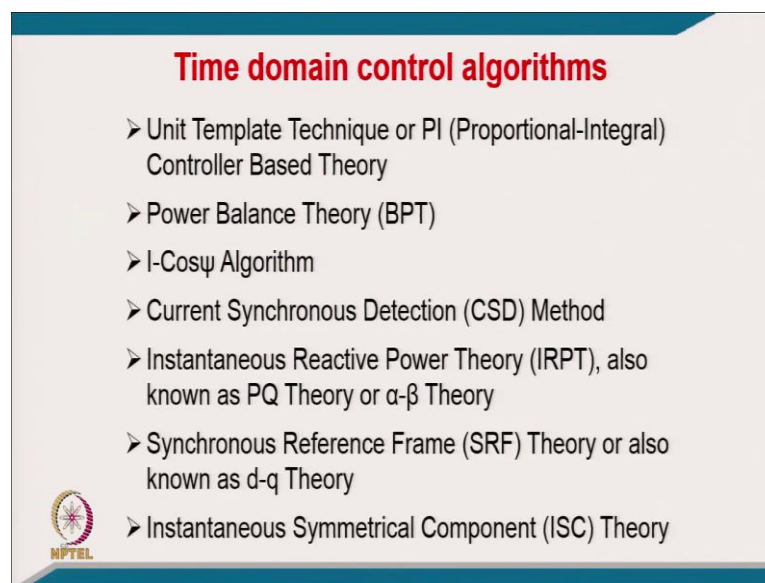


**Power Quality**  
**Prof. Bhim Singh**  
**Department of Electrical Engineering**  
**Indian Institute of Technology, Delhi**

**Lecture - 21**  
**Shunt Active Power Filters (contd.)**

Welcome to the course on Power Quality. We will discuss the control operation of the Shunt Active Power Filter. We classify these control algorithm into two categories.

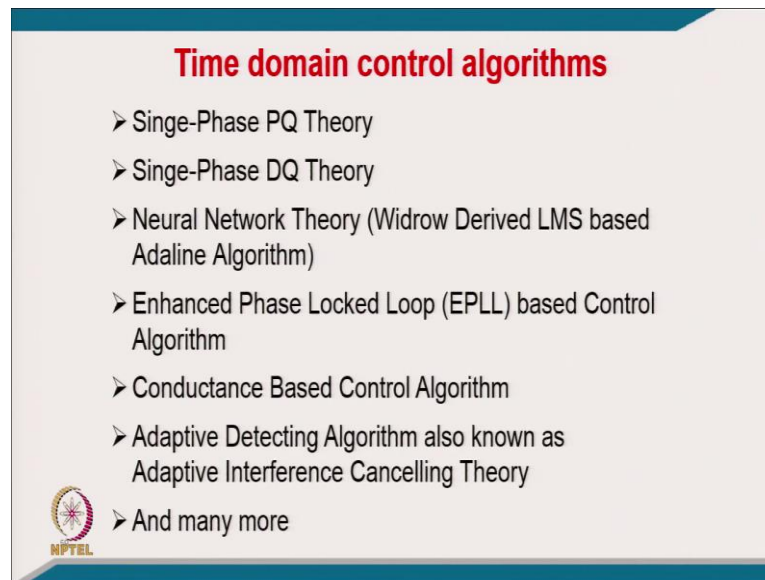
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First category is the time domain control algorithm. Few examples are


- Unit template based algorithm or PI controller based algorithm
- Power balance theory based control algorithm
- I-cos  $\phi$  algorithm
- Current synchronous detection algorithm
- Instantaneous reactive power theory also known PQ theory or alpha-beta theory.
- Synchronous reference frame theory also known as a d-q theory, or as symmetrical component theory.

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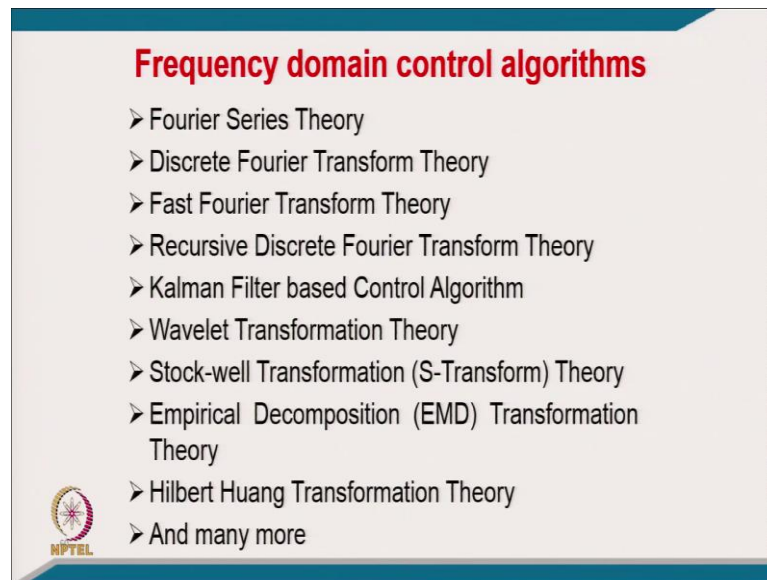
**Time domain control algorithms**

- Single-Phase PQ Theory
- Single-Phase DQ Theory
- Neural Network Theory (Widrow Derived LMS based Adaline Algorithm)
- Enhanced Phase Locked Loop (EPLL) based Control Algorithm
- Conductance Based Control Algorithm
- Adaptive Detecting Algorithm also known as Adaptive Interference Cancelling Theory
- And many more

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- Single phase PQ theories
- Single phase DQ theory
- Neural network theory
- Least mean square based Adaline algorithm
- Enhanced PLL based control algorithm
- Conductance based control algorithm.

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**Frequency domain control algorithms**

- Fourier Series Theory
- Discrete Fourier Transform Theory
- Fast Fourier Transform Theory
- Recursive Discrete Fourier Transform Theory
- Kalman Filter based Control Algorithm
- Wavelet Transformation Theory
- Stock-well Transformation (S-Transform) Theory
- Empirical Decomposition (EMD) Transformation Theory
- Hilbert Huang Transformation Theory
- And many more

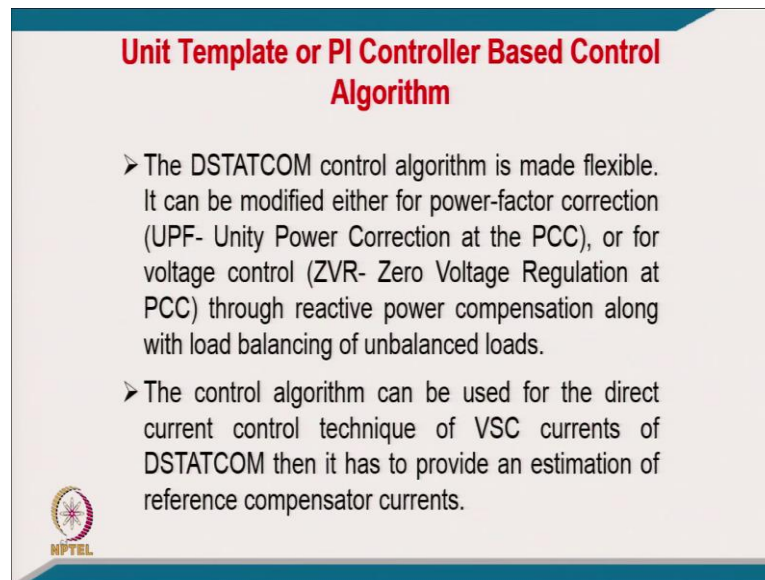


The second category is the frequency domain control algorithms like

- Fourier series theory
- Discrete Fourier transform theory
- Fast Fourier transform theory
- Recursive Discrete Fourier transform theor
- Kalman filter based control algorithm
- Wavelet transformation based theory
- Stock-well transformation based theory
- Empirical decomposition transformation theory
- Hilbert Huang transform theory


We cannot discuss all of them, but here we will discuss only a couple; just to give you an idea.

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**Unit Template or PI Controller Based Control Algorithm**

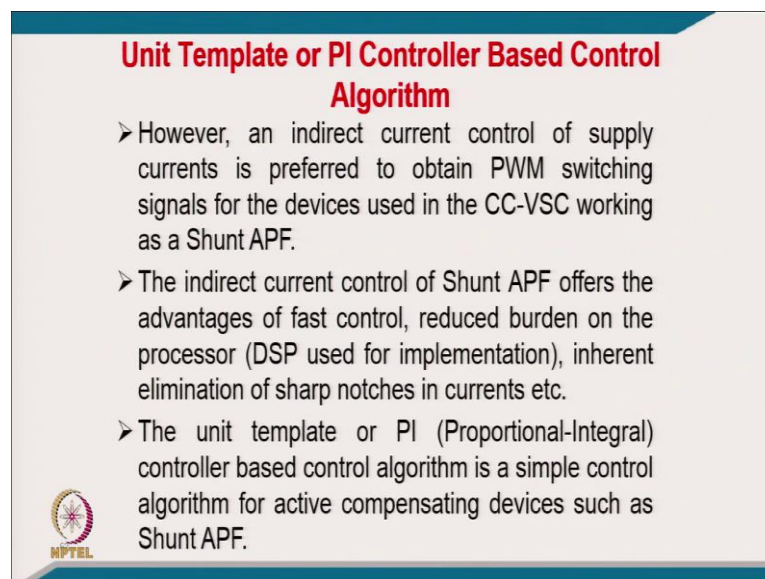
- The DSTATCOM control algorithm is made flexible. It can be modified either for power-factor correction (UPF- Unity Power Correction at the PCC), or for voltage control (ZVR- Zero Voltage Regulation at PCC) through reactive power compensation along with load balancing of unbalanced loads.
- The control algorithm can be used for the direct current control technique of VSC currents of DSTATCOM then it has to provide an estimation of reference compensator currents.



Here, DSTATCOM control theories are made flexible. It can be modified for power-factor correction or voltage regulation. Zero voltage regulation through reactive power compensation with load balancing and harmonic elimination.


This control algorithm can be used for direct current control of voltage source converter current.

