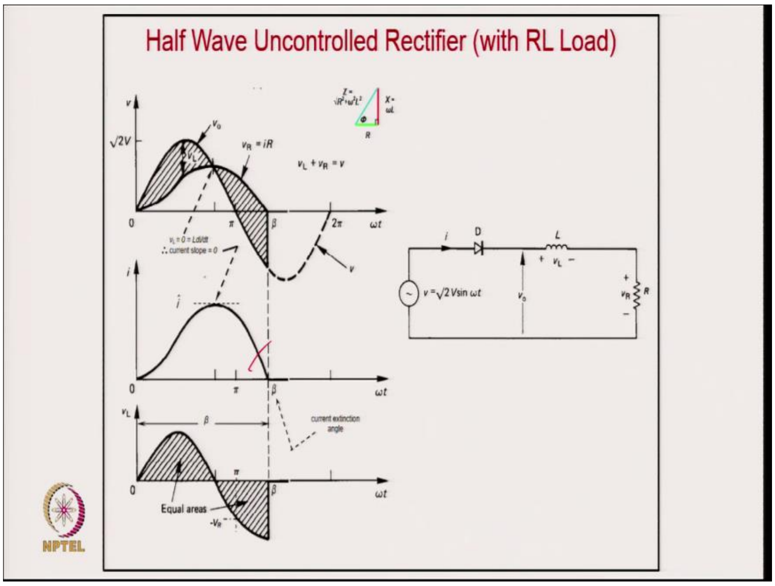

Now, coming to half wave uncontrolled rectifiers with RL loads. You can see how the current will be drawn from the supply during RL load. This type of circuits not only draws AC component from the supply but also draws DC component from it.

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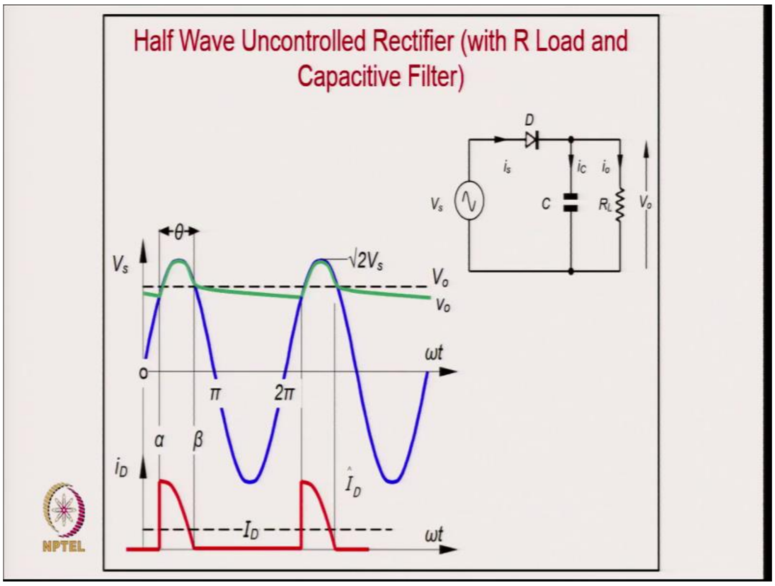

And this is the kind of current, a half wave uncontrolled rectifiers will draw from supply end in case of R loads with capacitive filters.

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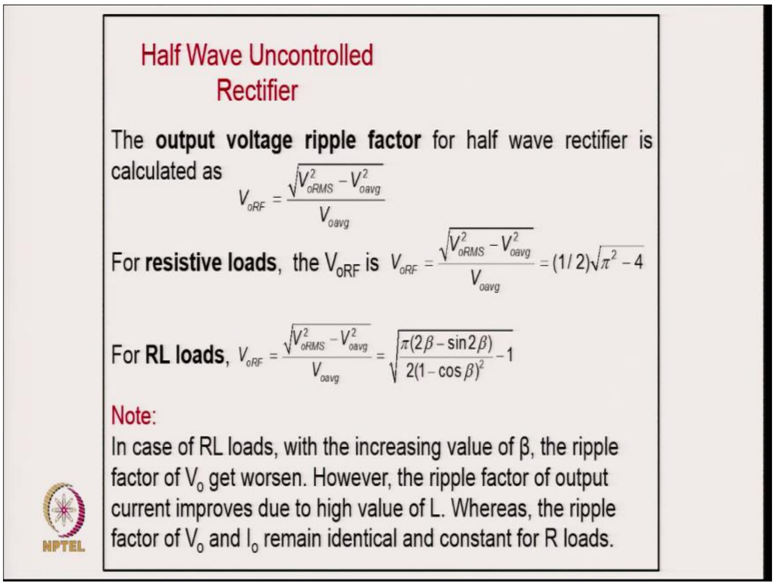

And then you can do the calculations for the output average voltage or RMS voltage.

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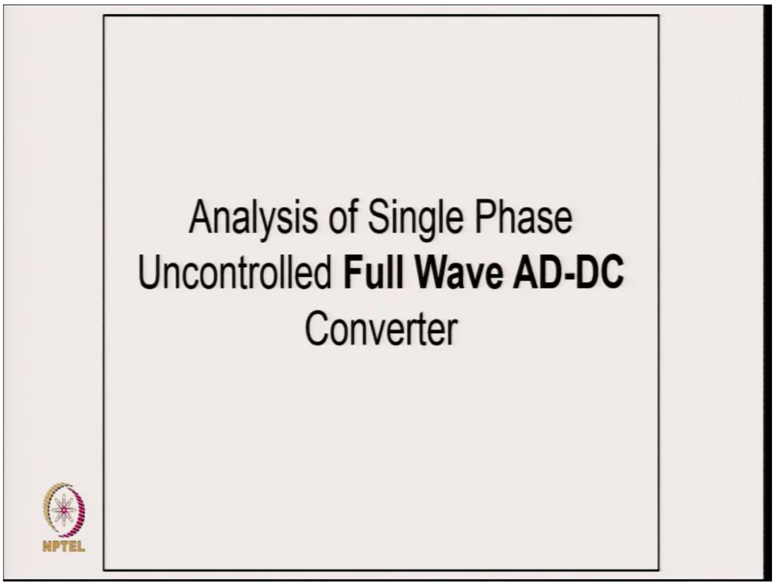

So, now coming to Single Phase Uncontrolled Full Wave AC-DC Converters.

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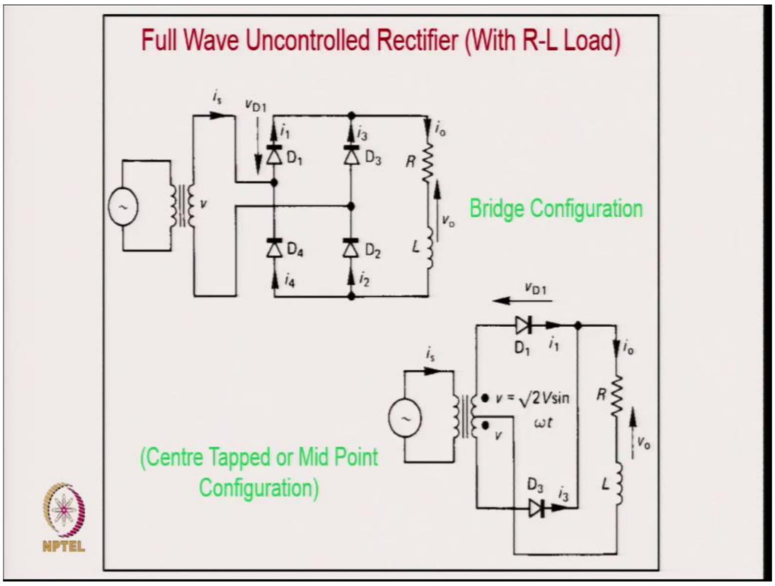

The full wave AC-DC converters can be a bridge type or it can be of midpoint configurations. Normally, the bridge type configuration is preferred, because this normally avoid the transformer, if the input and output voltages are matching. However, the center tapped or midpoint configuration have certainly less conduction losses because it has only single diode drop as compared to two diode drops in full bridge configuration.

