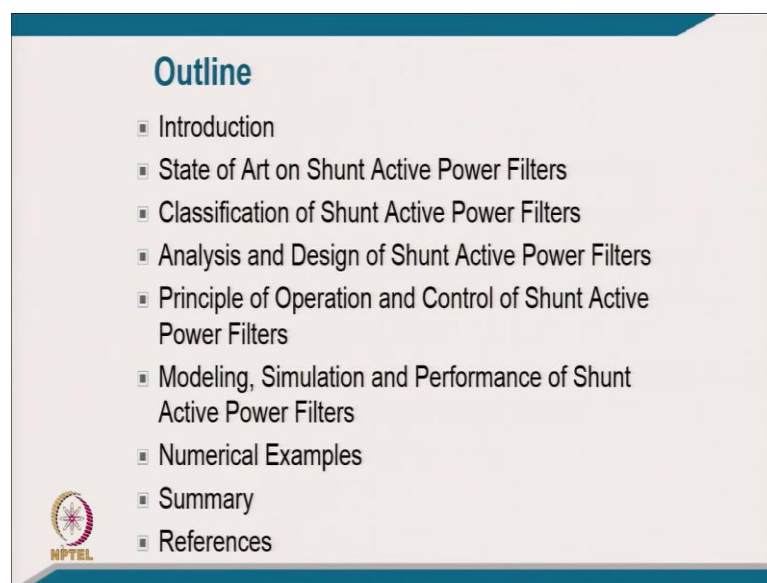


Power Quality
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Indian Institute of Technology, Delhi

Lecture - 20
Shunt Active Power Filters

Welcome to the course on Power Quality. Today we will discuss this topic of Shunt Active Power Filters.

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Coming to the outline of presentation, we would like to cover introduction, state of art on shunt active filter, classification of shunt active filter, analysis and design of shunt active filter, principle of operation and control of shunt active filter and modeling, simulation and performance of shunt active filter, then numerical examples, summary and references.

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INTRODUCTION

- Current based Power quality problems in distribution systems
 - Power factor** ✓ Increased rms supply current.
 - Voltage regulation** ✓ Increased losses (low system efficiency).
 - Unbalanced currents** ✓ Poor power factor.
 - Excessive neutral current** ✓ Poor utilization of distribution system.
 - Harmonics** ✓ Heating of components of distribution system.




Current based power quality problems in distribution system are again highlighted here in this screenshot.

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- Current based Power quality problems in distribution systems
 - ✓ Derating of the distribution system.
 - ✓ Distortion in voltage waveform at PCC
 - ✓ Interference to communication system.
 - ✓ Disturbance to the nearby consumers etc.

➤ **Solution is the Shunt Active Power Filters (SAPF)**



Then the current based power quality problems result in derating of the distribution system, distortion and voltage waveform at the point of common coupling, interference to communication system disturbance to nearby consumers.

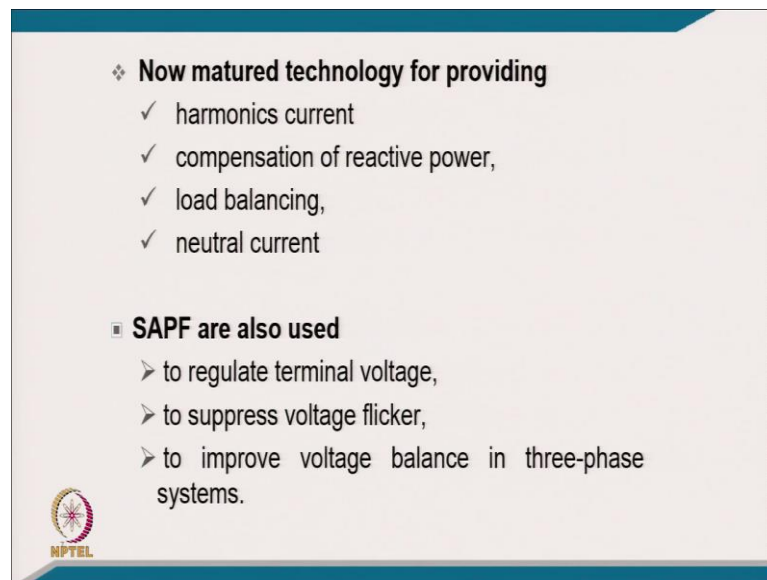
The complete solution to these problems is the Shunt Active Filter which will be discussed here in detail.

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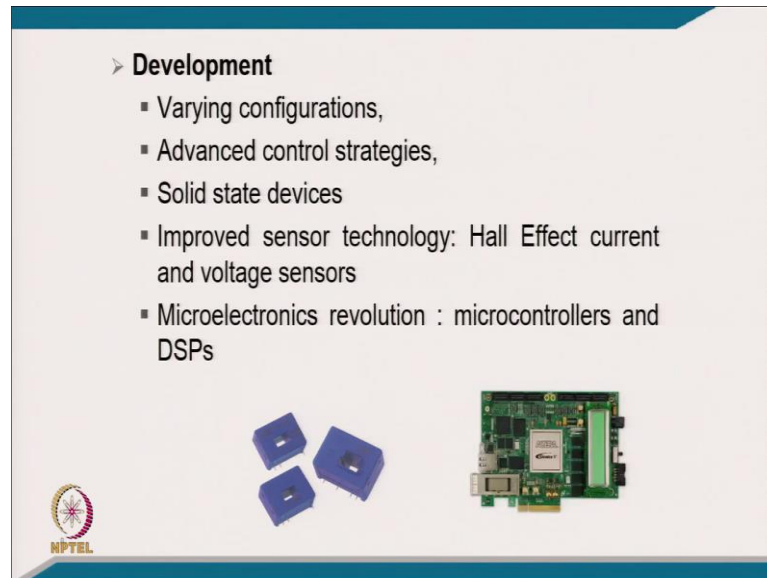
Shunt Active Power Filters are now matured technology used for providing harmonic current, compensation of reactive power, load balancing, and neutral current compensation.

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Also, the Shunt Active Power Filter is used to regulate the terminal voltage, to suppress the voltage flicker, and to improve the voltage balance in the 3-phase system.

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And of course, they are developed in varying configurations, have advanced control strategies, and utilize different solid-state devices. Improved sensor technology like Hall Effect current sensor and voltage sensor for giving a feedback signal is used for its control.