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**Unit Template or PI Controller Based Control Algorithm**

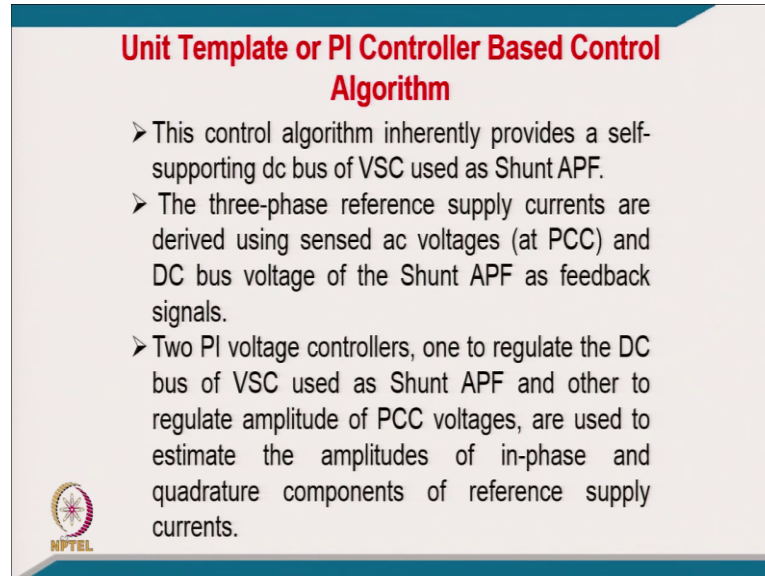
- However, an indirect current control of supply currents is preferred to obtain PWM switching signals for the devices used in the CC-VSC working as a Shunt APF.
- The indirect current control of Shunt APF offers the advantages of fast control, reduced burden on the processor (DSP used for implementation), inherent elimination of sharp notches in currents etc.
- The unit template or PI (Proportional-Integral) controller based control algorithm is a simple control algorithm for active compensating devices such as Shunt APF.



However, an indirect current control of supply current or grid current is generally preferred. The indirect current control of shunt active filter offers the advantage of fast


control, reduced burden on the processor for the implementation and inherent elimination of sharp notches in the current.

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**Unit Template or PI Controller Based Control Algorithm**

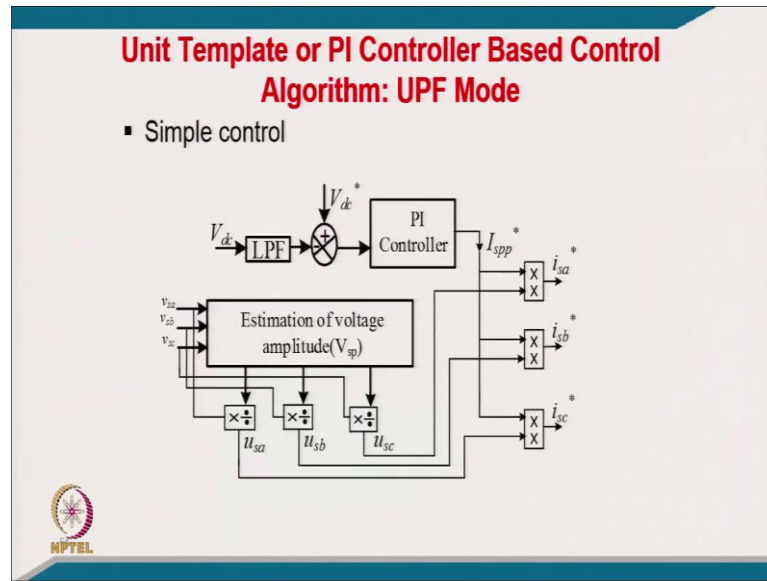
- This control algorithm inherently provides a self-supporting dc bus of VSC used as Shunt APF.
- The three-phase reference supply currents are derived using sensed ac voltages (at PCC) and DC bus voltage of the Shunt APF as feedback signals.
- Two PI voltage controllers, one to regulate the DC bus of VSC used as Shunt APF and other to regulate amplitude of PCC voltages, are used to estimate the amplitudes of in-phase and quadrature components of reference supply currents.

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The unit template or PI controller based control algorithm is simple control algorithm for active compensating devices such as shunt active filter. The control algorithm inherently provides a self-supporting dc bus used for shunt active power filter. And, the three-phase reference grid current are derived using a sensed ac voltage DC bus voltage of the shunt active filter as a feedback signal.

The two PI controller; one to regulate the DC bus of voltage source converter used as a shunt active filter and other to regulate the amplitude of PCC voltage are used to estimate the amplitude of in phase and quadrature component of reference supply current.

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These is the block diagram of the control scheme. The following screenshots represent the expressions used in the control strategy.

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**Unit Template or PI Controller Based Control  
Algorithm: UPF Mode**

$$\begin{bmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 & 0 \\ -1 & 1 & 0 \\ -1 & -2 & 0 \end{bmatrix} \begin{bmatrix} V_{sab} \\ V_{sbc} \\ 0 \end{bmatrix} \quad V_{sp} = \sqrt{\frac{2}{3}(V_{sa}^2 + V_{sb}^2 + V_{sc}^2)}$$

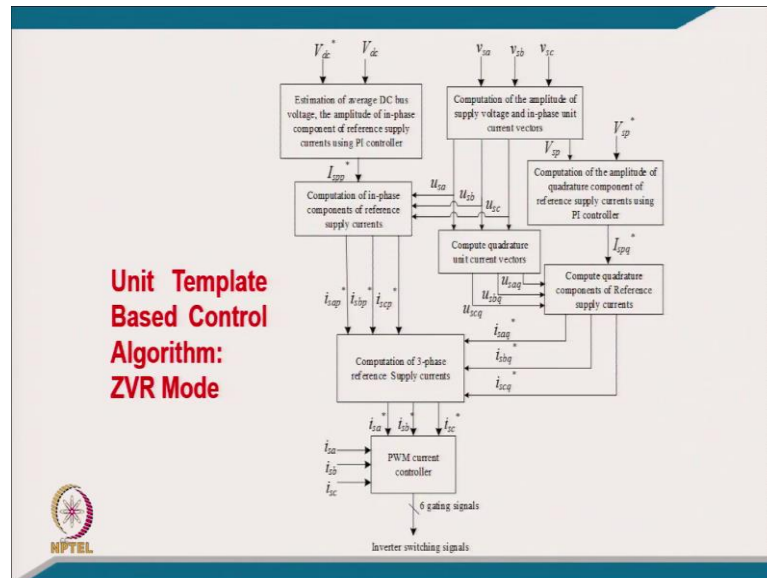
$$u_{sa} = V_{sa}/V_{sp}, \quad u_{sb} = V_{sb}/V_{sp}, \quad u_{sc} = V_{sc}/V_{sp}$$

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

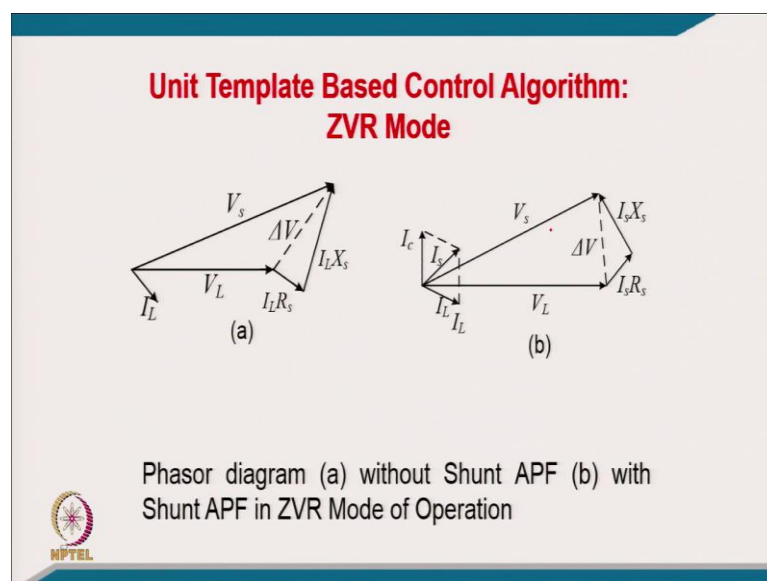
$$I_{spp}^*(n+1) = I_{spp}^*(n) + K_{pd} \{V_{dce}(n+1) - V_{dce}(n)\} + K_{id} V_{dce}(n+1)$$

$$i_{sa}^* = I_{spp}^* u_{sa}, \quad i_{sb}^* = I_{spp}^* u_{sb}, \quad i_{sc}^* = I_{spp}^* u_{sc}$$

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(Refer Slide Time: 06:58)



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**Unit Template Based Control Algorithm:  
ZVR Mode**


➤ Estimation of in-phase and quadrature unit templates vectors

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 & 0 \\ -1 & 1 & 0 \\ -1 & -2 & 0 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \\ 0 \end{bmatrix} \quad V_{sp} = \sqrt{\frac{2}{3}(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}$$

$$u_{sa} = v_{sa}/V_{sp}, u_{sb} = v_{sb}/V_{sp}, u_{sc} = v_{sc}/V_{sp}$$

$$u_{saq} = (-u_{sb} + u_{sc})/\sqrt{3}$$

$$u_{sbq} = (3u_{sa} + u_{sb} - u_{sc})/2\sqrt{3}$$

$$u_{scq} = (-3u_{sa} + u_{sb} - u_{sc})/2\sqrt{3}$$



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**Unit Template or PI Controller Based Control  
Algorithm: ZVR Mode**

➤ Estimation of direct component of reference supply currents

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

$$I_{spp}^*(n+1) = I_{spp}^*(n) + K_{pd} \{v_{dce}(n+1) - v_{dce}(n)\} + K_{id} (v_{dce}(n+1))$$

$$i_{sap}^* = I_{spp}^* u_{sa}, i_{sbp}^* = I_{spp}^* u_{sb}, i_{scp}^* = I_{spp}^* u_{sc}$$




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### Unit Template or PI Controller Based Control Algorithm: ZVR Mode


➤ Estimation of quadrature component of reference supply currents

$$v_{spe}(n) = V_{sp}^*(n) - V_{sp}(n)$$

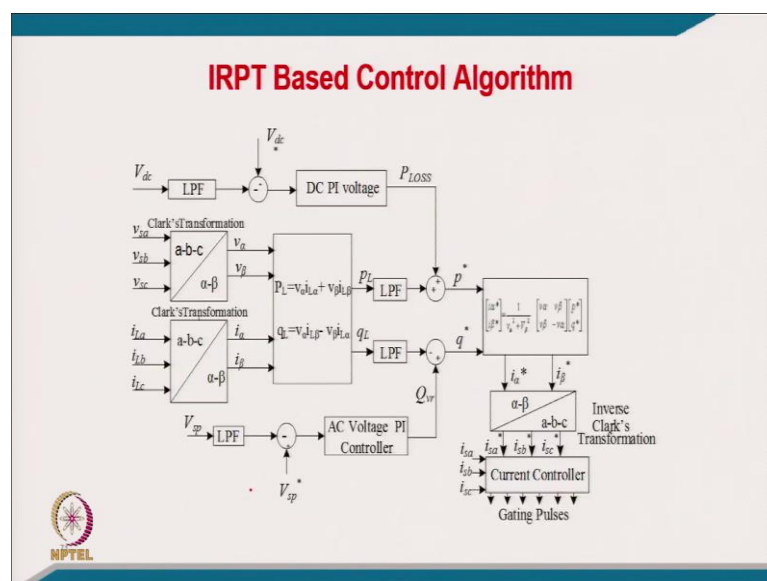
$$I_{spq}^*(n+1) = I_{spq}^*(n) + K_{pt} \{V_{spe}(n+1) - v_{spe}(n)\} + K_{it} (V_{spe}(n+1))$$

$$i_{saq}^* = I_{spq}^* U_{saq}, i_{sbq}^* = I_{spq}^* U_{sbq}, i_{scq}^* = I_{spq}^* U_{scq}$$

➤ Estimation of reference supply currents

$$i_{sa}^* = i_{sap}^* + i_{saq}^*, i_{sb}^* = i_{sbp}^* + i_{sbq}^*, i_{sc}^* = i_{scp}^* + i_{scq}^*$$


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This is another control algorithm which is derived from the instantaneous reactive power theory or alpha-beta theory. The control block diagram and associated expressions are detailed in the following screenshots.

