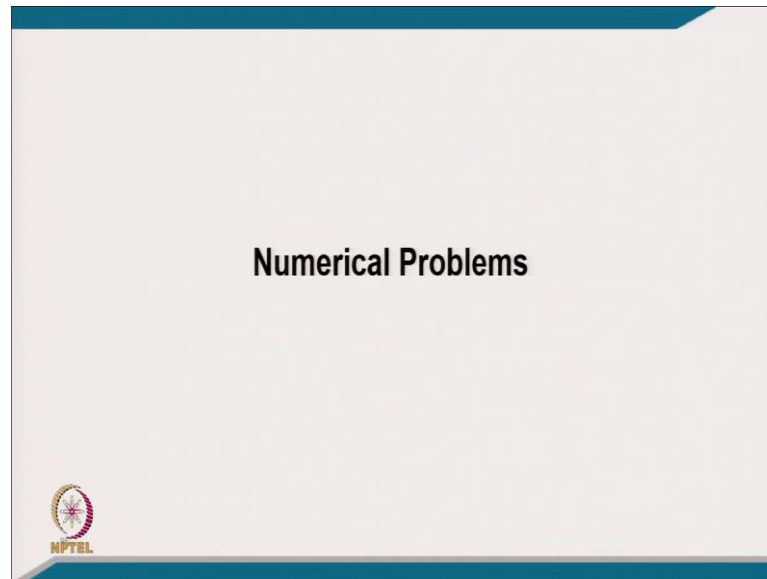


Power Quality
Prof. Bhim Singh
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Lecture - 19
Passive Power Filters (contd.)

(Refer Slide Time: 00:17)



Welcome to the course on Power Quality and we were Passive Power Filter. We have discussed the configuration design and limitations; we will now discuss the numerical problems on passive filters.

(Refer Slide Time: 00:46)

1. A single-phase diode bridge rectifier is supplied from 230 V, 50 Hz ac mains as shown in Fig. The load resistance is $R = 100 \Omega$. (a) Design a capacitive filter so that the ripple factor of the output voltage is less than 5%. (b) With this value of the capacitor, calculate the average load voltage V_{dc} .

Time (sec)

Starting from first problem, a single phase diode bridge rectifier is supplied from 230 Volt, 50 Hertz ac mains as shown in the figure. The load resistance is of 100 Ohm. Design a capacitive filter, so that ripple factor of output voltage is less than 5 percent. With this value of the capacitor, calculate the average load voltage.

You have a circuit here which consist typically of diode rectifier and a capacitive filter followed by the load.

(Refer Slide Time: 01:21)

Solution: Given that, supply rms voltage, $V_s = 230$ V, frequency of the supply, $f = 50$ Hz, $R = 100 \Omega$, ripple factor, $RF = 5\%$.


The amplitude of ac mains voltage is as, $V_{sm} = 230 \times \sqrt{2} = 325.269$ V.

(a) The ripple factor RF is defined as,

$$RF = \frac{V_{ac}}{V_{dc}} = \frac{1}{\{(4fRC_{dc}-1)\sqrt{2}\}}$$

The value of dc bus capacitor is as, $C_{dc} = \{1 + 1/(RF\sqrt{2})\} / (4fR) = 757.11 \mu\text{F}$.

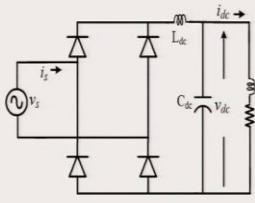
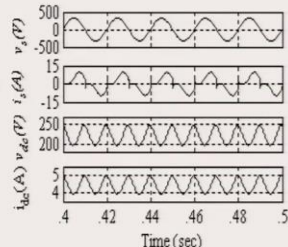

(b) The mean dc bus voltage V_{dc} is as, $V_{dc} = V_{sm} - V_{sm} / (4fRC_{dc}) = 303.78$ V.



The solution to the numerical is detailed in the screenshot.

(Refer Slide Time: 02:30)

2. A single-phase diode bridge rectifier is supplied from 230 V, 50 Hz ac mains as shown in Fig. The dc load resistance is $R = 30$ Ohms and load inductance is $L = 10$ mH. (a) Design a DC side LC (Inductive-Capacitive) filter so that the ripple factor of the output voltage is less than 10%.

Coming to an example 2, a single phase diode bridge rectifier is supplied from 230 Volts, 50 Hertz, ac mains as shown in the figure here. The dc load resistance is of 30 Ohm and the load inductance is your 10 milli Henry. Design a DC side LC field capacitive filter, so that the ripple factor of the output voltage is less than 10 percent.

(Refer Slide Time: 03:03)

Solution: The value of the filter capacitor is computed as,

$$\{R^2 + (2\omega L)^2\}^{1/2} = 10/(2\omega C_{dc}) \text{ or}$$

$$C_{dc} = 10/[4\pi f\{R^2+(2\omega L)^2\}^{1/2}] = 519.25 \mu\text{F}$$

The ripple factor RF is defined as,


$$RF = V_{ac}/V_{dc} = V_{2h}/[V_{dc}\{(4\pi f)^2 L_{dc} C_{dc} - 1\}],$$

$$V_{dc} = 2 V_{sm}/\pi,$$

$$V_{2h} = 4 V_{sm}/3\pi \sqrt{2},$$

$$RF = (\sqrt{2})/[3\{(4\pi f)^2 L_{dc} C_{dc} - 1\}] = 0.1$$


It results in as, $(4\pi f)^2 L_{dc} C_{dc} - 1 = 4.714$ or $L_{dc} = 27.87$ mH.



The solution to the numerical is detailed in the screenshot.

(Refer Slide Time: 03:35)

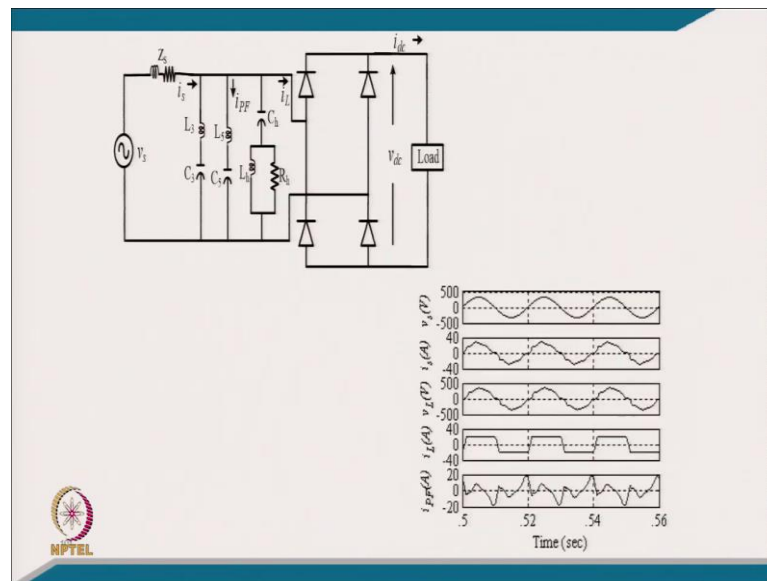
3. A single-phase three branch shunt passive filter (PF) (3rd, 5th and high pass filter) is employed to reduce the THD of supply current and to improve the displacement factor to unity, of a single-phase 230 V, 50 Hz fed diode bridge converter with an overlap angle of 30° drawing 30 A constant dc current as shown in Fig. Calculate (a) fundamental active power drawn by the load, (b) fundamental reactive power drawn by the load, (c) elements values of the passive filter, (d) current and VA rating of the passive filter.



Now, coming to the 3rd numerical problem, in which we have designed the ac side filter. A single phase three branch shunt passive filter consisting of 3rd, 5th and high pass filter

is used to reduce the total harmonic distortion of supply current and to improve the displacement factor to unity of single phase 230 Volt, 50 Hertz fed diode bridge rectifier with an overlap angle of 30 degree drawing 30 Ampere constant dc current as shown in the figure. And calculate the fundamental active power drawn by the load, fundamental reactive power drawn by the load, elements value of the passive filter, and current and VA rating of the passive filter like.

(Refer Slide Time: 04:18)




Here we have the circuit of total system; we have a diode rectifier with the load and we have a typically the filter component.

(Refer Slide Time: 04:39)

Solution: Given that, $V_s = 230$ V, $f = 50$ Hz, 230 V, 50 Hz ac supply with an overlap angle, $\mu = 30^\circ$, dc link current, $I_{dc} = 30$ A.

In single-phase uncontrolled bridge converter with an overlap angle, the waveform of the supply current (I_s) is a trapezoidal wave with the amplitude of dc link current (I_{dc}). Since this trapezoidal wave of input current is an odd and quarter cycle and half cycle symmetry, the supply rms value of it is computed as.

$$I_s = I_L = \sqrt{\left\{ \frac{1}{2\pi} \right\} (\text{Area of the total waveform})}$$

$$= \sqrt{\left(\frac{1}{2\pi} \right) \left(4 \int_0^{\mu/2} (2I_{dc}\theta / \mu)^2 d\theta + 2 \int_{\mu/2}^{\pi-\mu/2} I_{dc}^2 d\theta \right)}$$


The solution to the numerical is detailed in the screenshots.

(Refer Slide Time: 05:38)

$$= I_{dc} \sqrt{\left\{ \frac{1}{2\pi} \right\} \left\{ (2\mu/3) + 2(\pi - \mu) \right\}} = 0.94281 * 30$$

$$= 28.284 \text{ A.}$$


The trapezoidal wave of input current is an odd and quarter cycle and half cycle symmetry, the rms value of n^{th} harmonic RMS Current, I_{snrms} is computed as.

$$I_{snrms} = B_n / \sqrt{2} = \left[\frac{8}{2\pi} \int_0^{\pi/2} f(\theta) \sin n\theta d\theta \right]$$

$$I_{snrms} = \left[\frac{8}{2\pi} \left(\int_0^{\mu/2} (2I_{dc}\theta / \mu) \sin n\theta d\theta + \int_{\mu/2}^{\pi-\mu/2} I_{dc} \sin n\theta d\theta \right) \right]$$

$$I_{snrms} = I_{dc} \left[\frac{8}{\pi\mu n^2} \sin(n\mu/2) \right] / \sqrt{2}$$

(Since the trapezoidal wave will not have A_n)



(Refer Slide Time: 06:24)

Therefore, the RMS of fundamental current is as,
$$I_{L1} = I_{s1} = I_{dc} \left[\frac{8}{\pi\sqrt{2}} \sin(\mu/2) \right] = 0.89 * I_{dc} = 26.7A.$$


The active power component of supply current is as,
$$I_{s1a} = I_{L1a} = I_{s1} \cos\mu/2 = 25.79 A$$

(a) The input active power is as,
$$P = V_s I_{s1a} = V_s I_{s1} \cos\mu/2 = 230 * 25.79 = 5931.75 W.$$

(b) The input reactive power is as,
$$Q_1 = V_s I_{s1} \sin\mu/2 = 1589.408 VAR.$$

The mean output voltage is as,
$$V_{dc} = (\sqrt{2}/\pi) V_s (1 + \cos\mu) = 0.9 V_s (1 + \cos\mu)/2$$

$$= 193.202 V.$$



(Refer Slide Time: 07:36)

The mean voltage is also as,
$$V_{dc} = (2 \sqrt{2V_s^2 - 2\omega L_s I_{dc}}) / \pi$$


Therefore, the source inductance is estimated as,
$$L_s = 2.312 \text{ mH}.$$

Therefore, considering the source inductance as, $L_s = 3 \text{ mH}.$

The source impedance is as,
$$Z_s = jX_s = j\omega L_s = 314 * 0.003 = j0.942 \Omega.$$

The voltage drop in the source impedance is as,
$$V_{zs} = Z_s * I_{s1a} = j 25.79 * 0.942 = j 24.307 V.$$

The fundamental voltage across the load,
$$V_L = \sqrt{V_s^2 - V_{zs}^2} = 228.712 \approx 230 V.$$




(Refer Slide Time: 08:32)

The passive shunt filter has branch shunt passive filter (PF) (3rd, 5th and high pass damped filter). The value of this capacitor is as,
 $C = Q/(3V_s^2\omega) = 1589.408/(3*230^2*314) = 31.879 \mu\text{F}$.
 $C_3 = C_5 = C_H = C = 31.879 \mu\text{F}$.