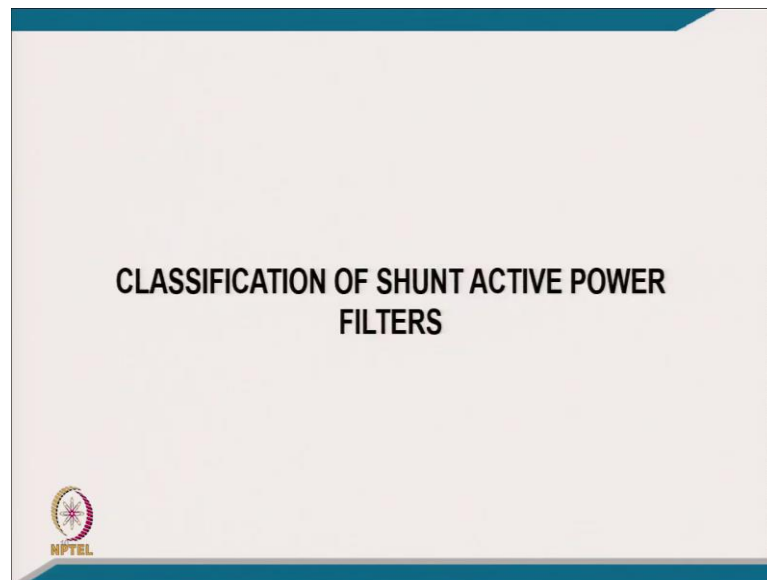
And then the microelectronics revolution has reduced the cost of microcontrollers and DSPs which have made it easier to implement the control for the Shunt Active Filters.

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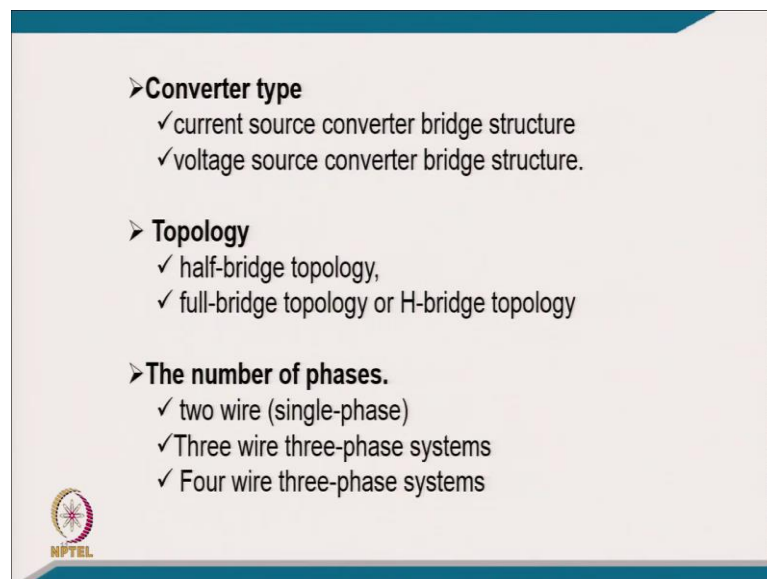
This is typically an industry made shunt active filter.

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Now coming to the classification of Shunt Active Power Filter.

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It is classified in the converter type as current source converter or voltage source converter. In the topology-wise classification, we can have a like a half-bridge topology and full-bridge topology or H-bridge topology.

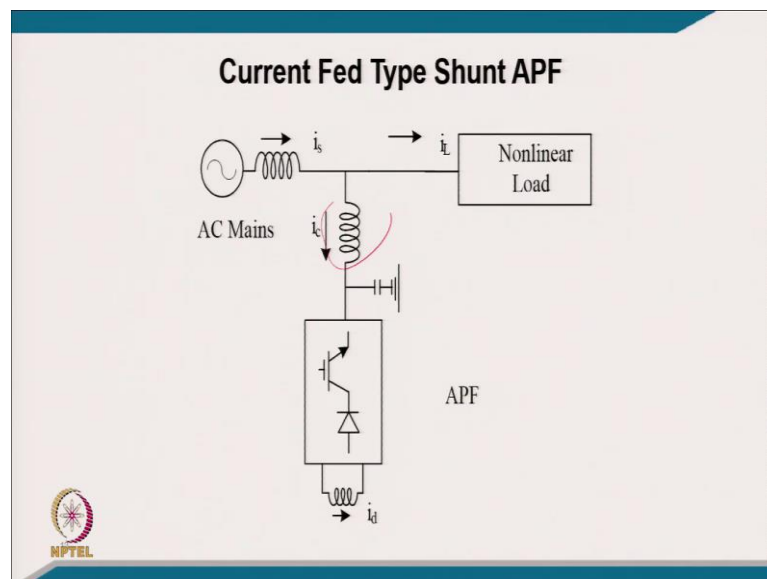
Then another classification in the on the number of phases. It can be two wire single phase system, three-wire three-phase system or four wire three-phase system.

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Now coming to the converter based classification.

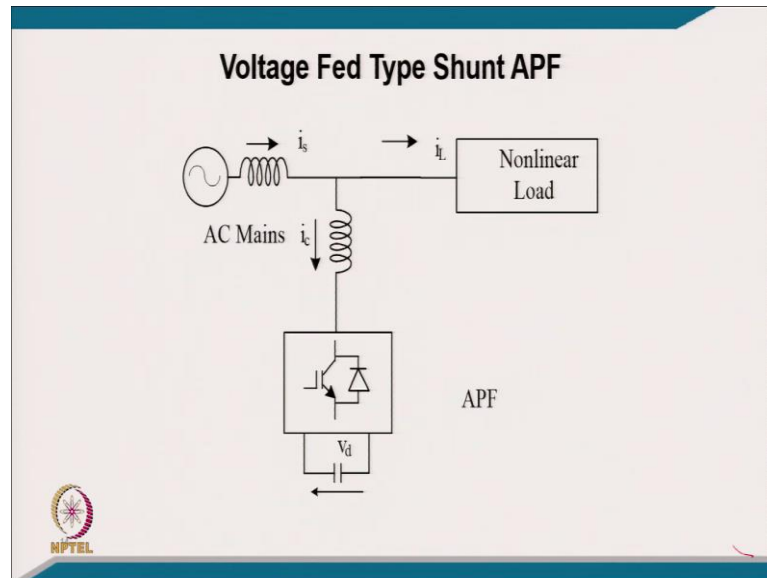
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We can have a current source converter for the shunt active filter. Additionally, we have the non-linear load and supply system with the source impedance.

This inductor is needed on the DC side. The drawback of this configurations is that the inductor is costly, bulky and noisy. While, designing the DC inductor is not so easy.