(Refer Slide Time: 09:50)

### IRPT Based Control Algorithm

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & 1 & 0 \\ -1 & 1 & 0 \\ -1 & -2 & 0 \end{bmatrix} \begin{bmatrix} v_{sab} \\ v_{sbc} \\ 0 \end{bmatrix}$$

The three phase filtered PCC phase voltages and load currents are transformed into two phase  $\alpha$ - $\beta$  orthogonal coordinates

$$\begin{pmatrix} v_{\alpha} \\ v_{\beta} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{pmatrix}, \quad \begin{pmatrix} i_{L\alpha} \\ i_{L\beta} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{pmatrix}$$


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### IRPT Based Control Algorithm


- The instantaneous active power  $p_L$  and the instantaneous reactive power  $q_L$  of the load

$$\begin{pmatrix} p_L \\ q_L \end{pmatrix} = \begin{pmatrix} v_{\alpha} & v_{\beta} \\ v_{\beta} & -v_{\alpha} \end{pmatrix} \begin{pmatrix} i_{L\alpha} \\ i_{L\beta} \end{pmatrix}, \quad p_L = \bar{p}_L + \tilde{p}_L, q_L = \bar{q}_L + \tilde{q}_L$$

$\bar{p}_L$  and  $\bar{q}_L$  are the DC component and  
 $\tilde{p}_L$  and  $\tilde{q}_L$  are the AC component

The DC components of active and reactive powers are extracted by using two LPFs (Low-Pass-Filters)

- Total active power ( $p^*$ ) and reactive power ( $q^*$ ) components of reference supply current

$$p^* = P_{LOSS} + \bar{p}_L, \quad q^* = Q_{vr} - \bar{q}_L$$



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### IRPT Based Control Algorithm

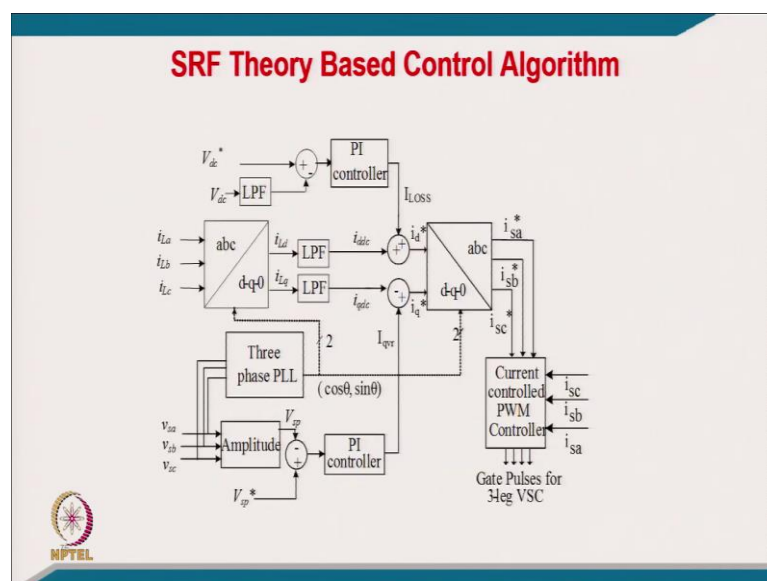
$$P_{LOSS}(n+1) = P_{LOSS}(n) + K_{pd} \{v_{dce}(n+1) - v_{dce}(n)\} + K_{id} (v_{dce}(n+1))$$

$$Q_{vr}(n+1) = Q_{vr}(n) + K_{pt} \{v_{spe}(n+1) - v_{spe}(n)\} + K_{it} (v_{spe}(n+1))$$

➤ Estimation of reference supply currents

$$\begin{pmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v_{\alpha} & v_{\beta} \\ -v_{\beta} & v_{\alpha} \end{pmatrix}^{-1} \begin{pmatrix} p^* \\ q^* \end{pmatrix}$$


(Refer Slide Time: 11:01)



This is another control algorithm which is called synchronous reference frame theory. It is very extensively used. The block diagram and control expressions are derived as follows.


(Refer Slide Time: 12:22)

### SRF Theory Based Control Algorithm

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

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

➤ Here,  $\theta$  is the grid voltage phase angle, which is estimated by using the three-phase PLL (phase locked loop) block. It is used to synchronize these signals with the PCC voltages.



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### SRF Theory Based Control Algorithm


$$i_{Ld} = i_{Ld dc} + i_{Ld ac}, i_{Lq} = i_{Lq dc} + i_{Lq ac}$$

➤ These d-q current components of load current are then passed through low pass filters (LPF) to extract the dc components of  $i_{Ld}$  and  $i_{Lq}$ .

➤ The amplitude direct axis ( $i_d^*$ ) and quadrature axis ( $i_q^*$ ) components of reference supply current

$$i_d^* = I_{LOSS} + i_{Ld dc}, i_q^* = I_{qvr} - i_{Lq dc}, i_0^* = 0$$

$$I_{LOSS}(n+1) = I_{LOSS}(n) + K_{pd} \{v_{dce}(n+1) - v_{dce}(n)\} + K_{id}(v_{dce}(n+1))$$

$$I_{qvr}(n+1) = I_{qvr}(n) + K_{pi} \{v_{spe}(n+1) - v_{spe}(n)\} + K_{is}(v_{spe}(n+1))$$



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**SRF Theory Based Control Algorithm**

➤ Estimation of reference supply currents


$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} i_d^* \\ i_q^* \\ i_0^* \end{bmatrix}$$

➤ Note: Inverse Park's Transformation matrix for an a-phase to d-axis alignment



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**MODELING, SIMULATION AND  
PERFORMANCE OF SHUNT ACTIVE  
POWER FILTERS**




Based on the discussed control algorithms, few shunt active filter configurations are modelled and the simulated performances are described here. Please refer the screenshots.

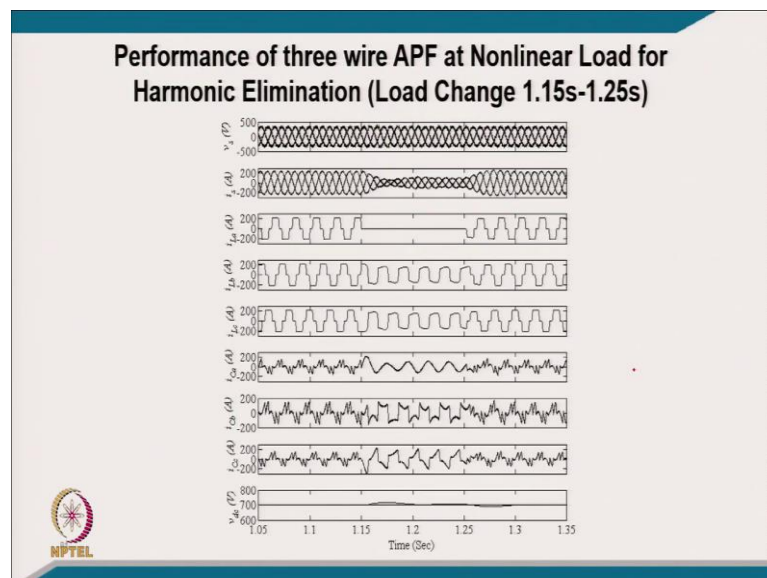
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### Modeling of Three-Phase Three-Wire Active Shunt Filter System

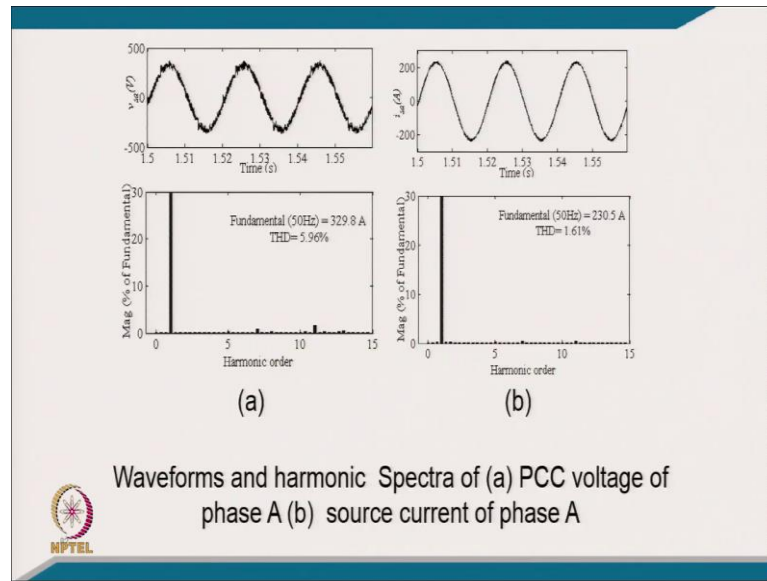
AC main Line Voltage and Frequency	Three phase, 415 V, 50 Hz (Grid)
Source Impedance	$R_s = 0.04 \Omega$ and $L_s = 1 \text{ mH}$
Nonlinear loads	Three phase rectifier with $R = 2.5 \Omega$ , $L = 25 \text{ mH}$
Cut off frequency of dc link low pass filter	10 Hz
Switching frequency	10kHz
Sampling Time	$10 \mu\text{s}$



