Power Quality Problems, Causes and Terminologies

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STATE OF ART ON POWER QUALITY

- ➢ **The customer's equipments have become much more sensitive to power quality problems than these have been earlier**

- ✓ **Due to use of digital control and power electronic converters, which are highly sensitive to the supply and other disturbances.**

- ➢ **The industries have also become more conscious for loss of production.**

- **The increased use of solid state controllers in number of equipments with other benefits such as decreasing the losses, increasing overall efficiency, reducing the cost of production, it has resulted in increased harmonic levels, distortion, notches, and other power quality problems.**

- **Typical examples of adjustable speed drives (ASDs) and energy saving electronic ballasts, have substantial energy saving and other benefits however; they are the sources of waveform distortion and much more sensitive to number of power quality disturbances.**

- The disturbances to other important appliances such as telecommunication network, TVs, computers, metering, protection systems have enforced to the end users either to reduce, or to eliminate power quality problems or dispense the use of power polluting devices and equipments.

- The deregulation of the utilities have increased the importance of power quality as consumers are using power quality as performance indicators and it has become difficult to maintain good power quality in the world of liberalization and privatization due to heavy competition on financial level.

- Distributed generation using renewable energy and other local energy sources has increased power quality problems as its needs in many situations solid state conversion and variations in input power adds new problems of voltage quality such as in solar PV generation and wind energy conversion systems.

- **In view of these issues and other benefits of improving power quality, an increased emphasis has been given on quantifying, monitoring, awareness, impacts and evolving the mitigation techniques of power quality problems.**

- **A substantial growth is observed in developing the customer's equipments with improved power quality and improving the utilities premises much better than what has been in the past for long time.**

- **Starting from conventional techniques used for mitigating power quality problems in the utilities, distribution systems and customers' equipments, a substantial literature has appeared in research publications, texts, patents and manufacturers manuals for the new techniques of mitigating power quality problems.**

- **Most of the technical institutions have introduced even the courses on the power quality for teaching and training the forthcoming generation of engineers in this field.**

➢ CLASSIFICATION OF POWER QUALITY PROBLEMS

Power quality problems may be classified on the basis of events as,

- ✓ **Transient and steady state,**
- ✓ **The quantity such as current, voltage and frequency, or the load and supply system etc**

➢ **The transient types of power quality problems include most of the phenomena occurring in transient nature such as impulse or oscillatory in nature, the sag (dip), swell, short duration voltage variations, power frequency variations, and voltage fluctuations**

- The steady state types of power quality problems **include long duration voltage variations, waveform distortions, voltage unbalance, notches, dc offset, flicker, poor power factor, load current unbalance, load harmonic currents, excessive neutral current etc.**

- The second classification may be made on the basis of quantity such **as voltage, current, frequency** etc.

- The third classification of power quality problems is based **on whether it is in the load or due to the load, or either due to or in the supply systems.**

- **Normally power quality problems due to nature of the load are such as fluctuating loads as furnaces or the load current consists of harmonics, reactive power component current, unbalance currents, neutral current, dc offset etc**

CAUSES OF POWER QUALITY PROBLEMS

- There are number of power quality problems in the present day fast changing electrical systems.
- The main cause for these power quality problems can be classified as natural and man made in the currents, voltages and frequency, etc.
- The natural causes for the presence of poor power quality are mainly due to faults, lightening, weather conditions such as storms, equipments failure etc

- **However, the man made causes are mainly due to loads or system operations.**

- **The causes due to the loads are nonlinear loads either such as**

- **Saturating transformers and other electrical machines, or loads with solid state controllers like vapor lamps based lighting systems, ASDs, UPSs, arc furnaces, power supplies of computers, TVs etc.**

- **The causes of power quality problems due to system operations are such as switching of transformers, capacitors, feeders and heavy loads**

- **The natural causes of power quality problems are generally of transient in nature such as voltage sag (dip), voltage distortion, and swell, impulsive and oscillatory transients.**

One of important power quality problems is the presence of harmonics which may be because of several loads which behave as nonlinear manner from classical such as Transformers,

Electrical machines,

Furnaces to new ones due to power converters in vapor lamps,

Switched mode power supplies (SMPS), ASDs using ac-dc converters,

Cycloconverters,

AC voltage controllers, HVDC transmission, static VAR compensators etc.

TABLE: Power Quality Problems, Causes and Effects

Problems	Category	Categorization	Causes	Effects
Transients	Impulsive	Peak, rise time and duration	Lightning strikes, transformer energisation, capacitor switching	Power system resonance
	Oscillatory	Peak magnitude and frequency components	Line, capacitor or load switching	System resonance
Short duration voltage variation	Sag	Magnitude, duration	Motor starting, single line to ground faults	Protection malfunction, loss of production
	Swell	Magnitude, duration	Capacitor switching, large load switching, faults	Protection malfunction, stress on computers, home appliances
	Interruption	Duration	Temporary faults	Loss of production, wrong operations of fire alarms
Long duration voltage variation	Sustained interruption	Duration	Faults	Loss of production
	Undervoltage	Magnitude, duration	Switching on loads, capacitor de-energisation	Increased losses, heating,
	Overvoltage	Magnitude, duration	Switching off loads, capacitor energisation	Damage to house hold appliances

