A PSERC Tutorial
on

Contemporary Topics in Electric Power Quality

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PSERC

Alias

A ‘Tutrial’ on Power Quality

PROGRAM

1. Power quality indices / pitfalls / three phase phenomena and applications / ‘interharmonics’ and other non-harmonics
2. Power acceptability, when is electric power delivered ‘acceptable’, vulnerability of loads
3. Series voltage boost hardware
4. Rectifier loads
5. Power quality standards
6. Why is power quality important? The salability of power quality

Power Quality Indices

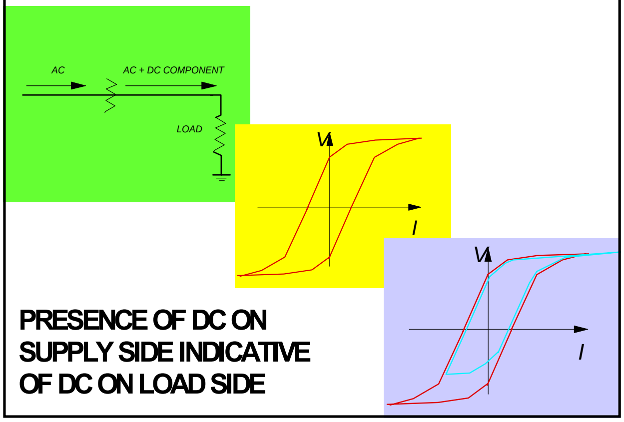
Power Quality Indices

Index	Definition	Main applications
Total harmonic distortion (THD)	$\left(\sqrt{\sum_{i=2}^{\infty} I_i}\right) / I_1$	General purpose; standards
Power factor (PF)	$P_{tot} / \lvert V_{rms}\rvert \lvert I_{rms}\rvert$	Potentially in revenue metering
Telephone influence factor	$\left(\sqrt{\sum_{i=2}^{\infty} w_i^2 I_i}\right) / I_{rms}$	Audio circuit interference
C message index	$\left(\sqrt{\sum_{i=2}^{\infty} c_i^2 I_i}\right) / I_{rms}$	Communications interference
IT product	$\sqrt{\sum_{i=1}^{\infty} w_i^2 I_i^2}$	Audio circuit interference; shunt capacitor stress
VT product	$\sqrt{\sum_{i=1}^{\infty} w_i^2 V_i^2}$	Voltage distortion index
K factor	$\left(\sum_{h=1}^{\infty} h^2 I_h^2\right) / \sum_{h=1}^{\infty} I_h^2$	Transformer derating
Crest factor	V_{peak} / V_{rms}	Dielectric stress
Unbalance factor	$\lvert V_-\rvert / \lvert V_+\rvert$	Three phase circuit balance
Flicker factor	$\Delta V / \lvert V\rvert$	Incandescent lamp operation; bus voltage regulation; sufficiency of short circuit capacity

EVEN HARMONICS

- THEORETICALLY IMPOSSIBLE FOR SIGNALS THAT ARE SYMMETRIC ABOUT THE TIME AXIS
- PRESENCE OF EVEN HARMONICS DO NOT IMPLY DC COMPONENTS IN THE GIVEN SIGNAL
- MOST COMMON OCCURRENCE OF EVEN HARMONICS IS IN THE SUPPLY CURRENT OF TRANSFORMERS WHOSE LOAD SIDE HAVE DC CURRENT COMPONENTS

EVEN HARMONICS



PRESENCE OF DC ON SUPPLY SIDE INDICATIVE OF DC ON LOAD SIDE

Displacement factor	(True) power factor
$DF = \cos(\phi_{60})$	$PF = (\Sigma P) / \lvert Vrms \rvert \lvert Irms \rvert$
'Power frequency power factor'	'Total power over total volt-amperes'

$$TPF \le DF$$

EXAMPLE

RMS	60 Hz	180 Hz	420 Hz
V	$1\angle 0^o$	$0.2\angle 20^o$	$0.5\angle 10^o$
I	$1\angle -30^o$	$0.2\angle 80^o$	$0.15\angle -20^o$

$$\Sigma P = (1)(1)\cos 30^o + (0.2)(0.2)\cos 60^o + (0.05)(0.15)\cos(30^o)$$

$$= 0.892$$

$$(Vrms)^2 = 1^2 + 0.2^2 + 0.05^2$$

$$Vrms = 1.021$$

$$(Irms)^2 = 1^2 + 0.2^2 + 0.15^2$$

$$Irms = 1.031$$

$$S = (Vrms)(Irms) = 1.052$$

$$TPF = \Sigma P / S = 0.848$$

$$DF = DPF = \cos(30^o) = 0.866 \text{ (lag)}$$

POWER FACTOR MULTIPLIERS

- BILLING MULTI[PLIERS TO SEND THE CUSTOMER THE PROPER SIGNAL CONCERNING POWER FACTOR
- MULTIPLIER NEAT 1.0 FOR ~86%PF LAG
- MULTIPLIER INCREASES TO ~1.3 FOR DECREASING POWER FACTOR
- MULTIPLIER DECREASES TO ~0.95 FOR PF NEAR UNITY
- e.g., 0.06 $/kWh AT 86% PF LAG, 0.08 $/kWh AT LOW POWER FACTOR
- WHICH PF? TPF? DISPLACEMENT FACTOR?
- CUSTOMERS FAVOR USE OF DF, UTILITIES FAVOR TPF
- LOSSES MORE CLOSELY RELATED TO TPF THAN DF
- REQUIRED kVA OF SUPPLY EQUIPMENT MORE CLOSELY RELATED TO TPF
- INSTRUMENTATION ISSUES