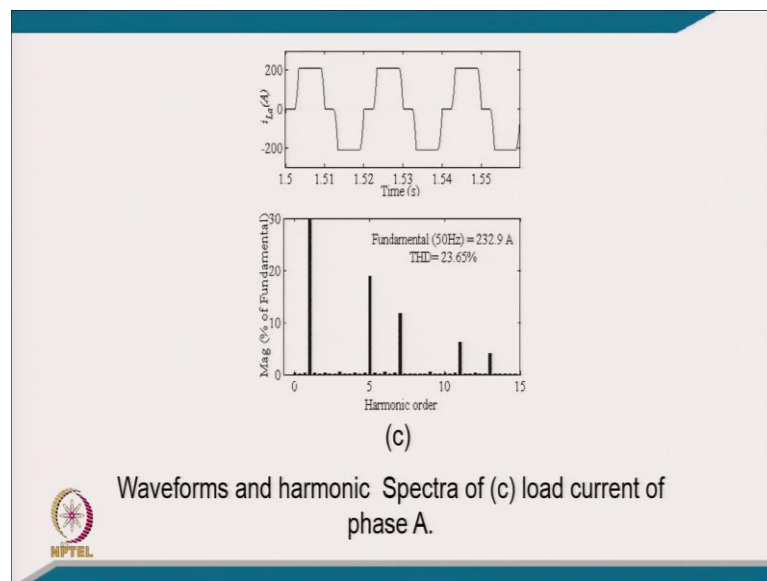
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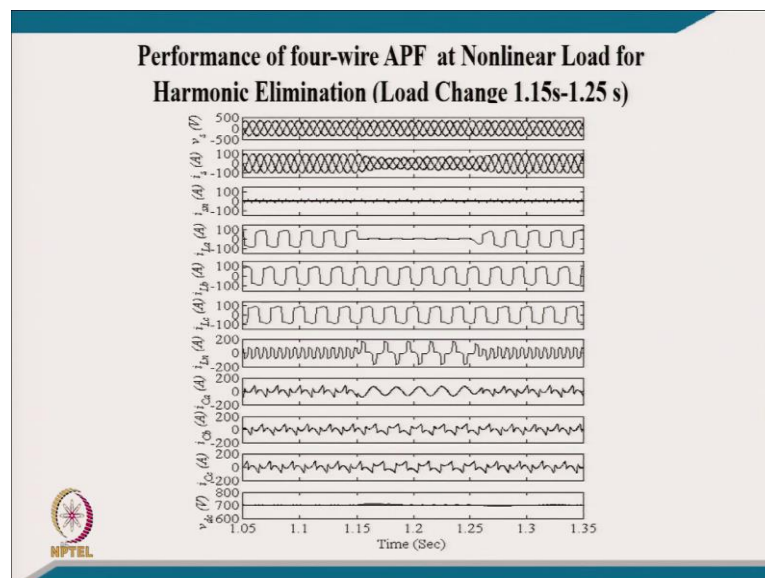
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### Modeling of Four-Leg Three-Phase, Four-Wire Shunt Active Filter System

AC Mains Line voltage and frequency	Three phase, 415 V, 50 Hz (Grid source)
Source Impedance	$R_s = 0.04 \Omega$ and $L_s = 1 \text{ mH}$
Nonlinear loads	Three single phase rectifier with $R = 2.5 \Omega$ , $L = 25 \text{ mH}$
Cut off frequency of DC link low pass filter	10 Hz
Switching frequency	10 kHz
Sampling Time	$10 \mu\text{s}$

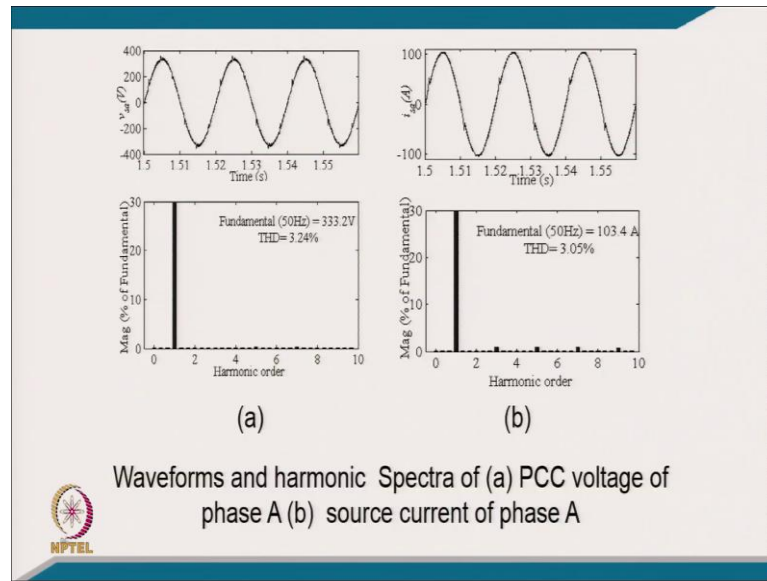


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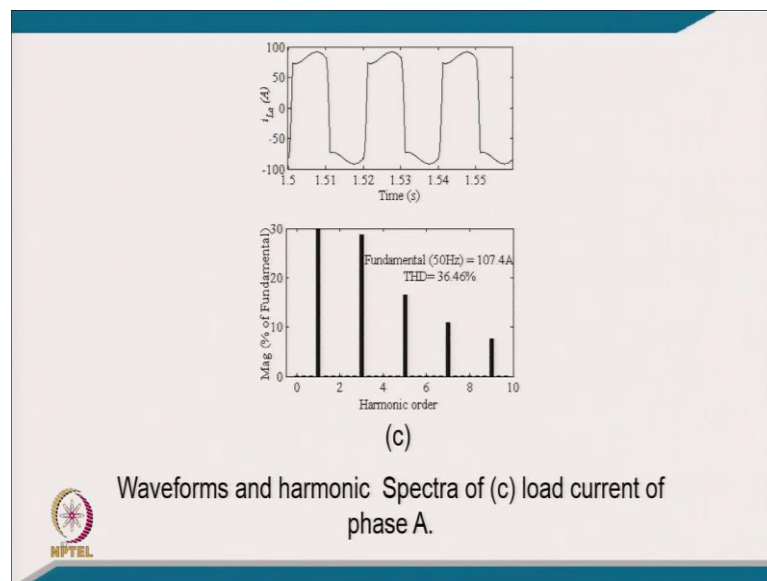




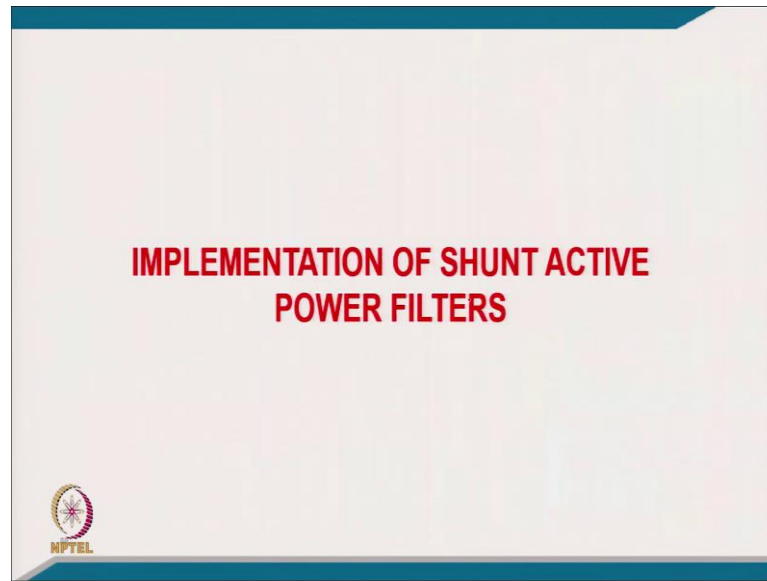
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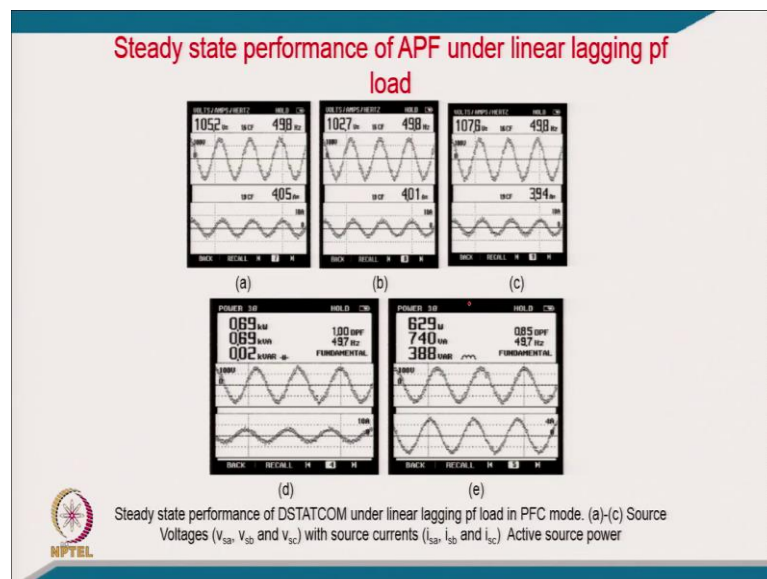


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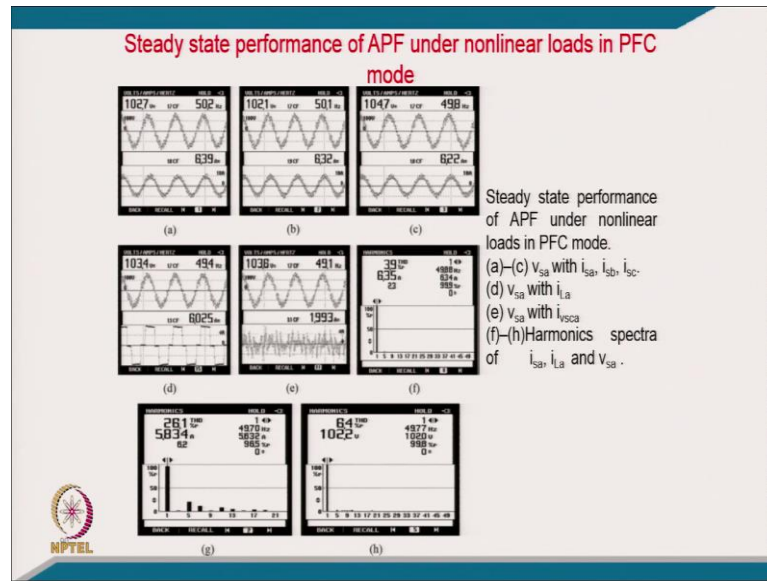


Now, experimental implementation of the above configurations are detailed.

