Power Quality

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Module - 02
Lecture - 32
Improved Power Quality Converters - AC-DC Buck Converters

Welcome to the course on Power Quality. Today, we would like to discuss improved power quality converters, in that, we will discuss AC to DC Buck Converter. Well, coming to outline of the presentation, we will like to introduce the improved power quality buck AC-DC converter, and then we will classify them.

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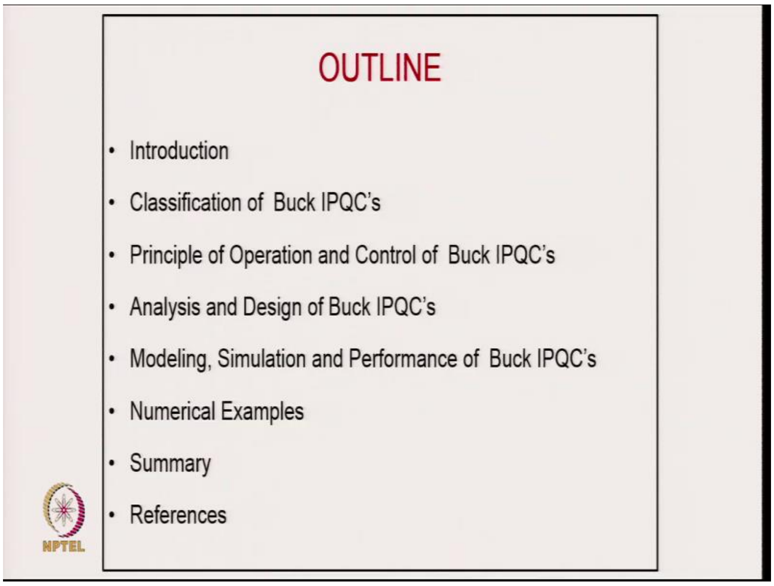

OUTLINE

- Introduction
- Classification of Buck IPQC's
- Principle of Operation and Control of Buck IPQC's
- Analysis and Design of Buck IPQC's
- Modeling, Simulation and Performance of Buck IPQC's
- Numerical Examples
- Summary
- References

We will also discuss principle, operation and control of buck improved power quality converters. Then, we will talk about analysis and design of buck improved power quality converter, and modeling, simulation performance of buck improved power quality converters, followed by some numerical examples. At last, we will summarize and then, have a references at the end of presentation.

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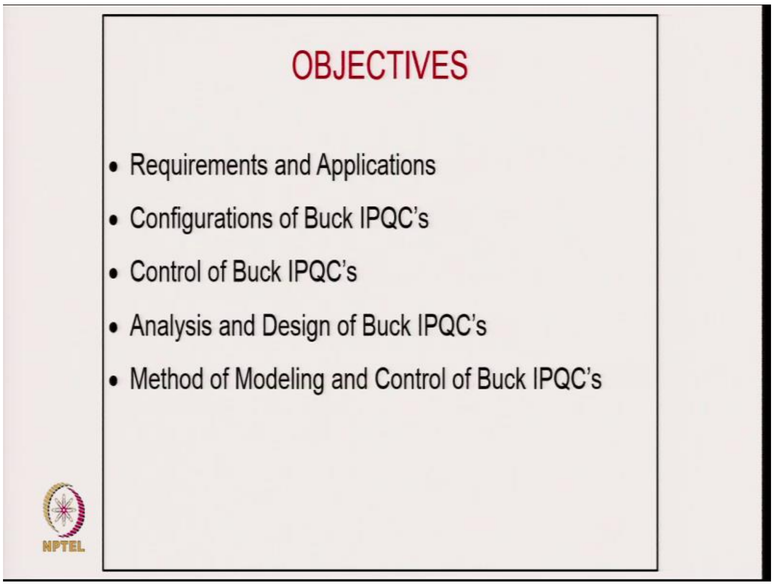

OBJECTIVES

- Requirements and Applications
- Configurations of Buck IPQC's
- Control of Buck IPQC's
- Analysis and Design of Buck IPQC's
- Method of Modeling and Control of Buck IPQC's

So, with this, we have the objectives of todays' lecture, as the requirement and application of buck improved power quality converters and we will talk about the configuration and control of buck improved power quality converters. Further, the design, method of modeling and control of buck improved power quality converters, are also discussed.

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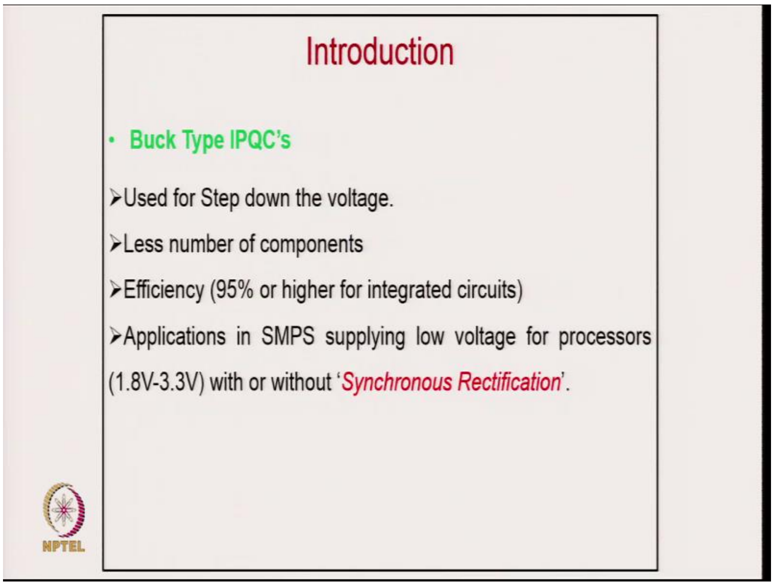

Introduction

- **Buck Type IPQC's**

➢Used for Step down the voltage.

➢Less number of components

➢Efficiency (95% or higher for integrated circuits)

➢Applications in SMPS supplying low voltage for processors (1.8V-3.3V) with or without '*Synchronous Rectification*'.

Well, coming to the buck type of improved power quality converter. Such converters are used for step down the voltage and of course, it has a less number of component and it offers quite good efficiency 95 percent or more. It has applications, of course, in switch mode power supply applying low voltage for processes like starting from 1.8 to 3 V, with or without synchronous rectification.

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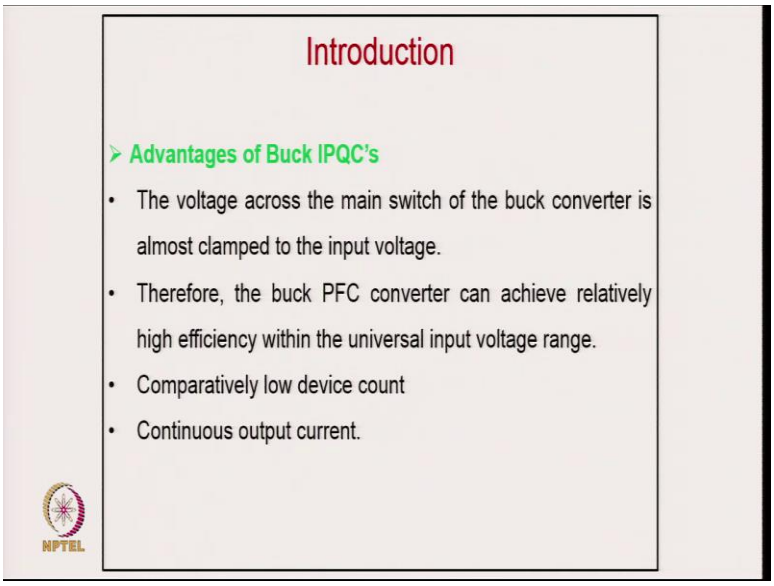

Introduction

➢ Advantages of Buck IPQC's

- The voltage across the main switch of the buck converter is almost clamped to the input voltage.
- Therefore, the buck PFC converter can achieve relatively high efficiency within the universal input voltage range.
- Comparatively low device count
- Continuous output current.

We will talk about more applications a little later. The advantages of the buck improved power quality converter are, the reduced voltage across the main switch, high efficiency over the universal input voltage range, low device count and continuous output current.

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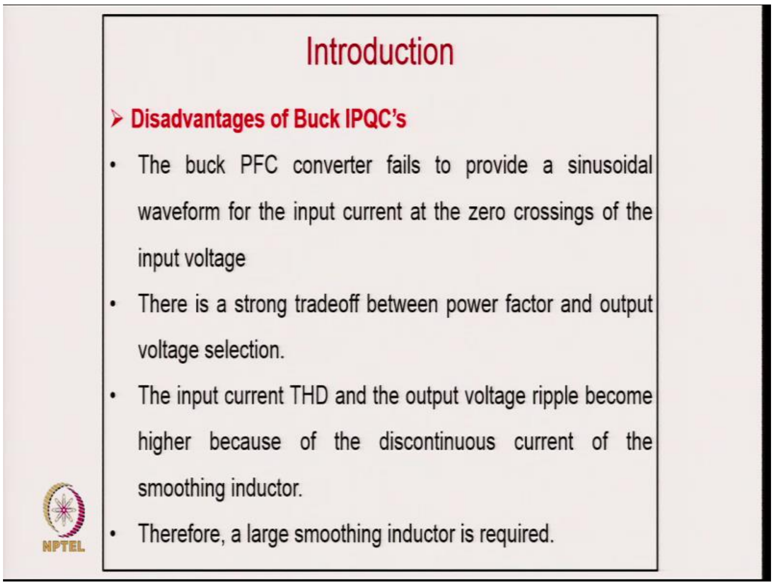

Introduction

➢ Disadvantages of Buck IPQC's

- The buck PFC converter fails to provide a sinusoidal waveform for the input current at the zero crossings of the input voltage
- There is a strong tradeoff between power factor and output voltage selection.
- The input current THD and the output voltage ripple become higher because of the discontinuous current of the smoothing inductor.
- Therefore, a large smoothing inductor is required.

Of course, there are some disadvantages of the buck improved power quality converter. The buck power factor correction converter fails to provide a sinusoidal waveform for the input current at the zero crossing of the input voltage. Further, there is a strong tradeoff between power factor and output voltage selection. The input current total harmonics distortion and output voltage ripple becomes higher because of discontinuous current of the smoothing inductor. Therefore, such converters require large smoothing inductor.

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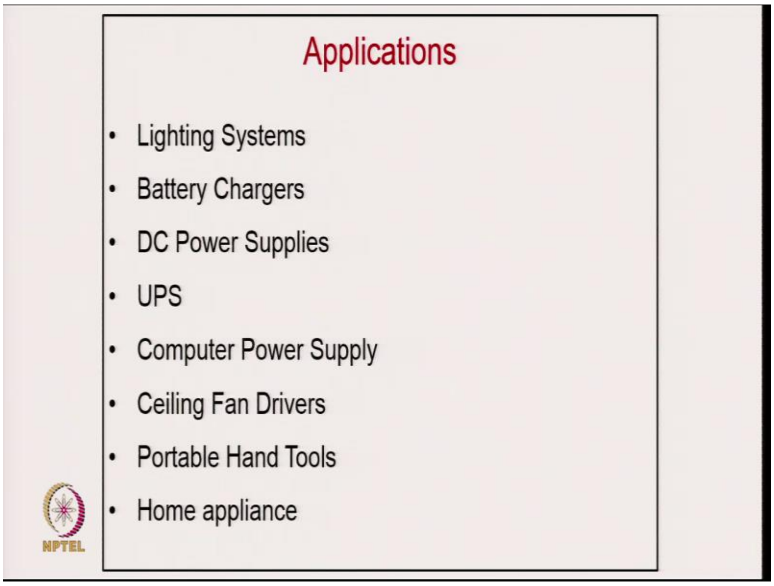

Applications

- Lighting Systems
- Battery Chargers
- DC Power Supplies
- UPS
- Computer Power Supply
- Ceiling Fan Drivers
- Portable Hand Tools
- Home appliance

Well, coming to the applications which we were mentioning; there are plenty of application where we use buck improved power quality converter such as, lighting system, normally in LED lighting system, we can reduce the voltage to the required level with a smaller number of components. Another major application is a battery charger, which are used very extensively number of applications like in electric vehicles or the battery chargers for many other applications.

Then, another application is DC power supplies to obtain a regulated power supply. The other applications are uninterrupted power supply, computer power supplies, ceiling fan, drives, portable hand tools and home appliances.

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Applications

Electronic Ballasts

LED Bulb Driver

So, these are some other applications you can think about, like in lighting systems, in electronic ballasts for fluorescent bulb, or for LED bulb driver, laptop charger, mobile charges, low battery/low power battery charges, uninterruptible power supply, DC power supplies, printer power supply, fax machine power supply, computer power supply and ceiling fan driver.

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Applications

Mobile Chargers

Laptop Chargers

Low Power Battery Chargers

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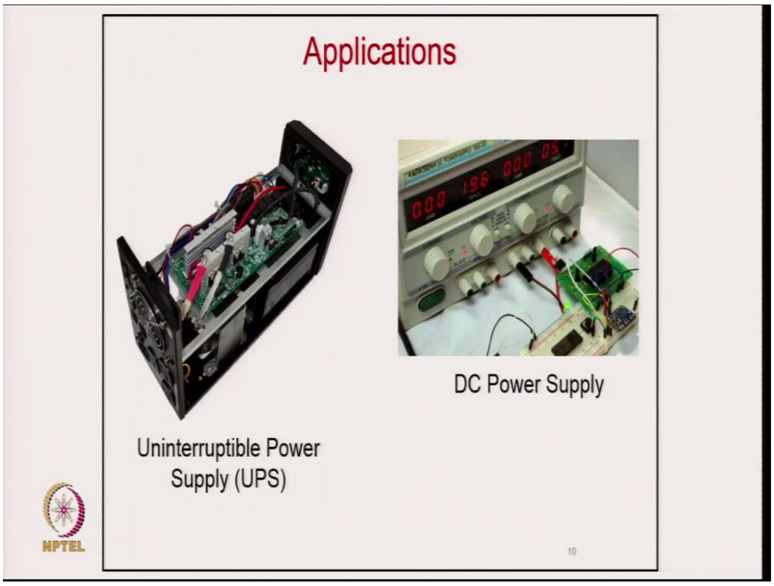

Applications

Uninterruptible Power Supply (UPS)

DC Power Supply

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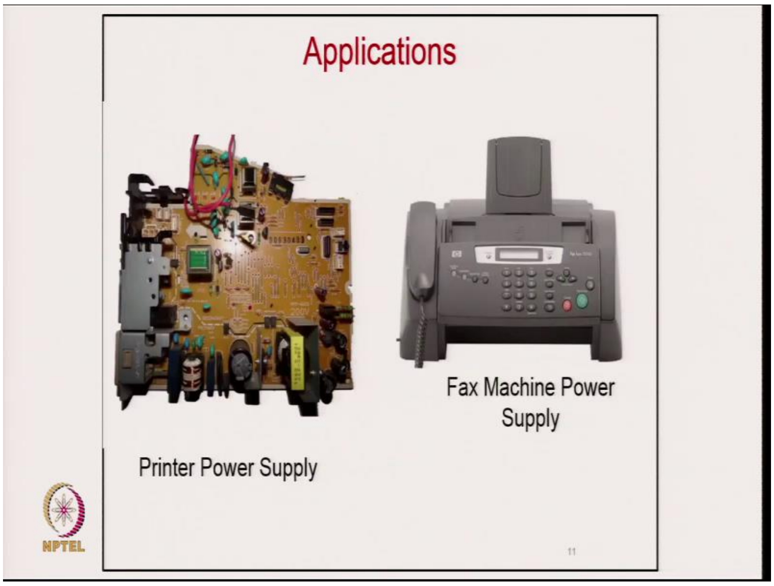

