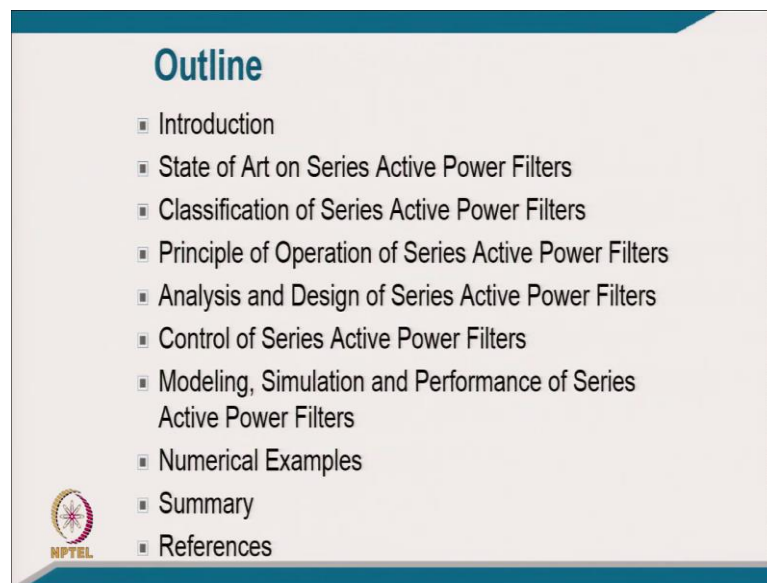


Power Quality
Prof. Bhim Singh
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Module - 07
Lecture - 23
Active Series Power Filters

Welcome to the course on Power Quality. Here we will like to cover Active Series Power Filter.

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The outline of the lecture, first we will explain the Introduction on Series Active Power Filter. Then we will talk about state of art on series active power filter, then classification of series active power filter, then the principle operation of series active power filter. And analysis and design of series active power filter, control of a series active power filter, modeling and modeling simulation and performance of series active power filter, numerical examples, summary with references.

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INTRODUCTION

▣ Voltage based power quality problems in distribution systems

Voltage quality problems	Voltage quality problems
sag	Notches,
Swell	Fluctuations
Voltage unbalance	Waveform distortion,
Flicker	Voltage imbalance,
Transients	Harmonics




Voltage based power quality problems in distribution system are voltage sag, voltage swell, voltage unbalance, voltage flicker, voltage transient, voltage notches, voltage fluctuations, voltage waveform distortion. For dealing with these we use the series active filter.

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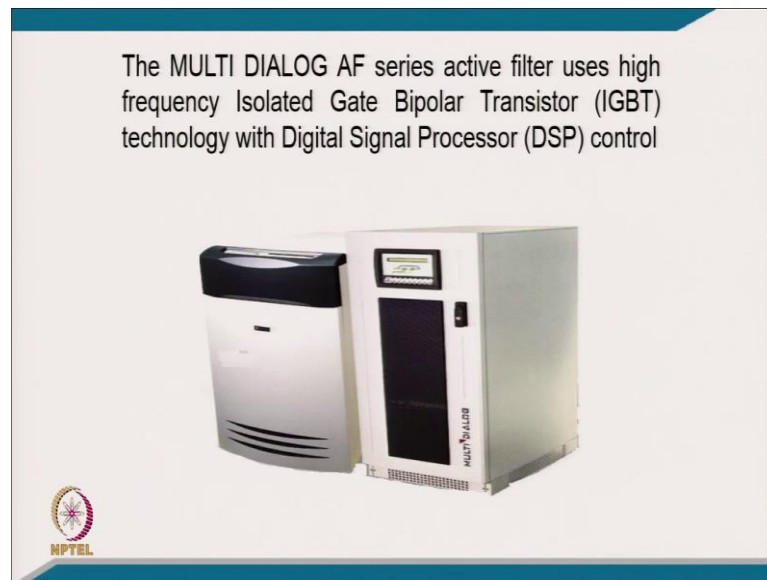
INTRODUCTION

- These power quality problems increase losses in many loads and sometimes trips the sensitive loads causing loss of production.
- **Solution is the Active Series Power Filters (ASPF)**
- The series active power filter (APF) protects such sensitive loads from these distortions in the voltage of ac mains



These power quality problems increase losses in many loads, and sometime trip the sensitive load causing the loss of production. Series active power filter protects such sensitive loads from these disturbances in the voltage of AC mains.

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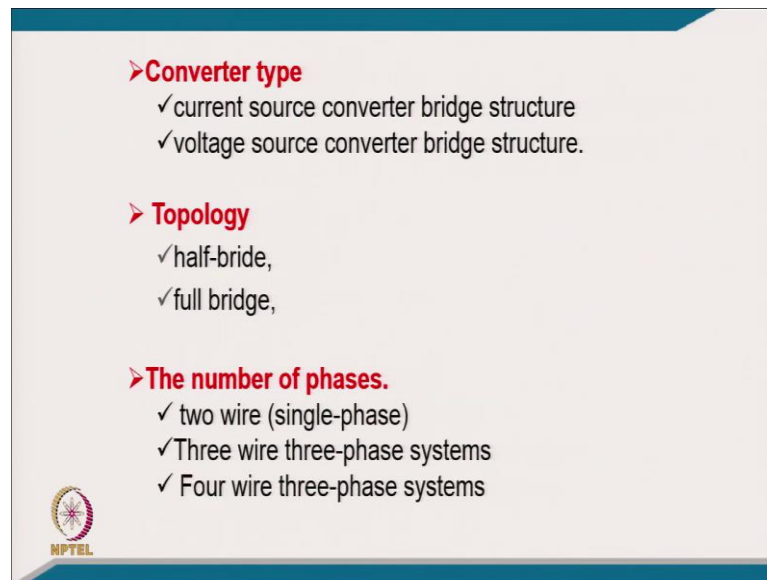
The active series filter uses the high frequency IGBT technology with the digital signal processor control.

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Now, coming to classification of active series filter power filter.

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➤ **Converter type**


- ✓ current source converter bridge structure
- ✓ voltage source converter bridge structure.

➤ **Topology**

- ✓ half-bridge,
- ✓ full bridge,

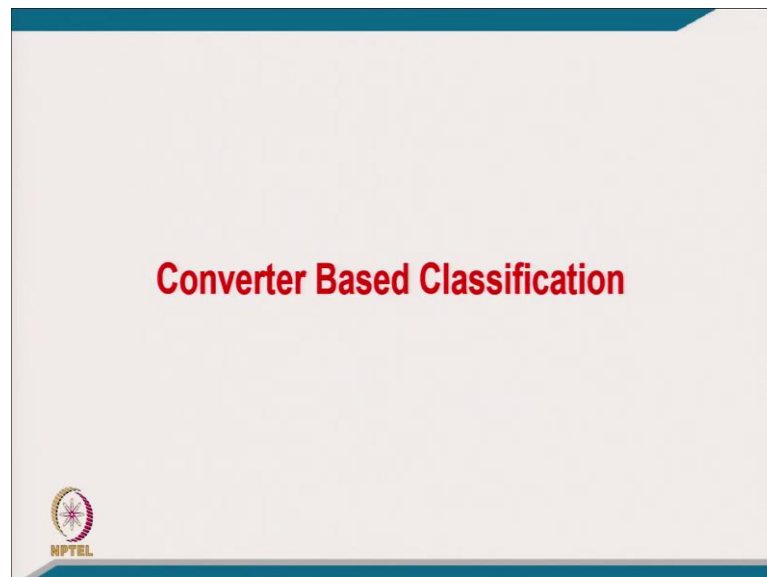
➤ **The number of phases.**

- ✓ two wire (single-phase)
- ✓ Three wire three-phase systems
- ✓ Four wire three-phase systems




First classification is on converter type: whether the current source converter bridge structure or voltage source bridge structure is used. Topology wise: whether we use half bridge or full bridge. Based on number of phases: two wire single-phase, three wire three-phase system or four wire three-phase system.