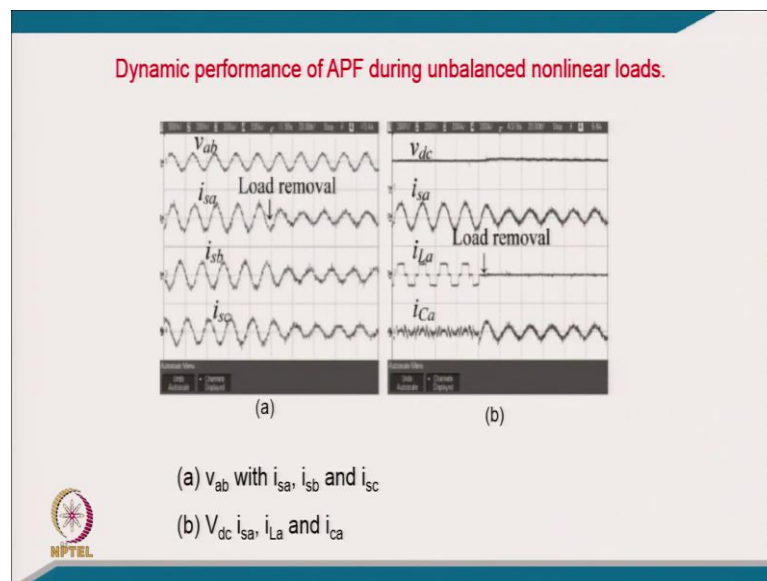
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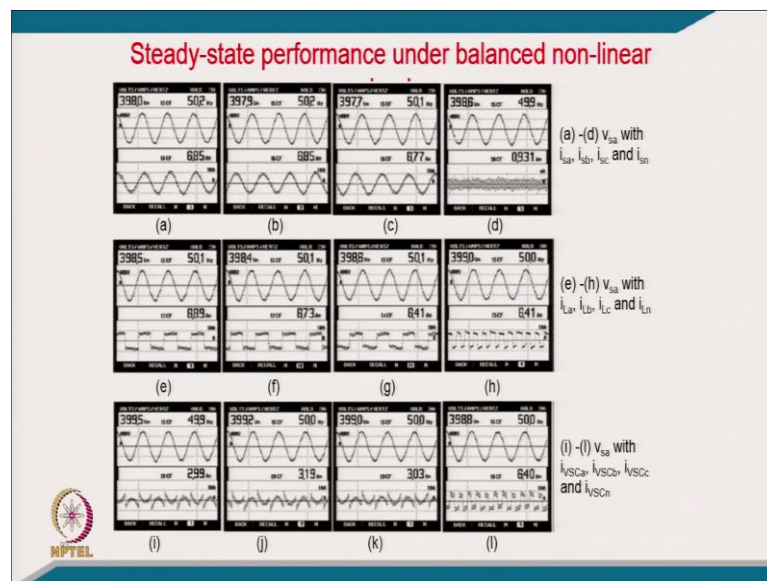


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### Implementation of three phase four-wire APF at Nonlinear Load for Harmonic Elimination and Neutral current compensation

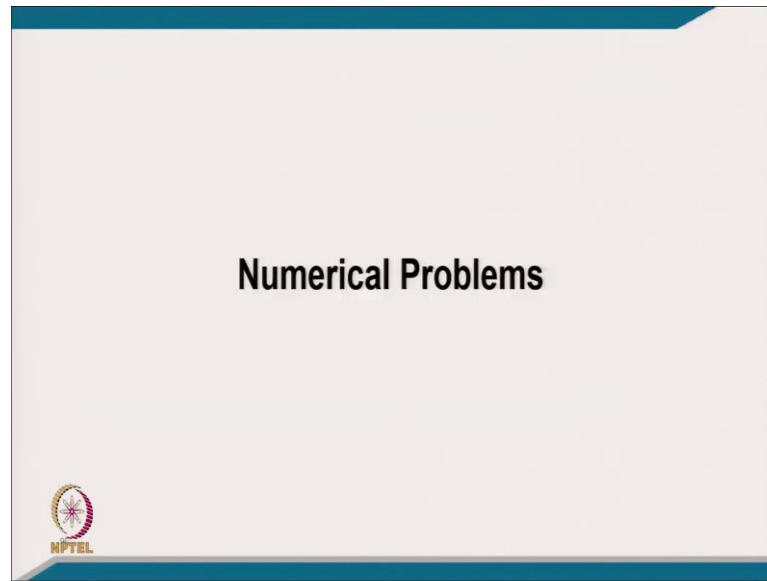


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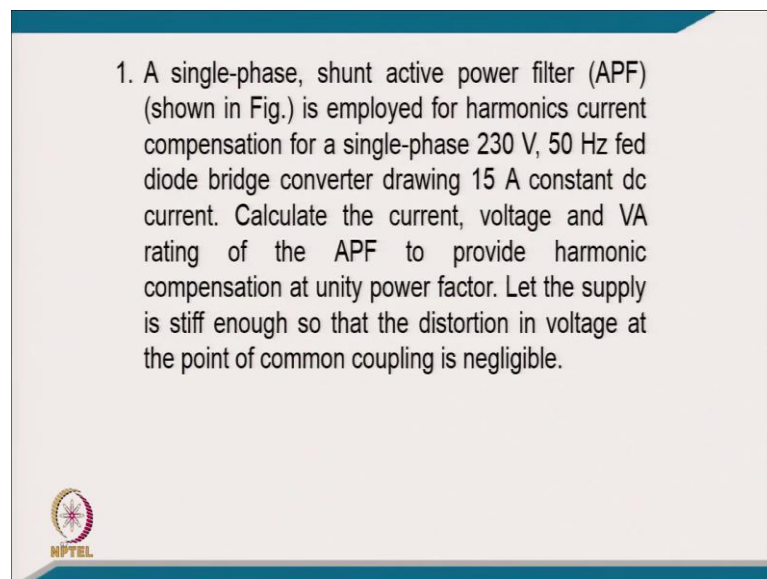


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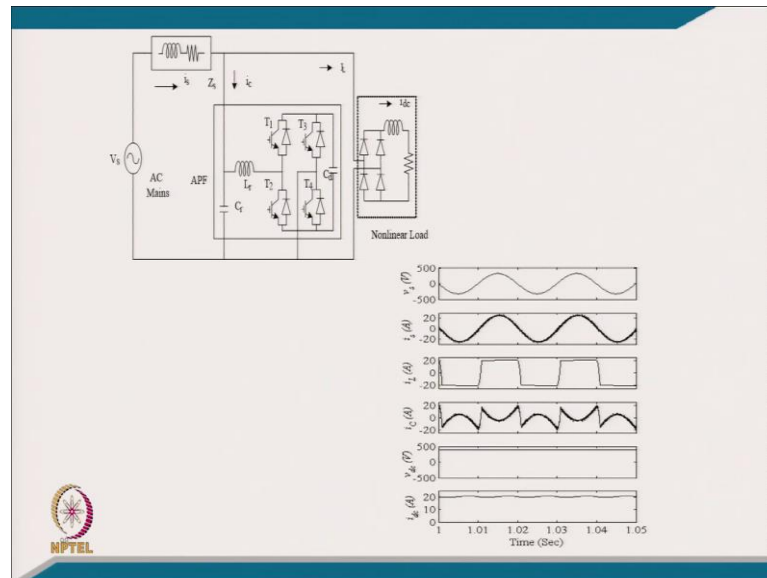
Now we will be talking about some of the numerical problems.

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A single-phase, shunt active filter, I mean is employed for harmonic current compensation of a single phase 230 volt, 50 Hertz fed diode bridge converter drawing fifteen ampere constant dc current. Calculate the current voltage and VA rating of the shunt active power filter to provide a harmonic compensation at unity power factor. Let the supply is a stiff enough so that the distortion in voltage at the point of common coupling is negligible.

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We have a non-linear load with diode rectifier with the RL load and constant current on DC side. The solution to the numerical is detailed in the following screenshots.

(Refer Slide Time: 21:27)

**Solution:** Given that,  $V_s = 230$  V,  $f=50$  Hz,  $I_{dc} = 15$ A.

In single-phase diode bridge converter:

$$I_s = I_{dc} = 15A$$

$$I_{s1} = (2\sqrt{2}/\pi) I_{dc} = 0.9 I_{dc} = 13.5$$
 A

Current rating of APF=current flowing through the filter


$$=I_f = I_h = \sqrt{(I_s^2 - I_{s1}^2)} = \sqrt{(15^2 - 13.5^2)} = 6.538A$$

Voltage rating of the APF=voltage across the filter =  $V_f$   
 $=V_s = 230$  V

VA Rating of the APF= $S = V_f I_f = 230 \times 6.538 = 1.503$  kVA.

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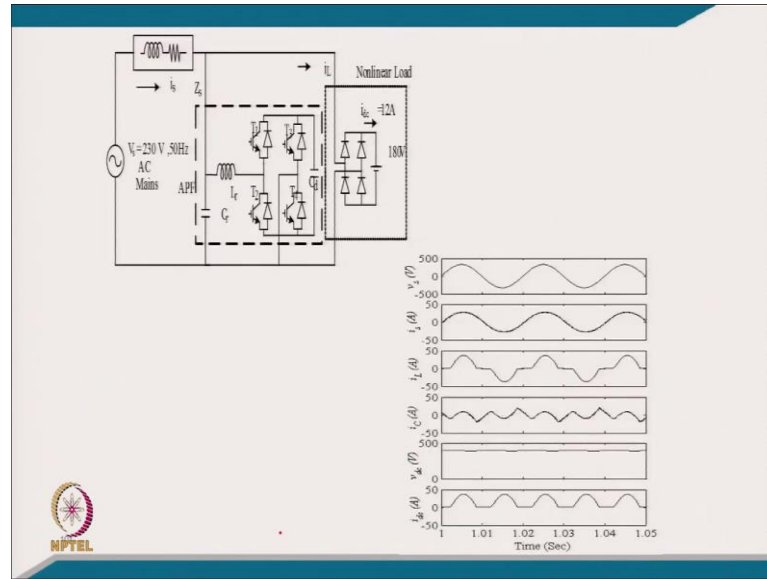
2. A shunt active power filter (VSI with ac series inductor and dc bus capacitor) (shown in Fig.) is used in parallel with single-phase ac supply of 230 V, 50 Hz feeding diode rectifier charging a battery of 180 V at 12 A average current with a small current limiting resistor to reduce the harmonics in ac mains current and to almost maintain UPF. Calculate (a) the value of current limiting resistor, (b) ac input current to diode rectifier, (c) voltage rating of APF, (d) current rating of APF, (e) VA rating of APF, (f) value of dc bus voltage of APF, (g) value of ac inductor of APF, and (h) value of dc bus capacitor of APF. Consider the switching frequency of 10 kHz and dc bus voltage has to be controlled within 5% range and ripple current in inductor is 8%.



