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

Lecture - 03
Power Quality Standards and Monitoring (contd.)

Welcome to “Power Quality Standards and Monitoring” lecture. In this part we cover Power Quality Standards.

(Refer Slide Time: 00:32)

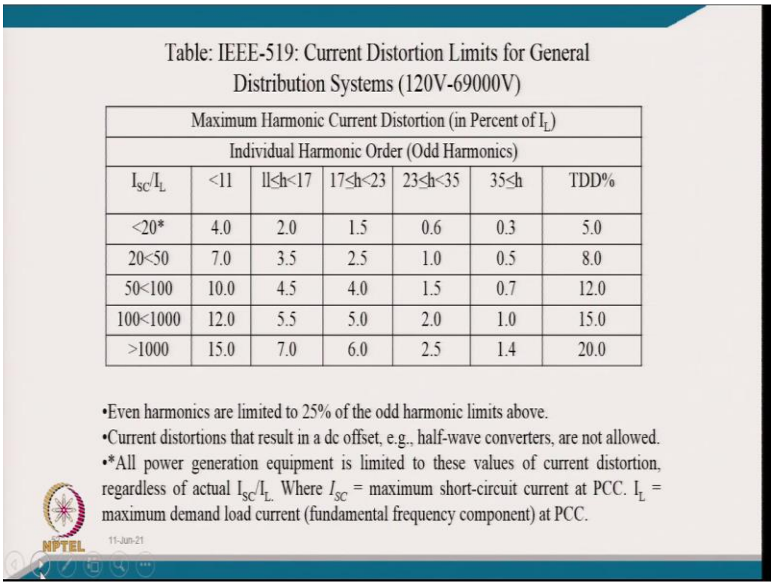


Table: IEEE-519: Current Distortion Limits for General Distribution Systems (120V-69000V)

Maximum Harmonic Current Distortion (in Percent of I_L)						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD%
<20*	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

- Even harmonics are limited to 25% of the odd harmonic limits above.
- Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.
- *All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L. Where I_{SC} = maximum short-circuit current at PCC. I_L = maximum demand load current (fundamental frequency component) at PCC.

11-Jun-21

There are many standards, but the most crucial standard widely referred to worldwide is IEEE-519. It talks about the current distortion limit for the 120 V to 69 kV supply system's general distribution system and most of the loads typically in the distribution system. Like in India, we also have a supply system 220-230 V, which comes in this category or 415V, 3 phase system.

All system comes under this category, and this is the maximum harmonic current distortion percentage of the load current that is IL, and these are the individual harmonics. And well, if we look into the first row, that is ISC/ IL, which is a short circuit current level divided by load current.

The first limit is up to 11th harmonics, and then the second limit is 11 to 17, then 17 to 23rd, 23rd to 35, and less than 35 and total demand distortion factor.

- If you look at the first row of the table, the short circuit current level is given a 20 percent, which means that your source impedance is typically a 5 percent. In that case, this distortion can be permitted up to 5 percent.

- If your short circuit current level is between 20 pu to 50 pu, your source impedance is typically 2%. In that is will be permitted up to 8 percent.

- If your short circuit current level is more than 1000, distortion can be permitted up to 20 percent.

- The source impedance causes a voltage drop corresponding to those harmonics, the voltage distortion should not go more than a particular value.

- Even harmonics are limited to 25 percent of the odd harmonic limits.

The current distortion that results in a DC offset like a half-wave rectifier or half-wave converter is not allowed.

All power generation equipment is limited to the value of current distortion regardless of your actual short circuit current level. The I_{SC} is the maximum short circuit current at the point of common coupling, and I_L is the maximum demand load current. That is typically a fundamental frequency component at the point of common coupling.

(Refer Slide Time: 03:33)

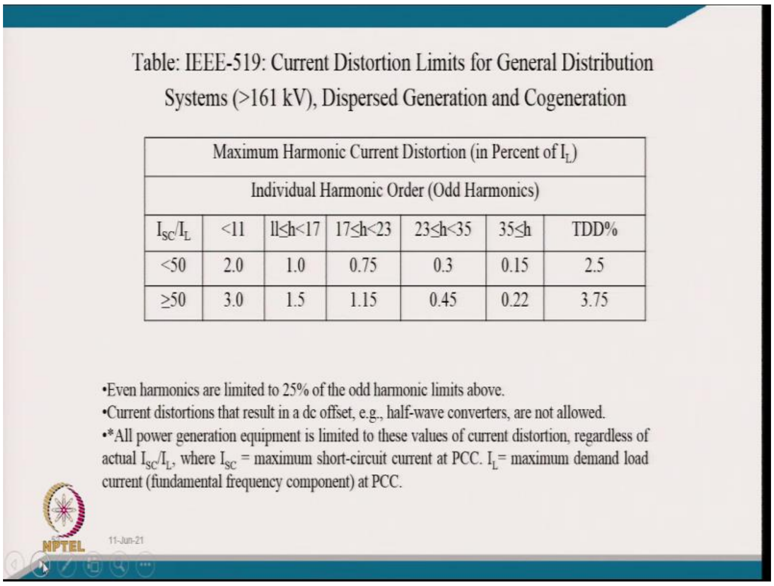


Table: IEEE-519: Current Distortion Limits for General Distribution Systems (>161 kV), Dispersed Generation and Cogeneration

Maximum Harmonic Current Distortion (in Percent of I_L)						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	$ll \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h$	TDD%
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

- Even harmonics are limited to 25% of the odd harmonic limits above.
- Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.
- *All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L, where I_{SC} = maximum short-circuit current at PCC. I_L = maximum demand load current (fundamental frequency component) at PCC.

11-Jun-21

This is the typical limit corresponding to the voltage when we have a current distortion limit for a general distribution system above 161 kV. The voltage level for 161, more than 161 kV, is undoubtedly typically maybe at the primary distribution or transmission level. There the harmonics level permitted much lower compared to the distribution system. If the short circuit current level of even less than 50, it is all permitted only 2.5 %, and well, if its short circuit level is above 50, then it is all allowed 3.75%.

(Refer Slide Time: 04:23)

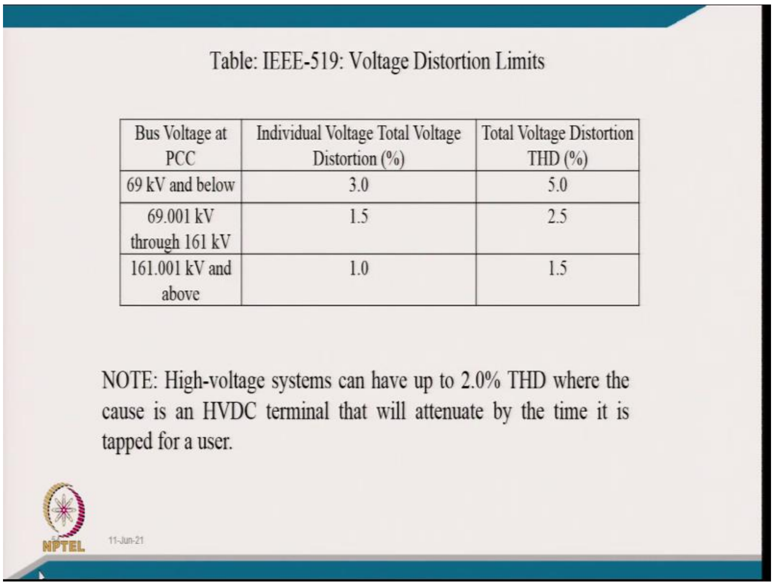


Table: IEEE-519: Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Total Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

11-Jun-21

This is a table corresponding to the voltage distortion limit and this also indirectly guides the previous table. Suppose the voltage level is 69 kV or below. In that case, the individual voltage total voltage distortion is not permitted to be more than 3 percent, and total voltage distortion is not permitted to be more than 5 percent.

Suppose the voltage level is between 69 kV to 161 kV. In that case, individual harmonics permitted is 1.5 percent and total voltage distortion permitted 2.5 percent. If it is 161 kV and above, then individual harmonic permitted 1 percent and total harmonic distortion not more than 1.5 percent.

High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

(Refer Slide Time: 05:29)

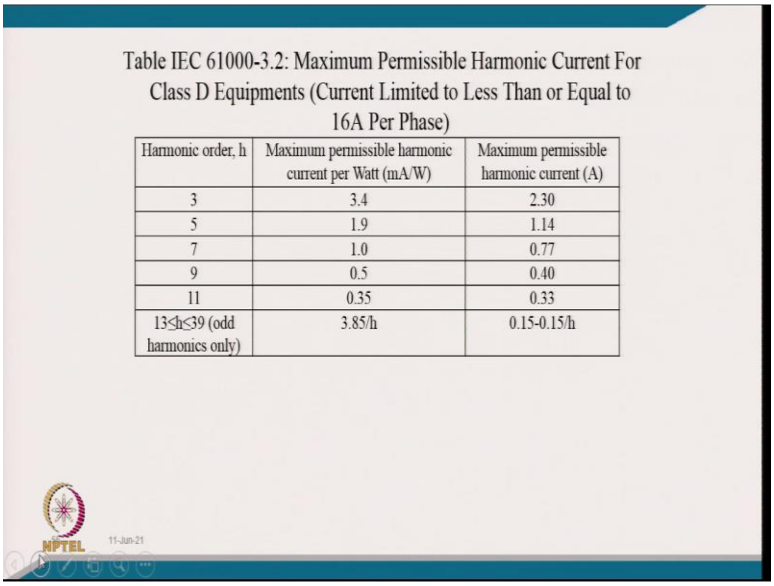


Table IEC 61000-3.2: Maximum Permissible Harmonic Current For Class D Equipments (Current Limited to Less Than or Equal to 16A Per Phase)

Harmonic order, h	Maximum permissible harmonic current per Watt (mA/W)	Maximum permissible harmonic current (A)
3	3.4	2.30
5	1.9	1.14
7	1.0	0.77
9	0.5	0.40
11	0.35	0.33
$13 \leq h \leq 39$ (odd harmonics only)	3.85/h	0.15-0.15/h

There is another standard discussed in the last lecture, it is IEC 61000, and there are several parts to this system. This is the typical table that is very widely used for IEC-61000-3.2 standard- the Maximum Permissible Harmonic limit for Class D Equipment, (Current limited to less than or equal to 16 Ampere per phase).

This table governs all the equipment connected in the distribution system. These are commercial standards we discussed last time also developed in Geneva. This International Electrotechnical Commission is typically installed there, and the harmonic order here you can see third permitted corresponding to 3.4 maximum harmonic current per Watt. So, this is 3.4 milli Ampere per Watt, and the maximum permissible harmonic current allowed is 2.3 Ampere.

Similarly, for fifth harmonics, you have a 1.9 milli Ampere per Watt, and maximum is permitted 1.14, and seventh harmonics, typically 1 milli Ampere per Watt and typically, a maximum is harmonic current permitted 0.77 A. Similarly 9, 0.5 milli Ampere per Watt and the total would 0.40. Similarly, 11, 0.35 milli Ampere per Watt and maximum permitted 0.33 Ampere.

And all the harmonics are 11 to 39 odd harmonics, they are permitted 3.85/h, where h is the order of harmonics milli Ampere per Watt. Indeed, the maximum allowed is 0.15 - 0.15/h.

(Refer Slide Time: 07:38)

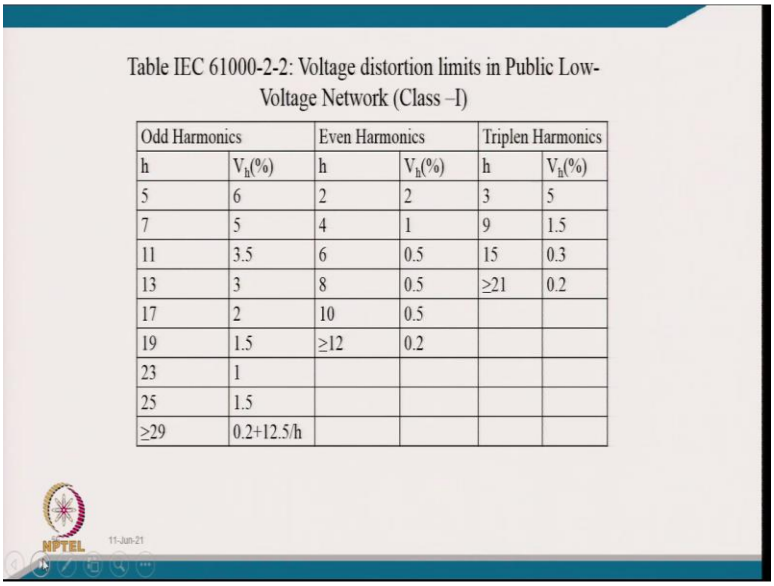


Table IEC 61000-2-2: Voltage distortion limits in Public Low-Voltage Network (Class –I)

Odd Harmonics		Even Harmonics		Triplen Harmonics	
h	V_h(%)	h	V_h(%)	h	V_h(%)
5	6	2	2	3	5
7	5	4	1	9	1.5
11	3.5	6	0.5	15	0.3
13	3	8	0.5	≥21	0.2
17	2	10	0.5		
19	1.5	≥12	0.2		
23	1				
25	1.5				
≥29	0.2+12.5/h				

11-Jun-21

Similarly, IEC 61000-2 is for voltage distortion limit in public low voltage distribution system Class 1. All 220 volt or 230-volt distribution system comes under in this category, and the different harmonics.