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Converter Based Classification



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CSC Based Single-phase Active Series Power Filter

- They (CSC) are considered **sufficiently reliable**, but have **high losses** and require **high values of parallel ac power capacitors**.
- They cannot be used in multilevel or multistep modes to improve performance in higher ratings.



Coming to the first type of convertor classification. The current source converter based series active power filter. There is a series connected injection transformer. We are typically injecting the voltage harmonics or voltage magnitude with this current source inverter. And current source inverter I mean you have a dc link inductor as the energy storage element.


This certainly creates a problem of large size, cost, weight, and losses. And the device here needs a negative reverse voltage blocking capability which your IGBT do not have, therefore we have to use the series diode.

These current source converter are considered sufficiently reliable, but have high losses and require high value of parallel AC power capacitors. And they cannot be used in multilevel or multistep modes to improve the performance in higher rating.

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VSC Based Single-phase Active Series Power Filter

➤ They are **lighter, cheaper** and **expandable** to multilevel and multistep versions, to enhance the performance with lower switching frequencies.



This is the voltage source based single-phase active series filter. In voltage source inverter, you have an IGBT with anti-parallel diode, and well, losses are low because either IGBT will conduct or diode will conduct. Thus compared to the current source, losses will be less in the switching devices. And then, on dc link we have an electrolytic capacitor as energy storage element.

This also have a small size, low cost and a small losses. But of course, they are also you need the injection transformer.

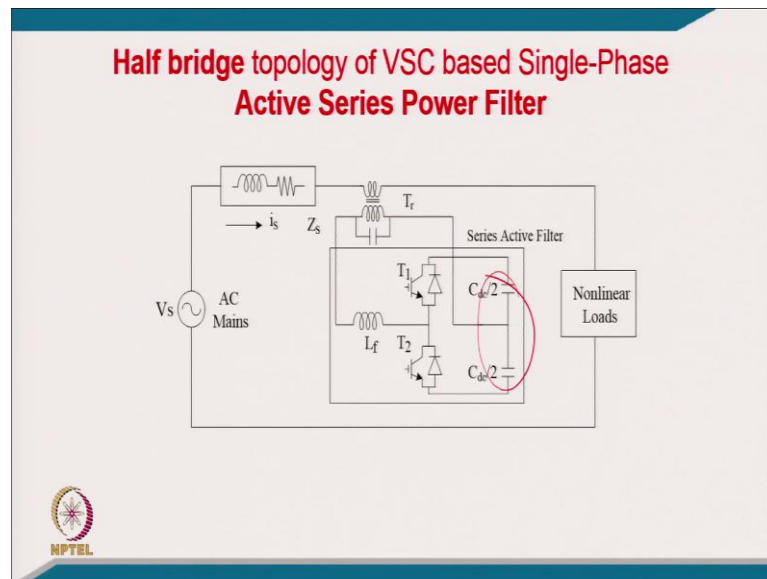
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Topology Based Classification



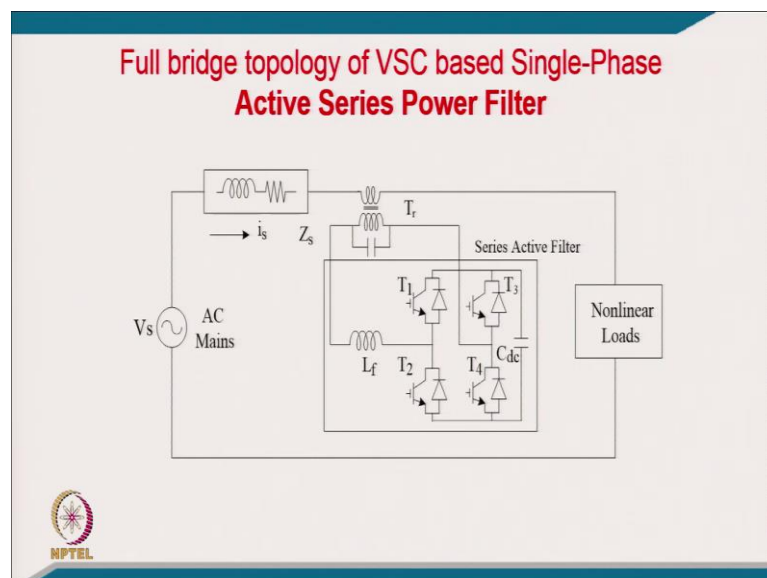
And coming to the classification on topology based classification.

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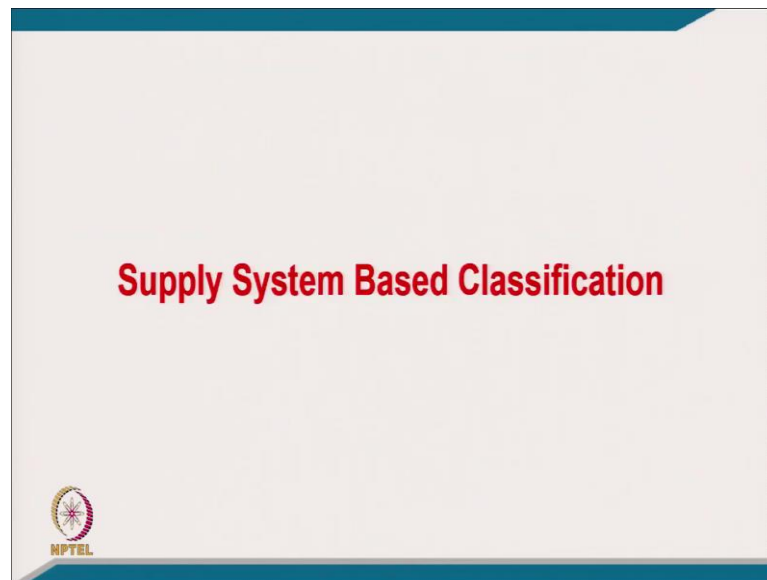
You can use this voltage source converter also with the half bridge. The only drawback is that these capacitor required quite high value, because the whole current will flow through these capacitor.

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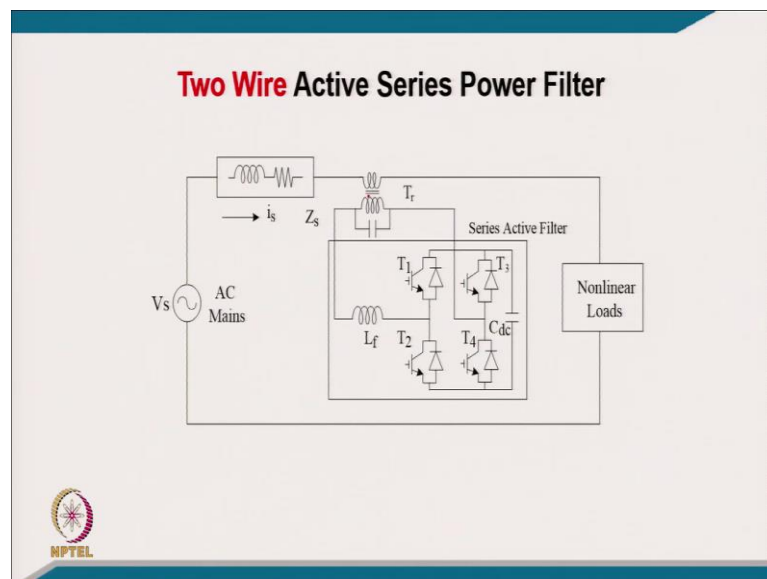
Then, this is the bridge structure which is preferred for series active filter.