THD

RMS	60 Hz	180 Hz	420 Hz
V	$1\angle 0^o$	$0.2\angle 20^o$	$0.5\angle 10^o$
I	$1\angle -30^o$	$0.2\angle 80^o$	$0.15\angle -20^o$

$$VTHD^2 = 0.2^2 + 0.05^2 / 1$$
$$ITHD^2 = 0.2^2 + 0.15^2 / 1$$

VTHD = 20.62% ITHD = 25%

THD

THE THD OF A SQUARE WAVE OF AMPLITUDE ± 1 IS EASILY FOUND NOTING THAT THE RMS VALUE OF SUCH A WAVE IS 1.000 AND THE FUNDAMENTAL COMPONENT IS $4/\Pi$ (ZERO TO PEAK). THE FUNDAMENTAL COMPONENT IS $(0.707)(4/\Pi) = (0.9002)$. THEREFORE THE SUM OF THE SQUARES OF THE HARMONIC COMPONENTS IS $1^2 - 0.9002^2 = (0.1896)$. THEN,

$$THD^2 = 0.1896/0.9002$$
$$THD = 45.89\%$$

THD - ANOTHER EXAMPLE

f	|*V*|	| *I* |
60	1.00	1.00
180	0.01	0.31
300	0.04	0.15
420	0.03	0.07
540	0.02	0.03
660	0.01	0.02

$$VTHD^2 = 0.01^2 + 0.04^2 + 0.03^2 + 0.02^2 + 0.01^2$$

VTHD = 5.57%

ITHD = 35.33%

Three Phase Considerations

Balanced THD

Based on positive and negative sequence THDs only

Residual THD

Based on zero sequence only

THD

THE RESIDUAL THD IS GENERALLY FAR MORE HARMFUL THAN BALANCED THD BECAUSE THERE IS NO 'CANCELLATION EFFECT' OF THE THREE PHASES OUT OF PHASE BY 120^o

THD

ADVANTAGE: EVERYONE USES IT, EASY TO CALCULATE, WIDELY USED IN STANDARDS AND GUIDES

DISADVANTAGES: DOES NOT ACCELERATE WITH FREQUENCY, BALANCED AND RESIDUAL THD NOT AS WELL KNOWN, DOES NOT TRULY SHOW THE INTERFERENCE IMPACT OF THE SIGNAL

TOTAL DEMAND DISTORTION (TDD)

TOTAL DEMAND DISTORTION IS A MEASURE OF THE THD TAKING INTO ACCOUNT THE CIRCUIT RATING. AS CIRCUIT RATING VERSUS LOAD CURRENT RISES, TDD DROPS

TDD = THD * (Fundamental load current / Circuit rating)

DISTORTION INDEX (DIN)

$$DIN = \frac{\sqrt{\sum_{2}^{\infty} I_i^2}}{I_{rms}}$$

TELEPHONE INFLUENCE FACTOR

$$TIF = \frac{\sqrt{\sum_{1}^{\infty} w_i^2 I_i^2}}{I_{rms}}$$

I*T PRODUCT

$$IT = TIF * I_{rms}$$

V*T PRODUCT

- DEFINED LIKE I*T PRODUCT USING VOLTAGE
- kVT = 1000 VT
- BALANCED AND RESIDUAL V*T PRODUCT
- USED IN SHUNT CAPACITOR STANDARDS - TO LIMIT HARMONIC CURRENTS

PEAK VALUES

PEAK VALUES CAN BE CHARACTERIZED BY A CREST FACTOR:

CF = PEAK VALUE / RMS VALUE

= 1.414 *FOR A PERFECT SINE WAVE*

ABSOLUTE LARGEST VALUE CAN BE OVERESTIMATED FOR ASYNCHRONOUS SIGNALS AS THE SIMPLE ALGEBRAIC SUM OF THE AMPLITUDES OF THE ASYNCHRONOUS FREQUENCIES

RMS VALUES

$$F_{RMS} = \sqrt{\frac{1}{T}\int_0^T f^2(t)dt}$$

RMS VALUES

If the function is not periodic, take limit as T --> infinity

Parseval's theorem -- for signals of different frequencies,

$(V_{rms})^2 = (V_{1rms})^2 + (V_{2rms})^2 + (V_{3rms})^2 + \ldots$

RMS VALUES

If signals are of the same frequency, need to combine the same frequency terms using phasor arithmetic, and then apply Parseval's theorem without regard for phase angles

RMS VALUES

Examples

$10\cos(t) + 2\cos(2t) + \sin(3t)$

$10\sqrt{2}\cos(t) + 10\sqrt{2}\sin(t)$

$10\cos(t) + 10\sin(\sqrt{2}t)$

$440\sqrt{2}\cos(314t) + 50\sqrt{2}\sin(314t) + 80\sqrt{2}\sin(492t) + 10\cos(1570t)$