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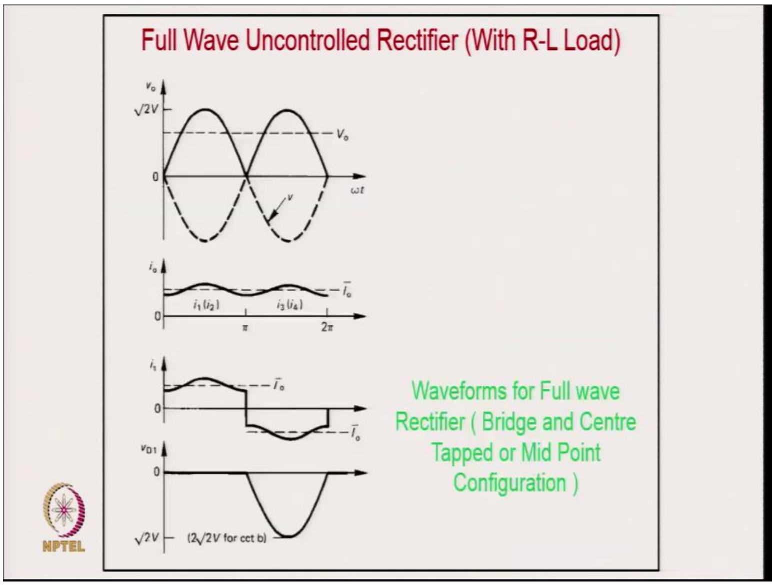

However, if you have a highly inductive load then certainly supply current will have a square type wave shape, whereas the output current remains almost constant. It is clearly seen that this type of load has substantial harmonics like it might have a THD of 48 % with 3^{rd} harmonic equal to $1/3^{rd}$ of the fundamental and 5^{th} harmonic equal to $1/5^{th}$ of the fundamental and so on.

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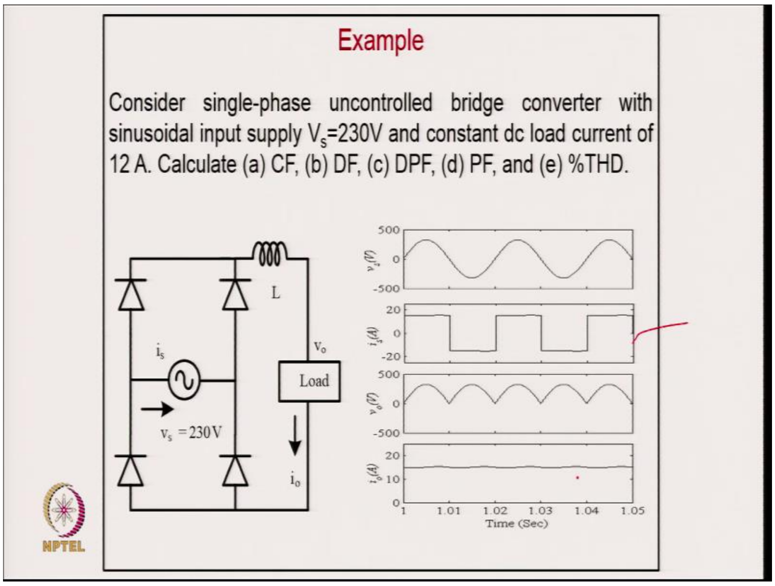

Now coming to an example of uncontrolled bridge type full wave AC-DC converter with highly inductive loads.

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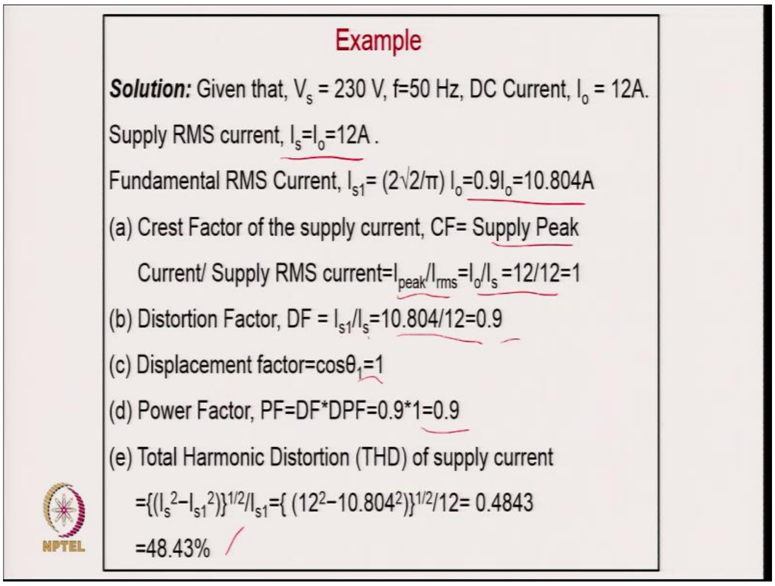

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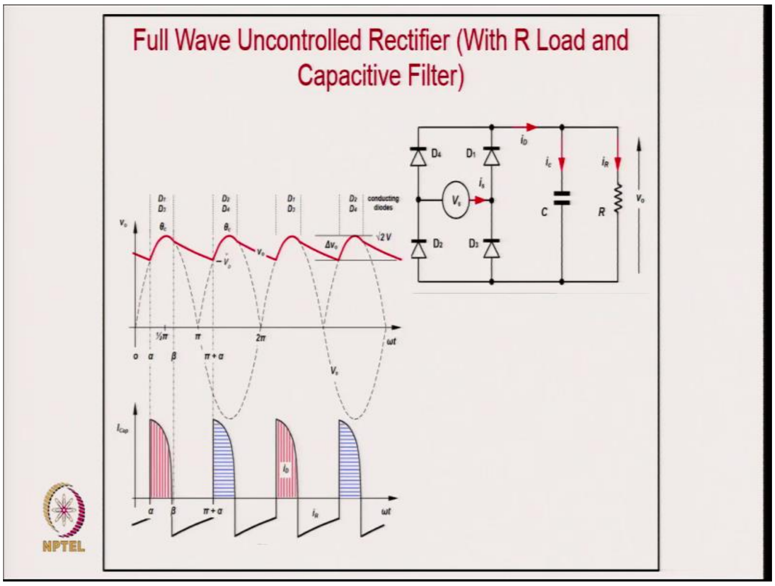

The previous case was with highly inductive loads, however, if you have a capacitive type load at the output of uncontrolled full wave bridge rectifiers, then, the load will draw peaky current during the positive half and negative half cycle of supply voltage. In such case, the current will be drawn only when the supply voltage goes more than the capacitor voltage, which is virtually the load voltage.