Voltage imbalance		Symmetrical components	Single-phase load, single-phasing	Heating of motors
Waveform distortion	DC offset	Volts, Amperes	Geo-magnetic disturbance, rectification	Saturation in transformers
	Harmonics	THD, Harmonic spectrum	ASDs, nonlinear loads	Increased losses, poor pf
	Interharmonics	THD, Harmonic spectrum	ASDs, Nonlinear loads	Acoustic noise in power equipment
	Notching	THD, Harmonic spectrum	Power electronic converters	Damage to capacitive components
	Noise	THD, Harmonic spectrum	Arc furnaces, arc lamps, power converters	Capacitor over loading, disturbances to appliances
Voltage flicker		Frequency of occurrence, modulating frequency	Arc furnaces, arc lamps	Human health, irritation, headache, migraines
Voltage fluctuations		Intermittent	Load changes	Protection malfunction, light intensity changes
Power frequency variations			Faults, disturbances in isolated customer owned systems and islanding operations	Damage to generator, turbine shafts,

EFFECTS OF POWER QUALITY PROBLEMS ON USERS

- Power quality problems affect to all concerned utilities, customers, manufacturers directly or indirectly in terms of a major financial loss due interruption of process, equipment damage, production loss, wastage of raw material, loss of important data etc.

- There are many instances and applications such automated industrial process namely semiconductor manufacturing, pharmaceutical industries, banking, where even a small voltage dip/sag has caused interruption of process for several hours, waste of raw material etc.

- **Some of the power quality problems affect the protection systems and result in mal-operation of protective devices.**

- **It interrupts many operations and processes in the industries and other establishments.**

- **These also affect many types of measuring instruments and metering of the various quantities such as voltage, current, power, energy etc. Moreover, these problems affect the monitoring systems in much critical, important, emergency, vital and costly equipment.**

- **Harmonics currents increase losses in number of electrical equipments and distribution systems and wastage of energy, poor utilization of utilities assets**

- ✓ **Such as transformers, feeders, overloading of power capacitors, etc., noise and vibrations in electrical machines, disturbance and interference to electronics appliances and communication networks.**

CLASSIFICATION OF MITIGATION TECHNIQUES OF POWER QUALITY PROBLEMS

- **In view of increased problems due to power quality in terms of financial loss, loss of production and waste of raw material, etc.**
- **A wide variety of mitigation techniques for improving the power quality are evolved in last quarter century.**
- **These include series of power filters, custom power devices, improved power quality ac-dc converters, matrix converters etc.**

LITERATURE AND RESOURCE MATERIAL ON POWER QUALITY

There are number of texts, standards, patents relating to power quality and many journals, magazines, conferences etc are publishing a number of research publications and case studies on power quality.

Some of the journals, magazines and conferences dealing with power quality are as followings.

IEEE Transactions on Aerospace and Systems
IEEE Transactions on Energy Conversion
IEEE Transactions on Industrial Electronics
IEEE Transactions on Industry Applications
IEEE Transactions on Industrial Informatics
IEEE Transactions on Magnetics
IEEE Transactions on Power Delivery
IEEE Transactions on Power Electronics
IEEE Transactions on Power Systems
IEEE Transactions on Smart Grid
IEEE Transactions on Sustainable Energy

IEEE Industry Applications Magazine
IEE/IET Proceedings on Electric Power Applications (EPA)
IEE/IET Proceedings on Generation, Transmission and Distribution (GTD)
IET Power Electronics (PE)
IET Renewable Power Generation (RPG)
Journal of Electrical Engineering in Japan
Journal of Electric Power Systems Research
International Journal of Electrical Engineering Education
International Journal on Electric Power Components and Systems
International Journal of Electrical Power & Energy Systems
European Transactions on Electrical Power Engineering (ETEP)

European Journal of Power Electronics (EPE)
International Journal of Emerging Electric Power Systems
Journal of Power Electronics (JPE)
International Journal of Power Electronics
International Journal of Power Electronics and Drive Systems (IJPEDS)
International Journal of Power Electronics and systems
International Journal of Energy Technology and Policy
International Journal of Global Energy Issues (IJGEI)
International Journal of Power System and Power Electronics Engineering (IJPSPEE)
International Journal of Power Electronics and Energy (IJPEE)
IEEE Applied Power Electronics Conference (APEC)
IEEE Energy Conversion Congress and Exposition (IEEE-ECCE)

IEEE International Telecommunications Energy Conference (IEEE-INTELEC)
European Power Electronics Conference (EPEC)
IEEE Industrial Electronics Conference (IECON)
IEEE International Symposium on Industrial Electronics (ISIE)
IEEE Industry Applications Annual Meeting (IAS)
IEEE International Conference on Power Electronics and Electric Drives (PEDS)
IEEE International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth (PEDES)
IEEE Inter Society Energy Conversion Engineering Conference (IECEC)
IEEE International Power Electronics Specialist Conference (PESC)
IEEE International Telecommunications Energy Conference (INTELEC)
IEEE Canadian Electrical and Computer Engineering Conference (CECEC)
IEEE International Electric Machines and Drives Conference (IEMDC)
International Power Electronics Conference (IPEC)

POWER QUALITY TERMINOLOGIES

- **Flicker:** Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

- **Fundamental (component):** The component of an order 1 (e.g., 50 Hz, 60 Hz) of the Fourier series of a periodic quantity.