RMS VALUES

First example

$$F_{rms}^2 = (\frac{10}{\sqrt{2}})^2 + (\frac{2}{\sqrt{2}})^2 + (\frac{1}{\sqrt{2}})^2$$

$$= 5.123$$

RMS VALUES

Second example

1. Gather like frequency terms

$$f(t) = 10\sqrt{2}(\sqrt{2}\cos(t + 45^o))$$

2. Find RMS value of result

$$F_{rms}^2 = \frac{20}{\sqrt{2}} = 14.14$$

RMS VALUES

Third example

This example is aperiodic -- but no change in application of Parseval's theorem:

$$F_{rms}^2 = \left(\frac{1}{\sqrt{2}}\right)^2 + \left(\frac{1}{\sqrt{2}}\right)^2$$

$$F_{rms} = 1.00$$

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RMS VALUES

Fourth example

First combine fundamental term

$$F_{1,rms} = \sqrt{440^2 + 50^2} = 442.83$$

Then apply Parseval's theorem

$$F_{rms} = \sqrt{442.83^2 + 80^2 + 10^2} = 450.11$$

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CONSEQUENCES OF HARMONICS

- I^2R HEATING DUE TO EXCESS CURRENT
- TRANSFORMER MAGNETIC LOSSES
- INCREASED MOTOR LOSSES
- INCREASED CREST CURRENT
- CIRCUIT BOARD HEATING

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TRANSFORMER DERATING

DEFINE P_{LL-R} AND P_{EC-R} AS THE FULL LOAD LOSSES AND CORE LOSSES PER-UNITIZED BY THE I^2R LOSSES. THEN THE DERATED TRANSFORMER MAXIMUM CURRENT IN PER UNIT IS

$$I_{derated} = \sqrt{\frac{P_{LL-R}}{1 + KP_{EC-R}}}$$

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TRANSFORMER DERATING

THIS DERATING IS CONSERVATIVE IN THAT ALL CORE LOSSES ARE INCREASED BY A FACTOR OF K -- THIS IS AN OVERESTIMATE OF THE *B-H* LOSSES. THE METHOD IS IN COMMON USE AS PRESCRIBED BY IEEE STANDARD C57.110, UL 1561 AND UL1562.

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APPLICATION OF IEEE C57.110 DERATING

BASIC METHOD

- CALCULATE TOTAL CORE LOSSES P_{EC}
- CALCULATE I^2R LOSSES, P_{I2R}
- CALCULATE TOTAL FULL LOAD LOSSES P_{LL}
- PERUNITIZE P_{LL} AND P_{EC} BY P_{I2R}
- CALCULATE THE K-FACTOR OF THE LOAD CURRENT
- CALCULATE DERATED RATING OF LOAD CURRENT

$$I_{derated} = \sqrt{\frac{P_{LL-R}}{1 + KP_{EC-R}}}$$

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IT MAY BE NECESSARY TO CALCULATE I^2R LOSSES USING FULL LOAD CURRENT AND NAMEPLATE RATING OF RESISTANCE --OR AN ESTIMATE OF THE RESISTANCE.

EXAMPLE

A 67.5 kVA 1Ø DISTRIBUTION TRANSFORMER IS RATED 7200 / 240 V. THE CORE LOSSES ARE 75 W AT RATED VOLTAGE, AND THE FULL LOAD LOSSES ARE 190 W. THE WINDING RESISTANCES ARE 0.5% TOTAL. FIND THE DERATED TRANSFORMER CAPACITY TO CARRY A LOAD CURRENT OF 150% THD WHICH IS COMPOSED OF FUNDAMENTAL AND THIRD HARMONIC.