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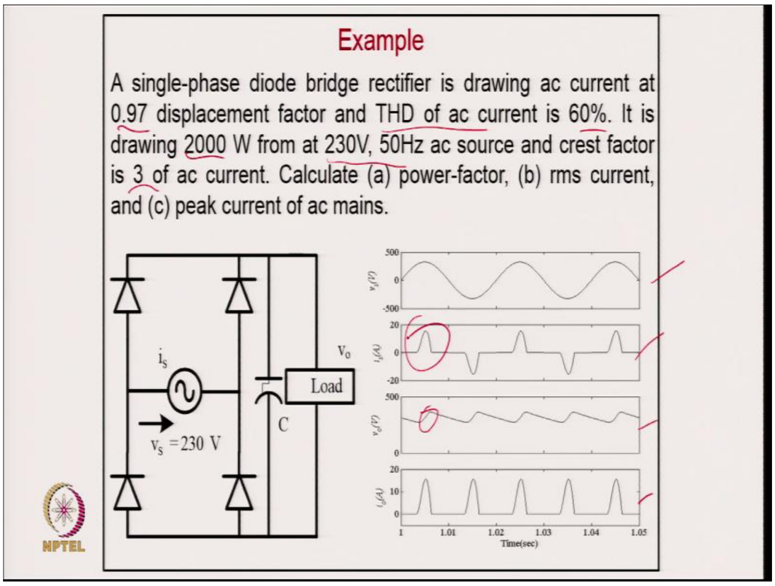

And the typical example corresponding to this is given as.

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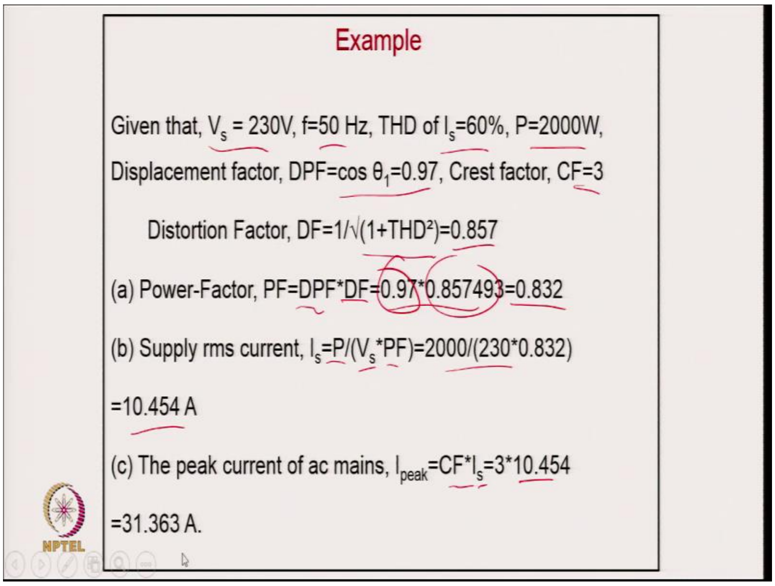

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Full Wave Uncontrolled Rectifier (Centre Tapped/ Mid Point/Bridge Configuration)

The form factor for the full wave rectifier is given as,

$$V_{oFF} = V_{oavg} / V_{oRMS} = \pi / 2\sqrt{2}$$

Similarly, the ripple factor is calculated as,

$$V_{oRF} = \frac{\sqrt{V_{oRMS}^2 - V_{oavg}^2}}{V_{oavg}} = (1/2\sqrt{2})\sqrt{\pi^2 - 8}$$

Both the form factor and the ripple factor shows considerable improvement over their half wave counter parts

These are the calculation for the output side parameters.

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Comparison of Single Phase Uncontrolled AC-DC Converters (Half Wave/ Full Wave Centre Tapped/Full Wave Bridge Configuration)

	Half-wave rectifier	Full-wave rectifier with center-tapped transformer	Full-wave bridge rectifier
Peak repetitive reverse voltage V_{RRM}	$3.14V_{dc}$	$3.14V_{dc}$	$1.57V_{dc}$
RMS input voltage per transformer leg V_s	$2.22V_{dc}$	$1.11V_{dc}$	$1.11V_{dc}$
Diode average current $I_{F(AV)}$	$1.00I_{dc}$	$0.50I_{dc}$	$0.50I_{dc}$
Peak repetitive forward current I_{FRM}	$3.14I_{F(AV)}$	$1.57I_{F(AV)}$	$1.57I_{F(AV)}$
Diode rms current $I_{F(RMS)}$	$1.57I_{dc}$	$0.785I_{dc}$	$0.785I_{dc}$
Form factor of diode current $I_{F(RMS)}/I_{F(AV)}$	1.57	1.57	1.57
Rectification ratio	0.405	0.81	0.81
Form factor	1.57	1.11	1.11
Ripple factor	1.21	0.482	0.482
Transformer rating primary VA	$2.69P_{dc}$	$1.23P_{dc}$	$1.23P_{dc}$
Transformer rating secondary VA	$3.49P_{dc}$	$1.75P_{dc}$	$1.23P_{dc}$
Output ripple frequency f_r	$1f_i$	$2f_i$	$2f_i$

Further, this is the comparison among different categories of single phase uncontrolled AC-DC converters.

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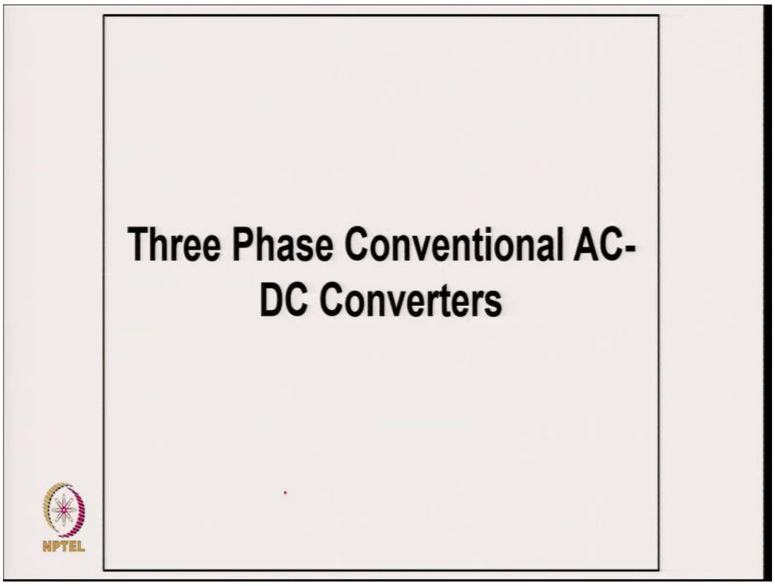

Now, coming to three phase conventional AC-DC converters.

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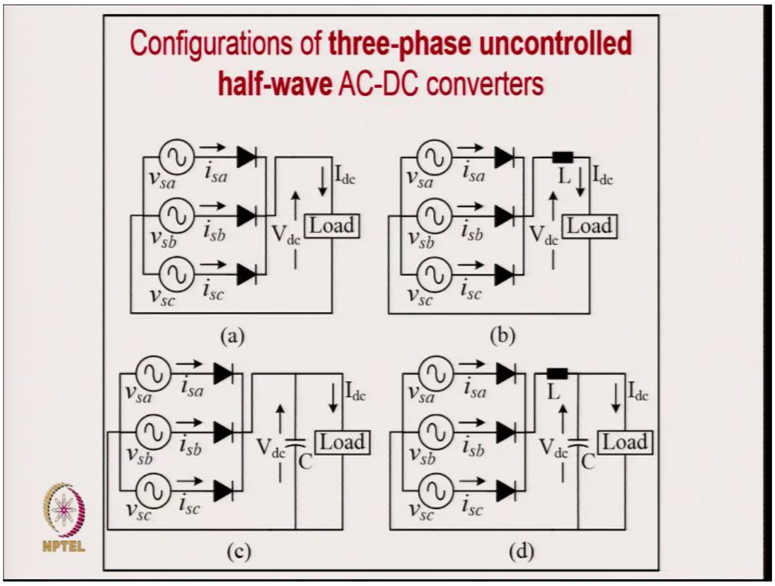

Such converters have also a lot of power quality problem. Like, three phase half wave AC-DC converters with no filter, with an inductive filter, with capacitive filter and with LC filter, draw not only the AC component from supply system but also draw DC component. That's why these are not used at high power level.