Applications

Printer Power Supply

Fax Machine Power Supply

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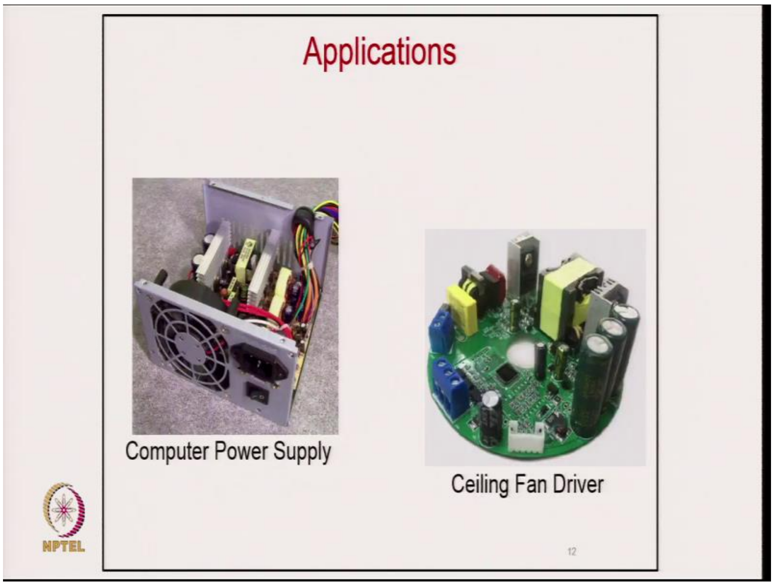

Applications

Computer Power Supply

Ceiling Fan Driver

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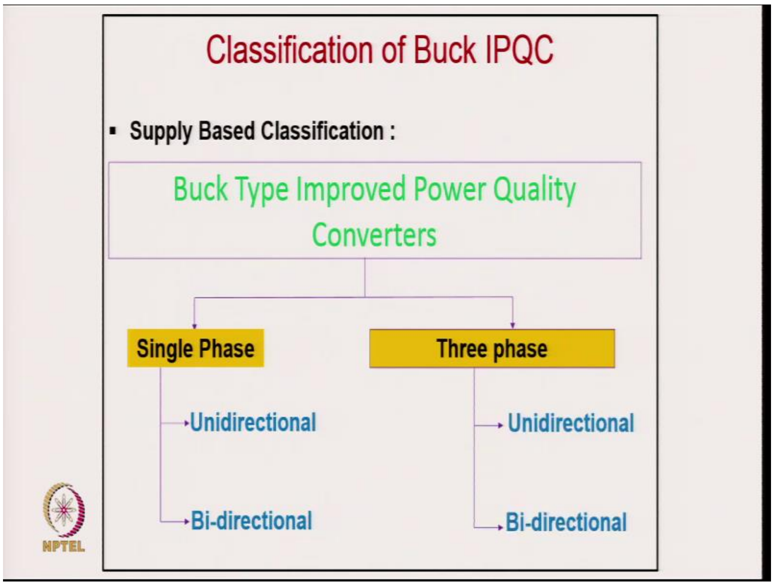

Classification of Buck IPQC

- **Supply Based Classification :**

Buck Type Improved Power Quality Converters

Single Phase
- Unidirectional
- Bi-directional

Three phase
- Unidirectional
- Bi-directional

We can classify buck improved power quality converter into many categories. First is the supply-based classification, which can be like single phase or three phase. You can have a further classification that, whether power flow is unidirectional or bidirectional, in single phase as well as in three phase.

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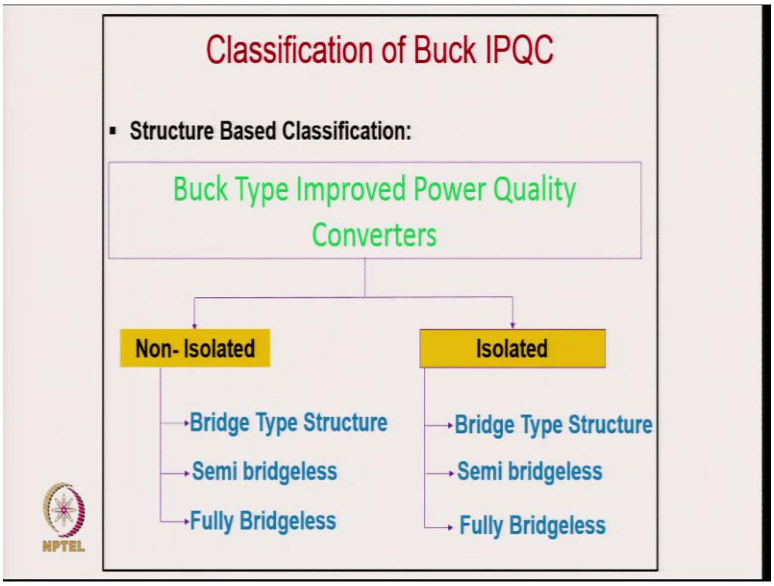

Classification of Buck IPQC

- **Structure Based Classification:**

Buck Type Improved Power Quality Converters

Non- Isolated
- Bridge Type Structure
- Semi bridgeless
- Fully Bridgeless

Isolated
- Bridge Type Structure
- Semi bridgeless
- Fully Bridgeless

Further, there is a structure-based classification, the buck type improved power quality converter either can be of non-isolated configuration or isolated configuration, which further can be classified like whether you are using a bridge type structure or you are using semi bridgeless or using fully bridgeless type configurations.

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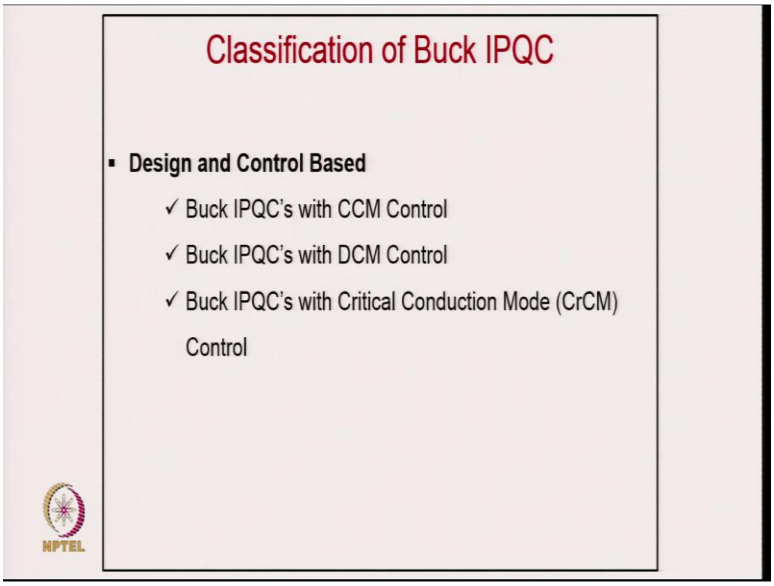

Classification of Buck IPQC

- **Design and Control Based**
  - ✓ Buck IPQC's with CCM Control
  - ✓ Buck IPQC's with DCM Control
  - ✓ Buck IPQC's with Critical Conduction Mode (CrCM) Control

Then, another aspect is the design and control. First, buck improved power quality converter with CCM (Continuous Conduction Mode) control. Another one is, the buck improved power converter with DCM (Discontinuous Conduction Mode) control.

Similarly, the buck improved power quality converters are also designed with the critical conduction mode. Critical conduction mode, is normally called as a boundary condition control in between DCM and CCM. Why we want to operate in this in critical conduction mode? Because we want to take advantage of both CCM as well as DCM.

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Single-Phase **Unidirectional** Buck IPQC

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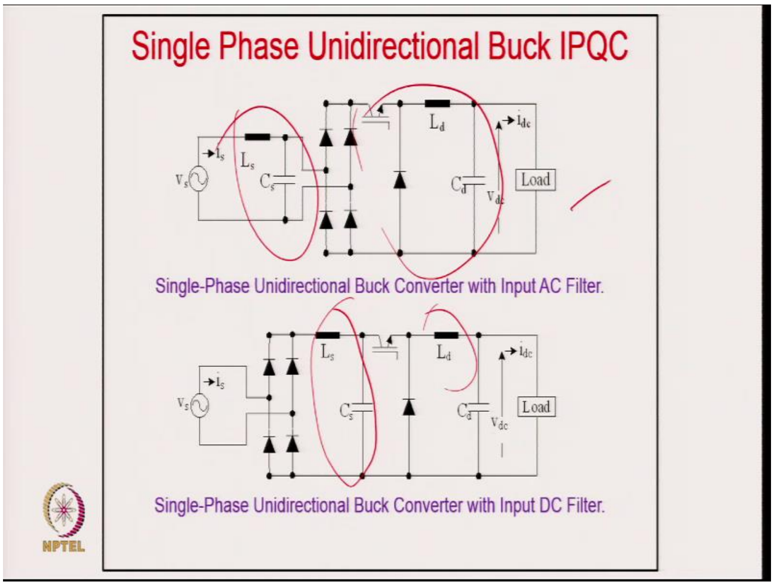

Single Phase Unidirectional Buck IPQC

Single-Phase Unidirectional Buck Converter with Input AC Filter.

Single-Phase Unidirectional Buck Converter with Input DC Filter.

Coming to single-phase unidirectional buck improved power quality converters. So, buck type IPQCs have many configurations, such as, a single phase unidirectional buck converter with input AC filter. In this, you can get either a variable voltage or you can get a constant voltage, it totally depends on the application requirement. Further, the benefit of keeping a filter at the output of diode rectifier is that, the diode can be of now power diode, because the current in the diode rectifier is continuous. In this, the switching device operate at high switching frequency. Why we operate this device at much higher switching frequency? Because there are benefits, such as, the size of filter component or energy storage component, especially, the L_d and C_d can be reduced.

In the first configuration (filter at supply side), the problem is, you have to select all semiconductor devices (even diodes of diode bridge rectifier) of high frequency. But in second configuration (filter after diode bridge rectifier), the diodes of the front-end rectifier can now a power diode and therefore, have much lower cost.

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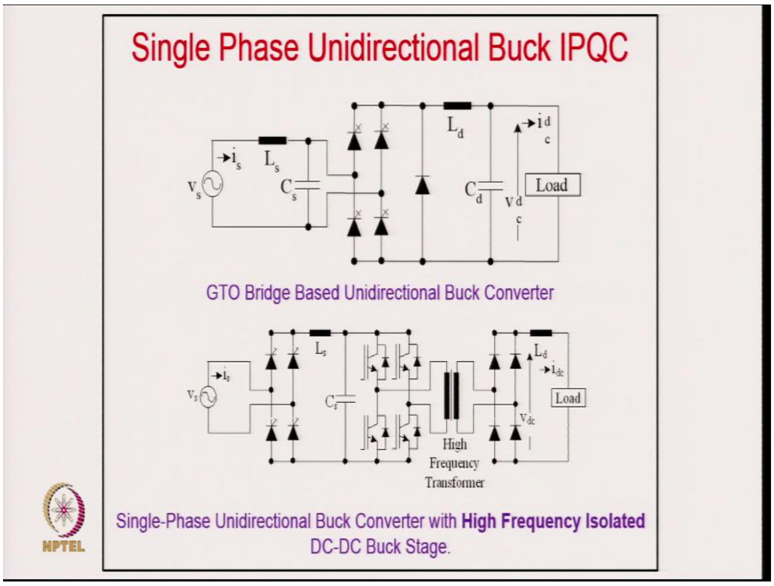

Single Phase Unidirectional Buck IPQC

GTO Bridge Based Unidirectional Buck Converter

Single-Phase Unidirectional Buck Converter with **High Frequency Isolated** DC-DC Buck Stage.

So, another configuration is that, you can have a self-commutating component with the diode and an EMI filter. Of course, in such cases, you cannot get high switching frequency. Another configuration can be that, after first configuration, you can have a like isolated buck converter, because in many applications, we have a requirement for isolation.

So, the buck operation can be a fixed buck operation, which can be changed by changing transformer turns ratio. Another can be that you can change the duty cycle and reduce the voltage at the output which are applied to the primary winding of the high frequency transformer.

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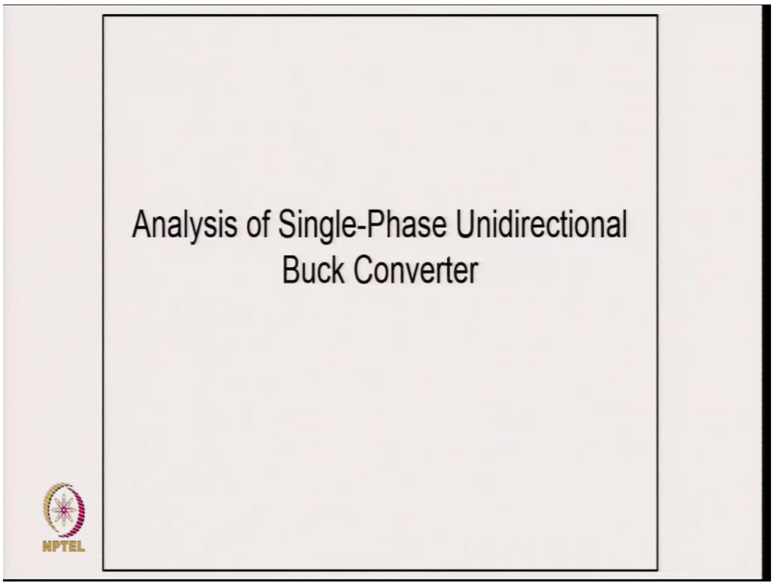

Analysis of Single-Phase Unidirectional Buck Converter

So, coming to analysis of the single-phase unidirectional buck improved power quality converter.