Therefore, the value of an inductor for 3rd harmonic tuned filter is as,
 $L_3 = 1/(\omega_3^2 C_3) = 35.314 \text{ mH}$.

The resistance of the inductor of 3th harmonic tuned filter is as,
 $R_3 = X_3/Q_3 = 0.666 \Omega$. (Considering $Q_3 = 50$)

The 3rd harmonic current in the load is as,
 $I_{L3} = I_{\text{dcl}}\{8/(9\pi\mu\sqrt{2})\}\sin(3\mu/2) = 8.106 \text{ A}$.



(Refer Slide Time: 09:54)


The 3rd harmonic current in the supply is as,
 $I_{s3} = I_{L3} * Z_{PF3}/(Z_{PF3} + Z_{s3}) = (I_{L3})R_3/(R_3 + jX_{s3})$
 $= (8.106) * 0.666 / \sqrt{0.666^2 + (3*0.942)^2} = 1.859 \text{ A}$.

The value of an inductor for 5th harmonic filter (tuned at 5th harmonic) is as, $L_5 = 1/(\omega_5^2 C_5) = 12.713 \text{ mH}$.

The resistance in parallel of an inductor of a 5th harmonic tuned filter is as, $R_5 = X_5/Q_5 = 0.399 \Omega$. (Considering $Q_3 = 50$)

The 5th harmonic current in the load is as,
 $I_{L5} = I_{\text{dcl}}\{8/(25\pi\mu\sqrt{2})\}\sin(5\mu/2) = 3.986 \text{ A}$.

The 5th harmonic current in the supply is as,
 $I_{s5} = I_{L5} * Z_{PF5}/(Z_{PF5} + Z_{s5}) = (I_{L5})R_5/(R_5 + jX_{s5})$
 $= (3.986) * 0.399 / \sqrt{0.399^2 + (5*0.942)^2} = 0.336 \text{ A}$.




(Refer Slide Time: 11:02)

The value of an inductor for high pass damped harmonic filter (tuned at 7th harmonic) is as,
 $L_H = 1 / (\omega_7^2 C_H) = 6.486 \text{ mH}.$

The resistance in parallel of an inductor of a high pass damped harmonic tuned filter is as,
 $R_H = X_H / Q_H = 14.264 \ \Omega.$ (Considering $Q_H = 1$)

All other harmonics load currents to flow in to high pass damped harmonic filter is as,
 $I_{LH} = \sqrt{[I_L^2 - I_{L1}^2 - I_{L3}^2 - I_{L5}^2]} = \sqrt{[28.284^2 - 26.7^2 - (8.106)^2 - (3.986)^2]} = 2.345 \text{ A}.$

$I_{SH} = I_{LH} * Z_{PFH} / (Z_{PFH} + Z_{SH}) = (I_{LH})R_H / (R_H + jX_{SH})$
 $= (2.345) * 14.264 / \sqrt{14.264^2 + (7 * 0.942)^2} = 2.129 \text{ A}.$





(Refer Slide Time: 12:10)

$THD_{I_s} = \{\sqrt{(I_{s3}^2 + I_{s5}^2 + I_{SH}^2)} / I_{s1a}\} = 0.11 = 11.04\%.$

$THD_{V_L} = [\sqrt{\{(X_{s3} I_{s3})^2 + (X_{s5} I_{s5})^2 + (X_{SH} I_{SH})^2\}} / V_{s1}] = 0.066 = 6.553\%.$

$I_{PF} = \sqrt{[I_s^2 - I_{s1a}^2 - I_{s3}^2 - I_{s5}^2 - I_{SH}^2]} = 11.259 \text{ A}.$

The VA rating of the passive shunt filter is as,
 $VA_{PF} = V_s * I_{PF} = 230 * 11.259 = 2589.509 \text{ VA}.$

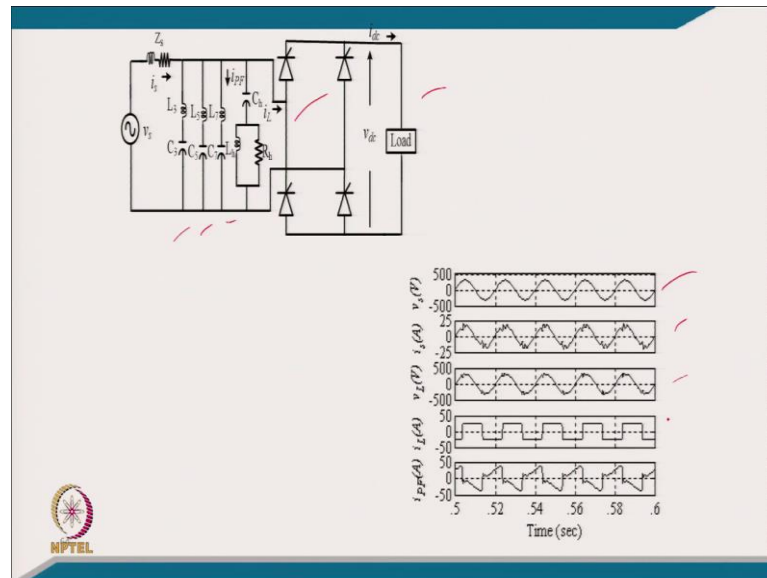
(Refer Slide Time: 12:48)

4. A single-phase four branch shunt passive filter (PF) (3rd, 5th, 7th and high pass filter) is used in a single-phase 220 V, 50 Hz system to reduce the THD of supply current and to improve the displacement factor to unity. It has a load of thyristor bridge converter operating at 60° firing angle drawing constant 25A dc current as shown in Fig. Calculate (a) the value elements of the passive filter, (b) total harmonic distortion of the supply current, (c) total harmonic distortion of the terminal voltage at the load end, (d) the current rating of the passive filter and (e) its kVA rating to provide harmonic and reactive power compensation. Let the supply has 5% source impedance mainly inductive.



Coming to example 4, a single phase four branch passive filter 3rd, 5th and 7th and high pass filter is used to single phase 220 Volt, 50 Hertz system to reduce the THD of supply current and to improve the displacement factor to unity. It has a load of thyristor bridge converter operating at 60 degree firing angle drawing constant 25 Ampere dc current as shown here. Calculate the value of elements of passive filter, the total harmonic distortion of supply current, the total harmonic distortion of thermal voltage, load end, and the current rating of the passive filter and e the kVA rating of kVA rating to provide harmonics and reactive power compensation. Let the supply has a 5 percent source impedance mainly inductive.

(Refer Slide Time: 13:34)



The solution to the numerical is detailed in the screenshots.

(Refer Slide Time: 13:52)

Solution: Given that, supply voltage, $V_s = 220$ V rms, frequency of supply, $f = 50$ Hz, with a source impedance of 5% mainly inductive feeding a nonlinear load of 220 V, 50 Hz single-phase thyristor bridge converter with constant dc current of 25 A at 60° firing angle of its thyristors.

In this system, the load current harmonics and reactive power compensation is provided by a single-phase four branch shunt passive filter (PF) (3^{rd} , 5^{th} , 7^{th} and high pass damped filter) to reduce the THD of the supply current and to improve the displacement factor close to unity.

The ac load rms current is as, $I_L = I_{dc} = 25$ A.

(Refer Slide Time: 14:33)

The fundamental rms input current of the thyristor bridge converter is as, $I_{L1} = (2\sqrt{2}/\pi) I_L = 0.9 \cdot 25 = 22.5 \text{ A}$.


The fundamental active component of load current is as, $I_{L1a} = I_{L1} \cos \alpha = 0.9 I_{dc} \cos 60^\circ = 11.25 \text{ A}$.

The fundamental active power of the load is as, $P_1 = V_{s1} I_{L1} \cos \theta_1 = V_{s1} I_{L1} \cos \alpha = V_{s1} I_{L1a} = 220 \cdot 11.25 = 2475 \text{ W}$.

The fundamental reactive power of the load is as, $Q_1 = V_{s1} I_{L1} \sin \theta_1 = V_{s1} I_{L1} \sin \alpha = 220 \cdot 22.5 \cdot 0.866 = 4286.8 \text{ VAR}$.

The source impedance is as, $Z_s = jX_s = j0.05 \cdot 220/25 = j0.44 \ \Omega$.

The voltage drop in the source impedance is as, $V_{zs} = j11.25 \cdot 0.44 = j4.95 \text{ V}$.




(Refer Slide Time: 15:27)

The fundamental voltage across the load is as, $V_L = \sqrt{(V_s^2 - V_{zs}^2)} = 219.94 \approx 220 \text{ V}$.

The passive shunt filter has four branch shunt passive filter (PF) (3rd, 5th, 7th and high pass damped filter). The reactive power of 4286.8 VAR required by single-phase thyristor rectifier has to be provided by all four branches of the passive shunt filter. Considering that all branches of the passive filter has equal capacitors, therefore, the value of this capacitor is as,

$$C = Q_1 / (4V_s^2 \omega) = 4286.8 / (4 \cdot 220^2 \cdot 314) = 70.48 \ \mu\text{F}$$
$$C_3 = C_5 = C_7 = C_H = C = 70.48 \ \mu\text{F}$$

Therefore, the value of an inductor for 3rd harmonic tuned filter is as,

$$L_3 = 1 / (\omega_3^2 C_3) = 16 \text{ mH}$$


(Refer Slide Time: 16:18)

The resistance of the inductor of 3rd harmonic tuned filter is as,

$$R_3 = X_3/Q_3 = 15.072/50 = 0.301 \Omega. \text{ (Considering } Q_3 = 50 \text{ as it may be in the range of 10-100 depending upon the design of the inductor).}$$


The 3rd harmonic current in the supply is as,

$$I_{s3} = I_{L3} * Z_{PF3} / (Z_{PF3} + Z_{s3}) = (I_{L1}/3)R_3 / (R_3 + jX_{s3}) = (22.5/3) * 0.301 / \sqrt{0.301^2 + (3 * 0.44)^2} = 1.667 \text{ A.}$$

The 3rd harmonic voltage at PCC is as,

$$V_{s3} = I_{s3} * Z_{s3} = 1.667 * 3 * 0.44 = 2.2016 \text{ V.}$$

Therefore, the value of an inductor for 5th harmonic tuned filter is as,

$$L_5 = 1 / (\omega_5^2 C_5) = 5.8 \text{ mH.}$$


(Refer Slide Time: 17:03)

The resistance of the inductor of 5th harmonic tuned filter is as,

$$R_5 = X_5/Q_5 = 8.949/50 = 0.1806 \Omega. \text{ (Considering } Q_5 = 50 \text{ as it may be in the range of 10-100 depending upon the design of the inductor).}$$


The 5th harmonic current in the supply is as,

$$I_{s5} = I_{L5} * Z_{PF5} / (Z_{PF5} + Z_{s5}) = (I_{load1}/5)R_5 / (R_5 + jX_{s5}) = (22.5/5) * 0.1806 / \sqrt{0.1806^2 + (5 * 0.44)^2} = 0.3683 \text{ A.}$$

