ENERGY LOSS
IN HARMONIC ENVIRONMENT

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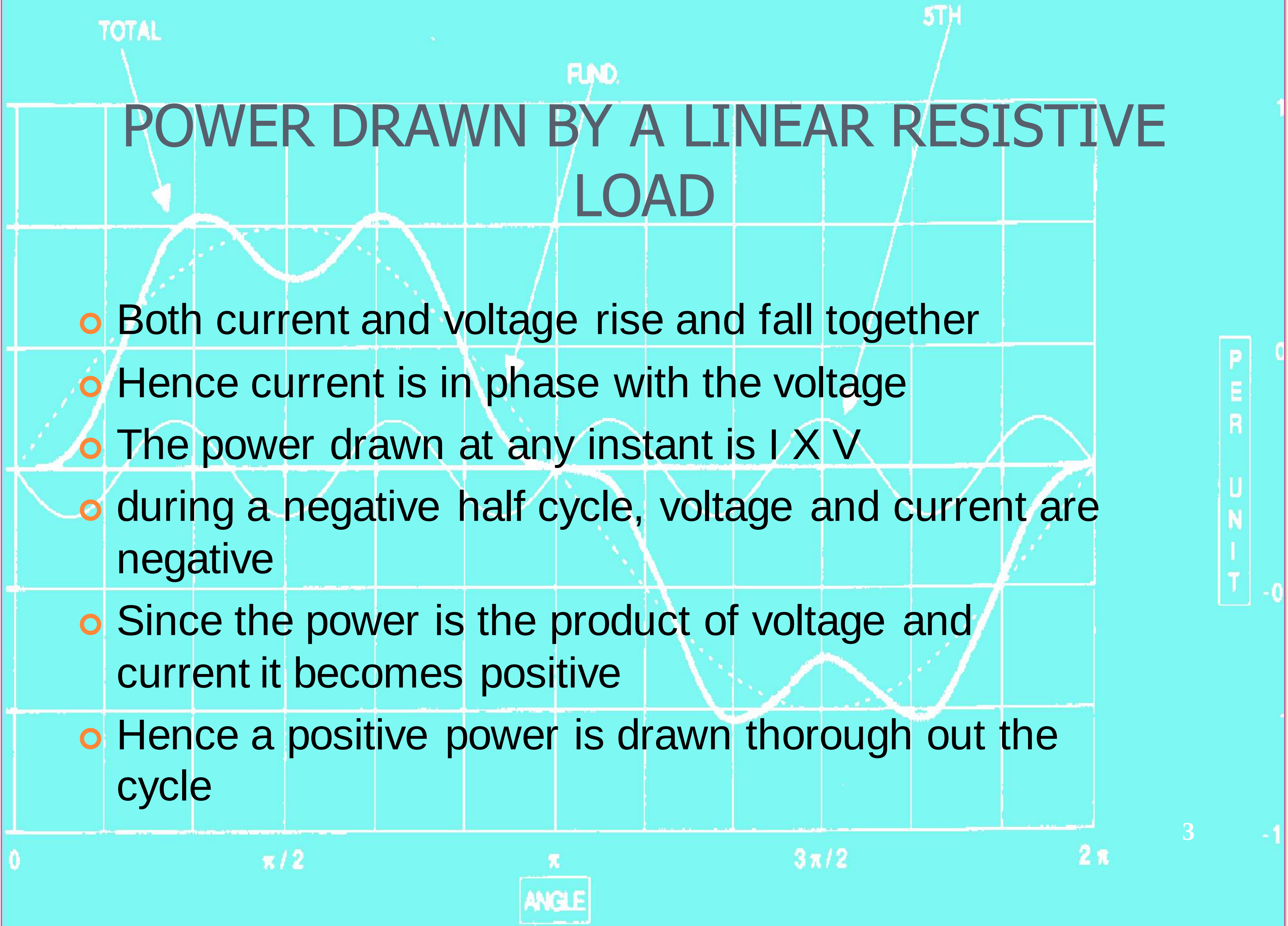
POWER UTILIZATION