(Refer Slide Time: 08:29)

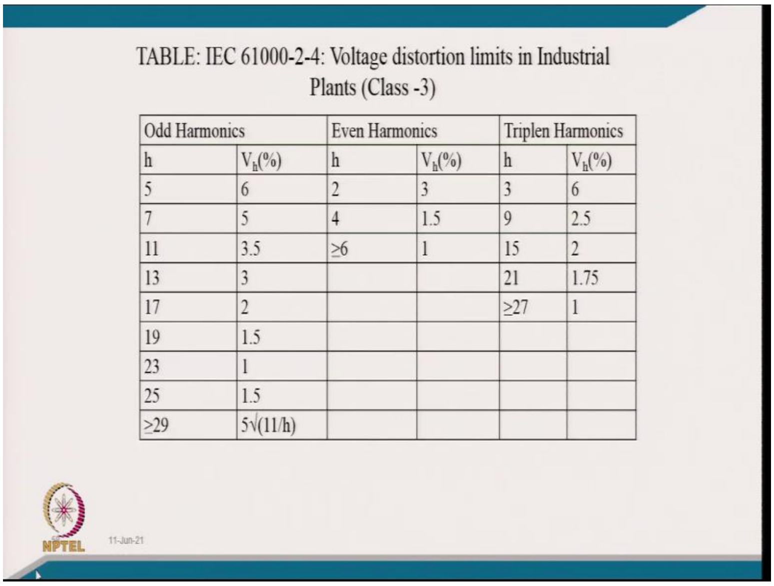


TABLE: IEC 61000-2-4: Voltage distortion limits in Industrial Plants (Class -3)

Odd Harmonics		Even Harmonics		Triplen Harmonics	
h	V_h(%)	h	V_h(%)	h	V_h(%)
5	6	2	3	3	6
7	5	4	1.5	9	2.5
11	3.5	≥6	1	15	2
13	3			21	1.75
17	2			≥27	1
19	1.5				
23	1				
25	1.5				
≥29	$5\sqrt{(11/h)}$				

11-Jun-21

Another table certainly has voltage distortion limits for the industrial plant, which is usually a higher voltage. Here are also odd harmonics you can see from fifth, seventh all odd harmonics and then, even harmonics and then, you have a triplen harmonics.

Typically, percentage harmonic distortion is permitted typically for this class 3 equipment we call it like in commercial applications.

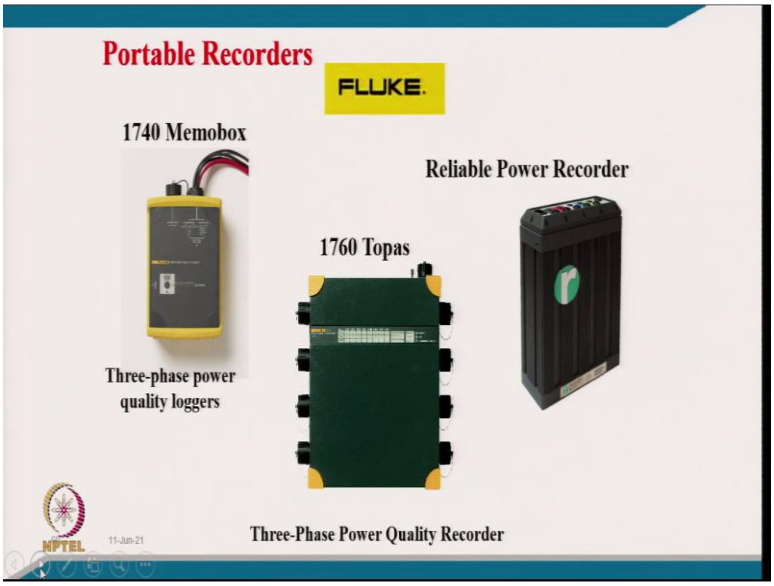
(Refer Slide Time: 08:52)

POWER QUALITY MONITORING

11-Jun-21

Well, this is about the standard limit which normally we follow a couple of a standard and there are many other standards for a specific one. These are very general-purpose equipment. Then, we like to talk about power quality monitoring.

(Refer Slide Time: 09:07)



Portable Recorders

FLUKE

1740 Memobox

Three-phase power quality loggers

1760 Topas

Three-Phase Power Quality Recorder

Reliable Power Recorder

11-Jun-21

For power quality monitoring, there are many new instruments available as a portable recorders because you have to go sometimes industry or other premises, where you look into there is a power quality problems, and you have to make a measurement and recording.

[FL], these are the some of the power quality, you can call it portable recorder from Fluke Corporation Limited and you have a similar Three-phase power quality loggers. You have a Three-phase power quality recorder, a Reliable power quality recorder.

(Refer Slide Time: 09:36)

Fixed Recorders

3 Phase Power Analyzer
Norma

Reliable Power Meters
Multipoint Power Recorder

11-Jun-21

[FL], similarly you have from other like a fixed recorder like 3 Phase Power Analyzer by Norma, Reliable Power Meters like Multipoint Power Recorder.

(Refer Slide Time: 09:44)

Other Recorders

Fluke 1735
Three-Phase Power Logger

E-Tracker MK2B
Energy Monitor

Hioki PQ3100-94 Three Phase
Power Quality Analyzer

Fluke 434/5
Three Phase Power Analyzer

Similarly, you have a recorder like Fluke 1735 for Three-Phase Power Logger and Hioki PQ3100-94 Three-Phase Power Quality Analyzer and then Fluke 434 or 435 for Three-Phase Power Analyzer and then E-Tracker MK2B Energy Monitor like.

(Refer Slide Time: 10:06)

Current Clamp, Probe

Current Clamp Meter
(Stand Alone)

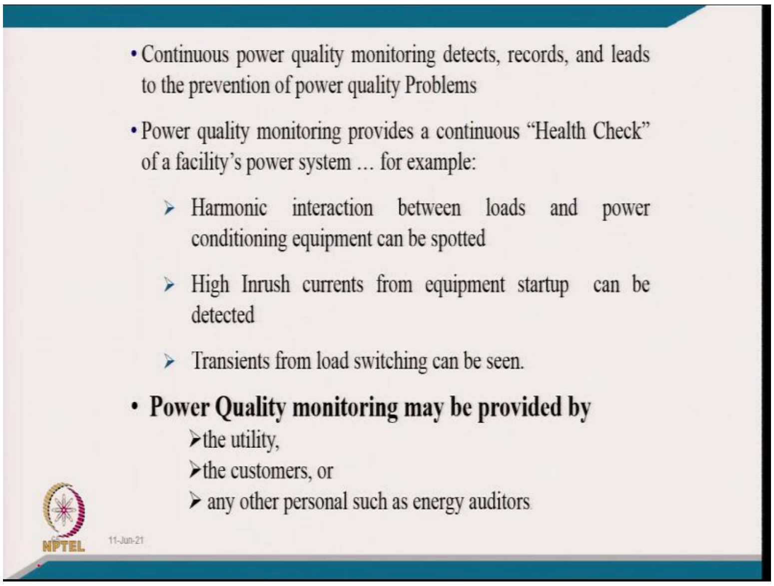
Ac Voltage Detector Audio/Visual

Phase Sequence Indicator

11-Jun-21

Then, you have a Current Clamps, which is typically used along with those recorders. You have a Current Clamp Stand Alone also as well as an ac Voltage Detector Outdoor Visual inspection and a Phase Sequence Indicator.

(Refer Slide Time: 10:19)



- Continuous power quality monitoring detects, records, and leads to the prevention of power quality Problems
- Power quality monitoring provides a continuous "Health Check" of a facility's power system … for example:
  - Harmonic interaction between loads and power conditioning equipment can be spotted
  - High Inrush currents from equipment startup can be detected
  - Transients from load switching can be seen.
- **Power Quality monitoring may be provided by**
  - the utility,
  - the customers, or
  - any other personal such as energy auditors

11-Jun-21

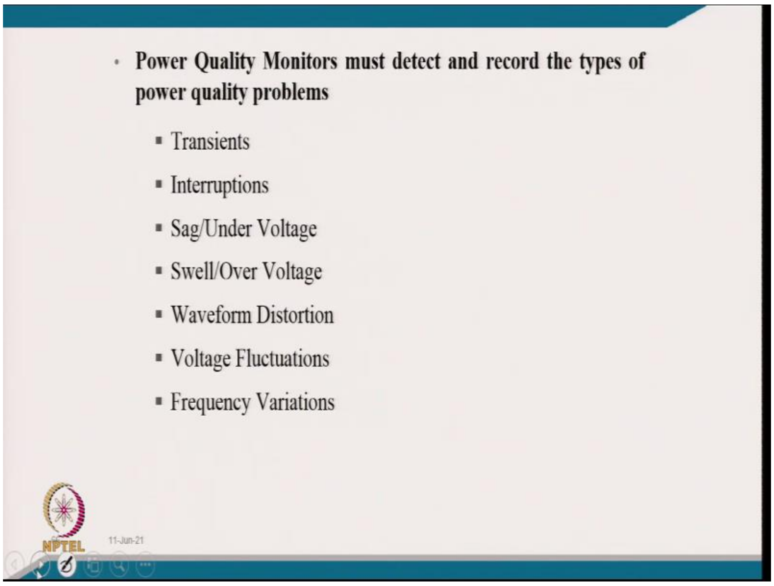
These are some of the instruments. There are many instruments from different other industries also like Yokogawa, or you can call it Hioki. Apart from that, there is a typical Agilent, and there are plenty of manufacturers like Trident and others.

These instruments are used, or recorders are used to record the power quality problems because you have to suggest the correct mitigation technique or mitigation equipment. You have to assess how much the power quality problem is typical through these recorders.

Continuous power quality monitoring and detection and recording lead to the prevention of power quality problems, and power quality monitoring provides a constant health checking facility of the power system. For example, harmonic interaction between the loads and power condition equipment can be spotted, high inrush current from equipment startup can be detected, and transient from load switching can be seen.

And this power quality monitoring may be provided by either the utility or customer or any other person such as an energy auditor appointed by typically either industry or the utility.

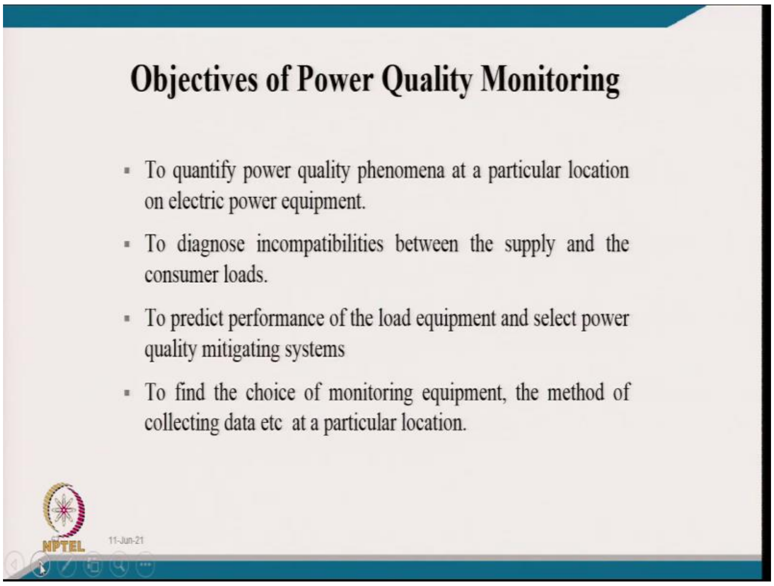
(Refer Slide Time: 11:29)



- **Power Quality Monitors must detect and record the types of power quality problems**
  - Transients
  - Interruptions
  - Sag/Under Voltage
  - Swell/Over Voltage
  - Waveform Distortion
  - Voltage Fluctuations
  - Frequency Variations

Power quality monitors must detect and record the types of power quality problems like they can record transients, interruption, voltage sag, under voltage, waveform distortion, or voltage fluctuations and frequency variations. So, these are the typical power quality parameters that these monitors can monitor.

(Refer Slide Time: 12:11)



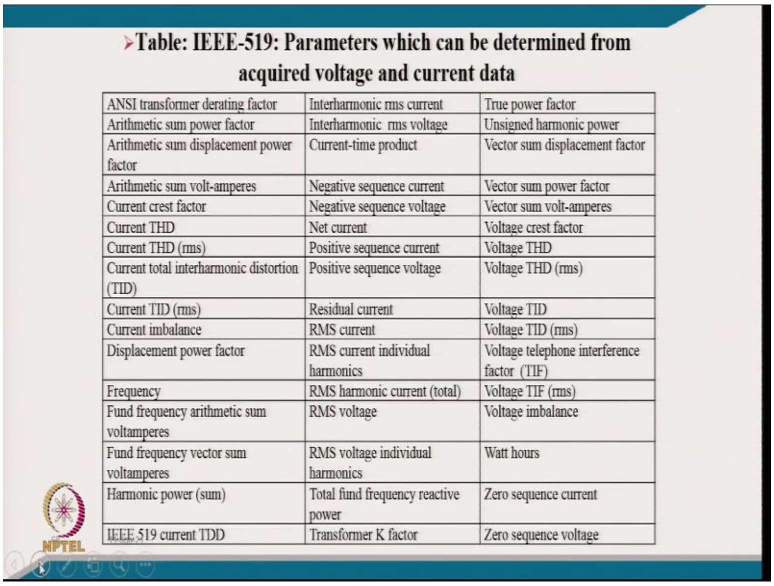
Objectives of Power Quality Monitoring

- To quantify power quality phenomena at a particular location on electric power equipment.
- To diagnose incompatibilities between the supply and the consumer loads.
- To predict performance of the load equipment and select power quality mitigating systems
- To find the choice of monitoring equipment, the method of collecting data etc at a particular location.

11-Jun-21

The very purpose of this power quality monitoring is to quantify the power quality phenomena at the particular location of electrical power equipment and diagnose incompatibility between the supply and the consumer loads and predict the performance of the load equipment and select power quality mitigation systems for that particular location. And to find out the choice of monitoring equipment, the method of collecting data, etcetera in a specific area.