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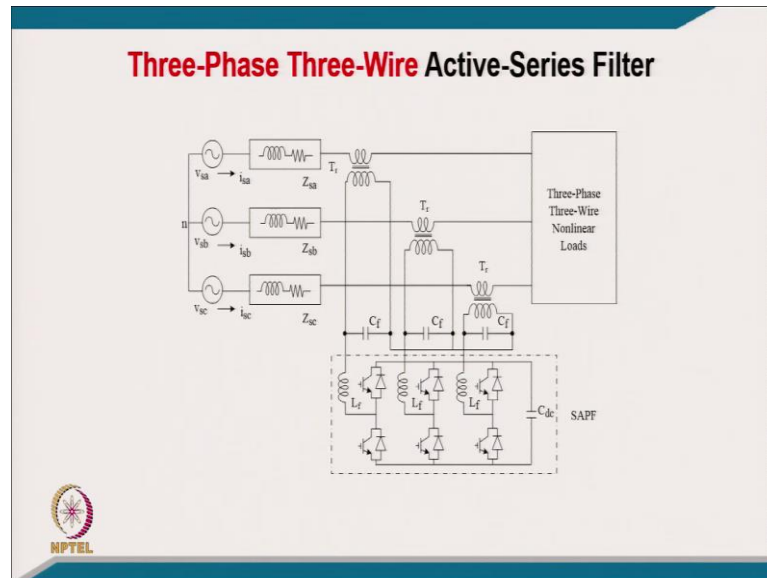
Coming to the supply based supply system based classification.

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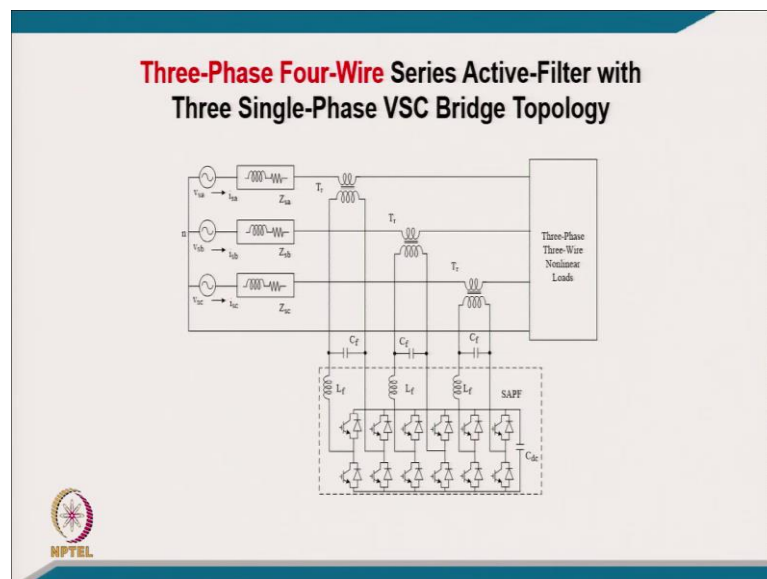
This is a single-phase two wire active series active filter, with the bridge structure.

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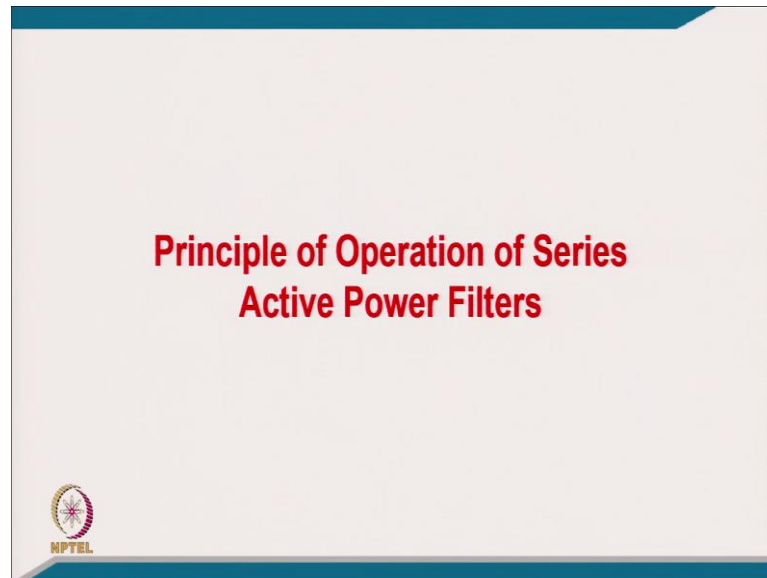
And this is three-phase three wire with a self-supporting bus.

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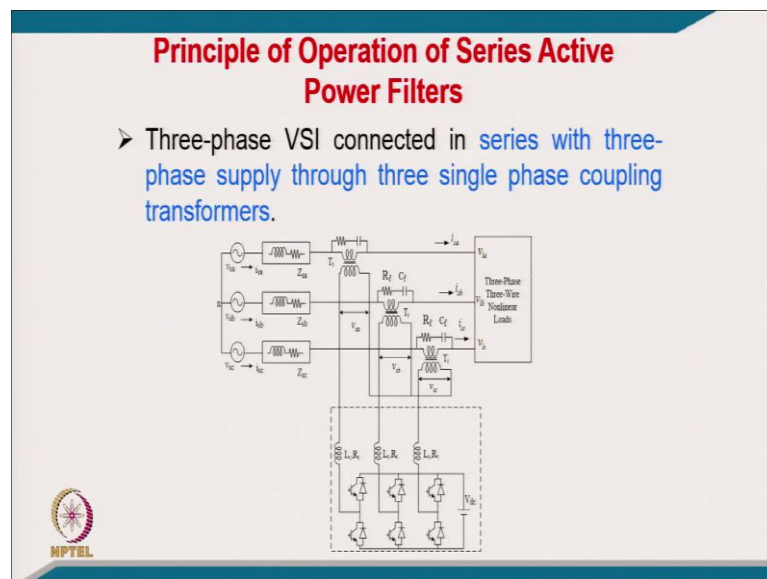
And this is the three-phase four wire configuration.

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Coming to principle of operation of the series active power filter.

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- For the **voltage fed nonlinear loads**, which consist of capacitive filter and an equivalent load at the dc-link of the three-phase diode rectifier, **a series APF alone can effectively maintain sinusoidal supply currents.**
- Whereas for **the current fed type of nonlinear loads**, which consist of the series connection of a resistor and an inductor in the dc-link of a three-phase diode rectifier or three-phase thyristors bridge converter, **a combined system of the shunt passive filters and a series active power filter is to be employed to effectively maintain sinusoidal supply currents.**

And it can be a very specific solution for the voltage fed non-linear load which consist of capacity filter and equivalent load at the dc link of the three-phase diode rectifier a series active filter can also effectively maintain the sinusoidal supply current.

Whereas, the current fed kind of non-linear load, which consist of series connection of a resistor and inductor at the dc-link of three-phase diode bridge rectifier or thyristors bridge converter a combined system of shunt passive filter and series active filter is to be employed to effectively maintain the supply current. So, that load is not really affected by that. But a series filter will be forcing the entire harmonics current into the shunt passive filter. Series filters are typically used for a small rating in those applications also.