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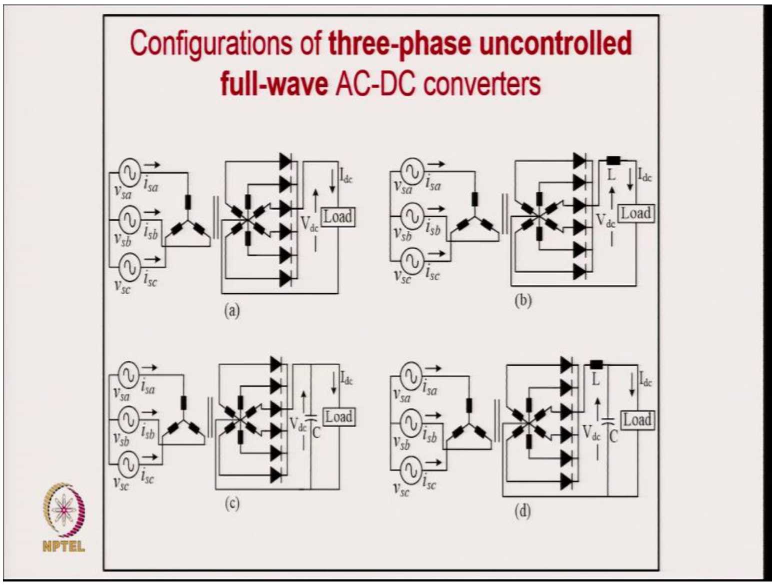

Now coming to three phase full wave converters, such converters use the transformer to convert three phase into six phases, which further connected to six diode rectifier. Such converters give the six pulses at the input end, and therefore, we will have a kind of quasi square wave current at the supply end, which we will discuss later. Of course, three phase full converters can also have inductive filter, capacitive filter and LC filter at their output end.

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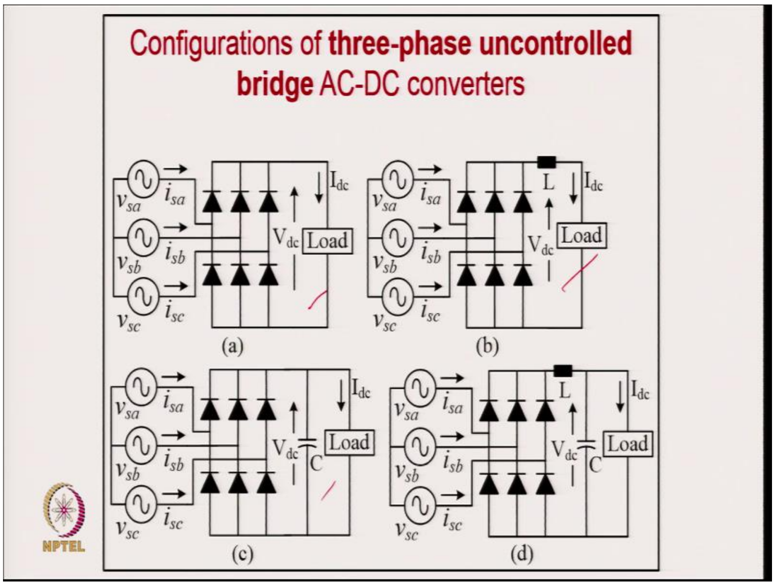

And these are the bridge type configurations of three phase full wave uncontrolled AC-DC converter. Normally, such configurations can have either simple resistive loads or can have highly inductive loads or capacitive loads at their output end. For example, all the variable frequency drives have capacitive load characteristics, and therefore, draw a very peaky current from the supply and the THD of the supply current might as high as 60 to 65 %. However, in case of inductive loads, the supply current THD might be reduced to 30 to 35%. But this is a still quite high.

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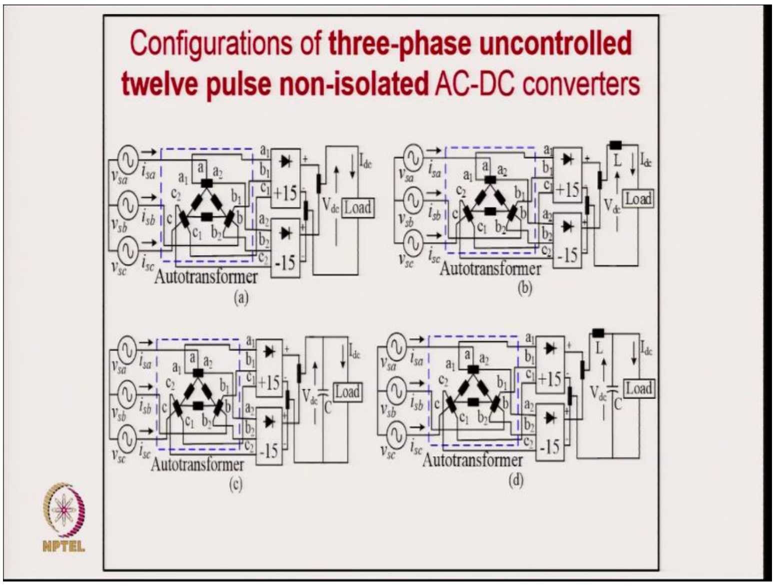

And these are the twelve pulse rectifiers with no filter, with inductive filter, with capacitive filter. As we increase the number of pulses the low frequency harmonics get eliminated, like in case of a 12 pulse rectifier below eleventh harmonics are eliminated automatically because of the design and construction of the rectifier, but higher order harmonics remain there substantially. So, we will still get around 15 to 20 % THD in the supply current which is not permitted by various power quality standards.

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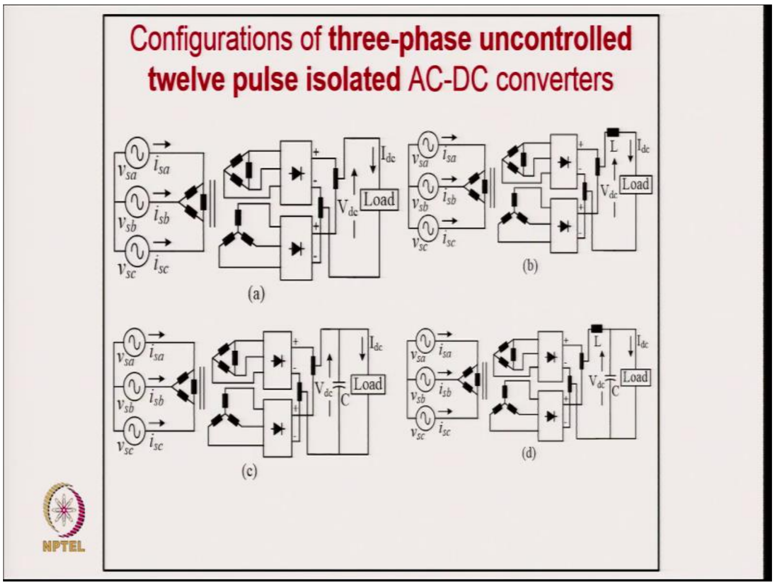

And these are the isolated configurations of twelve pulse rectifiers. Such configurations can be connected in series or parallel at output end due to their isolated structure. Such configurations have supply current THD of order typically around 15 to 16 %.