SOLUTION

$$I_{derated} = \sqrt{\frac{P_{LL-R}}{1 + KP_{EC-R}}}$$

$$= \sqrt{\frac{0.563}{1 + (6.54)(0.222)}}$$

$$= 0.479 \quad pu$$

SOLUTION

I_{rated} = (67.5 k) / 240 = 281.25 A

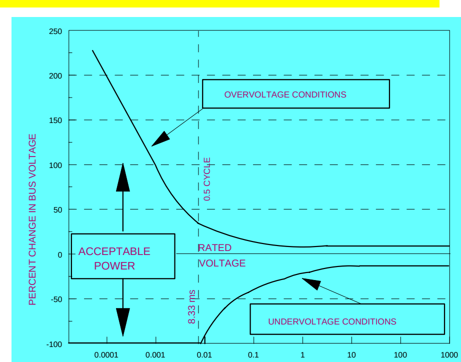
$I_{derated}$ = (281.25)(0.479)
= 138 A

APPROXIMATION

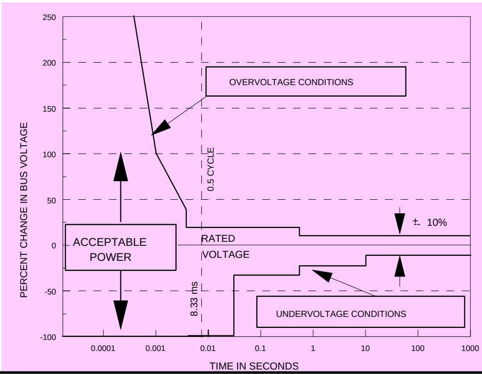
$$P_{LL-R} = P_{EC-R} + 1$$

Power Acceptability Curves

C
B
E
M
A

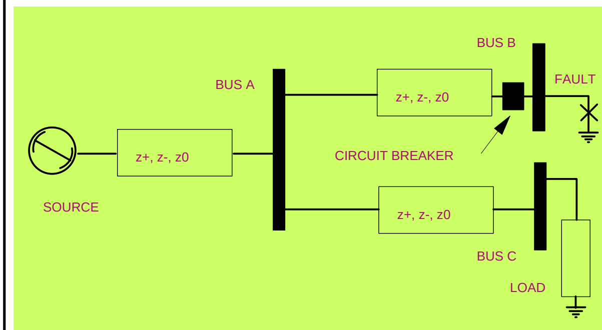


Power Acceptability Curves



I
T
I
C

Power Acceptability Curves



Power Acceptability Curves

Disturbances to loads, whether they be overvoltages or undervoltages, have an impact depending on how much excess energy *is delivered* to the load (in the overvoltage case) or how much energy *was not delivered* to the load (in the undervoltage case). If the cited energy level is too great, the operation of the load will be disrupted. This basic assumption is termed the 'constant energy model' because it implies that the power acceptability curves are loci of constant energy. When the disturbance energy exceeds the locus plotted, the power supply is 'unacceptable'.

Power Acceptability Curves

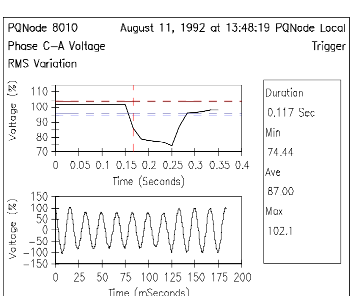
Main challenges

How to sell power quality as a service

How to sell PQ measurement services

How to compensate customers for 'unacceptable power'

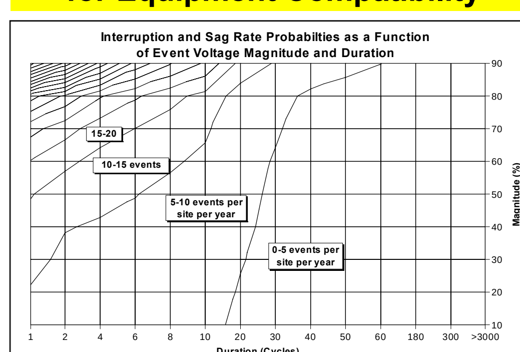
Voltage Sags



Variations in voltage that last less than *1 minute.*

Characterized by rms voltage vs. time plot.

IEEE P1346 - Displaying Sag Data for Equipment Compatibility



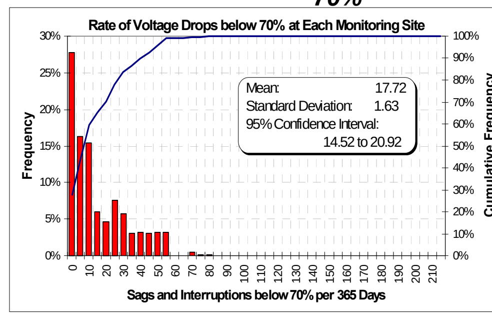
System Average RMS (Variation) Frequency Index Voltage Threshold -- *SARFI*$_{\%V}$

- Number of specified short-duration rms variation per system customer
- Voltage threshold allows assessment of compatibility for voltage-sensitive devices
- 60 second aggregation

$$SARFI_{\%V} = \frac{\sum N_i}{N_T}$$

%V rms voltage threshold
140, 120, 110, 90, 80, 70, 50, 10
N_i # customers experiencing rms < *%V* for variation *i* (rms > *%V* for *%V* >100)
N_T total # system customers

Experimental Results Taken by EPRI / Electrotek for *SARFI*$_{70\%}$



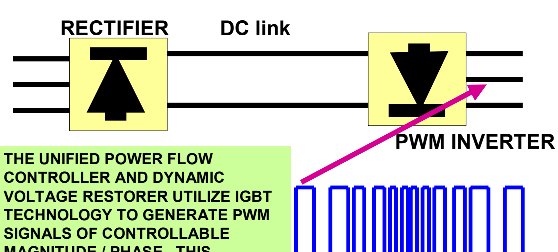
Series Voltage Boost Hardware

Inject series voltage for phase control / exchange energy between phases

Shunt positioning in system to inject current

Back - to - back rectifier / DC link / inverter

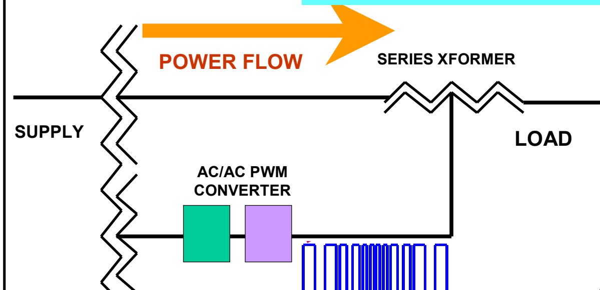
AC - AC Converter Technologies



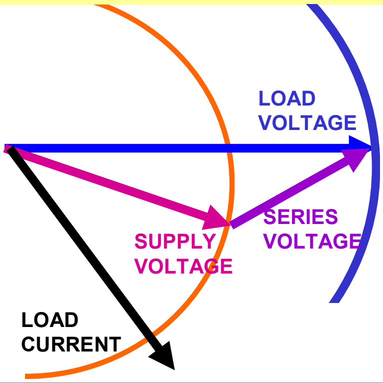
THE UNIFIED POWER FLOW CONTROLLER AND DYNAMIC VOLTAGE RESTORER UTILIZE IGBT TECHNOLOGY TO GENERATE PWM SIGNALS OF CONTROLLABLE MAGNITUDE / PHASE. THIS EFFECTIVELY CONTROLS THE ACTIVE POWER FLOW WHEN INJECTED AS A SERIES VOLTAGE