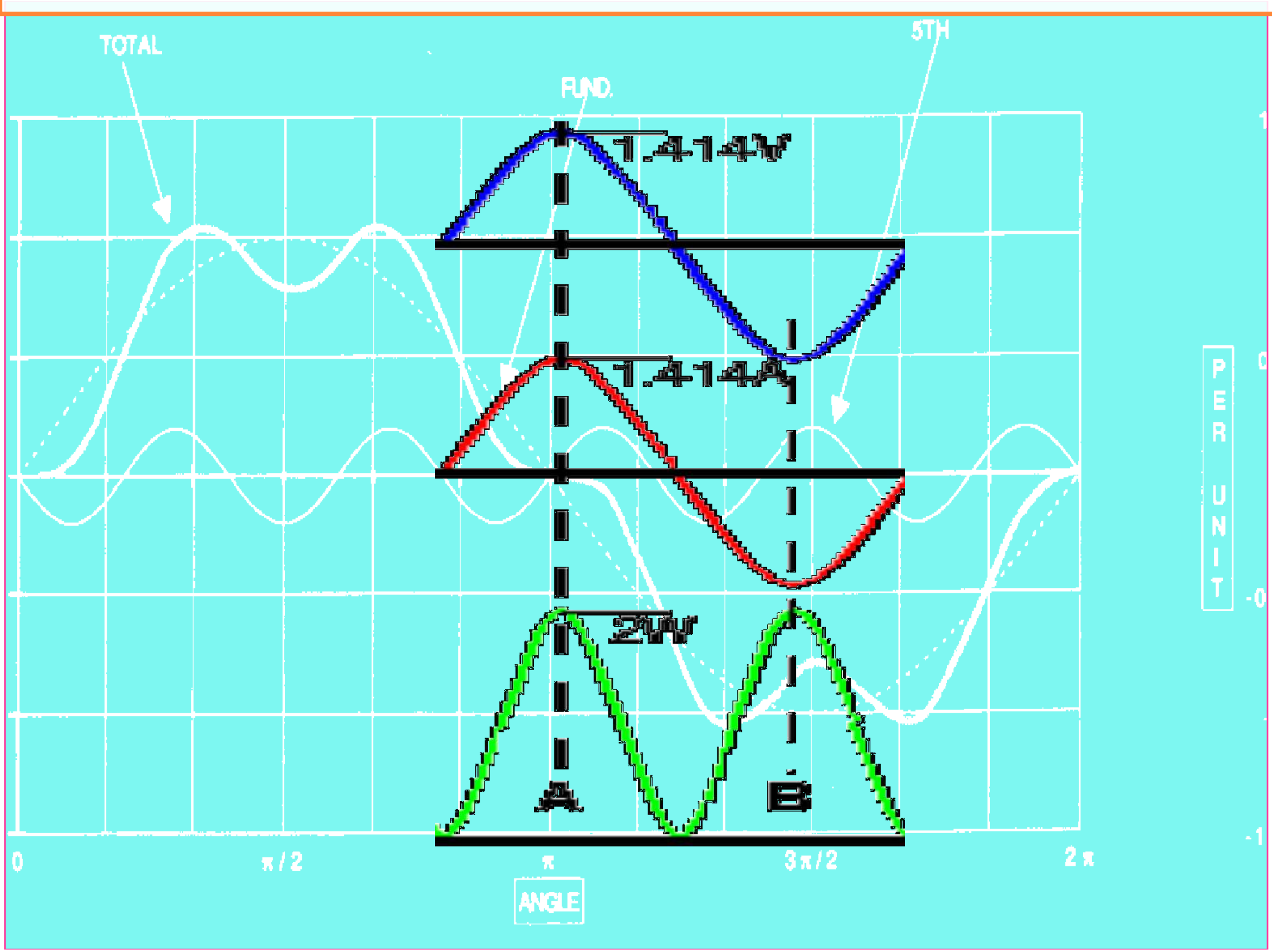
- All alternating current equipments and power distribution systems and elements
- Designed to work from a power source with voltages of 50 HZ frequency and a sinusoidal waveform
- Their behavior, energy utilization efficiency and other characteristics are much affected when supplied with distorted wave forms.
- Incandescent lamps, heaters, etc draw current proportional to the voltage
- Following sinusoidal waveform
- **Hence these loads are called linear loads**