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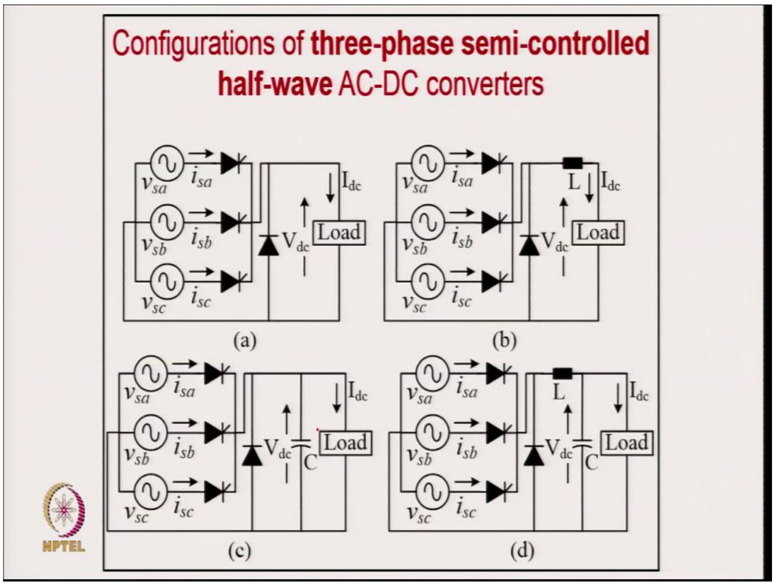

Coming to three phase semi controlled half wave AC-DC converters. Of course, such converters also draw the DC component from supply side, but these have a control of output voltage. However, these have a very poor power quality at supply side because such converters control the output voltage through firing angle control, which further put additional reactive power burden on the supply system. Thus, such converters not only draw distorted current at supply end (including DC components), but also put substantial reactive power burden on supply system.

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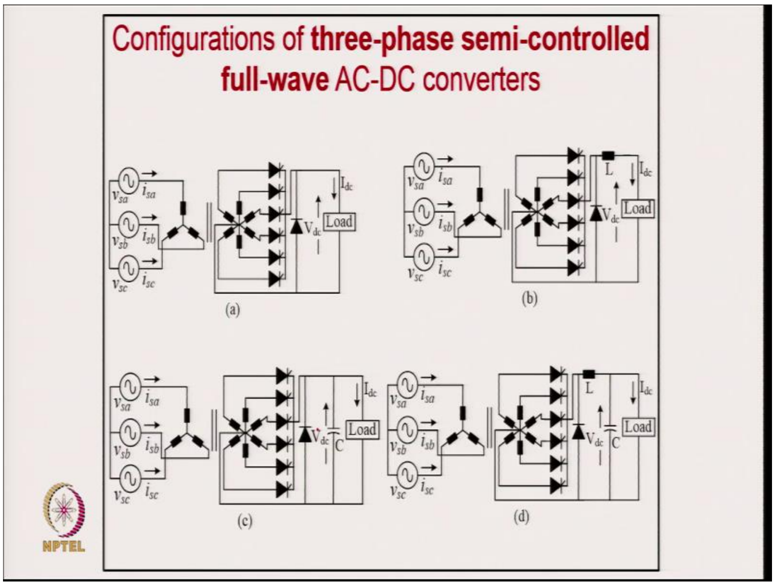

And these are the full wave semi controlled configurations. The diode at the output end will certainly cause the filling action and will not allow output voltage to go negative in any of the circuit. Of course, the output voltage can be varied from 0 to V, but you will be still having dependency upon the type of filter used in the circuit. Such configurations also have a good harmonic distortion as well as reactive power burden on the supply system.

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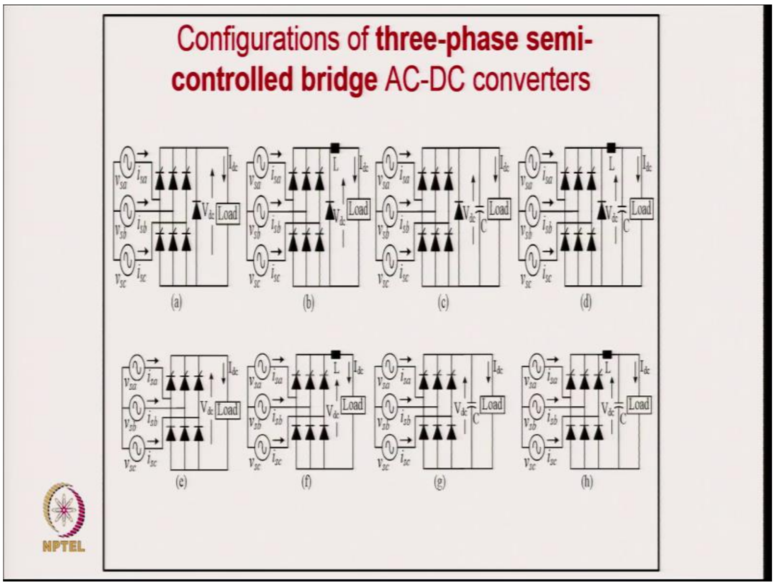

Similarly, in the semi controlled bridge type AC-DC converters, the output voltage remains positive, but such converters will have a reactive power and harmonics in the input supply.

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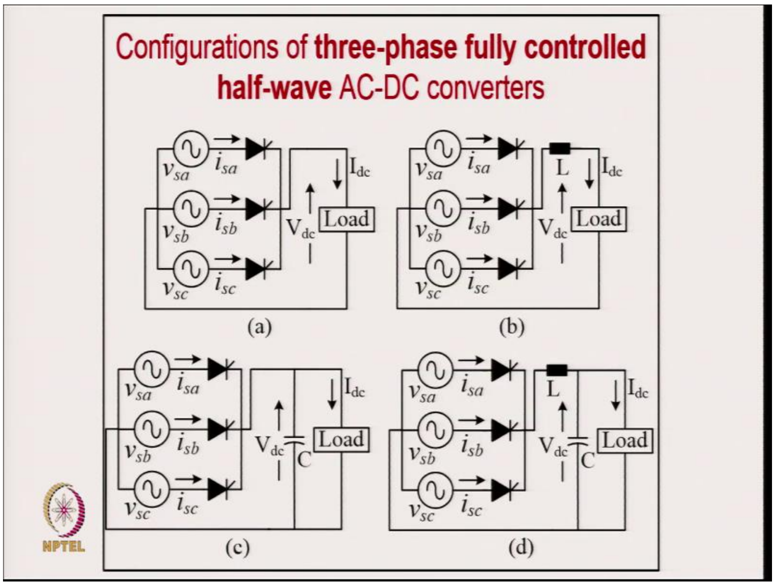

Now coming to three phase fully controlled AC-DC converters. Here, all configuration will certainly have the reactive power burden as well as harmonics distortion at the supply end.

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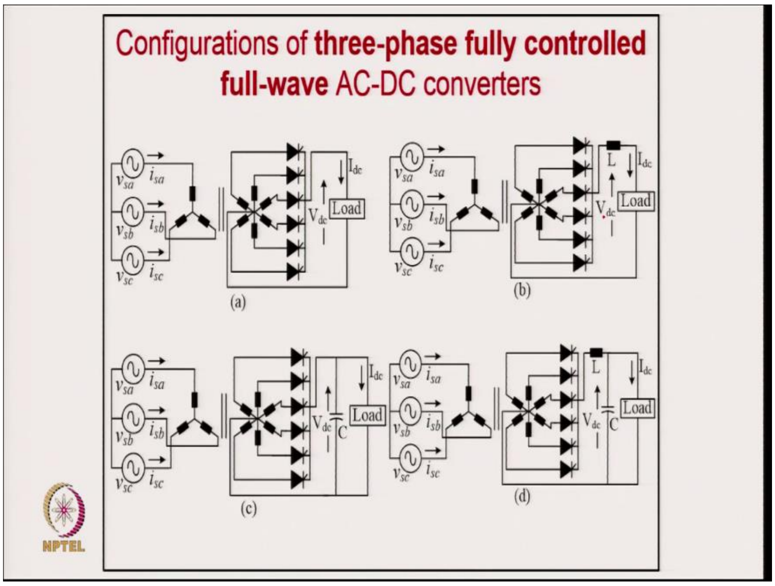

These are the three phase fully controlled full wave bridge type AC-DC converter configurations. In this case also, all configuration will certainly have the reactive power burden as well as harmonics distortion at the supply end.

