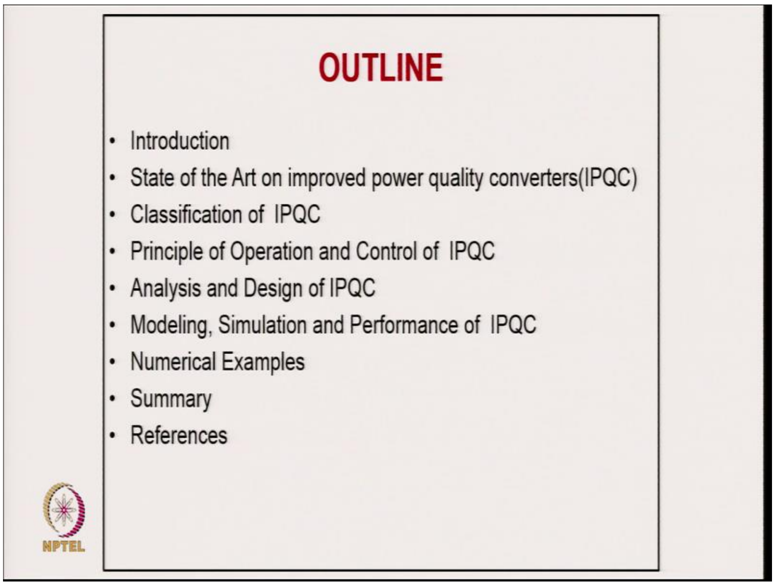
Power Quality
Prof. Bhim Singh
Department of Electrical Engineering
Indian Institute of Technology, Delhi

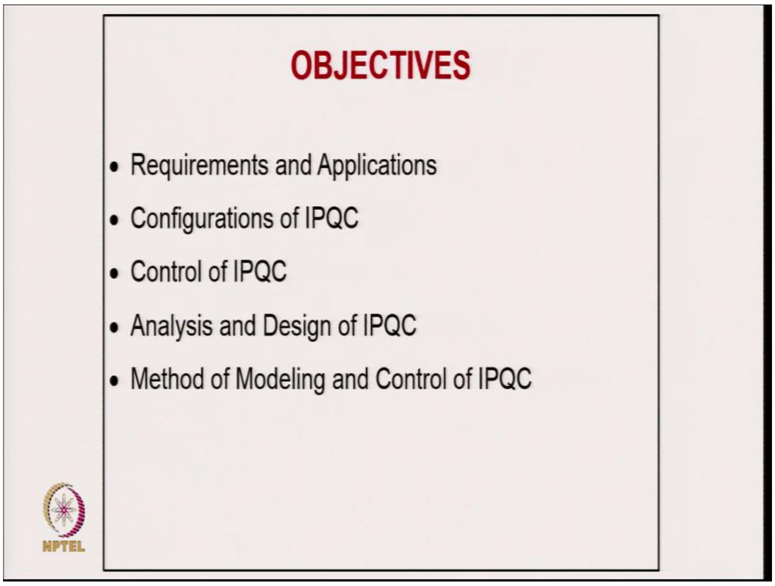
Module - 01
Lecture - 30
Improved Power Quality Converters- AC-DC Boost Converters

(Refer Slide Time: 00:29)



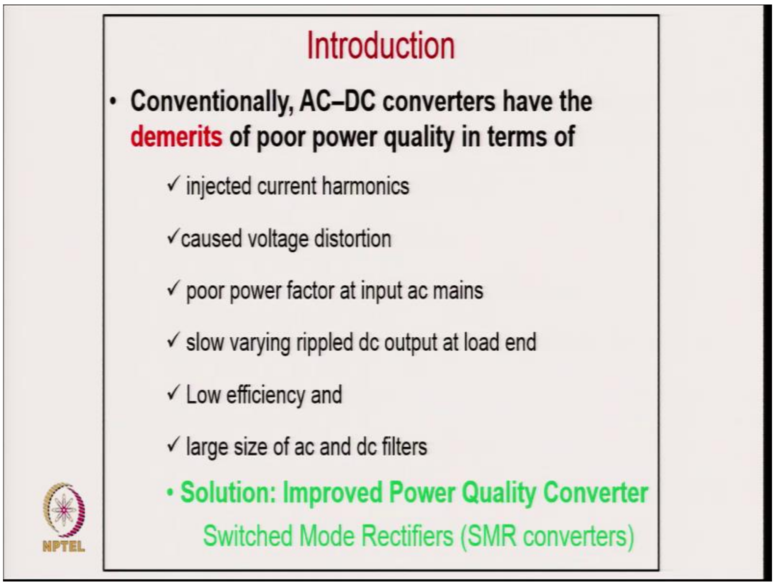
Welcome to the course on Power Quality. We will discuss today improved power quality converters AC to DC Boost Converter. Coming to outline part of it, starting with the introduction, state of art on improved power quality converters, we will discuss about classification, then principle of operation and control of improved power quality converters, then analysis and design of improved power quality converter, and modelling simulation and performance of improved power quality converter. We will have some numerical examples followed by summary and references.

(Refer Slide Time: 00:55)



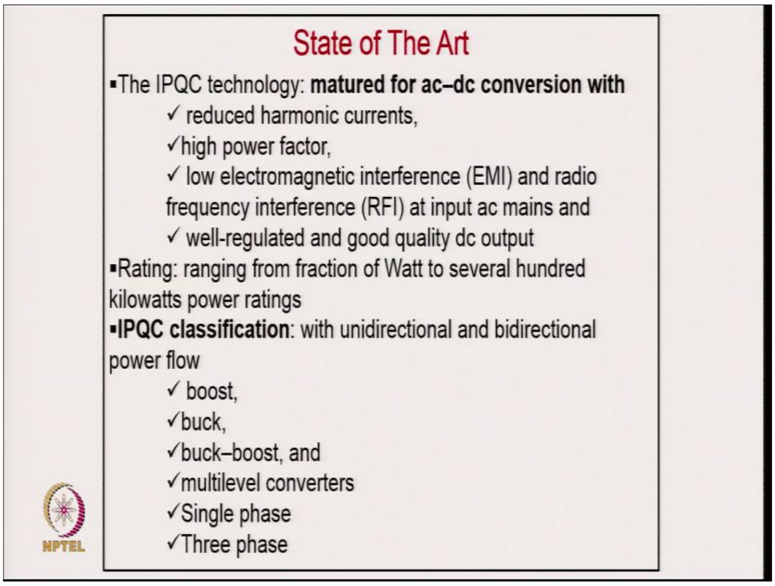
First, we would like to discuss about the objectives of this lecture which mainly include the requirement and applications of the improved power quality converters (IPQCs), configuration of IPQCs, control of IPQCs, analysis and design IPQCs, and method of modelling and control of IPQCs.

(Refer Slide Time: 01:19)



Well, conventional AC-DC converters have demerits of poor power quality in terms of injected current harmonics, which causes the voltage distortion at the point of common coupling where they are connected and also caused poor power factor at the input AC mains, Further, the slow varying ripple in the DC output at load end, low efficiency, and large size of AC and DC filters are other major shortcoming of conventional AC-DC converters. The solution to these problems are improved power quality converters which also known as switched mode rectifier or also in short we call it switched mode SMR converters.

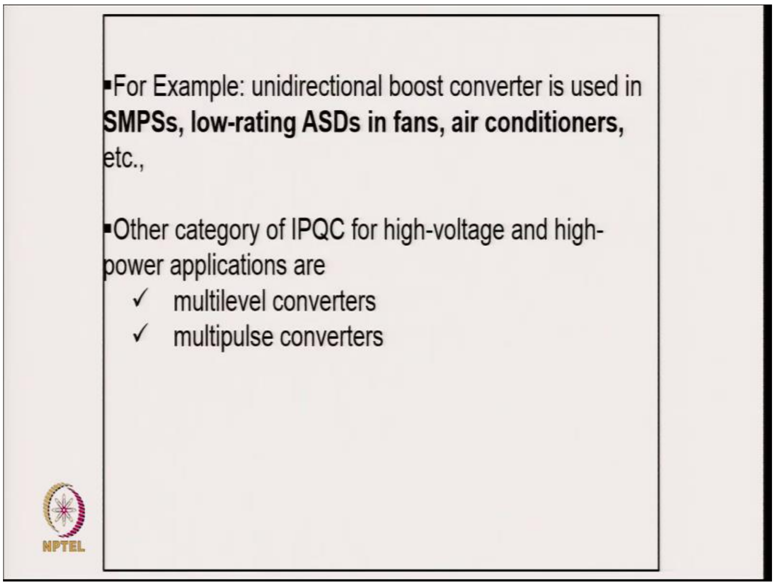
(Refer Slide Time: 02:03)



Coming to the state of art, the improved power quality converter technology is matured for AC-DC conversion with reduce harmonic currents, high power factor, low electromagnetic interference and radio frequency interference at input mains with well-regulated DC output. The rating of these converters varies from fraction of watt to several 100-kW.

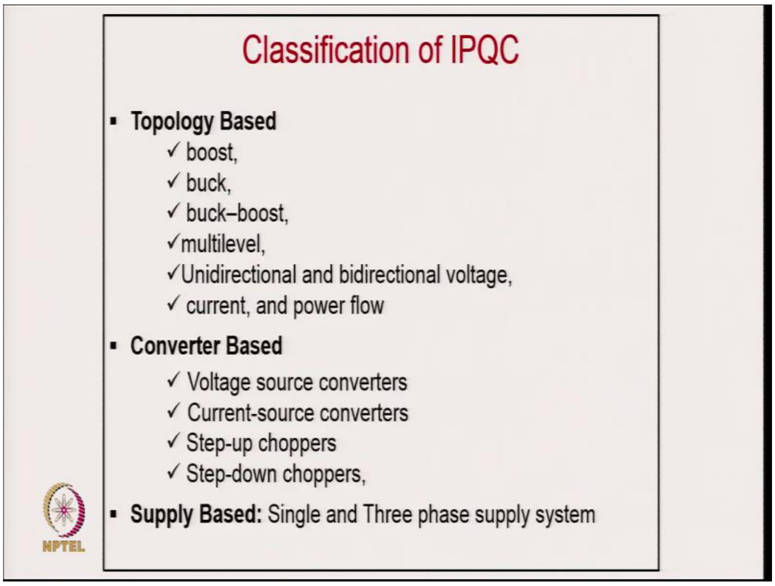
Further, the improved power quality converters are classified into different category and these are the typical classification with unidirectional and bidirectional power flow like boost converters buck converter, buck boost converter, multi-level converters. Of course, the another classification is based on type of supply like single phase and three phase supply.

(Refer Slide Time: 02:55)



For example, the unidirectional boost converter is used in switched mode power supplies, low power adjustable speed drive in fans, air conditioners, welding machines, and in other home appliances like in washing machines, ceiling fans, etc. The other category of improved power quality converters for high voltage and high power applications are like multi-level converters and multi-pulse converters.

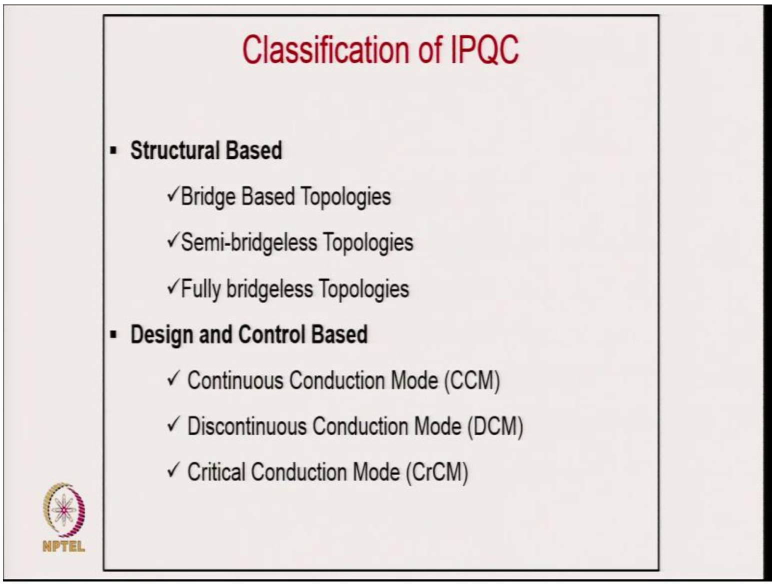
(Refer Slide Time: 03:27)



Now coming to the classification of the improved power quality converters (IPQCs), based on topology the IPQCs are classified into boost converter, buck converter, buck boost converters, and multilevel converters.