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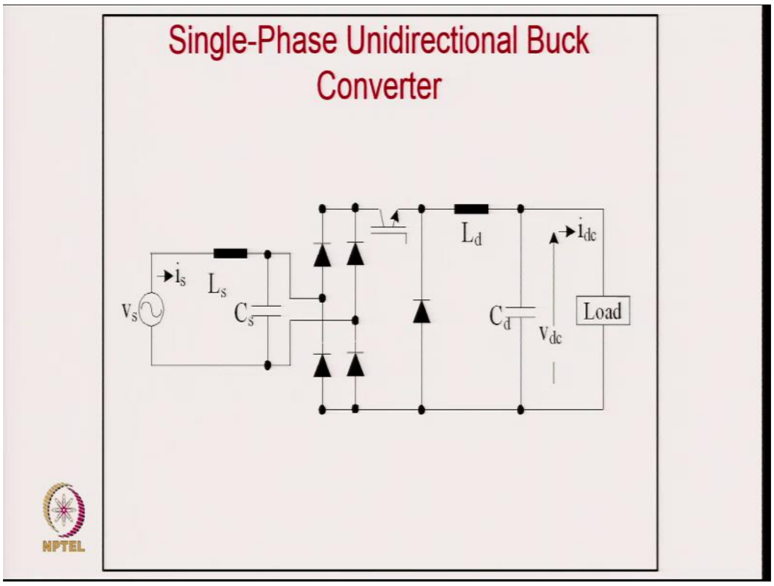

Single-Phase Unidirectional Buck Converter

I mean this is the typical first configuration we have talked about

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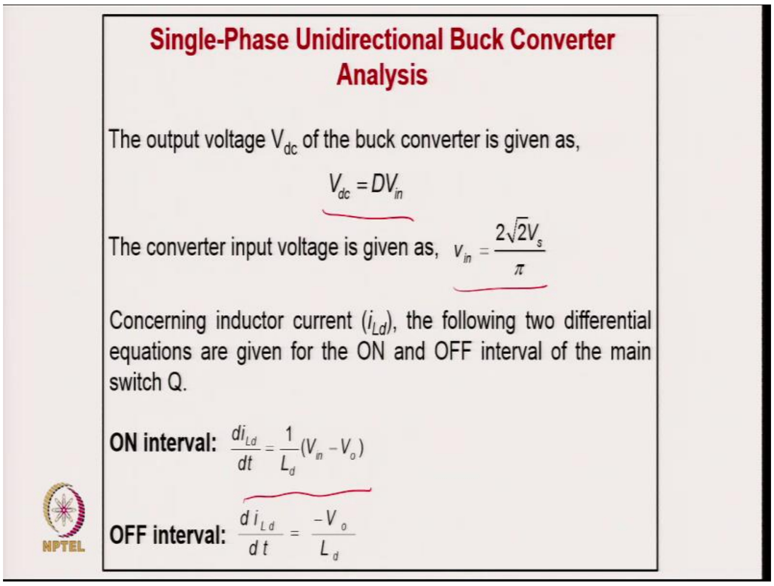

Single-Phase Unidirectional Buck Converter Analysis

The output voltage V_{dc} of the buck converter is given as,

$$V_{dc} = DV_{in}$$

The converter input voltage is given as, $v_{in} = \frac{2\sqrt{2}V_s}{\pi}$

Concerning inductor current (i_{Ld}), the following two differential equations are given for the ON and OFF interval of the main switch Q.

ON interval: $\frac{di_{Ld}}{dt} = \frac{1}{L_d}(V_{in} - V_o)$

OFF interval: $\frac{di_{Ld}}{dt} = \frac{-V_o}{L_d}$

You can go to the relation for the buck converter operating in CCM operation. So, the output DC voltage will be equal to the duty cycle multiplied Vin; where, the Vin is the average output voltage of the diode rectifier. Then, you can have a inductor current in the two modes i.e. ON and OFF mode. It is noteworthy that, if converter operating in DCM operation, then even after OFF interval, the current inductor becomes 0, so, you will have a third mode where neither the switch nor the diode will conduct.

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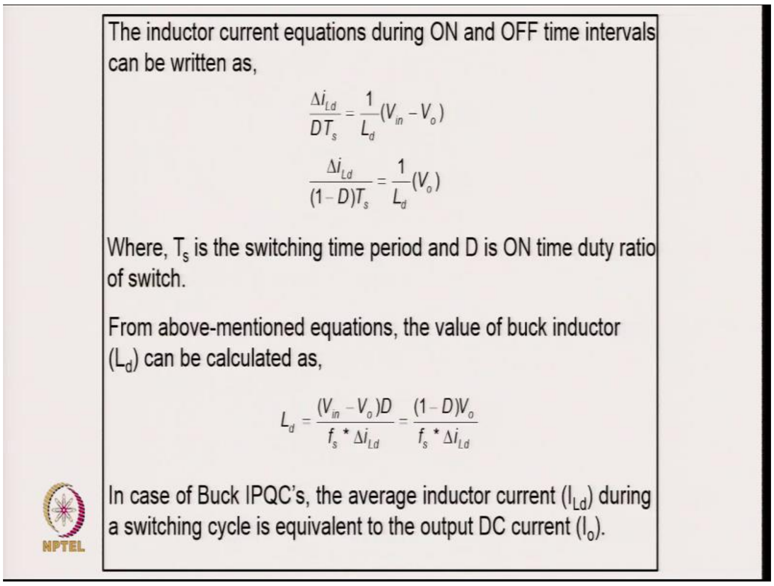

The inductor current equations during ON and OFF time intervals can be written as,

$$\frac{\Delta i_{Ld}}{DT_s} = \frac{1}{L_d}(V_{in} - V_o)$$

$$\frac{\Delta i_{Ld}}{(1-D)T_s} = \frac{1}{L_d}(V_o)$$

Where, T_s is the switching time period and D is ON time duty ratio of switch.

From above-mentioned equations, the value of buck inductor (L_d) can be calculated as,

$$L_d = \frac{(V_{in} - V_o)D}{f_s * \Delta i_{Ld}} = \frac{(1-D)V_o}{f_s * \Delta i_{Ld}}$$

In case of Buck IPQC's, the average inductor current (I_{Ld}) during a switching cycle is equivalent to the output DC current (I_o).

As you increase the switching frequency higher, the value of the inductor can be reduced. And it also depends on current ripple in the inductor, so, if you allow the current ripple more, then the inductor further can be reduced. In case of buck improved power quality converter, the average inductor current during the switching cycle is equivalent to the output current.

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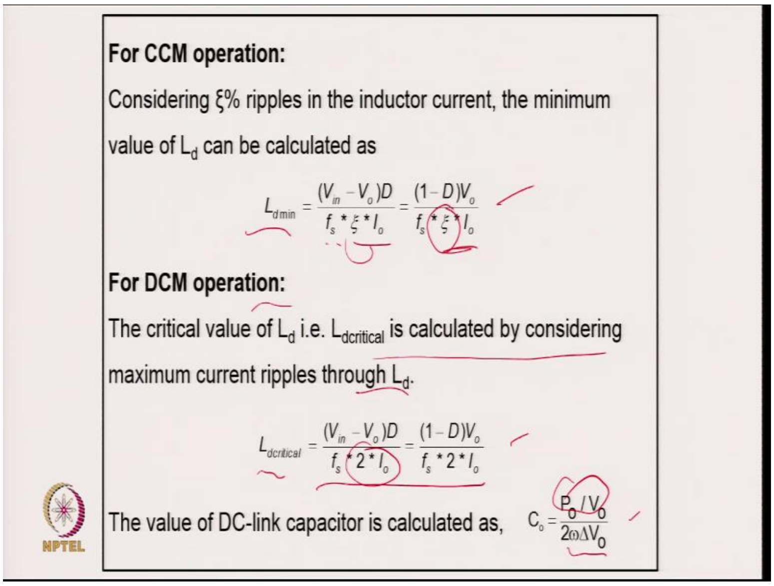

For CCM operation:

Considering ξ% ripples in the inductor current, the minimum value of L_d can be calculated as

$$L_{d\min} = \frac{(V_{in} - V_o)D}{f_s * \xi * I_o} = \frac{(1-D)V_o}{f_s * \xi * I_o}$$

For DCM operation:

The critical value of L_d i.e. $L_{dcritical}$ is calculated by considering maximum current ripples through L_d.

$$L_{dcritical} = \frac{(V_{in} - V_o)D}{f_s * 2 * I_o} = \frac{(1-D)V_o}{f_s * 2 * I_o}$$

The value of DC-link capacitor is calculated as, $C_o = \frac{P_0 / V_0}{2\omega \Delta V_0}$

From the given equations, considering percentage current ripple in the inductor current and switching frequency; the minimum value of the inductor can be calculated. During DCM operation the inductor ripple current will be twice of your output current. Virtually, you are going from 0 to twice; twice of output current. In such case, you are allowing the current twice, so, we call it critical conduction mode. But if you want to operate in DCM, certainly the inductance would be much lesser than this critical inductance. It means, you can further reduce the size of the inductor, in case if you want to go to in DCM operation.

But you can understand, once your maximum current is twice of output current, it means your device rating; the peak current rating of the device will be even more than the twice of the output current. So, this is a kind of penalty of DCM operation.

As far as, output capacitor selection is concerned, in a single phase power factor correction converter, the output capacitor calculation depends upon the second harmonic voltage ripple at the capacitor. So, the output capacitor value is depends on how much ripple you are permitting and how much is the load. So, as you increase the output power for a given output voltage, you will find the capacitor required higher. And apart from that, even though if you are permitting voltage ripple less, then also capacitor required is higher. I mean, it depends on application that how much percentage of voltage ripple, you can permit.

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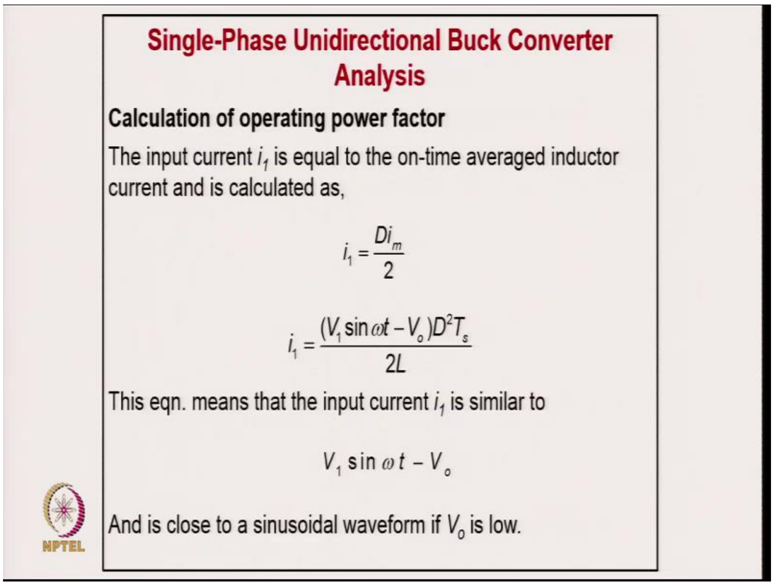

Single-Phase Unidirectional Buck Converter Analysis

Calculation of operating power factor

The input current i_1 is equal to the on-time averaged inductor current and is calculated as,

$$i_1 = \frac{Di_m}{2}$$

$$i_1 = \frac{(V_1 \sin\omega t - V_o)D^2 T_s}{2L}$$

This eqn. means that the input current i_1 is similar to

$$V_1 \sin\omega t - V_o$$

And is close to a sinusoidal waveform if V_o is low.

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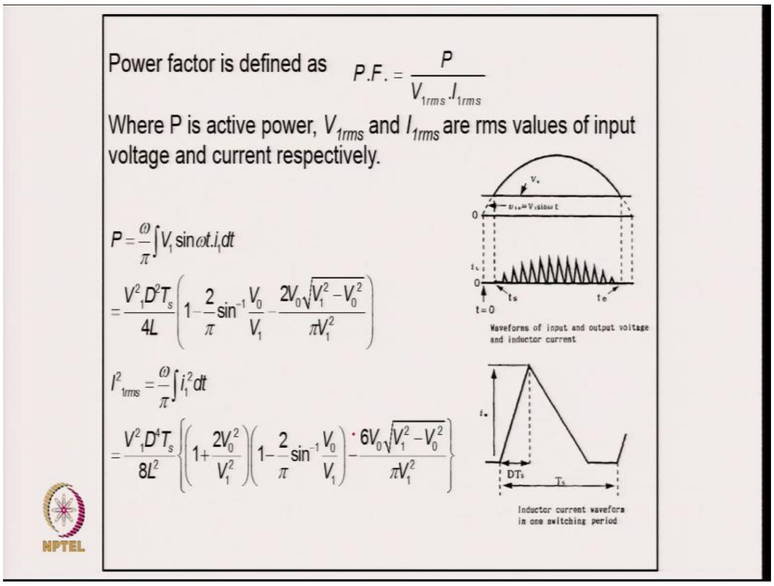

Power factor is defined as $P.F. = \frac{P}{V_{1rms}.I_{1rms}}$

Where P is active power, V_{1rms} and I_{1rms} are rms values of input voltage and current respectively.

$$P = \frac{\omega}{\pi}\int V_1 \sin\omega t . i_1 dt$$

$$= \frac{V_1^2 D^2 T_s}{4L}\left(1 - \frac{2}{\pi}\sin^{-1}\frac{V_0}{V_1} - \frac{2V_0\sqrt{V_1^2 - V_0^2}}{\pi V_1^2}\right)$$

$$I^2_{1rms} = \frac{\omega}{\pi}\int i_1^2 dt$$

$$= \frac{V_1^2 D^4 T_s}{8L^2}\left\{\left(1 + \frac{2V_0^2}{V_1^2}\right)\left(1 - \frac{2}{\pi}\sin^{-1}\frac{V_0}{V_1}\right) - \frac{6V_0\sqrt{V_1^2 - V_0^2}}{\pi V_1^2}\right\}$$

Waveforms of input and output voltage and inductor current

Inductor current waveform in one switching period

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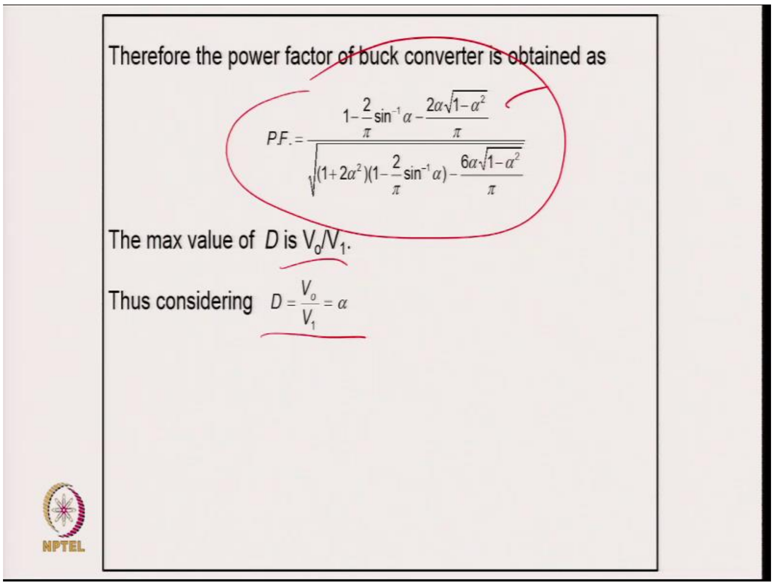

Therefore the power factor of buck converter is obtained as

$$P.F.=\frac{1-\frac{2}{\pi}\sin^{-1}\alpha-\frac{2\alpha\sqrt{1-\alpha^2}}{\pi}}{\sqrt{(1+2\alpha^2)(1-\frac{2}{\pi}\sin^{-1}\alpha)-\frac{6\alpha\sqrt{1-\alpha^2}}{\pi}}}$$

The max value of D is V_0/V_1.

