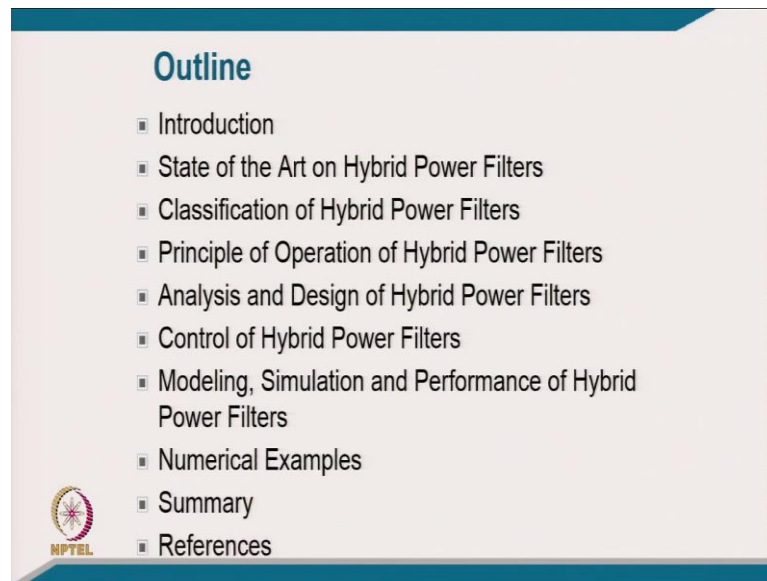


**Power Quality**  
**Prof. Bhim Singh**  
**Department of Electrical Engineering**  
**Indian Institute of Technology, Delhi**

**Lecture - 26**  
**Hybrid Power Filters**

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Welcome to the course on Power Quality. Today we will start the Hybrid Power Filters. We will start from introduction. We will talk about the state of art on hybrid power filter. We classify the hybrid power filter, then we will discuss principle of operation of hybrid power filter.

And we will go to analysis and design of hybrid power filter, and we will talk about the control of hybrid power filter then modelling, simulation and performance of hybrid power filter with some case studies. Then, we will discuss numerical examples we will summarize and then the references will be provided.


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**INTRODUCTION**

- ▣ Power quality problems in distribution systems
  - ✓ Increased rms supply current
  - ✓ Increased losses (low system efficiency ).
  - ✓ Poor power factor.
  - ✓ Poor utilization of distribution system.
  - ✓ Heating of components of distribution system.
  - ✓ Derating of the distribution system.

**Voltage quality problems especially Harmonics**


**Current quality problems especially Harmonics**



Power quality problem in distribution system, we have both voltage quality problems and the current power quality problems. We have a harmonics in the voltage and in the current and that is the reason we have to use the hybrid filter filters.

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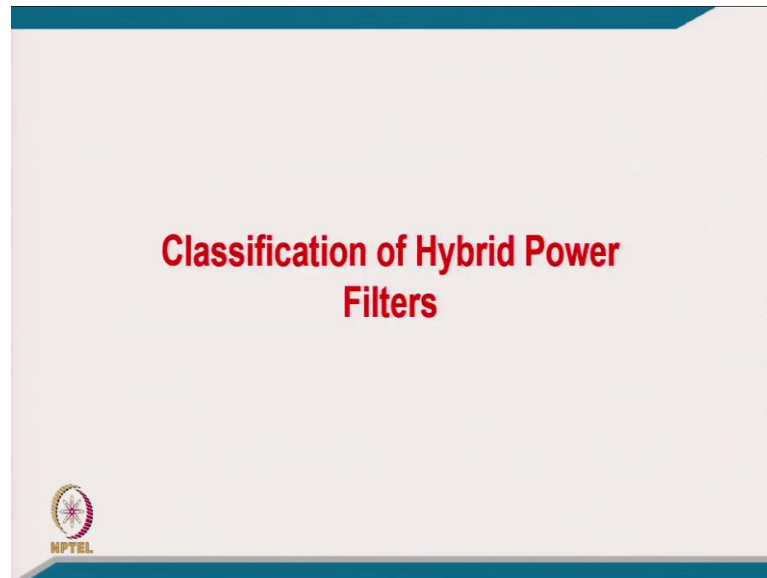
- ▣ Power quality problems in distribution systems
  - ✓ Distortion in voltage waveform at PCC
  - ✓ Interference to communication system.
  - ✓ Disturbance to the nearby consumers etc.
- **Single Solution is the Hybrid Power Filters or universal active power filters (UAPF)**
- Combination
  1. Active shunt power filter and active series power filter
  2. Passive power filter and active series power filter



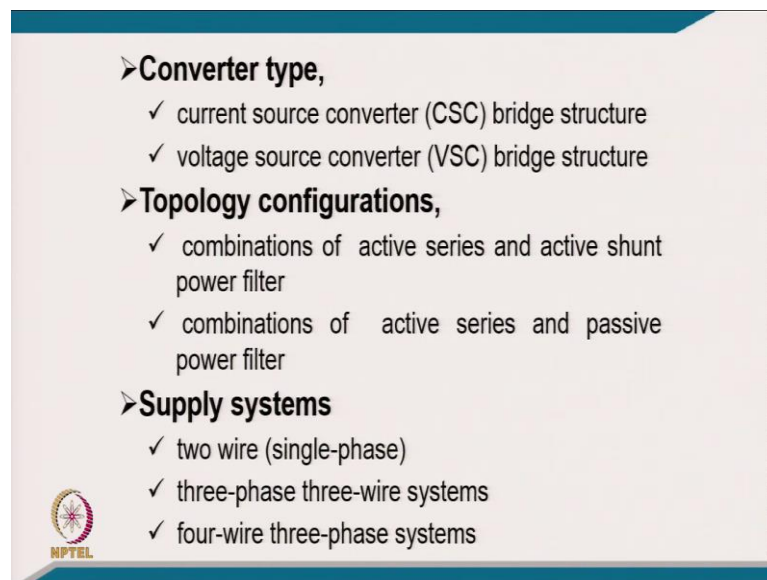
Coming to power quality problem in the distribution system. The distortion in voltage waveform, the interference to communication system, disturbance to nearby consumers. And, the single solution to these problem is the hybrid power filter of or we also call it universal active power filter. It is a combination of active shunt power filter and active

series power filter. Sometimes we also use the passive power filter along with a small rating active series filter.

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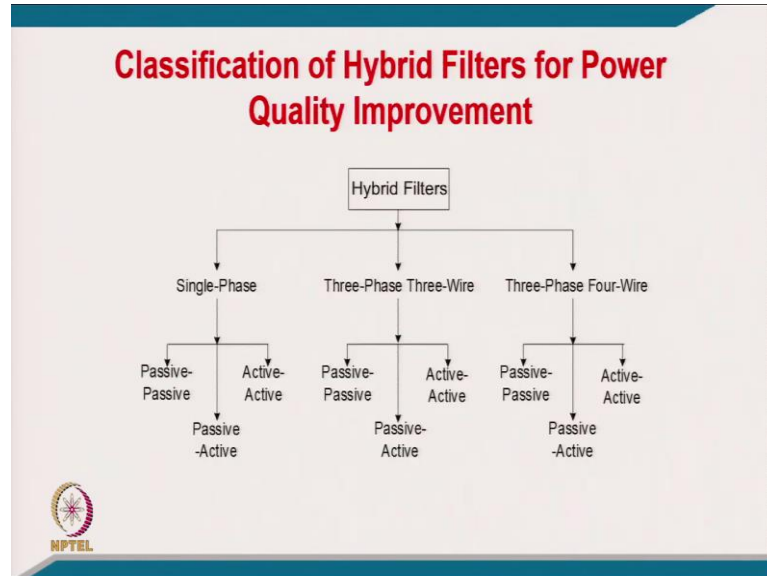


Coming to the classification of hybrid power filter. It can be classified in many categories. First category is the converter type. Whether we are using current source converter bridge structure or we are using voltage source converter bridge structure.

Second is the topology configuration; the combination of active series and active shunt power filter or combination of active series and passive filter.

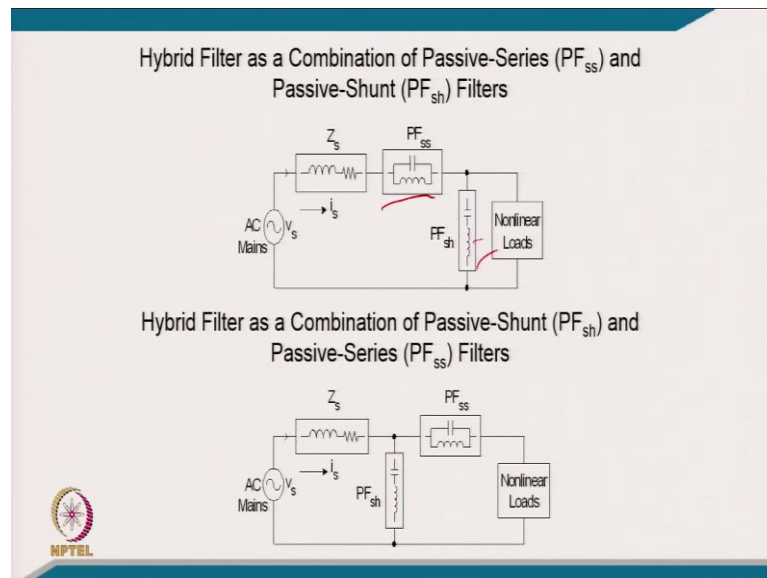
Another classification is supply based. You might be using this in a two wire system or three-phase three-wire system or four-wire three-phase system.

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The broad classification is also shown in the screenshot.

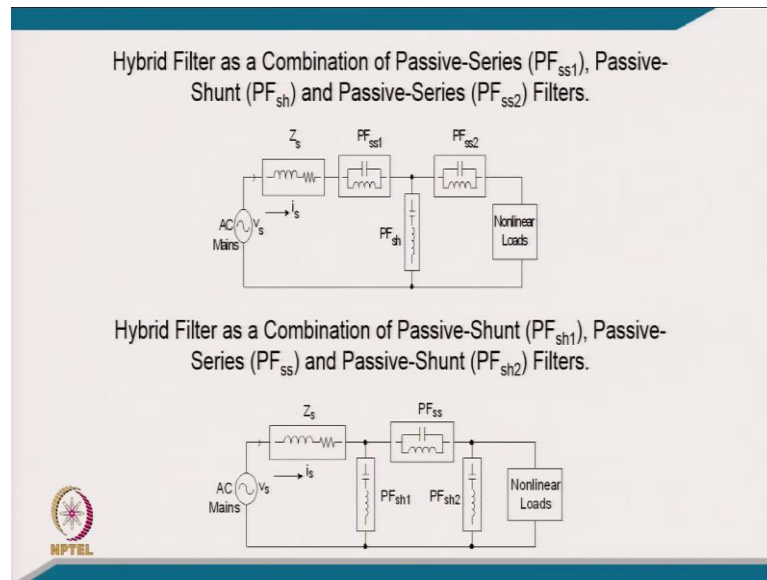
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And now, coming to the hybrid filter as a circuit configuration.