(Refer Slide Time: 12:44)

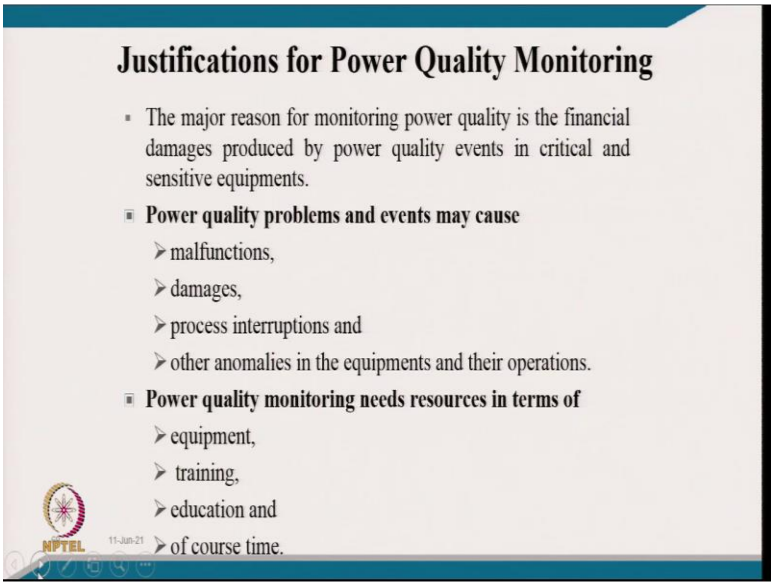


➢ Table: IEEE-519: Parameters which can be determined from acquired voltage and current data

ANSI transformer derating factor	Interharmonic rms current	True power factor
Arithmetic sum power factor	Interharmonic rms voltage	Unsigned harmonic power
Arithmetic sum displacement power factor	Current-time product	Vector sum displacement factor
Arithmetic sum volt-amperes	Negative sequence current	Vector sum power factor
Current crest factor	Negative sequence voltage	Vector sum volt-amperes
Current THD	Net current	Voltage crest factor
Current THD (rms)	Positive sequence current	Voltage THD
Current total interharmonic distortion (TID)	Positive sequence voltage	Voltage THD (rms)
Current TID (rms)	Residual current	Voltage TID
Current imbalance	RMS current	Voltage TID (rms)
Displacement power factor	RMS current individual harmonics	Voltage telephone interference factor (TIF)
Frequency	RMS harmonic current (total)	Voltage TIF (rms)
Fund frequency arithmetic sum voltamperes	RMS voltage	Voltage imbalance
Fund frequency vector sum voltamperes	RMS voltage individual harmonics	Watt hours
Harmonic power (sum)	Total fund frequency reactive power	Zero sequence current
IEEE 519 current TDD	Transformer K factor	Zero sequence voltage

The IEEE-519 gives a table of parameters that can be determined from this acquired voltage and current data. As can be seen here, all these data we discussed last time also like ANSI transformer derating factor, arithmetic sum power factor, arithmetic sum displacement factor, arithmetic sum voltage ampere, current crest factor.

(Refer Slide Time: 13:37)



Justifications for Power Quality Monitoring

- The major reason for monitoring power quality is the financial damages produced by power quality events in critical and sensitive equipments.
- **Power quality problems and events may cause**
  - ➢ malfunctions,
  - ➢ damages,
  - ➢ process interruptions and
  - ➢ other anomalies in the equipments and their operations.
- **Power quality monitoring needs resources in terms of**
  - ➢ equipment,
  - ➢ training,
  - ➢ education and
  - ➢ of course time.

11-Jun-21

Well, what is the justification for power quality monitoring?

How can you convince the industry? Why should we go to power quality monitoring? The primary reason for monitoring the power quality is the financial damages produced by the power quality events in critical and sensitive equipment or in the process or manufacturing industries. Power quality problems and events may cause malfunctions of the equipment or process, can cause damage, and it can cause process interruption and other anomalies in the equipment and its operations. The power quality monitoring needs resources in terms of like equipment, training, education, and of course, the time.

(Refer Slide Time: 14:20)

➢Some of the following aspects may be used to convince users for power quality monitoring

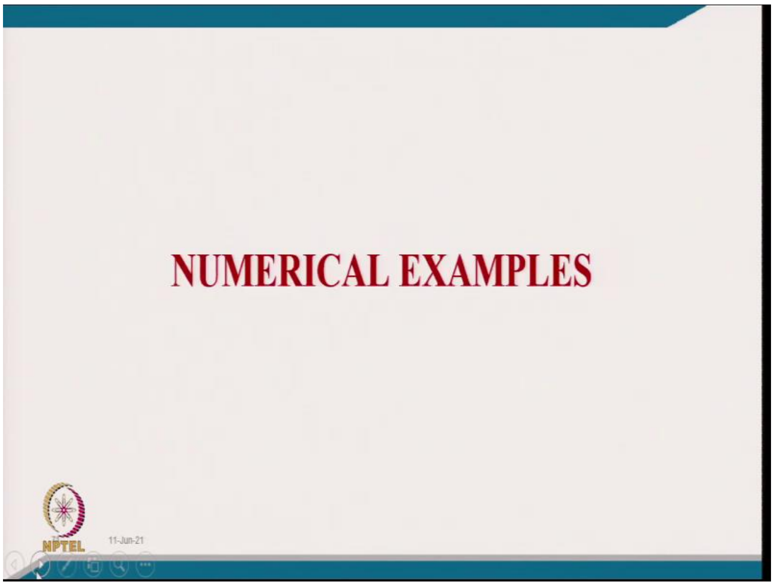
- To find out the need for mitigation of power quality problems
- To schedule preventive and predictive maintenance
- To ensure the performance of equipment
- To assess the sensitivity of equipment to power quality disturbances
- To identify power quality events and problems
- To reduce the power losses in the process and distribution system
- To reduce the loss in production and to improve equipment availability

11-Jun-21

Well, some of the following aspect may be used to convince the users for power quality monitoring;

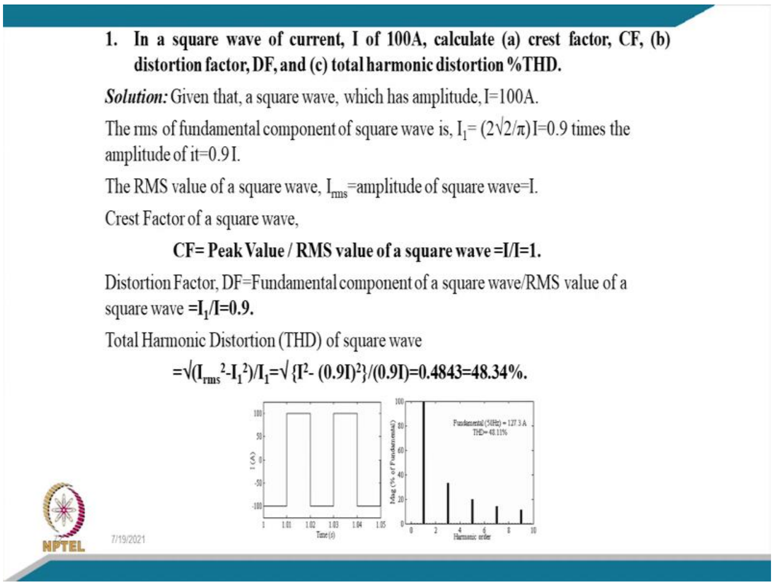
- To find out the need for mitigation of power quality problems
- To schedule preventive and predictive maintenance
- To ensure the performance of equipment
- To assess the sensitivity of equipment to power quality disturbances
- To identify power quality events and problems
- To reduce the power losses in the process and distribution system
- To reduce the loss in production and to improve equipment availability

(Refer Slide Time: 14:54)



NUMERICAL EXAMPLES

11-Jun-21



1. **In a square wave of current, I of 100A, calculate (a) crest factor, CF, (b) distortion factor, DF, and (c) total harmonic distortion %THD.**

Solution: Given that, a square wave, which has amplitude, I=100A.

The rms of fundamental component of square wave is, $I_1 = (2\sqrt{2}/\pi)I = 0.9$ times the amplitude of it=0.9I.

The RMS value of a square wave, I_{rms}=amplitude of square wave=I.

Crest Factor of a square wave,

CF= Peak Value / RMS value of a square wave =I/I=1.

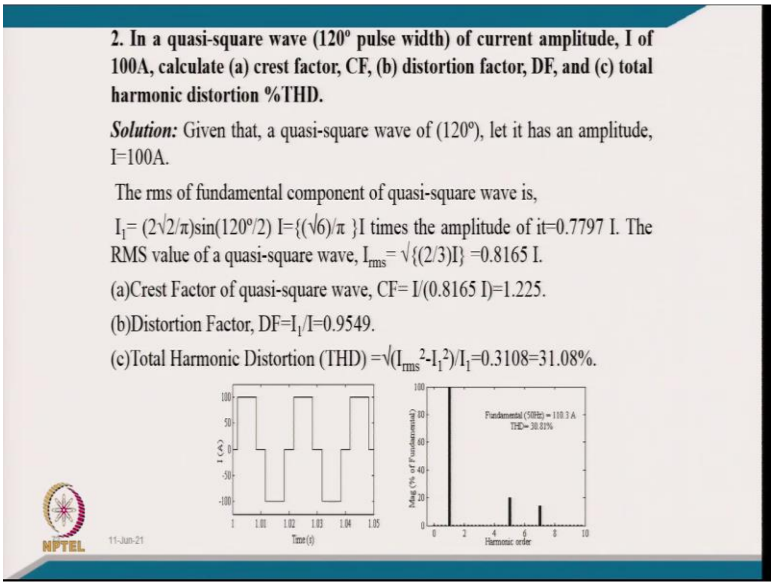
Distortion Factor, DF=Fundamental component of a square wave/RMS value of a square wave **$=I_1/I=0.9$.**

Total Harmonic Distortion (THD) of square wave

$$=\sqrt{(I_{rms}^2 - I_1^2)}/I_1 = \sqrt{\{I^2 - (0.9I)^2\}}/(0.9I) = 0.4843 = 48.34\%.$$

7/19/2021

(Refer Slide Time: 18:08)



2. In a quasi-square wave (120° pulse width) of current amplitude, I of 100A, calculate (a) crest factor, CF, (b) distortion factor, DF, and (c) total harmonic distortion %THD.

Solution: Given that, a quasi-square wave of (120°), let it has an amplitude, I=100A.

The rms of fundamental component of quasi-square wave is,

$I_1 = (2\sqrt{2}/\pi)\sin(120°/2)\ I = \{(\sqrt{6})/\pi\}I$ times the amplitude of it=0.7797 I. The RMS value of a quasi-square wave, $I_{rms} = \sqrt{\{(2/3)I\}} = 0.8165\ I$.

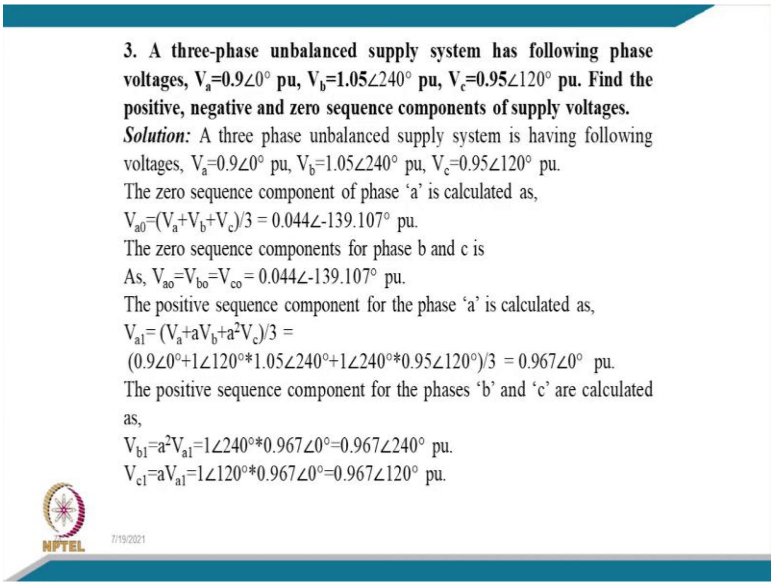
(a)Crest Factor of quasi-square wave, $CF = I/(0.8165\ I) = 1.225$.

(b)Distortion Factor, $DF = I_1/I = 0.9549$.

(c)Total Harmonic Distortion (THD) $= \sqrt{(I_{rms}^2 - I_1^2)}/I_1 = 0.3108 = 31.08\%$.

11-Jun-21

(Refer Slide Time: 21:54)



3. A three-phase unbalanced supply system has following phase voltages, $V_a = 0.9\angle 0°$ pu, $V_b = 1.05\angle 240°$ pu, $V_c = 0.95\angle 120°$ pu. Find the positive, negative and zero sequence components of supply voltages.

Solution: A three phase unbalanced supply system is having following voltages, $V_a = 0.9\angle 0°$ pu, $V_b = 1.05\angle 240°$ pu, $V_c = 0.95\angle 120°$ pu.

The zero sequence component of phase 'a' is calculated as,

$V_{a0} = (V_a + V_b + V_c)/3 = 0.044\angle -139.107°$ pu.

The zero sequence components for phase b and c is

As, $V_{ao} = V_{bo} = V_{co} = 0.044\angle -139.107°$ pu.

The positive sequence component for the phase 'a' is calculated as,

$V_{a1} = (V_a + aV_b + a^2V_c)/3 =$

$(0.9\angle 0° + 1\angle 120° * 1.05\angle 240° + 1\angle 240° * 0.95\angle 120°)/3 = 0.967\angle 0°$ pu.

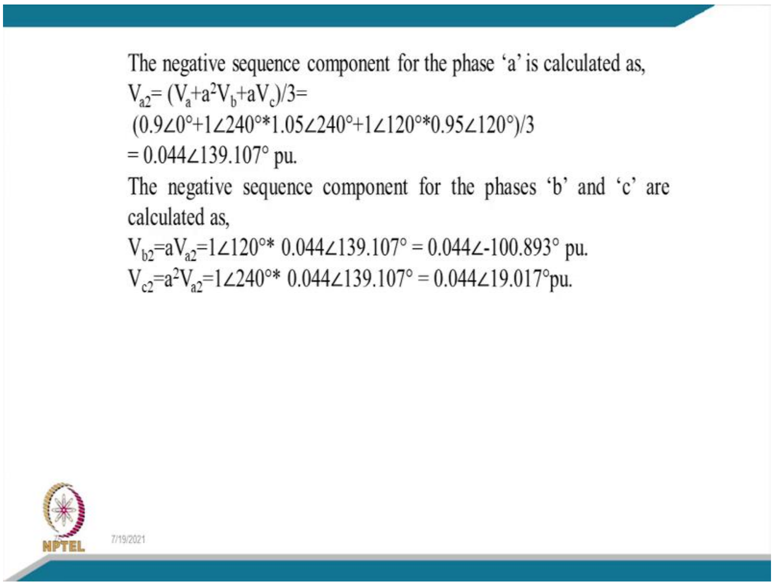
The positive sequence component for the phases 'b' and 'c' are calculated as,

$V_{b1} = a^2V_{a1} = 1\angle 240° * 0.967\angle 0° = 0.967\angle 240°$ pu.