Thus considering $D=\frac{V_o}{V_1}=\alpha$

And you can define the power factor in terms of your duty cycle, where the alpha is duty cycle. Of course, it should be completely non-linear function.

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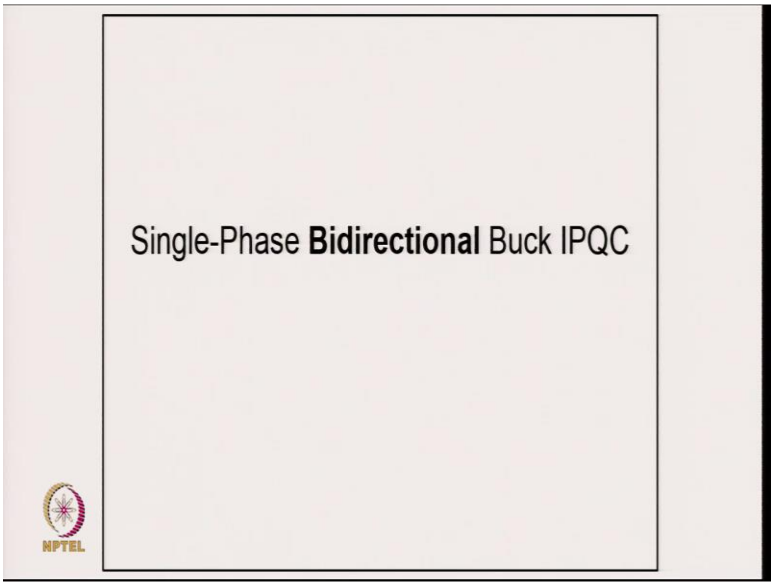

Single-Phase **Bidirectional** Buck IPQC

Now coming to the bidirectional buck IPQCs. Although many applications require unidirectional power flow; but some applications require bidirectional power flow also.

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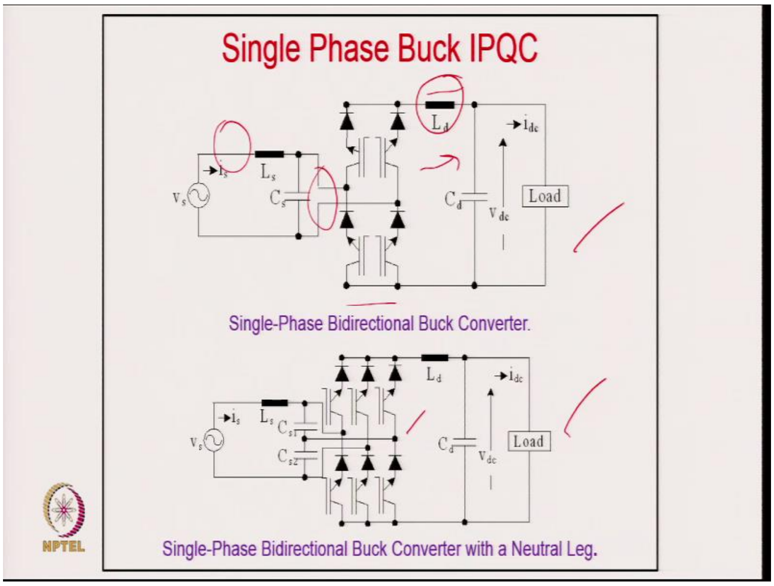

Single Phase Buck IPQC

Single-Phase Bidirectional Buck Converter.

Single-Phase Bidirectional Buck Converter with a Neutral Leg.

These are the different configuration of bidirectional buck IPQCs. First one is a current source inverter with an LC filter at the input end, and the current can be sinusoidal in phase with the voltage so that you can get unity power factor. In this, you can have a either power flow from AC to DC side or DC to AC side, this that is the reason, we call it a bidirectional power flow.

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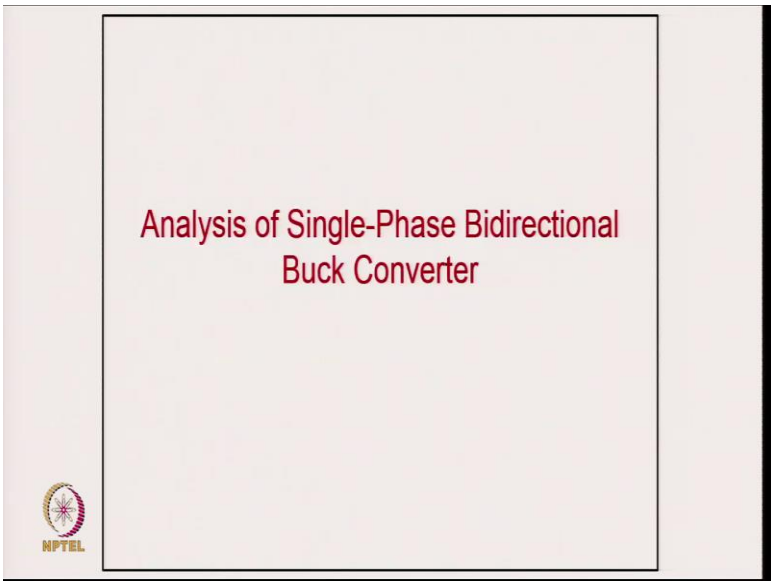

Analysis of Single-Phase Bidirectional Buck Converter

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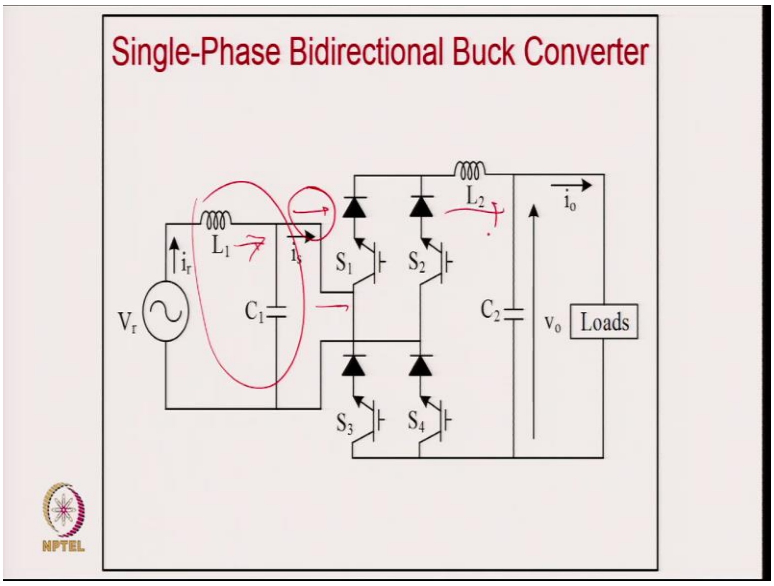

Single-Phase Bidirectional Buck Converter

Now, coming to the analysis of the single phase bidirectional buck IPQC. This is the circuit. Why EMI filter is required? Because current before EMI filter will be a PWM current and we want a continuous current at unity power factor at AC side. So, this EMI filter is required. Of course, at DC side, voltage direction can be changed, but current direction cannot be changed because of constant current characteristic, to enable bidirectional power flow.

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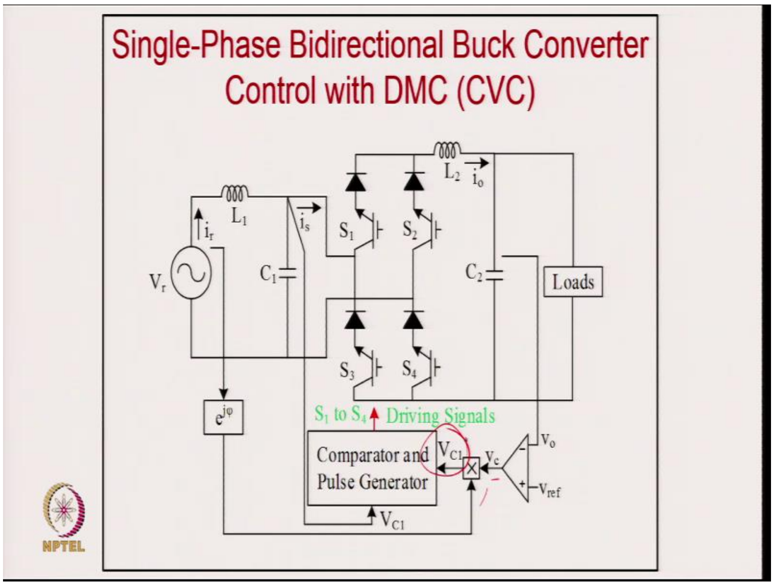

Single-Phase Bidirectional Buck Converter Control with DMC (CVC)

Coming to control part, control is quite straight forward. We need to regulate output voltage and we have a reference output voltage, so, we will get this with the controller, you can call it the control voltage.

At the output, this is not only array amplifier; but it is a kind of a PID controller. So, we get amplitude and we are getting the phase from input side. We will multiply both to get a reference and we are sensing this capacitor voltage. We are estimating reference capacitor voltage and we are getting a capacitor voltage, which control the switches. If we maintain the capacitor voltage in a way with the angle, then, we expect that you can have a power factor close to unity as you can see from the phasor diagram.

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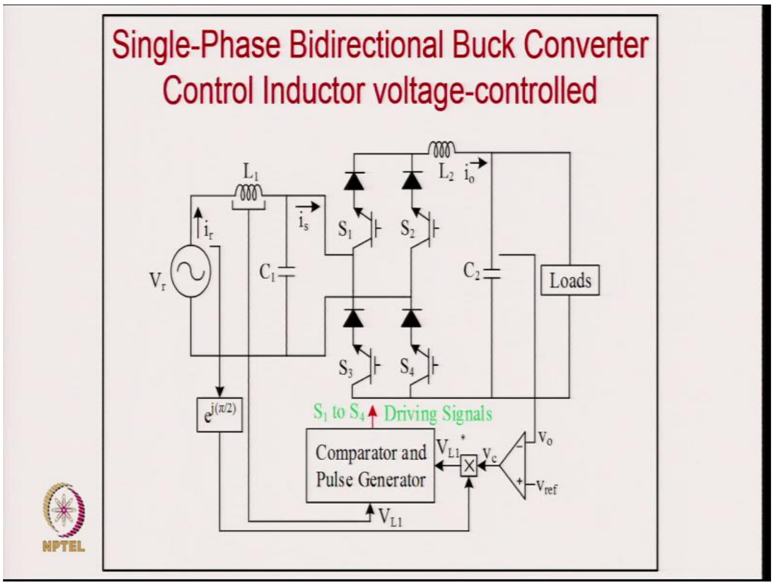

Single-Phase Bidirectional Buck Converter
Control Inductor voltage-controlled

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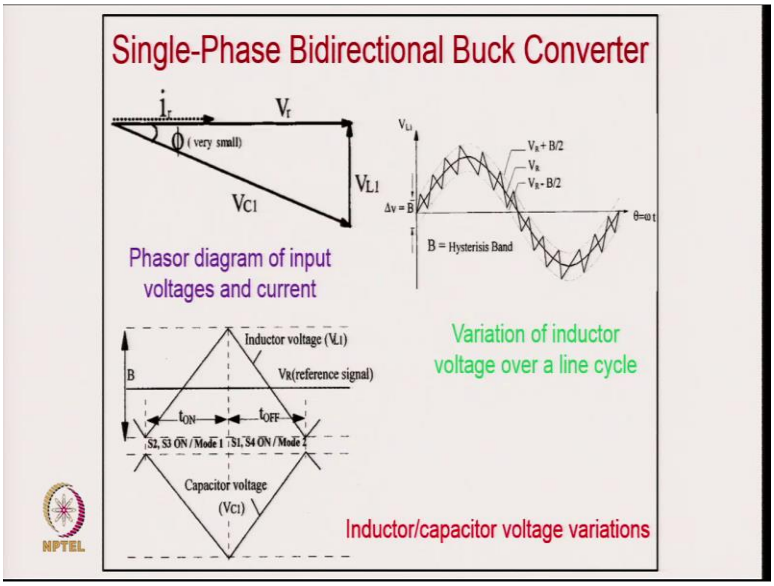
Single-Phase Bidirectional Buck Converter

Phasor diagram of input voltages and current

Variation of inductor voltage over a line cycle

Inductor/capacitor voltage variations

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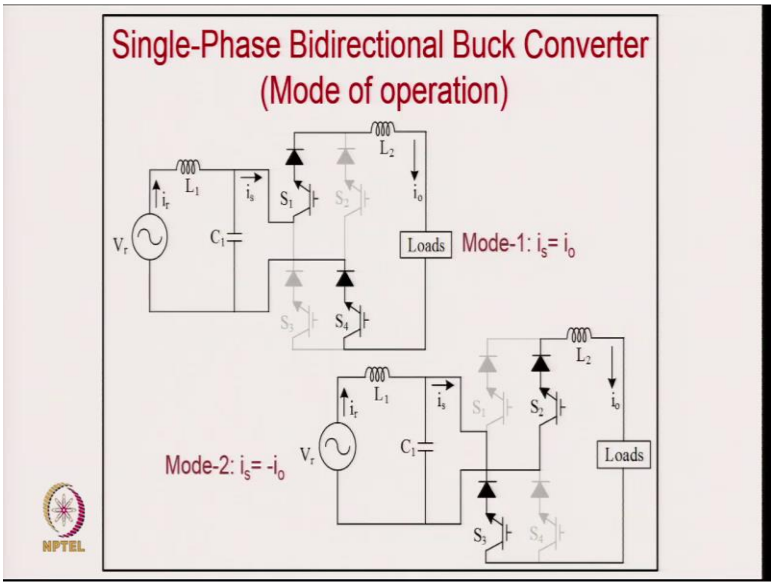
Single-Phase Bidirectional Buck Converter (Mode of operation)

Mode-1: $i_s = i_o$

Mode-2: $i_s = -i_o$

And these are the switching modes of bidirectional buck IPQCs. But in between these two states, another mode, where you will have a freewheeling action, where i_s will be equal i_o, and that state is responsible for typically controlling the current.