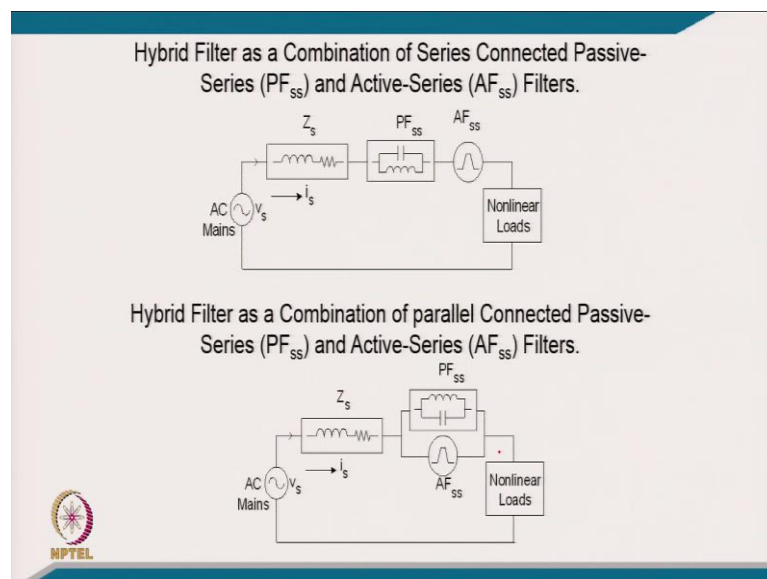
Here is a combination of passive series and passive shunt filter.

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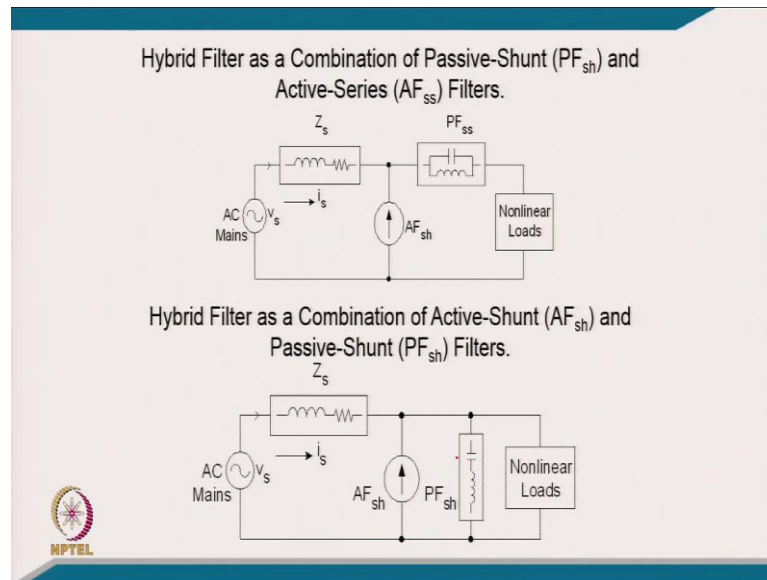
This hybrid filter has two passive series filter one on the load side another on the grid side and then passive shunt in between, like a T network. It can also be present in the form of a pi network.

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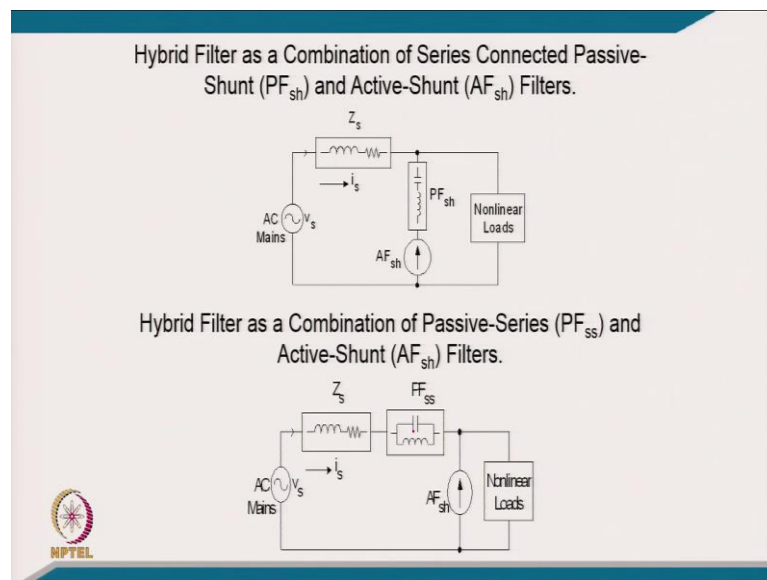
Passive series filter can be used along with the active series filter as shown here.

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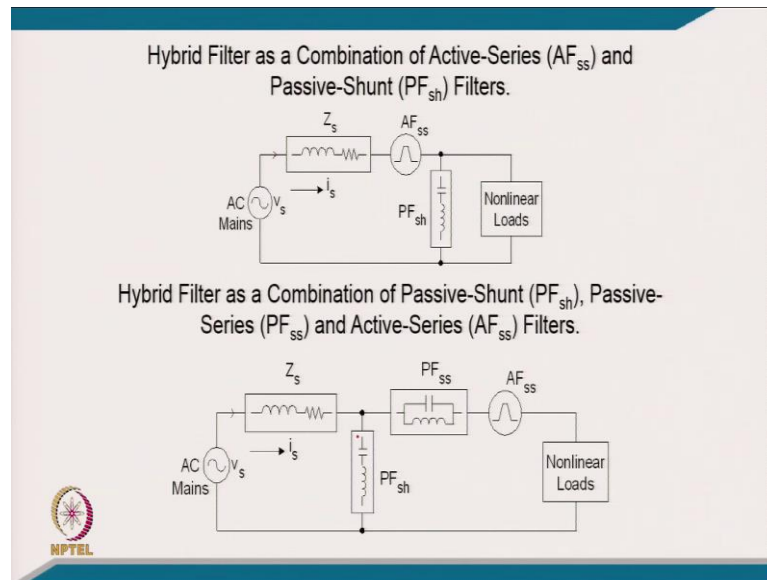
And, there is another hybrid filter with a passive filter in series and then active filter in shunt. Or you can have both passive shunt and active shunt connected in parallel.

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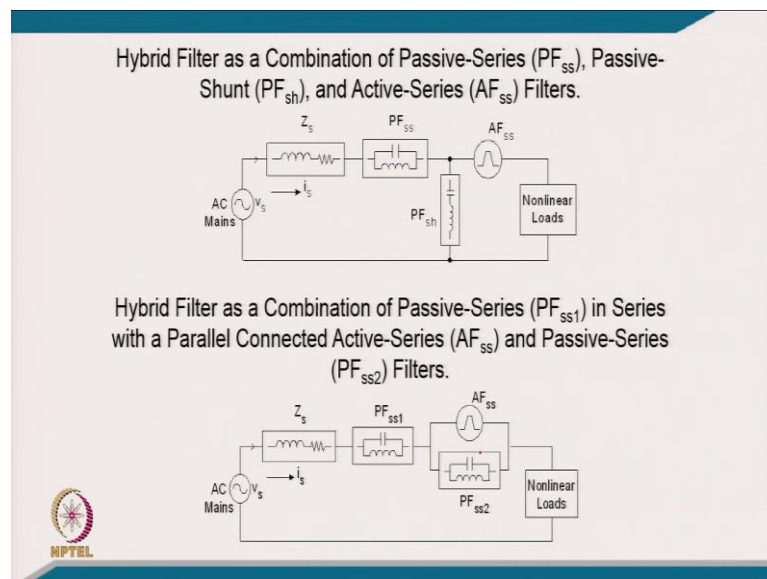
This is another very popular configuration, where a passive filter to make with a small series active filter is present.

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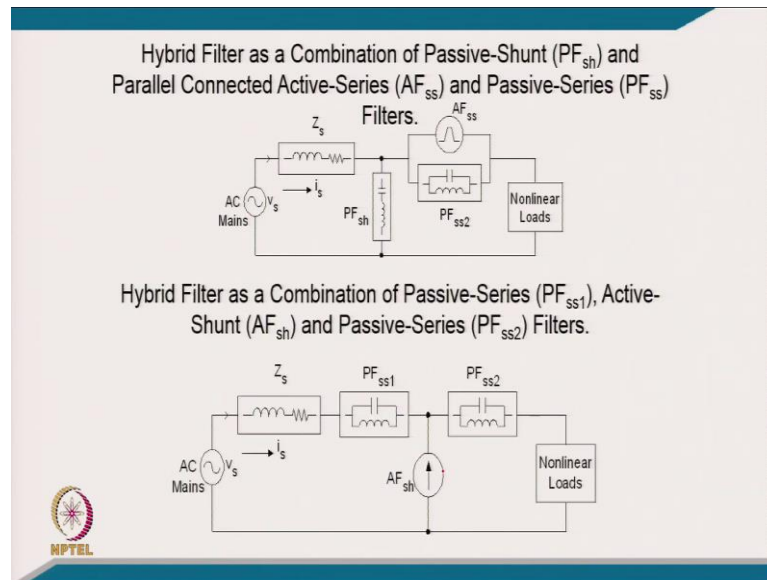


Few more configurations of the hybrid filter are provided in the screenshots herein.