- **Imbalance (voltage** or **current):** The ratio of the negative sequence component to the positive sequence component, usually expressed as a percentage. Syn: **unbalance (voltage** or **current)**.

- **Impulsive transient:** A sudden nonpower frequency change in the steady-state condition of voltage or current that is unidirectional in polarity (primarily either positive or negative).

▪**Instantaneous:** When used to quantify the duration of a short-duration root-mean-square (rms) variation as a modifier, refers to a time range from 0.5 cycles to 30 cycles of the power frequency.

•**Interharmonic (component):** A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating (e.g., **50 Hz, 60 Hz**).

•**Long-duration root-mean-square (rms) variation:** A variation of the rms value of the voltage or current from the nominal for a time greater than 1 min. The term is usually further described using a modifier indicating the magnitude of a voltage variation (e.g., under voltage, overvoltage, voltage interruption).

•**Momentary interruption:** A type of short-duration root-mean-square (rms) voltage variation where a complete loss of voltage (<0.1 pu) on one or more phase conductors is for a time period between 0.5 cycles and 3 s.

▪**Root-mean-square (rms) variation:** A term often used to express a variation in the rms value of a voltage or current measurement from the nominal. See: **sag**, **swell**, **momentary interruption**, **temporary interruption**, **sustained interruption**, **undervoltage**, **overvoltage**.

•**Short-duration root-mean-square (rms) variation:** A variation of the rms value of the voltage or current from the nominal for a time greater than 0.5 cycles of the power frequency but less than or equal to 1 min. When the rms variation is voltage, it can be further described using a modifier indicating the magnitude of a voltage variation (e.g., sag, swell, interruption) and possibly a modifier indicating the duration of the variation (e.g., instantaneous, momentary, temporary).

•**Sustained interruption:** A type of long-duration root-mean-square (rms) voltage variation where the complete loss of voltage **(<0.1 pu)** on one of more phase conductors is for a time greater than 1 min.

•**Temporary interruption:** A type of short-duration root-mean-square (rms) variation where the complete loss of voltage **(<0.1 pu)** on one or more phase conductors is for a time period between 3 s and 1 min.

▪**Voltage change:** A variation of the root-mean-square (rms) or peak value of a voltage between two consecutive levels sustained for definite but unspecified durations.

•**Voltage fluctuation:** A series of voltage changes or a cyclical variation of the voltage envelope.

•**Voltage interruption:** The disappearance of the supply voltage on one or more phases. It is usually qualified by an additional term indicating the duration of the interruption (e.g., momentary, temporary, sustained).

Waveform distortion: A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation

For the purposes of standardisation, the following additional terms and definitions are also used

Accuracy

Calibration

Common-mode voltage

Coupling

Current transformer (CT)

Dropout

Electromagnetic compatibility (EMC)

Electromagnetic disturbance

Equipment grounding conductor

Failure mode

Frequency deviation

Ground

Ground loop

Harmonic

Harmonic components

Harmonic content

Immunity (to a disturbance):

Impulse

Isolated equipment ground

Maximum demand

Momentary

Momentary interruption

Noise

Nominal voltage

Nonlinear load

Normal-mode

Phase shift

Power disturbance

Sustained interruption

Temporary interruption

Total harmonic distortion (THD)

Transient

Voltage regulation

Voltage imbalance (unbalance)

POWER QUALITY MONITORING

- PQ events are random in nature, which occur arbitrarily.
- Monitoring of these PQ phenomena becomes almost essential for critical and sensitive equipments in which a huge loss of revenue is expected by PQ problems.
- The monitoring system used for assessing PQ events may provide enough data to decide for curing and mitigating the power quality problems provided these recording/measuring instruments are selected properly to record PQ events

Objectives of PQ Monitoring

- PQ monitoring is required to quantify PQ phenomena at a **particular location on electric power equipment.**

- In some situations, the objective of the monitoring may be **to diagnose incompatibilities between the supply and the consumer loads**.

- In some cases, monitoring may be used to predict **performance of the load equipment and select power quality mitigating systems**

- The objectives of PQ monitoring for a particular location need to find the choice of **monitoring equipment, the method of collecting data etc**.

- The recorded information need only to meet the objectives of the monitoring objectives in order for the monitoring to be successful.

- The methodology for quantifying monitoring objectives may differ in nature.

- For example, when PQ monitoring is required to find out shutdown problems in critical equipment, *The aim may be to record tolerance events of few types.*

- Preventive and predictive monitoring may require recorded voltages and currents to quantify the existing level of power quality.