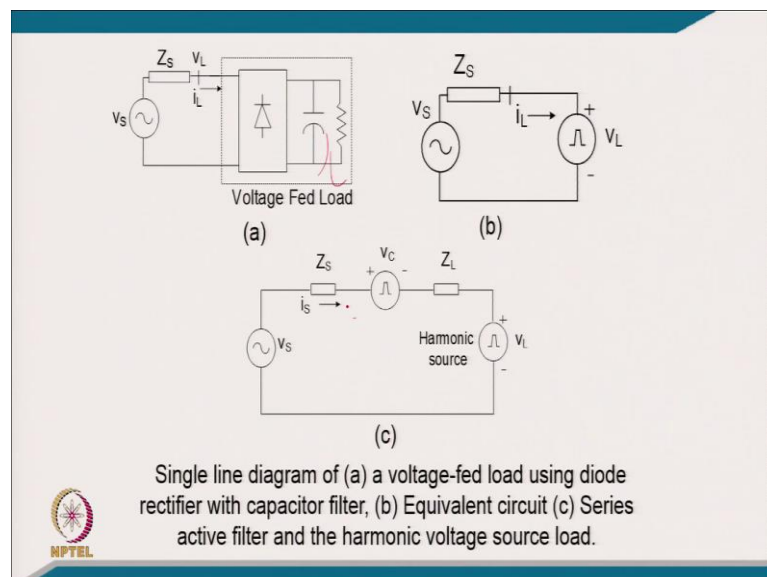
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- The control algorithm of the series active filter to eliminate current harmonics is suitable for both series active filter and hybrid configurations of a series active power filter with a shunt passive filter.
- For voltage sensitive loads, to eliminate the voltage harmonics, unbalance and to maintain zero voltage regulation at PCC, series APF is directly controlled to inject sufficient voltage in series with the supply.




The control algorithm series active power filter is to eliminate current harmonics and is suitable for both series active power filter and hybrid configuration of series active filter and with shunt passive filter. For voltage sensitive load, to eliminate the voltage harmonics, unbalance and to maintain zero voltage regulation PCC, a series active filter is directly controlled to inject sufficient voltage in series with the supply.

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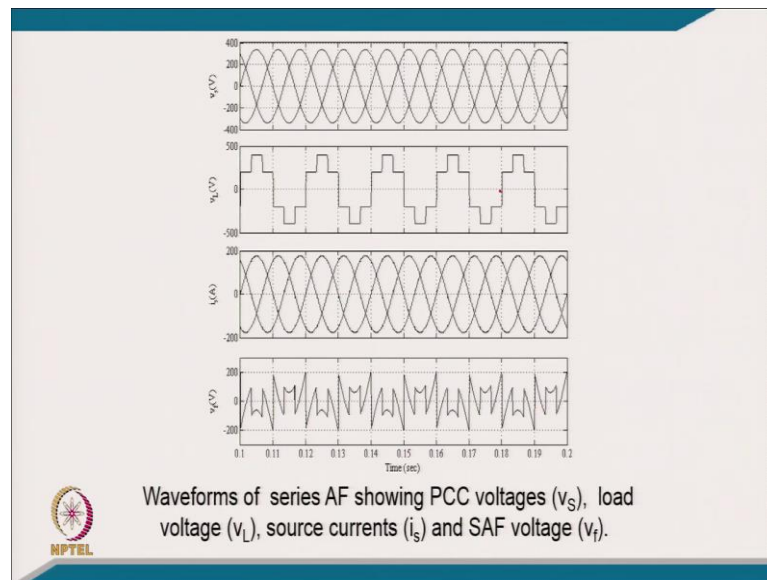


- The load is represented as a voltage source (v_L) with fundamental as well as harmonic voltage.
- The harmonic current (i_L) originates from this rectifier voltage (v_L).
- The series AF is controlled as a current controlled harmonic voltage source (V_C), to offer low impedance at fundamental frequency and acts as a high valued resistor for harmonic currents in ac mains.
- This satisfies the need of harmonic currents required by the load and prevents the flow of harmonic currents into ac source.
- Along with this, the series AF requires a small fundamental voltage drop across the coupling transformer to draw active power for maintaining the dc bus of VSC of series AF.

The load is represented as a voltage source with a fundamental as well as a harmonic voltage and the harmonic current originate from this rectifier voltage. And the series active power filter is control as a current control harmonic voltage source to offer low impedance at the fundamental frequency and acts as a high value resistor for harmonic current in the ac mains.

This satisfy, the need of harmonic currents required by the load and prevents the flow of harmonic currents into the ac source. And along with this a series active power filter requires a small fundamental voltage drop across the coupling transformer to draw active power for maintaining the dc bus of voltage source converter which normally realize with help of control like.

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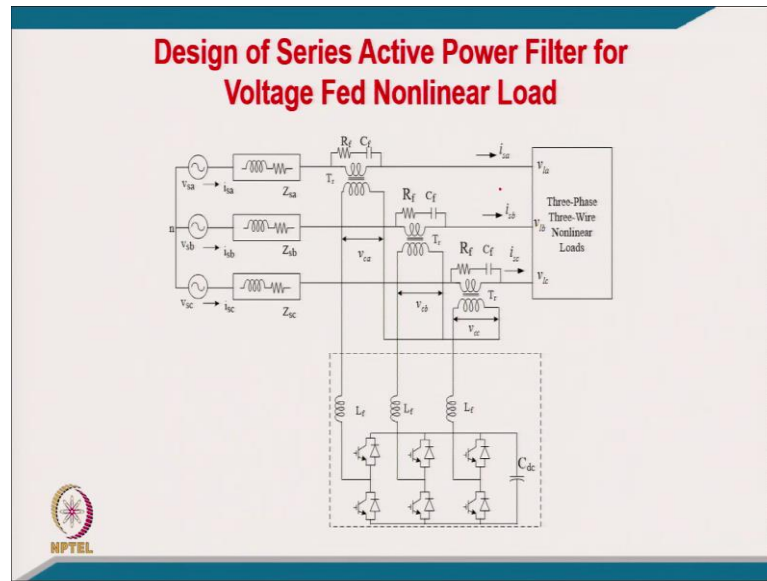
The screenshot shows the simulated performance.

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Analysis and Design of Active-Series Power Filter

Coming to analysis and design of series active power filter.

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- ### Designed Parameters of DSTATCOM
- **Supply:** A 3-phase 415 V (phase voltage, $V_{ph} = 239.6$ V)
 - **Load:** 25 kW load Non-Linear Load (three phase diode rectifier with a capacitive filter)
 - **Switching Frequency:** $f_s = 10$ kHz
 - **Inductor Current Ripple:** $\Delta I_f = 5\%$
 - **DC Link Voltage:** $V_{dc} = 700$ V
 - **DC Link Voltage Ripple:** $\Delta V_{dc} = 5\%$
- NPTEL

The screenshots herein describe the design procedure for the series active power filter.


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• Design of VSC of Series Active Power Filter

The design of the series active power filter is based on the dc bus voltage of the three-phase rectifier load. The series active power filter is operated for eliminating harmonics in the supply currents and hence it injects only harmonics voltage. It is clear that the fundamental component of load voltage is the PCC voltage as the series AF injects the harmonic component of the load voltage. Hence the fundamental component of load ac voltage is as,

$$V_{LL} = (\sqrt{6} / \pi) V_d = 0.779 * V_d$$

For a given line voltage of 415 V and a dc load voltage, V_d of 540 V.




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• Design of VSC of Series Active Power Filter

The voltage rating of the series AF is obtained from the difference of PCC and load voltages and hence the SAF voltage is calculated as,

$$V_f = \left(\frac{1}{\pi} \right) \left\{ \int_0^{\pi/3} (V_{ph} \sqrt{2} \sin \theta - V_d/3)^2 d\theta + \int_{\pi/3}^{2\pi/3} (V_{ph} \sqrt{2} \sin \theta - 2V_d/3)^2 d\theta + \int_{2\pi/3}^{\pi} (V_{ph} \sqrt{2} \sin \theta - V_d/3)^2 d\theta \right\} = 75.6415 \text{ V}$$

$V_{ph} = 239.6 \text{ V}, V_d = 540 \text{ V}$



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• Design of Current Rating of VSC of Series Active Power Filter


The current rating of series APF depends on the fundamental component of load current and it is obtained as.