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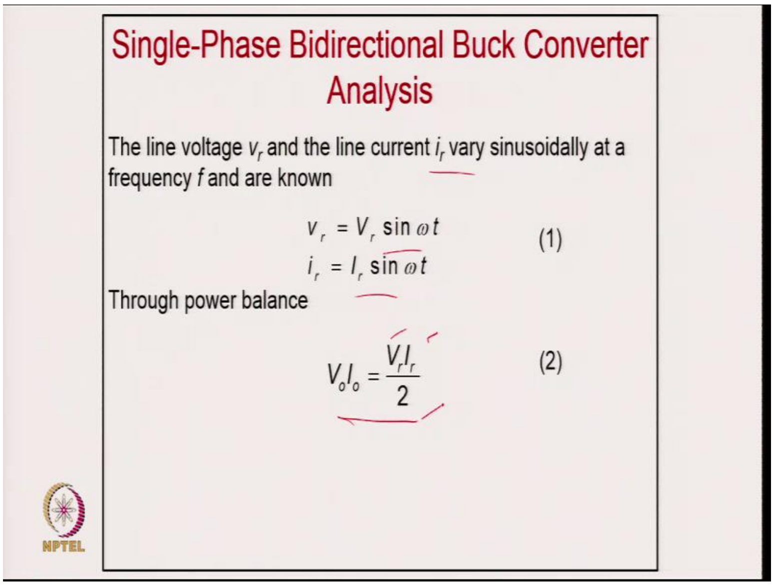

Single-Phase Bidirectional Buck Converter Analysis

The line voltage v_r and the line current i_r vary sinusoidally at a frequency f and are known

$$v_r = V_r \sin \omega t \qquad (1)$$
$$i_r = I_r \sin \omega t$$

Through power balance

$$V_o I_o = \frac{V_r I_r}{2} \qquad (2)$$

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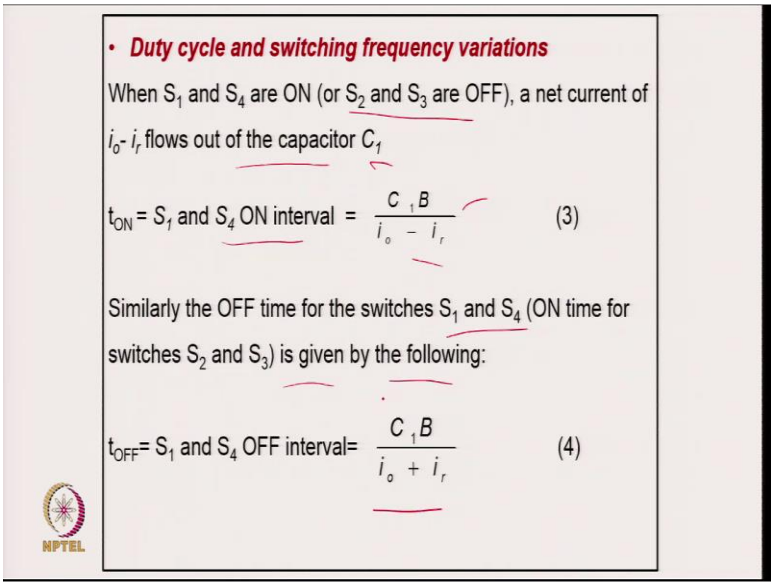

- ***Duty cycle and switching frequency variations***

When S_1 and S_4 are ON (or S_2 and S_3 are OFF), a net current of $i_o - i_r$ flows out of the capacitor C_1

$$t_{ON} = S_1 \text{ and } S_4 \text{ ON interval } = \frac{C_1 B}{i_o - i_r} \qquad (3)$$

Similarly the OFF time for the switches S_1 and S_4 (ON time for switches S_2 and S_3) is given by the following:

$$t_{OFF} = S_1 \text{ and } S_4 \text{ OFF interval} = \frac{C_1 B}{i_o + i_r} \qquad (4)$$

When, S1 and S4 are ON, S2 and S3 will be OFF. The net current flow is the difference of i_o and i_r and it flows to the capacitor, and you can call it capacitor current. Similarly, in OFF period, when S1 and S4 are OFF and S2 and S3 are ON, the current flowing into the circuit is given as follows.

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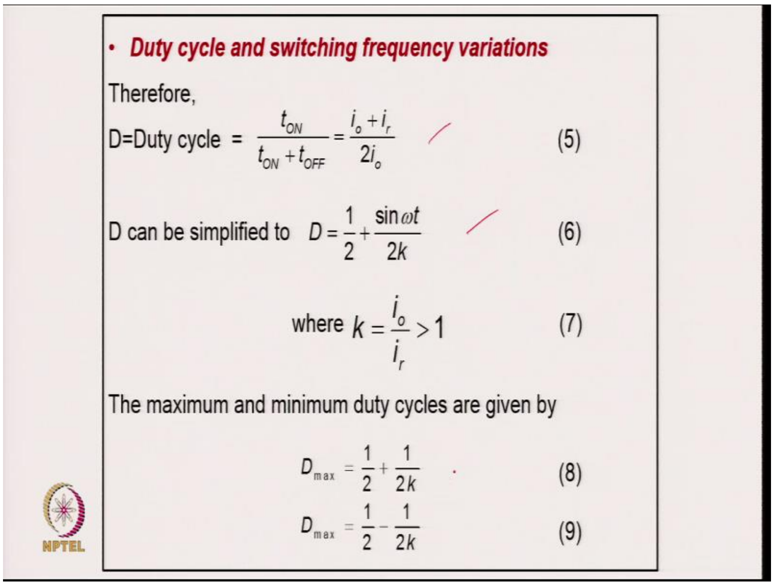

- Duty cycle and switching frequency variations

Therefore,

D=Duty cycle = $\frac{t_{ON}}{t_{ON}+t_{OFF}}=\frac{i_o+i_r}{2i_o}$ (5)

D can be simplified to $D=\frac{1}{2}+\frac{\sin\omega t}{2k}$ (6)

where $k=\frac{i_o}{i_r}>1$ (7)

The maximum and minimum duty cycles are given by

$$D_{max}=\frac{1}{2}+\frac{1}{2k} \quad (8)$$

$$D_{max}=\frac{1}{2}-\frac{1}{2k} \quad (9)$$

From this, you can have a relation for the duty cycle for maintaining this and from this, you can find out minimum and maximum duty cycle.

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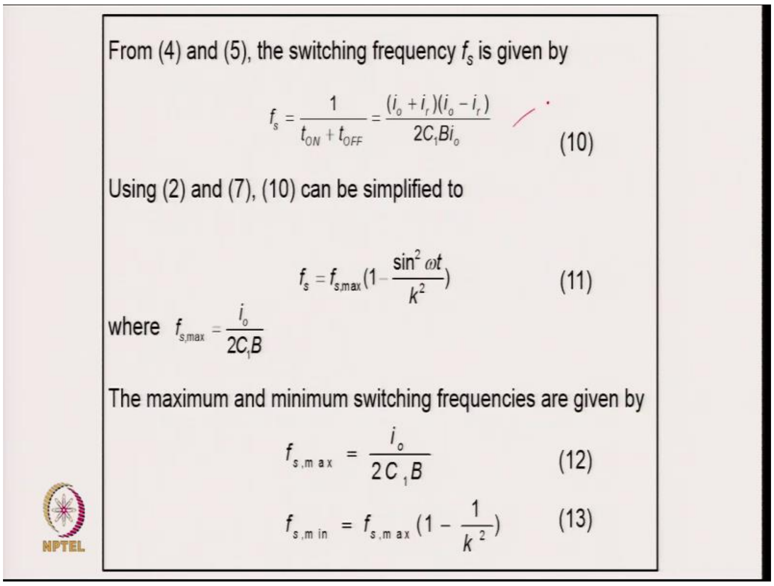

From (4) and (5), the switching frequency f_s is given by

$$f_s=\frac{1}{t_{ON}+t_{OFF}}=\frac{(i_o+i_r)(i_o-i_r)}{2C_1Bi_o} \quad (10)$$

Using (2) and (7), (10) can be simplified to

$$f_s=f_{s,max}\left(1-\frac{\sin^2\omega t}{k^2}\right) \quad (11)$$

where $f_{s,max}=\frac{i_o}{2C_1B}$

The maximum and minimum switching frequencies are given by

$$f_{s,max}=\frac{i_o}{2C_1B} \quad (12)$$

$$f_{s,min}=f_{s,max}\left(1-\frac{1}{k^2}\right) \quad (13)$$

Then, switching frequency which have a relation like this.

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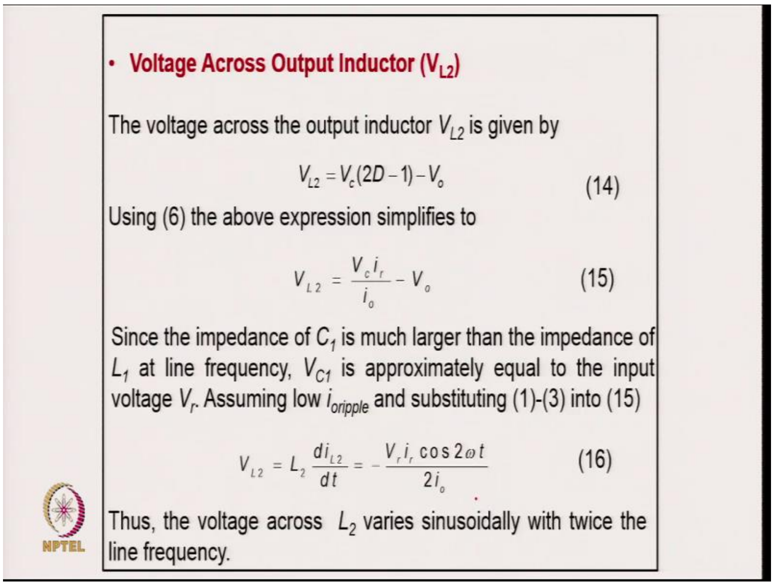

- **Voltage Across Output Inductor (V_{L2})**

The voltage across the output inductor V_{L2} is given by

$$V_{L2} = V_c(2D-1) - V_o \qquad (14)$$

Using (6) the above expression simplifies to

$$V_{L2} = \frac{V_c i_r}{i_o} - V_o \qquad (15)$$

Since the impedance of C_1 is much larger than the impedance of L_1 at line frequency, V_{C1} is approximately equal to the input voltage V_r. Assuming low $i_{oripple}$ and substituting (1)-(3) into (15)

$$V_{L2} = L_2 \frac{di_{L2}}{dt} = -\frac{V_r i_r \cos 2\omega t}{2 i_o} \qquad (16)$$

Thus, the voltage across L_2 varies sinusoidally with twice the line frequency.

And then, the voltage, you can call it voltage across the output inductor is given by these expressions.

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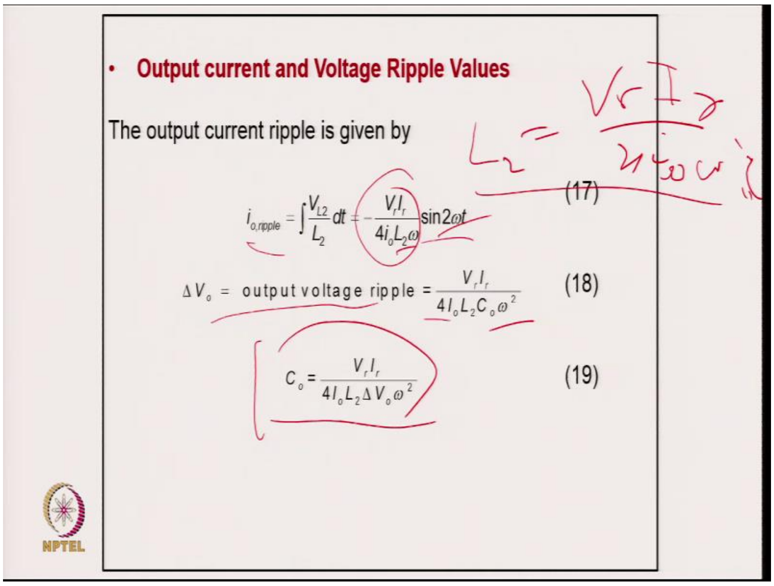

- **Output current and Voltage Ripple Values**

The output current ripple is given by

$$L_2 = \frac{V_r I_r}{4 i_o \omega i}$$

$$i_{o,ripple} = \int \frac{V_{L2}}{L_2} dt = -\frac{V_r I_r}{4 i_o L_2 \omega} \sin 2\omega t \qquad (17)$$

$$\Delta V_o = \text{output voltage ripple} = \frac{V_r I_r}{4 I_o L_2 C_o \omega^2} \qquad (18)$$

$$C_o = \frac{V_r I_r}{4 I_o L_2 \Delta V_o \omega^2} \qquad (19)$$

So, the inductor value can be obtained like this. Once you know the inductor, I mean for giving output voltage ripple from this relation, you can find out the value of capacitor. So, that gives the value of the inductor and capacitor as far as the design of bidirectional buck IPQC is concerned.

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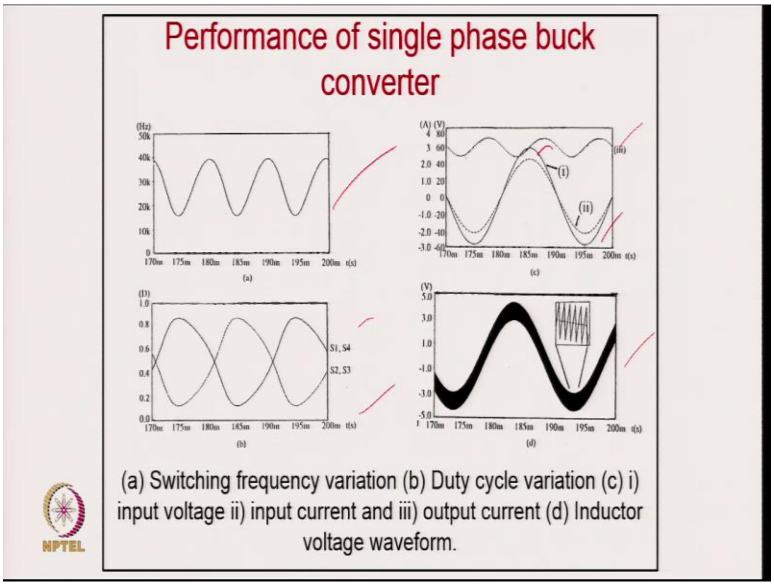


Performance of single phase buck converter

(a) Switching frequency variation (b) Duty cycle variation (c) i) input voltage ii) input current and iii) output current (d) Inductor voltage waveform.

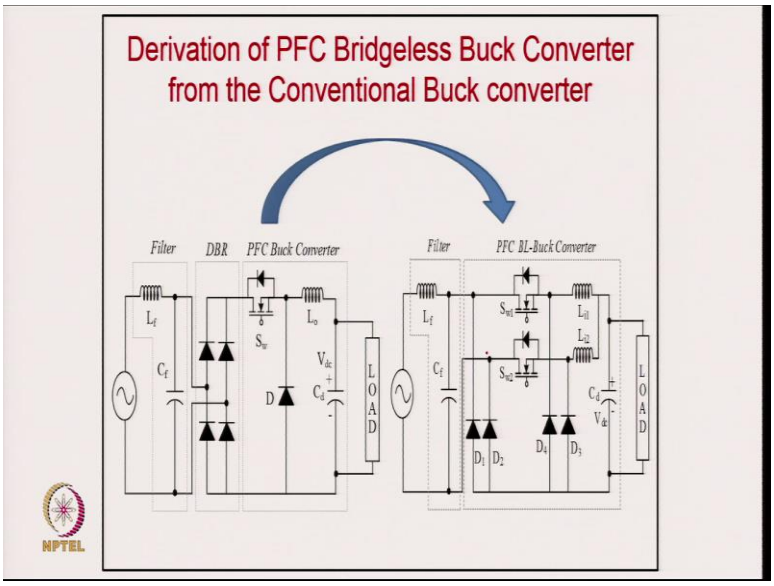
And after having a design, this is the performance analysis of the bidirectional buck IPQC.

(Refer Slide Time: 22:25)

Analysis, Design, Simulation and Performance of PFC **Bridgeless Buck** Converter

Now coming to analysis, design and simulation performance of PFC bridgeless buck converters.