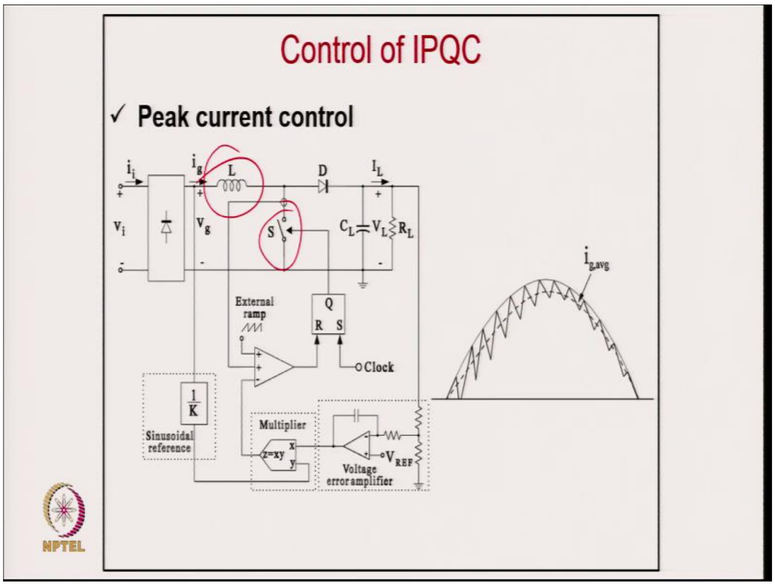
Well, another classification is based on the type of converters, i.e., voltage source converters or current source converters. Similarly, another classification is based on type of supply like single phase and three phase supply.

(Refer Slide Time: 04:04)



Based on structure, the IPQCs can be like a bridge-based topology or semi bridgeless topology or fully bridgeless topology. Further, based on the design and control, the IPQCs can be designed and controlled in continuous conduction mode, discontinuous conduction mode or critical conduction mode.

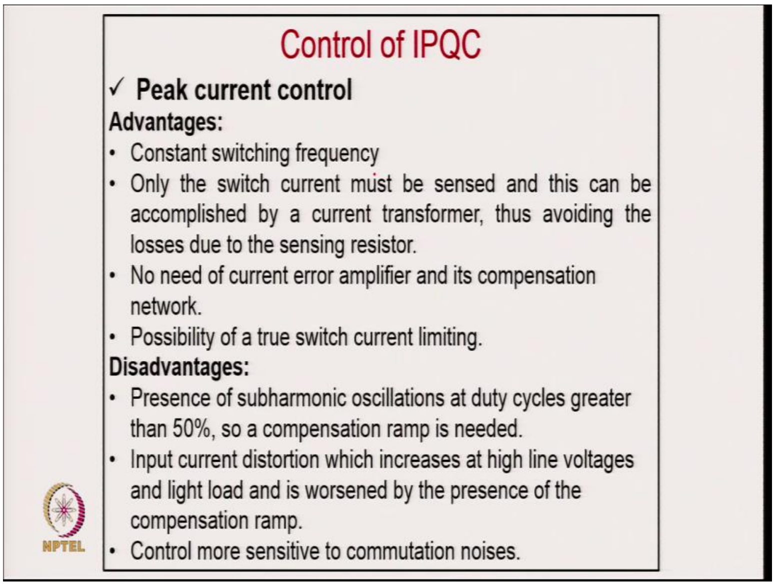
(Refer Slide Time: 04:45)



Starting with a single-phase boost IPQC, it consists of a simple diode rectifier followed by an inductor and the switch and diode and filter capacitor. The very purpose of this is to get a regulated output DC voltage with improved power quality at AC mains. In boost type IPQCs, the output voltage always remains greater than the peak of input AC voltage. It is also known as boost power factor corrected converter and extensively used in plenty of applications because the major advantage of such converters is that, you get regulated DC voltage irrespective of varying AC mains voltage.

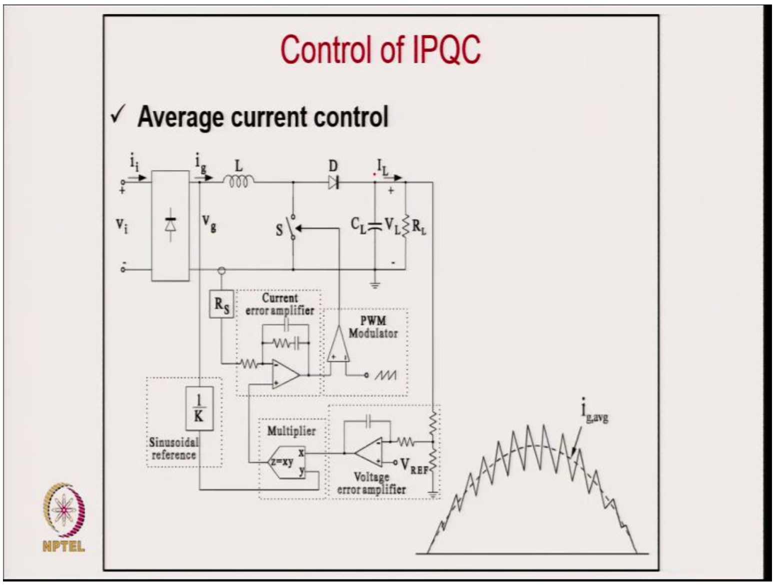
As far as the control of IPQCs is concerned, several types of control approaches are discussed here. Starting with the peak current control, the concept of peak current control is to control the output voltage across the load, while controlling peak current through active semiconductor switch. Here, the output voltage is feedback and we have a reference voltage at which the output voltage needs to be regulated. Then, we have an error amplifier, which is normally a PI controller, to reduce the error between reference and feedback voltage. The output of error amplifier is considered as the amplitude of supply current, which is multiplied by the rectified voltage to obtain reference current waveform. Now, the reference current is compared with sensed switch peak current and the error is then compared with the external ramp. Finally, the R S digital flip flop provides the required gating signal to the semiconductor switch.

(Refer Slide Time: 08:58)



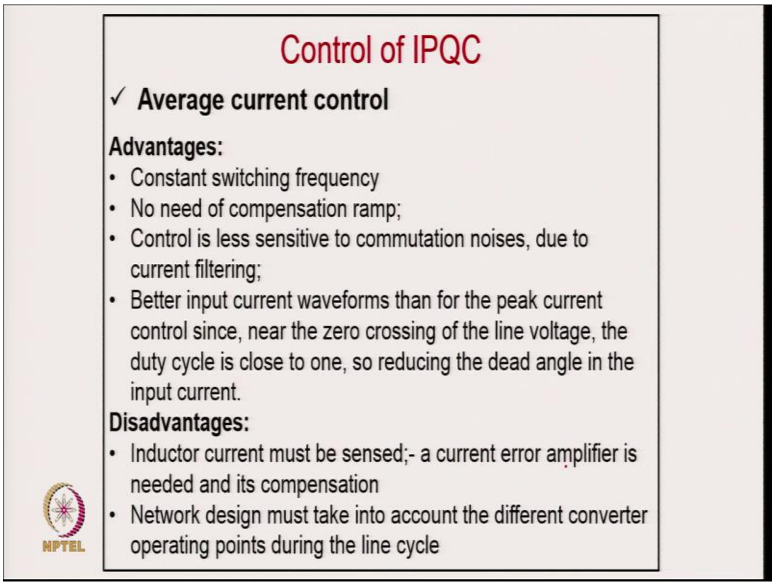
These are the advantages and disadvantages of the peak current control.

(Refer Slide Time: 09:55)



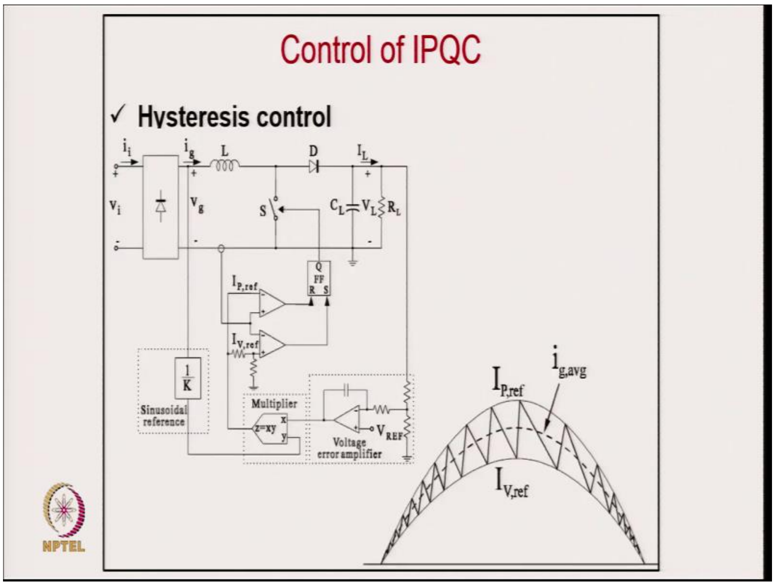
Well, the another control for the boost power factor corrected converter is the average current control. In this, the control action is based on the inductor average current and the control loop remain identical to previous control.

(Refer Slide Time: 10:43)



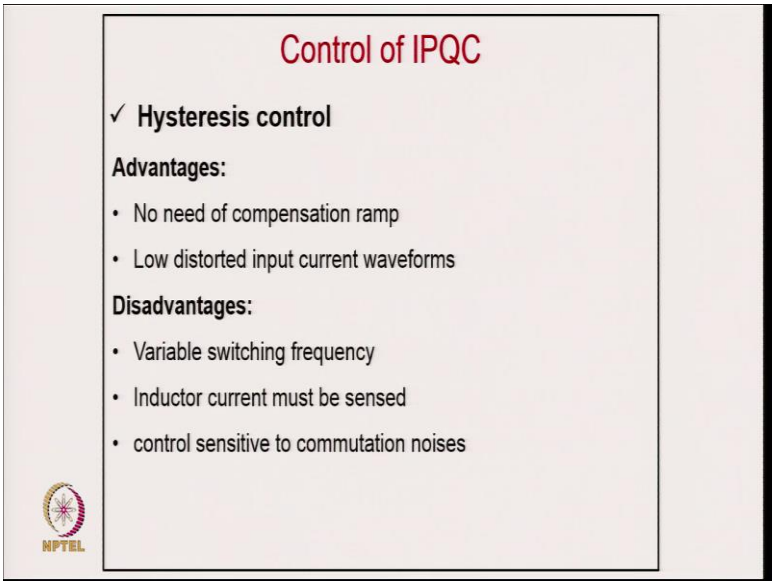
These are the advantages and disadvantages of the average current control.

(Refer Slide Time: 11:18)



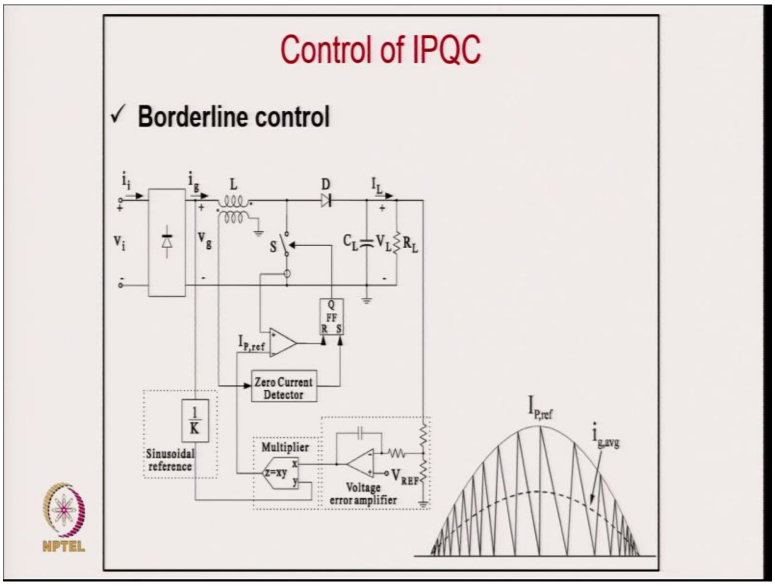
The third control is the hysteresis control. The concept of hysteresis is that the supply current should be maintained within the defined hysteresis band. In this the hysteresis band is realized by two comparator and the current is maintained within that hysteresis band. The control architecture remains identical to the previous control.