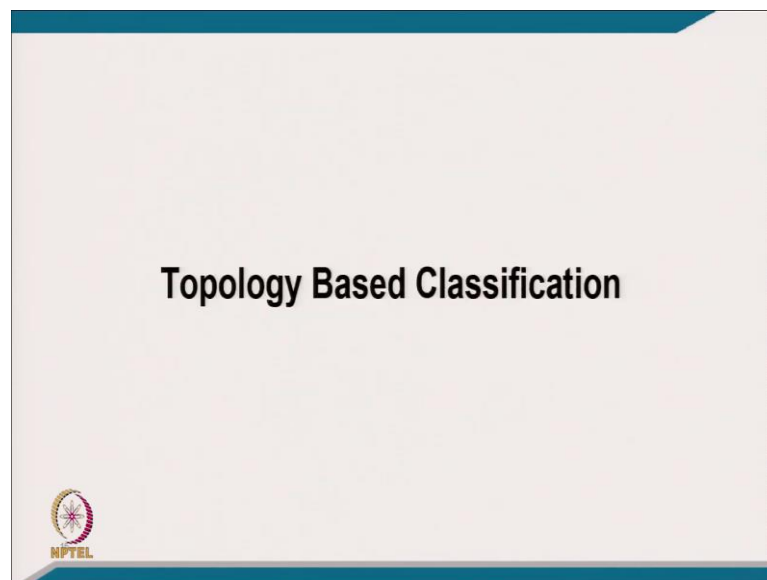
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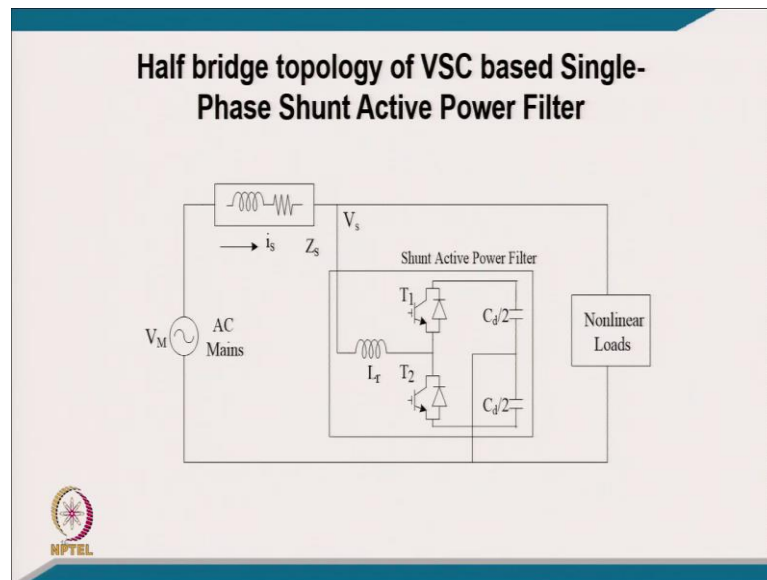
This is a shunt filter with a DC link capacitor. It is an electrolytic capacitor. This makes the voltage fed type shunt active power filter cheap, less losses, and small size.

Because of these reasons, voltage source converter based shunt filter are more popular.

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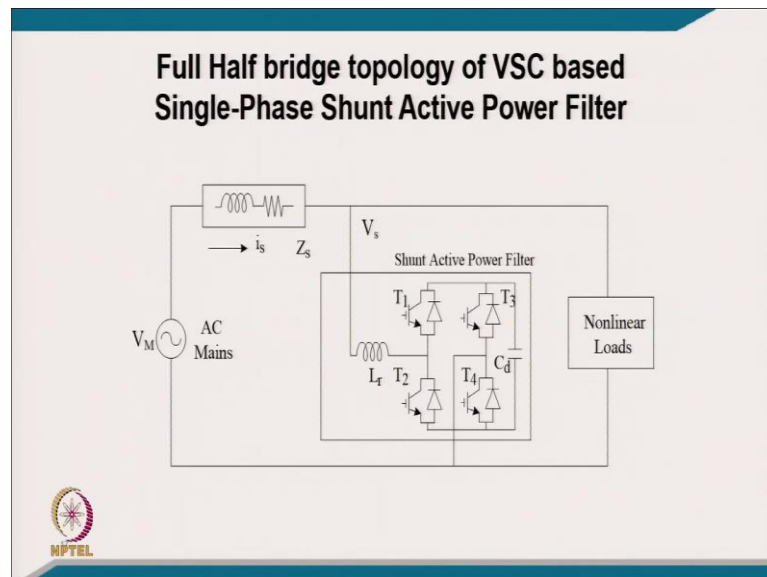


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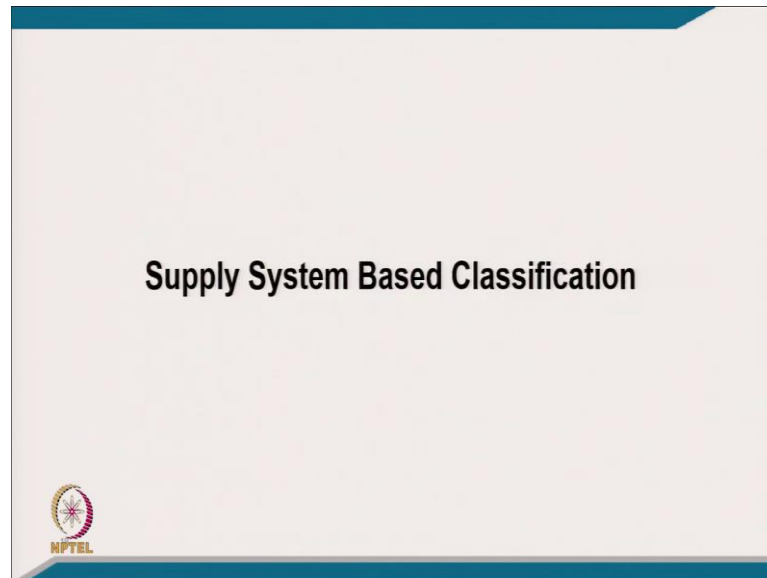
Topology-based classification, we have a half-bridge for shunt active filter using voltage source converter. But the major drawback of this is that the current flow through the capacitor is large. Thus, size of the capacitor or value of capacitor is very high. It cannot be scaled for large rating.

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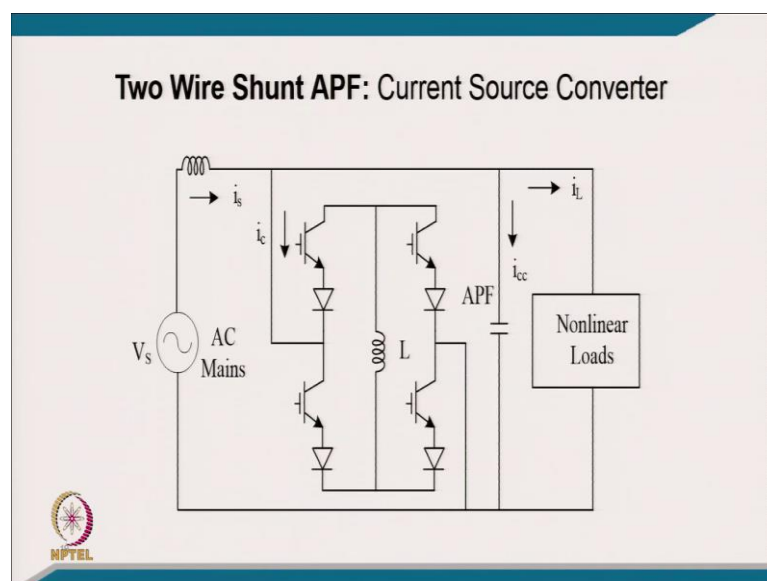


But this is the bridge structure with a capacitor filter. You can use it at higher rating. This bridge structure have a many benefit. You can use the unipolar switching.