The 5th harmonic voltage at PCC is as,

$$V_{s5} = I_{s5} * Z_{s5} = 0.3683 * 5 * 0.44 = 0.81 \text{ V.}$$

Therefore, the value of an inductor for 7th harmonic tuned filter is as,

$$L_7 = 1 / (\omega_7^2 C_7) = 2.9 \text{ mH.}$$


(Refer Slide Time: 17:34)

The resistance of the inductor of 7th harmonic tuned filter is as,

$$R_7 = X_7/Q_7 = 6.37/50 = 0.129 \Omega. \text{ (Considering } Q_7 = 50 \text{ as it may be in the range of 10-100 depending upon the design of the inductor).}$$


The 7th harmonic current in the supply is as,

$$I_{s7} = I_{L7} * Z_{PF7} / (Z_{PF7} + Z_{s7}) = (I_{L1}/7) R_7 / (R_7 + jX_{s7}) = (22.5/7) * 0.129 / \sqrt{0.129^2 + (7 * 0.44)^2} = 0.134 \text{ A.}$$

The 7th harmonic voltage at PCC is as,

$$V_{s7} = I_{s7} * Z_{s7} = 0.134 * 7 * 0.44 = 0.4144 \text{ V.}$$

The value of an inductor for high pass damped harmonic filter (tuned at 9th harmonic) is as,

$$L_H = 1 / (\omega_9^2 C_H) = 1.8 \text{ mH.}$$


(Refer Slide Time: 18:13)


The resistance in parallel of an inductor of a high pass damped harmonic tuned filter is as,

$$R_H = X_H/Q_H = 5.08/2 = 2.508 \Omega. \text{ (Considering } Q_H = 2 \text{ as it may be in the range of 0.5-5 depending upon the attenuation required)}$$

All other harmonics load currents to flow in to high pass damped harmonic filter is as,

$$I_{LH} = \sqrt{[I_L^2 - I_{L1}^2 - I_3^2 - I_5^2 - I_7^2]} = \sqrt{[25^2 - 22.5^2 - (22.5/3)^2 - (22.5/5)^2 - (22.5/7)^2]} = 5.649 \text{ A.}$$
$$I_{sH} = I_{LH} * Z_{PFH} / (Z_{PFH} + Z_{sH}) = (I_{LH}) R_H / (R_H + jX_{sH}) = (5.649) * 2.508 / \sqrt{2.508^2 + (9 * 0.44)^2} = 3.0237 \text{ A.}$$

The high pass harmonic voltage at PCC is as,

$$V_{sH} = I_{sH} * Z_{sH} = 3.0237 * 9 * 0.44 = 11.97 \text{ V.}$$


(Refer Slide Time: 18:49)


$$\text{THD}_{I_s} = \{\sqrt{(I_{s3}^2 + I_{s5}^2 + I_{sH}^2)} / I_{s1a}\} = 0.31 = 30.89\%$$

$$\text{THD}_{V_L} = [\sqrt{\{(X_{s3}I_{s3}^2 + (X_{s5}I_{s5})^2 + (X_{s7}I_{s7})^2 + (X_{sH}I_{sH})^2\}} / V_{s1}] = 0.055 = 5.55\%$$

The current rating of the passive shunt filter is as,

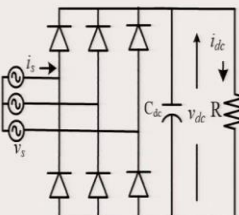
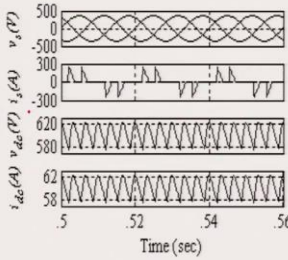

$$I_{PF} = \sqrt{[I_L^2 - I_{L1a}^2 - I_{s3}^2 - I_{s5}^2 - I_{s7}^2 - I_{sH}^2]} = 22.054 \text{ A.}$$

The VA rating of the passive shunt filter is as,

$$\text{VA}_{PF} = V_{PF} * I_{PF} = 220 * 22.0548 = 4851.9 \text{ VA.}$$


(Refer Slide Time: 19:18)

5. A three-phase diode bridge rectifier is supplied from 415 V, 50 Hz ac mains as shown in Fig. The load resistance is $R = 20 \text{ Ohms}$. (a) Design a dc bus parallel capacitive filter so that the ripple factor of the output voltage is less than 5%, (b) with this value of capacitor, calculate the average load voltage V_{dc} .

Coming to the fifth example, a three phase diode bridge rectifier is supplied from 415 Volt, 50 hertz ac mains as shown in the figure below and load resistance is R equal to 20 Ohm. Designed a dc bus parallel capacitive filter, so that the ripple filter of the output voltage is less than 5 percent And with this value capacitor, calculate the average voltage dc.

(Refer Slide Time: 19:50)

Solution: Given that, $V_s = 415$ V, $f = 50$ Hz, $R = 20$ Ω ,
 $RF = 5\%$.

The amplitude of ac mains voltage is as, $V_{sm} = 415 \sqrt{2} = 586.899$ V.

(a) The dc bus capacitance for a given ripple factor, RF in a 3-phase diode bridge rectifier is defined as,

$$C_{dc} = \{1/(12fR)\} \{1 + 1/(RF\sqrt{2})\} = 1261.845 \mu\text{F}.$$

(b) The average load voltage V_{dc} is estimated as,

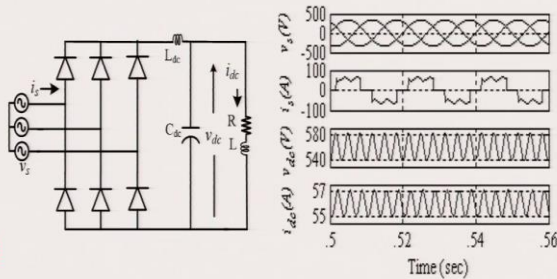
$$V_{dc} = V_{sm} - V_{sm}/(12fRC_{dc}) = 548.139 \text{ V}.$$



The solution to the numerical is detailed in the screenshots.

(Refer Slide Time: 20:32)

6. A three-phase diode bridge rectifier is supplied from 415 V, 50 Hz ac mains as shown in Fig. The dc load resistance is $R = 10$ Ohms and the load inductance is 10mH. Design a DC side LC (Inductive- Capacitive) filter so that the ripple factor of the output voltage is less than 10%.



(Refer Slide Time: 21:07)

Solution: Given that, supply rms voltage, $V_s = 415$ V, frequency of supply, $f = 50$ Hz, $R = 10$ Ω , $L = 10$ mH, Ripple Factor, $RF = 10\%$.

The value of the filter capacitor is computed as,

$$\{R^2 + (6\omega L)^2\}^{1/2} = 10 / (6\omega C_{dc}) \text{ or } C_{dc} = 10 / [12\pi f \{R^2 + (6\omega L)^2\}^{1/2}] = 248.63 \mu\text{F}.$$

The ripple factor RF is estimated as,

$$RF = V_{ac} / V_{dc} = V_{6\pi} / [V_{dc} \{(12\pi f)^2 L_{dc} C_{dc} - 1\}]$$

$$RF = 2 / [35 \{(12\pi f)^2 L_{dc} C_{dc} - 1\}] = 0.1$$

It results in as,

$$(12\pi f)^2 L_{dc} C_{dc} - 1 = 0.57 \text{ or } L_{dc} = 1.8 \text{ mH}.$$

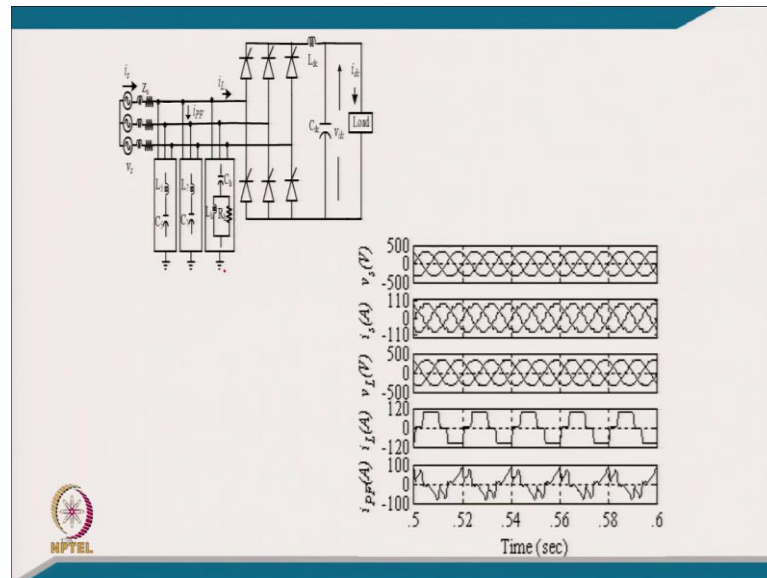


(Refer Slide Time: 21:47)

7. A three-phase three branch shunt passive filter (tuned 5th, 7th and high pass) is employed to reduce the THD of supply current and to improve the displacement factor to unity for a three-phase 415 V, 50 Hz fed 6-pulse thyristor bridge converter drawing 100 A constant dc current at 30° firing angle of its thyristors as shown in Fig. Calculate (a) fundamental active power drawn by the load, (b) fundamental reactive power drawn by the load, (c) values of filter elements, (d) THD of supply current, and (e) THD of load voltage, (f) the voltage, current and VA rating of the passive filter. Let the supply has 5% source impedance mainly inductive.



(Refer Slide Time: 22:28)



(Refer Slide Time: 22:50)

Solution: Given that, supply voltage, $V_s = 415/\sqrt{3} = 239.6$ V rms, frequency of supply, $f = 50$ Hz, with a source impedance of 5% mainly inductive feeding a nonlinear load of 415 V, 50 Hz three-phase thyristor bridge converter with constant dc current of 100 A at 30° firing angle of its thyristors.

In this system, the load current harmonics and reactive power compensation is provided by a three-phase three branch shunt passive filter (PF) (5th, 7th and high pass damped filter) to reduce the THD of the supply current and to improve the displacement factor close to unity.

The ac load rms current is as, $I_L = I_{dc}\sqrt{2/\sqrt{3}} = 81.65$ A.



(Refer Slide Time: 23:30)


The fundamental rms input current of thyristor bridge converter is as, $I_{L1} = (\sqrt{6}/\pi) I_L = 0.7797 \cdot 100 = 77.98 \text{ A}$.

The fundamental active component of load current is as, $I_{L1a} = I_{L1} \cos \alpha = 77.98 \cos 30^\circ = 67.52 \text{ A}$.

The fundamental active power of the load is as, $P_1 = 3V_{s1} I_{L1} \cos \theta_1 = 3V_{s1} I_{L1} \cos \alpha = 3 \cdot 239.6 \cdot 67.52 = 48536.05 \text{ W}$.

The fundamental reactive power of the load is as, $Q_1 = 3V_{s1} I_{L1} \sin \theta_1 = 3V_{s1} I_{L1} \sin \alpha = 3 \cdot 239.6 \cdot 77.98 \cdot 0.5 = 28026.01 \text{ VAR}$.

The source impedance is as, $Z_s = jX_s = j0.05 \cdot 239.6 / 81.6 = j0.1468 \Omega$.



(Refer Slide Time: 24:23)


The voltage drop in the source impedance is as, $V_{zs} = j67.52 \cdot 0.1468 = j9.91 \text{ V}$.

The fundamental voltage across the load is as, $V_L = \sqrt{V_s^2 - V_{zs}^2} = 239.17 \approx 239.2 \text{ V}$.