The load power is calculated as,

$$P_{dc} = (V_d^2/R)$$

where, R is the equivalent resistance of the dc load at the output of diode bridge rectifier.

For a given load of 25 kW at 540 V dc bus voltage of the load, the equivalent resistance is as,

$$R = 11.664 \Omega.$$


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Design of Current Rating of VSC of Series Active Power Filter

Considering a UPF supply current and lossless series AF, the rms supply current is calculated as,


$$I_{sa} = P/(\sqrt{3} V_{LL}) = 25000/(\sqrt{3} \cdot 415) = 34.78 \text{ A}$$

The current rating of VSC is obtained as,

$$I_f = 34.78 \text{ A.}$$

kVA Rating of VSC of Series Active Power Filter

The kVA rating of VSC of SAF is calculated as,

$$\text{kVA} = 3 \cdot V_f \cdot I_f / 1000 = 3 \cdot 75.6415 \cdot 34.78 = 7.892 \text{ kVA}$$


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Rating of an Injecting Transformer of Series Active Power Filter


The injection transformer is designed considering the optimum voltage level of the VSC.

The maximum ac voltage on ac side of VSC of series APF may be

$$m_a * V_{dc} / (2 * \sqrt{2}) = 0.8 * 700 / (2 * \sqrt{2}) = 197.99 \text{ V (considering the modulation index, } m_a = 0.8)$$

and on the supply side, it must be $V_{supply} = V_f$.

The turn's ratio of the coupling transformer is as,

$$N_{vsc} / N_{supply} = V_{vsc} / V_f = 197.99 \text{ V} / 75.6415 \text{ V} = 2.62$$


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Rating of an Injecting Transformer of Series Active Power Filter

The kVA rating of the injection transformer is same as that of VSC rating and is calculated as,

$$\text{kVA} = 3 * V_f * I_f / 1000 = 3 * 75.6415 * 34.78 = 7.892 \text{ kVA.}$$

DC Capacitance of VSC of Series Active Power Filter

The dc bus capacitance is selected based on the transient energy required during change in the loads:

$$(1/2) C_{dc} (V_{dc}^2 - V_{dc1}^2) = 3V_f * I_f * \Delta t$$


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DC Capacitance of VSC of Series Active Power Filter


where, V_{dc} is the rated voltage and V_{dc1} is the drop in dc bus voltage allowed during transients and Δt is the time for which support is required and C_{dc} is the dc bus capacitance.

Considering $\Delta t = 0.1$ ms,

$$V_{dc} = 700 \text{ V}, V_{dc1} = 700 - (5\% \text{ of } 700) = 665 \text{ V.}$$
$$\frac{1}{2} * C_{dc} (700^2 - 665^2) = 3 * 75.6415 * 34.78 * 0.1 * 10^{-3}$$

It gives, $C_{dc} = 3304 \text{ } \mu\text{F}$.

Hence, a dc bus capacitor of 4000 μF , 700 V is selected for series AF.




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Interfacing Inductor for VSC of Series Active Power Filter

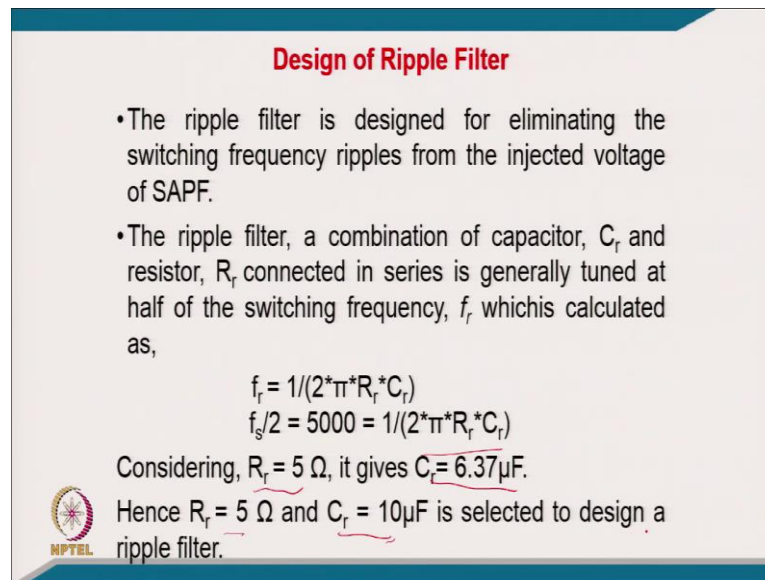
The value of interfacing inductor is selected based on the current ripple in the current of the series AF. By considering ripple current in the inductor is 5% and overloading factor, $a = 1.2$, the inductor is calculated as,

$$L_f = N_{vsf} / N_{supply} \{ (\sqrt{3}/2) m_a V_{dc} / (6 a f_s \Delta I_f) \}$$
$$L_f = 2.62 \{ (\sqrt{3}/2) * .8 * 700 / (6 * 1.2 * 10000 * 0.05 * 34.78) \}$$
$$L_f = 10.148 \text{ mH.}$$

Hence, an interfacing inductor of 12 mH and 40 A current carrying capacity is selected in the series AF.



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Design of Ripple Filter

- The ripple filter is designed for eliminating the switching frequency ripples from the injected voltage of SAPF.
- The ripple filter, a combination of capacitor, C_r and resistor, R_r connected in series is generally tuned at half of the switching frequency, f_r which is calculated as,

$$f_r = 1/(2*\pi*R_r*C_r)$$
$$f_s/2 = 5000 = 1/(2*\pi*R_r*C_r)$$

Considering, $R_r = 5 \Omega$, it gives $C_r = 6.37 \mu F$.

Hence $R_r = 5 \Omega$ and $C_r = 10 \mu F$ is selected to design a ripple filter.



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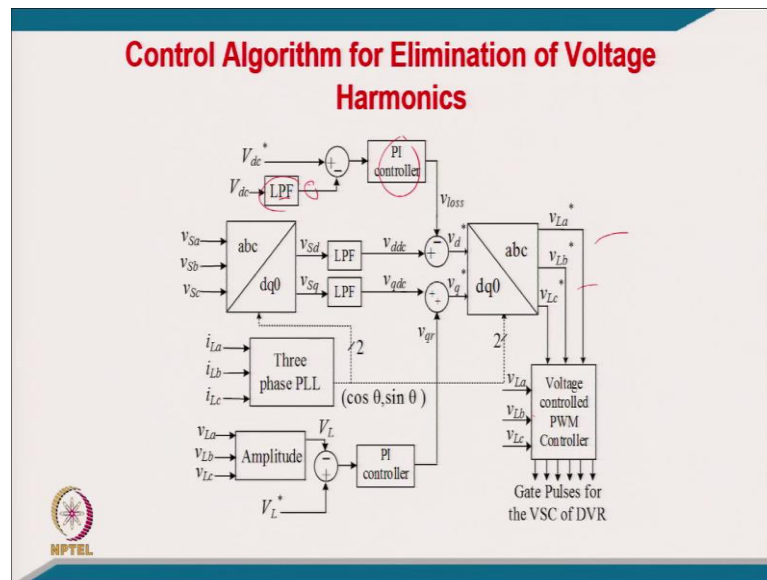


Control of Series Active Power Filters



The control algorithm used for series active power filters for elimination of voltage harmonics is described in the screenshots herein.

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Control Algorithm for Elimination of Voltage Harmonics

- The components of the PCC voltages in d-axis and q-axis

$$V_{Sd} = \underline{v_{ddc}} + V_{dac}, \quad V_{Sq} = \underline{v_{qdc}} + V_{qac}$$
- The harmonics and the oscillatory components (v_{dac} , v_{qac}) are eliminated using low pass filters (LPF)
- In order to maintain the dc bus voltage, a PI controller is used at the dc bus voltage of VSC and the output is considered as the voltage loss (v_{loss}) for meeting its losses.