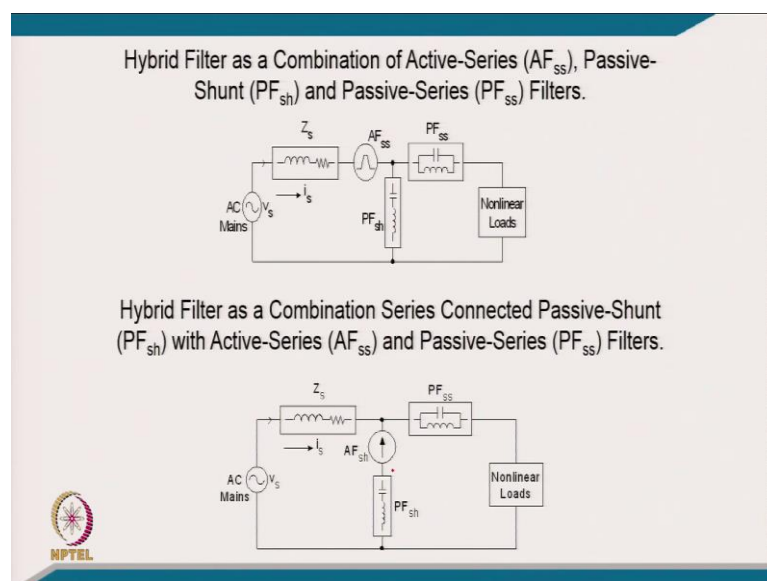
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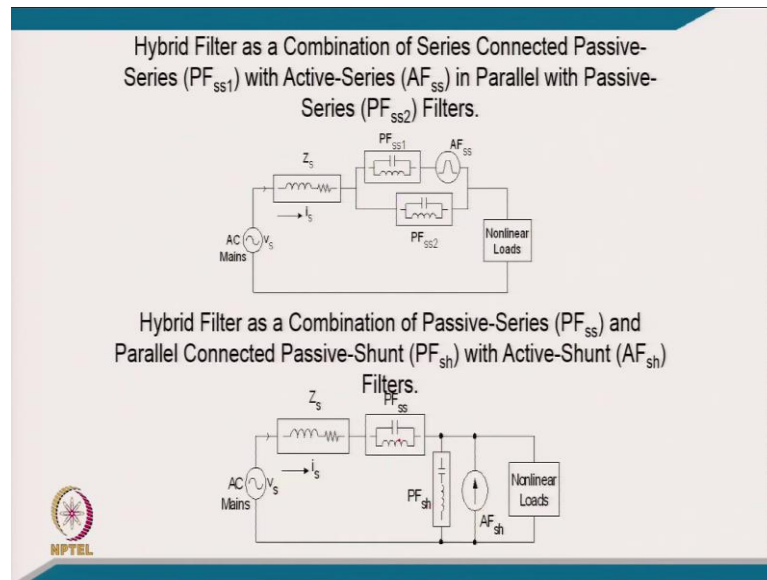


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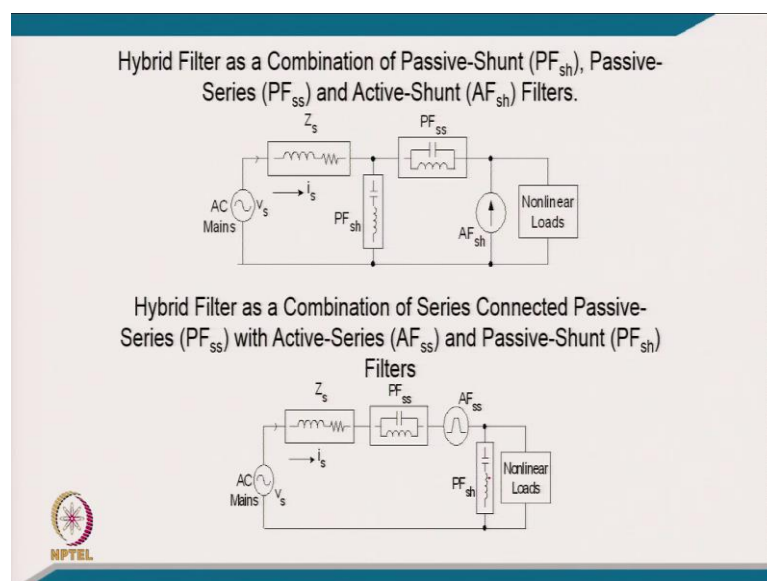