The UPFC and DVR

The UPFC is intended for use at transmission levels and the DVR is intended for use at distribution levels



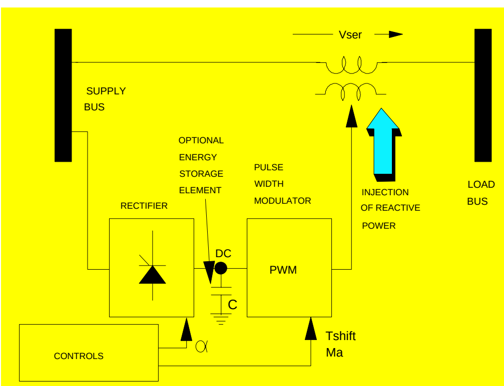
THE UPFC and DVR



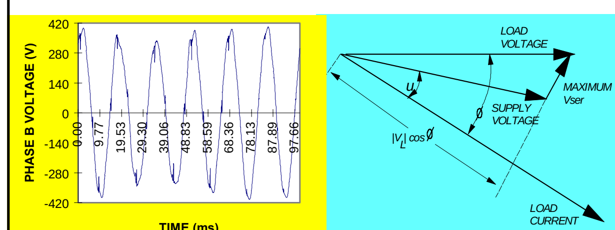
THE UPFC / DVR

- 1/4 cycle response time
- Very low DC link power
- Can be protected by crowbaring supply
- Individual phase control / exchange energy between phases
- Controls slow variations in supply voltage
- The distribution version (DVR) can improve supply power factor and power quality
- For the distribution version, potential elimination of vulnerable load problems
- For UPFC, can reduce transmission congestion as well as improve dynamic response

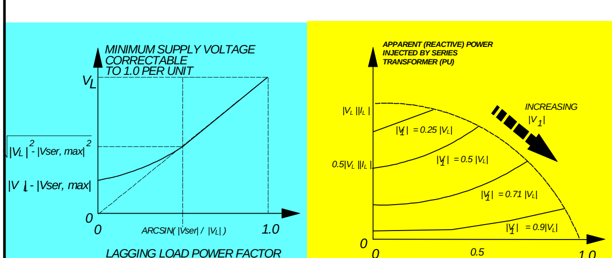
- Cost is very high
- Local solution (?)
- Controls are tricky
- Solution of diversity of ownership problems
- Relatively low power injected
- Limited experience in applications



DVR FOR VOLTAGE REGULATION AT THE DISTRIBUTION LEVEL



DVR FOR VOLTAGE REGULATION AT THE DISTRIBUTION LEVEL



Rectifier Loads and their Harmonic Impact

1Ø RECTIFIER LOADS

LINE COMMUTATED INFINITE DC INDUCTANCE FIXED DC CURRENT ZERO SUPPLY INDUCTANCE	$V_{dc} = \frac{2\sqrt{2}}{\pi} V_{ac}$ $I_{acfundamental} = \frac{2\sqrt{2}}{\pi} I_{dc}$ $I_{supply,h} = I_{acfundamental} / h$ $THD = 48.43\%$ $DPF = 1$ $TPF = \frac{2\sqrt{2}}{\pi}$ $P_{dc} = P_{ac} = \frac{2\sqrt{2}}{\pi} V_{s,rms} I_{dc}$

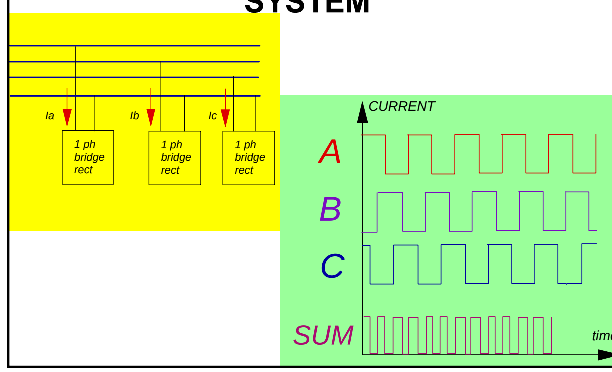
1Ø RECTIFIER LOADS

LINE COMMUTATED INFINITE DC INDUCTANCE FIXED DC CURRENT NONZERO SUPPLY INDUCTANCE	$\cos(u) = 1 - \frac{2\omega I_{dc} L_s}{\sqrt{2} V_s}$ $V_{dc} = \frac{2\sqrt{2}}{\pi} V_s - \frac{2\omega L_s I_{dc}}{\pi}$ $DPF \approx \cos(\frac{u}{2})$ $P = V_s I_{ac,fundamental} DPF = V_{dc} I_{dc}$