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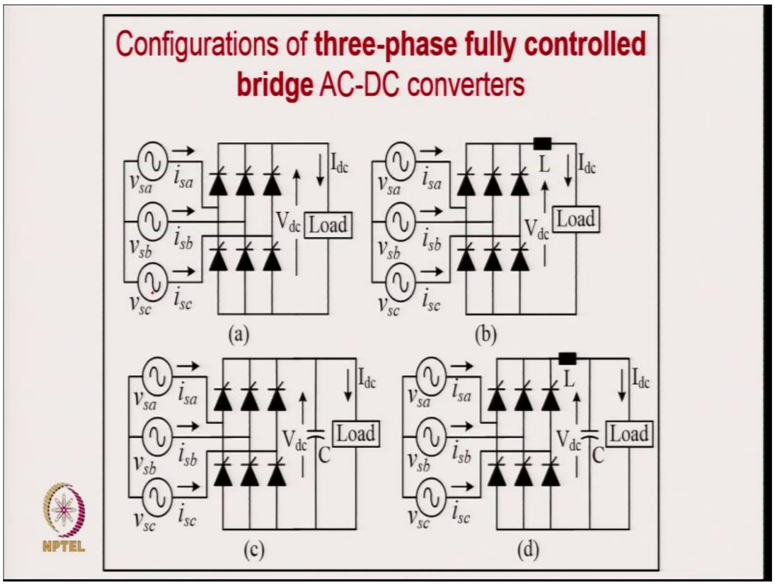

These are the three phase fully controlled full wave bridge type AC-DC converter configurations. In this case also, all configuration will certainly have the reactive power burden as well as harmonics distortion at the supply end.

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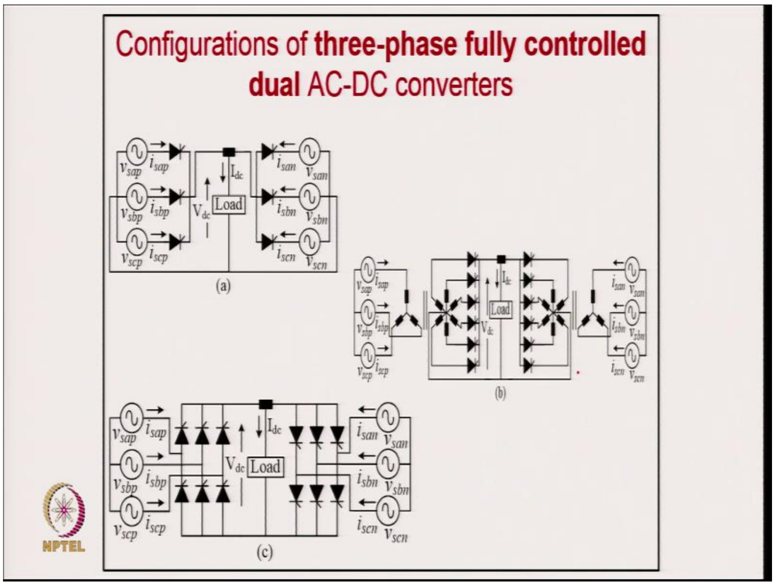

Now, coming to dual converters, such converters can also have half wave, full wave and bridge type configurations. These converters also draw a harmonics rich current and reactive power from the supply end. But of course, at the load end, such converters can have four quadrant operation, which is certainly requires in many applications like in a DC motor drive.

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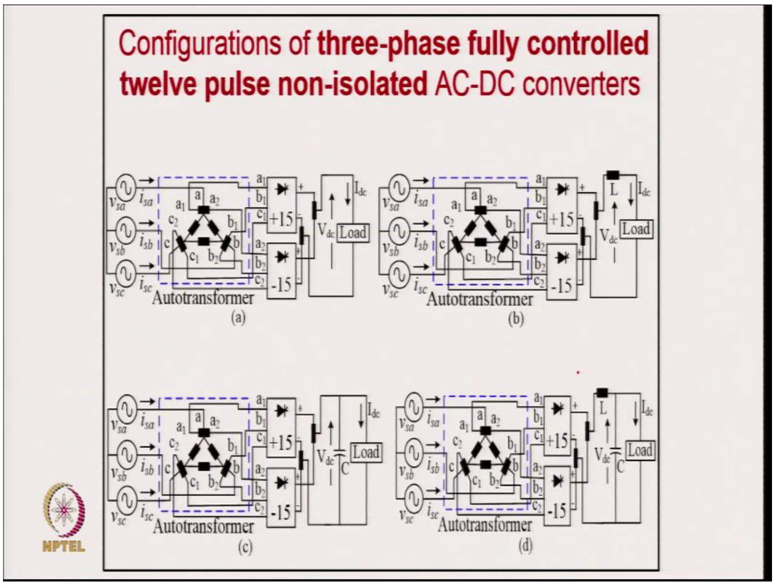

These are the three phase fully controlled twelve pulse non isolated AC-DC converter configurations.

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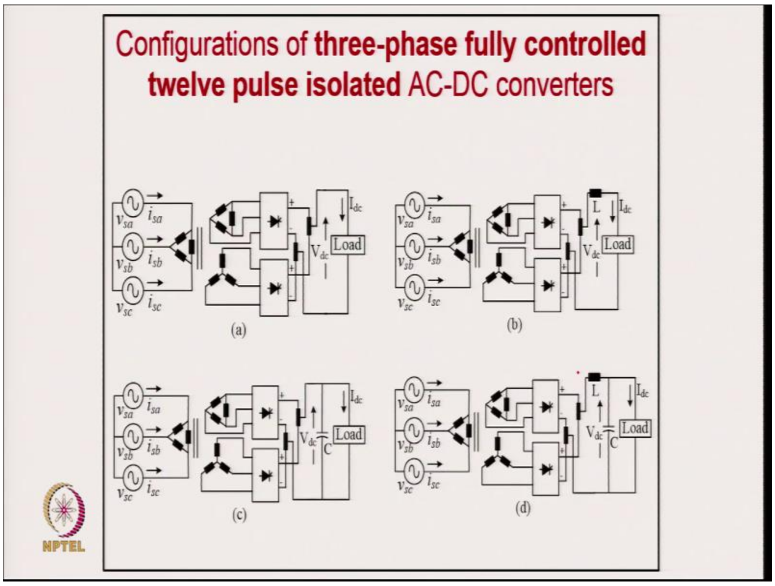

And these are of course isolate topologies of the three phase fully controlled twelve pulse AC-DC converters.

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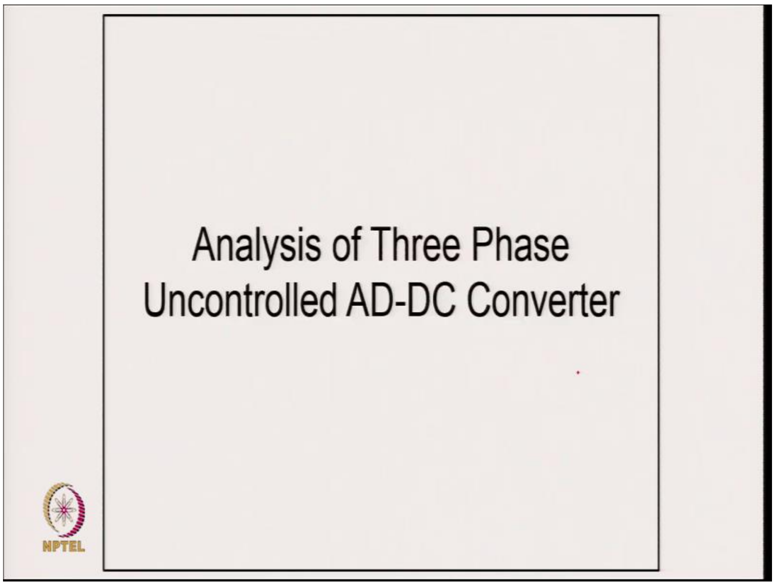

So, coming to the analysis part of these three phase uncontrolled AC-DC converters.