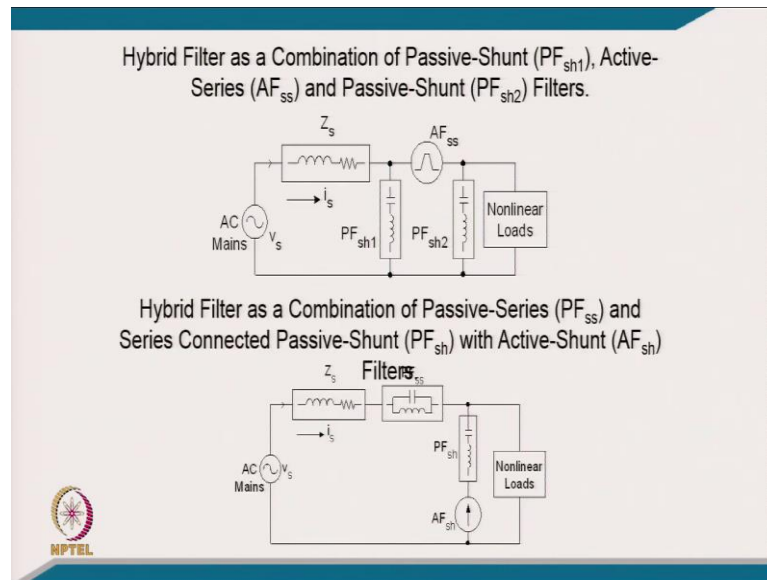
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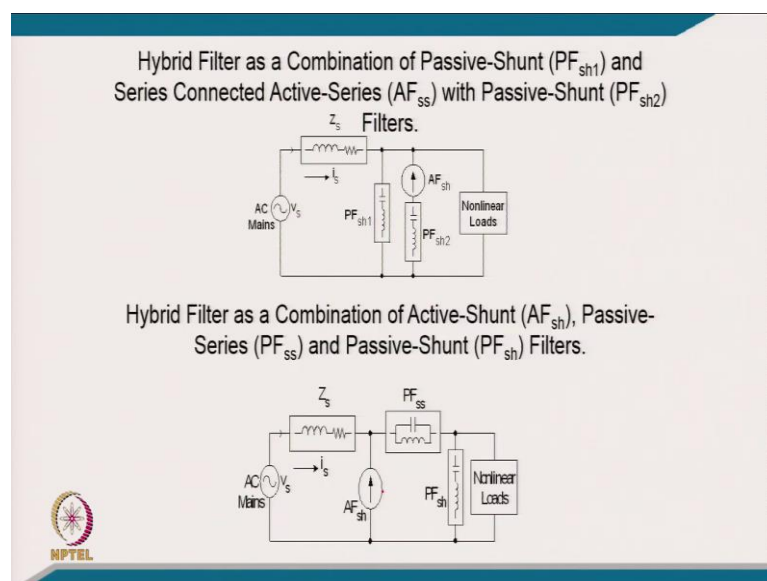
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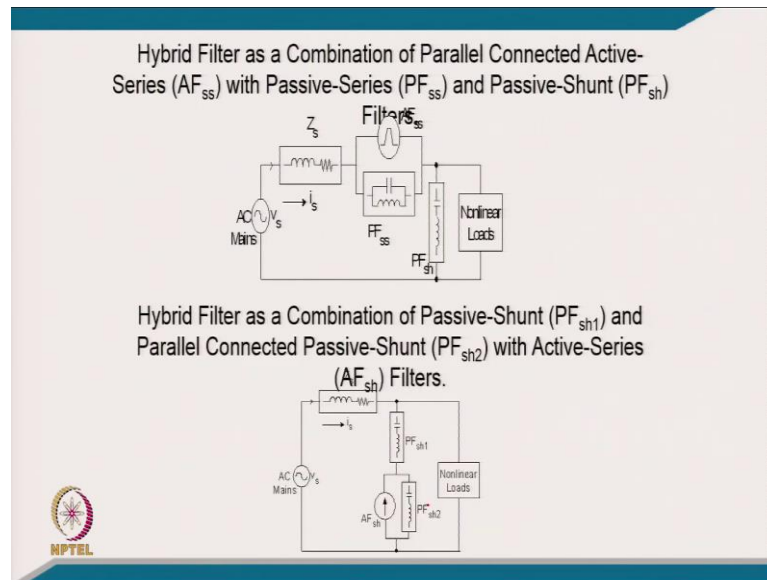
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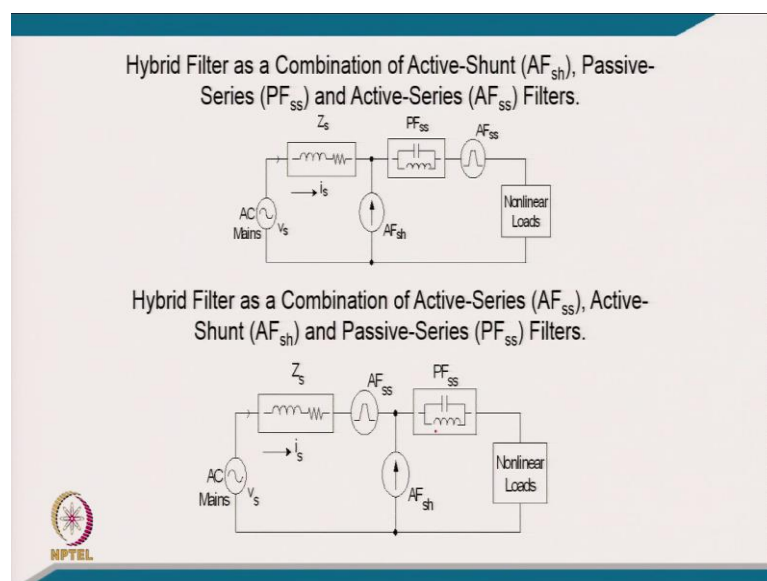
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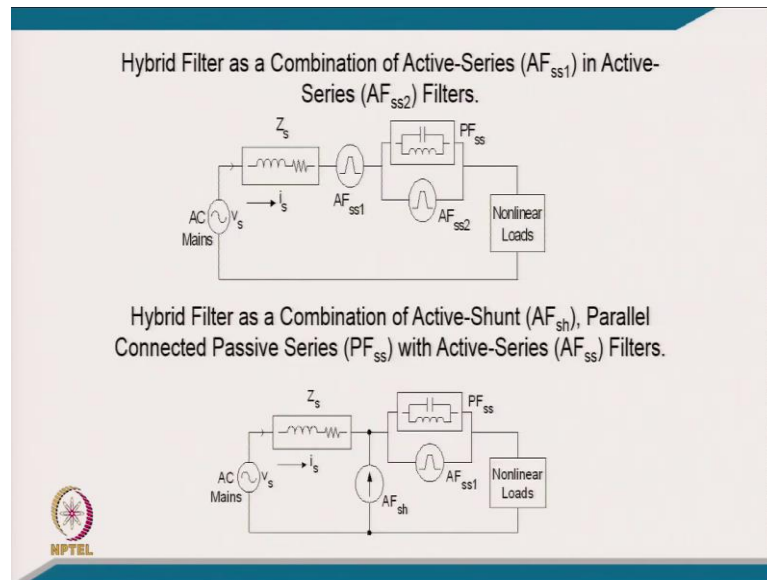
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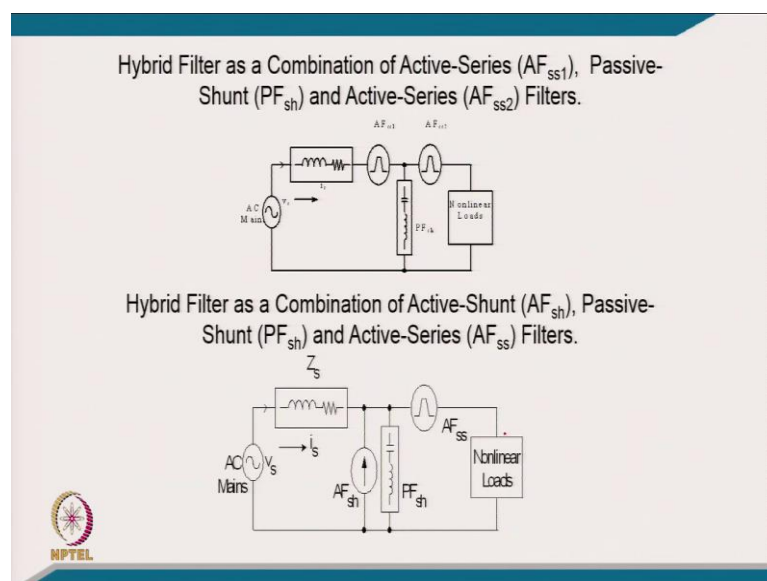
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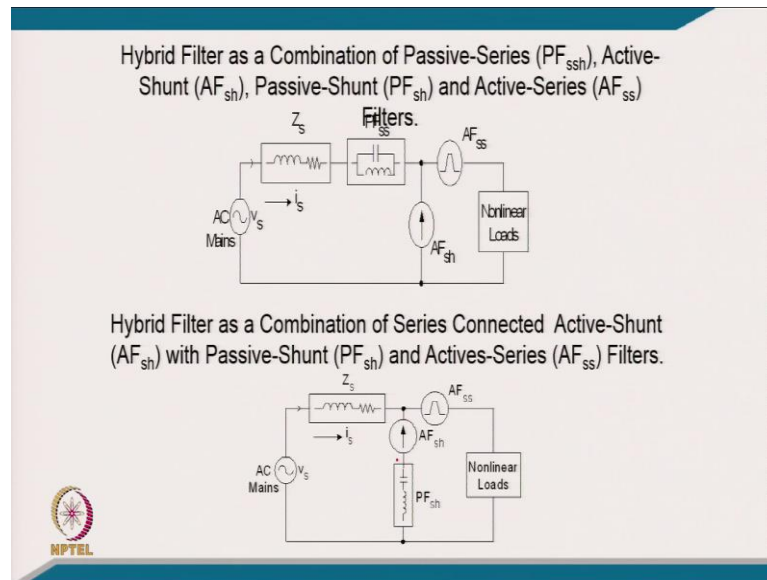
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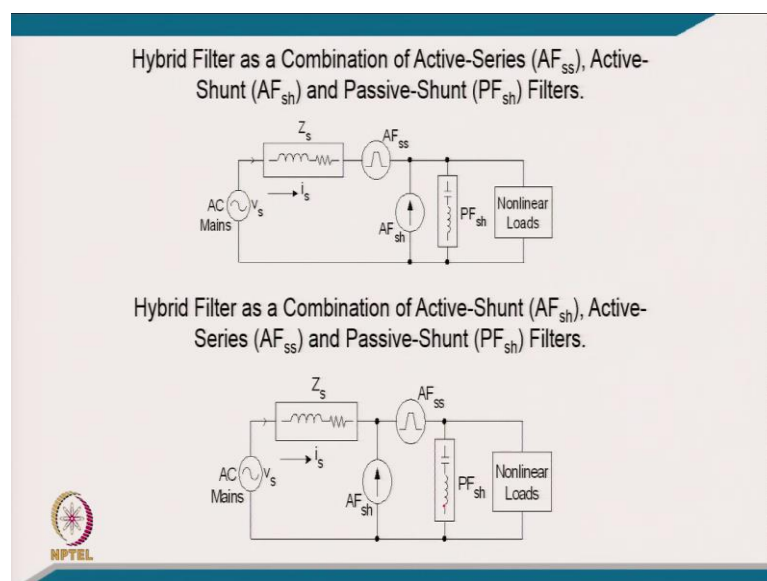
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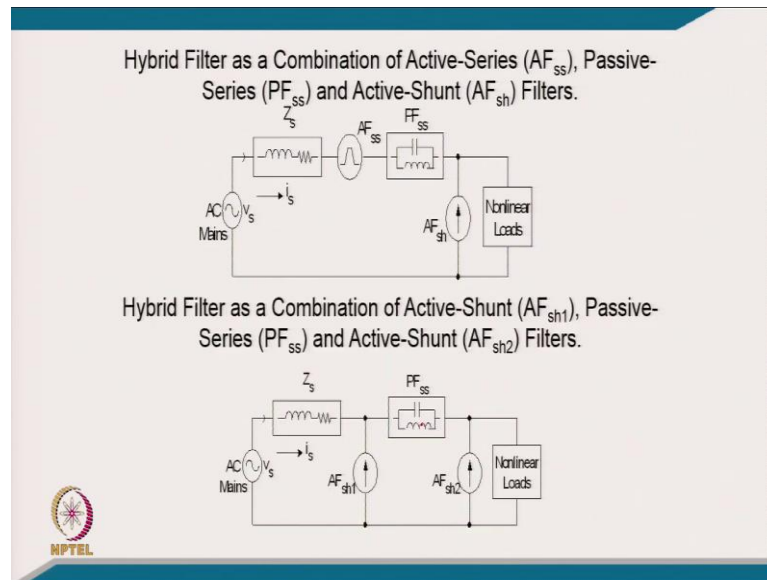
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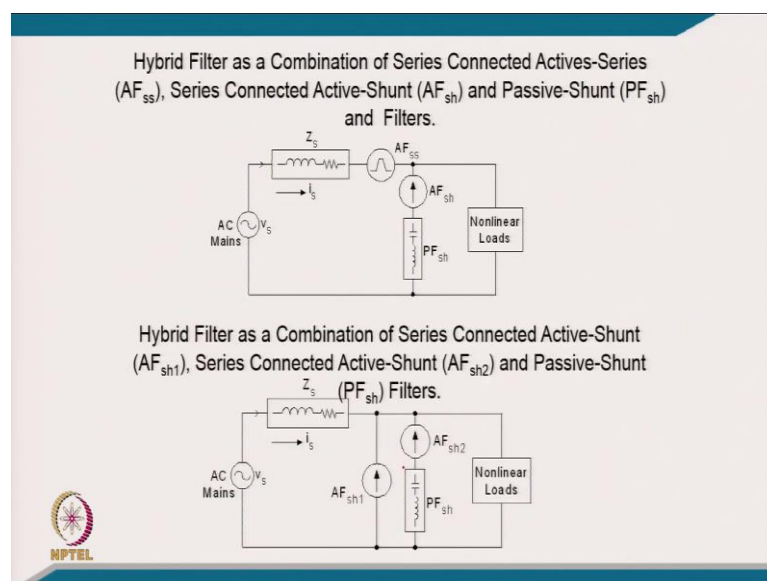
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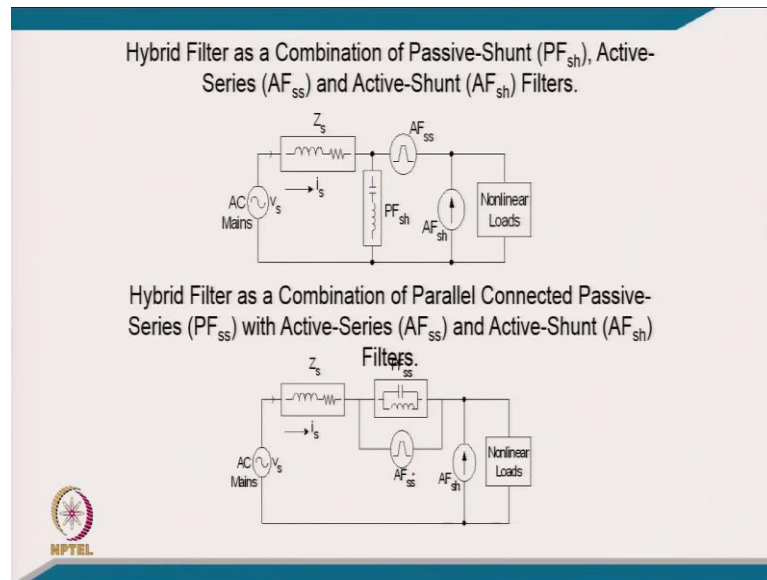
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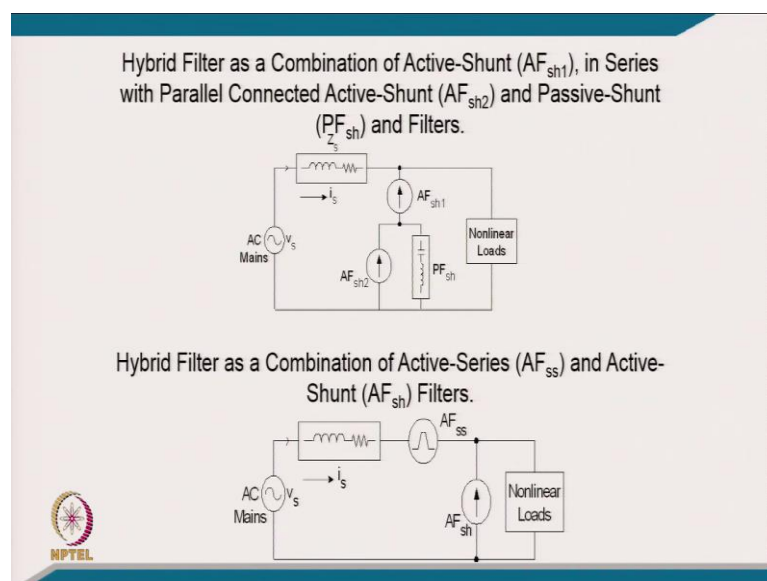
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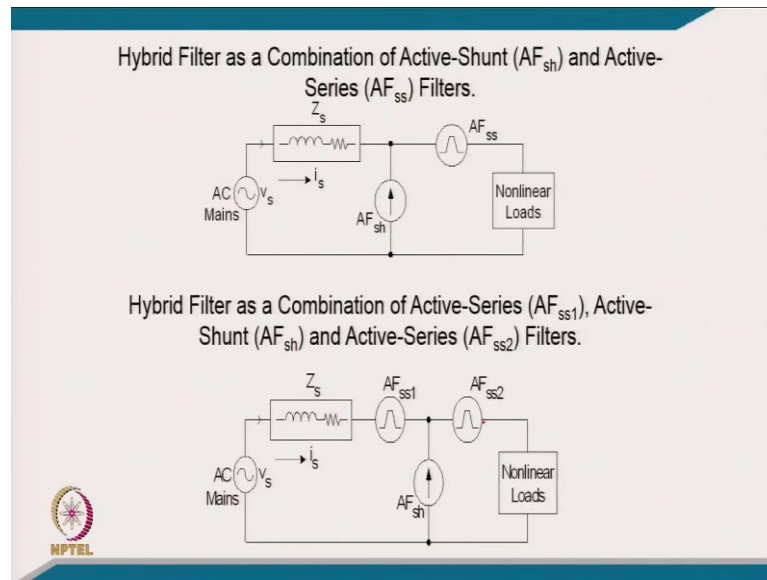
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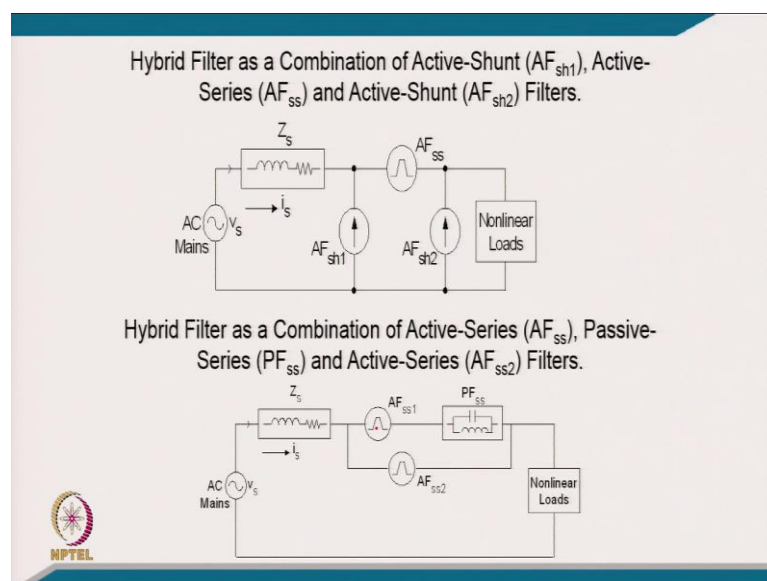
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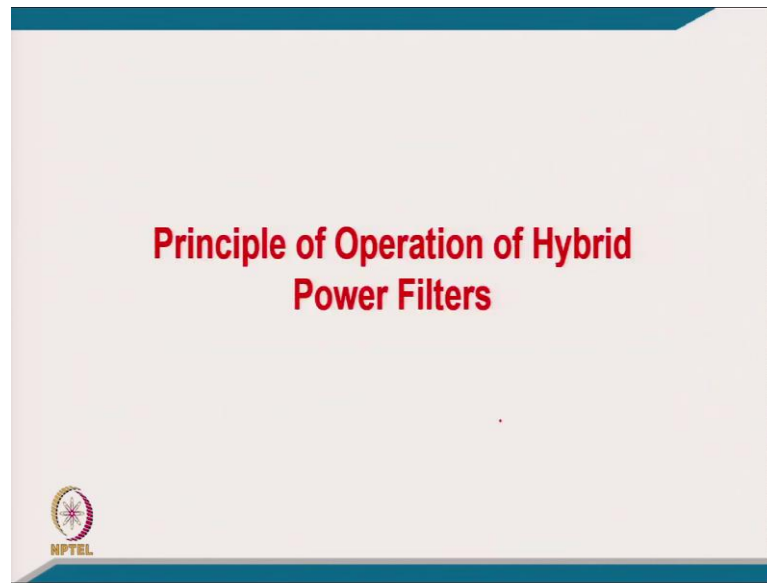