1Ø RECTIFIER LOADS

FORCED COMMUTATED INFINITE DC INDUCTANCE FIXED DC CURRENT NONZERO SUPPLY INDUCTANCE	$\cos(\alpha + u) = \cos(\alpha) - \frac{2\omega L_s I_{dc}}{V_s \sqrt{2}}$ $DPF = \cos(\alpha + \frac{u}{2})$ $I_{supply\ fundamental} = \frac{\frac{2\sqrt{2}}{\pi} V_s I_{dc} \cos(\alpha) - \frac{2\omega L_s}{\pi} I_{dc}^2}{V_s \cos(\alpha + \frac{u}{2})}$ $V_{dc} = \frac{2\sqrt{2}}{\pi} V_s \cos(\alpha) - \frac{2}{\pi} \omega L_s I_{dc}$

A NOTE ON SINGLE PHASE RECTIFIER LOADS SUPPLIED BY A THREE PHASE SYSTEM



3Ø RECTIFIER LOADS six pulse

LINE COMMUTATED SIX PULSE INFINITE DC INDUCTANCE FIXED DC CURRENT ZERO SUPPLY INDUCTANCE	$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL}$ $I_{s,rms} = \sqrt{2/3}\, I_{dc}$ $I_{supply,fundamental} = \frac{\sqrt{6}}{\pi} I_{dc}$ $DPF = 1$ $TPF = \frac{3}{\pi}$ $THD = 31.08\%\ (5,7,11,...)$

3Ø RECTIFIER LOADS six pulse

LINE COMMUTATED SIX PULSE INFINITE DC INDUCTANCE FIXED DC CURRENT NONZERO SUPPLY INDUCTANCE	$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL} - \frac{3\omega L_s}{\pi} I_{dc}$ $\cos(u) = 1 - \frac{2\omega L_s I_{dc}}{\sqrt{2} V_{LL}}$ $DPF \approx \cos(\frac{u}{2})$ $P = \sqrt{3} V_{LL} I_{supply,fundamental} \cos(\frac{u}{2}) = V_{dc} I_{dc}$

3Ø RECTIFIER LOADS six pulse

FORCED COMMUTATED SIX PULSE INFINITE DC INDUCTANCE FIXED DC CURRENT NONZERO SUPPLY INDUCTANCE	$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL} \cos(\alpha) - \frac{3\omega L_S}{\pi} I_{dc}$ $\cos(\alpha + u) = \cos(\alpha) - \frac{2\omega L_s I_{dc}}{\sqrt{2} V_{LL}}$ $DPF \approx \cos(\alpha + \frac{u}{2})$

CALCULATION OF HARMONIC LOADS CURRENTS FROM SINGLE PHASE AND THREE PHASE RECTIFIERS

THE HARMONIC LOAD CURRENT DEMANDS OF RECTIFIERS MAY BE CALCULATED FROM THE RECTIFIER FORMULAS TO FIND I1 - THEN FIND THE ODD HARMONICS (SINGLE PHASE) OR 5, 7, 11, 13TH HARMONICS (SIX PULSE) USING THE 1/h RULE

EXAMPLE

A 1000 kVA three phase six-pulse rectifier serves a 2000 V DC load using the delay angle to hold the DC voltage constant over all loads in the range 100 to 250 kW. The supply transformer is rated 1100 kVA, 13.8 kV / 6900 V, x=20%, 50 Hz. Estimate the fifth and seventh harmonic currents on the high voltage side of the transformer in the 100 - 250 kW operating range.

SOLUTION

Find transformer reactance

$x_{base} = V^2 / S = [(6900/\sqrt{3})^2 / (1.1M/3)]$

$= 43.28$ ohms

$\omega L_S = x_S = 8.656$ ohms

SOLUTION

FORCED COMMUTATED SIX PULSE INFINITE DC INDUCTANCE FIXED DC CURRENT NONZERO SUPPLY INDUCTANCE	$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{LL} \cos(\alpha) - \frac{3\omega L_S}{\pi} I_{dc}$ $\cos(\alpha + u) = \cos(\alpha) - \frac{2\omega L_s I_{dc}}{\sqrt{2} V_{LL}}$ $DPF \approx \cos(\alpha + \frac{u}{2})$