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Control Algorithm for Elimination of Voltage Harmonics

$$V_{loss(n)} = V_{loss(n-1)} + K_{p1}(V_{de(n)} - V_{de(n-1)}) + K_{i1}V_{de(n)}$$

$$V_{de(n)} = V_{dc}^* - V_{dc(n)}$$

- The amplitude of load terminal voltage (v_L) is controlled to its reference voltage (v_L^*) using another PI controller.
- The output of PI controller is considered as the reactive component of voltage (v_{qr}) for voltage regulation of load terminal voltage.

$$V_{qr(n)} = V_{qr(n-1)} + K_{p2}(V_{te(n)} - V_{te(n-1)}) + K_{i2}V_{te(n)}$$

$$V_{te(n)} = V_L^* - V_{L(n)}$$



(Refer Slide Time: 22:53)

Control Algorithm for Elimination of Voltage Harmonics

- The direct axis (v_d^*) and quadrature axis (v_q^*) component of the reference load voltage

$$V_d^* = V_{d0c} - V_{loss}, \quad V_q^* = V_{q0c} + V_{qr}, \quad V_0^* = 0$$


- The reference load voltages (v_{La}^* , v_{Lb}^* , v_{Lc}^*) in a-b-c frame

$$\begin{bmatrix} V_{La}^* \\ V_{Lb}^* \\ V_{Lc}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} V_d^* \\ V_q^* \\ V_0^* \end{bmatrix}$$


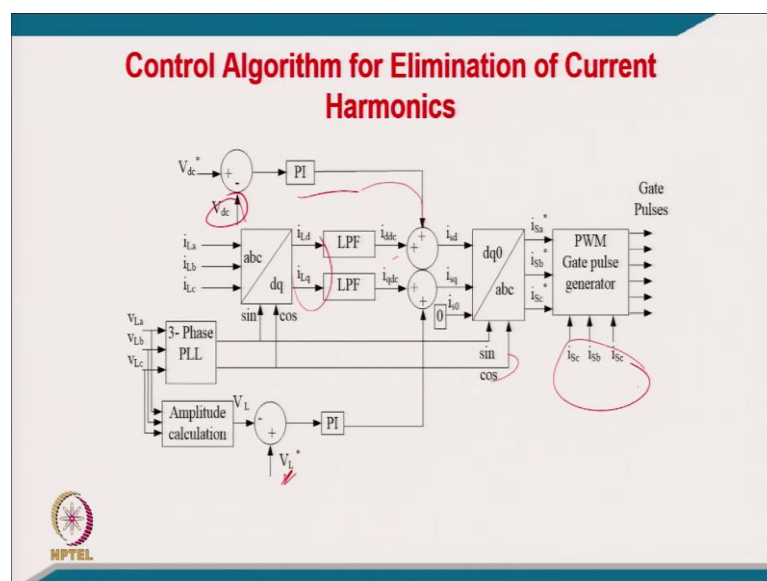
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Control Algorithm for Elimination of Voltage Harmonics

- The error between the sensed load voltages and the reference load voltages are used in the PWM controller to generate gating pulses to the VSC of Series APF.



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The control algorithm used for series active power filters for elimination of voltage harmonics is described in the screenshots herein.

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Control Algorithm for Elimination of Current Harmonics

- The series AF is used to inject a voltage in series with the terminal voltage to block harmonic currents.
- The harmonics in the supply currents are compensated by controlling the series AF and the algorithm inherently provides a self-supporting dc bus for series AF.
- Three-phase reference supply currents (i_{sa}^* , i_{sb}^* , i_{sc}^*) are derived using the sensed load voltages (v_{La} , v_{Lb} , v_{Lc}) and dc bus voltage (V_{dc}) of the VSC as feedback signals.




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Control Algorithm for Elimination of Current Harmonics

- The load currents in the three-phases are converted into the d-q-0 frame using the Park's transformation as

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix}$$

- A three-phase PLL (phase locked loop) is used to synchronize these signals with the PCC/load voltages (v_{La} , v_{Lb} , v_{Lc}).




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Control Algorithm for Elimination of Current Harmonics

- The d-q components are then passed through low pass filters to extract the dc components of i_{Ld} and i_{Lq} .
- The error between the reference dc capacitor voltage and the sensed dc bus voltage of VSC is given to a PI controller, the output of which is considered as the loss component (I_{LOSS}) of current and is added to the dc component of i_{Ld} .

$$I_{loss(n)} = I_{loss(n-1)} + K_{p1}(V_{de(n)} - V_{de(n-1)}) + K_{i1}V_{de(n)}$$

$$V_{de(n)} = V_{dc}^* - V_{dc(n)}$$


(Refer Slide Time: 27:01)


Control Algorithm for Elimination of Current Harmonics

- Amplitude of the load voltage (V_L)

$$V_L = (2/3)^{1/2} (V_{La}^2 + V_{Lb}^2 + V_{Lc}^2)^{1/2}$$

- Another PI controller is used to regulate the amplitude of the load voltage (V_L).
- The amplitude of the load terminal voltage is employed over the reference amplitude and the output of PI controller added with the dc component of i_{Lq} .

$$I_{qr(n)} = i_{qr(n-1)} + K_{p2}(V_{te(n)} - V_{te(n-1)}) + K_{i2}V_{te(n)}$$

$$V_{te(n)} = V_L^* - V_{L(p)}$$



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Control Algorithm for Elimination of Current Harmonics

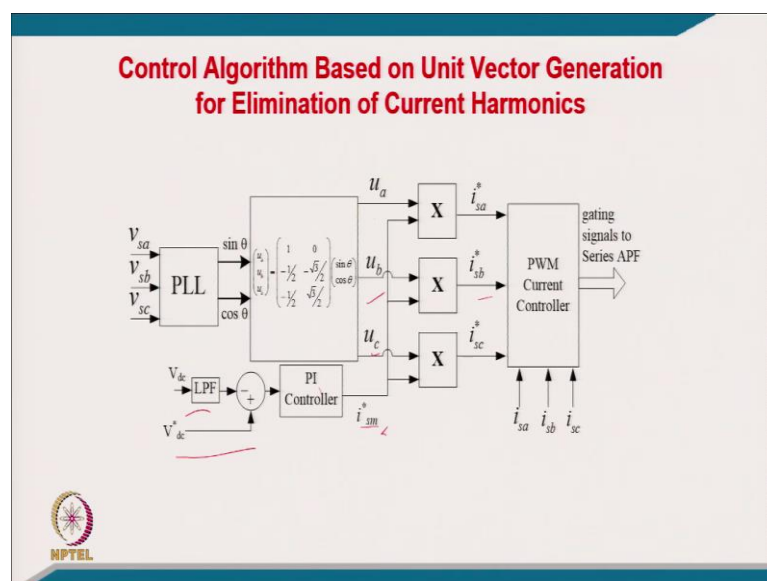
- The direct axis (i_d^*) and quadrature axis (i_q^*) component of the reference grid current

$$i_{sd}^* = i_{ddc} + I_{loss}, \quad i_{sq}^* = i_{qdc} + i_{qr}, \quad i_{s0}^* = 0$$

- The reference grid current (i_{sa}^* , i_{sb}^* , i_{sc}^*) in a-b-c frame

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i_{sd}^* \\ i_{sq}^* \\ i_{s0}^* \end{bmatrix}$$



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(Refer Slide Time: 29:13)

Control Algorithm Based on Unit Vector Generation for Elimination of Current Harmonics


- A simple control algorithm of series active filter for current harmonics elimination with self supporting dc bus.
- The series active filter is controlled such that it injects a set of voltages (v_{ca} , v_{cb} , v_{cc}) which cancels out the distortions present in the supply currents (i_{sa} , i_{sb} , i_{sc}) and making perfectly balanced and sinusoidal with desired amplitude.
- Since the PCC voltages (v_{sa} , v_{sb} , v_{sc}) are unbalanced and/or distorted, a phase locked loop (PLL) is used to get the synchronization with the PCC voltages.