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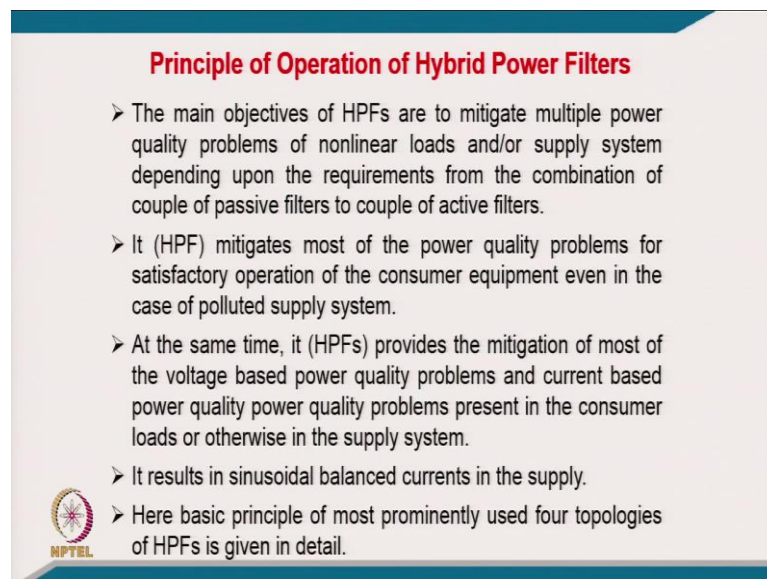


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Now coming to principle of operation of this hybrid passive filter.

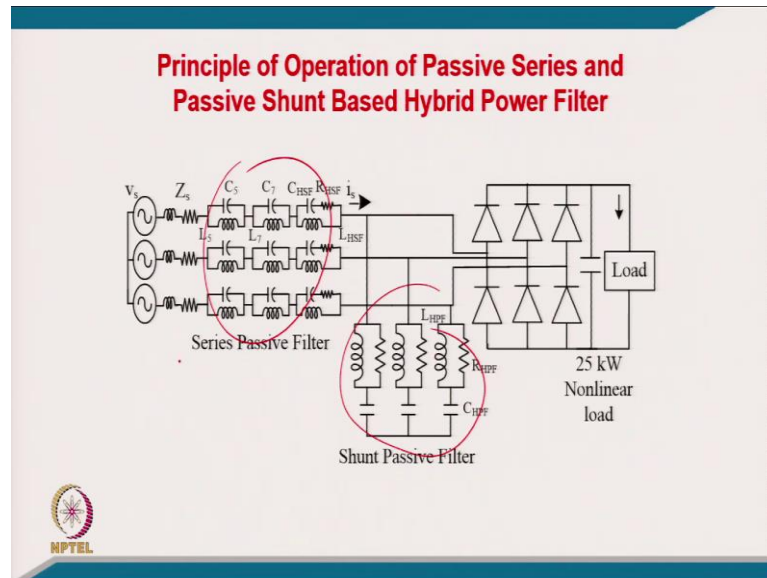
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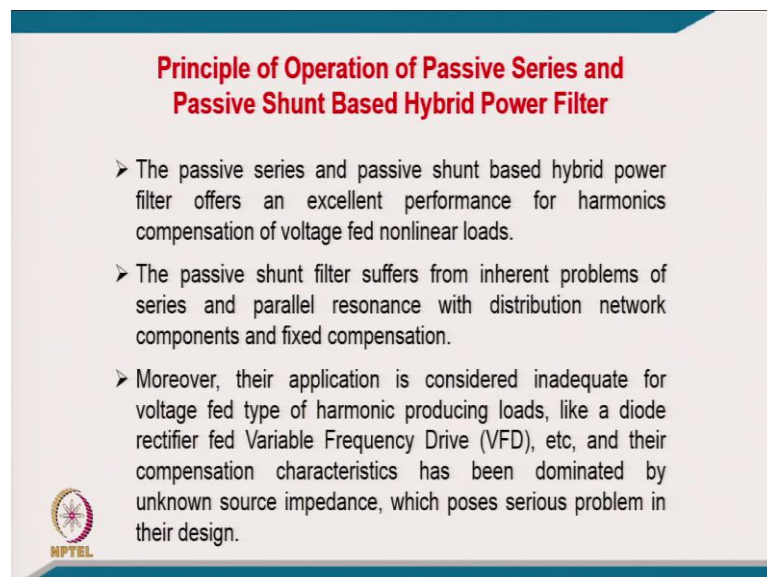
The main objective of hybrid filters are to mitigate the multiple power quality problems of non-linear load and or supply system depending upon the requirement from the combination of couple of passive filter to couple of active filter. And, in hybrids it hybrid filter mitigate most of the power quality problem for satisfactory operation of the consumer equipment even in the cases of polluted supply system.

At the same time, if hybrid filter provides the mitigation of most of the voltage based power quality problem and current based power quality problem present in the consumer loads or otherwise in the supply system. And, it results sinusoidal balance current supply current in the supply. Here the basic principle of most prominently used four wire topology of which given here in detail.

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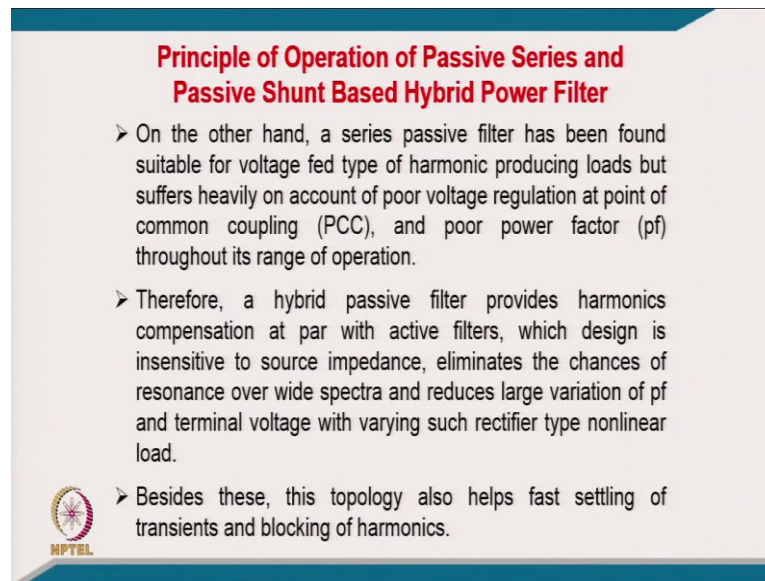


The passive series and passive shunt based hybrid power filter offers excellent performance for harmonic compensation of voltage fed non-linear load. And, the passive

shunt filter suffers from inherent problem of series and parallel resonance with distribution network component and fixed compensation.


Moreover, their application is considered inadequate for the voltage fed kind of harmonic producing load, like a diode rectifier for fed variable frequency drive, and their compensation characteristic has been dominated by unknown source impedance, which pose a serious problem in their design.

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**Principle of Operation of Passive Series and Passive Shunt Based Hybrid Power Filter**

- On the other hand, a series passive filter has been found suitable for voltage fed type of harmonic producing loads but suffers heavily on account of poor voltage regulation at point of common coupling (PCC), and poor power factor (pf) throughout its range of operation.
- Therefore, a hybrid passive filter provides harmonics compensation at par with active filters, which design is insensitive to source impedance, eliminates the chances of resonance over wide spectra and reduces large variation of pf and terminal voltage with varying such rectifier type nonlinear load.
- Besides these, this topology also helps fast settling of transients and blocking of harmonics.

 NPTEL


On the other hand, a series passive filter has been found suitable for voltage fed kind of harmonic producing load, but suffers heavily on account of poor voltage regulation at the point of common coupling, and poor power factor throughout its a range of operation.

Therefore, a hybrid passive filter provides a harmonic compensation at par with a active filter, which design is insensitive to source impedance, eliminate the chances of resonance over the wide spectra and reduces the large variation of power factor and terminal voltage with varying such rectifier type of non-linear load. And beside these, this topology also helps in fast settling of the transient and blocking the harmonics.