- Measurement of PQ includes both time and frequency domain variables, which may be in the form of over voltages and under voltages, interruptions, sags and swells, surges, spikes, notches, transients, phase imbalance, frequency deviations, and harmonic distortion.

- PQ monitoring may be provided by the utility, the customers, or any other personal such as energy auditors.

➢some important parameters which can be determined using suitable algorithms from the voltage and current waveforms which are acquired, digitized, and stored in the memory.

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

Justifications for PQ Monitoring

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

- The PQ monitoring may be used as a tool for availability of power to the customers

- Some of the following aspects may be used to convince users for PQ monitoring

✓ To find out the need for mitigation of PQ problems
✓ To schedule preventive and predictive maintenance
✓ To ensure the performance of equipment

- To assess the sensitivity of equipment to PQ 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

- Power quality problems caused by various events and disturbances occurring are specified in terms of different performance indices which are monitored by various instruments.

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NUMERICAL EXAMPLES

Q.1. In a square wave, calculate (a) crest factor, CF, (b) distortion factor, DF, and (c) total harmonic distortion %THD.

Solution: Given that, a square wave, which has amplitude of I.

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

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

1.Crest Factor of a square wave, CF= Peak Value / RMS value of a square wave $=I/I=1$.

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

3.Total Harmonic Distortion (THD) of square wave =

$\sqrt{(I_{rms}^2-I_1^2)}/I_1=\sqrt{\{I^2-(0.9I)^2\}}/(0.9I)=0.4843=48.43\%$.

Q.2 In a quasi-square wave (120º pulse width), calculate (a) crest factor, CF, (b) distortion factor, DF, and (c) total harmonic distortion %THD.

Solution: Given that, a quasi-square wave of (120º), let it has amplitude of I.

The rms of fundamental component of quasi-square wave is, $I_1=(2\sqrt{2}/\pi)\sin(120^\circ/2)$ I=$\{(\sqrt{6})/\pi\}$I times the amplitude of it=0.7798 I.

The RMS value of a quasi-square wave, $I_{rms}=\sqrt{\{(2/3)I\}}$ =0.8165 I.

- Crest Factor of quasi-square wave, CF= peak value/RMS value of quasi-square wave=I/(0.8165 I)=1.225.
- Distortion Factor, DF=Fundamental component of a quasi-square wave/RMS value of a quasi-square wave $=I_1/I=0.9549$.
- Total Harmonic Distortion (THD) of quasi-square wave$=\sqrt{(I_{rms}^2-I_1^2)}/I_1=0.3108=31.08\%$.

Q.3 For a trapezoidal wave(90º flat portion), calculate (a) crest factor, CF, (b) distortion factor, DF, and (f) total harmonic distortion %THD.

Solution: Given that, a trapezoidal wave (90º flat portion), let it has amplitude of I. From Fourier analysis of trapezoidal wave, amplitude of h^{th} harmonic is, as,

$$I_h = \sum_{h=1}^{\infty} [\{8\sqrt{2}/(h\pi)^2\}(-1)^{(h-1)/2} \sin(h\theta)]/\sqrt{2} = 8\sqrt{2}I/\{(\sqrt{2})(\pi h)^2\}$$

The rms of fundamental component of trapezoidal wave (90º flat portion), is,
$I_1=(8/\pi^2)\ I=0.8105\ I$.
The rms value of a trapezoidal wave,
$I_{rms}=0.810\ I\sqrt{\{1+1/9+1/25+1/49+1/81+1/121+1/169+1/225+----\}}=0.817\ I$.
•Crest Factor of a trapezoidal wave, CF= peak value / rms value of a trapezoidal wave $=I/(0.817I)= 1.224$.
•Distortion Factor, DF=(Fundamental /rms value) of a trapezoidal wave $=I_1/I_{rms}=0.8105I/0.817I=0.9921$.
•Total Harmonic Distortion (THD) of trapezoidal wave =
$\sqrt{(I_{rms}^2-I_1^2)}/I_1=0.1261=12.61\%$.

Q.4 Estimate the K factor rating of a single-phase transformer used to feed a single-phase diode bridge rectifier with constant DC load current.

Solution : Given that the input current (transformer secondary current) to the single-phase diode bridge rectifier with constant DC load current is a square wave which can be expressed as.

$i(t)=(4I_a/\pi)\{\sin\omega t+(1/3)\sin3\omega t+(1/5)\sin5\omega t+(1/7)\sin5\omega t+(1/9)\sin9\omega t+(1/11)\sin11\omega t+\ldots\ldots\}$

K-factor$=\sum I^2_h h^2$, where I_h is the fraction of the total rms load current at harmonic h.

$I_{Trms}= I_a$, as total rms current of square wave is equal to its amplitude.

$I_1=(4I_a/\pi)/\sqrt{2}=0.9\ I_a=0.9\ I_{Trms}$

Let us consider, only first six harmonics as the magnitude of 11^{th} order harmonic is less than 1%. Moreover, with such small currents of high order is not supposed to cause much eddy current losses due reduced depth of penetration and in actual practice magnitude of higher order harmonics further reduces drastically because source impedance and other nonlinearity.