The passive shunt filter has three branch shunt passive filter (PF) (5th, 7th and high pass damped filter). The reactive power of 28026.01 VAR required by three-phase thyristor rectifier has to be provided by all three branches of the passive shunt filter. Considering that all three branches of the passive filter has equal capacitors, therefore, the value of this capacitor is as,

$C = Q_1 / (9V_s^2 \omega) = 28026.01 / (9 \cdot 239.6^2 \cdot 314) = 172.75 \mu\text{F}$.

$C_5 = C_7 = C_H = C = 172.75 \mu\text{F}$.



(Refer Slide Time: 25:32)

Therefore, the value of an inductor for 5th harmonic tuned filter is as,

$$L_5 = 1/(\omega_5^2 C_5) = 2.35 \text{ mH.}$$

The resistance of the inductor of 5th harmonic tuned filter is as,

$$R_5 = X_5/Q_5 = 3.687/30 = 0.1229 \Omega. \text{ (Considering } Q_5 = 30 \text{ as it may be in the range of 10-100 depending upon the design of the inductor)}$$

The 5th harmonic current in the supply is as,

$$I_{s5} = I_{L5} * Z_{PF5} / (Z_{PF5} + Z_{s5}) = (I_{L1}/5) R_5 / (R_5 + jX_{s5}) = (77.98/5) * 0.1229 / \sqrt{0.1229^2 + (5 * 0.1468)^2} = 2.5765 \text{ A.}$$



The 5th harmonic voltage at PCC is as,

$$V_{s5} = I_{s5} * Z_{s5} = 2.5765 * 5 * 0.1468 = 1.89 \text{ V.}$$

(Refer Slide Time: 26:58)

The value of an inductor for high pass damped harmonic filter (tuned at 11th harmonic) is as,

$$L_H = 1/(\omega_{11}^2 C_H) = 0.4852 \text{ mH.}$$

The resistance in parallel of an inductor of a high pass damped harmonic tuned filter is as,

$$R_H = X_H/Q_H = 1.676/2 = 0.835 \Omega. \text{ (Considering } Q_H = 5 \text{ as it may be in the range of 0.5-5 depending upon the attenuation required).}$$

All other harmonics load currents to flow in to high pass damped harmonic filter is as,

$$I_{LH} = \sqrt{[I_L^2 - I_{L1}^2 - I_5^2 - I_7^2]} = \sqrt{[81.65^2 - 77.98^2 - (77.98/5)^2 - (77.98/7)^2]} = \sqrt{218.51} = 14.78 \text{ A.}$$



$$I_{sH} = I_{LH} * Z_{PFH} / (Z_{PFH} + Z_{sH}) = (I_{LH}) R_H / (R_H + jX_{sH}) = (14.78) * 0.835 / \sqrt{0.835^2 + (11 * 0.1468)^2} = 6.837 \text{ A.}$$

(Refer Slide Time: 27:52)


The high pass harmonic voltage at PCC is as,
 $V_{sH} = I_{sH} * Z_{sH} = 6.837 * 11 * 0.1468 = 11.035 \text{ V.}$

$THD_{I_s} = \{\sqrt{(I_{s5}^2 + I_{s7}^2 + I_{sH}^2)} / I_{s1}\} = 0.1091 = 10.91\%.$

$THD_{V_L} = [\sqrt{\{(X_{s5} I_{s5})^2 + (X_{s7} I_{s7})^2 + (X_{sH} I_{sH})^2\}} / V_{s1}] = 4.69\%.$


The current rating of the passive shunt filter is as,
 $I_{PF} = \sqrt{[I_L^2 - I_{L1a}^2 - I_{s5}^2 - I_{s7}^2 - I_{sH}^2]} = 45.309 \text{ A.}$

The VA rating of the passive shunt filter is as,
 $VA_{PF} = 3 V_{PF} * I_{PF} = 3 * 239.6 * 45.309 = 32568 \text{ VA.}$



(Refer Slide Time: 28:43)

8. A three-phase one branch shunt passive filter (11th order high pass damped filter) is employed to reduce the THD of supply current and to improve the displacement factor to unity of a three-phase 415 V, 50 Hz, nonlinear load consisting of a 12-pulse thyristor bridge converter with 200 A constant dc current at 30° firing angle of its thyristors as shown in Fig. This converter consists of an ideal transformer with single primary star connected winding and two secondary windings connected in star and delta with same line voltages to provide 30° phase shift between two sets of three-phase output voltages. Two 6-pulse thyristors bridges are connected in series to form this 12-pulse ac-dc converter. Calculate (a) fundamental active power drawn by the load, (b) fundamental reactive power drawn by the load, (c) values of filter elements, (d) THD of supply current with the passive filter, and (e) THD of load voltage with the passive filter, (f) the voltage, current and VA rating of the passive filter. Let the supply has 5% source impedance mainly inductive.

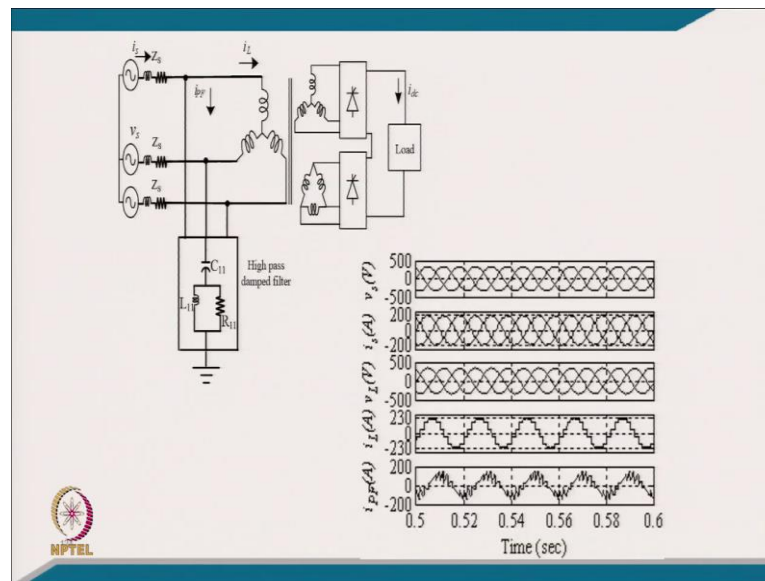


Now, coming to the 8th numerical problem, a three phase one branch shunt passive filter 11th order high pass damped filter is employed to reduce the THD of the supply current and to improve the displacement factor to unity of three phase 415 Volt, 50 Hertz, non-linear load consisting of 12 pulse thyristor converter the 200 Ampere constant dc current at 30 degree firing angle of its thyristor as shown in figure. And the converter consists of ideal transformer with single primary star connected winding and two secondary winding connected in star and delta with same line voltage to provide 30 degree phase shift between the two sets of three phase output voltage. The two 6 pulse thyristor bridges are

connected in series to form this 12 pulse ac dc converter. Calculate a fundamental active power drawn by the load, fundamental reactive power drawn by the load, value of filter elements, total harmonic distortion of supply current with the passive filter, the total harmonic distortion of voltage with passive filter, voltage, current and VA rating of the passive filter.

Let the supply has a 5 percent source impedance mainly inductive.

(Refer Slide Time: 29:49)



The solution to the numerical is detailed in the screenshots.

(Refer Slide Time: 30:23)

Solution: Given that, $V_s = 415/\sqrt{3} = 239.6$ V, Frequency of the supply, $f = 50$ Hz, $I_{dc} = 200$ A, $\alpha = 30^\circ$.

In three-phase 12-pulse thyristor bridge converter, the waveform of the input ac current (I_s) is a stepped waveforms as (i) first step of $\pi/6$ angle {from α to $(\alpha+\pi/6)$ } and input current magnitude of $(I_{dc}/\sqrt{3})$, (ii) second step of $\pi/6$ angle {from $(\alpha+\pi/6)$ to $(\alpha+\pi/3)$ } and input current magnitude of $\{I_{dc}(1+1/\sqrt{3})\}$, (iii) third step of $\pi/6$ angle {from $(\alpha+\pi/3)$ to $(\alpha+\pi/2)$ } and input current magnitude of $\{I_{dc}(1+2/\sqrt{3})\}$ and it has all four symmetric segments of such steps.

Therefore, rms of 12-pulse converter input current is as,
 $I_s = 1.57735 I_{dc} = 315.47$ A.

(Refer Slide Time: 31:22)

Moreover, the rms of 12-pulse converter fundamental ac current is as,

$$I_{s1} = \{(2\sqrt{6})/\pi\}I_{dc} = 1.559393I_{dc} = 311.879 \text{ A.}$$

Active power component of supply current is as,

$$I_{s1a} = I_{s1} \cos \theta_1 = I_{s1} \cos \alpha$$
$$I_{s1a} = 155.94 \cos 30^\circ = 270.095 \text{ A.}$$

(a) The active power drawn by the load is as,

$$P = 3V_s I_{s1} \cos \theta_1 = 194.145 \text{ kW.}$$


(b) The fundamental reactive power is as,

$$Q_1 = 3V_s I_{s1} \sin \theta_1 = 3V_s I_{s1} \sin \alpha = 112.089 \text{ kVAR.}$$

The source impedance is as,

$$Z_s = jX_s = j0.05 * 239.6 / 315.47 = j0.038 \Omega.$$

The voltage drop in the source impedance is as,

$$V_{zs1} = j270.095 * 0.038 = j10.257 \text{ V.}$$


(Refer Slide Time: 32:52)

The fundamental voltage across the load is as,

$$V_L = \sqrt{(V_s^2 - V_{zs}^2)} = 239.38 \approx 239.6 \text{ V.}$$


(c) The passive shunt filter has one branch shunt passive filter (PF) (11th order high pass damped filter). The value of this capacitor is as,

$$C = Q_1 / (3V_s^2 \omega) = 112089 / (3 * 239.6^2 * 314) = 2071.659 \mu\text{F.}$$
$$C_H = C = 2071.659 \mu\text{F.}$$

The value of an inductor for high pass damped harmonic filter (tuned at 11th harmonic) is as,

$$L_H = 1 / (\omega_{11}^2 C_H) = 0.040 \text{ mH.}$$

The resistance in parallel of an inductor of a high pass damped harmonic tuned filter is as,


$$R_H = X_H / Q_H = 0.07 \Omega. \text{ (Considering } Q_H = 2)$$


(Refer Slide Time: 33:47)

All other harmonics load currents to flow in to high pass damped harmonic filter is as,

$$I_{LH} = \sqrt{I_s^2 - I_{s1}^2} = \sqrt{315.47^2 - 311.879^2} = 47.464 \text{ A.}$$
$$I_{sH} = I_{LH} * Z_{PFH} / (Z_{PFH} + Z_{sH}) = (I_{LH})R_H / (R_H + jX_{sH})$$
$$= (47.464) * 0.07 / \sqrt{0.07^2 + (11 * 0.038)^2} = 7.839 \text{ A.}$$

The high pass harmonic voltage at PCC is as,


$$V_{sH} = I_{sH} * Z_{sH} = 7.839 * 11 * 0.038 = 3.277 \text{ V}$$
$$THD_{I_s} = \{\sqrt{I_{sH}^2} / I_{s1a}\} = 0.029 = 2.902\%.$$
$$THD_{V_L} = [\sqrt{(X_{sH} I_{sH})^2} / V_{s1}] = .014 = 1.368\%.$$


(Refer Slide Time: 34:35)