At 250 kW

$2000 = (3\sqrt{2}/\pi)(6900)(\cos\alpha) - ((3)(8.656)/\pi)(250k/2k)$

$\alpha = 71.003^o$

SOLUTION

$\cos(\alpha + u) = \cos\alpha - (2\omega L_S I_{dc}/\sqrt{2} V_{LL})$

$\cos(71.003+u)=\cos(71.003)-(2)(8.656)(250k)/(6900)(\sqrt{2})(2k)$

$u = 13.042^o$

$DPF = \cos(\alpha + u/2) = 0.216$

SOLUTION

$$I_1 = S/V = (1.157M/3)/(13.8k/1.732) = 48.405\ A$$

$$I_5 = (1/5)\ I_1 = 9.68\ A$$

$$I_7 = (1/7)\ I_1 = 6.92\ A$$

SOLUTION

DPF = cos(α + u/2) = 0.2149

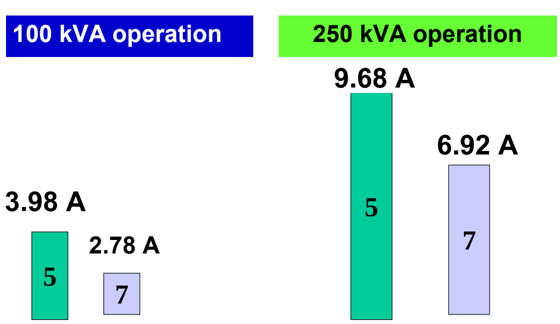
S = P/DPF = 100k/0.2149 = 465.4 kVA

$$I_1 = S/V = (465.4k/3)/(13.8k/1.732) = 19.472\ A$$

$$I_5 = (1/5)\ I_1 = 3.89\ A$$

$$I_7 = (1/7)\ I_1 = 2.78\ A$$

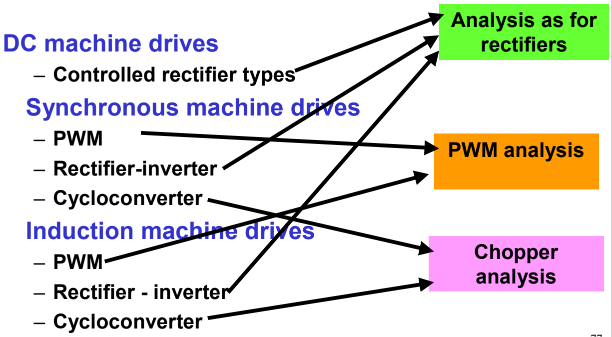
SUMMARY



ANALYSIS OF HIGHER PULSE ORDER CONVERTERS

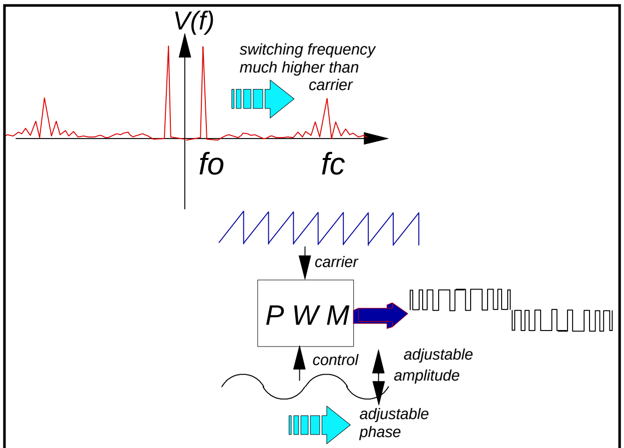
- BREAK CIRCUIT INTO SEVERAL IDENTICAL SIX PULSE CONVERTERS
- EACH SIX PULSE CONVERTER OPERATES AT IDENTICAL P, I, V
- HARMONICS AT pn $\pm$ 1

ADJUSTABLE SPEED DRIVES



PWM DRIVES

THE PWM DRIVE TECHNOLOGY RELIES ON THE USE OF A PULSE WIDTH MODULATOR THAT MODULATES A HIGH FREQUENCY WAVE (e.g., 10 kHz, THE CARRIER) WITH A SINUSOIDAL WAVE OF ARBITRARY FREQUENCY AND PHASE



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Power Quality Standards

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Who Develops PQ Standards?

- International Standards Groups
  - IEC (mostly TC 77)
  - CIGRE (SC 36)
  - The European Norm (EN)
  - National standards worldwide (e.g., BNS)
- Standards Groups in North America
  - IEEE (really international, mostly PES and IAS)
  - ANSI
  - UL, NEMA, NFPA, NIST

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Structure of Basic and Generic EMC Standards

Part 1: General (IEC Pub 1000-1)
fundamental principles, definitions, terminology

Part 2: Environment (IEC Pub 1000-2)
description, classification and compatibility levels

Part 3: Limits (IEC Limits 1000-3)
emission and immunity limits, generic standards

Part 4: Testing and measurement (IEC Pub 1000-4)
techniques for conducting

Part 5: Installation and mitigation (IEC Guide 1000-5)
installation guidelines, mitigation methods and devices

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IEC Approach

- Limit harmonic currents for individual equipment (type testing)
- IEC 1000-3-2 for equipment up to 16 amps
- IEC 1000-3-4 for equipment up to 75 amps (under development)
- This should limit overall harmonic distortion levels to acceptable values
- Procedure for evaluating customers supplied at medium voltage and high voltage (1000-3-6)

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IEC Equipment Limits (IEC 1000-3-3, IEC 1000-3-5)

- Limits for unbalance
  - LV-MV: 2%
  - HV: 1%
- Limits for flicker

Voltage Level	Pst (pu)	Plt (pu)
LV	1	0.74
MV	1	0.74
HV	0.85	0.62
EHV	0.7	0.5

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IEC Standards for Harmonic Distortion Levels

- **Customer/System Limits**
  - IEEE 519-1992
  - IEC 1000-2-2 (Compatibility Levels)
  - IEC 1000-3-6
  - G5/3 (United Kingdom)
- **Equipment Limits**
  - IEC 1000-3-2 (Formerly IEC 555-2) *up to 16 amps*
  - IEC 1000-3-4 *16-75 amps*
  - New Task Force in IEEE (Harmonic Limits for Single Phase Loads)
- **How to Measure Harmonics**
  - IEC 1000-4-7

IEC 1000-2-2 Compatibility Levels

Harmonic Voltage COMPATIBILITY LEVELS (IEC 1000-2-2)