(Refer Slide Time: 11:52)



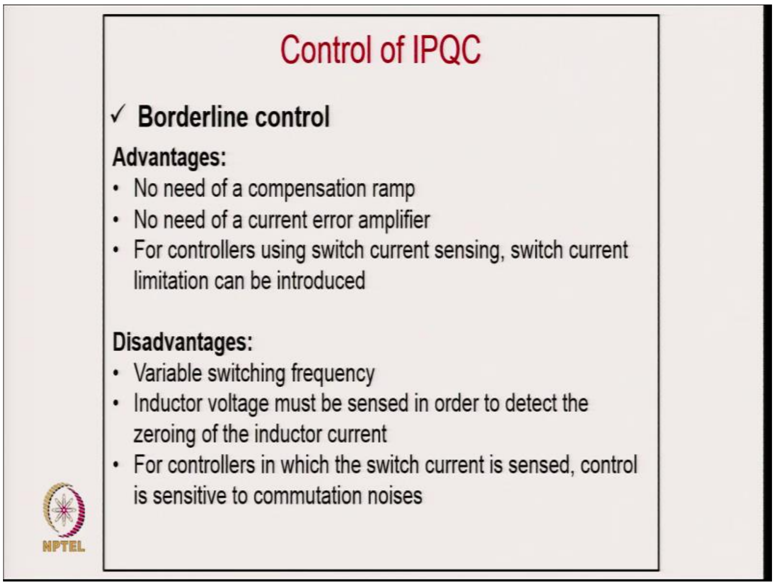
These are the advantages and disadvantages of the hysteresis current control.

(Refer Slide Time: 12:05)



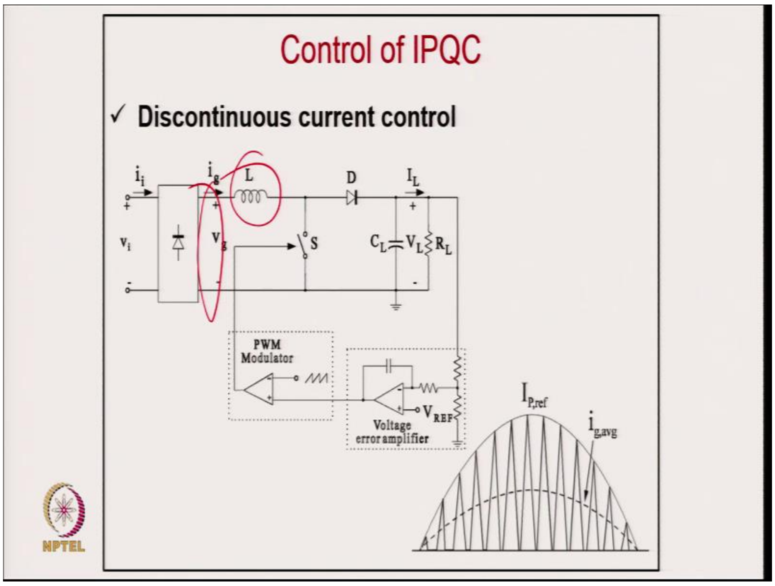
Another control is the borderline control, which is also known as the critical conduction mode. In this control, the current is reduced to zero just at the end of a switching cycle. Thus, the converter operates at the boundary of discontinuous current mode conduction and continuous current mode conduction, and therefore, utilizes the benefits of both controls.

(Refer Slide Time: 13:06)



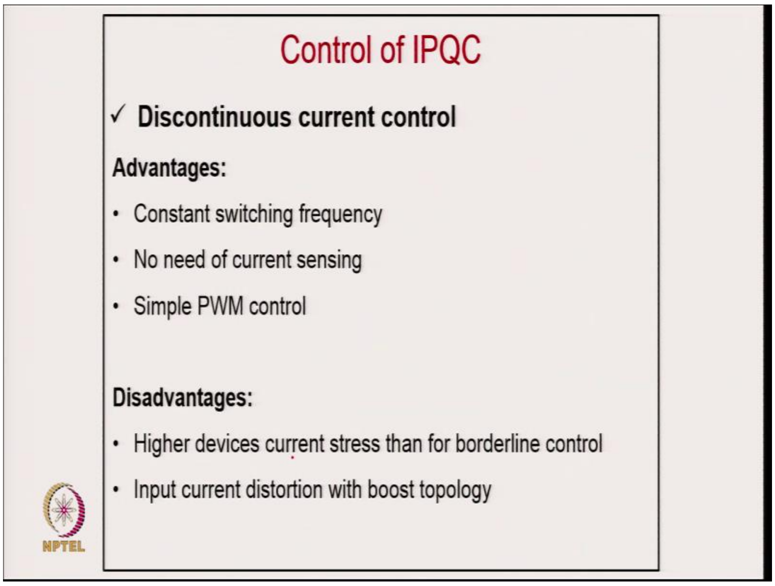
These are the advantages and disadvantages of the discontinuous current control.

(Refer Slide Time: 13:31)



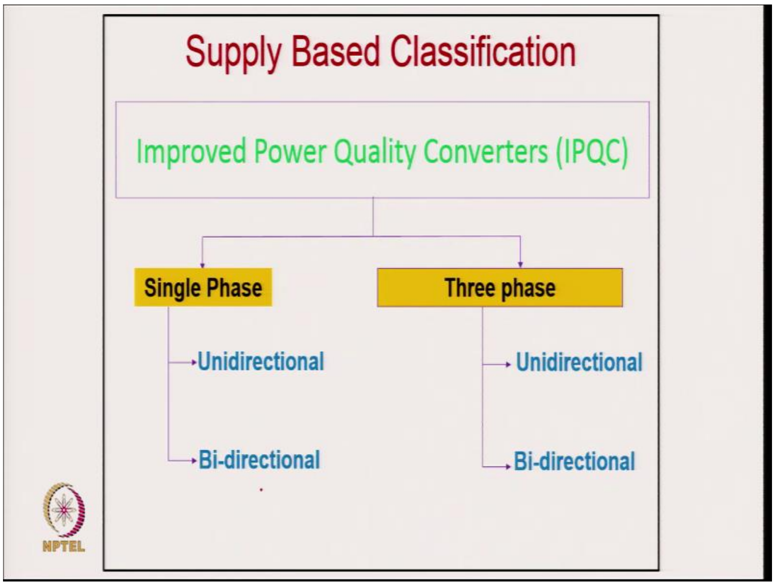
Well, the another control is the discontinuous current control. This control is very interesting in a sense that you do not need the sensor on AC side and it realizes inherent power factor at AC mains. Another major benefit of discontinuous current control is the reduced size of magnetic component. However, the peak current in such control is much higher as compared to other control methods.

(Refer Slide Time: 15:13)



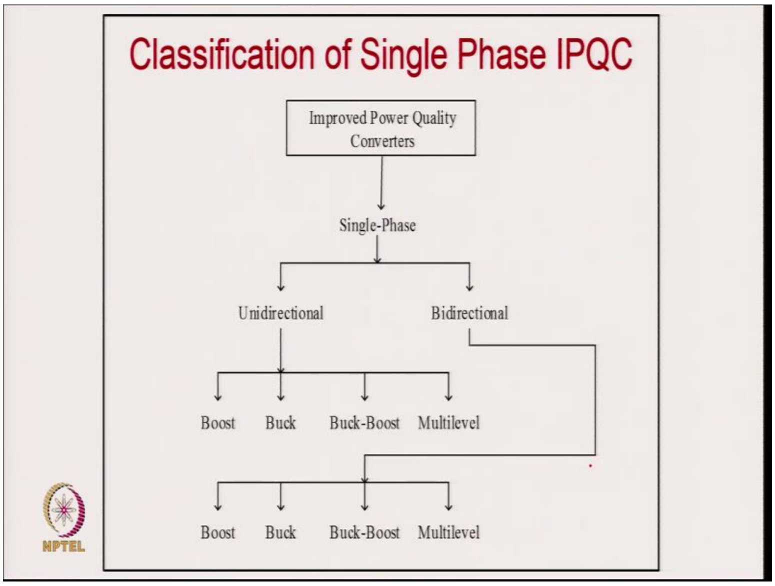
Well the advantage of this discontinuous current is constant switching frequency, no need of current sensing and simple control. Disadvantage high higher device current stress than the borderline control and input current distortion with boost topology or so.

(Refer Slide Time: 15:27)



Coming to supply based classification of improved power quality converters, the IPQCs can be classified in a single phase or a three phase. In which, we can have a unidirectional power flow or bidirectional power flow in single phase as well as we can have in three phase also unidirectional power flow and bidirectional power flow.

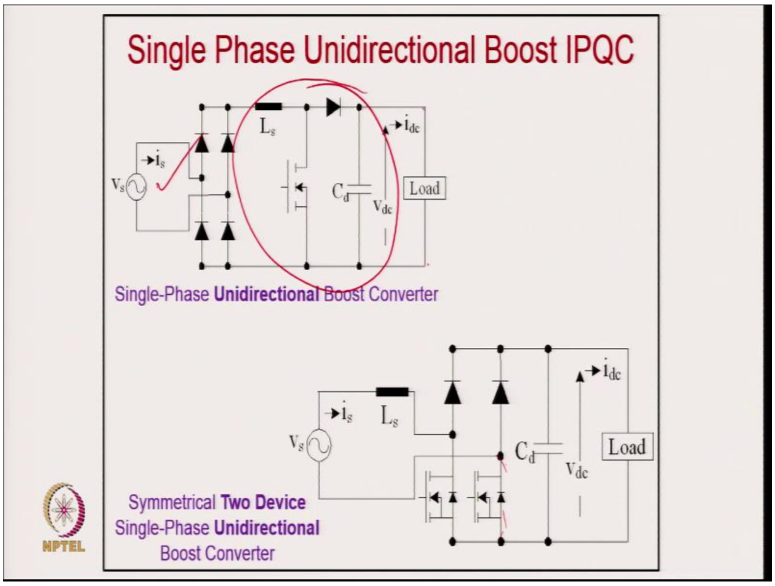
(Refer Slide Time: 15:47)



And coming to like a further of classification of single phase we can have unidirectional and bidirectional, and in unidirectional we can further have a boost, buck, buck-boost and multilevel. Further, in the bidirectional category, of course, we can have boost, buck, buck-boost and multi-level converters. So, this is the classification, in which the single phase improved power quality converter can be divided into 8 categories.

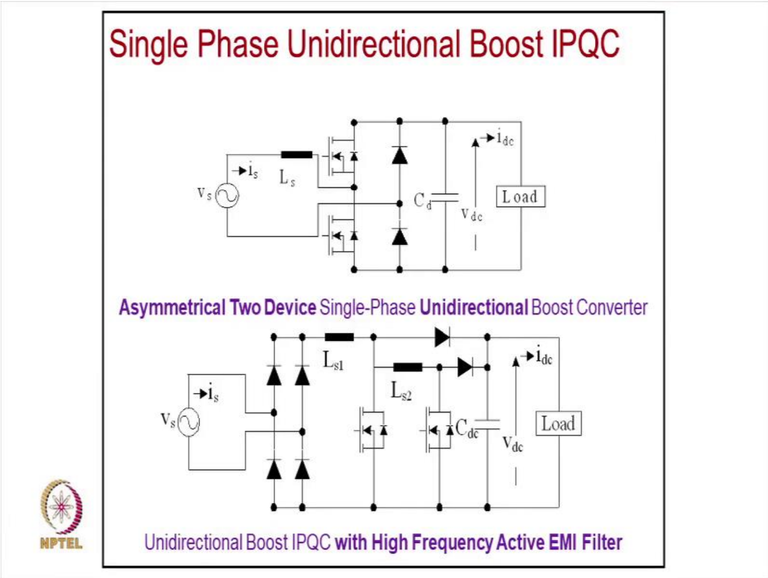
(Refer Slide Time: 17:01)

(Refer Slide Time: 17:02)



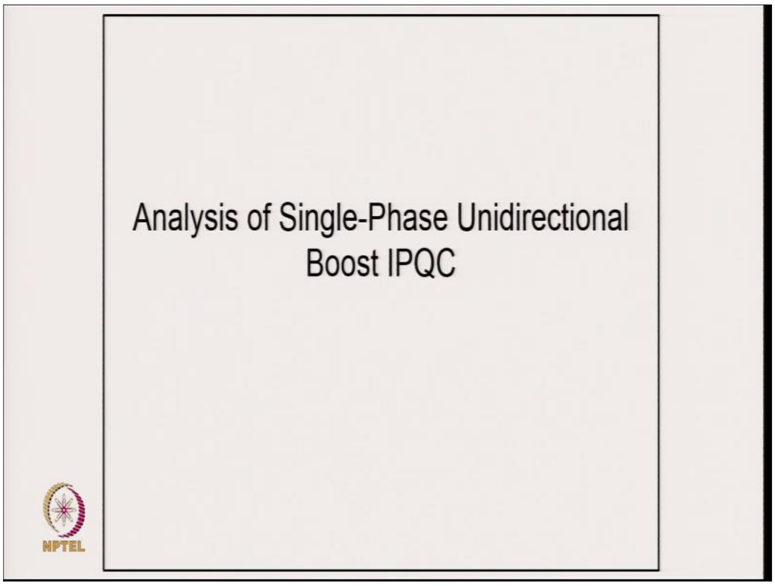
Now coming to the single phase unidirectional boost improved power quality converter. In boost converter with proper design and proper control, we can get regulated DC output voltage and power factor correction at the input supply. That means, supply current remain in phase with the voltage and THD also gets reduced quite low maybe less than 5 percent. As we have already discussed its various control. So, if you are designing it in DCM, the benefit is that, you are able to reduce the size of the input inductor. Further, another circuit is presented, which has two devices and bridgeless unidirectional structure. The benefit of bridgeless topology is that, the inductor is moved to AC side, which makes inductor design quite simple because now it is an AC inductor. The another benefit is lower device count and associated conduction losses, as the current is flowing through only two devices here, as compared to three devices of non-bridgeless circuits. The third major benefit is that, it can give a good quality at AC mains, even up to quite low voltage. So, this we call it a bridgeless boost converter or two devices single phase unidirectional boost converter.