Coming to the typically second numerical problems; The shunt active power filter the voltage source inverter with the ac series inductor and dc capacitor shown in the figure is used in parallel with a single phase supply of 230 volt 50 Hertz feeding diode base rectifier charging a battery of 180 volt at 12 ampere average current with a small current limiting resistor to reduce the harmonics in ac mains current and to almost maintain unity power factor. Calculate the value of current limiting resistor the, ac input current to diode rectifier, the voltage rating of shunt active power filter, the current rating of active power filter, VA rating of active power filter, the value of dc bus voltage of active power filter, the value of ac inductor of active power filter and the value of dc bus capacitor of active power filter. Consider the switching frequency of 10 kilohertz and the dc bus voltage has to be controlled 5 percent and the ripple current inductor is to be 8 percent.



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The solution to the numerical is detailed in the following screenshots.

(Refer Slide Time: 23:57)

**Solution:** Given that,  $V_s=230\text{V}$ ,  $V_{sm}=325.27\text{V}$ ,  $f=50\text{ Hz}$ , Load  $I_{dc}=12\text{A}$ ,  $E=180\text{V}$ ,  $f_s=10\text{ kHz}$ ,  $\Delta I_f=8\%$ ,  $\Delta V_{dc\text{cap}}=5\%$ .

In single-phase diode bridge converter, with RE load,  
 $\alpha = \sin^{-1}(E/V_{sm}) = \sin^{-1}(180/325.27) = 33.59^\circ$   
 $\beta = \pi - \alpha = 146.40^\circ$ ,  
 The conduction angle =  $\beta - \alpha = 112.81^\circ$   
 The current limiting resistor (R) is as.  
 $R = \{1/(\pi I_{dc})\}(2V_{sm} \cos \alpha + 2E \alpha - \pi E) = 4.973\Omega$   
 RMS ac input current to diode rectifier ( $I_{Dac}$ ) is rms of discontinuous current in the ac mains as.  
 $I_{dac} = \{[1/(\pi R^2)]\{(0.5V_{sm}^2 + E^2)(\pi - 2\alpha) + 0.5V_{sm}^2 \sin 2\alpha - 4V_{sm} E \cos \alpha\}\}^{1/2}$   
 $I_{dac} = 16.687\text{ A}$

(Refer Slide Time: 25:14)

Active power drawn from ac mains,  $P = I_s^2 R + E I_{dc} = 3554.762 \text{ W}$


The Fundamental RMS current from ac mains,  
 $I_{s1} = P/V_s = 3554.762/230 = 15.412 \text{ A}$

(a) The current limiting resistor,  
 $R = \{1/(\pi I_{dc})\} (2V_{sm} \cos \alpha + 2E - \pi E) = 4.973 \Omega$

(b) RMS ac input current to diode rectifier ( $I_{dac}$ ) is rms of discontinuous current in the ac mains as.  
 $I_{dac} = \{[1/(\pi R^2)] \{ (0.5V_{sm}^2 + E^2)(\pi - 2\alpha) + 0.5V_{sm}^2 \sin 2\alpha - 4V_{sm} E \cos \alpha \}\}^{1/2}$   
 $= 16.687 \text{ A}$

(c) Voltage rating of the APF = voltage across the filter =  
 $V_f = V_s = 230 \text{ V}$

(d) Current rating of APF  $= I_f = I_h = \sqrt{(I_{dac}^2 - I_{s1}^2)} = 6.397 \text{ A}$




(Refer Slide Time: 26:03)

(e) VA Rating of the APF  
 $S = V_f I_f = 230 * 6.397 = 1471.389 \text{ VA}$

(f) The value of dc bus voltage of APF,  
 $V_{dcapf} = \sqrt{2} V_f / m_a = \sqrt{2} V_f / 0.8 = 406.59 \text{ V} \approx 400 \text{ V}$


(g) The interfacing inductance of the APF,  
 $L_f = V_{dcapf} / (4f_s \Delta I_f) = 400 / (4 * 10000 * 0.512) = 19.539 \text{ mH}$

(h) The dc bus capacitance of an APF is computed from change in stored energy during dynamics as.  
 The change in stored energy during dynamics,  
 $\Delta E = \frac{1}{2} C_{dc} (V_{dcapf}^2 - V_{dcminapf}^2) = V_f * I_f * \Delta t$   
 $\Delta E = \frac{1}{2} C_{dc} (400^2 - 380^2) = 230 * 6.397 * 10 / 1000$   
 $C_{dc} = 1886.295 \mu\text{F}$



(Refer Slide Time: 27:01)

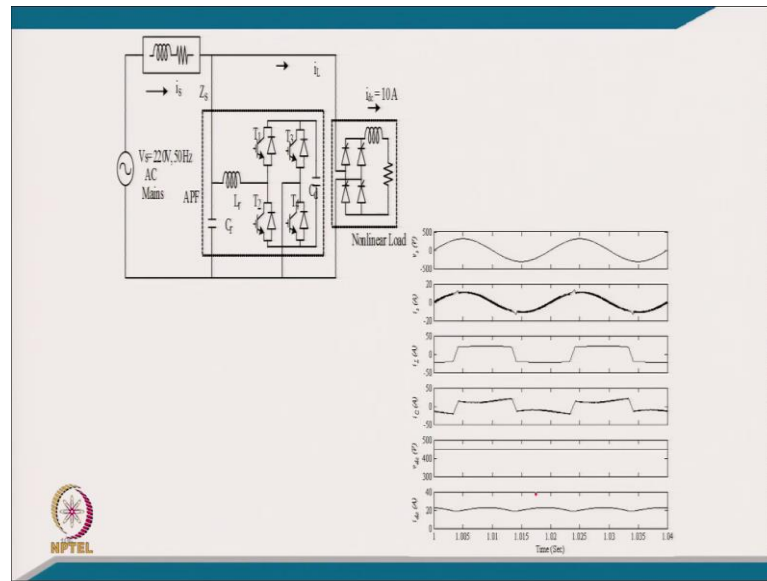
3. A single-phase, shunt active power filter (SAPF) (shown in Fig.) is employed for harmonics currents and reactive power compensation for a single-phase 220V, 50 Hz fed thyristor fully controlled bridge converter drawing 10 A constant dc current operating at  $30^\circ$  firing angle of its thyristors. Calculate the current, voltage and VA rating of the SAPF to provide (a) only harmonic compensation, (b) only reactive power compensation and (c) harmonic and reactive power compensation at unity power factor. Let the supply is stiff enough so that the distortion in voltage at the point of common coupling is negligible.



Coming to third numerical problem: A single phase shunt active power filter is employed for the harmonic currents and reactive power compensation, for a single phase 230 volt 50 Hertz fed thyristor fully control converter drawing a 10 ampere dc current operating at 30 degree fire angle of it is thyristor.

Calculate the current, voltage and VA rating of the shunt active power filter to provide; a, only harmonics compensation; b, only reactive power compensation; c, harmonics and reactive power compensation at the unity power factor. Let the supply is stiff enough so that the distortion in voltage at the point of common coupling is negligible.

(Refer Slide Time: 27:36)



(Refer Slide Time: 27:58)

The solution to the numerical is detailed in the following screenshots.

**Solution:** Given that,  $V_s = 220\text{ V}$ ,  $f = 50\text{ Hz}$ ,  $I_{dc} = 10\text{ A}$ ,  
 $\alpha = 30^\circ$

In single-phase thyristor bridge converter:

$I_s = I_{dc} = 10\text{ A}$  and  
 $I_{s1} = 0.9 I_{dc} = 9\text{ A}$

Hence total rms harmonic current,  
 $I_h = \sqrt{(I_s^2 - I_{s1}^2)} = \sqrt{(10^2 - 9^2)} = 4.359\text{ A}$


Active power component of supply current  
 $I_{s1a} = I_{s1} \cos \theta_1 = I_{s1} \cos \alpha = 9 \cos 30^\circ = 7.794\text{ A}$

Total harmonics and reactive current ;  
 $I_f = \sqrt{(I_s^2 - I_{s1a}^2)} = \sqrt{(10^2 - 7.794^2)} = 6.265\text{ A}$

(Refer Slide Time: 28:53)


(a) Only Harmonic compensation  
Current rating = current flowing through the filter  
 $I_f = I_h = \sqrt{(I_s^2 - I_{s1}^2)} = \sqrt{(10^2 - 9^2)} = 4.359 \text{ A}$   
Voltage rating = voltage across the filter =  $V_f = 220 \text{ V}$   
VA Rating of APF,  $S = V_f I_f = 220 * 4.359 = 959.98 \text{ VA}$

(b) Only reactive power compensation  
Current rating = Filter current  $I_f =$  Reactive current  
 $I_R = I_{s1} \sin \theta_1 = I_{s1} \sin \alpha = 9 \sin 30^\circ = 4.5 \text{ A}$   
Voltage rating of the filter = Voltage across the filter  
 $= V_f = V_s = 220 \text{ V}$   
VA Rating of APF,  $S = V_f I_f = 220 * 4.5 = 990 \text{ VA}$



(Refer Slide Time: 29:35)

(c) Harmonics current and reactive power compensation  
Current rating of shunt active filter  
 $I_f = \sqrt{(I_s^2 - I_{s1a}^2)} = \sqrt{(10^2 - 7.794^2)} = 6.265 \text{ A}$   
Voltage rating of the filter = Voltage across the filter  
 $= V_f = V_s = 220 \text{ V}$   
VA Rating of APF,  $S = V_f I_f = 220 * 6.265 = 1378.30 \text{ VA}$



(Refer Slide Time: 30:07)

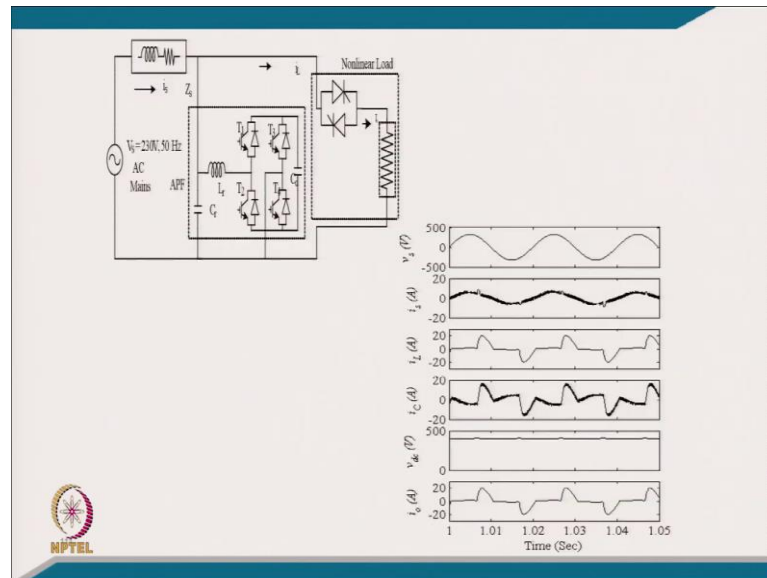
4. A resistive heating load of 20 ohms (shown in Fig.) is fed from a single-phase, 230 V rms, 50 Hz ac source through a phase controlled ac controller at a firing angle of  $120^\circ$ . Calculate (a) fundamental active power drawn by the load, (b) fundamental reactive power drawn by the load, (c) VA rating of APF to provide (i) only harmonic compensation, (ii) only reactive power compensation and (iii) harmonic and reactive power compensation at unity power factor. Let the supply is stiff enough so that the distortion in voltage at the point of common coupling is negligible.