ODD HARMONICS						EVEN HARMONICS		
not multiple of 3			multiples of 3					
	Harmonic Voltage (%)			Harmonic Voltage (%)			Harmonic Voltage (%)	
Order h	LV-MV	HV	Order h	LV-MV	HV	Order h	LV-MV	HV
5	6	2	3	5	2	2	2	2
7	5	2	9	1.5	1	4	1	1
11	3.5	1.5	15	0.3	0.3	6	0.5	0.5
13	3	1.5	21	0.2	0.2	8	0.5	0.5
17	2	1				10	0.2	0.5
19	1.5	1	>21	0.2	0.2	12	0.2	0.2
23	1.5	0.7						
25	1.5	0.7				>12	0.2	0.2
>25	0.2+1.3(25/h)	0.2+0.5(25/h)						

THD Limit = 8% for LV-MV Systems

Key PQ Publications / Commonly used standards

IEEE P519A - Harmonics
IEEE 1250
IEEE P1346 - Voltage sags
Gold book - Reliability
IEC 1000-5-#

IEEE

Guide

Recommended Practice

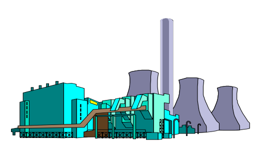
Standard

Power Quality Related Standards of the IEEE

Recommended Practices

IEEE 446 - Emergency and Standby Power
IEEE 519 - Harmonic Control
IEEE 1001 - Interface with Dispersed Generation
IEEE 1100 - Power and Grounding Electronics
IEEE 1159 - Monitoring Power Quality
IEEE 1250 - Service to Critical Loads
IEEE 1346 - System Compatibility in Industrial Environments
IEEE 1366 - Electric Utility Reliability Indices

Philosophy of IEEE 519



The utility is responsible for maintaining quality of voltage waveform.

The customer is responsible for limiting harmonic currents injected onto the power system.

IEEE 519 Harmonic Voltage Limits

Bus Voltage	Maximum Individual Harmonic Component (%)	Maximum THD (%)
69 kV and below	3.0%	5.0%
115 kV to 161 kV	1.5%	2.5%
Above 161 kV	1.0%	1.5%

Harmonic Voltage Limits - Utility Responsibility

Meeting Voltage Distortion Limits

- **Limit the harmonic currents from nonlinear devices on the system (*customer harmonic current limits*)**
- **Make sure that system resonances do not result in excessive magnification of the customer harmonic currents (*utility control of system response)***

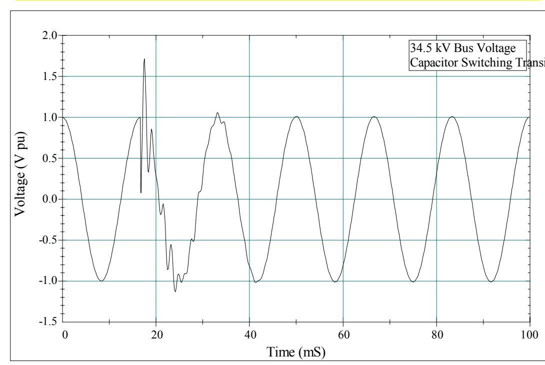
IEEE 519 Harmonic Current Limits

Harmonic Current Limits - Customer Responsibility

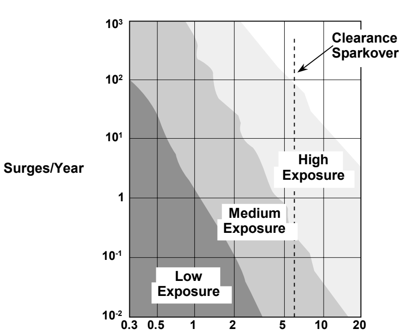
SCR $=I_{sc}/I_L$	<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20 - 50	7.0	3.5	2.5	1.0	0.5	8.0
50 - 100	10.0	4.5	4.0	1.5	0.7	12.0
100 - 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Values shown are in percent of "*average maximum demand load current*"
SCR = short circuit ratio (utility short circuit current at point of common coupling divided by customer average maximum demand load current)
TDD = Total Demand Distortion (uses maximum demand load current as the base, rather than the fundamental current)
PCC = measurements taken at point of common coupling

Transients: ANSI C62.41



Environment - (IEEE/ANSI C62.41)



Graph for a 1 kV circuit

Rate of surge occurrences versus voltage level at unprotected locations

Why is Power Quality Important?

- Cost
- Competitiveness
- Down time
- Losses
- Loss of life
- Metering error
- EMC
- Proper service to the load

The Cost of Power Quality

Calculated by the sum of the costs of the measures taken to improve PQ; or the cost of customer losses in industrial production; or the payment to customers for PQ problems; or the total active power energy loss plus metering error plus loss of life plus cost to serve peak including harmonic loss?

The Cost of Power Quality

Alternatively estimated at 6B$ (BMI / Electrotek), 3B$ annually (EPRI) or 1B$ (Heydt at IEEE-T&D Meeting)

Whatever the figure is, it is avoidable to some degree, and when costs occur, they can create *real* problems

Losses and Loss of Life

- Losses depend on $|I|^2R$
- Excess heating in iron components may be problematic
- Losses = costs, especially at peak periods
- Loss of life depends on Dakin's rule, rate of reaction doubles every 20^{O} C rise

Downtime / Proper service to Load

- Telephone interference (TIF)
- Computer interference (C-message weight index)
- Momentary outage hardening (CBEMA, ITIC)
- UPS and power conditioner applications

Questions?

Comments?

Complaints?