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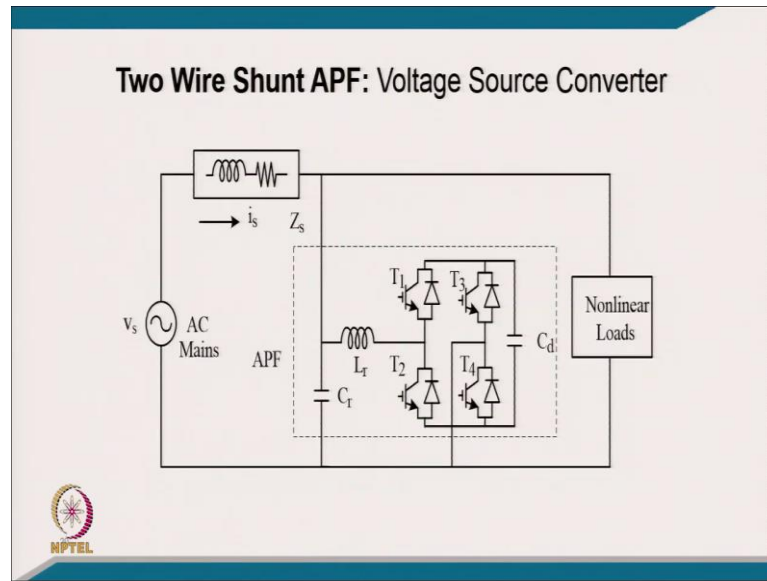


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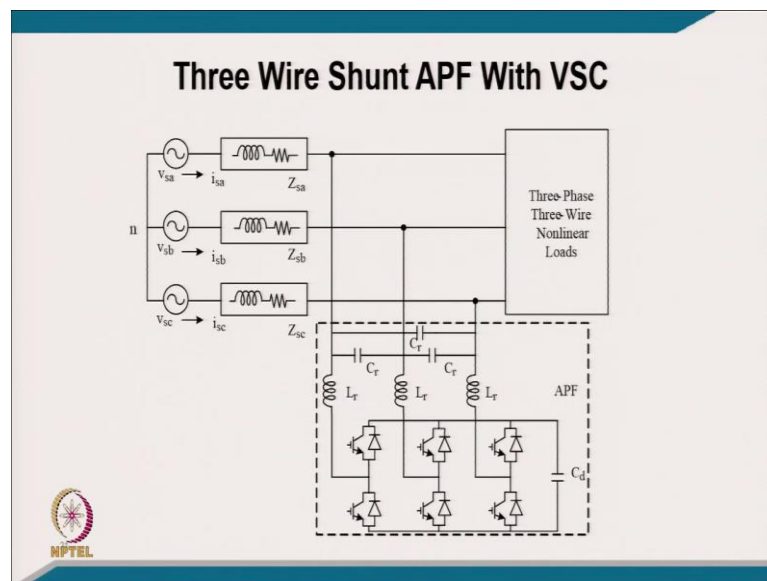


Coming to supply-based classification and supply based classification we have single phase two-wire systems, three-phase three wire systems and three phase four wire systems, and few other configurations which are presented in the screenshots underneath.

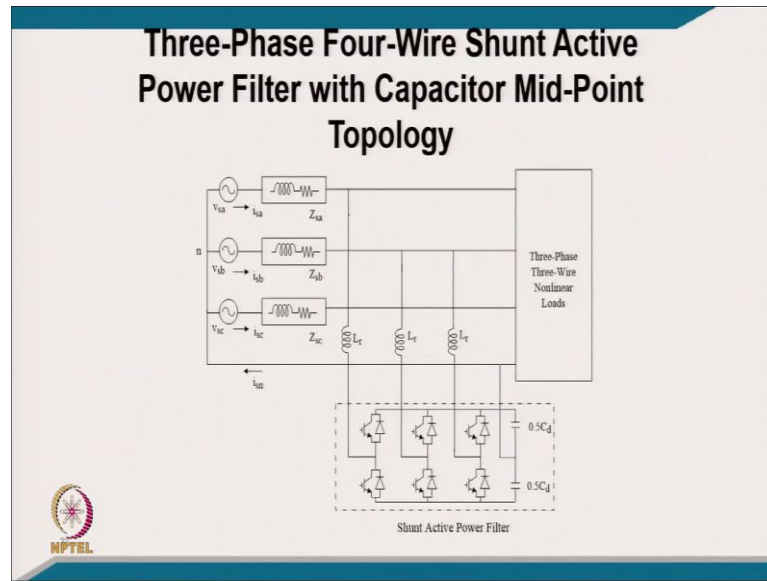
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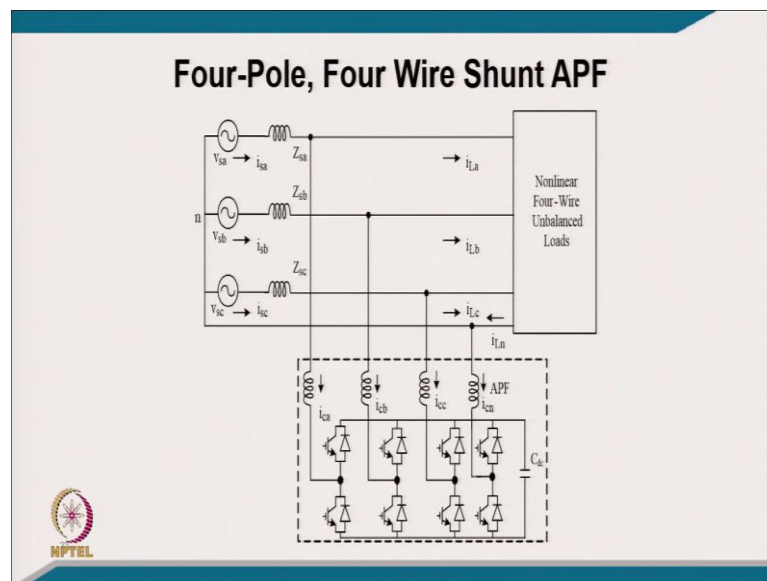
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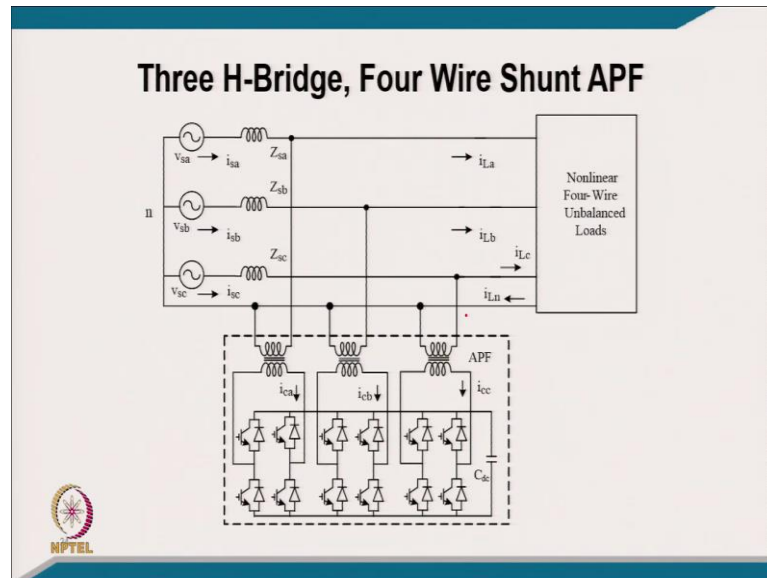
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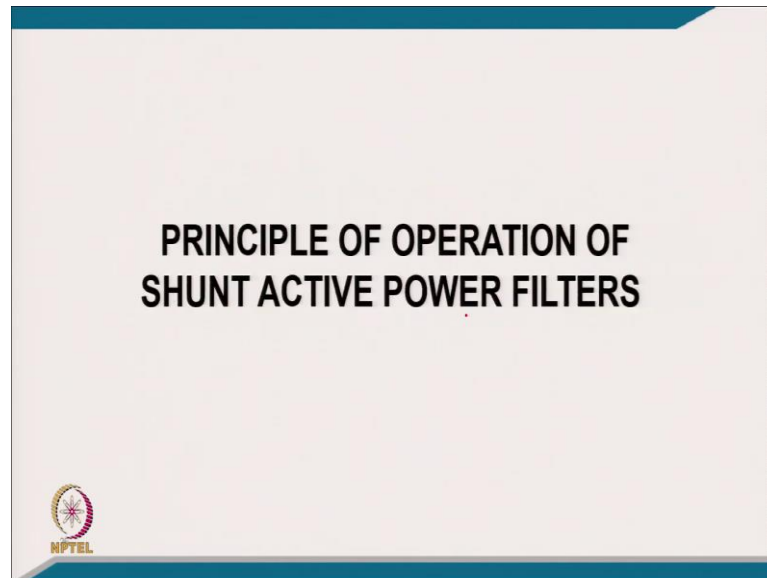