(Refer Slide Time: 19:34)

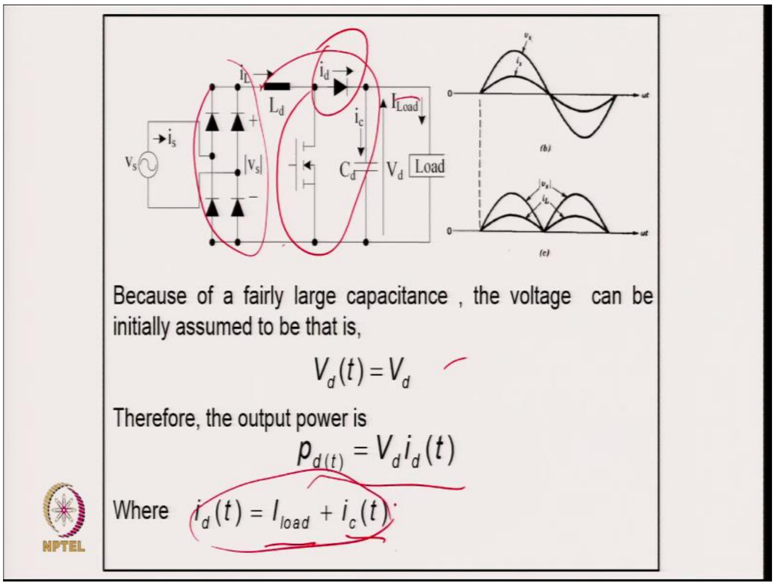


The third topology of course, you can have a asymmetric configuration for typically the same boost converter. The unidirectional boost IPQC with high frequency active EMI filter is an interesting topology, this boost converter that have two cells of single phase unidirectional boost converter. In these two cells, 90 % energy or power is at low frequency. So, we design one cell at typically low frequency and an another with the high frequency to handle 10 % remaining power.

(Refer Slide Time: 20:28)

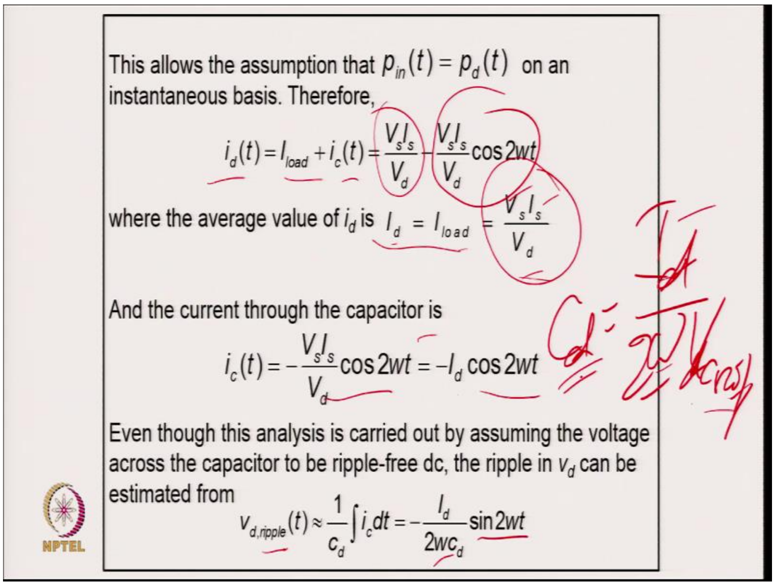


(Refer Slide Time: 20:53)



So, this is the basic analysis and design of boost IPQCs.

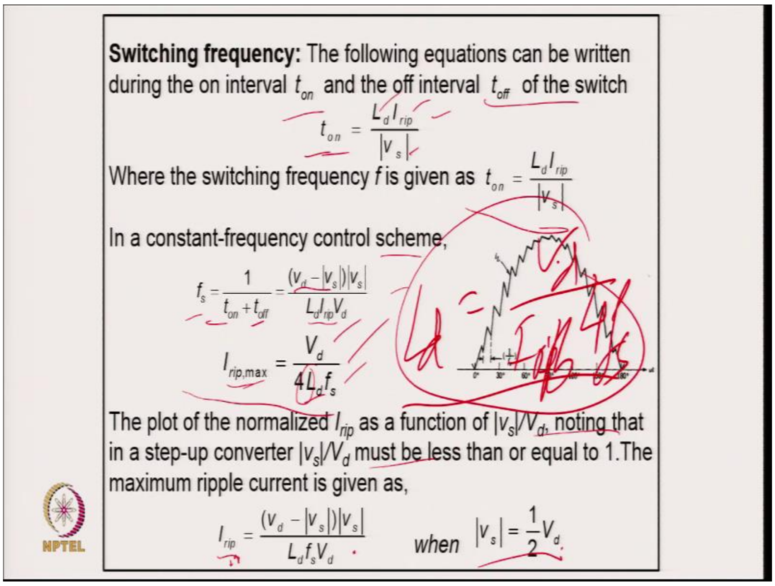
(Refer Slide Time: 21:50)



The output diode current (Id) can be written like a load plus capacitor current. The capacitor supposed to take the all ripple and here the lowest frequency ripple will be the second harmonic ripples. The size of capacitor depends on how much ripple you can permit in the output; you can call it depends on your fundamental frequency because it is supposed to absorb second harmonics. So, with the given output load current, voltage ripples and supply frequency, you can get the value of C_d.

The capacitor value does not depend on switching frequency it depends on how much ripple you can allow and how much is the load current. If you allow the ripple more, the capacitor value will low, and if load current is more the capacitor will be more because it directly proportional to that.

(Refer Slide Time: 23:51)

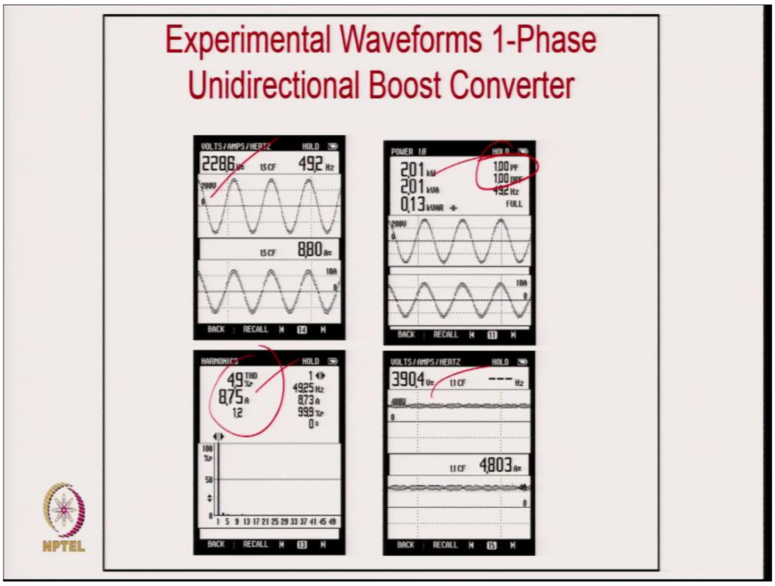


Now, this is the design of boost inductor. The maximum value of inductor ripple current depends on DC link voltage and switching frequency. From the given relation, we can find out, taking the inductor and ripple current, the inductor depend certainly on DC link voltage.

So, if you have a low DC link voltage you will require a higher value inductor and if you have a higher switching frequency inductor will reduce, and if you allow higher ripple current then also inductor will reduce.

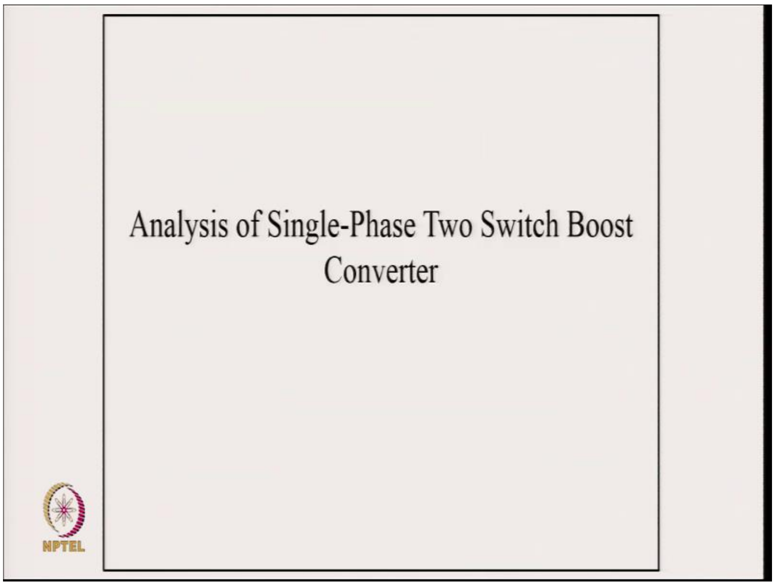
With this, we are able to get the design of boost IPQC converter.

(Refer Slide Time: 26:37)

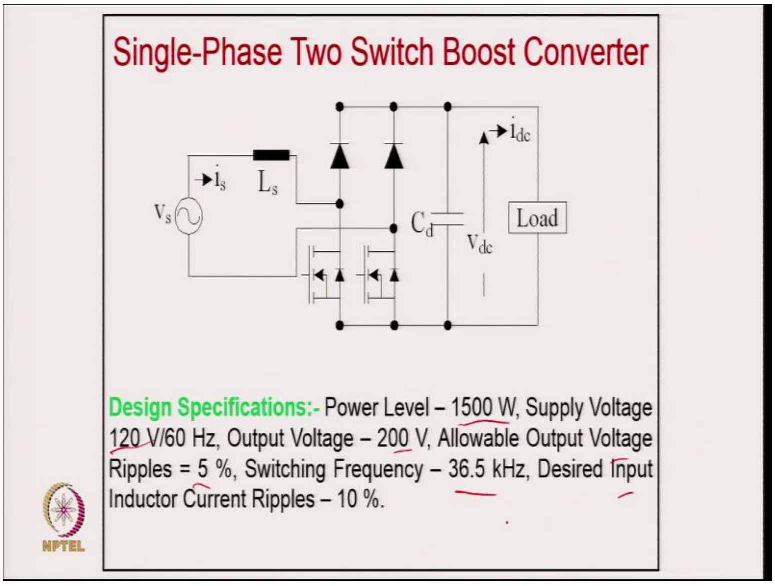


Of course, we have also develop boost IPQC converter and these are the typical experimental result corresponding to 230 V supply voltage. Where, for the design of 2 kW power and output voltage of 390 V, the THD is only 4.9 % and the power factor is unity.