POWER DRAWN BY A LINEAR RESISTIVE LOAD



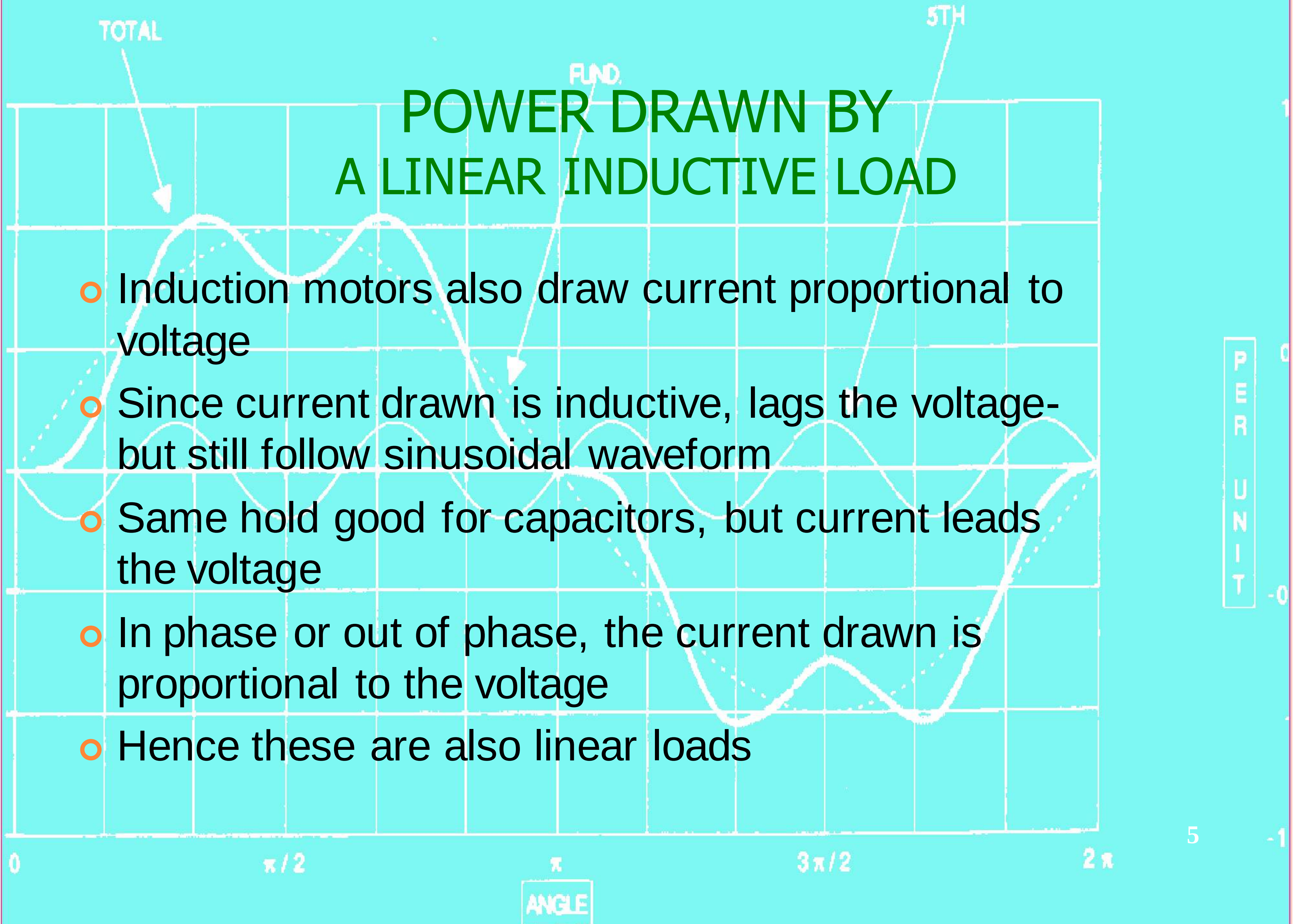
- Both current and voltage rise and fall together
- Hence current is in phase with the voltage
- The power drawn at any instant is I X V
- during a negative half cycle, voltage and current are negative
- Since the power is the product of voltage and current it becomes positive
- Hence a positive power is drawn thorough out the cycle