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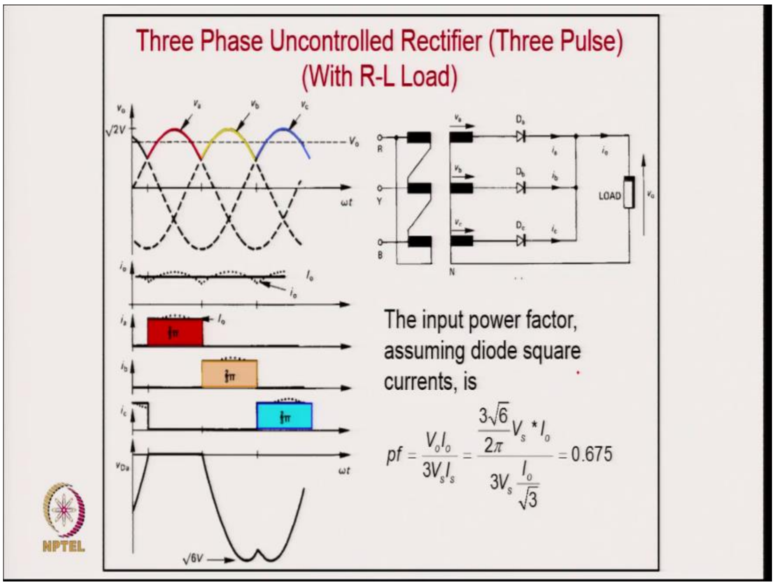

So, as mentioned previously, the isolated half wave AC-DC converters with R-L loads, will certainly draw DC component. So, such type of converters draws substantial low frequency harmonics from the supply end.

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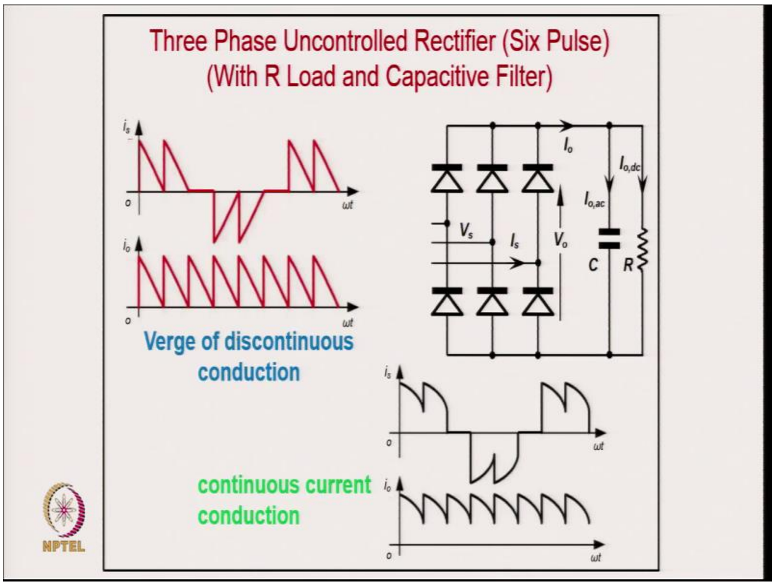

And if it is a bridge configuration with a capacitive filter, then it will draw hardly two notches, and these notches might be of discontinuous nature. So, such converters draw quite large amount of harmonics from supply and depending upon the nature of the load, the supply current THD may goes around 60 to 65 percent.

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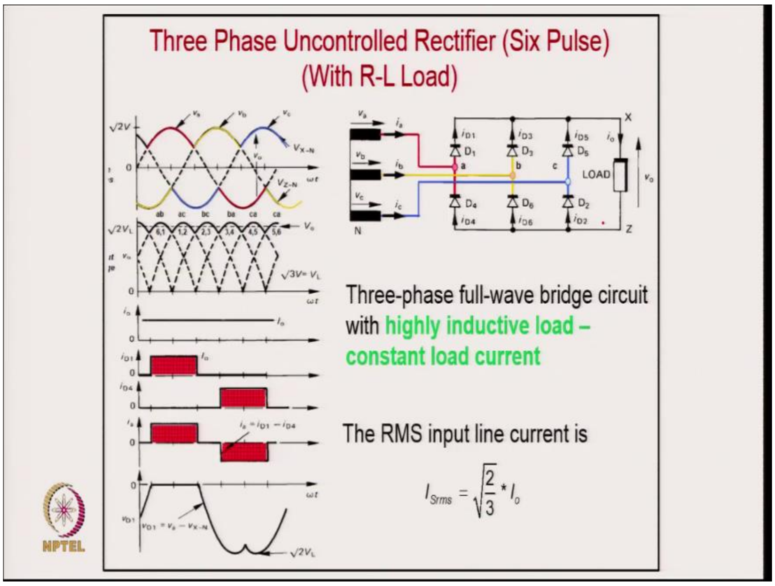

And then this is a typical example, if three phase uncontrolled bridge rectifiers have a highly inductive load, then such converters will draw typically quasi square wave supply current and therefore can have supply current THD of around 31 % like or so.

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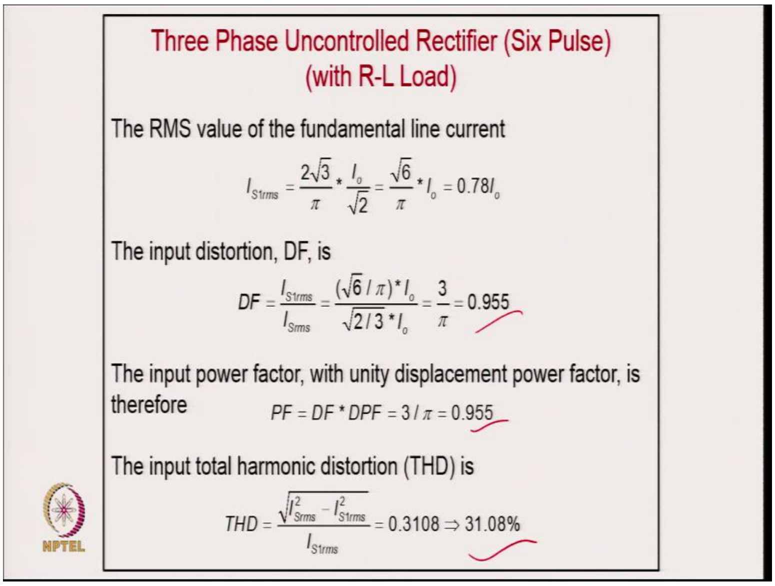

And these are the typical calculations for the uncontrolled rectifier with an RL loads.