(Refer Slide Time: 27:07)

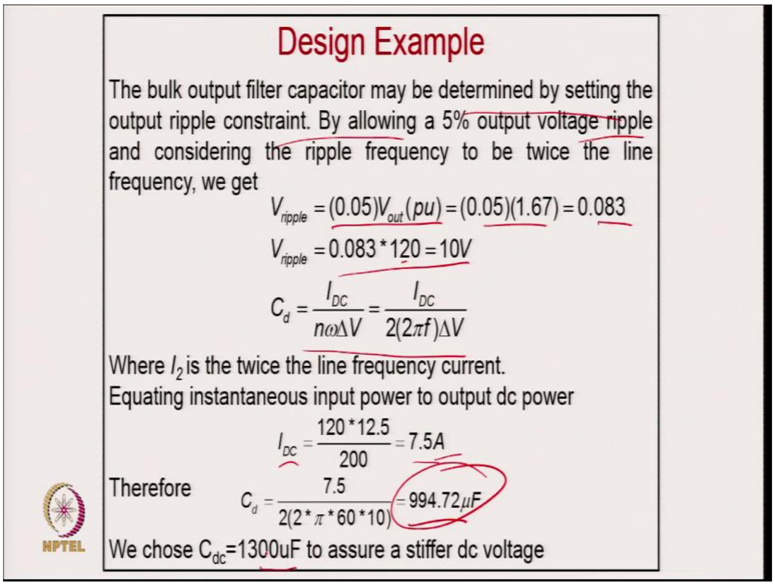


(Refer Slide Time: 27:12)

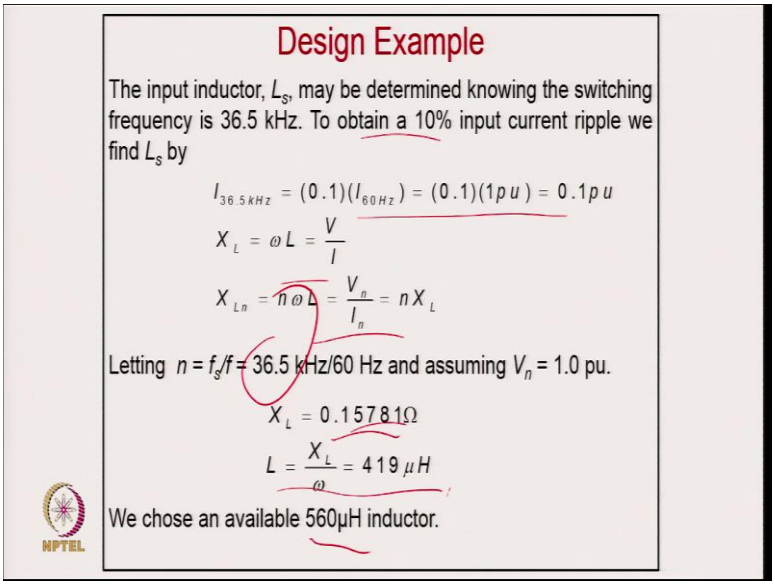


Now, coming to the design example of single phase two switch boost IPQC. The design specifications are given as follows.

(Refer Slide Time: 28:12)

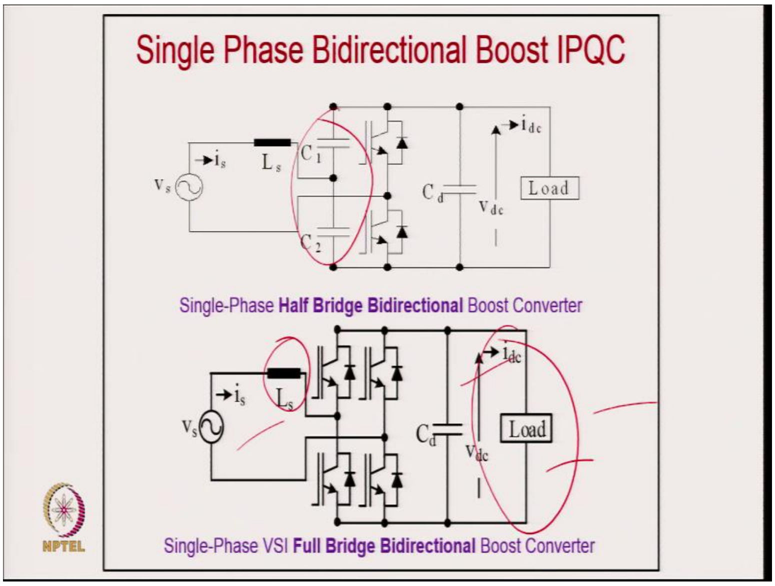


(Refer Slide Time: 28:50)



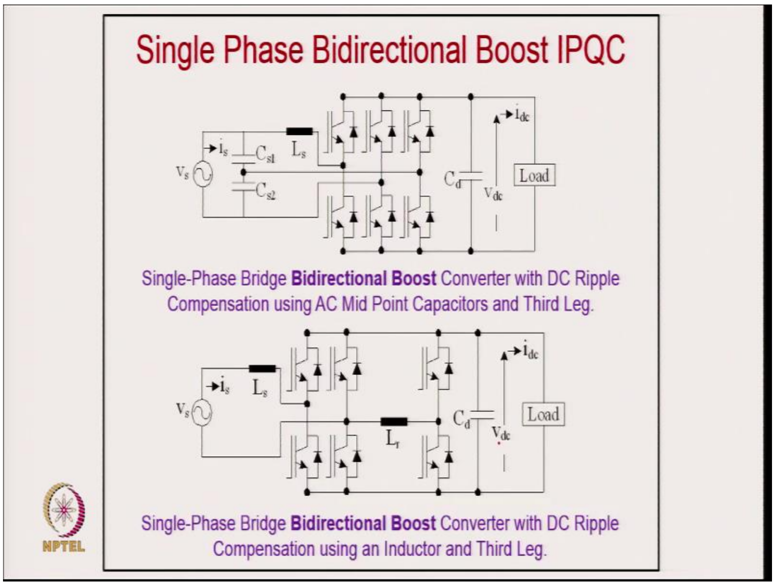
(Refer Slide Time: 29:38)

(Refer Slide Time: 29:48)



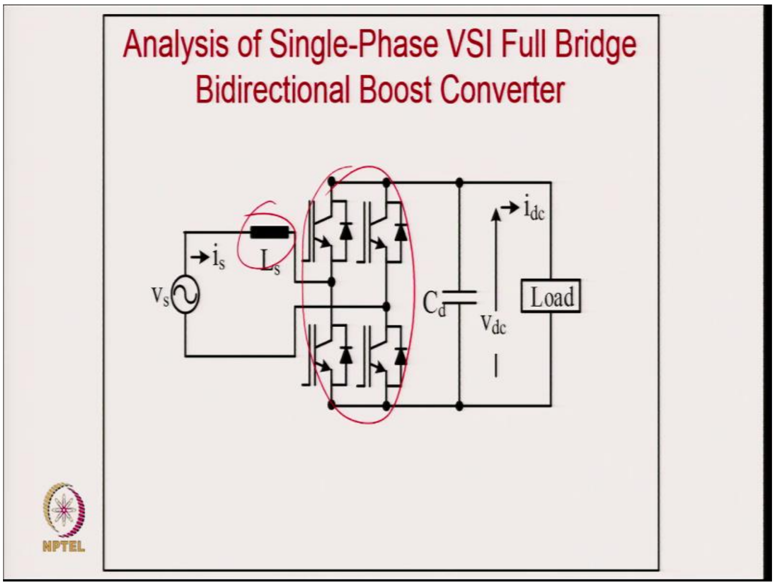
Previously, the unidirectional boost IPQCs of two kinds were given with example as well as the design concept. Now, coming to the single phase bidirectional boost converter. The first circuit of bidirectional boost converter has two devices and two midpoint output capacitors. The disadvantage with this is that, the entire current have to flow through output capacitor, so the size of the capacitor will be large. And the output voltage have to be high as compared to full bridge type configuration. The full bride type boost converter is quite versatile converter, as you can have 4 quadrant operation of P and Q on supply side. So, this converter used very extensively for many applications such as for solar grid interface, i.e. the DC side maybe the solar system with the MPPT and you can push the power to the grid.

(Refer Slide Time: 31:39)



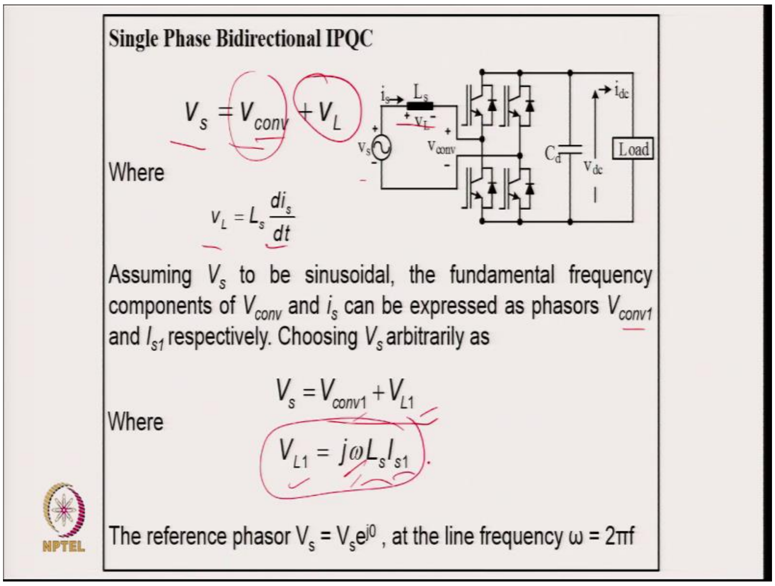
Or you can extend bidirectional full bridge boost converter configuration for reducing the ripples on DC link, by considering one more leg for reducing the ripple, as demonstrated here.

(Refer Slide Time: 31:50)



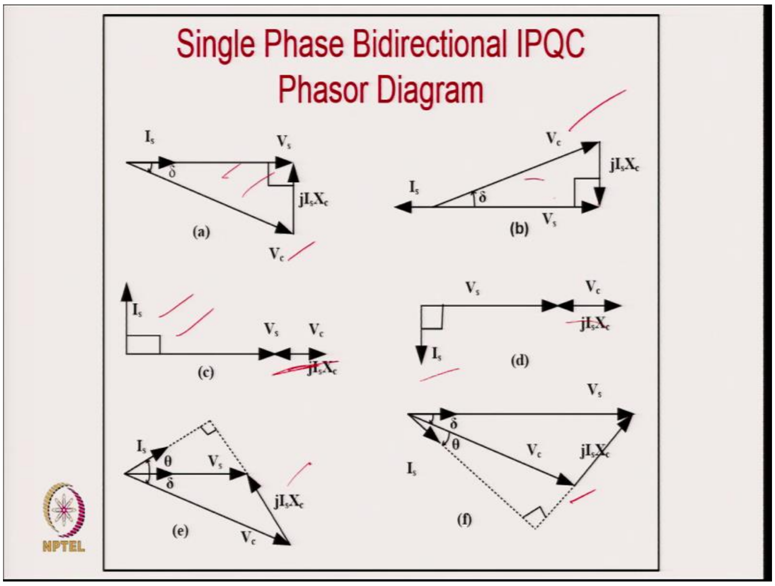
The another benefit of single phase bridge converter is that, this can operate with the unipolar switching and the benefit of unipolar switching is that you are switching the devices at some particular frequency like 10 kilo hertz, but the ripple in the inductor will be of 20 kilo hertz or you can say you can reduce the switching ripples to approximately half in this phase configuration.

(Refer Slide Time: 32:18)



Now, this is the design part of bidirectional full bridge boost converter.

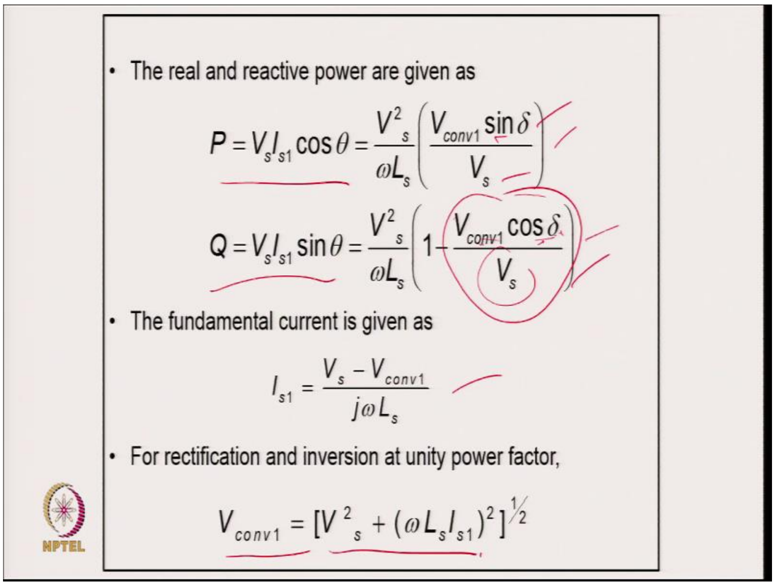
(Refer Slide Time: 33:14)



Now these are the phasor corresponding to different operating condition. So, let us say, the boost converter is working as rectifier and power is feeding to the converter, then considering unity power factor operation, the supply voltage and supply current remain in phase. And for this condition (as given in Fig. a), the phasor sum of converter fundamental voltage and inductor voltage, will become virtually the supply voltage. Fig. b shows the phasor corresponding to when current is out of the phase it means, you are feeding a power back to the grid.