$V_{c1} = aV_{a1} = 1\angle 120° * 0.967\angle 0° = 0.967\angle 120°$ pu.

7/19/2021

(Refer Slide Time: 24:04)



The negative sequence component for the phase 'a' is calculated as,

$V_{a2}=(V_a+a^2V_b+aV_c)/3=$

$(0.9\angle 0^\circ+1\angle 240^\circ*1.05\angle 240^\circ+1\angle 120^\circ*0.95\angle 120^\circ)/3$

$= 0.044\angle 139.107^\circ$ pu.

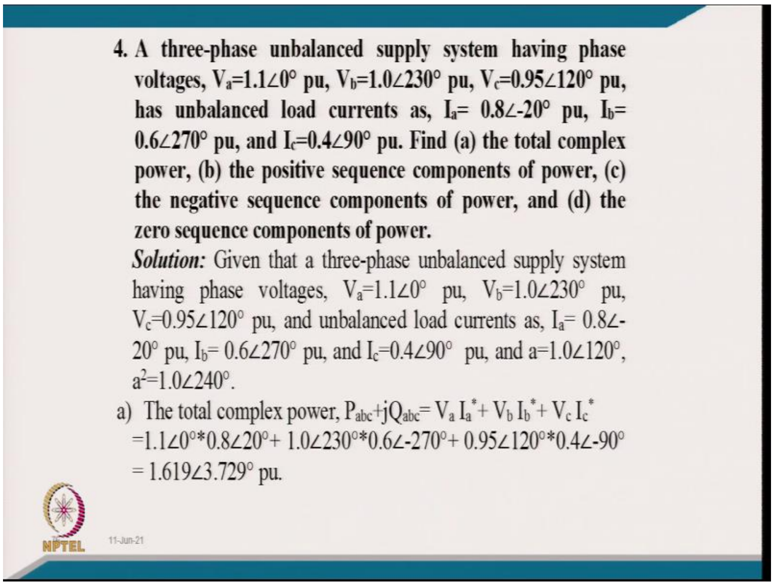
The negative sequence component for the phases 'b' and 'c' are calculated as,

$V_{b2}=aV_{a2}=1\angle 120^\circ*\ 0.044\angle 139.107^\circ = 0.044\angle -100.893^\circ$ pu.

$V_{c2}=a^2V_{a2}=1\angle 240^\circ*\ 0.044\angle 139.107^\circ = 0.044\angle 19.017^\circ$pu.

7/19/2021

(Refer Slide Time: 24:52)



4. A three-phase unbalanced supply system having phase voltages, $V_a=1.1\angle 0^\circ$ pu, $V_b=1.0\angle 230^\circ$ pu, $V_c=0.95\angle 120^\circ$ pu, has unbalanced load currents as, $I_a= 0.8\angle -20^\circ$ pu, $I_b= 0.6\angle 270^\circ$ pu, and $I_c=0.4\angle 90^\circ$ pu. Find (a) the total complex power, (b) the positive sequence components of power, (c) the negative sequence components of power, and (d) the zero sequence components of power.

Solution: Given that a three-phase unbalanced supply system having phase voltages, $V_a=1.1\angle 0^\circ$ pu, $V_b=1.0\angle 230^\circ$ pu, $V_c=0.95\angle 120^\circ$ pu, and unbalanced load currents as, $I_a= 0.8\angle -20^\circ$ pu, $I_b= 0.6\angle 270^\circ$ pu, and $I_c=0.4\angle 90^\circ$ pu, and $a=1.0\angle 120^\circ$, $a^2=1.0\angle 240^\circ$.

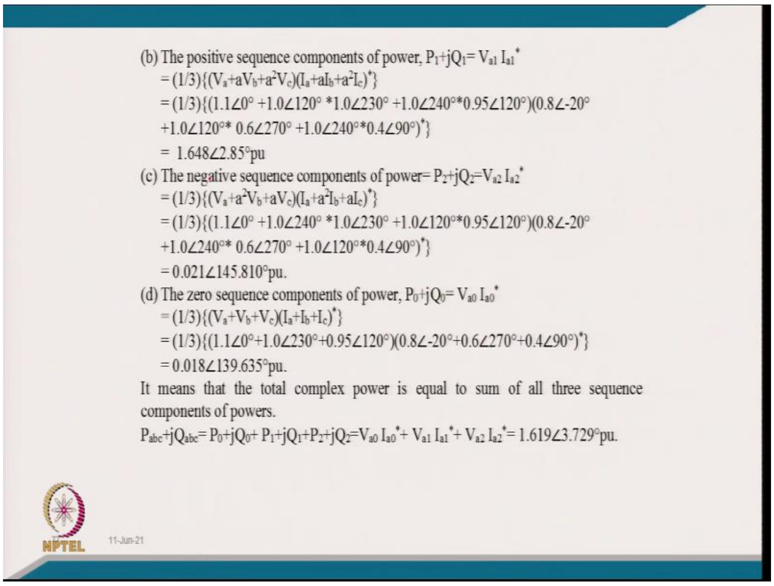
a) The total complex power, $P_{abc}+jQ_{abc}= V_a I_a^*+ V_b I_b^*+ V_c I_c^*$

$=1.1\angle 0^\circ*0.8\angle 20^\circ+ 1.0\angle 230^\circ*0.6\angle -270^\circ+ 0.95\angle 120^\circ*0.4\angle -90^\circ$

$= 1.619\angle 3.729^\circ$ pu.

11-Jun-21

(Refer Slide Time: 26:04)



(b) The positive sequence components of power, $P_1+jQ_1= V_{a1}\, I_{a1}^*$

$=(1/3)\{(V_a+aV_b+a^2V_c)(I_a+aI_b+a^2I_c)^*\}$

$=(1/3)\{(1.1\angle 0^\circ +1.0\angle 120^\circ *1.0\angle 230^\circ +1.0\angle 240^\circ *0.95\angle 120^\circ)(0.8\angle -20^\circ$
$+1.0\angle 120^\circ * 0.6\angle 270^\circ +1.0\angle 240^\circ *0.4\angle 90^\circ)^*\}$

$= 1.648\angle 2.85^\circ$pu

(c) The negative sequence components of power= $P_2+jQ_2=V_{a2}\, I_{a2}^*$

$=(1/3)\{(V_a+a^2V_b+aV_c)(I_a+a^2I_b+aI_c)^*\}$

$=(1/3)\{(1.1\angle 0^\circ +1.0\angle 240^\circ *1.0\angle 230^\circ +1.0\angle 120^\circ *0.95\angle 120^\circ)(0.8\angle -20^\circ$
$+1.0\angle 240^\circ * 0.6\angle 270^\circ +1.0\angle 120^\circ *0.4\angle 90^\circ)^*\}$

$=0.021\angle 145.810^\circ$pu.

(d) The zero sequence components of power, $P_0+jQ_0= V_{a0}\, I_{a0}^*$

$=(1/3)\{(V_a+V_b+V_c)(I_a+I_b+I_c)^*\}$

$=(1/3)\{(1.1\angle 0^\circ+1.0\angle 230^\circ+0.95\angle 120^\circ)(0.8\angle -20^\circ+0.6\angle 270^\circ+0.4\angle 90^\circ)^*\}$

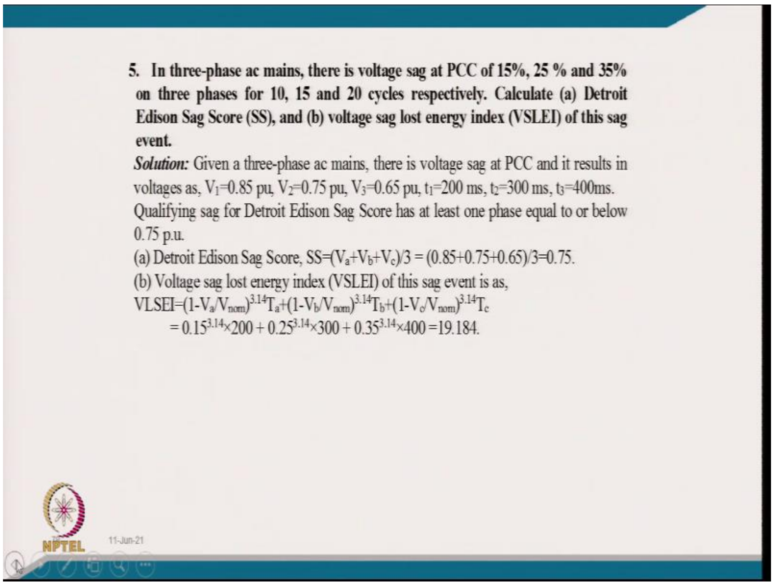
$=0.018\angle 139.635^\circ$pu.

It means that the total complex power is equal to sum of all three sequence components of powers.

$P_{abc}+jQ_{abc}= P_0+jQ_0+ P_1+jQ_1+P_2+jQ_2=V_{a0}\, I_{a0}^*+ V_{a1}\, I_{a1}^*+ V_{a2}\, I_{a2}^*= 1.619\angle 3.729^\circ$pu.

11-Jun-21

(Refer Slide Time: 27:41)



5. In three-phase ac mains, there is voltage sag at PCC of 15%, 25 % and 35% on three phases for 10, 15 and 20 cycles respectively. Calculate (a) Detroit Edison Sag Score (SS), and (b) voltage sag lost energy index (VSLEI) of this sag event.

Solution: Given a three-phase ac mains, there is voltage sag at PCC and it results in voltages as, V_1=0.85 pu, V_2=0.75 pu, V_3=0.65 pu, t_1=200 ms, t_2=300 ms, t_3=400ms. Qualifying sag for Detroit Edison Sag Score has at least one phase equal to or below 0.75 p.u.

(a) Detroit Edison Sag Score, $SS=(V_a+V_b+V_c)/3 = (0.85+0.75+0.65)/3=0.75$.

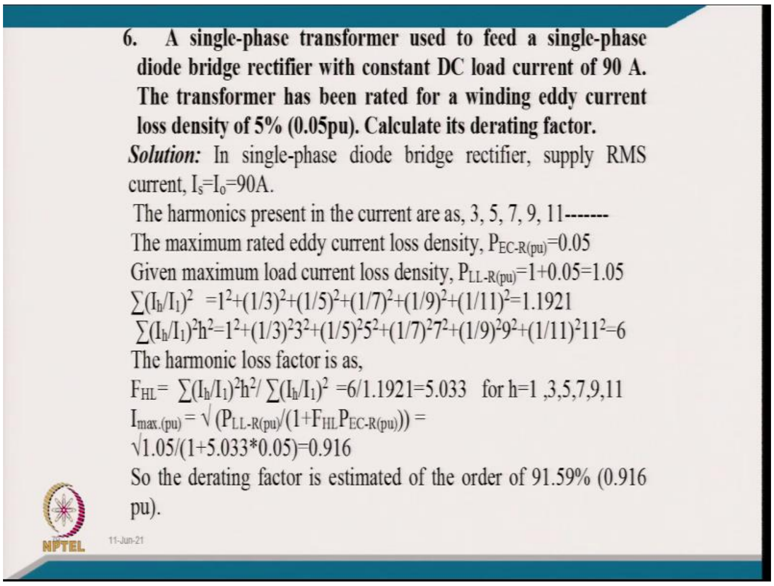
(b) Voltage sag lost energy index (VSLEI) of this sag event is as,

$VLSEI=(1-V_a/V_{nom})^{3.14}T_a+(1-V_b/V_{nom})^{3.14}T_b+(1-V_c/V_{nom})^{3.14}T_c$

$= 0.15^{3.14}\times 200 + 0.25^{3.14}\times 300 + 0.35^{3.14}\times 400 =19.184.$

11-Jun-21

(Refer Slide Time: 29:24)



6. **A single-phase transformer used to feed a single-phase diode bridge rectifier with constant DC load current of 90 A. The transformer has been rated for a winding eddy current loss density of 5% (0.05pu). Calculate its derating factor.**

Solution: In single-phase diode bridge rectifier, supply RMS current, I_s=I_0=90A.