POWER DRAWN BY A LINEAR RESISTIVE LOAD



POWER DRAWN BY
A LINEAR INDUCTIVE LOAD

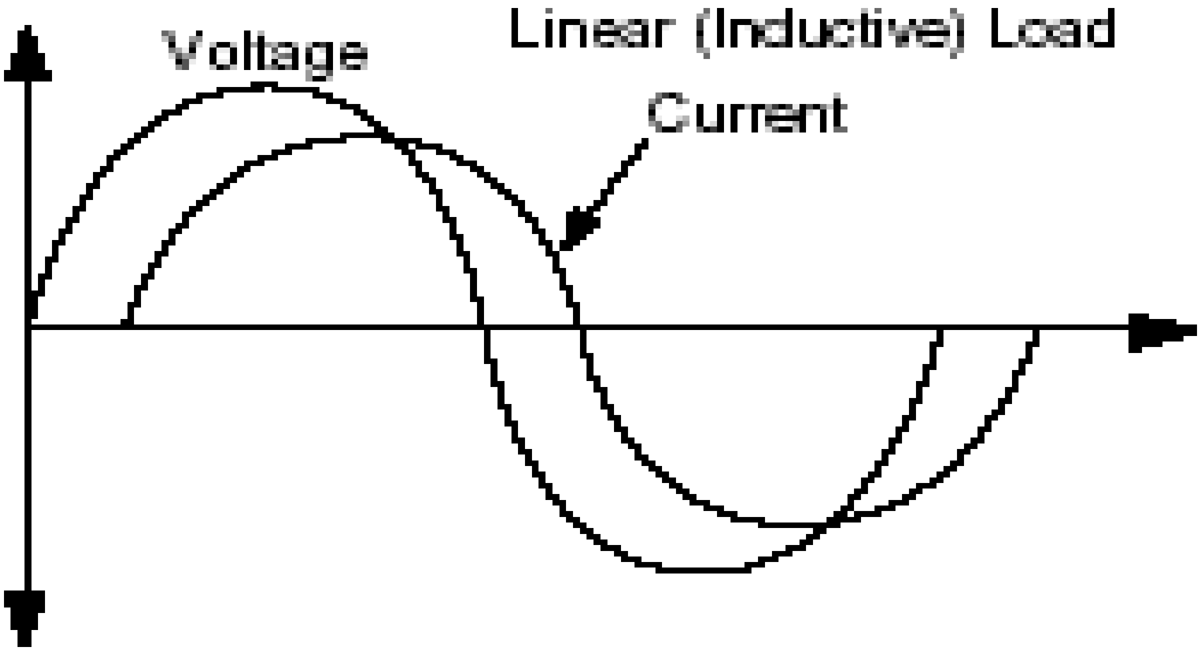
- Induction motors also draw current proportional to voltage
- Since current drawn is inductive, lags the voltage- but still follow sinusoidal waveform
- Same hold good for capacitors, but current leads the voltage
- In phase or out of phase, the current drawn is proportional to the voltage
- Hence these are also linear loads



POWER UTILIZATION
INDUCTIVE LOAD

- Though current follows voltage waveform, the peak and the zero value of the current is displaced by an angle from the peak and zero point of voltage waveform
- With respect to the instantaneous voltage value, the current value becomes a function of the Cosine of the angle (between voltage and current)
- Hence power at any instant is equal to Voltage X Current X Cos of the angle between them