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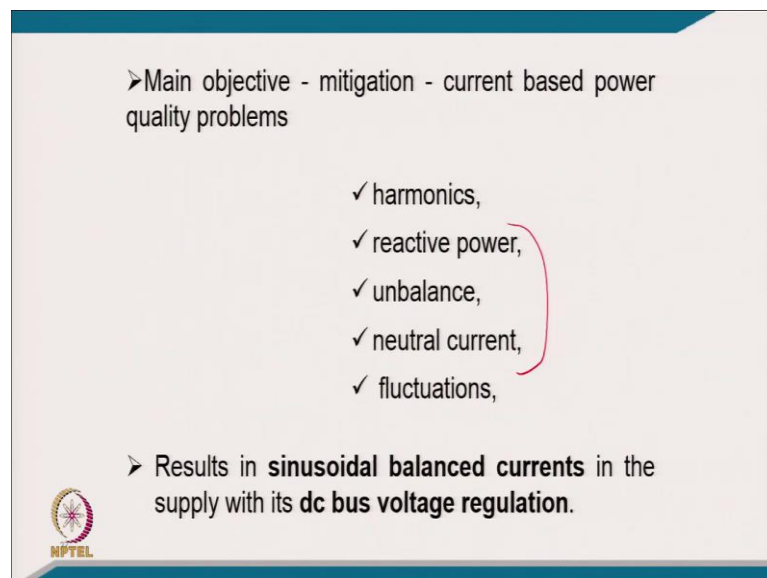
PRINCIPLE OF OPERATION AND CONTROL OF SHUNT ACTIVE POWER FILTERS.

Now, coming to Principle of Operation and Control of the Shunt Active Filter.

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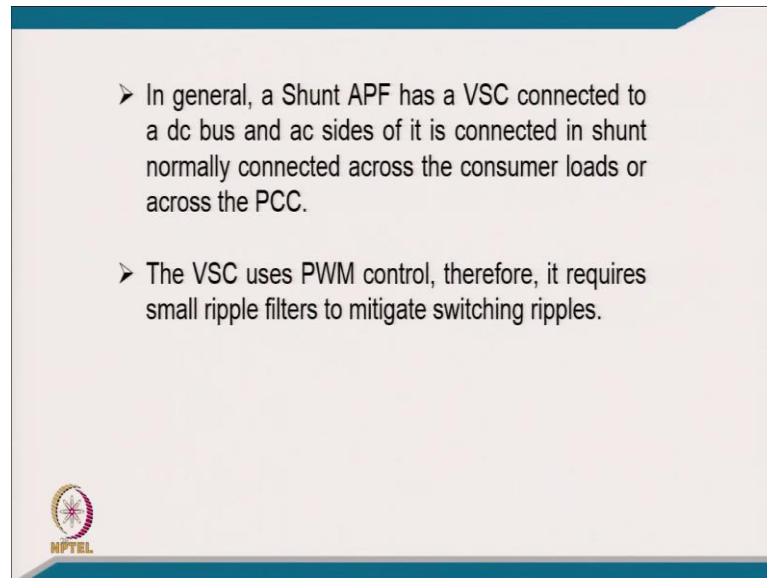
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The main objective is mitigation of current based power quality problems like harmonics, reactive power requirement, unbalance current, and excessive neutral current.


However, KVA rating of the converter is undoubtedly increased to accommodate for all the functionalities.

(Refer Slide Time: 12:11)



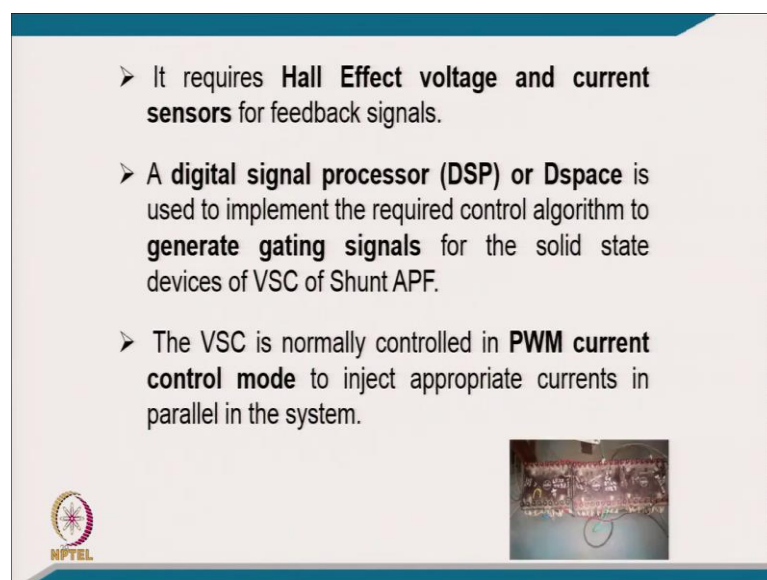
➤ In general, a Shunt APF has a VSC connected to a dc bus and ac sides of it is connected in shunt normally connected across the consumer loads or across the PCC.