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### Principle of Operation of Passive Series and Passive Shunt Based Hybrid Power Filter


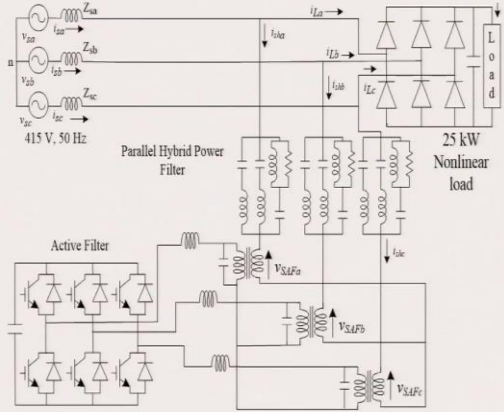
- This passive hybrid filter provides an effective compensation of current harmonics for such voltage fed loads with slightly detuned resonant points (corresponding to available component values), for effective and efficient operation under varying load conditions.
- Moreover, drawbacks of series passive filter behaving as an inductive impedance drop at a fundamental frequency are eliminated by the passive shunt filter.
- In addition, drawbacks of shunt passive filter having the resonance with the source impedance and fixed compensation are eliminated by the passive series filter.



This passive hybrid filter provides an effective compensation of current harmonics for such voltage fed load with slightly detuned resonant points corresponding to available component value, for effective and efficient operation under varying load condition. Moreover, the drawbacks of series passive filter behaving as an inductive impedance drop at a fundamental frequency are eliminated by the passive shunt filter. And, in addition, the drawbacks of shunt passive filter having the resonance with source impedance and fixed compensation are eliminated by passive series filter.

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### Principle of Operation of Passive Shunt and Active Series Based Hybrid Power Filter



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**Principle of Operation of Passive Shunt and Active Series Based Hybrid Power Filter**

- The passive shunt and active series based hybrid power filter provides for harmonics compensation of voltage fed nonlinear loads as a cost effective and adjustable solution for eliminating current harmonics.
- This hybrid filter is formed by series connection of passive filter and a small capacity active filter.
- The passive filter suppresses harmonic currents produced by the load, whereas the active filter improves the filtering characteristics of the passive filter.
- As a result, the hybrid filter system can solve the problems inherent in using only the passive filter.




The passive shunt and active series hybrid filter provides the typically for harmonic compensation of voltage fed non-linear load as well as cost effective and adjustable solution for eliminating the current harmonic. This hybrid filter is formed by series connection of passive shunt a small capacity active filter. The passive filter suppresses harmonic current produced by the load, where as the active filter improve the filtering characteristic of passive filter. As a result the hybrid filter system can solve the problem of inherent by using only the passive filter.

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**Principle of Operation of Passive Shunt and Active Series Based Hybrid Power Filter**

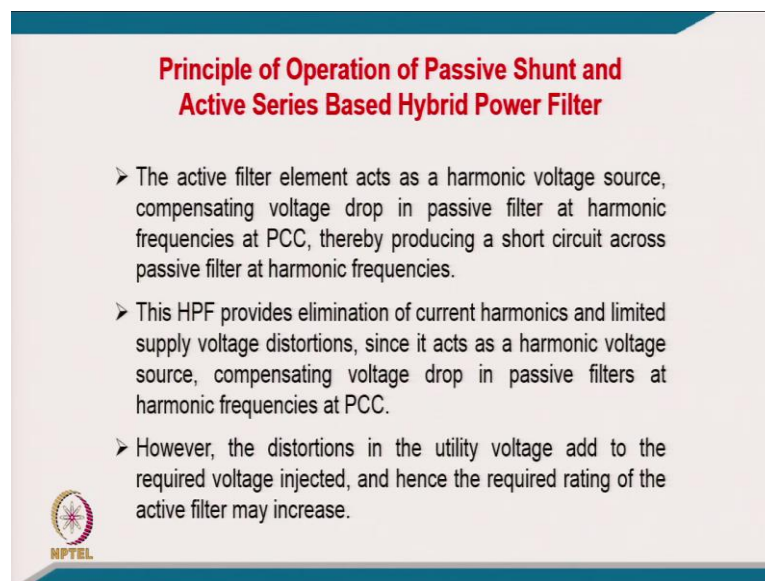
- The series connected active filter is controlled to act as a harmonic compensator for the load by constraining all the harmonic currents to sink into passive filters.
- This eliminates the possibility of series and parallel resonances.
- By actively improving the compensation characteristics of the tuned passive filters, the need for precise tuning of the passive filters is avoided and the design of the passive filter becomes insensitive to supply impedance up to some extent.
- This topology is also suited for the harmonics compensation of the load connected to stiff supply.






The series connected active filter is controlled to act as a harmonic compensator for the load by constraining all the harmonics current to sink into the passive filter. And this eliminates the possibility of series and parallel resonances. By actively improving the compensation characteristic of the tune passive filter the need for precise tuning of passive filters is avoided and the design of the passive filter becomes insensitive to supply impedance up to some extent. And, this topology is also suited for harmonics compensation of load connected to stiff supply system.

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**Principle of Operation of Passive Shunt and Active Series Based Hybrid Power Filter**

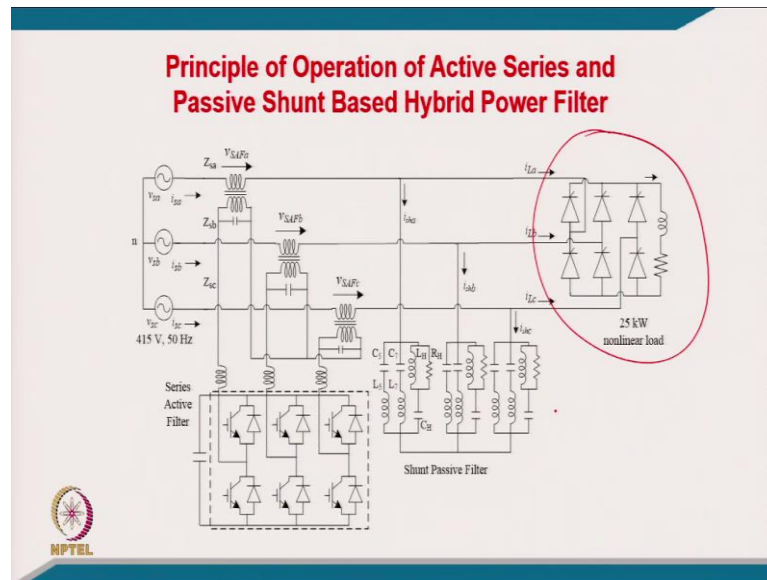
- The active filter element acts as a harmonic voltage source, compensating voltage drop in passive filter at harmonic frequencies at PCC, thereby producing a short circuit across passive filter at harmonic frequencies.
- This HPF provides elimination of current harmonics and limited supply voltage distortions, since it acts as a harmonic voltage source, compensating voltage drop in passive filters at harmonic frequencies at PCC.
- However, the distortions in the utility voltage add to the required voltage injected, and hence the required rating of the active filter may increase.

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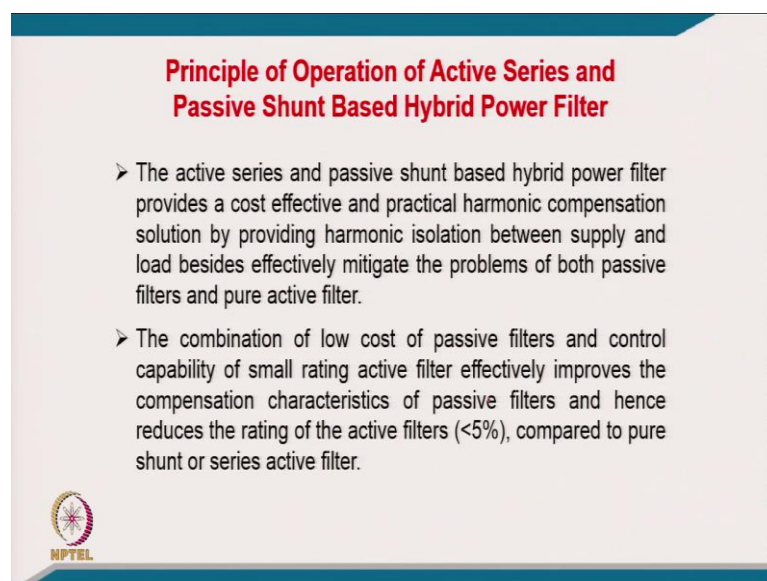
And, the active filter element acts as a harmonic voltage source compensating voltage drop in passive filter at harmonic frequency at PCC, thereby producing a short circuit across the passive filter at harmonic frequency.

This hybrid filter provides the elimination of current harmonics and limited supply voltage distortion, since it acts as a harmonic voltage source, compensating the voltage drop in passive filter at the harmonic frequency at PCC. However, the distortion in the supply voltage adds to the required voltage injected and hence the required rating of active filter may increase.

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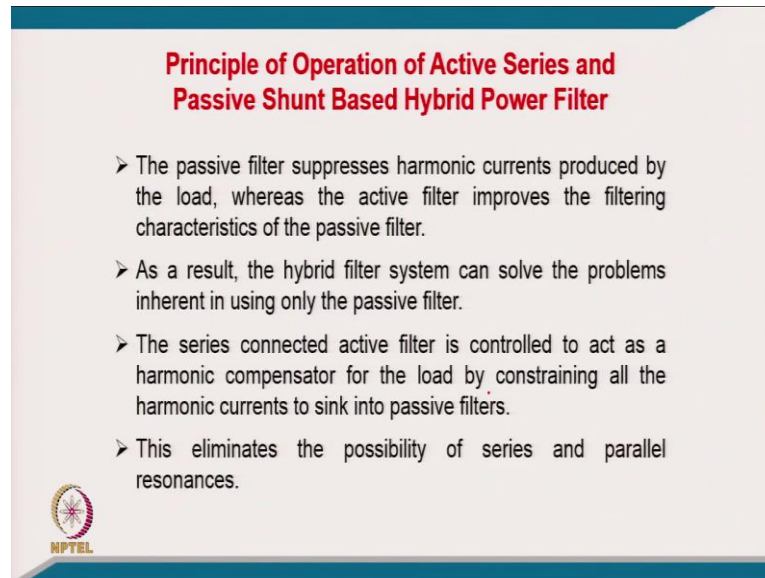


Active series and passive shunt based hybrid filter provides a cost effective and practical harmonic compensation solution by providing harmonic isolation between supply and load, besides the effectively mitigate the problems of both passive filters and pure active filter.

And the combination of low cost of passive filters and control capability of a small rating active filter effectively improve the compensation characteristic of passive filter and


hence reduces the rating of active filters less than 5 percent compared to the pure shunt or series active filter.