(Refer Slide Time: 22:33)


Derivation of PFC Bridgeless Buck Converter from the Conventional Buck converter

I mean this is what we are talking about, so, first one is with the diode bridge and second is a bridgeless version of buck IPQC.

You can see why this is bridgeless? So, we are alimenting the diode bridge up to some extent and now the converter will operate as per the polarity of supply voltage.

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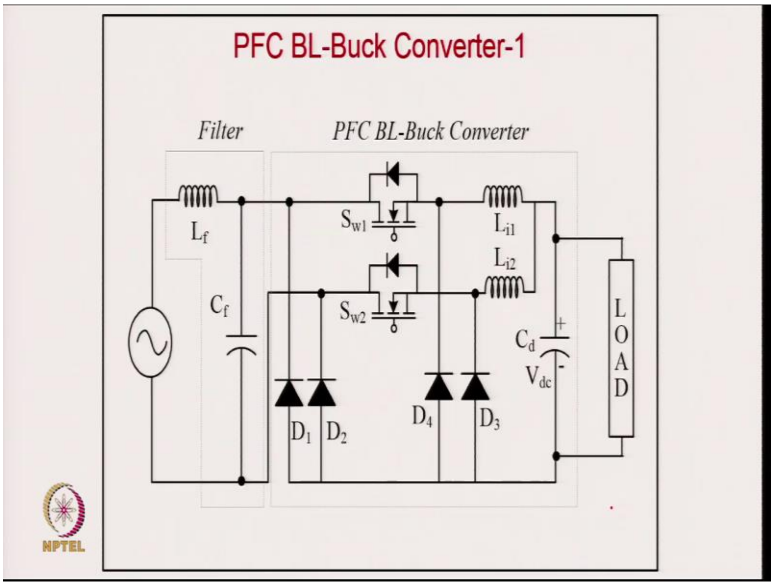
PFC BL-Buck Converter-1

And coming to this, there are many topologies of bridgeless version of buck IPQC. So, this is the first topology which we have in previous slide.

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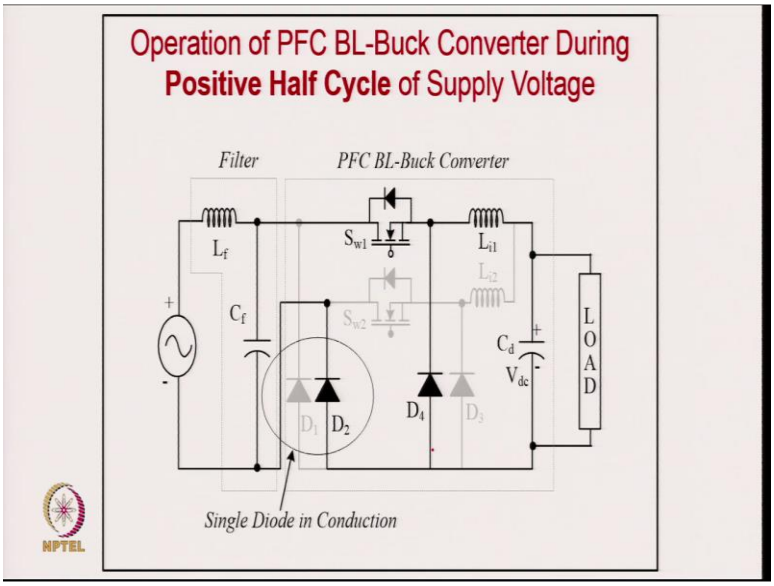


Operation of PFC BL-Buck Converter During **Positive Half Cycle** of Supply Voltage

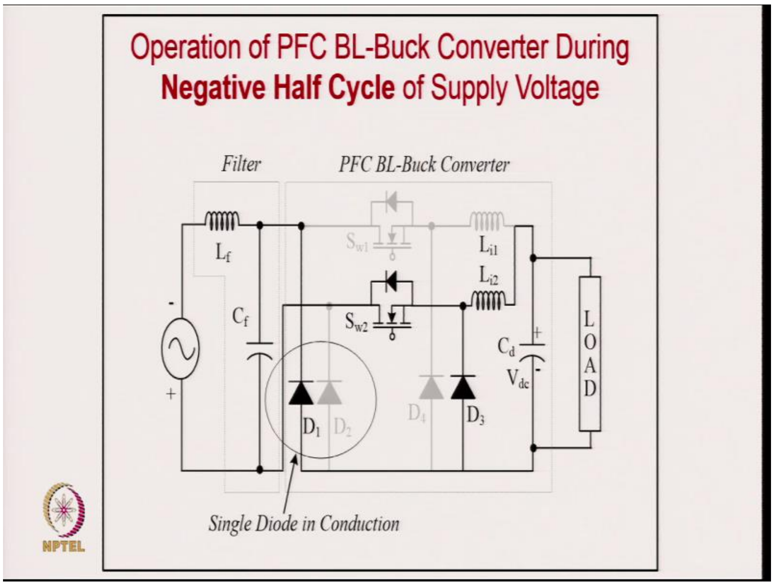
Filter

PFC BL-Buck Converter

Single Diode in Conduction

And, how the operation is, this is the bridgeless working for positive half cycle.

(Refer Slide Time: 23:32)



Operation of PFC BL-Buck Converter During **Negative Half Cycle** of Supply Voltage

Filter

PFC BL-Buck Converter

Single Diode in Conduction

And then, you have circuit like this, for negative half cycle of supply voltage.

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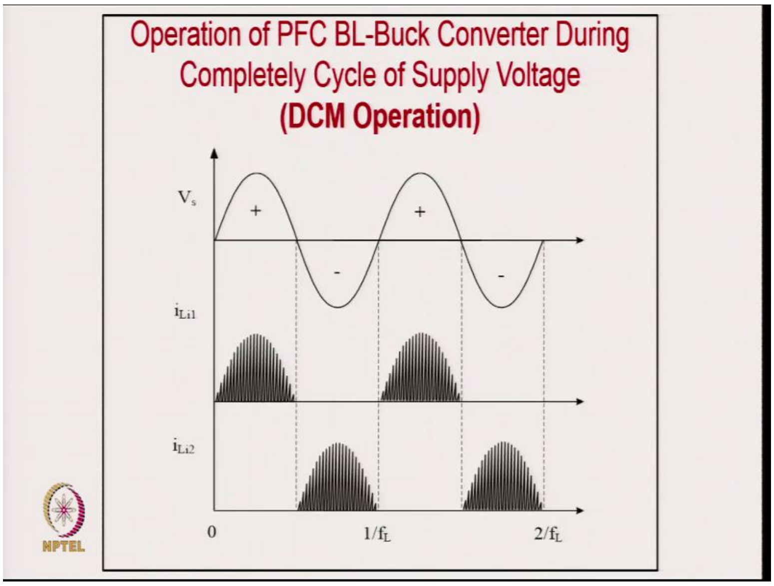
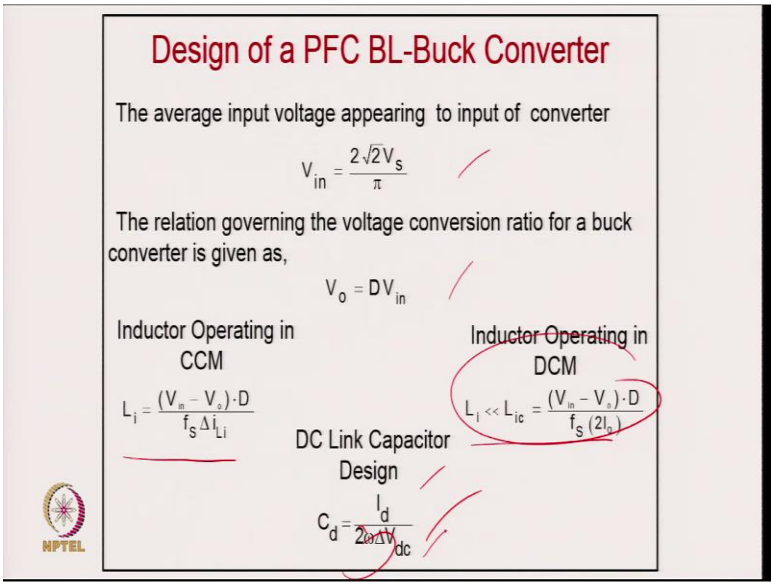


Operation of PFC BL-Buck Converter During Completely Cycle of Supply Voltage (DCM Operation)

And of course, these are the waveforms for buck IPQCs under DCM mode operation.

(Refer Slide Time: 24:05)



Design of a PFC BL-Buck Converter

The average input voltage appearing to input of converter

$$V_{in} = \frac{2\sqrt{2}V_s}{\pi}$$

The relation governing the voltage conversion ratio for a buck converter is given as,

$$V_o = DV_{in}$$

Inductor Operating in CCM

$$L_i = \frac{(V_{in} - V_o)\cdot D}{f_S \Delta i_{Li}}$$

Inductor Operating in DCM

$$L_i << L_{ic} = \frac{(V_{in} - V_o)\cdot D}{f_S (2I_o)}$$

DC Link Capacitor Design

$$C_d = \frac{I_d}{2\omega\Delta V_{dc}}$$

And these are the typical relations for the design of bridgeless buck IPQCs under both CCM and DCM operation.

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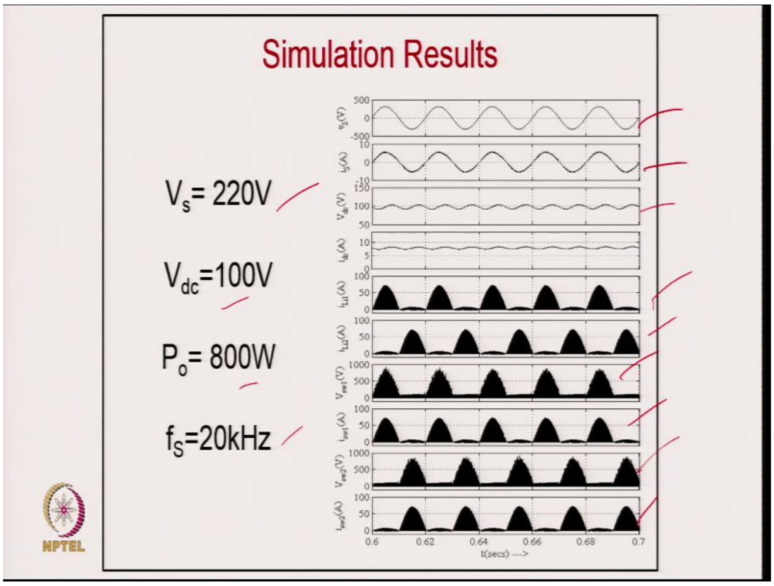


Simulation Results

V_s= 220V

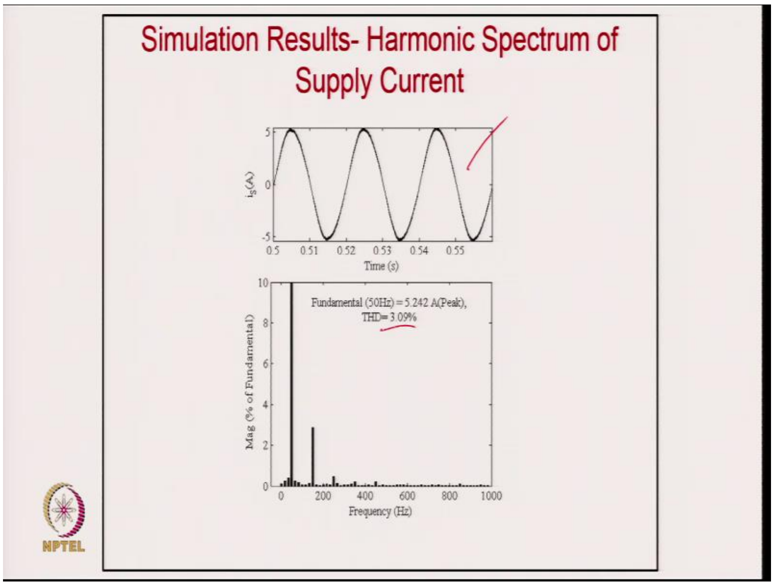
V_{dc}=100V

P_o= 800W

f_S=20kHz

So, this is a case study, where, the supply voltage is 220 V rms. You can see in phase and almost sinusoidal supply current. This is the DC link voltage which have some second harmonic ripple depends how much in the design is permitted. The output voltage is 100 V, the power level is 800 W, the switching frequency is 20 kHz.

(Refer Slide Time: 25:26)



Simulation Results- Harmonic Spectrum of Supply Current

Fundamental (50Hz) = 5.242 A(Peak), THD= 3.09%

And the THD of supply current is maintained less than 5 percent and found nearly 3.09 percent. You can see the current is sinusoidal and in phase with the supply voltage having a power factor correction to unity neither reactive power nor harmonics in the input supply current.

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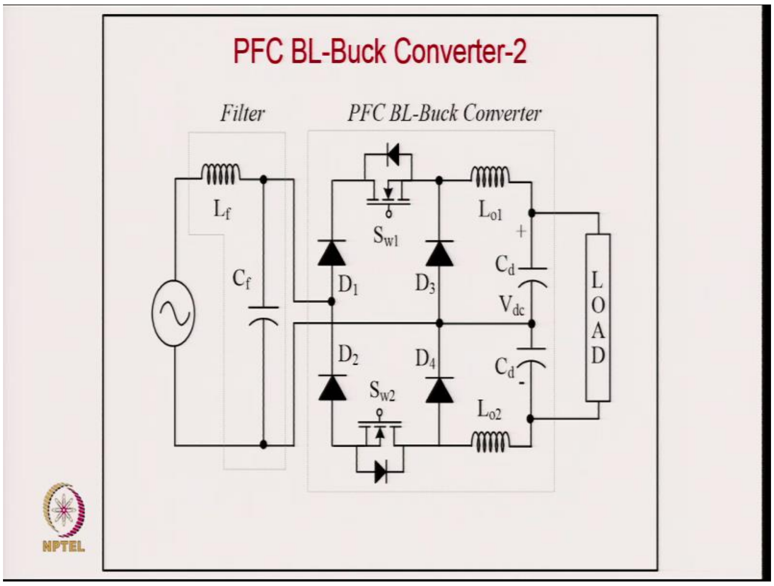


PFC BL-Buck Converter-2

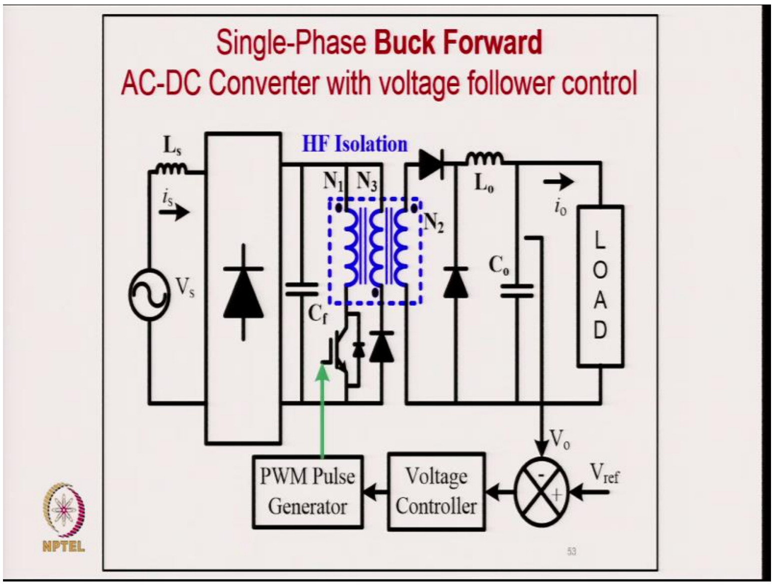
Now, this another configuration of your bridgeless buck converter, I mean the modification to previous one.