➤ The VSC uses PWM control, therefore, it requires small ripple filters to mitigate switching ripples.



In general, a Shunt Active Power Filter has a voltage source converter connected to the dc bus and ac side of it is connected in shunt normally across the consumer load and across the PCC, point of common coupling voltage. The voltage source converter uses pulse width modulation control. Therefore, it requires a small ripple filter to mitigate the switching ripple.



(Refer Slide Time: 12:31)



➤ It requires **Hall Effect voltage and current sensors** for feedback signals.

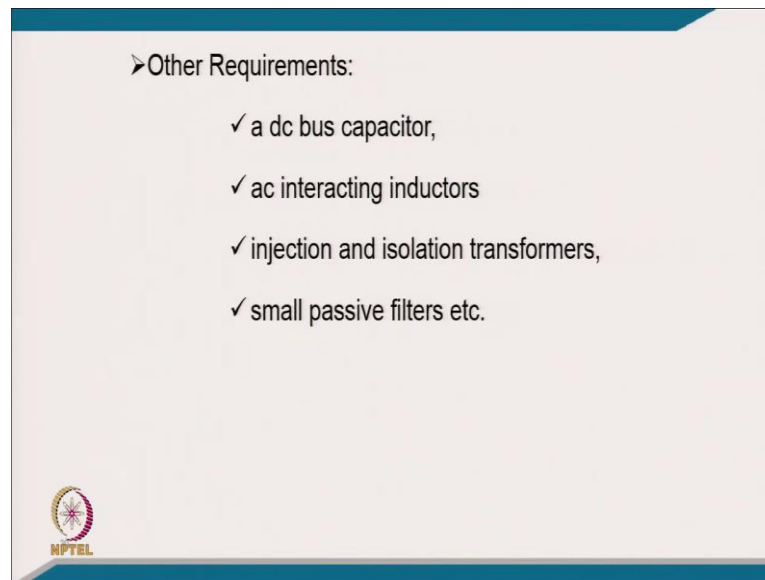
➤ A **digital signal processor (DSP) or Dspace** is used to implement the required control algorithm to **generate gating signals** for the solid state devices of VSC of Shunt APF.

➤ The VSC is normally controlled in **PWM current control mode** to inject appropriate currents in parallel in the system.



It also requires Hall effect voltage sensor and current sensor for the feedback signal for implementing the control algorithm in the DSP.

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Other requirement is like a DC bus capacitor. To sustain the DC bus, you require interfacing inductors in between the supply voltage and the PWM voltage generated by the voltage source converter.

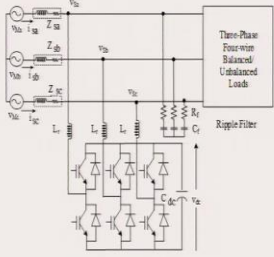
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The below discussion and screenshots detail the design and analysis of the three phase three leg shunt active power filter.


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Design of Three-Phase, Three-Leg VSC Based DSTATCOM



➤ Selection Requirements:

- ✓ a dc bus capacitor and its voltage,
- ✓ ac interacting inductors
- ✓ injection and isolation transformers,
- ✓ small passive filters etc.



(Refer Slide Time: 14:23)

Designed Parameters of DSTATCOM - *APL =*


- **Supply:** A 3-phase, 415V, 50 Hz, with source resistance (R_s)= 0.04 Ω , source inductance (L_s)=1mH is considered here.
- **Load:** A 3-phase, 3-wire rectifier is used as a nonlinear load and with a rectifier output current, $I_d = 224.17$ A.

RMS value of rectifier input current

$$(I_{Lms}) = 0.816 * 224.17 = 182.92 \text{ A.}$$

Fundamental component value of rectifier input current (I_{L1}) = $0.779 * 224.17 = 174.78 \text{ A.}$

Harmonic current (I_h) = $\sqrt{I_{Lms}^2 - I_{L1}^2} = 55.86 \text{ A.}$



(Refer Slide Time: 15:14)

Designed Parameters of DSTATCOM

Rating of shunt APF, $S = 3 \cdot V_f \cdot I_f = 3 \cdot 239.6 \cdot 55.86 = 40.21 \cdot 1.25$ (25% Extra for dynamics) = 50.19 kVA

(Considering 50 kVA).

Shunt Active Filter (SAF) Rating $S_f = 50.19$ kVA


SAF Voltage Rating $V_f = 415$ V

SAF Current Rating $I_f = 69.825$ A

Allowable Voltage Ripple at DC link $\Delta V_{dc} = 5\%$ of V_{dc}

Allowable Ripple in SAF Current $I_{cr(p-p)}$

$I_{cr(p-p)} = 10\%$ of $I_f = 6.983$ A




(Refer Slide Time: 15:52)

➤ Selection of DC Bus Voltage

$$V_{dc} = 2\sqrt{2}V_{LL} / (\sqrt{3}m)$$
$$V_{dc} = 2\sqrt{2} \times 415 / (\sqrt{3} \times 1) = 677.692 \text{ V}$$

- Here, m is the modulation index and is considered as 1.
- Thus, V_{dc} is obtained as 677.69 V for a V_{LL} of 415 V AC distribution network.
- Here, it is selected as 700 V.




(Refer Slide Time: 16:18)

➤ **Selection of DC Bus Capacitor**

$$0.5 \times C_{dc} \{ (V_{dc}^2) - (V_{dc1}^2) \} = k_1 3V_f (aI_f) t$$
$$V_{dc1} = (1 - \Delta V_{dc}) \times V_{dc} = (1 - 0.05) \times 700 = 665 \text{ V}$$
$$0.5 \times C_{dc} (700^2 - 665^2) = 0.1 \times 3 \times 239.6 \times 1.2 \times 69.825 \times 0.03$$
$$(k_1 = 0.1, a = 1.2, t = 30 \text{ ms})$$
$$C_{dc} = 7564 \mu\text{F}$$

➤ Here, V_{dc} is the nominal DC voltage, V_{dc1} is the minimum voltage level of the DC bus, a is the overloading factor, and t is the time by which the DC bus voltage is to be recovered.

➤ The calculated value of C_{dc} is 7564 μF and it is selected as 7600 μF .




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➤ **Selection of DC Bus Capacitor**

$$C_{dc} = (I_0) / (2 \times w \times \Delta V_{dc})$$
$$I_0 = (S_f / V_{dc}) = 50.19 \times 10^3 / 700 = 71.7 \text{ A}$$
$$\Delta V_{dc} = 0.05 \times V_{dc} = 35 \text{ V}$$
$$C_{dc} = 71.7 / (2 \times 2\pi \times 50 \times 35) = 3260.421 \mu\text{F}$$

➤ Here, I_0 is the capacitor current, w is the angular frequency, and $v_{dc(pp)}$ is the ripple in capacitor voltage.

➤ C_{dc} is obtained as 3572.847 μF . Thus, the highest capacitance value (in both method) is chosen to be 7600 μF .