The harmonics present in the current are as, 3, 5, 7, 9, 11-------

The maximum rated eddy current loss density, $P_{EC-R(pu)}=0.05$

Given maximum load current loss density, $P_{LL-R(pu)}=1+0.05=1.05$

$\sum(I_h/I_1)^2 = 1^2+(1/3)^2+(1/5)^2+(1/7)^2+(1/9)^2+(1/11)^2=1.1921$

$\sum(I_h/I_1)^2h^2=1^2+(1/3)^2 3^2+(1/5)^2 5^2+(1/7)^2 7^2+(1/9)^2 9^2+(1/11)^2 11^2=6$

The harmonic loss factor is as,

$F_{HL}= \sum(I_h/I_1)^2h^2/ \sum(I_h/I_1)^2 =6/1.1921=5.033$ for h=1 ,3,5,7,9,11

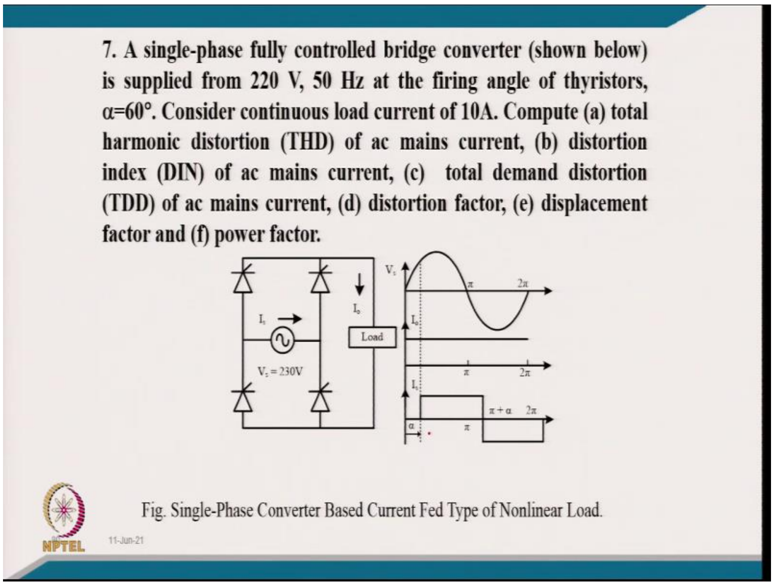
$I_{max.(pu)} = \sqrt{}\,(P_{LL-R(pu)}/(1+F_{HL}P_{EC-R(pu)})) =$

$\sqrt{}1.05/(1+5.033*0.05)=0.916$

So the derating factor is estimated of the order of 91.59% (0.916 pu).

11-Jun-21

(Refer Slide Time: 32:00)

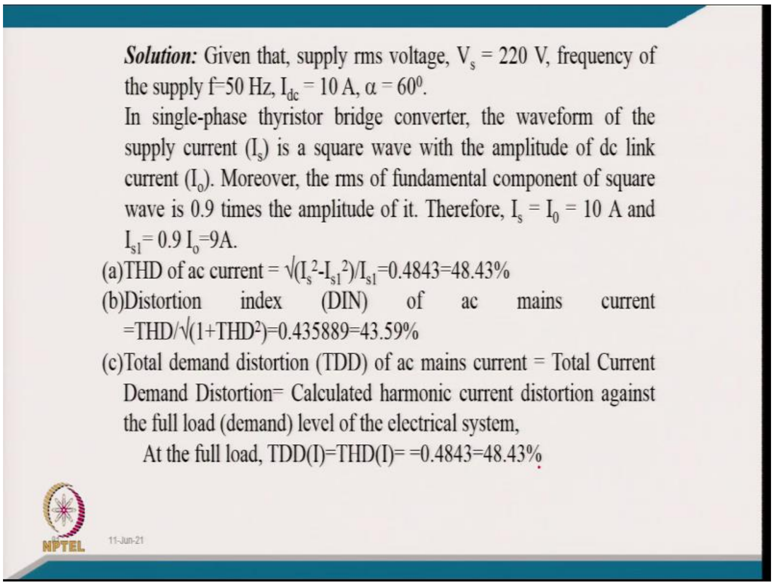


7. A single-phase fully controlled bridge converter (shown below) is supplied from 220 V, 50 Hz at the firing angle of thyristors, α=60°. Consider continuous load current of 10A. Compute (a) total harmonic distortion (THD) of ac mains current, (b) distortion index (DIN) of ac mains current, (c) total demand distortion (TDD) of ac mains current, (d) distortion factor, (e) displacement factor and (f) power factor.

Fig. Single-Phase Converter Based Current Fed Type of Nonlinear Load.

11-Jun-21

(Refer Slide Time: 32:57)



Solution: Given that, supply rms voltage, $V_s = 220$ V, frequency of the supply f=50 Hz, $I_{dc} = 10$ A, $\alpha = 60^0$.

In single-phase thyristor bridge converter, the waveform of the supply current (I_s) is a square wave with the amplitude of dc link current (I_0). Moreover, the rms of fundamental component of square wave is 0.9 times the amplitude of it. Therefore, $I_s = I_0 = 10$ A and $I_{s1} = 0.9\, I_o = 9$A.

(a)THD of ac current = $\sqrt{(I_s^2 - I_{s1}^2)}/I_{s1} = 0.4843 = 48.43\%$

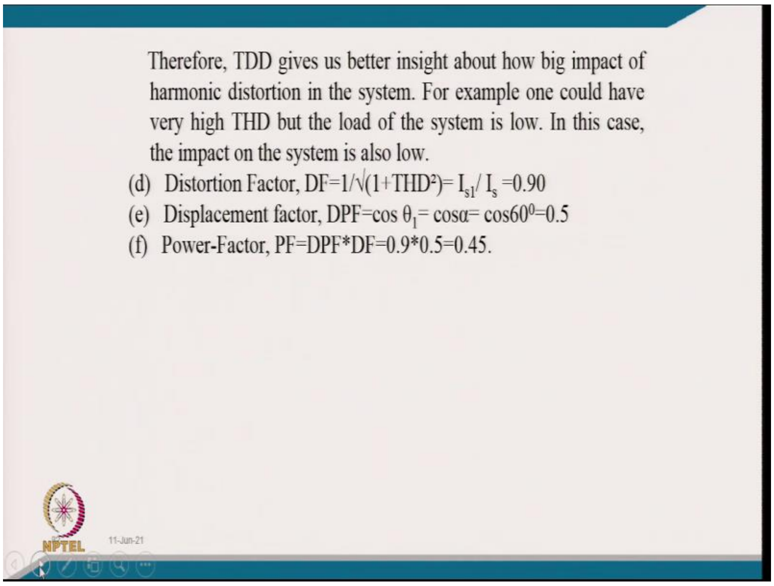
(b)Distortion index (DIN) of ac mains current $= \mathrm{THD}/\sqrt{(1+\mathrm{THD}^2)} = 0.435889 = 43.59\%$

(c)Total demand distortion (TDD) of ac mains current = Total Current Demand Distortion= Calculated harmonic current distortion against the full load (demand) level of the electrical system,

At the full load, TDD(I)=THD(I)= =0.4843=48.43%

11-Jun-21

(Refer Slide Time: 34:16)



Therefore, TDD gives us better insight about how big impact of harmonic distortion in the system. For example one could have very high THD but the load of the system is low. In this case, the impact on the system is also low.

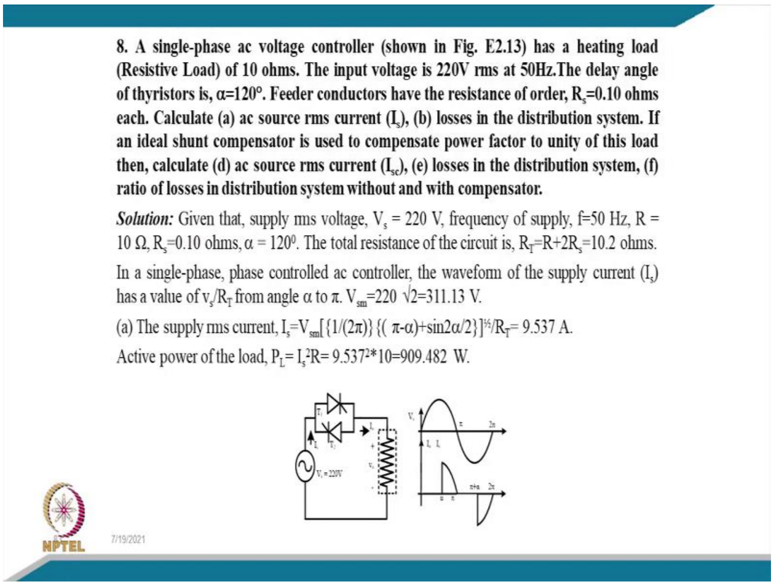
(d) Distortion Factor, $\mathrm{DF} = 1/\sqrt{(1+\mathrm{THD}^2)} = I_{s1}/\, I_s = 0.90$

(e) Displacement factor, $\mathrm{DPF} = \cos\theta_1 = \cos\alpha = \cos 60^0 = 0.5$

(f) Power-Factor, PF=DPF*DF=0.9*0.5=0.45.

11-Jun-21

(Refer Slide Time: 35:11)



8. A single-phase ac voltage controller (shown in Fig. E2.13) has a heating load (Resistive Load) of 10 ohms. The input voltage is 220V rms at 50Hz.The delay angle of thyristors is, α=120°. Feeder conductors have the resistance of order, R_s=0.10 ohms each. Calculate (a) ac source rms current (I_s), (b) losses in the distribution system. If an ideal shunt compensator is used to compensate power factor to unity of this load then, calculate (d) ac source rms current (I_{sc}), (e) losses in the distribution system, (f) ratio of losses in distribution system without and with compensator.

Solution: Given that, supply rms voltage, V_s = 220 V, frequency of supply, f=50 Hz, R = 10 Ω, R_s=0.10 ohms, α = 120⁰. The total resistance of the circuit is, R_T=R+2R_s=10.2 ohms.

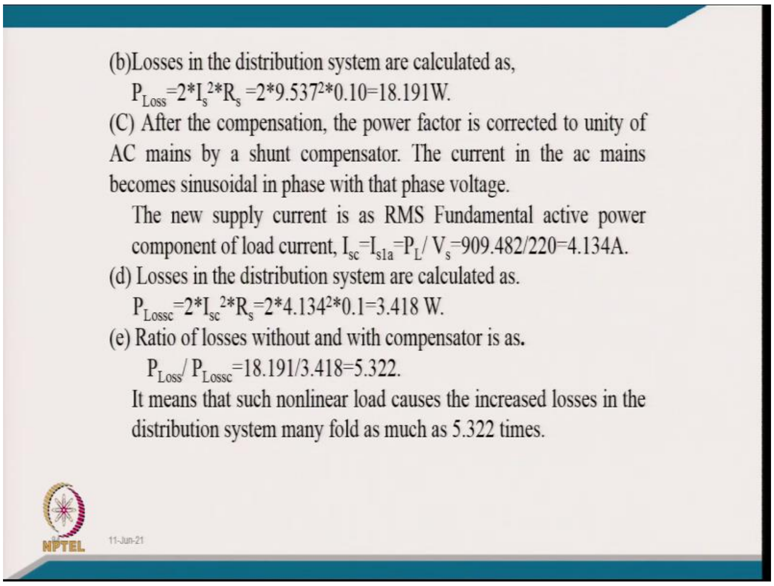
In a single-phase, phase controlled ac controller, the waveform of the supply current (I_s) has a value of v_s/R_T from angle α to π. V_{sm}=220 √2=311.13 V.

(a) The supply rms current, $I_s=V_{sm}[\{1/(2\pi)\}\{(\pi-\alpha)+\sin 2\alpha/2\}]^{1/2}/R_T$= 9.537 A.

Active power of the load, $P_L= I_s^2R$= 9.537^2*10=909.482 W.

7/19/2021

(Refer Slide Time: 37:43)



(b)Losses in the distribution system are calculated as,

$P_{Loss}=2*I_s^2*R_s=2*9.537^2*0.10$=18.191W.

(C) After the compensation, the power factor is corrected to unity of AC mains by a shunt compensator. The current in the ac mains becomes sinusoidal in phase with that phase voltage.

The new supply current is as RMS Fundamental active power component of load current, $I_{sc}=I_{s1a}=P_L/V_s$=909.482/220=4.134A.

(d) Losses in the distribution system are calculated as.

$P_{Lossc}=2*I_{sc}^2*R_s=2*4.134^2*0.1$=3.418 W.

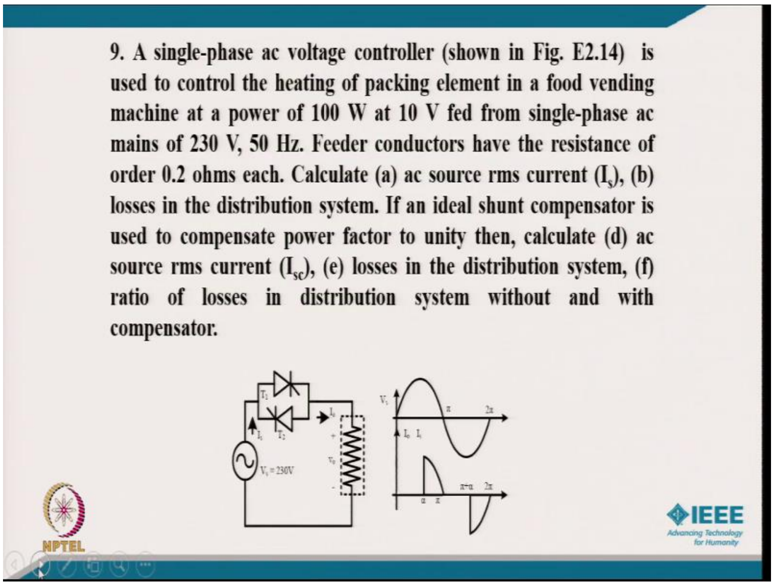
(e) Ratio of losses without and with compensator is as.

P_{Loss}/P_{Lossc}=18.191/3.418=5.322.

It means that such nonlinear load causes the increased losses in the distribution system many fold as much as 5.322 times.