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Control Algorithm Based on Unit Vector Generation for Elimination of Current Harmonics


- Three-phase distorted/unbalanced PCC voltages are sensed and given to PLL (Phase Locked Loop) which generates two quadrature unit vectors ($\sin\theta$, $\cos\theta$).
- The in-phase sine and cosine outputs from the PLL are used to compute the PCC in-phase, 120° displaced three unit vectors (u_a , u_b , u_c) as,

$$\begin{pmatrix} u_a \\ u_b \\ u_c \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{pmatrix} \begin{pmatrix} \sin\theta \\ \cos\theta \end{pmatrix}$$


(Refer Slide Time: 30:09)

Control Algorithm Based on Unit Vector Generation for Elimination of Current Harmonics

- The reference supply currents are generated by controlling the dc bus voltage of VSC.
- The dc link voltage, V_{dc} is sensed and compared with the reference value of the dc link voltage, V_{dc}^* .
- The voltage error is passed through a PI controller to generate the peak value (I_{sm}^*) of reference supply currents (i_{sa}^* , i_{sb}^* , i_{sc}^*).

$$I_{sm(n)}^* = I_{sm(n-1)}^* + K_{p1}(V_{de(n)} - V_{de(n-1)}) + K_{i1}V_{de(n)}$$
$$V_{de(n)} = V_{dc}^* - V_{dc(n)}$$



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Control Algorithm Based on Unit Vector Generation for Elimination of Current Harmonics

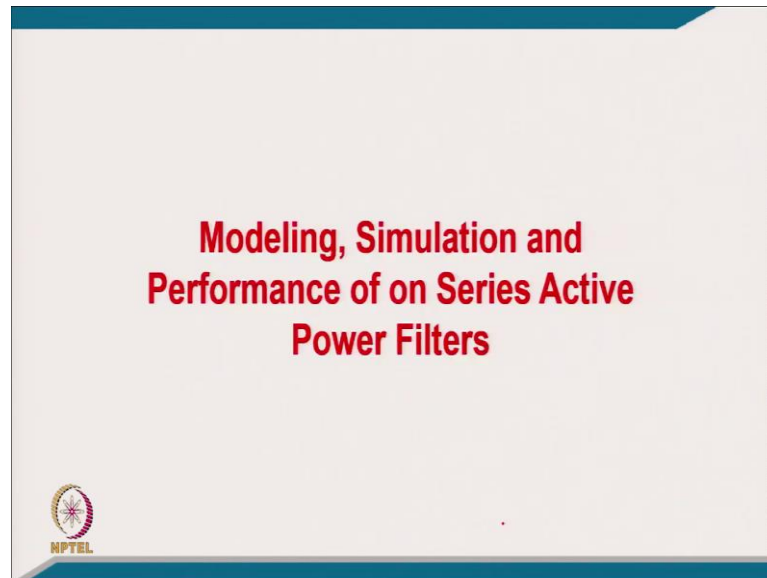
- This peak value is multiplied by the unit vectors to generate the reference supply/load currents

$$\begin{pmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{pmatrix} = I_{sm}^* \begin{pmatrix} U_a \\ U_b \\ U_c \end{pmatrix}$$

- Switching signals for the IGBTs of VSC are generated by a PWM current controller which takes sensed supply currents (i_{sa} , i_{sb} , i_{sc}) and reference supply currents (i_{sa}^* , i_{sb}^* , i_{sc}^*) as inputs

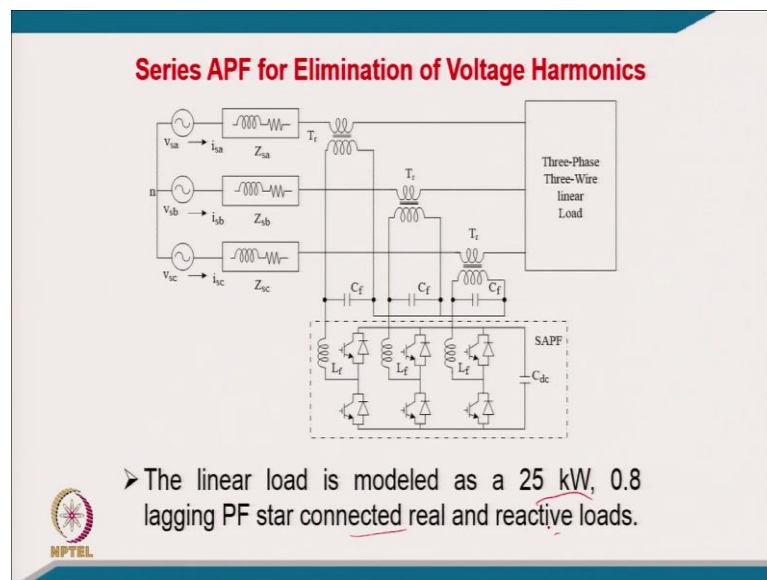


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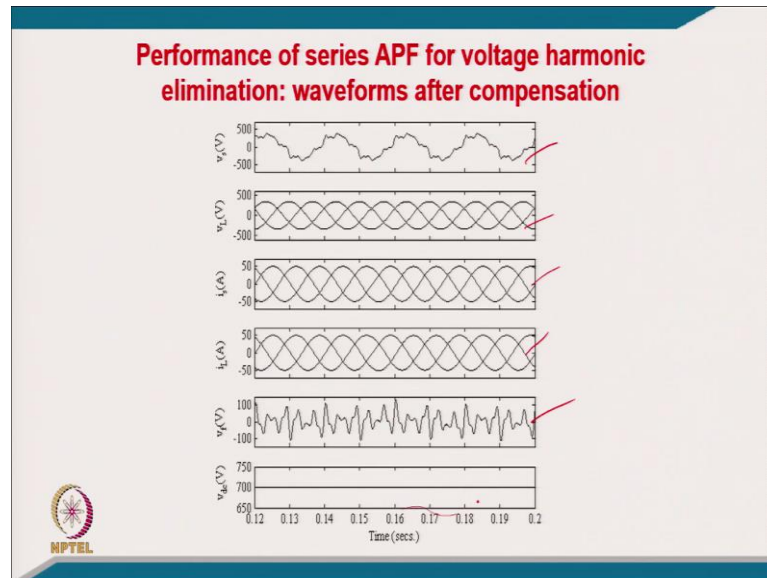
The modeling and simulation performance of series active power filter is presented in the screenshots herein.

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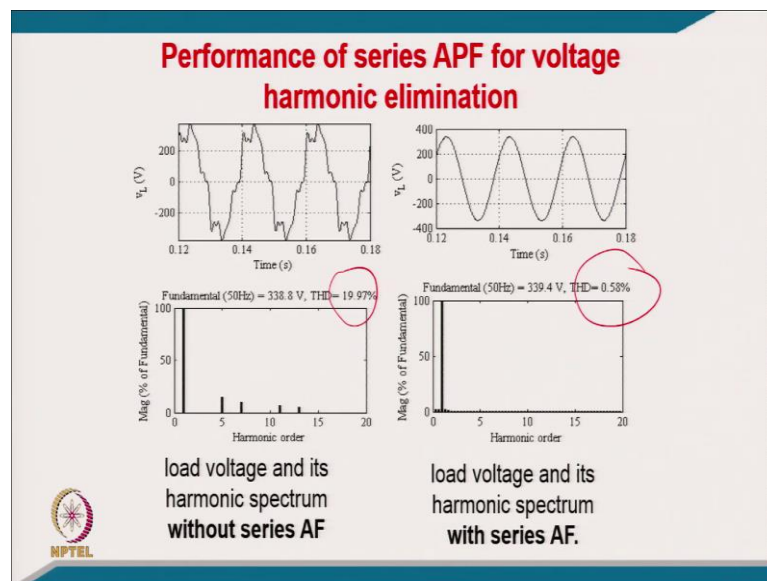


This is the circuit of three-phase three wire series active filter with a linear load of 25 kilowatt 0.8 lagging power factor. The supply voltages are distorted.