The current rating of the passive shunt filter is as,

$$I_{PF} = \sqrt{I_s^2 - I_{s1a}^2 - I_{sH}^2} = 162.815 \text{ A.}$$

The VA rating of the passive shunt filter is as,

$$VA_{PF} = 3V_{PF} * I_{PF} = 3V_S * I_{PF}$$
$$= 3 * 239.6 * 162.815 = 117.031 \text{ kVA.}$$


(Refer Slide Time: 35:06)

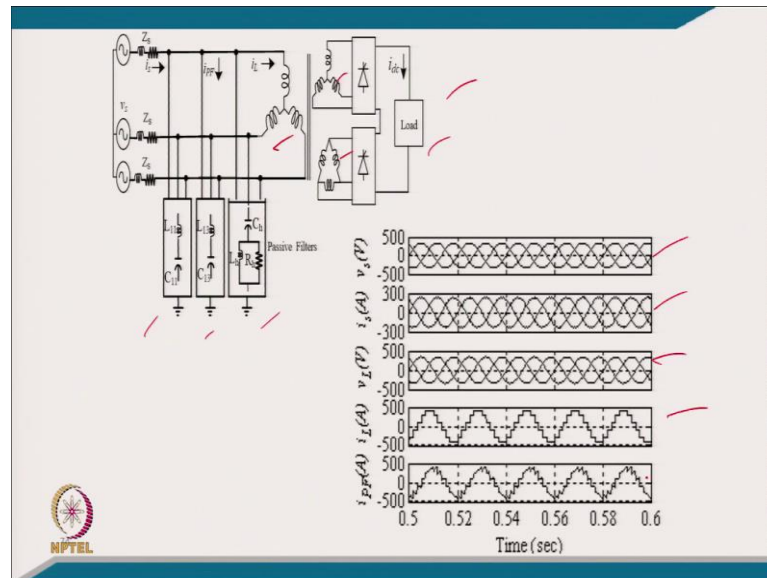


9. A three-phase three branch shunt passive filter (tuned 11th, 13th and high pass) is employed to reduce the THD of supply current and to improve the displacement factor to unity of a three-phase 415 V, 50 Hz, nonlinear load consisting of a 12-pulse thyristor bridge converter with 200 A constant dc current at 60° firing angle of its thyristors as shown in Fig. This converter consists of an ideal transformer with single primary star connected winding and two secondary windings connected in star and delta with same line voltages to provide 30° phase shift between two sets of three-phase output voltages. Two 6-pulse thyristors bridges are connected in series to form this 12-pulse ac-dc converter. Calculate (a) fundamental active power drawn by the load, (b) fundamental reactive power drawn by the load, (c) values of filter elements, (d) THD of supply current with the passive filter, and (e) THD of load voltage with the passive filter, (f) the voltage, current and VA rating of the passive filter. Let the supply has 5% source impedance mainly inductive.

Coming to example 9, a three phase three branch shunt passive filter tuned for 11th and 13th and high pass is employed to reduce the THD of supply current and to improve the displacement factor to unity of three phase 415 Volt, 50 Hertz non-linear load consisting of 12 pulse thyristor bridge converter with 200 Ampere constant dc current at 60 degree firing angle of its thyristor as shown in figure. This converter consists of ideal transformer with single primary star connected winding and two secondary is connected in star and delta with the same line voltage to provide 30 degree phase shift between two sets of three phase output voltage. [FL] two single pulse two 6 pulse thyristor bridges are connected in series to form a 12 pulse ac dc converter. Calculate a fundamental active power drawn by the load; b fundamental reactive power drawn by the load; c the value of filter elements; d the THD of supply current with the passive filter; and e the THD of load voltage with the passive filter; f the voltage current and VA rating of the passive filter.

Let the supply has a 5 percent source impedance mainly inductive.

(Refer Slide Time: 36:08)



The solution to the numerical is detailed in the screenshots.

(Refer Slide Time: 36:30)

Solution: Given that, supply rms voltage, $V_s = 415/\sqrt{3} = 239.6$ V, frequency of the supply, $f = 50$ Hz, $I_{dc} = 200$ A, $\alpha = 60^\circ$.

In a three-phase 12-pulse thyristor bridge converter, the waveform of the input ac current (I_s) is a stepped waveform as (i) first step of $\pi/6$ angle {from α to $(\alpha+\pi/6)$ } and input current magnitude of $(I_{dc}/\sqrt{3})$, (ii) second step of $\pi/6$ angle {from $(\alpha+\pi/6)$ to $(\alpha+\pi/3)$ } and input current magnitude of $\{I_{dc}(1+1/\sqrt{3})\}$, (iii) third step of $\pi/6$ angle {from $(\alpha+\pi/3)$ to $(\alpha+\pi/2)$ } and input current magnitude of $\{I_{dc}(1+2/\sqrt{3})\}$ and it has all four symmetric segments of such steps.

Therefore, rms of 12-pulse converter input current is as,
 $I_s = I_L = 1.57735 I_{dc} = 315.47$ A.

(Refer Slide Time: 37:25)

Moreover, the rms of 12-pulse converter fundamental ac current is as, $I_{s1} = I_{L1} = \{(2\sqrt{6})/\pi\}I_{dc} = 1.559393I_{dc} = 311.8786 \text{ A}$.


Active power component of supply current is as, $I_{s1a} = I_{s1} \cos \theta_1 = I_{s1} \cos \alpha = 311.8786 \cos 60^\circ = 155.9393 \text{ A}$.

(a) The active power drawn by the load is as, $P = 3V_s I_{s1} \cos \theta_1 = 112.08895 \text{ kW}$.

(b) The fundamental reactive power is as, $Q_1 = 3V_s I_{s1} \sin \theta_1 = 3V_s I_{s1} \sin \alpha = 194.1437 \text{ kVAR}$.

The source impedance is as, $Z_s = jX_s = j0.05 * 239.6 / 315.47 = j0.037975 \Omega$.

The voltage drop in the source impedance is as, $V_{zs} = 155.9393 * 0.037975 = j5.922 \text{ V}$.




(Refer Slide Time: 38:18)

The fundamental voltage across the load is as, $V_L = \sqrt{(V_s^2 - V_{zs}^2)} = 239.53 \approx 239.6 \text{ V}$.

(c) The passive shunt filter has three branch shunt passive filter (PF) (11th, 13th and high pass damped filter). The reactive power of 194143.7 VAR required by three-phase thyristor rectifier has to be provided by all nine branches of the passive shunt filter. Considering that all branches of the passive filter has equal capacitors, therefore, the value of this capacitor is as,

$$C = Q_1 / (9V_s^2 \omega) = 194143.7 / (9 * 239.6^2 * 314) = 1196.68 \mu\text{F}$$

$C_{11} = C_{13} = C_H = C = 1196.68 \mu\text{F}$.



(Refer Slide Time: 39:04)

Therefore, the value of an inductor for 11th harmonic tuned filter is as,

$$L_{11} = 1 / (\omega_{11}^2 C_{11}) = 0.07 \text{ mH.}$$


The resistance of the inductor of 11th harmonic tuned filter is as,

$$R_{11} = X_{11} / Q_{11} = 0.2419 / 20 = 0.0121 \Omega. \text{ (Considering } Q_{11} = 20 \text{ as it may be in the range of 10-100 depending upon the design of the inductor).}$$

The 11th harmonic current in the supply is as,

$$I_{s11} = I_{L11} Z_{PF11} / (Z_{PF11} + Z_{s11}) = (I_{L11} / 11) R_{11} / (R_{11} + jX_{s11}) = (311.88 / 11) * 0.0121 / \sqrt{(0.0121^2 + (11 * 0.037975)^2)} = 0.821 \text{ A.}$$

The 11th harmonic voltage at PCC is as,

$$V_{s11} = I_{s11} * Z_{s11} = 0.821 * 11 * 0.037975 = 0.343 \text{ V}$$


(Refer Slide Time: 39:38)

Therefore, the value of an inductor for 13th harmonic tuned filter is as,

$$L_{13} = 1 / (\omega_{13}^2 C_{13}) = 0.0502 \text{ mH.}$$


The resistance of the inductor of 13th harmonic tuned filter is as,

$$R_{13} = X_{13} / Q_{13} = 0.2047 / 20 = 0.01024 \Omega. \text{ (Considering } Q_{13} = 20 \text{ as it may be in the range of 10-100 depending upon the design of the inductor).}$$

The 13th harmonic current in the supply is as,

$$I_{s13} = I_{L13} * Z_{PF13} / (Z_{PF13} + Z_{s13}) = (I_{L13} / 13) R_{13} / (R_{13} + jX_{s13}) = (311.88 / 13) * 0.01024 / \sqrt{(0.01024^2 + (13 * 0.0379)^2)} = 0.497 \text{ A.}$$

The 13th harmonic voltage at PCC is as,

$$V_{s13} = I_{s13} * Z_{s13} = 0.497 * 13 * 0.0379 = 0.2455 \text{ V}$$


(Refer Slide Time: 40:14)

The value of an inductor for high pass damped harmonic filter (tuned at 23rd harmonic) is as,


$$L_H = 1/(\omega_{23}^2 C_H) = 0.016 \text{ mH.}$$

The resistance in parallel of an inductor of a high pass damped harmonic tuned filter is as,

$$R_H = X_H/Q_H = 0.1157/2 = 0.0579 \Omega. \text{ (Considering } Q_H = 2 \text{ as it may be in the range of } 0.5\text{-}5 \text{ depending upon the attenuation required).}$$

All other harmonics load currents to flow in to high pass damped harmonic filter is as,

$$I_{LH} = \sqrt{[I_L^2 - I_{L1}^2 - I_{11}^2 - I_{13}^2]} = \sqrt{[315.47^2 - 311.88^2 - (311.88/11)^2 - (311.88/13)^2]} = 29.54 \text{ A.}$$

$$I_{SH} = I_{LH} * Z_{PFH} / (Z_{PFH} + Z_{SH}) = (I_{LH})R_H / (R_H + jX_{SH}) = (29.54) * 0.0579 / \sqrt{0.0579^2 + (23 * 0.0379)^2} = 1.958 \text{ A.}$$


(Refer Slide Time: 40:54)

The high pass harmonic voltage at PCC is as,

$$V_{SH} = I_{SH} * Z_{SH} = 1.958 * 23 * 0.0379 = 1.71 \text{ V}$$


$$THD_{I_s} = \{ \sqrt{(I_{s11}^2 + I_{s13}^2 + I_{SH}^2)} / I_{s1a} \} = 0.014 = 1.4\%.$$

$$THD_{V_L} = [\sqrt{ \{ (X_{s11} I_{s11})^2 + (X_{s13} I_{s13})^2 + (X_{SH} I_{SH})^2 \} } / V_{s1}] = 0.0074 = 0.74 \%$$

The current rating of the passive shunt filter is as,


$$I_{PF} = \sqrt{[I_s^2 - I_{s1a}^2 - I_{s11}^2 - I_{s13}^2 - I_{SH}^2]} = 274.14 \text{ A.}$$

The VA rating of the passive shunt filter is as,

$$VA_{PF} = 3V_{PF} * I_{PF} = 3 * 239.6 * 274.14 = 197060 \text{ VA.}$$


(Refer Slide Time: 46:10)

11. An industry is fed electric power from a three-phase 33 kV, 50 Hz ac mains. The data of the supply feeder are as: short-circuit level 150 MVA and an X/R ratio of 3. A step-down transformer is placed between ac mains and this industry with a rating of 1500 kVA, 33 kV/440 V, $R = 1\%$ and $X = 5\%$. A 300 kVA, 440 V, three-phase thyristor bridge converter fed dc motor drive is used in this industry along with other linear loads as shown in Fig. If a 1000 kVAR ac capacitor bank is used at the PCC for power factor correction of the industry, calculate (a) PCC voltage and its THD without capacitor bank, (b) PCC voltage and its THD with the capacitor bank, and (c) current in the capacitor bank. The harmonic spectrum of ac current of 300 kVA, 440 V, three-phase thyristor bridge converter fed dc motor drive is given in Table-E8.20-1.