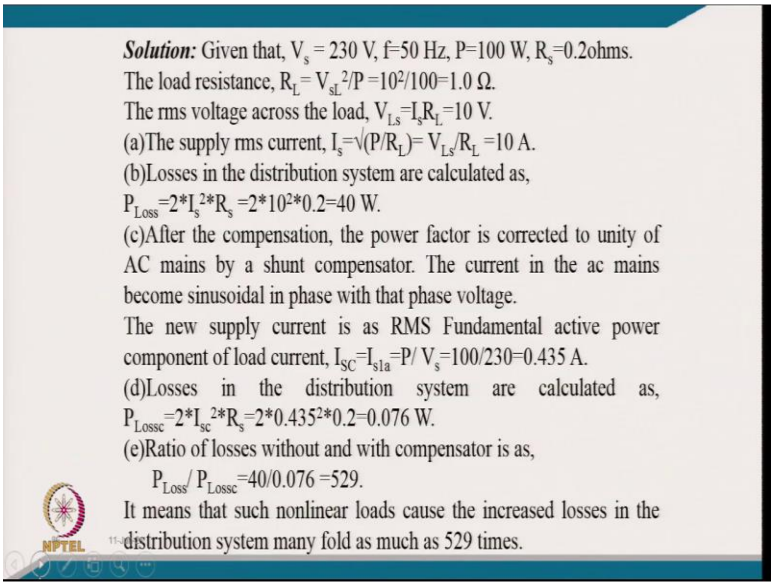
11-Jun-21

(Refer Slide Time: 39:35)



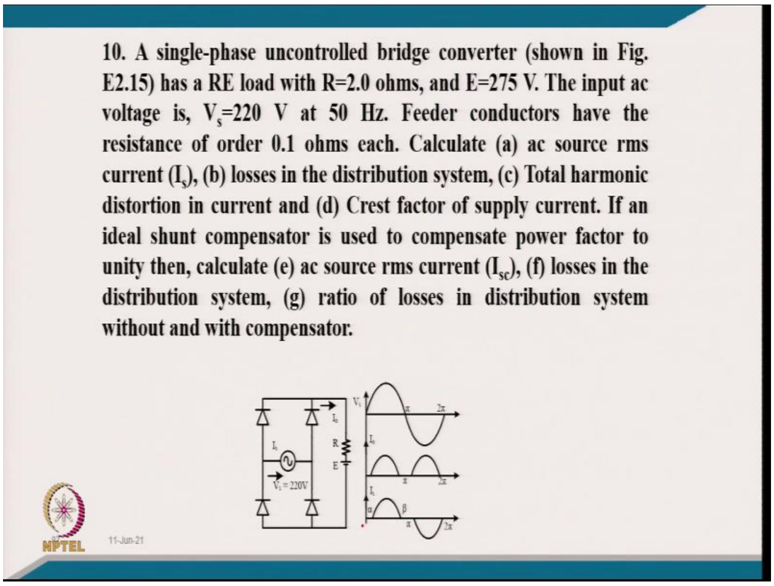
9. A single-phase ac voltage controller (shown in Fig. E2.14) is used to control the heating of packing element in a food vending machine at a power of 100 W at 10 V fed from single-phase ac mains of 230 V, 50 Hz. Feeder conductors have the resistance of order 0.2 ohms each. Calculate (a) ac source rms current (I_s), (b) losses in the distribution system. If an ideal shunt compensator is used to compensate power factor to unity then, calculate (d) ac source rms current (I_{sc}), (e) losses in the distribution system, (f) ratio of losses in distribution system without and with compensator.

(Refer Slide Time: 40:32)



Solution: Given that, $V_s = 230$ V, f=50 Hz, P=100 W, R_s=0.2ohms.
The load resistance, $R_L = V_{sL}{}^2/P = 10^2/100 = 1.0\ \Omega$.
The rms voltage across the load, $V_{Ls} = I_s R_L = 10$ V.
(a)The supply rms current, $I_s = \sqrt{(P/R_L)} = V_{Ls}/R_L = 10$ A.
(b)Losses in the distribution system are calculated as,
$P_{Loss} = 2 * I_s{}^2 * R_s = 2*10^2*0.2 = 40$ W.
(c)After the compensation, the power factor is corrected to unity of AC mains by a shunt compensator. The current in the ac mains become sinusoidal in phase with that phase voltage.
The new supply current is as RMS Fundamental active power component of load current, $I_{SC} = I_{s1a} = P/V_s = 100/230 = 0.435$ A.
(d)Losses in the distribution system are calculated as, $P_{Lossc} = 2 * I_{sc}{}^2 * R_s = 2*0.435^2*0.2 = 0.076$ W.
(e)Ratio of losses without and with compensator is as,
$P_{Loss}/P_{Lossc} = 40/0.076 = 529$.
It means that such nonlinear loads cause the increased losses in the distribution system many fold as much as 529 times.

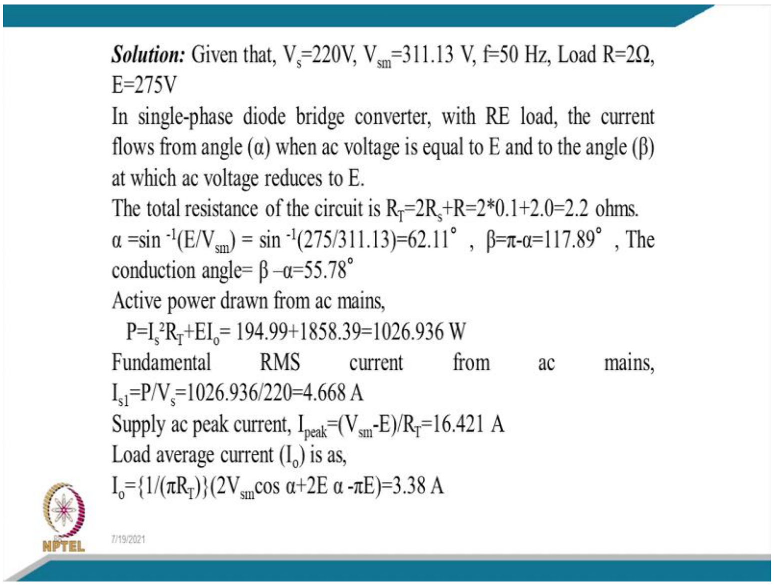
(Refer Slide Time: 42:39)



10. A single-phase uncontrolled bridge converter (shown in Fig. E2.15) has a RE load with R=2.0 ohms, and E=275 V. The input ac voltage is, V_s=220 V at 50 Hz. Feeder conductors have the resistance of order 0.1 ohms each. Calculate (a) ac source rms current (I_s), (b) losses in the distribution system, (c) Total harmonic distortion in current and (d) Crest factor of supply current. If an ideal shunt compensator is used to compensate power factor to unity then, calculate (e) ac source rms current (I_{sc}), (f) losses in the distribution system, (g) ratio of losses in distribution system without and with compensator.

11-Jun-21

(Refer Slide Time: 44:06)



Solution: Given that, V_s=220V, V_{sm}=311.13 V, f=50 Hz, Load R=2Ω, E=275V

In single-phase diode bridge converter, with RE load, the current flows from angle (α) when ac voltage is equal to E and to the angle (β) at which ac voltage reduces to E.

The total resistance of the circuit is $R_T=2R_s+R=2*0.1+2.0=2.2$ ohms.

$\alpha = \sin^{-1}(E/V_{sm}) = \sin^{-1}(275/311.13)=62.11°$, $\beta=\pi-\alpha=117.89°$, The conduction angle= $\beta-\alpha=55.78°$

Active power drawn from ac mains,

$P=I_s^2R_T+EI_o= 194.99+1858.39=1026.936$ W

Fundamental RMS current from ac mains, $I_{s1}=P/V_s=1026.936/220=4.668$ A

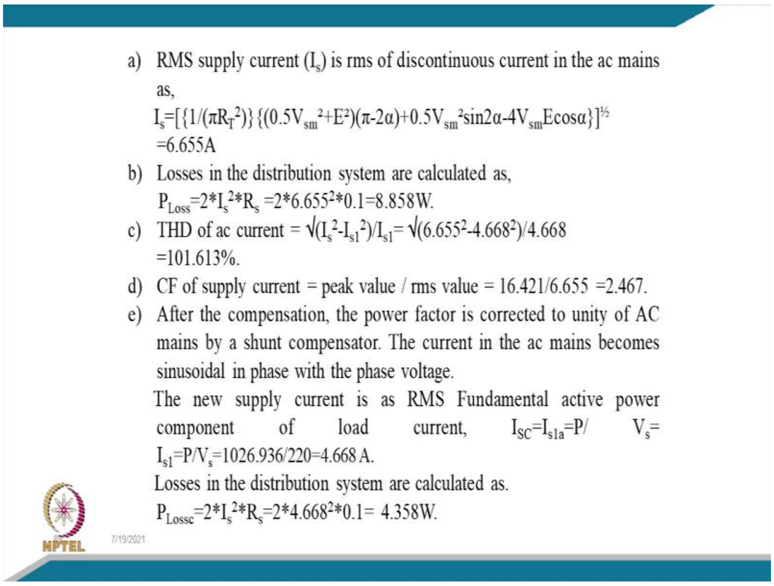
Supply ac peak current, $I_{peak}=(V_{sm}-E)/R_T=16.421$ A

Load average current (I_o) is as,

$I_o=\{1/(\pi R_T)\}(2V_{sm}\cos\alpha+2E\alpha-\pi E)=3.38$ A

7/19/2021

(Refer Slide Time: 46:19)



a) RMS supply current (I_s) is rms of discontinuous current in the ac mains as,
$I_s=[\{1/(\pi R_T^2)\}\{(0.5V_{sm}^2+E^2)(\pi-2\alpha)+0.5V_{sm}^2\sin 2\alpha-4V_{sm}E\cos\alpha\}]^{1/2}$
$=6.655A$

b) Losses in the distribution system are calculated as,
$P_{Loss}=2*I_s^2*R_s=2*6.655^2*0.1=8.858W$.

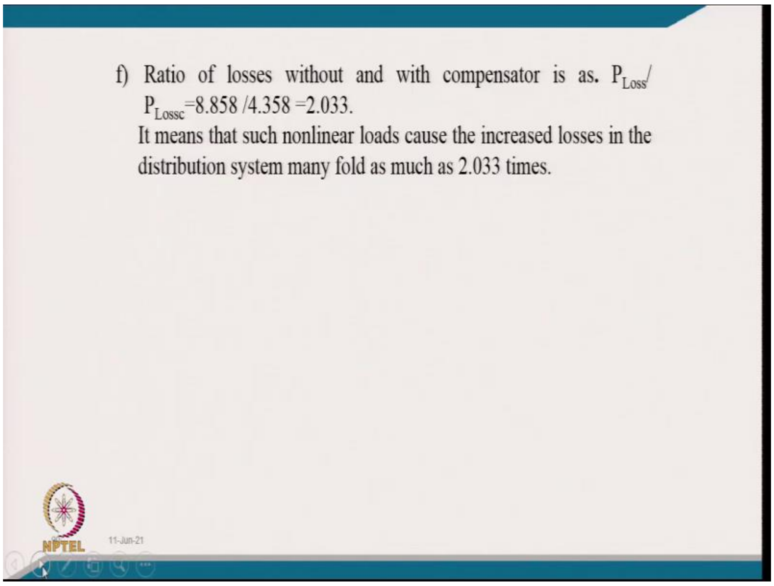
c) THD of ac current $=\sqrt{(I_s^2-I_{s1}^2)}/I_{s1}=\sqrt{(6.655^2-4.668^2)}/4.668$
$=101.613\%$.

d) CF of supply current = peak value / rms value = 16.421/6.655 =2.467.

e) After the compensation, the power factor is corrected to unity of AC mains by a shunt compensator. The current in the ac mains becomes sinusoidal in phase with the phase voltage.
The new supply current is as RMS Fundamental active power component of load current, $I_{SC}=I_{s1a}=P/V_s=I_{s1}=P/V_s=1026.936/220=4.668$ A.
Losses in the distribution system are calculated as.
$P_{Lossc}=2*I_s^2*R_s=2*4.668^2*0.1=4.358W$.

7/19/2021

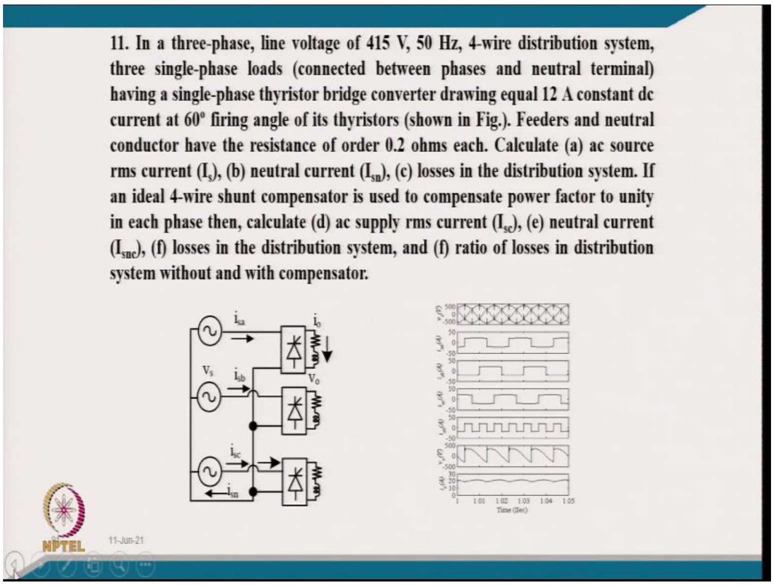
(Refer Slide Time: 47:55)



f) Ratio of losses without and with compensator is as. $P_{Loss}/P_{Lossc}=8.858/4.358=2.033$.
It means that such nonlinear loads cause the increased losses in the distribution system many fold as much as 2.033 times.

11-Jun-21

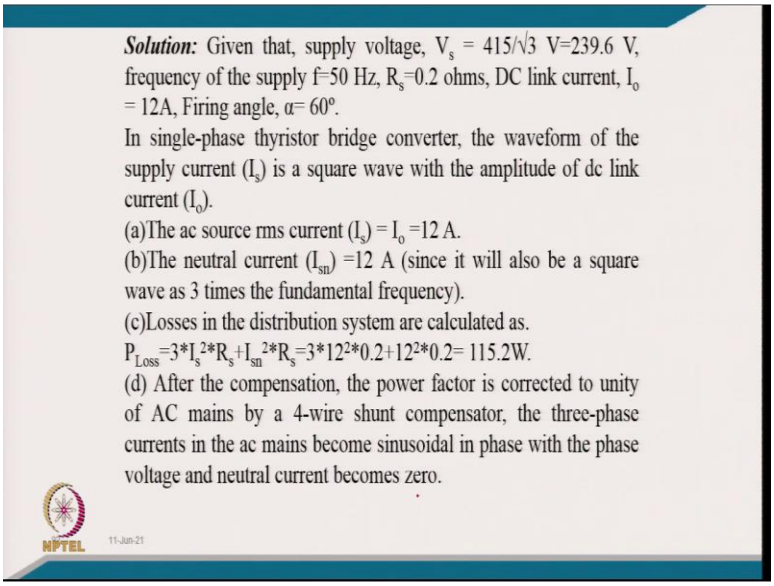
(Refer Slide Time: 48:22)



11. In a three-phase, line voltage of 415 V, 50 Hz, 4-wire distribution system, three single-phase loads (connected between phases and neutral terminal) having a single-phase thyristor bridge converter drawing equal 12 A constant dc current at 60° firing angle of its thyristors (shown in Fig.). Feeders and neutral conductor have the resistance of order 0.2 ohms each. Calculate (a) ac source rms current (I_s), (b) neutral current (I_{sn}), (c) losses in the distribution system. If an ideal 4-wire shunt compensator is used to compensate power factor to unity in each phase then, calculate (d) ac supply rms current (I_{sc}), (e) neutral current (I_{snc}), (f) losses in the distribution system, and (f) ratio of losses in distribution system without and with compensator.