Now, coming to the fourth numerical problem: Resistive heating load of 20 ohm is fed from a single phase 230 volt rms, 50 Hertz ac source through a phase control ac controller at a firing angle of 120 degree.

Calculate the fundamental active power drawn by the load, fundamental reactive power drawn by the load, VA rating of active shunt filter to provide the only harmonic compensation; b, only reactive power compensation and third is a harmonics and reactive power compensation at unity power factor let the supply voltage is stiff enough so that the distortion in voltage at the point of common coupling negligible.

(Refer Slide Time: 30:45)



The solution to the numerical is detailed in the following screenshots.

(Refer Slide Time: 31:19)

**Solution:** Given that,  $V_s = 230\text{ V}$ ,  $f = 50\text{ Hz}$ ,  $R = 20\ \Omega$ ,  
 $\alpha = 120^\circ$

In a single-phase, phase controlled ac controller, the waveform of the supply current ( $i_s$ ) has a value of  $v_s/R$  from angle  $\alpha$  to  $\pi$ .

$V_{sm} = 230\sqrt{2} = 325.27\text{ V}$

RMS supply current

$$I_s = V_{sm} \left[ \frac{1}{2\pi} \left\{ (\pi - \alpha) + \frac{\sin 2\alpha}{2} \right\} \right]^{1/2} / R = 5.085\text{ A}$$

Fundamental RMS current

$$I_{s1} = V_{sm} / (2\pi R \sqrt{2}) \left[ (\cos 2\alpha - 1)^2 + \{ \sin 2\alpha + 2(\pi - \alpha) \}^2 \right]^{1/2}$$


$$= 3.549\text{ A}$$

$\theta_1 = \tan^{-1} \left[ (\cos 2\alpha - 1) / \{ \sin 2\alpha + 2(\pi - \alpha) \} \right] = 50.69^\circ$

RMS Active power fundamental component of supply current,

(Refer Slide Time: 32:27)

$I_{s1a} = I_{s1} \cos \theta_1 = 2.248 \text{ A}$   
Hence total rms harmonic current,  
 $I_h = \sqrt{(I_s^2 - I_{s1}^2)} = \sqrt{(5.085^2 - 3.549^2)} = 3.642 \text{ A}$   
RMS reactive power fundamental component of supply current,  
 $I_{s1r} = I_{s1} \sin \theta_1 = I_{s1} \sqrt{(1 - \cos^2 \theta_1)} = 2.746 \text{ A}$   
Total harmonics and reactive current =  $I_f$   
 $= \sqrt{(I_s^2 - I_{s1a}^2)} = \sqrt{(5.085^2 - 2.248^2)} = 4.561 \text{ A}$   
(a) Fundamental active power drawn by the load,  
 $P_1 = V_s I_{s1} \cos \theta_1 = 517.04 \text{ W}$   
(b) Fundamental reactive power drawn by the load,  
 $Q_1 = V_s I_{s1} \sin \theta_1 = 631.580 \text{ VAR}$




(Refer Slide Time: 33:18)

(c) VA rating of APF to provide

**(i) Only Harmonic compensation**  
Current rating = current flowing through the filter  
 $I_f = I_h = \sqrt{(I_s^2 - I_{s1}^2)} = \sqrt{(5.085^2 - 3.549^2)} = 3.642 \text{ A}$   
Voltage rating = voltage across the filter =  $V_f = 230 \text{ V}$   
VA Rating of APF,  $S = V_f I_f = 230 * 3.642 = 792.26 \text{ VA}$

**(ii) Only reactive power compensation**  
Current rating = Filter current  $I_f =$  Reactive current  
 $I_R = I_{s1} \sin \theta_1 = I_{s1} \sin \theta_1 = I_{s1} \sqrt{(1 - \cos^2 \theta_1)} = 2.746 \text{ A}$   
Voltage rating of the filter = Voltage across the filter  
 $= V_f = V_s = 230 \text{ V}$   
VA Rating of APF,  $S = V_f I_f = Q_1 = V_s I_{s1} \sin \theta_1$   
 $S = 631.580 \text{ VAR}$






(Refer Slide Time: 34:27)

(iii) Harmonics current and reactive power compensation

$$I_f = I_f = \sqrt{(I_s^2 - I_{s1a}^2)} = \sqrt{(5.085^2 - 2.248^2)} = 4.561 \text{ A}$$


Voltage rating of the filter=Voltage across the filter  
 $=V_f=V_s=230 \text{ V}$

VA Rating of APF,  $S = V_f I_f = 230 * 4.561 = 1049.03 \text{ VA}$



(Refer Slide Time: 35:17)

5. A three-phase, shunt active power filter (APF) (shown in Fig.) is employed for harmonics current compensation for a three-phase 415V, 50 Hz fed diode bridge converter drawing 100 A constant dc current. Calculate (a) active power drawn by the load, (b) the current rating of the APF, (c) the voltage of the APF, (d) the VA rating of the APF to provide harmonics current compensation at unity power factor, (e) value of dc bus voltage of APF, (f) value of ac inductor of APF, and (g) value of dc bus capacitor of APF. Consider the switching frequency of 10 kHz and dc bus voltage has to be controlled within 5% range and ripple current in inductor is 8%.

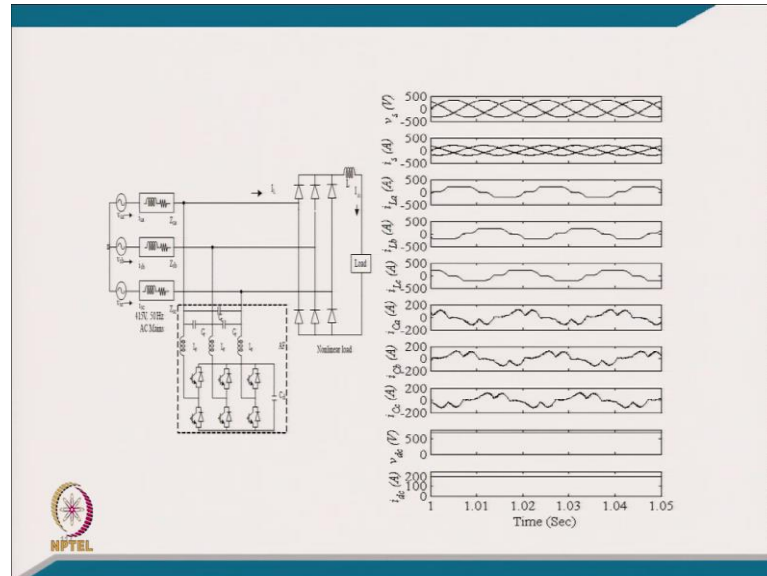


Coming to the 5th numerical problem: A three-phase, shunt active power filter is employed for harmonic current compensation for three-phase 415 volt 50 Hertz fed diode bridge converter drawing 100 ampere constant dc current.

Calculate active power drawn by the load, current rating of active filter, voltage rating of active filter, the VA rating of active filter to provide harmonic current compensation at unity power factor, value of dc bus capacitor, value of ac inductor the value of dc bus

capacitor of APF and consider the switching frequency of 10 kilohertz and dc bus voltage to be controlled within 5 percent and the ripple current is 8 percent like.

(Refer Slide Time: 36:00)



The solution to the numerical is detailed in the following screenshots.

(Refer Slide Time: 36:24)

**Solution:** Given that,  $V_s = 415/\sqrt{3} = 239.6$  V,  $f = 50$  Hz,  
 $I_{dc} = 100$  A  
 The rms of quasi-square wave load current,  
 $I_s = I_{dc} \sqrt{2/3} = 81.65$  A  
 Moreover, the rms of fundamental component of quasi-square wave,  
 $I_{s1} = \{(\sqrt{6})/\pi\} I_{dc} = 77.97$  A  
 (a) The active power drawn by the load,  
 $P = 3V_s I_{s1} \cos\theta_1 = 56.045$  kW  
 (b) The current rating of APF = The total rms harmonic current,  
 $I_{APF} = I_f = I_h = \sqrt{(I_s^2 - I_{s1}^2)} = 24.236$  A,

(Refer Slide Time: 37:19)

(c) The voltage rating of the filter = Voltage across the filter

$$V_f = V_s = 239.60 \text{ V}$$


(d) The VA Rating of APF,

$$S = 3V_f I_f = 3 * 239.60 * 24.236 = 17.421 \text{ kVA.}$$

(e) The value of dc bus voltage of APF,

$$V_{\text{dcapf}} = 2\sqrt{2}V_f/m_a = 2\sqrt{2}V_f/0.9 = 752.99 \approx 750 \text{ V}$$

(f) The interfacing inductance of the APF,

$$L_f = \{(\sqrt{3}/2)m_a V_{\text{dcapf}} / (6af_s \Delta I_f)\}$$
$$L_f = \{(\sqrt{3}/2) * 0.9 * 750 / (6 * 1.2 * 10000 * 1.939)\} = 4.187 \text{ mH.}$$



(Refer Slide Time: 37:57)

(g) The dc bus capacitance of an APF is computed from change in stored energy during dynamics as.