$I_h/I_1= I_1/h=$ 1, 1/3, 1/5, 1/7, 1/9, 1/11 =1, 0.333, 0.2, 0.143, 0.111, 0.091, for h=1,3,5,7,9,11

$I_h/I_{Trms} = (I_h/I_1)*(I_1/I_{Trms})=(I_h/I_1)*0.9=$0.9, 0.9/3, 0.9/5, 0.9/7, 0.9/9,0.9/11, for h=1,3,5,7,9,11

I_h (pu) with a base $I_{Trms}=I_h/I_{Trms}=$ 0.9, 0.3, 0.18, 0.1285, 0.1, 0.0819, for h=1,3,5,7,9,11

K factor$=\sum I^2_h h^2=0.9^2*1^2+0.3^2*3^2+0.18^{2*}5^2+0.1285^{2*}7^2+0.1^{2*}9^2+0.08197^{2*}11^2=4.86$.

Q.5 Estimate the K factor rating of a three-phase transformer used to feed a three-phase diode bridge rectifier with constant DC load current.

Solution : The current generated have the following harmonic current is as.

$i_A(t)=(2\sqrt{3}I/\pi)\{\cos\omega t-(1/5)\cos5\omega t+(1/7)\cos7\omega t$
$(1/13)\cos13\omega t+(1/17)\cos17\omega t-\ldots\ldots.\}$

K-factor$=\sum I^2{}_h h^2$ for h=1 to n

I_h/I_1=1, 0.2, 0.143, 0.091, 0.077, 0.059 for h=1, 5, 7, 11, 13, 17
$(I_h/I_1)^2$=1, 0.04, 0.02, 0.008, 0.005, 0.003

$I_{Trms}=\sum(I_h/I_1)^2=1.038$
$I_h(pu)=(1/I_{Trms})\ (I_h/I_1)$= 0.963, 0.193, 0.138, 0.088, 0.074, 0.057
$I^2{}_h h^2$=0.927, 0.931, 0.933, 0.937, 0.925, 0.939
K-factor=5.592.

Q.6 A single-phase uncontrolled bridge converter (shown in Fig.) has a RE load with R=1.0 ohms, and E=275 V. The input ac voltage is V_s=220 V at 50 Hz. Feeder conductors have the resistance of order 0.05 ohms each. Calculate (a) ac source rms current (I_s), (b) losses in the distribution system. (c) Total harmonic distortion in current. (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

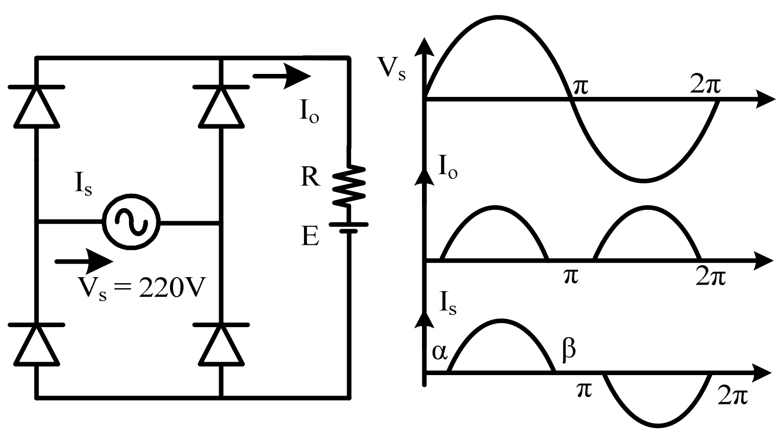

Fig. A single-phase uncontrolled bridge converter with RE load.

Solution: Given that, supply voltage, V_s=220V, V_{sm}=311.13 V, frequency of the supply f=50 Hz, Load R=1Ω, 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 $R_T=2R_s+R=2*0.05+1.0=1.1$ 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=2053.39 W

Fundamental RMS current from ac mains, $I_{s1}=P/V_s$=2053.39/220=9.33 A

Supply ac peak current, $I_{peak}=(V_{sm}-E)/R_T$=32.85 A

Load Average current (I_o) is as:

$I_o=\{1/(\pi R_T)\}(2V_{sm}\cos\alpha+2E\alpha-\pi E)$=6.76 A

(a) RMS supply current (I_s) is rms of discontinuous current in the ac mains as:

$I_s=[\{1/(\pi R_T{}^2)\}\{(0.5V_{sm}{}^2+E^2)(\pi-2\alpha)+0.5V_{sm}{}^2\sin 2\alpha-4V_{sm}E\cos\alpha\}]^{1/2}=13.31A$

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

$P_{Loss}=2*I_s{}^2*R_s=2*13.31^2*0.1=35.43W$.

(c)Total Harmonic Distortion (THD) of ac current$=\sqrt{(I_s{}^2-I_{s1}{}^2)}/I_{s1}=\sqrt{(13.31^2-9.33^2)}/9.33=1.0174=101.74\%$.