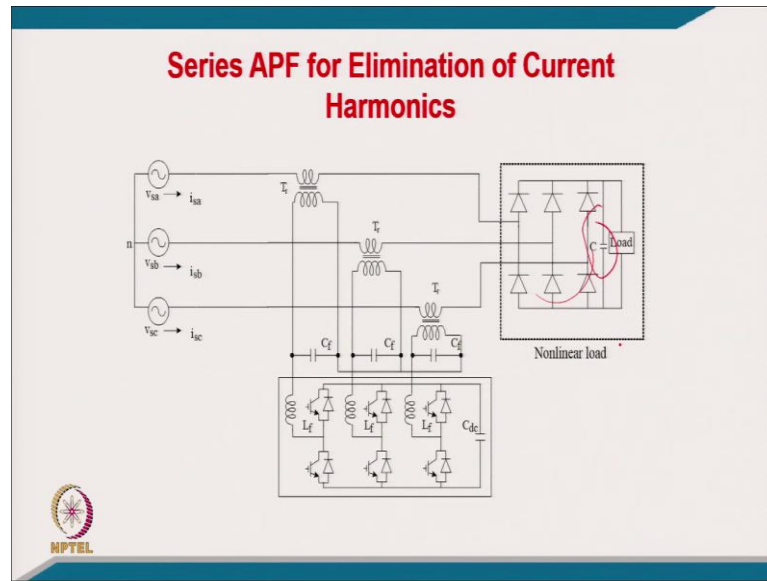
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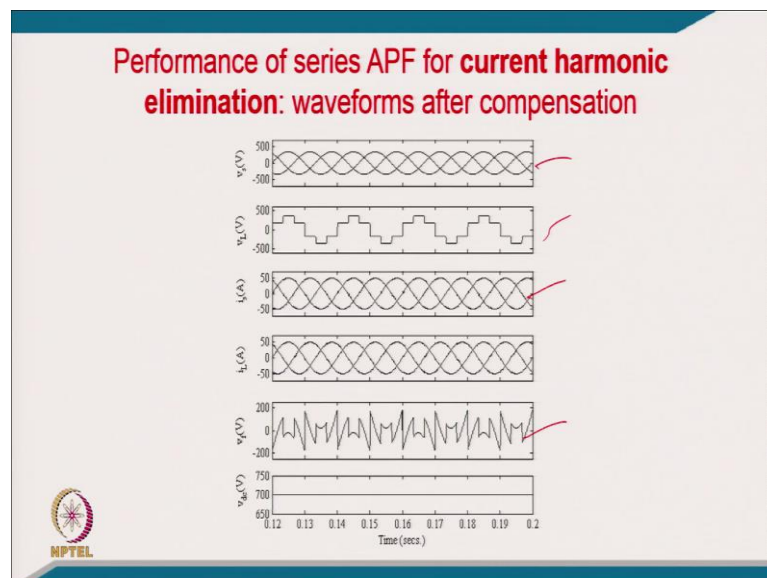
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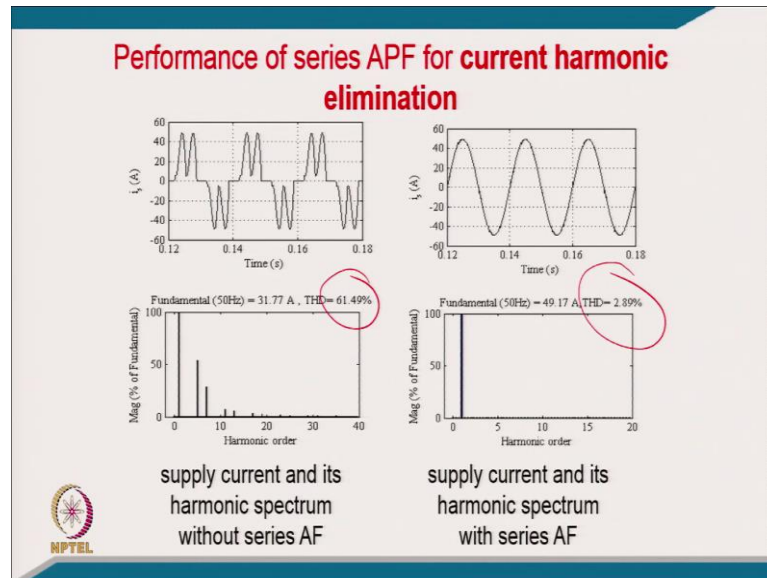
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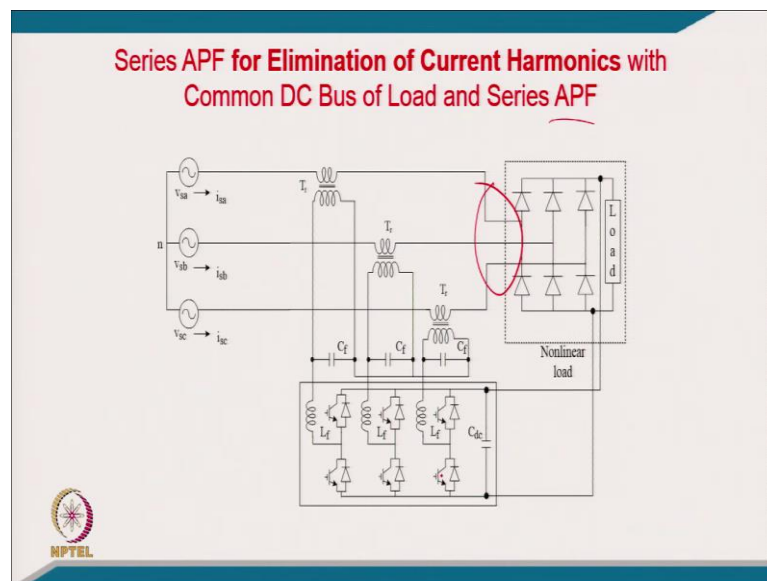
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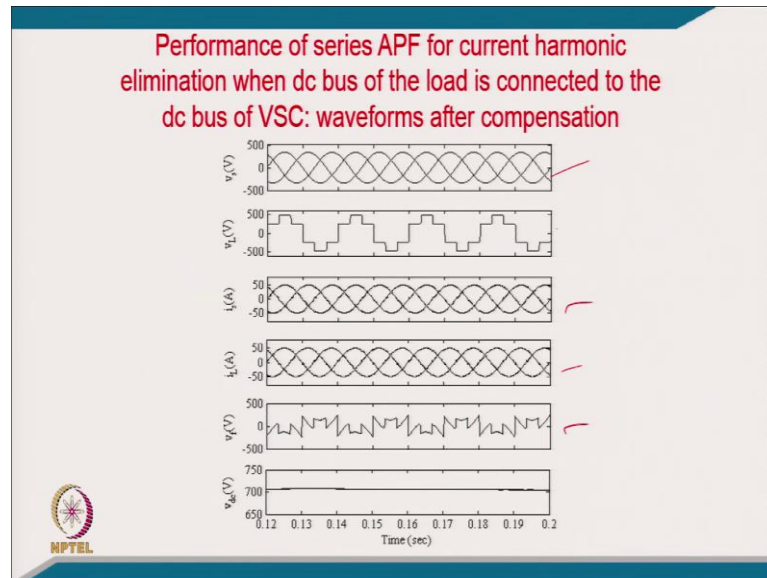
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