Coming to now another numerical problem, an industry is fed from electric power from a three phase 33, 50 Hertz ac mains the data of the supply feeder are as short circuit impedance level is 1 150 k 50 kVA, X R upon 3. And step down transformer is placed between the ac mains and the industry with a rating of 1500 kVA, 33 kV upon 440 with the resistance of 1 percent, X equal to 5 percent at 3 kVA, 440 Volt, three phase thyristor converter, where dc motor drive is used in this industry along with the other linear load as shown in the figure. If a 1000 kVAR capacitor is used at the point of common coupling for power factor correction of the industry. Calculate the PCC voltage and its total harmonic distortion without capacitor bank, PCC voltage and total harmonic distance of capacitor at its THD with the capacitor bank and current in the capacitor bank, harmonic spectrum of ac current of the 300 kVA, 50 Hertz, three phase thyristor converter for dc type is given in the table next table.

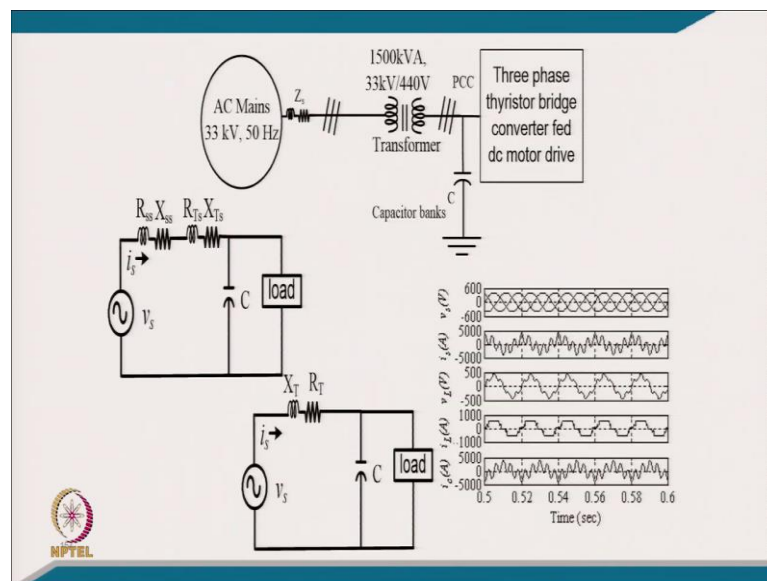
(Refer Slide Time: 47:12)

Table-E8.20-1: Harmonics Spectrum of 300 kVA, 440 V, three-phase thyristor converter fed dc motor drive

Harmonic order	Frequency (Hz)	I_h (A)
5th	250	70
7th	350	40
11th	550	20
13th	650	10
17th	850	3



(Refer Slide Time: 47:28)




The solution to the numerical is detailed in the screenshots.

(Refer Slide Time: 48:01)

Solution: Given that, a three-phase 33 kV, 50 Hz ac mains has a feeder with data as: short-circuit level 150 MVA and an X/R ratio of 3. A step-down transformer is placed between ac mains and this industry with a rating of 1500 kVA, 33 kV/440 V, R = 1% and X = 5%.

A 300 kVA, 440 V, three-phase thyristor bridge converter fed dc motor drive is used in this industry along with other linear loads. A 1000 kVAR ac capacitor bank is used at the PCC for power factor correction of the industry. The total system and its equivalent circuit are shown in Fig.




(Refer Slide Time: 48:41)

The total system and its equivalent circuit are shown in Fig. Here feeder impedance is given in terms of short circuit MVA (MVA_{SC}) and X/R ratio and voltage level.

The values of the feeder resistance and reactance in ohms are calculated as,

$$R_s = (kV_{LL}^2 / MVA_{SC}) \cos \{ \tan^{-1}(X_s / R_s) \}$$
$$= (33^2 / 150) \cos(\tan^{-1}(3)) = 2.2958 \Omega.$$
$$X_s = (kV_{LL}^2 / MVA_{SC}) \sin \{ \tan^{-1}(X_s / R_s) \}$$
$$= (33^2 / 150) \sin(\tan^{-1}(3)) = 6.8874 \Omega.$$

These data of the feeder in ohms are referred to LV side of the transformer as follows,


$$R_{ss} = R_s / n^2 = 2.2958 / (33000 / 440)^2 = 0.00040814 \Omega.$$
$$X_{ss} = X_s / n^2 = 6.8874 / (33000 / 440)^2 = 0.0012244 \Omega.$$


(Refer Slide Time: 49:21)

The equivalent circuit parameters of the transformer referred to secondary winding are calculated as,

$$R_{Ts} = R_{Trpu} (1000 \text{ kV}^2 / \text{kVA}_{Tr})$$
$$= 0.01 * 1000 * (0.440)^2 / 1500 = 0.001291 \Omega.$$
$$X_{Ts} = X_{Trpu} (1000 \text{ kV}^2 / \text{kVA}_{Tr})$$
$$= 0.05 * 1000 * (0.440)^2 / 1500 = 0.006453 \Omega.$$

Total equivalent circuit parameters of the system (shown in Fig. E8.20c) are as follows,

$$R_T = R_{ss} + R_{Ts} = 0.00040814 + 0.001291 = 0.00169914 \Omega.$$
$$X_T = X_{ss} + X_{Ts} = 0.0012244 + 0.006453 = 0.0076777 \Omega.$$
$$L_T = X_T / (2\pi f) = 24.45138 \mu\text{h}.$$


(Refer Slide Time: 49:57)

The equivalent reactance of the capacitor bank is as follows,


$$X_c = (1000 * \text{kV}_c^2) / \text{kVAR}_c = 1000 * (0.44)^2 / 1000 = 0.1936 \Omega.$$
$$C = 1 / (2\pi f X_c) = 16449.97 \mu\text{F}.$$

The magnitude of fundamental current of the converter supplying dc motor is as,

$$I_{s1} = 300 * 1000 / (\sqrt{3} * 440) = 393.65 \text{ A}.$$

•PCC voltage and its THD without capacitor bank are computed as follows.

Without capacitor bank, the supply impedance is computed at harmonics. The voltage drop because of each harmonic current of the load is computed by multiplying the supply impedance at that harmonic frequency and harmonic current. These computed values are given in a Table-E8.20-2.



(Refer Slide Time: 50:40)

Table-E8.20-2 Harmonics Voltages at PCC without capacitor bank


h	F (Hz)	R _T (Ω)	X _T (Ω)	Z _T (Ω)	I _h (A)	V _h (V)
5th	250	0.00169914	0.0383885	0.038426085	70	2.69
7th	350	0.00169914	0.0537439	0.053770753	40	2.15
11th	550	0.00169914	0.0844547	0.084471791	20	1.69
13th	650	0.00169914	0.0998101	0.099824562	10	0.99
17th	850	0.00169914	0.1305209	0.130531959	3	0.39

The rms value of the supply current is as,

$$I_{s_{rms}} = \sqrt{(393.65^2 + 70^2 + 40^2 + 20^2 + 10^2 + 3^2)} = 402.45 \text{ A.}$$

The Total Harmonic Distortion (THD) of supply current is as,

$$THD_{I_s} = \frac{\sqrt{(I_{s_{rms}}^2 - I_{s1}^2)}}{I_{s1}} = \frac{\sqrt{(402.45^2 - 393.65^2)}}{393.65} = 0.2127 = 21.27\%.$$



(Refer Slide Time: 51:21)


The rms value of the PCC voltage is as,

$$V_{s_{rms}} = \sqrt{(254^2 + 2.69^2 + 2.15^2 + 1.69^2 + 0.99^2 + 0.39^2)} = 254.0633 \text{ V.}$$

The Total Harmonic Distortion (THD) of PCC voltage is as,

$$THD_{V_s} = \frac{\sqrt{(V_{s_{rms}}^2 - V_{s1}^2)}}{V_{s1}} = \frac{\sqrt{(254.0633^2 - 254^2)}}{254} = 0.0157 = 1.57\%.$$

(b) PCC voltage and its THD with the capacitor bank
 The parallel impedance Z_i at each frequency is calculated from capacitor value and then harmonic voltage across the parallel impedance and then capacitor current from that harmonic voltage. These calculated values are given in Table-E8.20-3.




(Refer Slide Time: 52:07)

Table-E8.20-3 Harmonics Voltages at PCC with Capacitor Bank

h	f (Hz)	R_T (Ω)	$X_T = \omega L_T$ (Ω)	Z_T (Ω)	$X_C = 1/\omega C$ (Ω)	$Z = \sqrt{(R_T + X_T)^2 + (X_C - X_T)^2}$ (Ω)	I_h (A)	V_h (V)	I_C (A)
5	250	0.0016991 4	0.0383885	0.03842608 5	0.03872	0.85944949973	70	60.16	1553
7	350	0.0016991 4	0.0537439	0.05377075 3	0.02766	0.05686459737	40	02.27	82.07
11	550	0.0016991 4	0.0844547	0.08447179 1	0.01760	0.02223065231	20	0.445	25.26
13	650	0.0016991 4	0.0998101	0.09982456 2	0.01489	0.01750305258	10	0.175	11.75
17	850	0.0016991 4	0.1305209	0.13053195 9	0.01139	0.01247665779	3	0.037	3.29

The rms value of the PCC voltage is as,
 $V_{s_{rms}} = \sqrt{(254^2 + 60.16^2 + 2.27^2 + 0.445^2 + 0.175^2 + 0.037^2)} = 261.04 \text{ V.}$

The Total Harmonic Distortion (THD) of PCC voltage is as,
 $THD_{V_s} = \{\sqrt{(V_{s_{rms}}^2 - V_{s1}^2)}\} / V_{s1} = \{\sqrt{(261.04^2 - 254^2)}\} / 254 = 0.2370 = 23.70\%.$




(Refer Slide Time: 53:28)

(c) The current in the capacitor bank is calculated as,


The fundamental value of the capacitor current is as,
 $I_{c1} = 1000000 / (3 * 254) = 1332.34 \text{ A.}$

The rms capacitor current is as,
 $I_{c_{rms}} = \sqrt{(1332.34^2 + 1553.76^2 + 82.07^2 + 25.26^2 + 11.75^2 + 3.29^2)} = 2035.66 \text{ A.}$

This capacitor current is 153% of its rated current because of parallel resonance of this power factor correction capacitor with supply impedance. This magnitude of capacitor current is likely to blow the fuse of capacitor bank or its breaker to trip. It may also damage the capacitor bank.



(Refer Slide Time: 54:07)



12. An industry is fed electric power from a three-phase 33 kV, 50 Hz ac mains. The data of the supply feeder are as: short-circuit level 150 MVA and an X/R ratio of 3. A step-down transformer is placed between ac mains and this industry with a rating of 1500 kVA, 33 kV/440 V, R = 1% and X = 5%. A 300 kVA, 440 V, three-phase thyristor bridge converter fed dc motor drive is used in this industry along with other linear loads as shown in Fig. If a 1000 kVAR ac capacitor bank used at the PCC for power factor correction of the industry, is tuned to lowest harmonic (5th) passive shunt filter, calculate (a) parallel resonance frequency, (b) the filter harmonic current spectrum and rms current of the filter, (c) PCC voltage and its THD with the passive filter, and (d) rms capacitor voltage. Harmonic spectrum of input ac current of 300 kVA, 440 V, three-phase thyristor bridge converter fed dc motor drive is given in Table-E8.21-1.