11-Jun-21

(Refer Slide Time: 49:58)



Solution: Given that, supply voltage, V_s = 415/√3 V=239.6 V, frequency of the supply f=50 Hz, R_s=0.2 ohms, DC link current, I_o = 12A, Firing angle, α= 60°.

In single-phase thyristor bridge converter, the waveform of the supply current (I_s) is a square wave with the amplitude of dc link current (I_o).

(a)The ac source rms current (I_s) = I_o =12 A.

(b)The neutral current (I_{sn}) =12 A (since it will also be a square wave as 3 times the fundamental frequency).

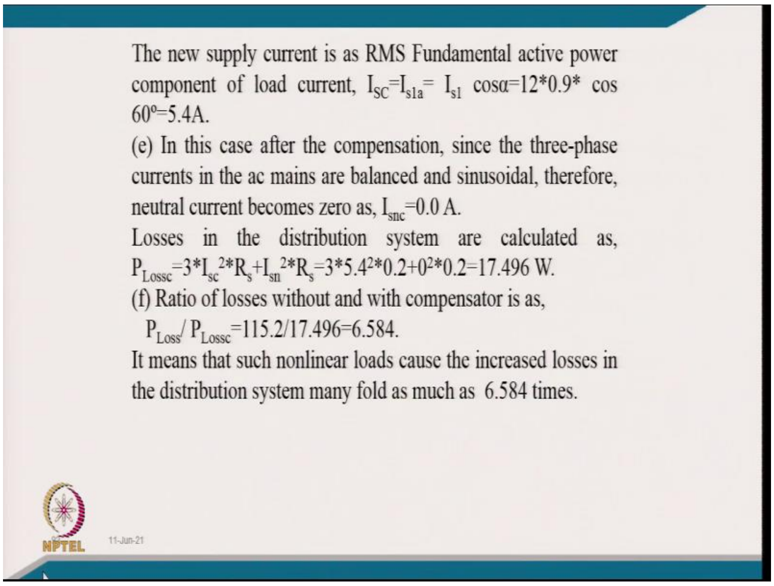
(c)Losses in the distribution system are calculated as.

$P_{Loss}=3*I_s^2*R_s+I_{sn}^2*R_s=3*12^2*0.2+12^2*0.2=115.2$W.

(d) After the compensation, the power factor is corrected to unity of AC mains by a 4-wire shunt compensator, the three-phase currents in the ac mains become sinusoidal in phase with the phase voltage and neutral current becomes zero.

11-Jun-21

(Refer Slide Time: 51:15)



The new supply current is as RMS Fundamental active power component of load current, $I_{SC}=I_{s1a}= I_{s1}\ \cos\alpha=12*0.9*\cos 60^o=5.4A$.

(e) In this case after the compensation, since the three-phase currents in the ac mains are balanced and sinusoidal, therefore, neutral current becomes zero as, $I_{snc}=0.0$ A.

Losses in the distribution system are calculated as, $P_{Lossc}=3*I_{sc}{}^2*R_s+I_{sn}{}^2*R_s=3*5.4^2*0.2+0^2*0.2=17.496$ W.

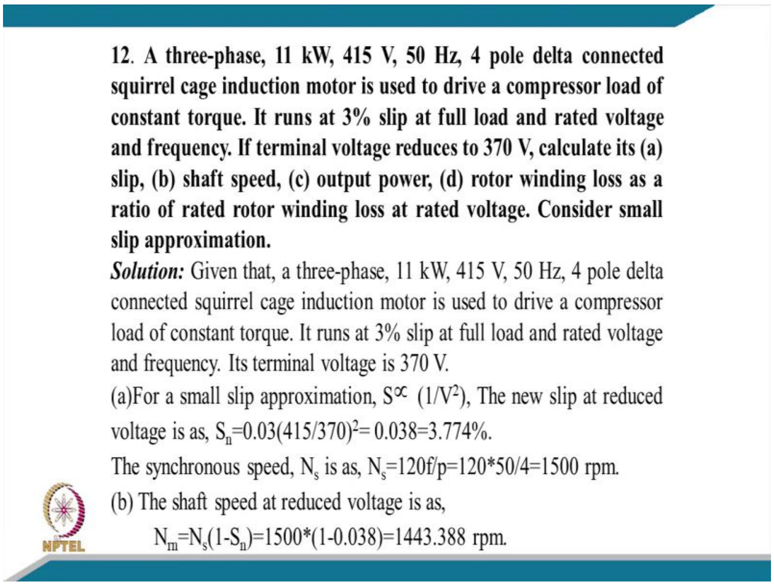
(f) Ratio of losses without and with compensator is as,

$P_{Loss}/P_{Lossc}=115.2/17.496=6.584$.

It means that such nonlinear loads cause the increased losses in the distribution system many fold as much as 6.584 times.

11-Jun-21

(Refer Slide Time: 52:25)



12. A three-phase, 11 kW, 415 V, 50 Hz, 4 pole delta connected squirrel cage induction motor is used to drive a compressor load of constant torque. It runs at 3% slip at full load and rated voltage and frequency. If terminal voltage reduces to 370 V, calculate its (a) slip, (b) shaft speed, (c) output power, (d) rotor winding loss as a ratio of rated rotor winding loss at rated voltage. Consider small slip approximation.

Solution: Given that, a three-phase, 11 kW, 415 V, 50 Hz, 4 pole delta connected squirrel cage induction motor is used to drive a compressor load of constant torque. It runs at 3% slip at full load and rated voltage and frequency. Its terminal voltage is 370 V.

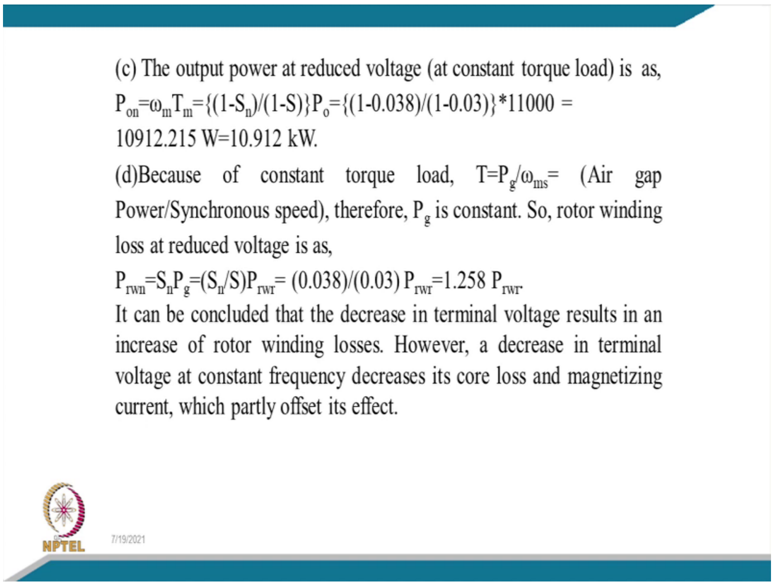
(a)For a small slip approximation, $S\propto (1/V^2)$, The new slip at reduced voltage is as, $S_n=0.03(415/370)^2= 0.038=3.774\%$.

The synchronous speed, N_s is as, $N_s=120f/p=120*50/4=1500$ rpm.

(b) The shaft speed at reduced voltage is as,

$N_m=N_s(1-S_n)=1500*(1-0.038)=1443.388$ rpm.

(Refer Slide Time: 53:53)



(c) The output power at reduced voltage (at constant torque load) is as,

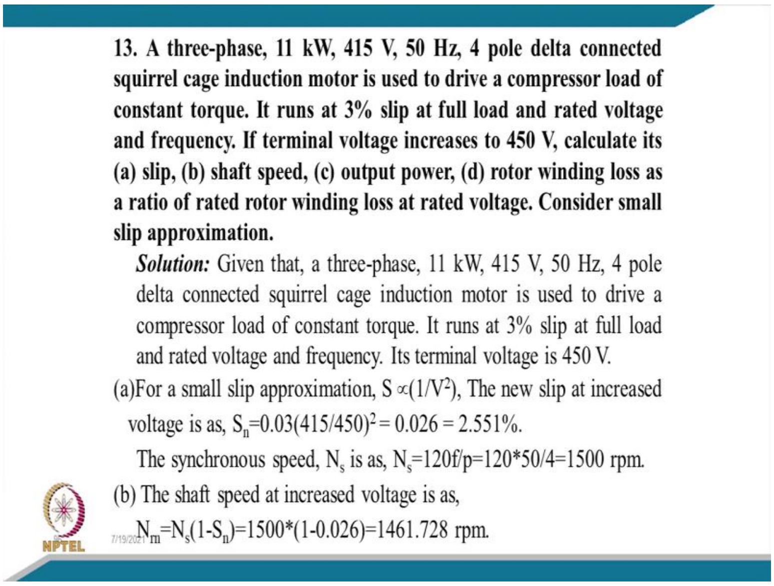
$P_{on}=\omega_m T_m=\{(1-S_n)/(1-S)\}P_o=\{(1-0.038)/(1-0.03)\}*11000 = 10912.215\ W=10.912\ kW.$

(d)Because of constant torque load, $T=P_g/\omega_{ms}=$ (Air gap Power/Synchronous speed), therefore, P_g is constant. So, rotor winding loss at reduced voltage is as,

$P_{rwn}=S_n P_g=(S_n/S)P_{rwr}=(0.038)/(0.03)\ P_{rwr}=1.258\ P_{rwr}.$

It can be concluded that the decrease in terminal voltage results in an increase of rotor winding losses. However, a decrease in terminal voltage at constant frequency decreases its core loss and magnetizing current, which partly offset its effect.

(Refer Slide Time: 54:45)



13. A three-phase, 11 kW, 415 V, 50 Hz, 4 pole delta connected squirrel cage induction motor is used to drive a compressor load of constant torque. It runs at 3% slip at full load and rated voltage and frequency. If terminal voltage increases to 450 V, calculate its (a) slip, (b) shaft speed, (c) output power, (d) rotor winding loss as a ratio of rated rotor winding loss at rated voltage. Consider small slip approximation.

Solution: Given that, a three-phase, 11 kW, 415 V, 50 Hz, 4 pole delta connected squirrel cage induction motor is used to drive a compressor load of constant torque. It runs at 3% slip at full load and rated voltage and frequency. Its terminal voltage is 450 V.

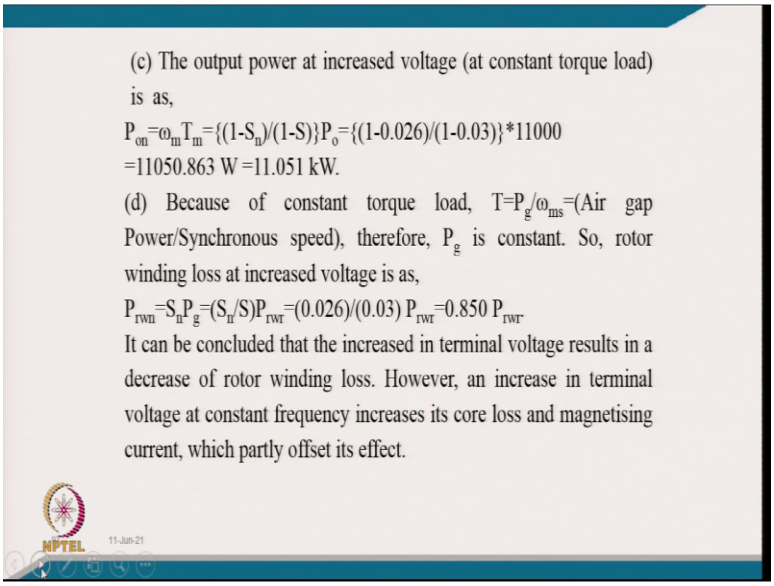
(a)For a small slip approximation, $S \propto (1/V^2)$, The new slip at increased voltage is as, $S_n=0.03(415/450)^2 = 0.026 = 2.551\%$.

The synchronous speed, N_s is as, $N_s=120f/p=120*50/4=1500$ rpm.

(b) The shaft speed at increased voltage is as,

$N_m=N_s(1-S_n)=1500*(1-0.026)=1461.728$ rpm.

(Refer Slide Time: 55:45)



(c) The output power at increased voltage (at constant torque load) is as,

$P_{on}=\omega_m T_m=\{(1-S_n)/(1-S)\}P_o=\{(1-0.026)/(1-0.03)\}*11000$
$=11050.863$ W =11.051 kW.