(d)Crest factor of supply current, CF= peak value / rms value =32.85/9.33=3.52.

(e)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, $I_{SC}=I_{s1a}=P/V_s=I_{s1}=P/V_s=2053.39/220=9.33$ A.

Losses in the distribution system are calculated as. $P_{Lossc}=2*I_s{}^2*R_s=2*9.33^2*0.1=17.41$ W.

(f)Ratio of losses without and with compensator is as. $P_{Loss}/P_{Lossc}=35.43/17.41=2.04$.

It means that such nonlinear loads cause the increased losses in the distribution system many fold as much as 2.04 times.

Q.7 In a three-phase, line voltage of 415 V, 50 Hz, 4-wire distribution system, a single-phase load (connected between phase and neutral) having a 125 A, 0.8 lagging power factor. Feeders and neutral conductor have the resistance of order 0.1 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 source rms current (I_{sc}), (e) neutral current (I_{snc}), (f) losses in the distribution system, (f) ratio of losses in distribution system without and with compensator.

Solution: Given that, Supply voltage, V_s = 415/√3 V=239.6 V, frequency of the supply f=50 Hz, R_s=0.1 ohms, a single-phase load (connected between phase and neutral) having a 125 A, 0.8 lagging power factor.

(a)The ac source rms current (I_s) = 125 A

(b)The neutral current (I_{sn}) =125 A (same as phase current).

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

$P_{Loss}=2*I_s^2*R_s=2*125^2*0.1=3125$ 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 that phase voltage and neutral current becomes zero. In this case, because of loading this current is divided in all three phase of the ac mains.

The new supply current is as RMS Fundamental active power component of load current, $I_{SC}=I_{s1a}=I_{s1}\cos\theta$ $=125*0.8/3=100/3=33.33$ A.

(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.

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

$P_{Lossc}=3*I_{sc}^{2}*R_s=3*33.33^2*0.1=333.33$ W.

(g) Ratio of losses without and with compensator is as**.** $P_{Loss}/P_{Lossc}=3125/333.33=9.375$.

It means that such unbalanced lagging power factor loads cause the increased losses in the distribution system many fold as much as 9.375 times.

Q.8 A three-phase, 22 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 4% slip at full load and rated voltage and frequency. If terminal voltage increases to 440 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

(a) For a small slip approximation, $S \propto (1/V^2)$, The new slip at increased voltage is as,

$S_n=0.04(415/440)^2= 0.03558=3.558\%$.

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,

$N_{rn}=N_s(1-S_n)=1500*(1-0.03558)=1446.62$ rpm.

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

$P_{on}=\omega_m T_m=\{(1-S_n)/(1-S)\}P_o=\{(1-0.03558)/(1-0.04)\}*22000=22101.21$ W=22.101 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,

$P_{rwn}=S_nP_g=(S_n/S)P_{rwr}=(0.03558)/(0.04)\ P_{rwr}=0.8895\ P_{rwr}$.

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.

Q.9 A single-phase ac voltage controller (shown in Fig.) has a heating load (Resistive Load) of 20 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=0.20 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 = 20 Ω, R_s=0.20 ohms, $\alpha = 120^0$. The total resistance of the circuit is $R_T=R+2R_s$=20.4 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. $V_{sm}=220\sqrt{2}=311.13$ V.

(a) The supply rms current, $I_s=V_{sm}[\{1/(2\pi)\}\{(\pi-\alpha)+\sin2\alpha/2\}]^{½}/R_T=4.768$ A.

Active power of the load, $P_L= I_s^2R=4.768^2*20=454.75$ W.

•Losses in the distribution system are calculated as.

$P_{Loss}=2*I_s^2*R_s=2*4.768^2*0.20=9.1$ W.

•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, $I_{sc}=I_{s1a}=P_L/V_s=454.75/220=2.067$ A.

•Losses in the distribution system are calculated as.

$P_{Lossc}=2*I_{sc}^2*R_s=2*2.067^2*0.2=1.71$ W.

•Ratio of losses without and with compensator is as. $P_{Loss}/P_{Lossc}=9.1/1.71=5.322$.

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

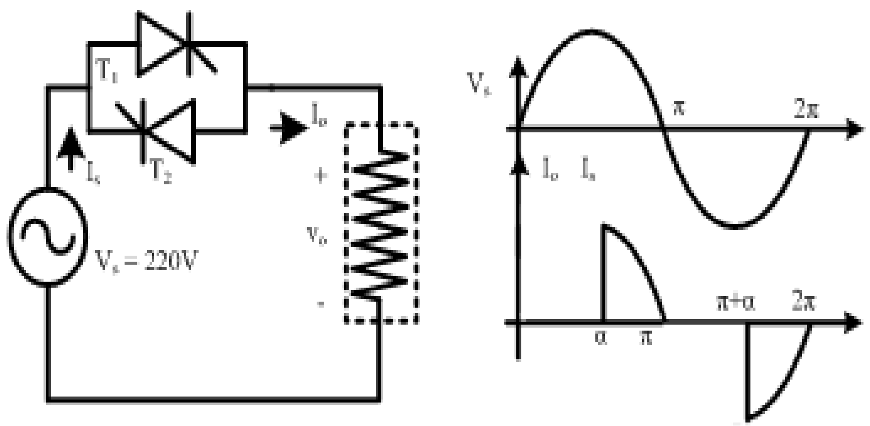

Fig. Single-phase ac voltage controller feeding a heating load with phase control

Q.10A three-phase fully controlled bridge converter (shown in Fig.) feeds power to a load having a resistance of R=10 ohms and very large inductance to result in continuous current with an input from a three-phase supply 415 V, 50 Hz. Feeder conductors have the resistance of order 0.1 ohms each. For firing angles of 60^0, 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.