Now, coming to a 12th problem, an industry is fed from electric power from a three phase 33, 50 Hertz ac mains. The data of supply feeder are, as like a short circuit current level of 150 kVA, X upon R ratio of 3. A step down transformer is placed between the ac mains and this industry of 1500 kVA, 33 kV by 440 with the resistance of 1 percent and reactance of 5 percent.


A 300 kV, 440 Volt, three phase thyristor converter bridge dc drive is used in this industry with other linear load. And if 1000 kVAR capacitor bank is used at the PCC with the power factor correction, it tuned to lowest harmonic 5th harmonics passive shunt filter. Calculate the parallel resonance frequency, the filter harmonic spectrum, current top filter PCC voltage and THD of passive filter.

The rms capacitor voltage harmonic spectrum of ac mains current of 300 kVA of this is given in table 1.

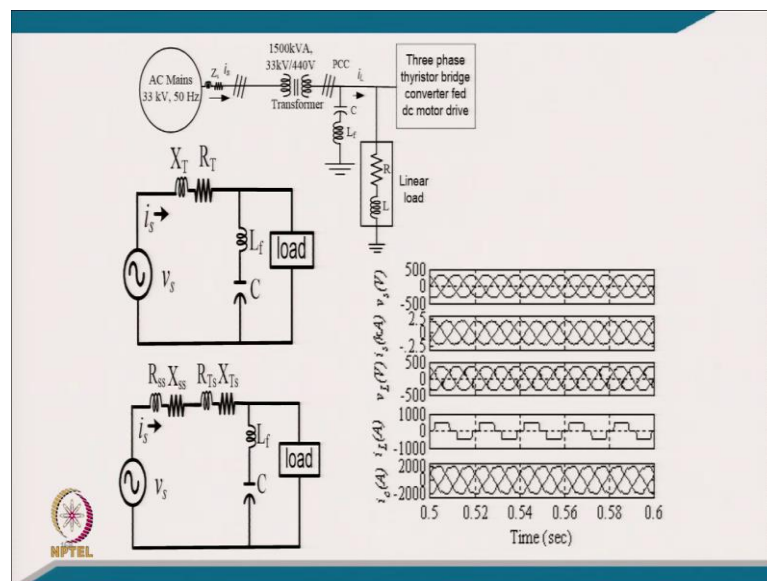
(Refer Slide Time: 54:57)

Table-E8.21-1: Harmonics Spectrum of 300 kVA, 440 V, three-phase thyristor converter fed dc motor drive

Harmonic order	Frequency (Hz)	I_h (A)
5th	250	70
7th	350	40
11th	550	20
13th	650	10
17th	850	3



(Refer Slide Time: 55:07)




The solution to the numerical is detailed in the screenshots.

(Refer Slide Time: 55:52)

Solution: Given that, a three-phase 33 kV, 50 Hz ac mains has a feeder with data as: short-circuit level 150 MVA and an X/R ratio of 3. A step-down transformer is placed between ac mains and this industry with a rating of 1500 kVA, 33 kV/440 V, R = 1% and X = 5%. A 300 kVA, 440 V, three-phase thyristor bridge converter fed dc motor drive is used in this industry along with other linear loads. A 1000 kVAR ac capacitor bank is used at the PCC for power factor correction of the industry. The total system and its equivalent circuit are shown in Fig.

Here feeder impedance is given in terms of short circuit MVA (MVA_{SC}) and X/R ratio and voltage level.

The values of the feeder resistance and reactance in ohms are calculated as,




(Refer Slide Time: 56:35)

$$R_s = (kV_{LL}^2 / MVA_{SC}) \cos \{ \tan^{-1}(X_s / R_s) \}$$
$$= (33^2 / 150) \cos \{ \tan^{-1}(3) \} = 2.2958 \Omega.$$
$$X_s = (kV_{LL}^2 / MVA_{SC}) \sin \{ \tan^{-1}(X_s / R_s) \}$$
$$= (33^2 / 150) \sin \{ \tan^{-1}(3) \} = 6.8874 \Omega.$$

These data of the feeder in ohms are referred to LV side of the transformer as follows,

$$R_{ss} = R_s / n^2 = 2.2958 / (33000 / 440)^2 = 0.00040814 \Omega.$$
$$X_{ss} = X_s / n^2 = 6.8874 / (33000 / 440)^2 = 0.0012244 \Omega.$$

The equivalent circuit parameters of the transformer referred to secondary winding are calculated as,

$$R_{Ts} = R_{Tpu} (1000 \text{ kV}^2 / kVA_{Tr})$$
$$= 0.01 * 1000 * (0.440)^2 / 1500 = 0.001291 \Omega.$$



(Refer Slide Time: 57:04)

$$X_{Ts} = X_{Trpu}(1000 \text{ kV}^2/\text{kVA}_{Tr})$$
$$= 0.05 \cdot 1000 \cdot (0.440)^2 / 1500 = 0.006453 \Omega.$$

Total equivalent circuit parameters of the system (shown in Fig.) are as follows,

$$R_T = R_{ss} + R_{Ts} = 0.00040814 + 0.001291 = 0.00169914 \Omega.$$
$$X_T = X_{ss} + X_{Ts} = 0.0012244 + 0.006453 = 0.0076777 \Omega.$$
$$L_T = X_T / (2\pi f) = 24.45138 \mu\text{H}.$$

The equivalent reactance of the capacitor bank is as follows,


$$X_c = (1000 \cdot \text{kV}_c^2) / \text{kVAR}_c = 1000 \cdot (0.44)^2 / 1000$$
$$= 0.1936 \Omega.$$
$$C = 1 / (2\pi f X_c) = 16449.97 \mu\text{F}.$$


(Refer Slide Time: 57:43)

The passive shunt tuned filters are tuned at a frequency 5% to 10% lower than actual harmonic present to be reduced in the system. Normally 5th harmonic filter is tuned at 4.7th order frequency of the supply system. Therefore, tuning 5th harmonic filter at 4.7th order frequency of the supply system, the inductor of the filter is calculated as,

$$L_f = 1 / \{(4.7 \cdot 2 \cdot \pi \cdot f)^2 \cdot C\} = 1 / \{(4.7 \cdot 2 \cdot \pi \cdot 50)^2 \cdot 16449.97 \cdot 10^{-6}\} = 27.883 \mu\text{H}.$$
$$X_{Lf} = 2 \cdot \pi \cdot f \cdot L_f = 0.0087597 \Omega.$$

The magnitude of fundamental current of the converter supplying dc motor is as,

$$I_{s1} = 300 \cdot 1000 / (\sqrt{3} \cdot 440) = 393.65 \text{ A}.$$


(Refer Slide Time: 58:36)


(a) The parallel resonance frequency with passive tuned filter can be calculated as,

Total impedance of the equivalent circuit shown in Fig.8.21c at any frequency ω_a can be calculated as,

$$Z_i = \frac{[(R_T + j\omega_a L_T) \{j\omega_a L_f - j/(\omega_a C)\}]}{R_T + j\omega_a L_T + j\omega_a L_f - j/(\omega_a C)}$$

where L_f is the value of the filter inductor.


Under parallel resonance, the denominator of impedance Z_i must be minimum value or its imaginary part of its denominator is equal to zero. It will be of minimum value at a frequency ω_r , when an inductance reactance is equal to capacitive reactance.



(Refer Slide Time: 59:15)

$$\omega_r(L_T + L_f) = 1/(\omega_r C), \quad \omega_r = 1/\sqrt{(L_T + L_f)C}, \quad \text{and}$$
$$f_r = \omega_r/(2\pi) = 1/[2\pi\sqrt{(L_T + L_f)C}]$$
$$= 1/[2\pi\sqrt{\{(24.45138 \times 10^{-6} + 27.883 \times 10^{-6}) \times 16449.97 \times 10^{-6}\}}]$$
$$= 171.51 \text{ Hz.}$$

This parallel resonance phenomenon is now avoided from 5th harmonic and it is shifted to occur this parallel resonance frequency (f_r) at a value less than the lowest order harmonic current present in the harmonic producing loads at 3.43 order harmonic. Therefore, this shifting of parallel resonance frequency (f_r) to much lower frequency (3.43 order harmonic) than harmonics present in the loads, avoids the amplification of harmonic current and PCC voltage distortion is minimized in the system.




(Refer Slide Time: 60:08)

(b) The filter harmonic current spectrum and rms current of the filter can be calculated as follows.

The fundamental current of the filter can be calculated as,

$$I_{f1} = \text{Nominal phase voltage} / \{j\omega_s L_f - j/(\omega_s C)\}$$
$$= (440/\sqrt{3}) / \{j[2\pi \cdot 50 \cdot 27.883 \cdot 10^{-6}] - 1/(2\pi \cdot 50 \cdot 16449.97 \cdot 10^{-6})\}$$
$$= 254 / \{j(0.008755262 - 0.19360)\} = 1374.13 \text{ A.}$$

The currents flowing in the harmonic filter at any frequency ω_a calculated from following relation.

$$I_{fn} = I_h (R_T + j\omega_a L_T) / \{R_T + j\omega_a L_T + j\omega_a L_f - j/(\omega_a C)\}$$


(Refer Slide Time: 60:58)

Using this equation, harmonics currents in the passive filter is calculated and shown in Table-E8.21-2.

The rms filter current is as,

$$I_{frms} = \sqrt{(1374.13^2 + 61.58^2 + 24.60^2 + 10.35^2 + 5.02^2 + 1.46^2)}$$
$$= 1375.78 \text{ A.}$$


The rated current of the capacitor is as,

$$I_{crms} = 1000000 / (3 \cdot 254) = 1312.34 \text{ A.}$$

The rms filter current as % of rated current of the capacitor is as,

$$I_{frms} / I_{crms} = 1375.78 / 1312.34 = 1.04834 = 104.834\%$$

This filter current flowing through the capacitor is only 105% of its rated current, which is well within its considered rating.




(Refer Slide Time: 61:50)

Table-E8.21-2 Harmonics Voltages at PCC with Passive Filter

h	f (Hz)	R _T (Ω)	X _C =ω _a L _T (Ω)	Z _T (Ω)	X _C =1/ωC (Ω)	X _C =ω _a L _T (Ω)	I _h (A)	I _h (A)	I _h (A)	V _h (V)	V _h (V)	V _h (V)
5	250	0.00169914	0.0383885	0.038426085	0.03872	0.0437965	70	61.5	08.14	0.313	2.384	2.697
7	350	0.00169914	0.0537439	0.053770753	0.02766	0.0613179	40	24.6	15.40	0.828	0.681	1.509
11	550	0.00169914	0.0844547	0.084471791	0.01760	0.0963567	20	10.3	09.05	0.815	0.182	0.997
13	650	0.00169914	0.0998101	0.099824562	0.01489	0.1138761	10	05.0	04.98	0.497	0.075	0.572
17	850	0.00169914	0.1305209	0.130531959	0.01139	0.1489149	3	01.4	01.54	0.201	0.017	0.217

(c) The PCC voltage and its THD with the passive filter

For calculation of the voltage distortion, harmonics currents flowing in to the supply system at a frequency ω_a are computed and shown in Table-E8.21-2 from these relations,



(Refer Slide Time: 62:36)

$$I_{sh} = I_h(j\omega_a L_f - j/(\omega_a C)) / \{R_T + j\omega_a L_T + j\omega_a L_f - j/(\omega_a C)\}$$

The fundamental PCC voltage is as,

$$V_{s1} = 440/\sqrt{3} = 254 \text{ V.}$$

The harmonic voltage at each harmonic present at PCC may be calculated as,


$$V_h = I_{sh} (R_T + j\omega_a L_T)$$

These equations are used to calculate all harmonic voltages to find THD of the PCC voltage and calculated values are given Table-E8.21-2.