(Refer Slide Time: 26:12)

Single Phase Buck
IPQC's with High Frequency Transformer
Isolation

Now coming to single phase buck improved power quality converter with high frequency transformer isolation. I have already mentioned that we have many applications, where you require isolation. The very purpose of the transformer is number one; isolation and another is to get many output voltages.

(Refer Slide Time: 26:32)



Single-Phase **Buck Forward**

AC-DC Converter with voltage follower control

This is a buck forward improved power quality converter. In this, after the diode bridge, we have a forward converter and this forward converter is designed in DCM mode. So, for DCM mode, we have two energy storage elements; one is the output inductor, another is the magnetizing inductor. So, any one of them, we can put in DCM and once we design in DCM, due to voltage follower the input current will follow supply voltage only by the voltage control.

So, we have a reference voltage, we have a feedback voltage and we have a voltage controller; may be a PI controller or PID controller and directly, we are comparing it with the carrier wave to give the switching signal here. In this case, we are not sensing input voltage or input current; only by making the current in output inductor discontinuous, we are able to get inherent power factor correction, we call this a voltage follower approach.

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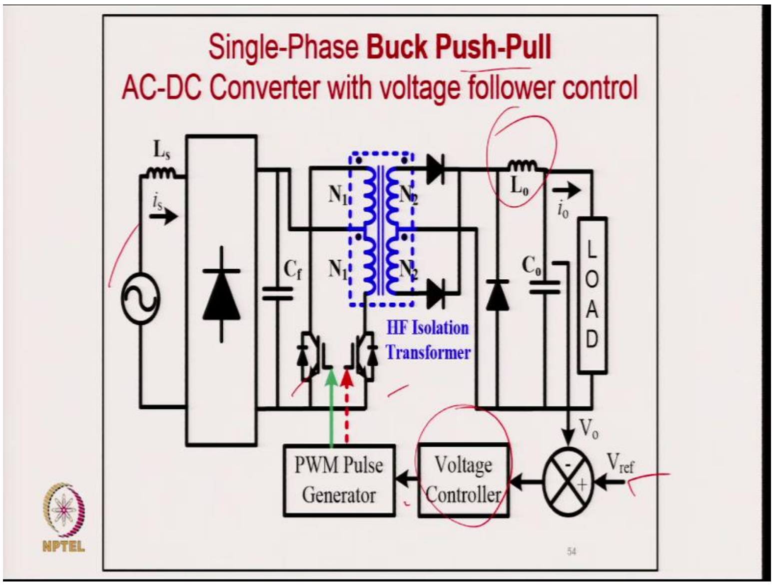
Single-Phase **Buck Push-Pull**
AC-DC Converter with voltage follower control

Similarly, we can have a buck push pull configuration. Here, the output inductor can be design in DCM or even the transformer magnetizing can have DCM operation. Here, the control remains identical due to DCM operation.

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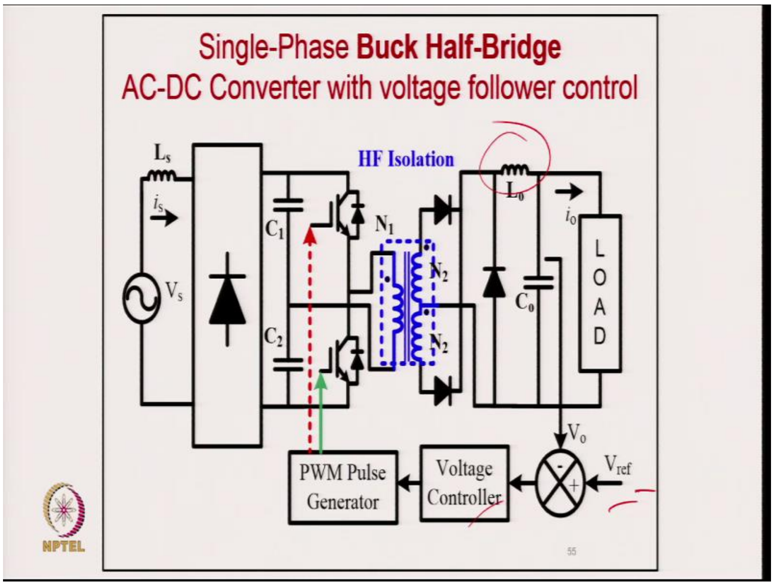
Single-Phase **Buck Half-Bridge**
AC-DC Converter with voltage follower control

Similarly, we have a buck half bridge. In this case, we are having output inductor designing a DCM. Here, the control remains identical due to DCM operation.

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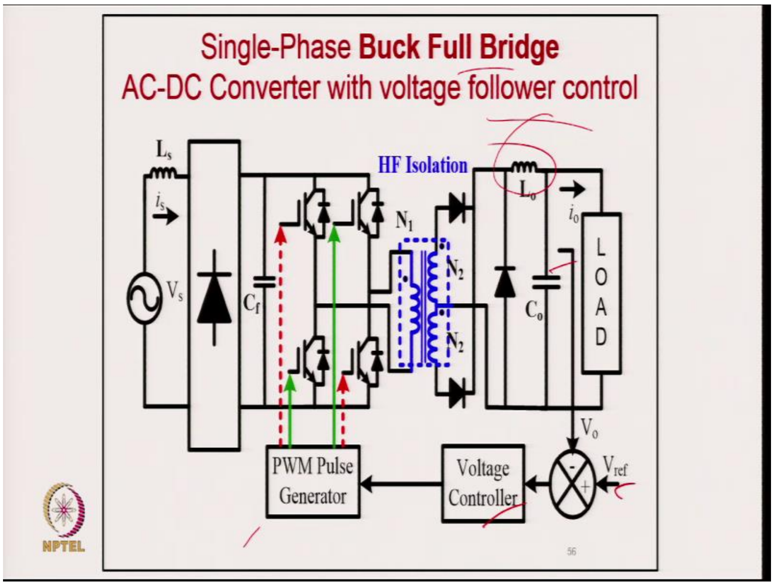

Single-Phase **Buck Full Bridge**
AC-DC Converter with voltage follower control

And finally, for very high power, we use the bridge configuration. Again, the output inductor is designed in DCM. Here, the control remains identical due to DCM operation.

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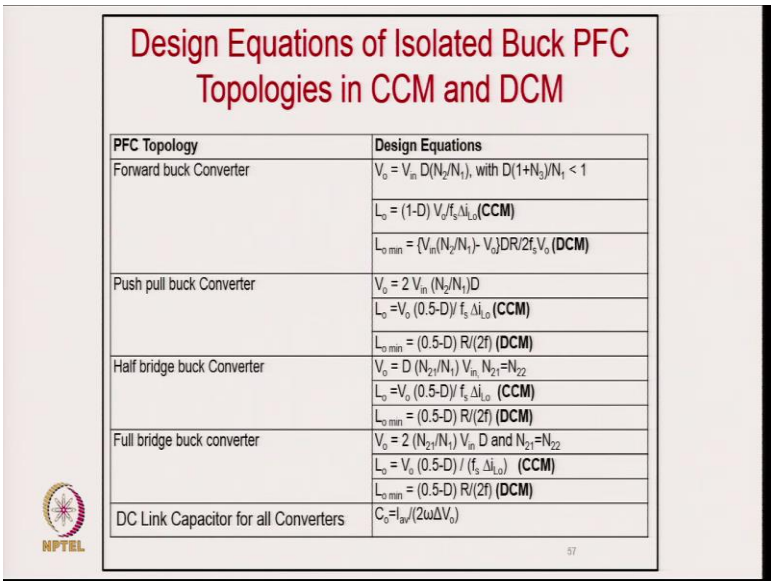

Design Equations of Isolated Buck PFC Topologies in CCM and DCM

PFC Topology	**Design Equations**
Forward buck Converter	$V_o = V_{in} D(N_2/N_1)$, with $D(1+N_3)/N_1 < 1$
	$L_o = (1-D) V_o/f_s \Delta i_{Lo}$**(CCM)**
	$L_{o\,min} = \{V_{in}(N_2/N_1) - V_o\}DR/2f_sV_o$ **(DCM)**
Push pull buck Converter	$V_o = 2 V_{in} (N_2/N_1)D$
	$L_o = V_o (0.5-D)/ f_s \Delta i_{Lo}$ **(CCM)**
	$L_{o\,min} = (0.5-D) R/(2f)$ **(DCM)**
Half bridge buck Converter	$V_o = D (N_{21}/N_1) V_{in,} N_{21}=N_{22}$
	$L_o = V_o (0.5-D)/ f_s \Delta i_{Lo}$ **(CCM)**
	$L_{o\,min} = (0.5-D) R/(2f)$ **(DCM)**
Full bridge buck converter	$V_o = 2 (N_{21}/N_1) V_{in}$ D and $N_{21}=N_{22}$
	$L_o = V_o (0.5-D) / (f_s \Delta i_{Lo})$ **(CCM)**
	$L_{o\,min} = (0.5-D) R/(2f)$ **(DCM)**
DC Link Capacitor for all Converters	$C_o = I_{av}/(2\omega\Delta V_o)$

And these are the design equations for all four topologies, i.e., the forward buck, push pull buck, half bridge buck, and full bridge buck, under both CCM and DCM operation.

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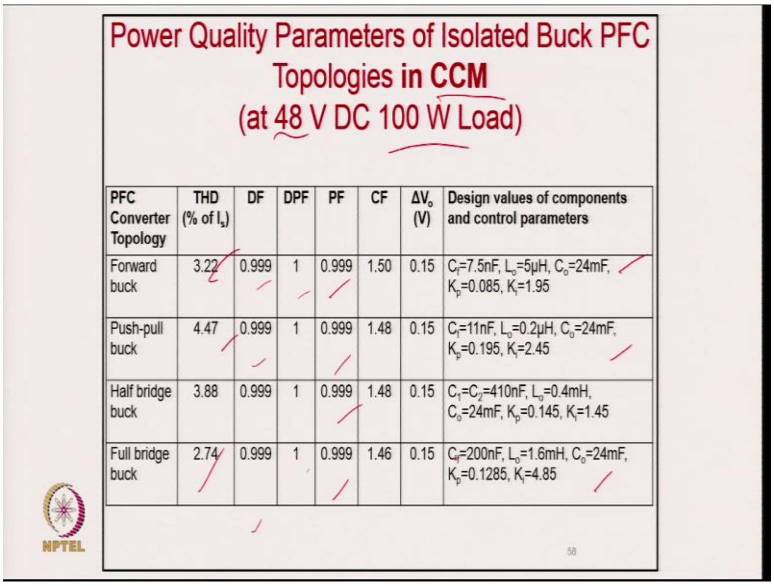

Power Quality Parameters of Isolated Buck PFC Topologies in CCM
(at 48 V DC 100 W Load)

PFC Converter Topology	THD (% of I_s)	DF	DPF	PF	CF	ΔV_o (V)	Design values of components and control parameters
Forward buck	3.22	0.999	1	0.999	1.50	0.15	C_f=7.5nF, L_o=5μH, C_o=24mF, K_p=0.085, K_i=1.95
Push-pull buck	4.47	0.999	1	0.999	1.48	0.15	C_f=11nF, L_o=0.2μH, C_o=24mF, K_p=0.195, K_i=2.45
Half bridge buck	3.88	0.999	1	0.999	1.48	0.15	C_1=C_2=410nF, L_o=0.4mH, C_o=24mF, K_p=0.145, K_i=1.45
Full bridge buck	2.74	0.999	1	0.999	1.46	0.15	C_f=200nF, L_o=1.6mH, C_o=24mF, K_p=0.1285, K_i=4.85

After designing all four topologies at 48 V and 100 W in continuous conduction mode operation, the performance of converters is analyzed through simulation. These are the performance parameters for all these four converters.

The distortion factor is almost 0.999 and the power factor is also almost close to unity and crest factor is also very close to sign wave with the small voltage ripple there. So, this is the performance with the CCM operation.

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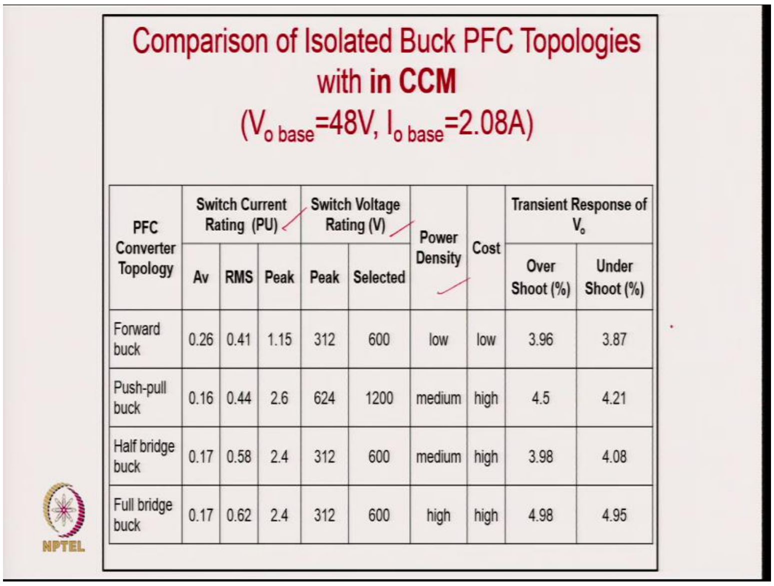

Comparison of Isolated Buck PFC Topologies with in CCM
($V_{o\ base}$=48V, $I_{o\ base}$=2.08A)

PFC Converter Topology	Switch Current Rating (PU)			Switch Voltage Rating (V)		Power Density	Cost	Transient Response of V_o	
	Av	RMS	Peak	Peak	Selected			Over Shoot (%)	Under Shoot (%)
Forward buck	0.26	0.41	1.15	312	600	low	low	3.96	3.87
Push-pull buck	0.16	0.44	2.6	624	1200	medium	high	4.5	4.21
Half bridge buck	0.17	0.58	2.4	312	600	medium	high	3.98	4.08
Full bridge buck	0.17	0.62	2.4	312	600	high	high	4.98	4.95

And this is typically, the switch voltage, switch current, switch voltage, power density, cost and other performance parameters for all four topologies under CCM operation.