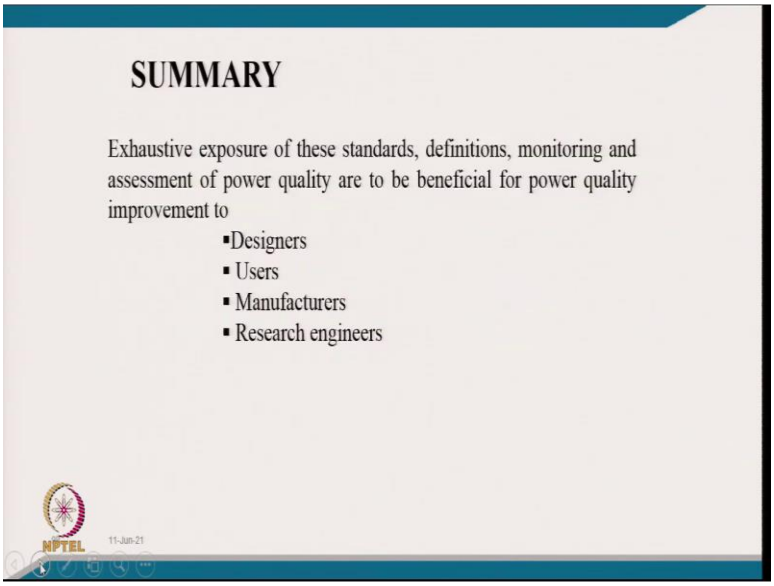
(d) Because of constant torque load, $T=P_g/\omega_{ms}$=(Air gap Power/Synchronous speed), therefore, P_g is constant. So, rotor winding loss at increased voltage is as,

$P_{rwn}=S_n P_g=(S_n/S)P_{rwr}=(0.026)/(0.03)\ P_{rwr}=0.850\ P_{rwr}$.

It can be concluded that the increased in terminal voltage results in a decrease of rotor winding loss. However, an increase in terminal voltage at constant frequency increases its core loss and magnetising current, which partly offset its effect.

11-Jun-21

(Refer Slide Time: 56:23)



SUMMARY

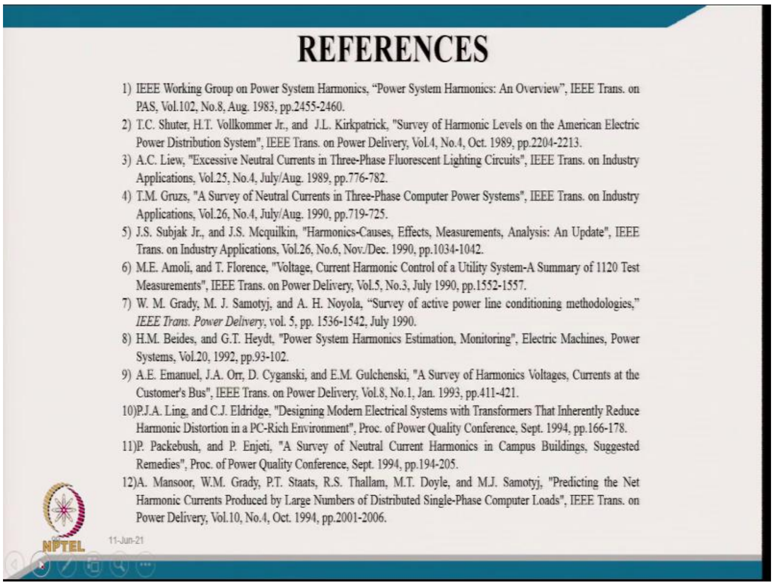
Exhaustive exposure of these standards, definitions, monitoring and assessment of power quality are to be beneficial for power quality improvement to

- Designers
- Users
- Manufacturers
- Research engineers

11-Jun-21

The exhaustive exposure of these standards, definitions, monitoring and assessment of power quality is beneficial for power quality improvement to the designers, users and manufacturers, and research engineers.

(Refer Slide Time: 56:40)



REFERENCES

1) IEEE Working Group on Power System Harmonics, “Power System Harmonics: An Overview”, IEEE Trans. on PAS, Vol.102, No.8, Aug. 1983, pp.2455-2460.

2) T.C. Shuter, H.T. Vollkommer Jr., and J.L. Kirkpatrick, "Survey of Harmonic Levels on the American Electric Power Distribution System", IEEE Trans. on Power Delivery, Vol.4, No.4, Oct. 1989, pp.2204-2213.

3) A.C. Liew, "Excessive Neutral Currents in Three-Phase Fluorescent Lighting Circuits", IEEE Trans. on Industry Applications, Vol.25, No.4, July/Aug. 1989, pp.776-782.

4) T.M. Gruzs, "A Survey of Neutral Currents in Three-Phase Computer Power Systems", IEEE Trans. on Industry Applications, Vol.26, No.4, July/Aug. 1990, pp.719-725.

5) J.S. Subjak Jr., and J.S. Mcquilkin, "Harmonics-Causes, Effects, Measurements, Analysis: An Update", IEEE Trans. on Industry Applications, Vol.26, No.6, Nov./Dec. 1990, pp.1034-1042.

6) M.E. Amoli, and T. Florence, "Voltage, Current Harmonic Control of a Utility System-A Summary of 1120 Test Measurements", IEEE Trans. on Power Delivery, Vol.5, No.3, July 1990, pp.1552-1557.

7) W. M. Grady, M. J. Samotyj, and A. H. Noyola, “Survey of active power line conditioning methodologies,” *IEEE Trans. Power Delivery*, vol. 5, pp. 1536-1542, July 1990.

8) H.M. Beides, and G.T. Heydt, "Power System Harmonics Estimation, Monitoring", Electric Machines, Power Systems, Vol.20, 1992, pp.93-102.

9) A.E. Emanuel, J.A. Orr, D. Cyganski, and E.M. Gulchenski, "A Survey of Harmonics Voltages, Currents at the Customer's Bus", IEEE Trans. on Power Delivery, Vol.8, No.1, Jan. 1993, pp.411-421.

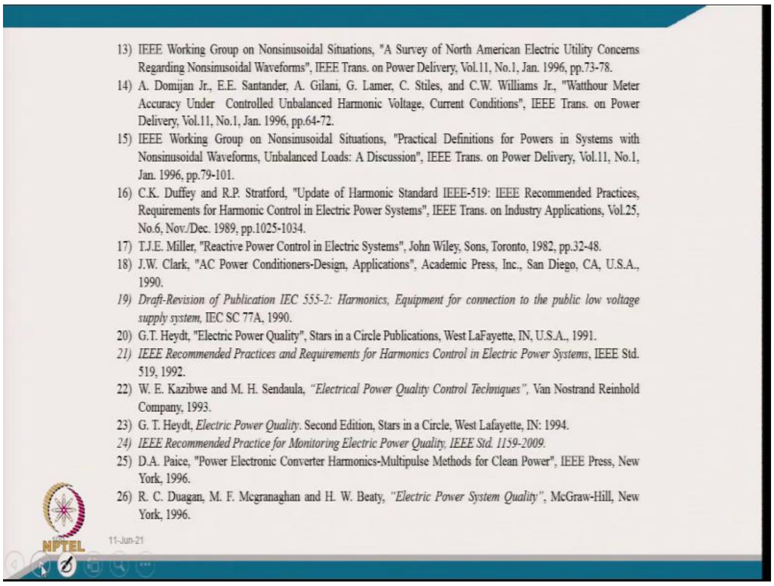
10)P.J.A. Ling, and C.J. Eldridge, "Designing Modern Electrical Systems with Transformers That Inherently Reduce Harmonic Distortion in a PC-Rich Environment", Proc. of Power Quality Conference, Sept. 1994, pp.166-178.

11)P. Packebush, and P. Enjeti, "A Survey of Neutral Current Harmonics in Campus Buildings, Suggested Remedies", Proc. of Power Quality Conference, Sept. 1994, pp.194-205.

12)A. Mansoor, W.M. Grady, P.T. Staats, R.S. Thallam, M.T. Doyle, and M.J. Samotyj, "Predicting the Net Harmonic Currents Produced by Large Numbers of Distributed Single-Phase Computer Loads", IEEE Trans. on Power Delivery, Vol.10, No.4, Oct. 1994, pp.2001-2006.

11-Jun-21

(Refer Slide Time: 56:41)



13) IEEE Working Group on Nonsinusoidal Situations, "A Survey of North American Electric Utility Concerns Regarding Nonsinusoidal Waveforms", IEEE Trans. on Power Delivery, Vol.11, No.1, Jan. 1996, pp.73-78.

14) A. Domijan Jr., E.E. Santander, A. Gilani, G. Lamer, C. Stiles, and C.W. Williams Jr., "Watthour Meter Accuracy Under Controlled Unbalanced Harmonic Voltage, Current Conditions", IEEE Trans. on Power Delivery, Vol.11, No.1, Jan. 1996, pp.64-72.

15) IEEE Working Group on Nonsinusoidal Situations, "Practical Definitions for Powers in Systems with Nonsinusoidal Waveforms, Unbalanced Loads: A Discussion", IEEE Trans. on Power Delivery, Vol.11, No.1, Jan. 1996, pp.79-101.

16) C.K. Duffey and R.P. Stratford, "Update of Harmonic Standard IEEE-519: IEEE Recommended Practices, Requirements for Harmonic Control in Electric Power Systems", IEEE Trans. on Industry Applications, Vol.25, No.6, Nov./Dec. 1989, pp.1025-1034.

17) T.J.E. Miller, "Reactive Power Control in Electric Systems", John Wiley, Sons, Toronto, 1982, pp.32-48.

18) J.W. Clark, "AC Power Conditioners-Design, Applications", Academic Press, Inc., San Diego, CA, U.S.A., 1990.

19) Draft-Revision of Publication IEC 555-2: Harmonics, Equipment for connection to the public low voltage supply system, IEC SC 77A, 1990.

20) G.T. Heydt, "Electric Power Quality", Stars in a Circle Publications, West LaFayette, IN, U.S.A., 1991.

21) IEEE Recommended Practices and Requirements for Harmonics Control in Electric Power Systems, IEEE Std. 519, 1992.

22) W. E. Kazibwe and M. H. Sendaula, *“Electrical Power Quality Control Techniques”*, Van Nostrand Reinhold Company, 1993.

23) G. T. Heydt, *Electric Power Quality*. Second Edition, Stars in a Circle, West Lafayette, IN: 1994.

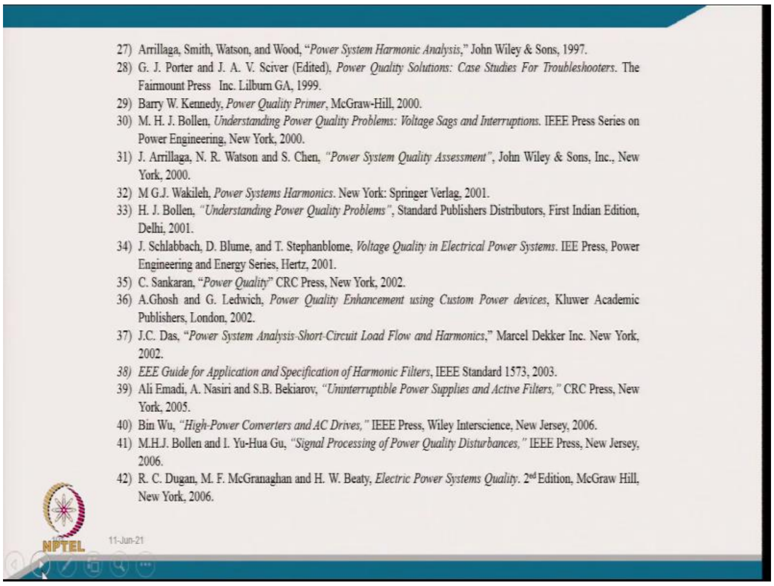
24) IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Std. 1159-2009.

25) D.A. Paice, "Power Electronic Converter Harmonics-Multipulse Methods for Clean Power", IEEE Press, New York, 1996.

26) R. C. Duagan, M. F. Mcgranaghan and H. W. Beaty, *"Electric Power System Quality"*, McGraw-Hill, New York, 1996.

11-Jun-21

(Refer Slide Time: 56:42)



27) Arrillaga, Smith, Watson, and Wood, "*Power System Harmonic Analysis,*" John Wiley & Sons, 1997.
28) G. J. Porter and J. A. V. Sciver (Edited), *Power Quality Solutions: Case Studies For Troubleshooters*. The Fairmount Press Inc. Lilburn GA, 1999.
29) Barry W. Kennedy, *Power Quality Primer*, McGraw-Hill, 2000.
30) M. H. J. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions.* IEEE Press Series on Power Engineering, New York, 2000.
31) J. Arrillaga, N. R. Watson and S. Chen, *"Power System Quality Assessment"*, John Wiley & Sons, Inc., New York, 2000.
32) M G.J. Wakileh, *Power Systems Harmonics*. New York: Springer Verlag, 2001.
33) H. J. Bollen, *"Understanding Power Quality Problems"*, Standard Publishers Distributors, First Indian Edition, Delhi, 2001.
34) J. Schlabbach, D. Blume, and T. Stephanblome, *Voltage Quality in Electrical Power Systems*. IEE Press, Power Engineering and Energy Series, Hertz, 2001.
35) C. Sankaran, "*Power Quality*" CRC Press, New York, 2002.
36) A.Ghosh and G. Ledwich, *Power Quality Enhancement using Custom Power devices*, Kluwer Academic Publishers, London, 2002.
37) J.C. Das, "*Power System Analysis-Short-Circuit Load Flow and Harmonics,*" Marcel Dekker Inc. New York, 2002.
38) *EEE Guide for Application and Specification of Harmonic Filters*, IEEE Standard 1573, 2003.
39) Ali Emadi, A. Nasiri and S.B. Bekiarov, *"Uninterruptible Power Supplies and Active Filters,"* CRC Press, New York, 2005.
40) Bin Wu, *"High-Power Converters and AC Drives,"* IEEE Press, Wiley Interscience, New Jersey, 2006.
41) M.H.J. Bollen and I. Yu-Hua Gu, *"Signal Processing of Power Quality Disturbances,"* IEEE Press, New Jersey, 2006.
42) R. C. Dugan, M. F. McGranaghan and H. W. Beaty, *Electric Power Systems Quality*. 2nd Edition, McGraw Hill, New York, 2006.

11-Jun-21

And of course, these are the some of the references like. [FL], we like to conclude this lecture and typically.

Thank you very much.