Solution: Given that, Supply rms voltage, $V_s=415/\sqrt{3}=239.6$ V, frequency of the supply f=50 Hz, $R_{dc}=10\ \Omega$, $\alpha=60^0$.

In three-phase thyristor bridge converter, the waveform of the supply current (I_s) is a quasi-square wave with the amplitude of dc link current (I_{dc}).

Average output dc voltage, $V_{dc}=(3\sqrt{3}\sqrt{2}V_s/\pi)\cos\alpha=280.125$ V

The dc link current, $I_{dc}=V_{dc}/R_{dc}=28.01$ A

(a) The ac source rms current is as, $I_s=\sqrt{(2/3)}I_{dc}=0.81649I_{dc}=22.87$ A

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

$P_{Loss}=3*I_s^2*R_s=3*22.87^2*0.1=156.94$ W.

(c)After the compensation, the power factor is corrected to unity of AC mains by a shunt compensator, the three-phase currents 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, $I_{SC}=I_{s1a}= I_{s1}\cos\alpha=\{(\sqrt{6})/\pi\}I_{dc}\cos\alpha= 28.01 * 0.78 * \cos 60^{o}=10.92$ A.

(d) Losses in the distribution system are calculated as. $P_{Lossc}=3*I_s^{2}*R_s =3*10.92^2=35.77$ W.

(e) Ratio of losses without and with compensator is as. $P_{Loss}/ P_{Lossc}=156.94 /35.77 =4.39$.

It means that such nonlinear loads cause the increased losses in the distribution system many fold as much as 4.39 times.

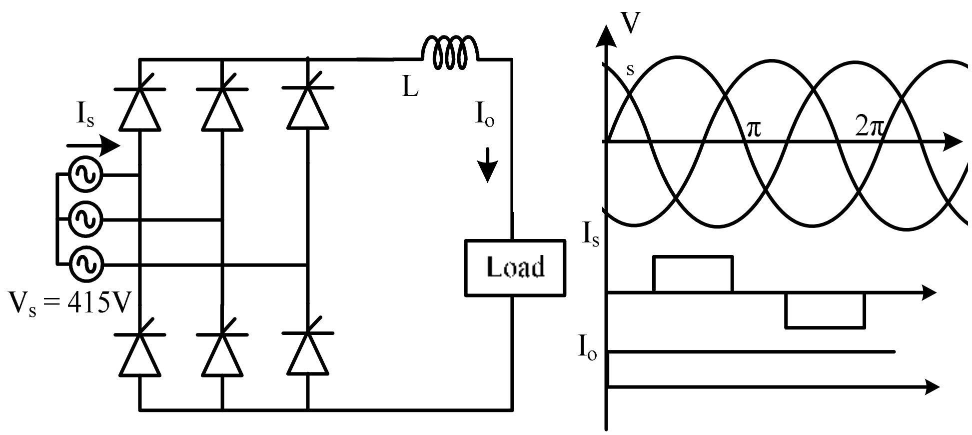

Fig. A three-phase fully controlled bridge converter feeding R-L load

Q.11 In three-phase ac mains, there is voltage sag at PCC of 10%, 20 % and 30% 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=0.9 pu, V_2=0.8 pu, V_3=0.7 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=(0.9+0.8+0.7)/3=0.8.

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

$VLSEI=(1-V_a/V_{nom})^{3.14}T_a+(1-V_b/V_{nom})^{3.14}T_b \quad +(1-V_c/V_{nom})^{3.14}T_c \quad = \\ =0.1^{3.14}200+0.2^{3.14}300+0.3^{3.14}400 =0.145+1.916+9.125=11.186.$

Q.12 In a three-phase, line voltage of 415 V, 50 Hz, 4-wire distribution system, three single-phase loads (connected between phases and neutral) having a single-phase thyristor bridge converter drawing equal 15 A constant dc current at 60^o firing angle of its thyristors (shown in Fig.). Feeders and neutral conductor have the resistance of order 0.1 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 source rms current (I_{sc}), (e) neutral current (I_{snc}), (f) losses in the distribution system, (f) ratio of losses in distribution system without and with compensator.

Solution: Given that, Supply voltage, V_s = 415/√3 V=239.6 V, frequency of the supply f=50 Hz, R_s=0.1 ohms, DC link current, I_{dc} = 15A, Firing angle, α= 60º.

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_{dc}).