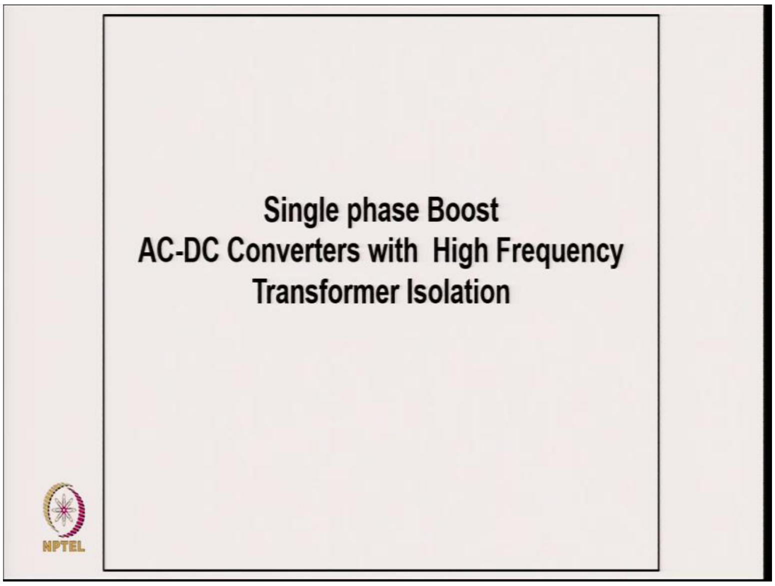
If boost converter work as a condenser, i.e., active power will be zero and only reactive power will be there. Then you can have a current at leading (as shown in Fig. c), and you can say Vs is there, but you will be adding the inductor voltage also in the same supply phase. Similarly, you can subtract that (as shown in Fig. d), corresponding to your inductive reactive power demand. So, the boost converter can work as a pure inductor it can work as a pure capacitor and in between both as shown in phasor diagrams of Fig. e and Fig. f.

(Refer Slide Time: 35:15)



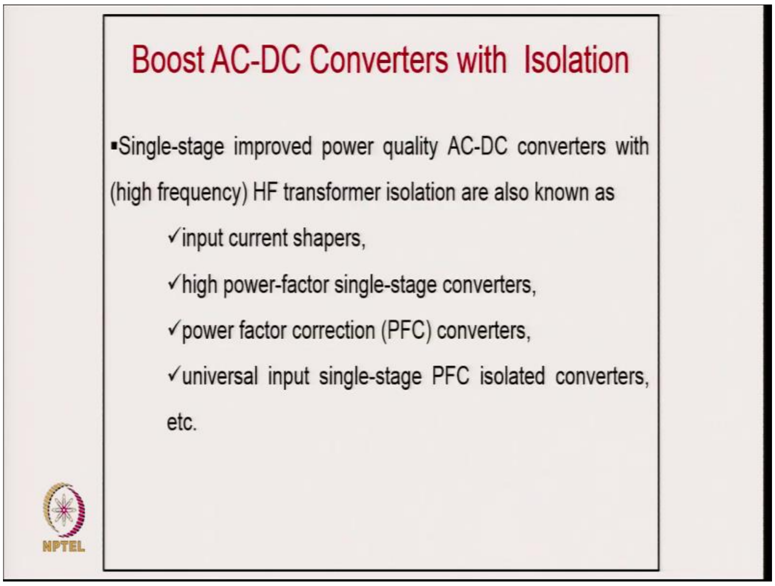
So, with this, we can have expressions of active power, reactive power, fundamental supply current and fundamental converter voltage. As demonstrated, the active and reactive power flow can be controlled either by controlling converter fundamental converter voltage or by controlling the angle delta.

(Refer Slide Time: 38:07)

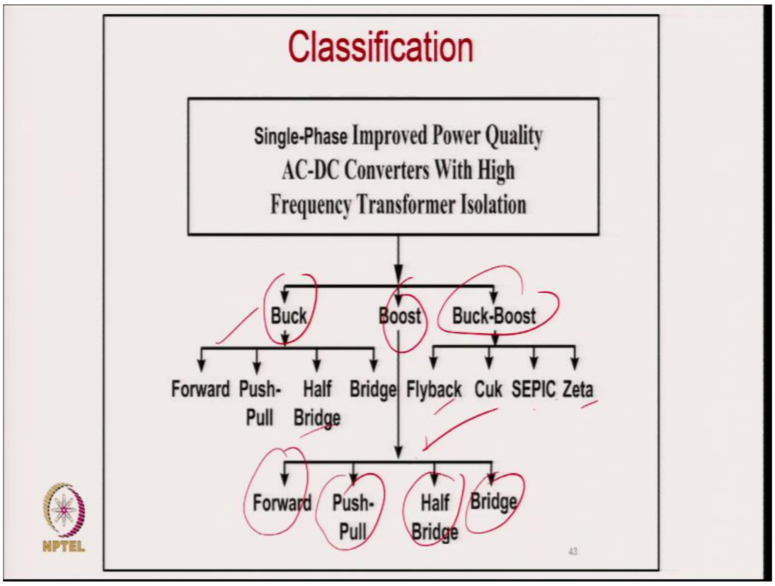


Now coming to like other topology of single phase boost AC-DC converter with the high frequency transformer isolation, they are vary extensively use in many applications, about which we will discuss latter.

(Refer Slide Time: 38:21)

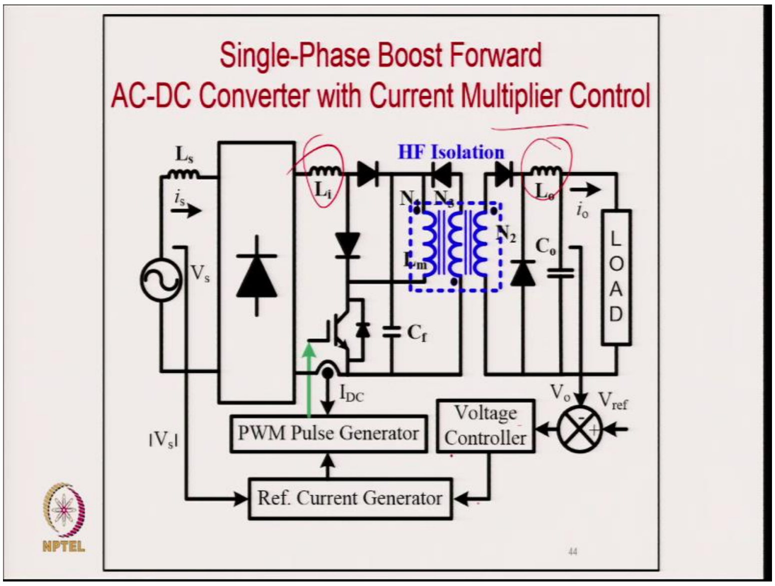


(Refer Slide Time: 38:43)



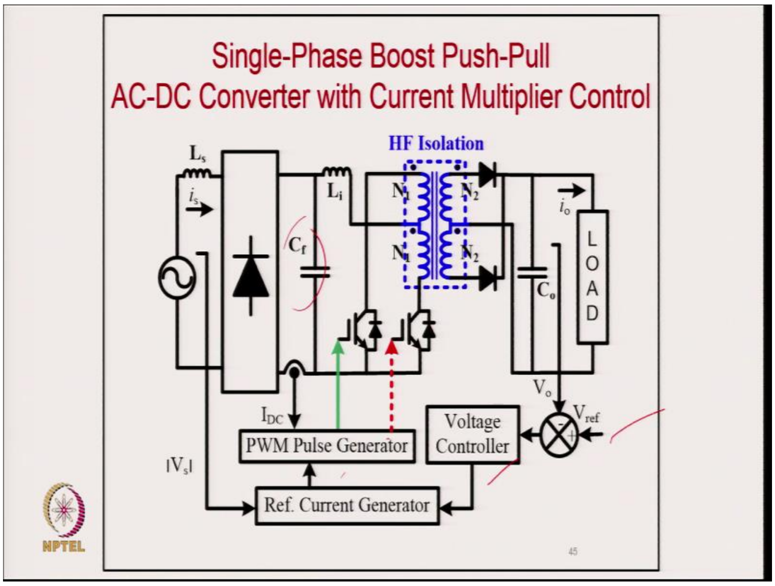
If you talk about classification with high frequency transformer isolation you can have buck you can have a boost or you can have buck boost. So, we will talk about boost here. Like, you can use, either forward or push pull configuration, half bridge configuration or bridge configuration and if you feed by current fed source, they will work as a boost converter. But if you feed directly with voltage source, then they will work as a buck converter.

(Refer Slide Time: 39:36)



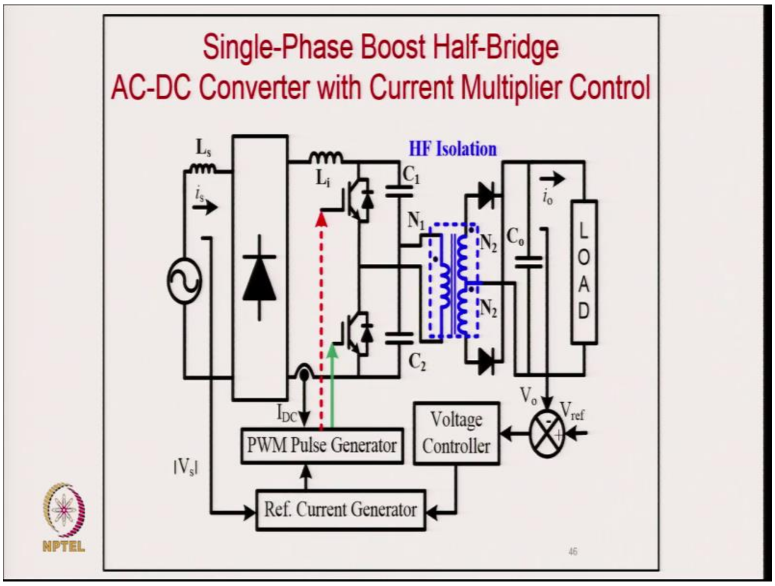
Now, coming to single phase boost isolated forward converter, so, the circuit diagram with current multiplier control, is given as follows. Current multiplier approach in the sense, we are sensing the voltage and input current as we have discuss in the PFC control part, you have to sense the voltage end current for current multiplier approach.

(Refer Slide Time: 40:50)



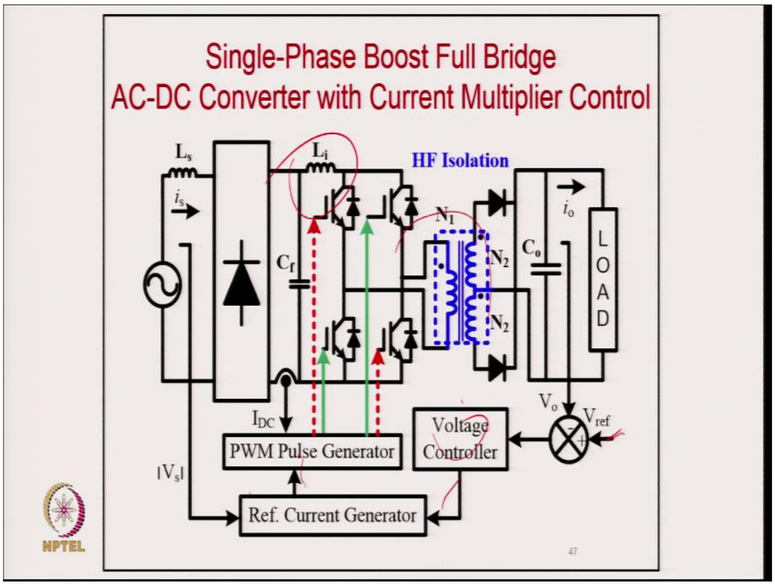
And, this is a boost push pull converter with current multiplier approach.

(Refer Slide Time: 41:41)



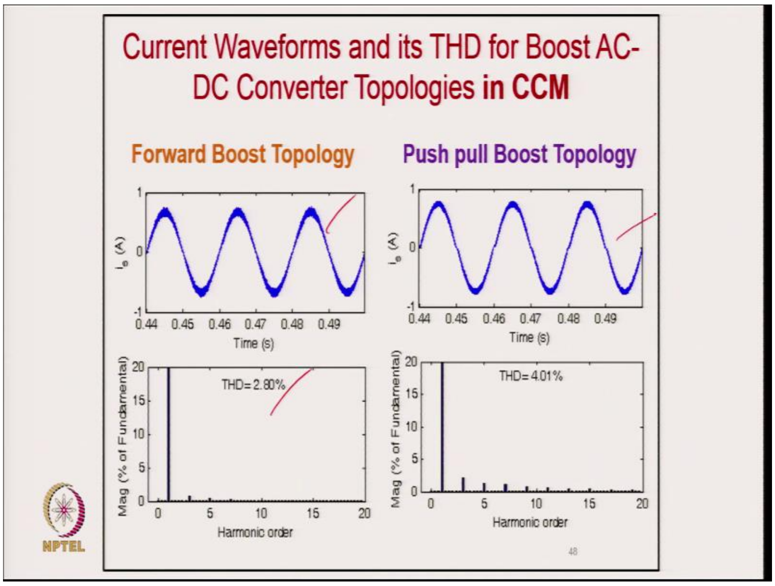
Similarly, for the half bridge, I mean we can switch on both the devices which stored the energy in the inductor and when you switch off one the energy get transfers to the secondary side.