The rms value of the supply current is from Table-E8.21-2 as,

$$I_{s_{rms}} = \sqrt{(393.65^2 + 8.14^2 + 15.4^2 + 9.65^2 + 4.98^2 + 1.54^2)} = 394.187 \text{ A.}$$

The THD of the supply current is as,

$$THD_{I_s} = [\sqrt{(393.187^2 - 393.65^2)}] / 393.65 = 0.0522 = 5.22\%.$$


(Refer Slide Time: 63:31)

The rms value of the PCC voltage is from Table-E8.21-2 as,


$$V_{\text{srms}} = \sqrt{(254^2 + 0.313^2 + 0.828^2 + 0.815^2 + 0.497^2 + 0.201^2)} = 254.003415 \text{ V.}$$

The THD of the PCC voltage is as,

$$\text{THD}_{V_s} = \frac{[\sqrt{(254.003415^2 - 254^2)}]}{254} = 0.005186 = 0.518 \%$$

This THD distortion in PCC voltage of 0.5186% is reduced from 2.234% without the filter. This THD distortion in PCC voltage of 0.5186% is also reduced from 23.70% in case of power factor correction capacitor.

(d) The rms capacitor voltage
The fundamental current filter can be calculated as,




(Refer Slide Time: 64:33)

$$I_{f1} = \text{Nominal phase voltage} / \{j\omega_s L_f - j/(\omega_s C)\}$$
$$= (440/\sqrt{3}) / \{j[2\pi \cdot 50 \cdot 27.883 \cdot 10^{-6}] - 1/(2\pi \cdot 50 \cdot 16449.97 \cdot 10^{-6})\}$$
$$= 254 / \{j(0.008755262 - 0.19360)\} = 1374.13 \text{ A.}$$

The fundamental capacitor voltage is as,

$$V_{c1} = I_{f1} \cdot X_{c1} = 1374.13 / (2\pi \cdot 50 \cdot 16449.97 \cdot 10^{-6})$$
$$= 1374.13 \cdot 0.19360 = 266.032 \text{ V.}$$

The harmonics voltages across the capacitor and an inductor is calculated as, $V_{Ch} = I_{fh} / (\omega_h C)$ and $V_{Lh} = I_{fh} \omega_h L_f$
These relations are used to compute harmonic voltages of the filter capacitor and inductor elements and are given Table-E8.21-2.



(Refer Slide Time: 64:55)


The rms voltage across the capacitor is as,

$$V_{\text{crms}} = \sqrt{(266.032^2 + 2.384^2 + 0.681^2 + 0.182^2 + 0.075^2 + 0.017^2)}$$
$$= 266.04 \text{ V.}$$

The rms capacitor voltage as percentage of rated voltage is as,

$$V_{\text{crms}}/V_S = 266.04319/254 = 1.04741 = 104.741\%.$$


As the voltage across the filter capacitor is higher by 4.741% and therefore, this capacitor is selected of high voltage rating. However, fundamental reactive power rating has to be derated as,

$$kVAR_A = kVAR_N (f_A/f_N) (V_A/V_N)^2$$
$$= 1000(50/50)(266.04319/254)^2 = 1097.076 \text{ kVARs.}$$


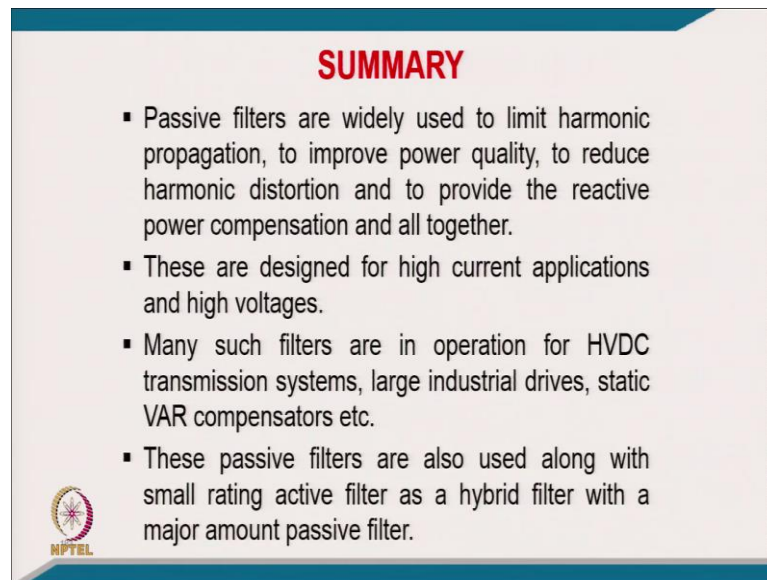
(Refer Slide Time: 65:19)

where A represents actual and N represents nominal or rated quantities.

Therefore, a capacitor bank of 1097.076 kVARs has to be used in place of 1000 kVARs, it means 9.7076% derating has to be there for the capacitor bank.




(Refer Slide Time: 65:34)



SUMMARY

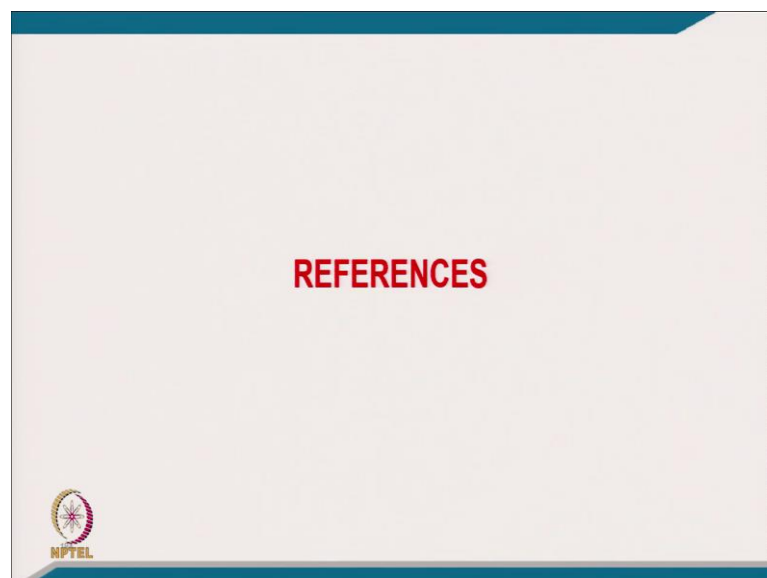
- Passive filters are widely used to limit harmonic propagation, to improve power quality, to reduce harmonic distortion and to provide the reactive power compensation and all together.
- These are designed for high current applications and high voltages.
- Many such filters are in operation for HVDC transmission systems, large industrial drives, static VAR compensators etc.
- These passive filters are also used along with small rating active filter as a hybrid filter with a major amount passive filter.

 NPTEL


Passive filter are widely used to limit the harmonic propagation, to improve the power quality, and to reduce the harmonic distortion and to provide the reactive power compensation and all together. And there are these are designed for high current applications and high voltage like HVDC and high rating current source converter one.

And many such filters are in operation for HVDC transmission system, large industrial drive, static VAR compensator. And these passive filters are also used along with the small rating active filter as a hybrid filter with a major amount of passive filter.

(Refer Slide Time: 66:07)




REFERENCES

 NPTEL

(Refer Slide Time: 66:09)

- 1) Bhim Singh, Anbesh Chandra and Kamal Al-Haddad, *Power Quality: Problems and Mitigation Techniques*, John Wiley & Sons Ltd, U.K, 2015.
- 2) E.W. Kimbark, *Direct Current Transmission, Vol. 1*, John Wiley & Sons, New York, 1971
- 3) Theodore R. Bolesta, *Introduction to Electrical Power System Technology*, Prentice Hall, New Jersey, USA, 1997
- 4) J.C. Das, *Power System Analysis-Short-Circuit Load Flow and Harmonics*, Marcel Dekker Inc. New York, 2002.
- 5) IEEE Guide for Application and Specification of Harmonic Filters, IEEE Standard 1573, 2003
- 6) R. Sastry Vadam and Mulakutla S. Sarma, *Power Quality VAR compensation in power Systems*, CRC Press, New York, 2008.
- 7) D.E. Steeper and R.P. Stratford, "Reactive Compensation, Harmonic Suppression for Industrial Power Systems Using Thyristor Converters," *IEEE Trans. on Industry Applications*, vol.12, no.3, pp.232-254, May/June 1976.
- 8) D.D. Shipp, "Harmonic Analysis, Suppression for Electrical Systems Supplying Static Power Converters, Other Non-Linear Loads," *IEEE Trans. on Industry Applications*, vol.15, no.5, pp.453-458, Sept./Oct. 1979
- 9) S.B. Dewan and E. B. Shatrook, "Design of an input filter for the Six-Pulse Bridge Rectifier," *IEEE Trans on Industry Applications*, vol. IA-21, no. 5, pp. 1168-1175, Sept/Dec. 1985.
- 10) D. A. Gonzalez and J.C. Maccoall, "Design of Filters to Reduce Harmonic Distortion in Industrial Power Systems," *IEEE Transactions on Industry Applications*, vol. IA-23, no. 3, pp. 504-511, May/June 1987
- 11) P. W. Hammond, "A harmonic filter installation to reduce voltage distortion from static power converters," *IEEE Trans on Industry Applications*, vol. 24, no. 1, pp. 53-58, Jan/Feb. 1988.
- 12) A. Ludbrook, "Harmonic filters for notch reduction," *IEEE Trans. on Industry Applications*, vol. 24, pp. 947-954, Sept./Oct. 1988.
- 13) K.H. Suaker, S.D. Hummel, and R.D. Argent, "Power factor correction and harmonic mitigation in a thyristor controlled glass melter," *IEEE Trans. Industry Applications*, vol. 25, no. 6, pp. 972-975, Nov/Dec. 1989.
- 14) M.M. Cameron, "Trends in power factor correction with harmonic filtering," *IEEE Trans. on Industry Applications*, vol.29, no.1, pp.60-65, Jan./Feb. 1993.
- 15) M.Z. Lowenstein and J.F. Hibbard, "Modeling and application of passive harmonic trap filters for harmonic reduction and power factor improvement," in *Proc. IEEE IAS Meeting 93*, 1993, vol.2, pp. 1570-1578.
- 16) M.Z. Lowenstein, "Improving power factor in the presence of harmonics using low-voltage tuned filters," *IEEE Trans. on Industry Applications*, vol.29, no.3, pp.528-535, May/June 1993.
- 17) E. B. Makran, E.V. Subramaniam, A.A. Girgis and R. Caloe, "Harmonic filter design using actual recorded data," *IEEE Trans. on Industry Applications*, vol.29, no.6, pp.1176-1183, Nov/Dec. 1993.
- 18) A. M. Sharaf and M. E. Fisher, "An optimization based technique for power system harmonic filter design," *Journal of Electric Power Systems Research*, vol. 30, pp. 63-67, June 1994.
- 19) M.M. Swamy, S.L. Rossiter, M.C. Spencer, and M. Richardson, "Case studies on mitigating harmonics in ASD systems to meet IEEE 519-1992 standards," in *Proc. IEEE IAS Annual Meeting Record 94*, 1994, pp. 665-682.
- 20) A. M. Sharaf and H. Huang, "Flicker control using rule based modulated passive power filters," *Journal of Electric Power Systems Research*, vol. 33, pp. 49-52, April 1995.



And these are the some of the references and.

Thank you.