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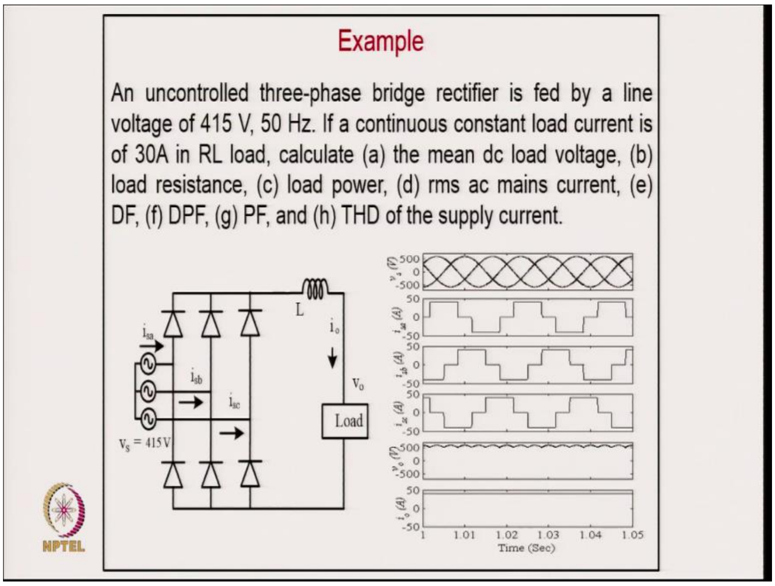

This an example of three phase bridge type uncontrolled AC-DC converter with heavy inductive load.

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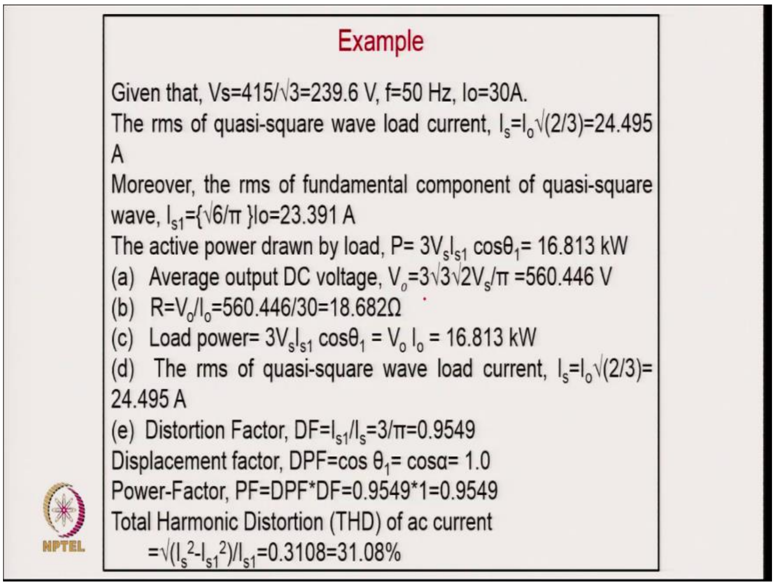

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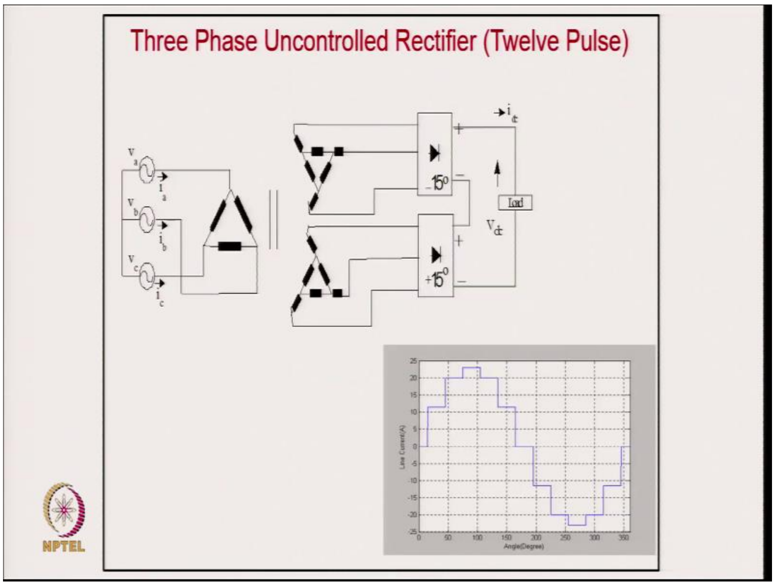

And this is the twelve pulse converter supply current waveform. Of course, the supply current will have twelve pulses and therefore, will not have less than eleventh harmonics. But, it still has around 15 to 16 % supply current THD.

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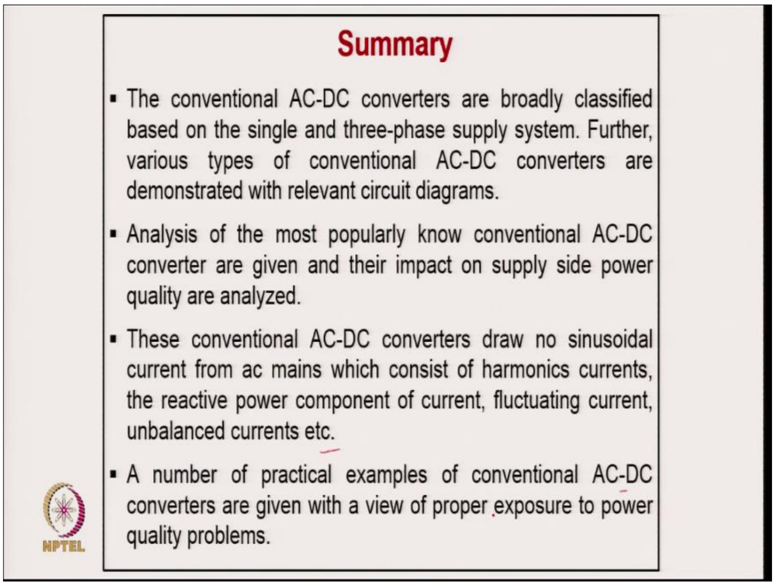

So, the conventional AC-DC converters are broadly classified based on single phase and three phase supply system. Further, various types of conventional AC-DC converters are demonstrated with relevant diagrams. Analysis of most of the popularly known conventional AC-DC converters are given and their impact on supply side quality and on power quality are analyzed.

These conventional AC-DC converters draw non sinusoidal current from AC mains which consist of harmonics and reactive power component of current, fluctuating current, unbalanced current. A number of practical examples of conventional AC-DC converter are given with a view of proper exposure to power quality problems.

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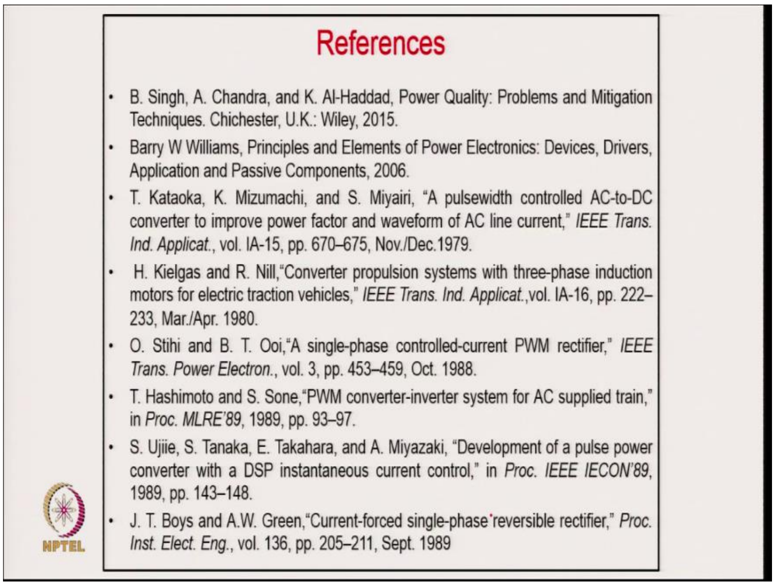

And these are the references.

Thank you.