LINEAR INDUCTIVE LOAD

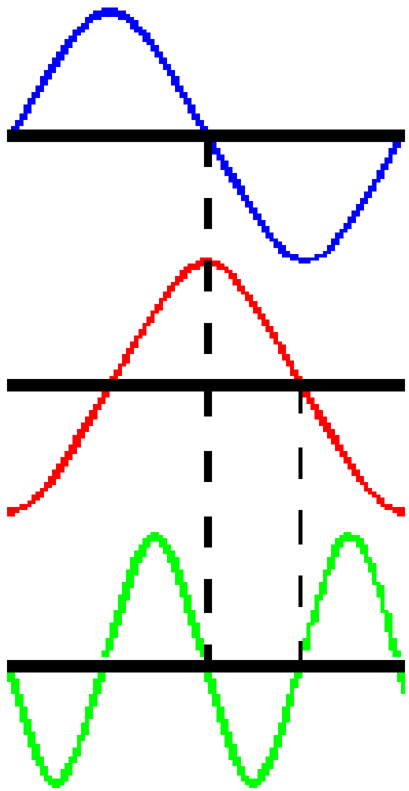


POWER UTILIZATION
INDUCTIVE LOADS

- If the load is totally inductive like a reactor or a induction coil the current drawn lags the voltage by 90 degrees
- Since power is the product of instantaneous voltage and current, its frequency is double of the voltage frequency
- It also passes through the negative half of the cycle
- Since the negative half and the positive half of the waveform are identical I.e. positive power and negative power, total power drawn by the load is zero