(Refer Slide Time: 17:29)

➤ **Selection of AC Inductor**


$$L_r = (\sqrt{3}mV_{dc}) / (12af_s I_{cr(p-p)})$$
$$L_r = (\sqrt{3} \times 1 \times 700) / (12 \times 1.2 \times 10000 \times 6.983)$$

($a = 1.2$, $f_s = 10$ kHz, $I_{cr(p-p)} = 0.1 \times I_f = 6.983$)

$$L_r = 1.206 \text{ mH}$$

➤ Here, m is the modulation index and a is the overloading factor.

➤ Considering $I_{cr(p-p)} = 10\%$, $f_s = 10$ kHz, $m = 1$, $V_{dc} = 700$ V (for $V_{LL} = 415$ V), and $a = 1.2$, the value of L_r is calculated to be 1.206 mH. Thus, the inductor of 1.5 mH is selected.



(Refer Slide Time: 18:07)

➤ **Selection of a Ripple Filter**

To filter out the noise from the voltage at PCC


The time constant $R_f C_f \ll T_s$, considering $R_f C_f = T_s / 10$

R_f is ripple filter resistance ,
 C_f is ripple filter capacitance,
 T_s is switching time

Ripple Filter Impedance

$$Z_f = \sqrt{(R_f)^2 + \{1/(w.C_f)\}^2}$$

Here, w is the frequency in rad/sec



(Refer Slide Time: 18:39)

➤ **Selection of a Ripple Filter**


For fundamental frequency ($f = 50$ Hz),

$$Z_f = \sqrt{(10)^2 + \left\{ \frac{1}{2\pi \times 50 \times 5.5 \times 10^{-6}} \right\}^2} = 578.832 \Omega$$

For switching frequency ($f_s = 1.8$ kHz),

$$Z_f = \sqrt{(10)^2 + \left\{ \frac{1}{2\pi \times 10000 \times 5.5 \times 10^{-6}} \right\}^2} = 10.410 \Omega$$

➤ Considering switching frequency (f_s) equal to 10 kHz, the ripple filter parameters are selected as $R_f = 10 \Omega$ and $C_f = 5.5 \mu\text{F}$.



(Refer Slide Time: 19:20)

➤ **Selection of a Ripple Filter**


➤ The impedance offered for switching frequency is 10.410Ω and impedance offered to fundamental frequency is 578.83Ω , which is sufficiently large and hence the ripple filter draws negligible fundamental frequency current.

➤ **Losses in Ripple Filter**

Total Losses in Ripple Filter $P_{L_f} = 3 \times I^2 \times R_f$ W

$$I = V_{sp} / Z_f$$

Losses at (50 Hz) ($Z_f = 578.832 \Omega$)

$$I = 239.6 / 578.832 = 0.414 \text{ A}$$
$$P_{L_f} = 3 \times 0.414^2 \times 10 = 5.14 \text{ W}$$


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➤ **Selection of Voltage Rating of the Solid State Switches**


$$V_{sw} = V_{dc} + V_d$$

Here, V_d is the 10% overshoot in the DC link voltage under dynamic condition.

$$V_{sw} = V_{dc} + V_d = V_{dc} + 0.1\% \text{ of } V_{dc}$$
$$V_{sw} = 700 + 70 = 770 \text{ V}$$

➤ The voltage rating of the switch is calculated as 770 V.

➤ With an appropriate safety factor, 1200 V, IGBTs are selected for the VSC used in the DSTATCOM.




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➤ **Selection of Current Rating of the Solid State Switches**

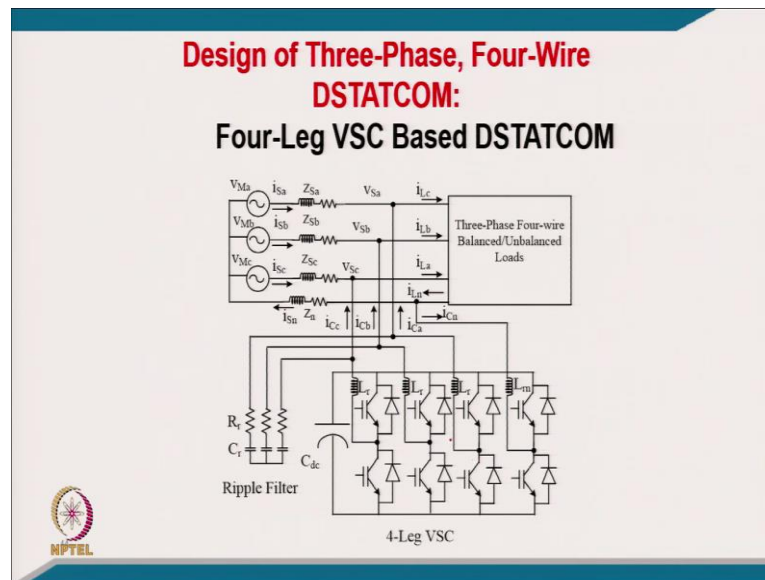
$$I_{sw} = 1.25(I_{cr(p-p)} + I_{f(p-p)})$$
$$I_{cr(p-p)} = 0.1 \times I_f = 0.1 \times 69.83 = 6.983 \text{ A}$$
$$I_{f(p-p)} = \sqrt{2} \times I_f = \sqrt{2} \times 69.83 = 98.755$$
$$I_{sw} = 1.25(6.983 + 98.755) = 132.172 \text{ A}$$

➤ The current rating of the switch is calculated as 132.172 A.

➤ Thus, a solid-state switch (IGBT) for the VSC is selected with the next available higher rating of 1200 V and 300 A.



(Refer Slide Time: 21:03)



The below discussion and screenshots detail the design and analysis of the three phase four leg shunt active power filter.

(Refer Slide Time: 21:12)

Designed Parameters of DSTATCOM

- **Supply:** A 3-phase, 415V, 50 Hz, with source resistance (R_s)= 0.04 Ω , source inductance (L_s)=1mH is considered here.
- **Load:** A set of three single-phase rectifiers with $R=2.5 \Omega$ and $L=25\text{mH}$ is considered as a nonlinear load and its rectifier output current is as, $I_d = 86.28 \text{ A}$.
The RMS value of rectifier input current is as,
 $(I_{L_{rms}}) = I_d = 86.28 \text{ A}$.
The RMS value of rectifier input fundamental current is as, $(I_{L1}) = 0.9 I_d = 77.65 \text{ A}$.

(Refer Slide Time: 21:57)


Designed Parameters of DSTATCOM

The RMS value of harmonics current is as,
 $(I_h) = \sqrt{(I_{Lrms}^2 - I_{L1}^2)} = 37.61 \text{ A.}$

The APF neutral current $I_{fn} = -I_{Ln} = 37.61 \text{ A}$
(since it has to cancel total load neutral current).

The VA rating of the APF, $S = 3V_{pf}I_f + V_{pf}I_{fn} = 36.096 \text{ kVA}$
(since $V_f = V_s = 239.6 \text{ V}$).