The change in stored energy during dynamics,


$$\Delta E = \frac{1}{2} C_{\text{dc}} (V_{\text{dcapf}}^2 - V_{\text{dcminapf}}^2) = 3 * V_f * I_f * \Delta t$$
$$\Delta E = \frac{1}{2} C_{\text{dc}} (750^2 - 712.5^2)$$
$$= 3 * 239.6 * 24.236 * 10 / 1000$$

(Considering  $\Delta t = 10 \text{ ms}$ )

$$C_{\text{dc}} = 6352.907 \text{ } \mu\text{F.}$$


(Refer Slide Time: 38:27)

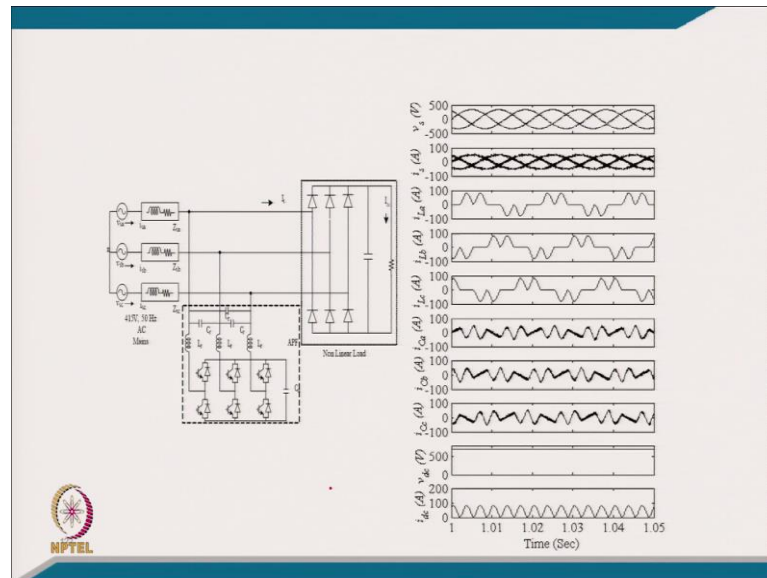
6. A three-phase, shunt active power filter (SAPF) (shown in Fig) is employed for reactive power compensation for a three-phase, 3-wire, 415V, 50 Hz system. A nonlinear load consisting of three-phase diode bridge rectifier is drawing ac current at 0.92 displacement factor and THD of its ac current is 60 percent. It is drawing 15 kW from ac source and crest factor is 2.5 of ac input current. Calculate the current, voltage and VA rating of the APF to provide (a) only harmonics current compensation, (b) only reactive power compensation and (c) harmonics current and reactive power compensation at unity power factor.



Coming to like another numerical problem, a three-phase shunt active power filter is employed for the reactive power compensation for a three-phase 3-wire 415 volt 50 Hertz system. A non-linear load consisting of three-phase diode rectifier sorry is drawing ac current at 0.92 displacement factor and THD of its ac current is 60 percent

It is drawing 15 kilowatt from ac source and crest factor is 2.5 of ac current calculate the current voltage and VA rating of active power filter to provide a only harmonics current compensation; b, only reactive power compensation; c, harmonic current and reactive power compensation.

(Refer Slide Time: 39:07)



The solution to the numerical is detailed in the following screenshots.

(Refer Slide Time: 39:50)

**Solution:** Given that,  $V_s = 415/\sqrt{3} = 239.6$  V,  $f = 50$  Hz, THD of  $I_s = 60\%$ ,  $DPF = 0.92$ , CF of  $I_s = 2.5$ , Active power,  $P = 15$  kW

In three-phase diode bridge converter, the fundamental active power component of supply current ( $I_{s1a}$ ) is as.

Therefore,  $I_{s1a} = P / (3V_s) = 20.868$  A

The RMS fundamental supply current ( $I_{s1}$ ) is as,

$$I_{s1} = I_{s1a} / DPF = 20.868 / 0.92 = 22.683$$
 A

Distortion factor is as  $DF = 1 / \sqrt{1 + THD^2} = 0.857$

The power factor is as,  $PF = DF * DPF = 0.789$

Moreover, RMS supply current is as,

$$I_s = P / (3V_s * PF) = 26.452$$
 A

(Refer Slide Time: 41:01)

VA rating of APF to provide

**(a) Only Harmonic compensation**

Current rating = current flowing through the filter

$$I_f = I_h = \sqrt{(I_s^2 - I_{s1}^2)} = \sqrt{(26.452^2 - 22.683^2)} = 13.608 \text{ A}$$

Voltage rating = voltage across the filter


$$= V_f = 239.60 \text{ V}$$

VA Rating of APF,

$$S = 3V_f I_f = 3 \times 239.6 \times 13.608 = 9.782 \text{ kVA}$$

**(b) Only reactive power compensation**

Current rating = Filter current  $I_f$  = Reactive current

$$I_R = I_{s1} \sin \theta_1 = I_{s1} \sqrt{(1 - \text{DPF}^2)} = 8.89 \text{ A}$$


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Voltage rating of the filter = Voltage across the filter

$$= V_f = V_s = 239.60 \text{ V}$$

VA Rating of APF,

$$S = 3V_f I_f = 3V_s I_{s1} \sin \theta_1 = 6.39 \text{ kVA}$$


**(c) Harmonics current and reactive power compensation**

$$I_f = \sqrt{(I_s^2 - I_{s1a}^2)} = \sqrt{(26.452^2 - 20.868^2)} = 16.255 \text{ A}$$

Voltage rating of the filter = Voltage across the filter


$$= V_f = V_s = 239.60 \text{ V}$$

VA Rating of APF,

$$S = 3V_f I_f = 11.684 \text{ kVA.}$$


(Refer Slide Time: 42:50)

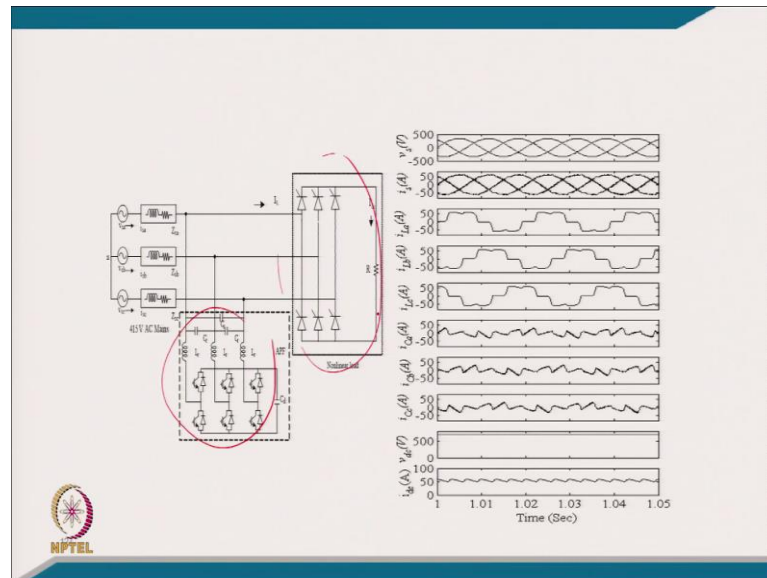
7. A three-phase, shunt active power filter (SAPF) (shown in Fig.) is employed for harmonics currents and reactive power compensation for a three-phase 415 V, 50 Hz fed thyristor bridge converter feeding a resistive load of 10 ohms at  $30^\circ$  firing angle of its thyristors. Calculate (a) fundamental active power drawn by the load, (b) fundamental reactive power drawn by the load, (c) VA rating of APF to provide (i) only harmonics current compensation, (ii) only reactive power compensation and (iii) full harmonics current and reactive power compensation at unity power factor. Let the supply is stiff enough so that the distortion in voltage at the point of common coupling is negligible.



Coming to the numerical example 7: A three-phase shunt active power filter is used is employed for harmonic currents and reactive power compensation for a three-phase 415 volt, 50 Hertz fed thyristor bridge converter drawing a resistive load of 10 ampere at 30 degree fire angle of thyristor.

Calculate the fundamental active power drawn, fundamental reactive power drawn, VA rating of active filter to provide only harmonic current compensation, only reactive power compensation, and along with a harmonics current and reactive power compensation at unity power factor. Let the supply is a stiff enough so that the distortion in the voltage at the point of common coupling is negligible.

(Refer Slide Time: 43:30)



The solution to the numerical is detailed in the following screenshots.

(Refer Slide Time: 43:58)

**Solution:** Given that, supply rms voltage,  $V_s = 415/\sqrt{3} = 239.6$  V, frequency of supply  $f=50$  Hz,  $R=10\Omega$ ,  $\alpha = 30^\circ$ .

In three-phase thyristor bridge converter, the waveform of the supply current ( $I_s$ ) is decided by load resistance and firing angle as.

Therefore,  $I_s = \{V_s/(R)\} \{[(2\pi+3\sqrt{3}\cos 2\alpha)]/\pi\}^{1/2} = 40.286$  A

RMS of fundamental component of load current,  
 $I_{s1} = \{(V_s/(2\pi R)) \{3\sqrt{3}\sin 2\alpha\}^2 + (2\pi+3\sqrt{3}\cos 2\alpha)^2\}^{1/2}$   
 $I_{s1} = 37.966$  A


Hence total rms harmonic current,  
 $I_h = \sqrt{I_s^2 - I_{s1}^2} = \sqrt{40.28^2 - 37.98^2} = 13.472$  A

The fundamental active power drawn by the load,  
 $P = 3\{V_s^2/(2\pi R)\} \{[(2\pi+3\sqrt{3}\cos 2\alpha)]\} = 24.34387$  kW




(Refer Slide Time: 44:56)

Active power component of supply current  
 $I_{s1a} = P / (3V_s) = 33.8667 \text{ A}$   
Displacement factor,  $\text{DPF} = \cos \theta_1 = I_{s1a} / I_{s1} = 0.892$ ;  
 $\sin \theta_1 = \sqrt{(1 - \text{DPF}^2)} = 0.45197$   
Total harmonics and reactive current =  
 $I_f = \sqrt{(I_s^2 - I_{s1a}^2)} = \sqrt{(40.28^2 - 33.86^2)} = 21.8176 \text{ A}$   
(a) Fundamental active power drawn by the load,  
 $P_1 = 3V_s I_{s1} \cos \theta_1 = 24.34387 \text{ kW}$   
(b) Fundamental reactive power drawn by the load,  
 $Q_1 = 3V_s I_{s1} \sin \theta_1 = 12.334 \text{ kVAR}$



(Refer Slide Time: 45:43)

(c) VA rating of APF to provide  
(i) **Only Harmonic compensation**  
Current rating = current flowing through the filter  
 $I_f = I_h = \sqrt{(I_s^2 - I_{s1}^2)} = 13.472 \text{ A}$   
Voltage rating = voltage across the filter =  $V_f = 239.60 \text{ V}$   
VA Rating of APF,  
 $S = 3V_f I_f = 3 * 239.6 * 13.472 = 9.68367 \text{ kVA}$   
(ii) **Only reactive power compensation**  
Current rating = Filter current  $I_f =$  Reactive current  $I_R$   
 $= I_{s1} \sin \theta_1 = 17.1597 \text{ A}$   
Voltage rating of the filter = Voltage across the filter =  $V_f$   
 $= V_s = 239.60 \text{ V}$



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VA Rating of APF,

$$S = 3V_f I_f = 3V_s I_{s1} \sin \theta_f = 12.33424 \text{ kVA}$$

(iii) Harmonics current and reactive power compensation

$$I_f = \sqrt{(I_s^2 - I_{s1a}^2)} = \sqrt{(40.28^2 - 33.86^2)} = 21.8176 \text{ A}$$

Voltage rating of the filter = Voltage across the filter =  $V_f$

$$= V_s = 239.60 \text{ V}$$

VA Rating of APF,

$$S = 3V_f I_f = 15.68261 \text{ kVA.}$$