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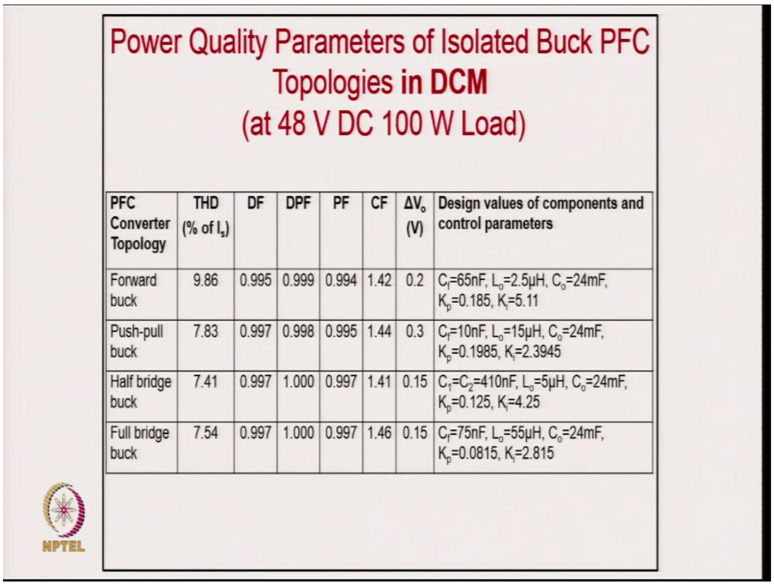

Power Quality Parameters of Isolated Buck PFC Topologies in DCM (at 48 V DC 100 W Load)

PFC Converter Topology	THD (% of I_s)	DF	DPF	PF	CF	ΔV_o (V)	Design values of components and control parameters
Forward buck	9.86	0.995	0.999	0.994	1.42	0.2	C_f=65nF, L_o=2.5μH, C_o=24mF, K_p=0.185, K_i=5.11
Push-pull buck	7.83	0.997	0.998	0.995	1.44	0.3	C_f=10nF, L_o=15μH, C_o=24mF, K_p=0.1985, K_i=2.3945
Half bridge buck	7.41	0.997	1.000	0.997	1.41	0.15	C_1=C_2=410nF, L_o=5μH, C_o=24mF, K_p=0.125, K_i=4.25
Full bridge buck	7.54	0.997	1.000	0.997	1.46	0.15	C_f=75nF, L_o=55μH, C_o=24mF, K_p=0.0815, K_i=2.815

The similar exercise is carried out for DCM operation with the same output power, i.e., 48 V and 100 W, to just give you an idea about that what is the relative component and gains and all that, for all four converters under DCM operation. So, here, of course, the THD slightly increases, but the power factor is still not very far from 0.99. So, these are the components value corresponding to design for all four converters in case of DCM operation.

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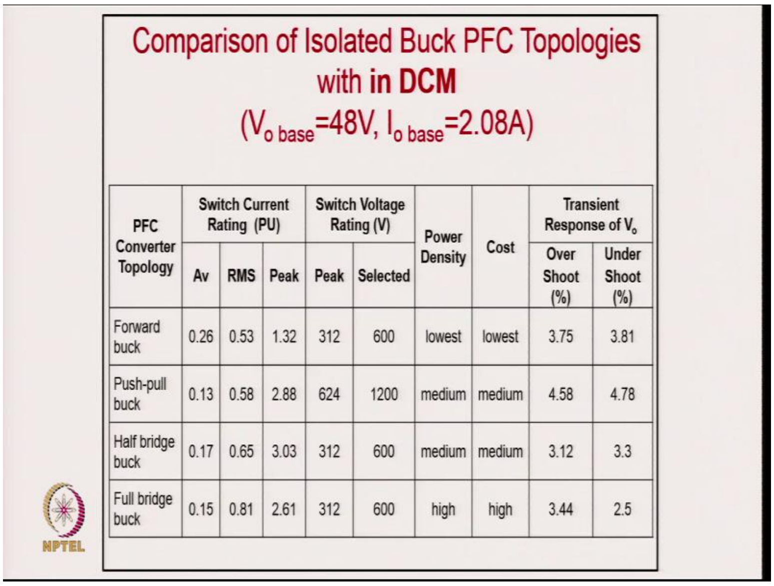

Comparison of Isolated Buck PFC Topologies with in DCM ($V_{o\,base}$=48V, $I_{o\,base}$=2.08A)

PFC Converter Topology	Switch Current Rating (PU)			Switch Voltage Rating (V)		Power Density	Cost	Transient Response of V_o	
	Av	RMS	Peak	Peak	Selected			Over Shoot (%)	Under Shoot (%)
Forward buck	0.26	0.53	1.32	312	600	lowest	lowest	3.75	3.81
Push-pull buck	0.13	0.58	2.88	624	1200	medium	medium	4.58	4.78
Half bridge buck	0.17	0.65	3.03	312	600	medium	medium	3.12	3.3
Full bridge buck	0.15	0.81	2.61	312	600	high	high	3.44	2.5

And these are the switch current rating, switch voltage rating, power density and transient response of all four converter topologies under DCM operation.

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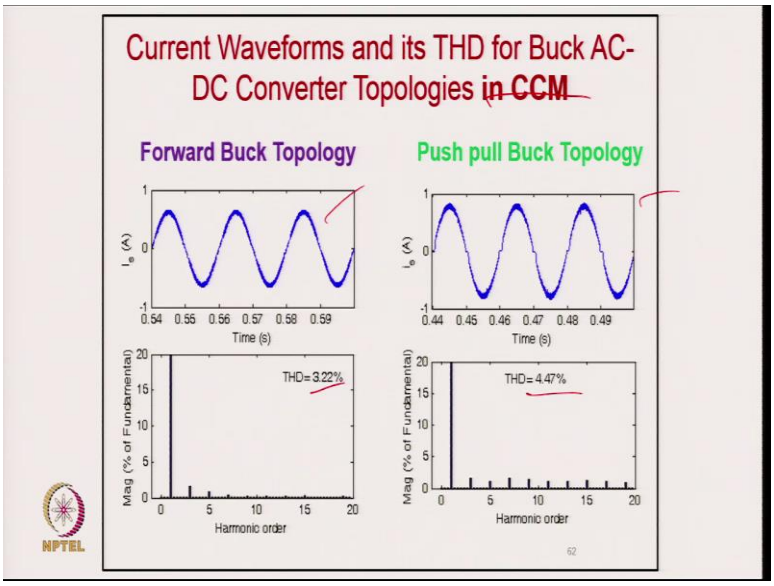

Current Waveforms and its THD for Buck AC-DC Converter Topologies in CCM

Forward Buck Topology

Push pull Buck Topology

This is the waveform of supply current with the THD of 3.2 % for the forward buck topology and the THD is increases slightly to 4.47 % in case of push pull buck converter. But it is still less than 5 percent.

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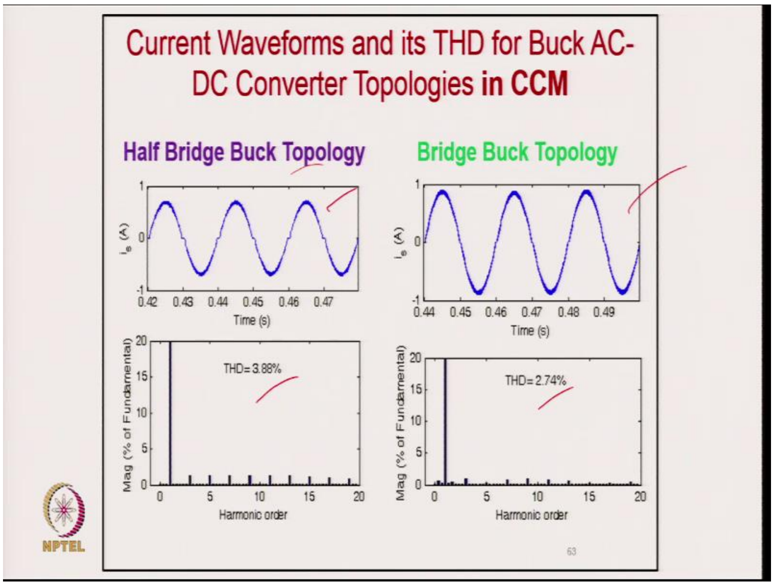

Current Waveforms and its THD for Buck AC-DC Converter Topologies in **CCM**

Half Bridge Buck Topology

Bridge Buck Topology

This is corresponding to the half bridge, the input supply current has 3.88 % THD, whereas, for the bridge configuration it is found nearly 2.74 %.

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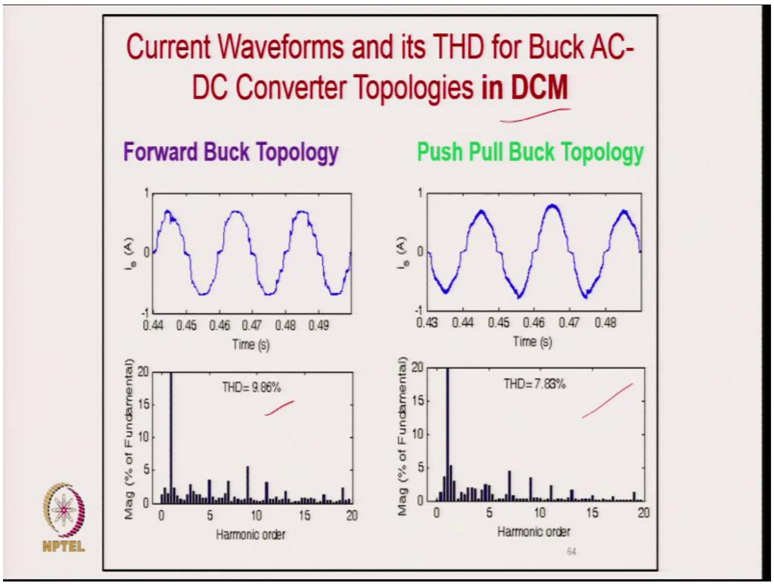

Current Waveforms and its THD for Buck AC-DC Converter Topologies in **DCM**

Forward Buck Topology

Push Pull Buck Topology

These are the waveforms under DCM operation, the THD is slightly higher than CCM operation. However, at low power, the standards allow up to 18% or 20% THD. So, this is still quite good THD under DCM operation.

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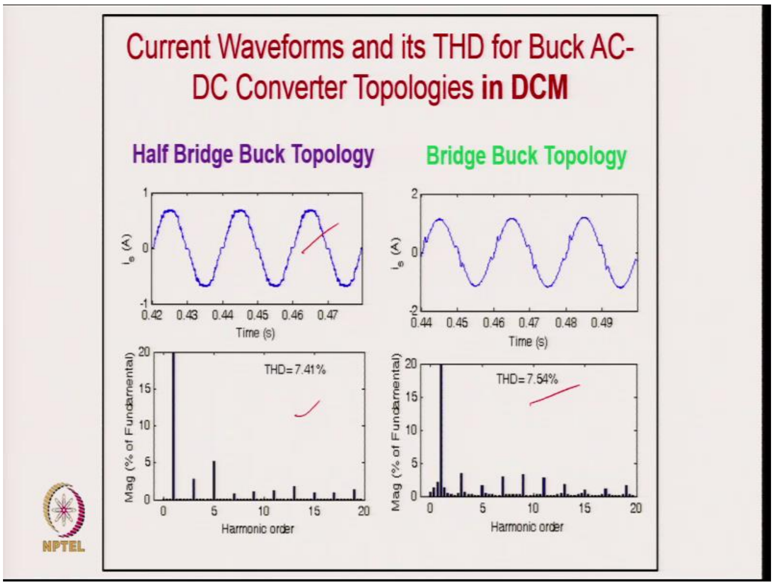

Current Waveforms and its THD for Buck AC-DC Converter Topologies in DCM

Half Bridge Buck Topology **Bridge Buck Topology**

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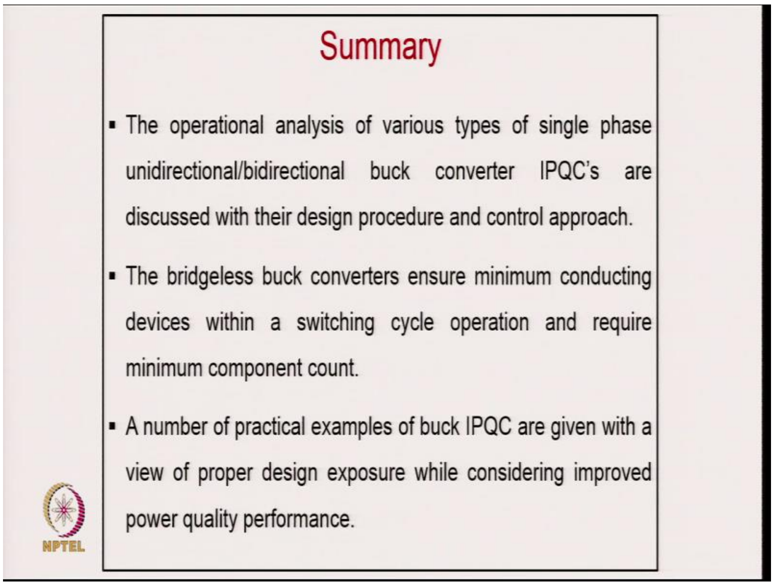

Summary

- The operational analysis of various types of single phase unidirectional/bidirectional buck converter IPQC's are discussed with their design procedure and control approach.
- The bridgeless buck converters ensure minimum conducting devices within a switching cycle operation and require minimum component count.
- A number of practical examples of buck IPQC are given with a view of proper design exposure while considering improved power quality performance.

Now coming to the summary of this lecture. The operational analysis of various type of single phase unidirectional and bidirectional buck converters are discussed with their design procedure and control approach. The bridgeless buck converters ensure minimum conducting device within switching cycle operation and require minimum component count. And a number of practical examples of buck improved power quality converters are given with the view of proper design exposure, while a while considering the improved power quality performance.

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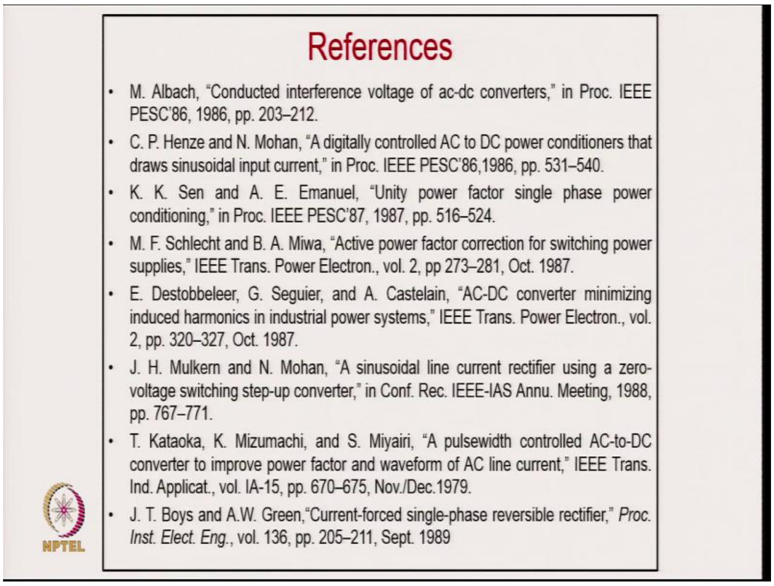

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And these are the references.

Thank you very much.