The rating of shunt APF = $36.096 * 1.25$
(25% Extra for dynamics) = 45.12 kVA
(Consider 45 kVA).




(Refer Slide Time: 22:28)

➤ Selection of DC Bus Voltage

$$V_{dc} = 2\sqrt{2}V_{LL} / (\sqrt{3}m)$$
$$V_{dc} = 2\sqrt{2} \times 415 / (\sqrt{3} \times 1) = 677.692 \text{ V}$$

- Here, m is the modulation index and is considered as 1.
- Thus, V_{dc} is obtained as 677.69 V for a V_{LL} of 415 V AC distribution network.
- Here, it is selected as 700 V .



(Refer Slide Time: 22:42)


➤ **Selection of DC Bus Capacitor**

$$0.5 \times C_{dc} \{ (V_{dc}^2) - (V_{dc1}^2) \} = k_1 3V_f (aI) t$$
$$V_{dc1} = (1 - \Delta V_{dc}) \times V_{dc} = (1 - 0.05) \times 700 = 665 \text{ V}$$
$$I = 1.25 \times I_f = 1.25 \times 37.61 = 47.013 \text{ A}$$

(25% more than phase current of the VSC),

$$0.5 \times C_{dc} (700^2 - 665^2) = 0.1 \times 3 \times 239.6 \times 1.2 \times 47.013 \times 0.03$$
$$(k_1 = 0.1, a = 1.2, t = 30 \text{ ms})$$
$$C_{dc} = \underline{5092.76 \mu\text{F}}$$

➤ The calculated value of C_{dc} is ~~5092.76~~ μF and it is selected as 5500 μF .




(Refer Slide Time: 22:58)

➤ **Selection of DC Bus Capacitor**

$$C_{dc} = (I_0) / (2 \times w \times \Delta V_{dc})$$
$$I_0 = (S_f / V_{dc}) = 45 \times 10^3 / 700 = 64.286 \text{ A}$$
$$\Delta V_{dc} = 0.05 \times V_{dc} = 35 \text{ V}$$
$$C_{dc} = 71.7 / (2 \times 2\pi \times 50 \times 35) = \underline{2923.254 \mu\text{F}}$$

➤ Here, I_0 is the capacitor current, w is the angular frequency, and $v_{dc(pp)}$ is the ripple in capacitor voltage.

➤ C_{dc} is obtained as 2923.254 μF . Thus, the highest capacitance value (in both method) is chosen to be 5500 μF .




(Refer Slide Time: 23:15)

➤ **Selection of AC Inductor (for Phase Leg)**

$$L_r = (\sqrt{3}mV_{dc}) / (12af_s I_{cr(p-p)})$$
$$L_r = (\sqrt{3} \times 1 \times 700) / (12 \times 1.2 \times 10000 \times 3.761)$$
$$(a = 1.2, f_s = 10 \text{ kHz},$$
$$I_{cr(p-p)} = 0.1 \times I_f = 0.1 \times 37.61 = 3.761)$$
$$L_r = \underline{2.239 \text{ mH}}$$

➤ The value of L_r is calculated to be 2.239 mH. Thus, the inductor of 2.5 mH is selected.




(Refer Slide Time: 23:25)

➤ **Selection of AC Inductor (for Neutral Leg)**

$$L_m = (mV_{dc}) / (3\sqrt{3}.af_s I_{cm(p-p)})$$
$$L_r = (1 \times 700) / (3\sqrt{3} \times 1.2 \times 10000 \times 3.761)$$
$$(a = 1.2, f_s = 10 \text{ kHz},$$
$$I_{cm(p-p)} = 0.1 \times I_{fn} = 0.1 \times 37.61 = 3.761)$$
$$L_r = \underline{2.985 \text{ mH}}$$

➤ $I_{cm(p-p)}$ is the allowable percentage ripple in filter neutral current (I_{fn}).

➤ The value of L_r is calculated to be 2.985 mH. Thus, the inductor of 3 mH is selected.



(Refer Slide Time: 23:42)

➤ Selection of a Ripple Filter

To filter out the noise from the voltage at PCC


The time constant $R_f C_f \ll T_s$, considering $R_f C_f = T_s / 10$

R_f is ripple filter resistance ,
 C_f is ripple filter capacitance,
 T_s is switching time

Ripple Filter Impedance

$$Z_f = \sqrt{(R_f)^2 + \{1/(w.C_f)\}^2}$$

Here, w is the frequency in rad/sec



(Refer Slide Time: 24:03)

➤ Selection of a Ripple Filter


For fundamental frequency ($f = 50$ Hz),

$$Z_f = \sqrt{(10)^2 + \{1/(2\pi \times 50 \times 5.5 \times 10^{-6})\}^2} = 578.832 \Omega$$

For switching frequency ($f_s = 10$ kHz),

$$Z_f = \sqrt{(10)^2 + \{1/(2\pi \times 10000 \times 5.5 \times 10^{-6})\}^2} = 10.410 \Omega$$

➤ Considering switching frequency (f_s) equal to 10 kHz, the ripple filter parameters are selected as $R_f = 10 \Omega$ and $C_f = 5.5 \mu\text{F}$.



(Refer Slide Time: 24:23)

➤ **Selection of a Ripple Filter**

➤ The impedance offered for switching frequency is 10.410Ω and impedance offered to fundamental frequency is 578.83Ω , which is sufficiently large and hence the ripple filter draws negligible fundamental frequency current.

➤ **Losses in Ripple Filter**


Total Losses in Ripple Filter $P_{Lf} = 3 \times I^2 \times R_f$ W

$I = V_{sp} / Z_f$

Losses at (50 Hz) ($Z_f = 578.832 \Omega$)

$I = 239.6 / 578.832 = 0.414$ A

$P_{Lf} = 3 \times 0.414^2 \times 10 = 5.14$ W



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➤ **Selection of Voltage Rating of the Solid State Switches**

$V_{sw} = V_{dc} + V_d$


Here, V_d is the 10% overshoot in the DC link voltage under dynamic condition.

$V_{sw} = V_{dc} + V_d = V_{dc} + 0.1\% \text{ of } V_{dc}$

$V_{sw} = 700 + 70 = 770$ V

➤ The voltage rating of the switch is calculated as 770 V.

➤ With an appropriate safety factor, 1200 V IGBTs are selected for the VSC used in the DSTATCOM.



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➤ **Selection of Current Rating of the Solid State Switches**

$$I_{sw} = 1.25(I_{cr(p-p)} + I_{f(p-p)})$$

$$I_{cr(p-p)} = 0.1 \times I_f = 0.1 \times 37.61 = 3.761 \text{ A}$$

$$I_{f(p-p)} = \sqrt{2} \times I_f = \sqrt{2} \times 37.61 = 53.189$$

$$I_{sw} = 1.25(3.761 + 53.189) = 71.188 \text{ A}$$

➤ The current rating of the switch is calculated as 71.188 A.

➤ Thus, a solid-state switch (IGBT) for the VSC is selected with the next available higher rating of 1200 V and 200 A.