(a) The ac source rms current (I_s) = I_{dc} =15 A

(b) The neutral current (I_{sn}) =15 A (since it will also be a square wave as 3 times the fundamental frequency).

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

$P_{Loss}=3*I_s^2*R_s+I_{sn}^2*R_s=3*15^2*0.1+15^2*0.1=88$ 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 that phase voltage and neutral current becomes zero.

The new supply current is as RMS Fundamental active power component of load current, $I_{SC}=I_{s1a}= I_{s1} \cos\alpha=15*0.9* \cos 60^{o}=6.75A$.

(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.

(f)Losses in the distribution system are calculated as. $P_{Lossc}=3*I_s{}^2*R_s+I_{sn}{}^2*R_s=3*6.75^2*0.1+0^2*0.1=13.67$ W.

(g)Ratio of losses without and with compensator is as. $P_{Loss}/P_{Lossc}=88/13.67=6.438$.

It means that such nonlinear loads cause the increased losses in the distribution system many fold as much as 6.438 times.

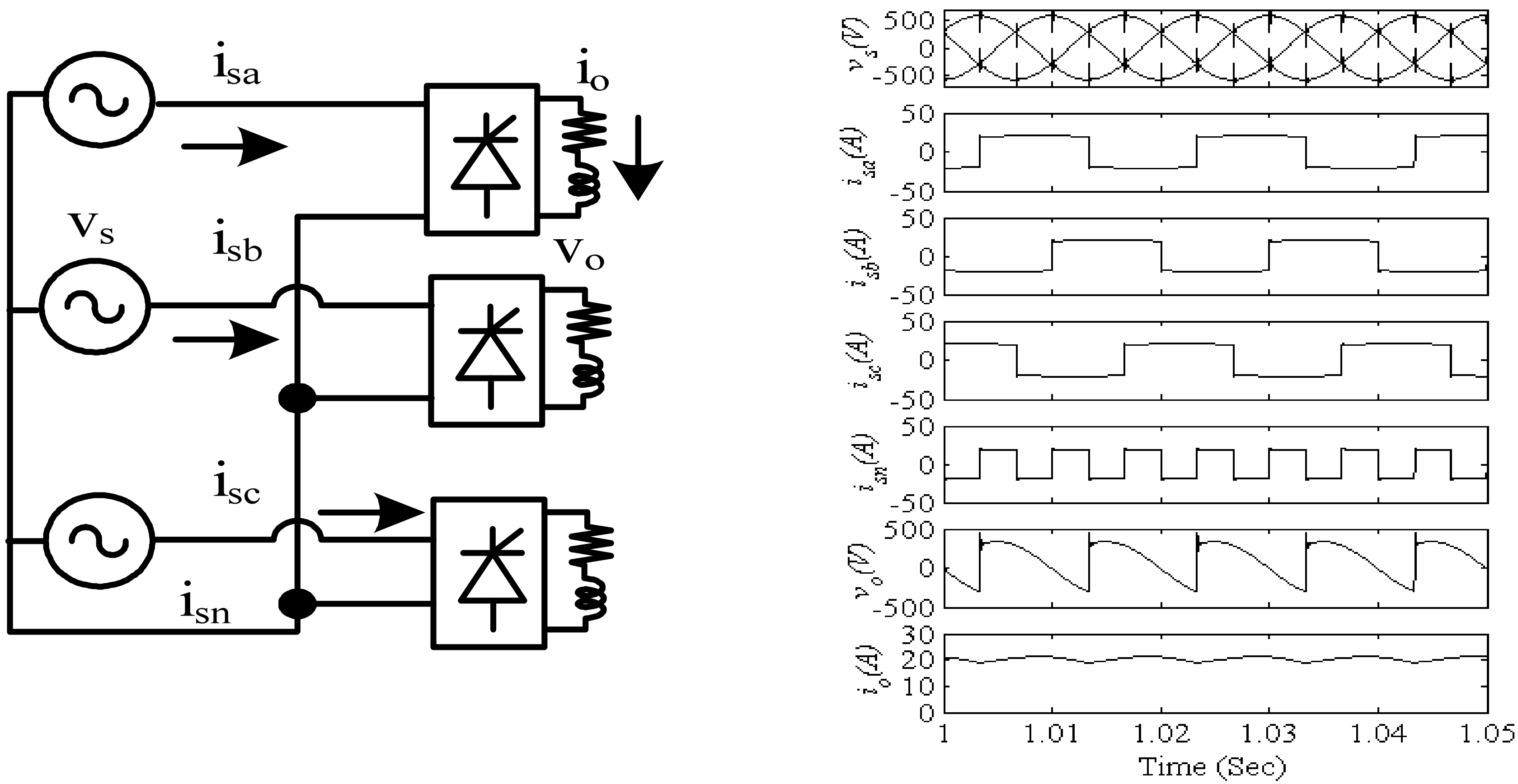

Fig. A three-phase, four-wire distribution system with three single-phase loads (connected between phases and neutral) having a single-phase thyristor bridge converter drawing equal 15 A constant dc current at 60º firing angle of its thyristors.

Thank You