(Refer Slide Time: 42:03)



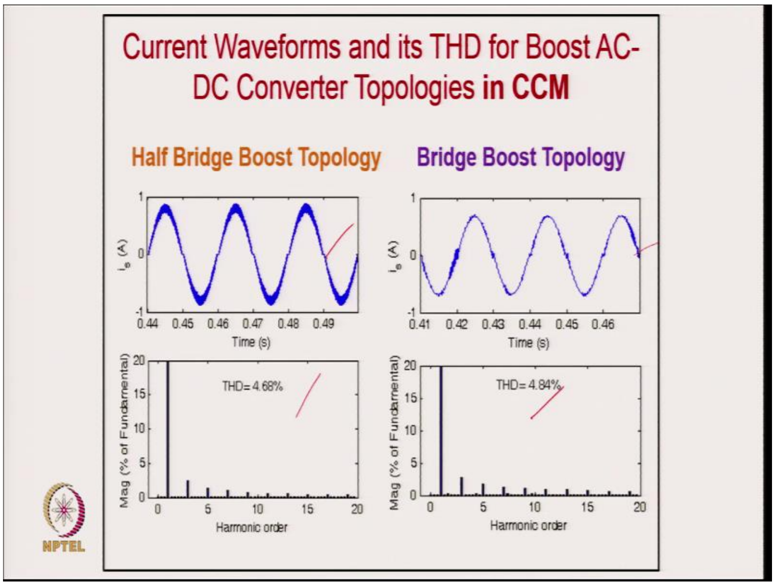
So, that was a half bridge. Now, we come to full bridge type isolated boost converter, this is normally used for high power rating. So, here we can switch on either one leg or both legs simultaneously, when we store the energy; and when we want to transfer, so, we can switch on diagonally. So, the transformer action is there and we can operate in the same manner.

(Refer Slide Time: 42:48)

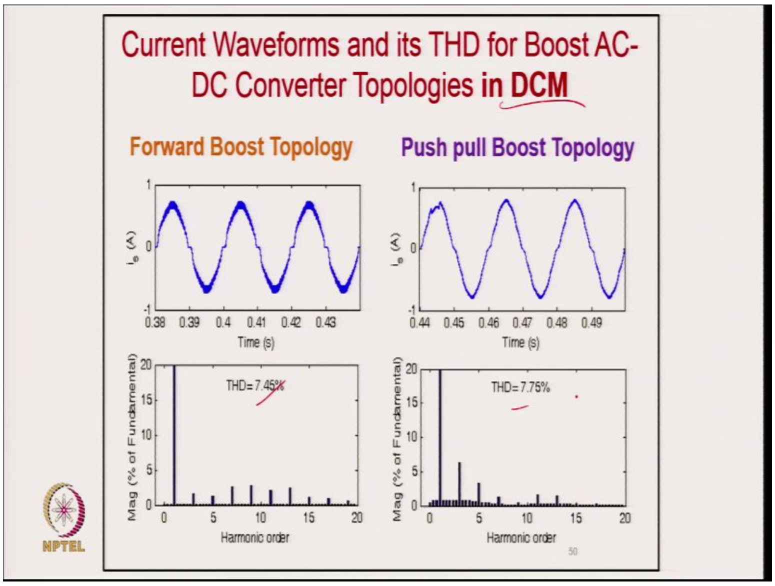


Well, coming to design and simulation. In the forward topology, under CCM operation, you can get the current very closed to sine wave with current THD of 2.8 % and for push pull this is the typical current THD is 4 %.

(Refer Slide Time: 43:04)

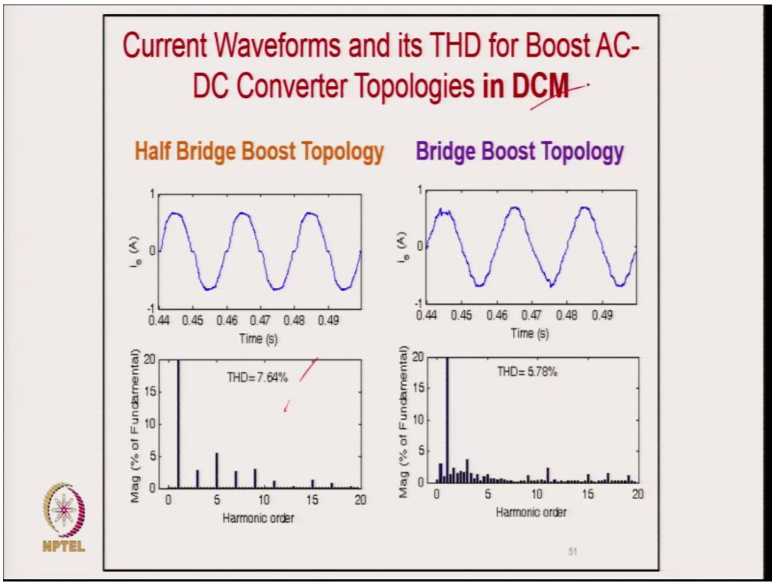


(Refer Slide Time: 43:18)



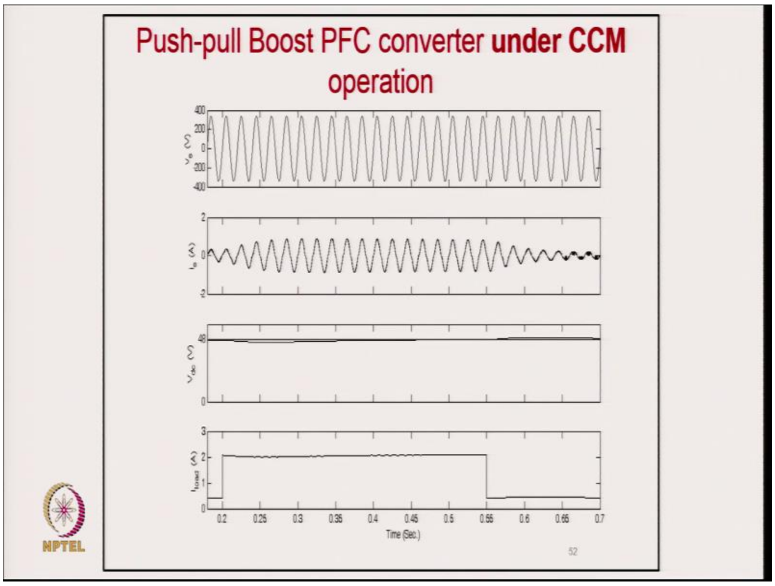
And then for the half bridge the current THD is found nearly 4.68 % and for full bridge, it is 4.84 %. So, all isolated boost IPQCS are able to get good power factor correction and low THD supply current during CCM operation. If you are operating converters in discontinuous mode, the THD slightly increases.

(Refer Slide Time: 43:33)



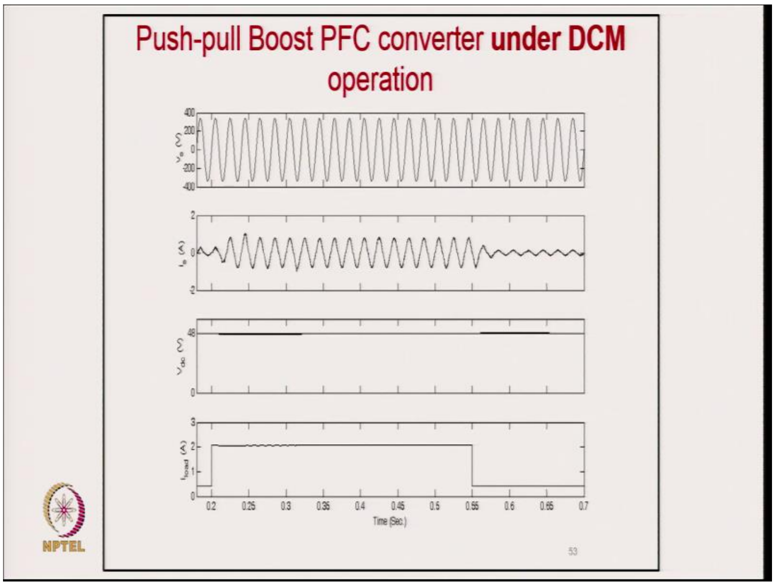
This is the performance analysis for push pull and for half bridge based isolated boost IPQCs

(Refer Slide Time: 43:46)



And this is the dynamic performance of push pull based isolated boost IPQCs in CCM mode. As you can see, on increasing and decreasing of load, the supply current remain in phase with the supply voltage, and DC link voltage remain regulated. The input current is increasing because output power is increased because of increased load on the DC side.

(Refer Slide Time: 44:06)

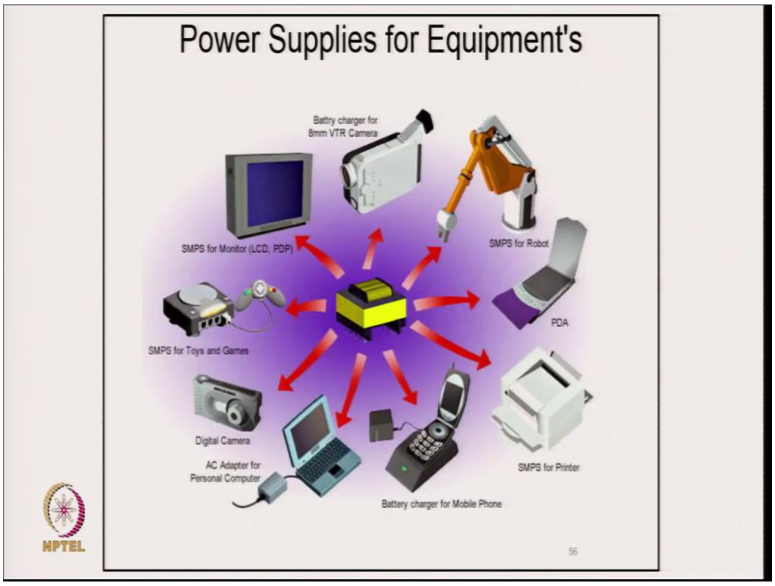


And this is the case corresponding to DCM operation of push pull based isolated boost IPQCs.

(Refer Slide Time: 44:31)

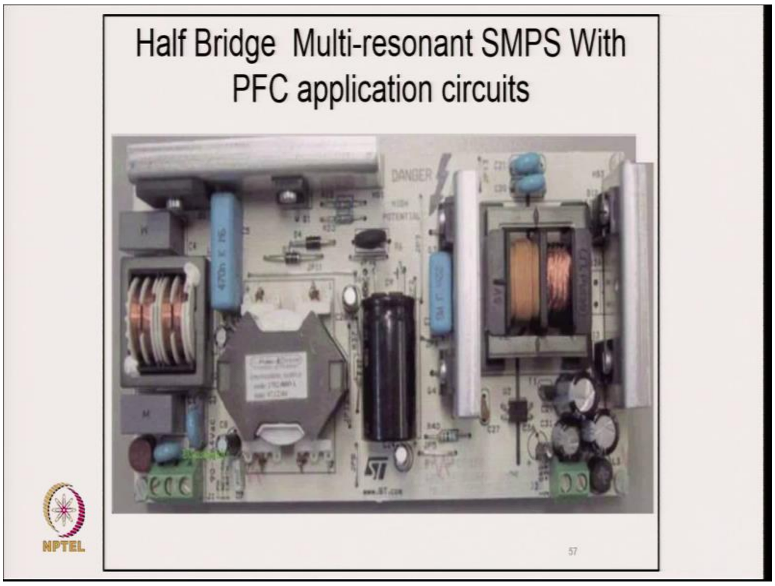
Now, coming to the applications where these converters are used like in a DC power supply, telecommunication power supply, improved power quality power factor ballast like lighting system, power supply for equipment like computer medical equipment printers, scanners and drive applications for power factor improvement at AC side electric welding, high frequency welding virtually and lighting such as CFL, LED lighting. In all these applications, we can use these PFC power factor correction converters. Of course, in some cases we use isolated and in some cases we need non isolated like computer supply we use the isolated one.

(Refer Slide Time: 45:05)



So, these are the power supply equipment, you can think about, where we are using the boost converters.