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**Principle of Operation of Active Series and Passive Shunt Based Hybrid Power Filter**

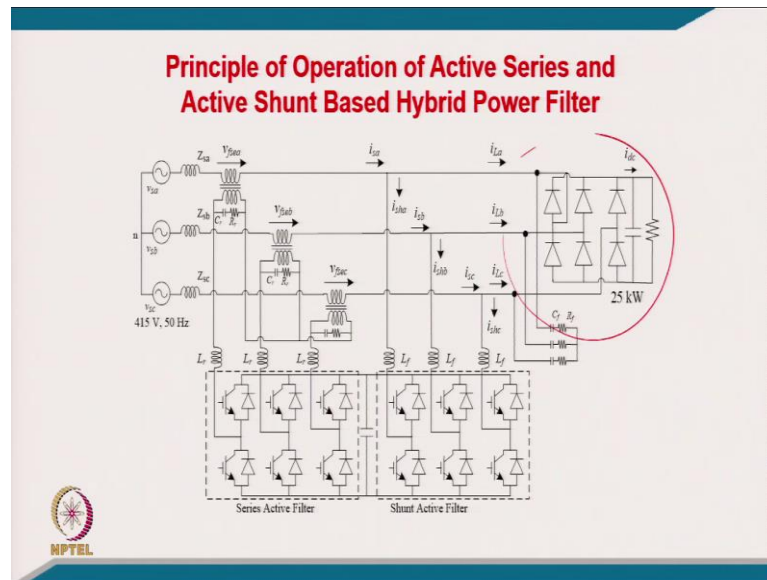
- The passive filter suppresses harmonic currents produced by the load, whereas the active filter improves the filtering characteristics of the passive filter.
- As a result, the hybrid filter system can solve the problems inherent in using only the passive filter.
- The series connected active filter is controlled to act as a harmonic compensator for the load by constraining all the harmonic currents to sink into passive filters.
- This eliminates the possibility of series and parallel resonances.

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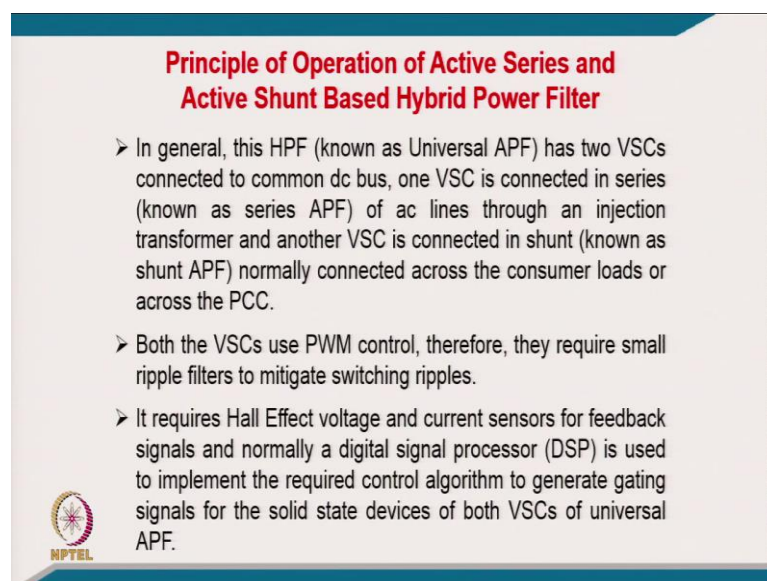
The passive filter suppresses the harmonic currents produced by the load, whereas the active filter improve the filtering characteristic of the passive filter, as a result the hybrid filter system can solve the problem of inherent in using only the passive filter. The series connected active filter is controlled to act as an harmonic compensator for the load by constraining all the harmonics current to sink into the passive filter, and this eliminate the possibility of series and parallel resonances.



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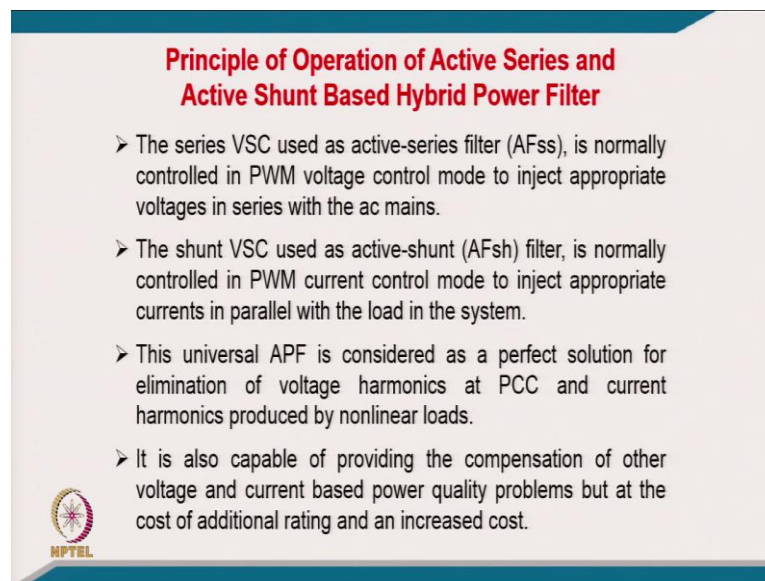
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In general this hybrid filter known as universal active filter had two voltage source converter connected to the common dc bus, one voltage source connect converter is connected in series and known as a series active power filter of ac line through an injection transformer another VSC is connected in shunt known as a shunt active power filter normally connected across the consumer load or across the p point of common coupling.


Both the voltage source converter use the PWM control, therefore, they require a small rating ripple filter to mitigate the switching ripple. And, it requires of course, the Hall Effect voltage sensor and current sensor for feedback signal and normally a digital signal processor is used to implement the required control algorithm to generate the gating signal for the solid state devices of both voltage source converter of universal active power filter.

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**Principle of Operation of Active Series and Active Shunt Based Hybrid Power Filter**

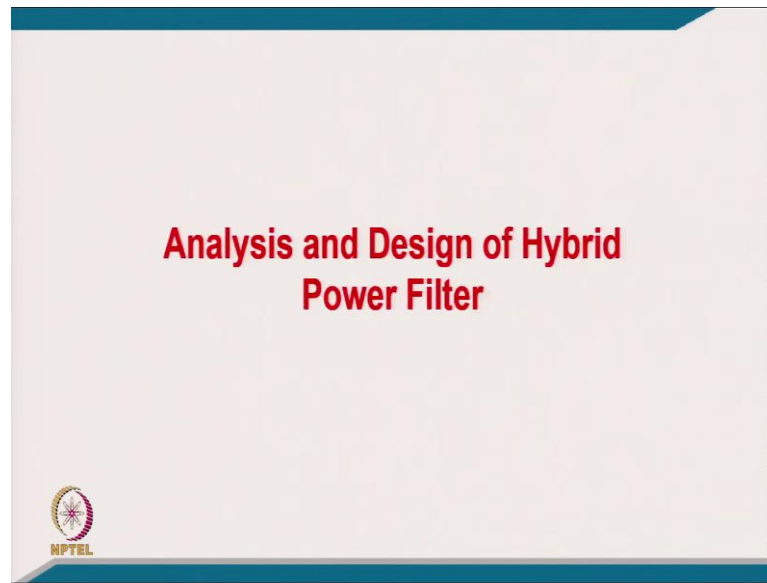
- The series VSC used as active-series filter (AFss), is normally controlled in PWM voltage control mode to inject appropriate voltages in series with the ac mains.
- The shunt VSC used as active-shunt (AFsh) filter, is normally controlled in PWM current control mode to inject appropriate currents in parallel with the load in the system.
- This universal APF is considered as a perfect solution for elimination of voltage harmonics at PCC and current harmonics produced by nonlinear loads.
- It is also capable of providing the compensation of other voltage and current based power quality problems but at the cost of additional rating and an increased cost.

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And the series voltage source converter is used as a series; active series filter and normally denoted AFsh, is controlled in PWM voltage control mode to inject the appropriate voltage in series with the ac main. And, the shunt voltage source converter used as a active shunt filter we call it a AFsh filter, is normally controlled in PWM current control mode to inject the appropriate current in parallel with the load in the system.

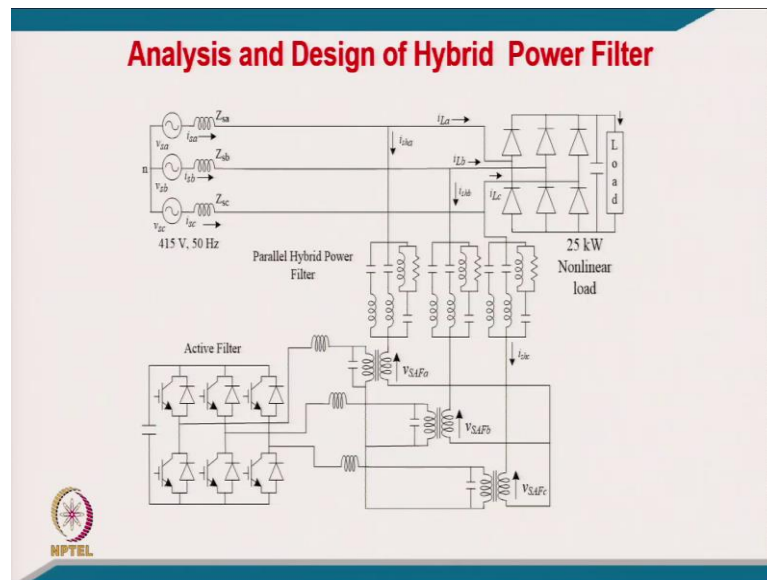
And this universal active power filter is considered as a perfect solution for elimination of voltage harmonics at the point of common coupling and current harmonics produced by non-linear load. It also capable of providing the compensation of other voltage and current based power quality problem, but at the cost of additional rating and an increased cost.

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The analysis, design, control scheme and simulation performance of the hybrid power filter is detailed in the following screenshots.


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### Analysis and Design of Hybrid Power Filter


- Since considered configuration of hybrid filter consists of passive filter along with a small active filter, therefore its design consists of both the components.
- This design procedure is adopted to design of a passive filter for a voltage fed load consisting of a diode rectifier with a filter capacitor and equivalent resistive load of 25 kW at 415 V, 3-phase 50 Hz supply system.



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### Design of Passive Filter


- The passive filter basically consists of a series combination of an inductor and a capacitor tuned to a particular frequency and acts as a low impedance path for that harmonic.
- The 5<sup>th</sup> and 7<sup>th</sup> harmonic filters are designed using a series tuned filter and high pass filter is designed using a second order damped filter.
- The design procedure of a series tuned passive filter is explained for a voltage fed load consisting of a diode rectifier with a filter capacitor and equivalent resistive load of 25 kW at 415 V, 3-phase 50 Hz supply system.



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### Design of Passive 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,  
$$C_n = \frac{Q_c}{m\omega V_s^2}$$
- To trap the  $n^{\text{th}}$  harmonic current, the inductance for  $n^{\text{th}}$  order filter is calculated as,  
$$L_n = \frac{1}{n^2\omega^2 C_n}$$
- The series resistance for inductor of  $n^{\text{th}}$  order filter is calculated as,  
$$R_n = \frac{n\omega L_n}{Q_n}$$



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### Design of Passive Filter

- where  $Q_n$  is the quality factor of inductor of  $n^{\text{th}}$  order filter, which is normally considered as between  $30 < Q < 100$ .
- In the design of second order damped filter, the filter parameters  $C_H$ ,  $L_H$  and  $R_H$  are calculated.
- However, the next dominant harmonic is considered as next value of  $n$  for high-pass filter and the quality factor ( $Q_H$ ) for high pass filter inductor is considered between,  $0.5 < Q < 5$ .