(Refer Slide Time: 45:49)



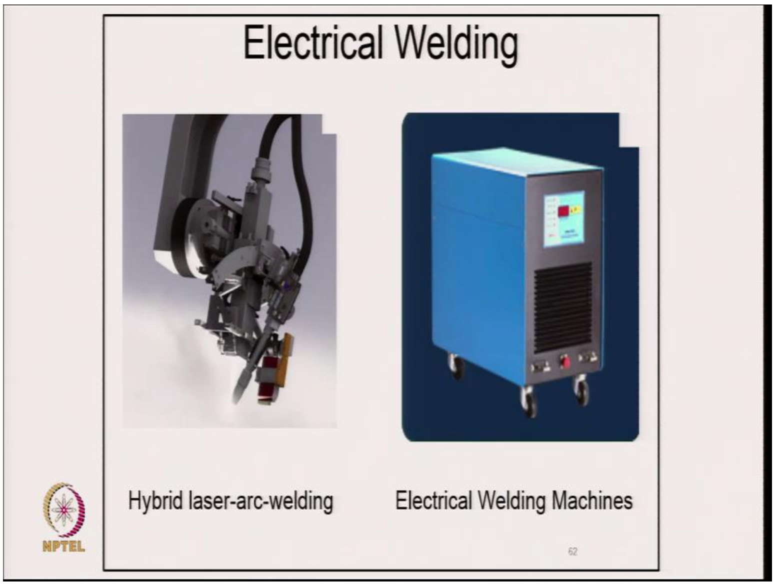
(Refer Slide Time: 45:58)

(Refer Slide Time: 46:06)

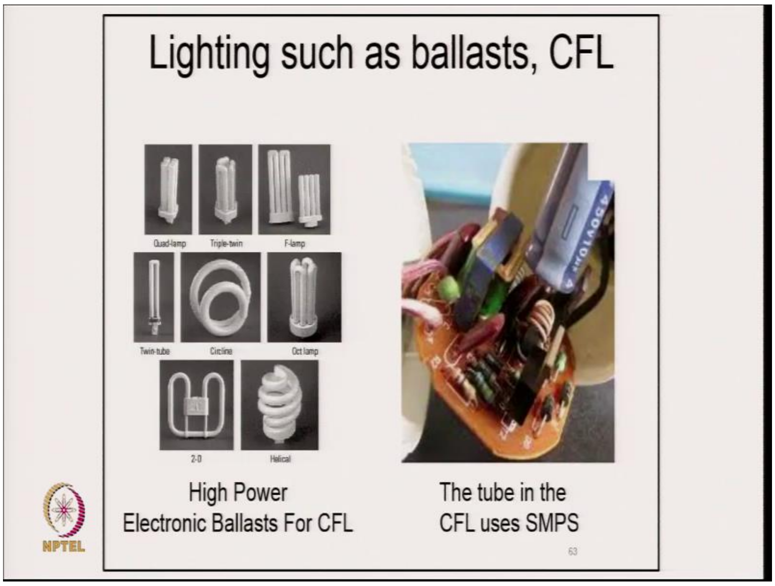
(Refer Slide Time: 46:14)

(Refer Slide Time: 46:19)

(Refer Slide Time: 46:30)



(Refer Slide Time: 46:41)

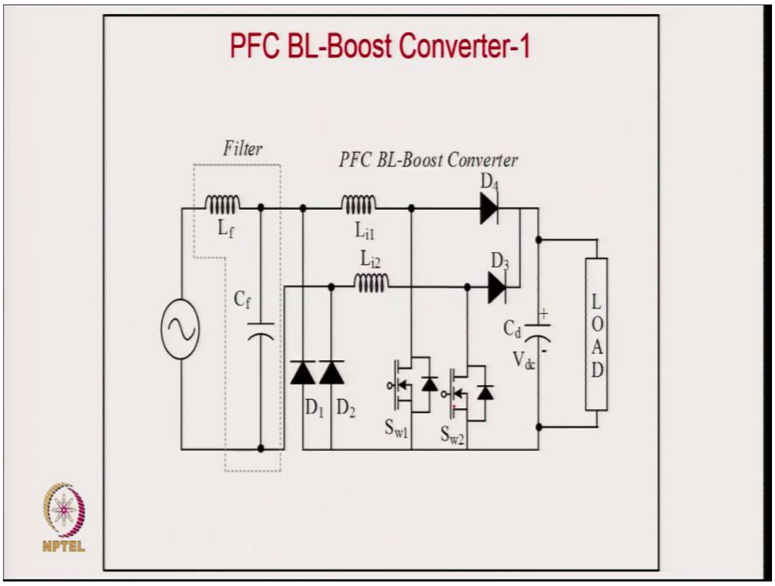


(Refer Slide Time: 46:47)

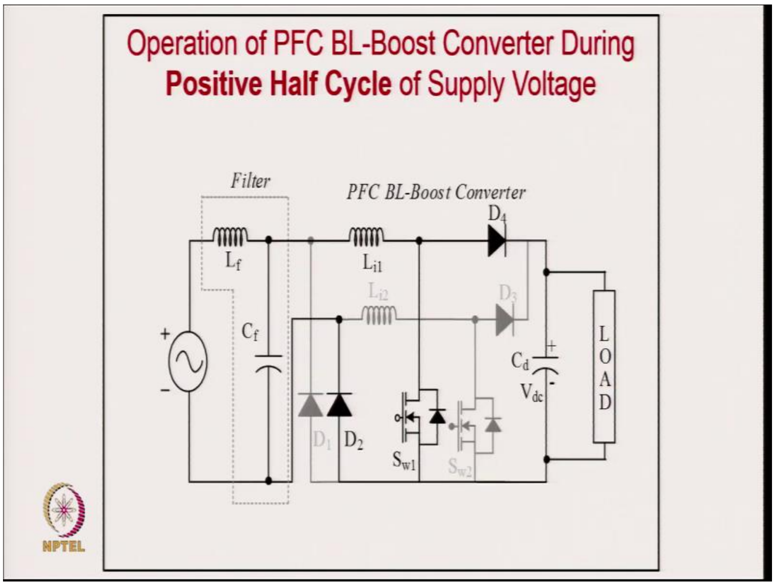
(Refer Slide Time: 46:51)

So, now coming to like analysis design and simulation of performance of PFC power factor correction bridgeless boost converter.

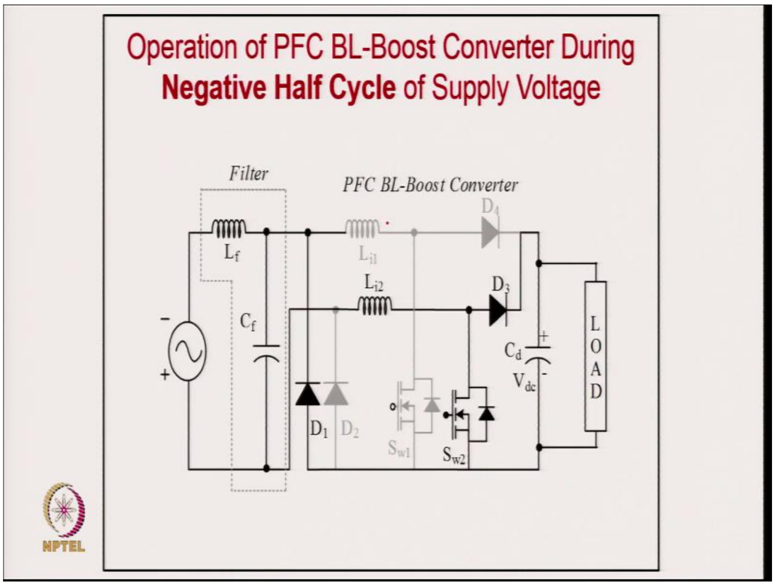
(Refer Slide Time: 46:59)



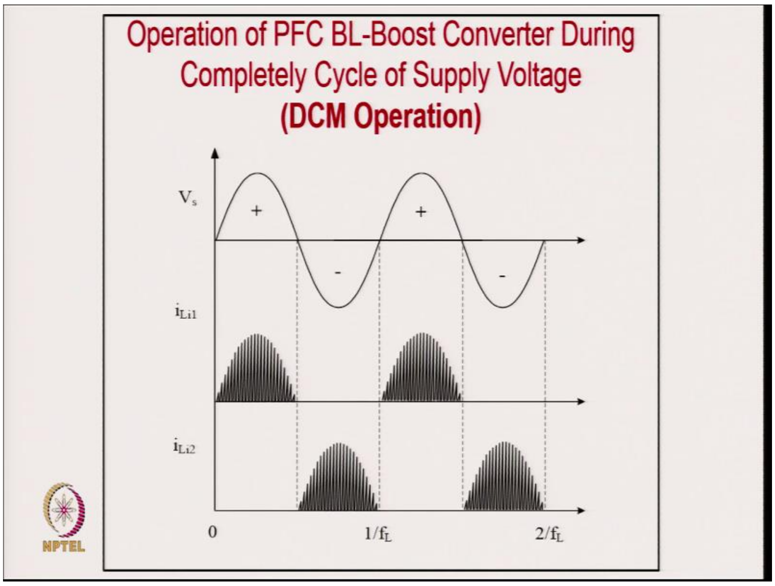
(Refer Slide Time: 47:18)



(Refer Slide Time: 47:28)

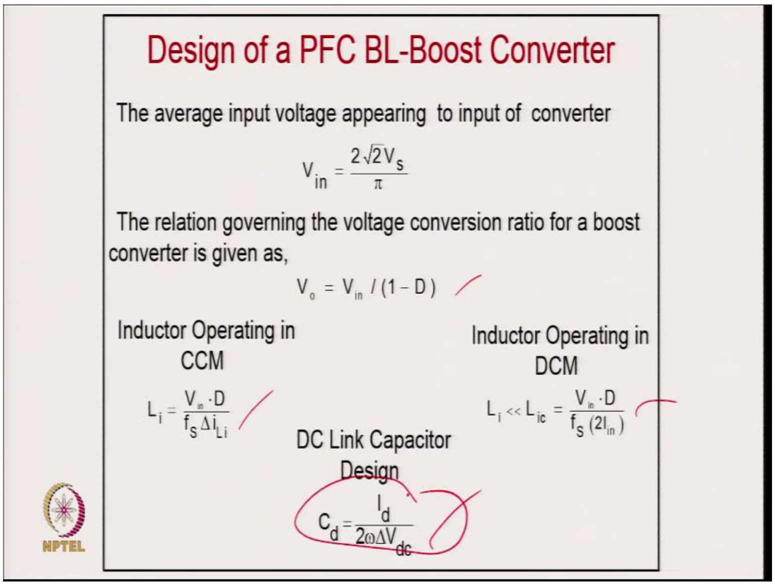


(Refer Slide Time: 47:31)



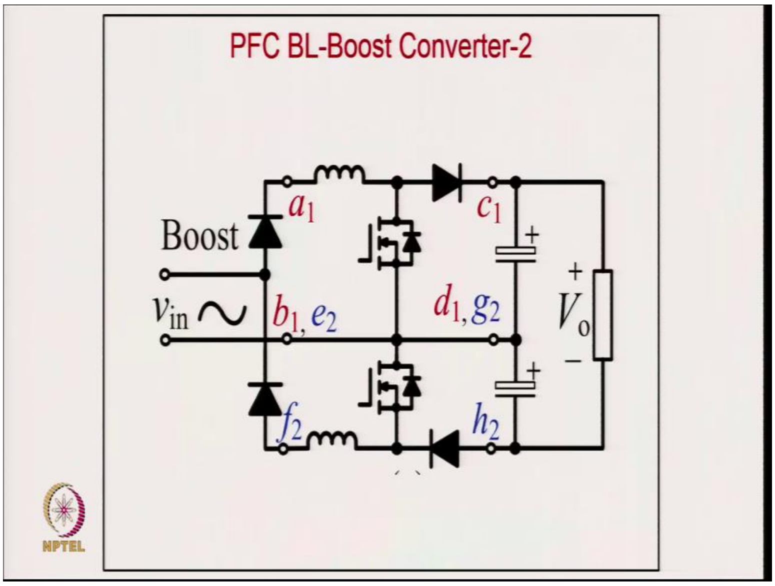
And this is typically the bridgeless boost converter, you can clearly see, here we have eliminated the bridge. So, one positive half cycle one boost converter work in another negative half cycle another converter will work.

(Refer Slide Time: 47:37)



And you can design this converter for both CCM and DCM operation by utilizing following equations.

(Refer Slide Time: 47:53)



And this is the another version of PFC power factor correction bridgeless boost converter. Of course, this converter uses two devices, but the you can understand in some application we require two equal voltage at output with power factor correction like in a switch reluctance motor (SRM) drive of four phase you require midpoint converter. So, this converter is suitable for such applications.