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**Design of Active Series Filter**

- The active filter is only small rating of order of 5% of the load rating.
- Moreover, this small rating active series filter is designed using same procedure given in Chapter-X.
- In addition, there are several numerical examples are illustrated on different topologies of HPFs consisting of such small rating series active filters.


**Design of Active Shunt Filter**

- The shunt active filter is designed using same procedure given in Chapter-IX.
- In addition, there are several numerical examples are illustrated on different topologies of UAPCs consisting of such active shunt filters.

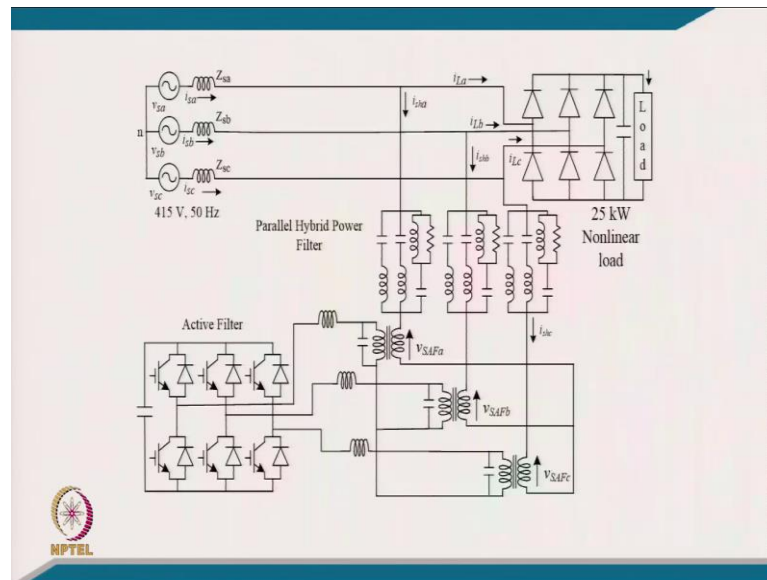


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**Control of Hybrid Power Filters**



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- The main objective of a control algorithm of the hybrid power filters is to estimate the reference voltages or reference currents using feedback signals depending upon their applications.
- Reference voltages or currents for the control of series active power filter have to be derived accordingly and these signals may be estimated using a number of control algorithms.
- There are many control algorithms reported in the literature for the control of series active power filter, which are classified as time domain and frequency domain control algorithms.
- There are more than couple of dozen of time domain and frequency domain control algorithms which are used for the control of series active power filter.
- These control algorithms are explained in Chapter-IV which may easily be modified for the control of series active power filter.










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### Control of Hybrid Filter using Instantaneous Reactive Power Theory

- Similarly three phase supply currents ( $i_{sa}$ ,  $i_{sb}$ ,  $i_{sc}$ ) are transformed into two phase  $\alpha$ - $\beta$  orthogonal coordinates ( $i_{s\alpha}$ ,  $i_{s\beta}$ ) as,  
$$\begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \end{pmatrix} = \frac{\sqrt{2}}{\sqrt{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{pmatrix}$$
- The instantaneous active power  $p_s$  and the reactive power  $q_s$  flowing from the supply side are calculated as  
$$\begin{pmatrix} p_s \\ q_s \end{pmatrix} = \begin{pmatrix} v_{s\alpha} & v_{s\beta} \\ v_{s\beta} & -v_{s\alpha} \end{pmatrix} \begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \end{pmatrix}, \quad p_s = \bar{p}_s + \tilde{p}_s, \quad q_s = \bar{q}_s + \tilde{q}_s$$


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



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### Control of Hybrid Filter using Instantaneous Reactive Power Theory

- In these expressions, the fundamental load power is transformed to dc components  $\bar{p}_s$  and  $\bar{q}_s$ , and the distortion or negative sequence are transformed to ac components.
- The AC components of active and reactive powers are extracted by using two HPFs (High-Pass-Filters).
- In addition, the active filter regulates its dc capacitor voltage without any external power supply.
- If the active filter outputs a fundamental voltage that is in phase with the fundamental leading current of the passive filter, the active power formed by the leading current and the fundamental voltage is supplied to the dc capacitor.
- Therefore, the electrical quantity to be controlled in a dc voltage of AF feedback loop is added to the reactive power



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### Control of Hybrid Filter using Instantaneous Reactive Power Theory


- For the buildup of dc bus voltage of AF, the error between the sensed dc bus voltage and reference dc bus voltage is given to a PI controller.

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

- The output of PI controller is added to the ac component of instantaneous reactive power.

$$x_{pi}(n+1) = x_{pi}(n) + K_{pd} \{V_{dce}(n+1) - v_{dce}(n)\} + K_{id} (V_{dce}(n+1))$$

- Hence the reference powers for the harmonic currents are estimated as,

$$p^* = \beta_{\theta}^*, \quad q^* = \theta_{\theta}^* + x_{pi}$$



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### Control of Hybrid Filter using Instantaneous Reactive Power Theory

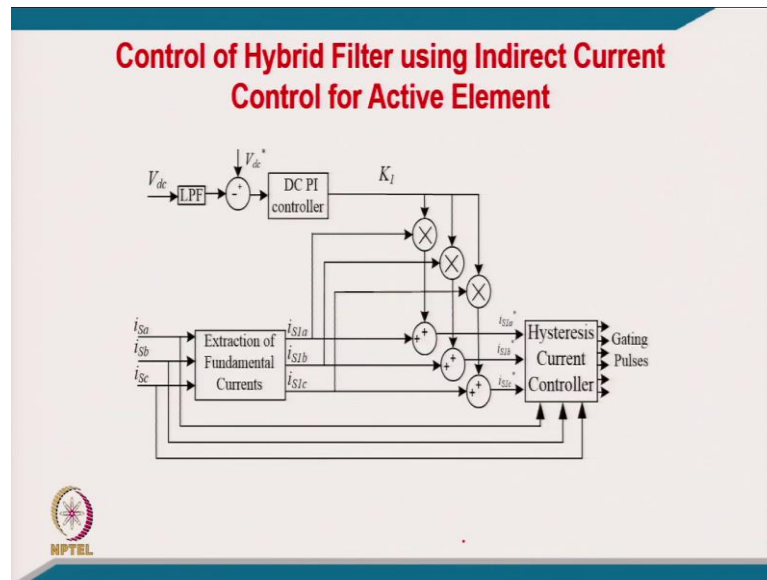
- The reference three-phase harmonics currents ( $i_{sha}^*$ ,  $i_{shb}^*$ ,  $i_{shc}^*$ ), are estimated as

$$\begin{pmatrix} i_{sha}^* \\ i_{shb}^* \\ i_{shc}^* \end{pmatrix} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} v_{s\alpha} & v_{s\beta} \\ -v_{s\beta} & v_{s\alpha} \end{pmatrix}^{-1} \begin{pmatrix} p^* \\ q^* \end{pmatrix}$$

- The estimated harmonic current in each phase  $i_{sh}$  is amplified by a gain 'K' and given as input to a PWM controller as a reference voltage,  $V_c^* = K^* i_{sh}$ .
- The gating signals are generated by comparing the reference voltage, with a triangle-wave carrier frequency.



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### Control of Hybrid Filter using Indirect Current Control for Active Element


- In this control algorithm, the computational delay and number of sensors are reduced than in the instantaneous reactive power theory, by indirectly controlling the three phase supply currents.
- In this control algorithm, the three-phase supply currents are sensed and their fundamental components are estimated with a similar algorithm adopted for active filter controlled using SRF theory.
- The SRF isolator extracts the fundamental positive sequence component of the supply currents by transformation of  $(i_{sa}, i_{sb}, i_{sc})$ , into d-q reference frame as,

The diagram illustrates the control loop for the active element of a hybrid filter. It starts with the DC link voltage  $V_{dc}$  being filtered by an LPF and compared with a reference  $V_{dc}^*$ . The resulting error signal is processed by a DC PI controller with gain  $K_I$ . The output of the PI controller is multiplied by three reference signals (indicated by 'x' blocks) to generate reference currents  $i_{S1a}^*$ ,  $i_{S1b}^*$ , and  $i_{S1c}^*$ . Simultaneously, the three-phase supply currents  $i_{Sa}$ ,  $i_{Sb}$ , and  $i_{Sc}$  are processed by an 'Extraction of Fundamental Currents' block to produce their fundamental components  $i_{S1a}$ ,  $i_{S1b}$ , and  $i_{S1c}$ . These fundamental components are then summed with the reference currents (indicated by '+' blocks) to produce the reference currents  $i_{S1a}^*$ ,  $i_{S1b}^*$ , and  $i_{S1c}^*$ . These reference currents are fed into a 'Hysteresis Current Controller', which generates the final 'Gating Pulses' for the active element. An NPTEL logo is present in the bottom left corner.

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$$\begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{pmatrix} \begin{pmatrix} i_{sa} \\ i_{sb} \\ i_{sc} \end{pmatrix}; \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} i_{s\alpha} \\ i_{s\beta} \end{pmatrix}$$

- The dc (stationary) transformed fundamental supply current components  $i_{sdD}$  and  $i_{sdQ}$  are extracted using two first order LPFs of low cut off frequency (typically 9-25 Hz).
- The fundamental component of supply current is extracted using Inverse Park's transform as,

$$\begin{pmatrix} i_{s1\alpha} \\ i_{s1\beta} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} i_{sdD} \\ i_{sdQ} \end{pmatrix}; \begin{pmatrix} i_{s1a} \\ i_{s1b} \\ i_{s1c} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 \\ -1/2 & -\sqrt{3}/2 \\ -1/2 & \sqrt{3}/2 \end{pmatrix} \begin{pmatrix} i_{s1\alpha} \\ i_{s1\beta} \end{pmatrix}$$


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- The DC bus voltage control of AF is achieved using a PI controller.
- A low pass filter is required to filter ripples in feedback path of dc bus voltage.
- The output of dc bus filter is represented as a gain  $K_1$ .
- The reference signal for current controller is given by,

$$\begin{pmatrix} i_{s1a}^* \\ i_{s1b}^* \\ i_{s1c}^* \end{pmatrix} = \begin{pmatrix} i_{s1a} \\ i_{s1b} \\ i_{s1c} \end{pmatrix} + K_1 \begin{pmatrix} i_{s1a} \\ i_{s1b} \\ i_{s1c} \end{pmatrix}$$

- Three-phase supply currents are controlled to follow the reference fundamental positive sequence currents by switching the VSC, through a hysteresis current controller, which results in an indirect current control.