POWER UTILIZATION
INDUCTIVE LOADS

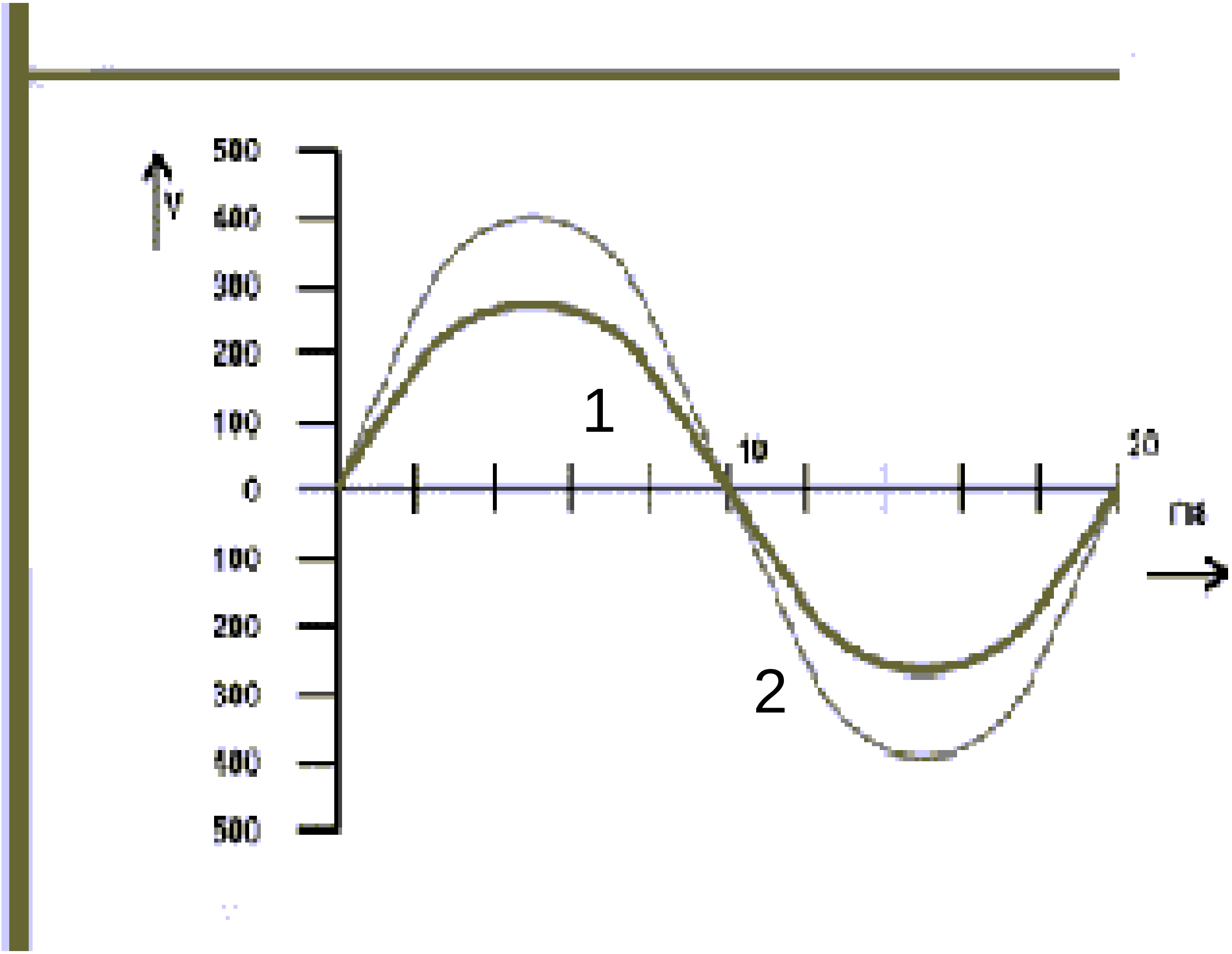
- No net power flows



POWER CONTROL

- In the past, a resistance or an auto transformer was employed to regulate power
- It controls the peak value of the voltage applied
- But still the voltage follows a sinusoidal waveform but with lesser amplitude
- Since power is a product of voltage and current, the power follows sinusoidal waveform
- With reduction in peak value the power drawn is also reduced
- But, involves wastage of power in the controlling element

LINEAR POWER CONTROL

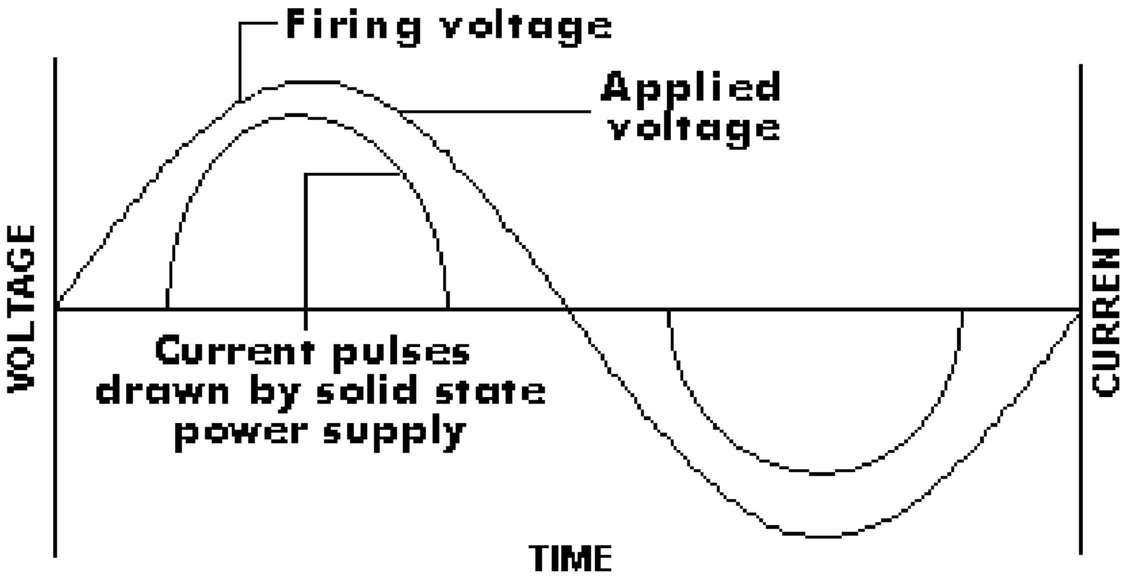


1. Line voltage, 2. Controlled voltage

SOLID STATE POWER CONTROL

- To eliminate the losses in the controlling elements.
- Solid state or thyristor controls employed.
- These follow different technique to control power
- Chops off a portion of the wave so that the volume of power to the load is reduced
- Now the current is not following the voltage waveform; it is like interrupted impulses of current
- This is a non sinusoidal distorted waveform

SOLID STATE CONTROL OF POWER
DISTORTS WAVEFORM



HARMONICS AND ENERGY LOSS

- Harmonic currents are just circulating in the network
- They do not contribute to the power delivered
- But causes I^2R losses
- In addition the magnetic effect of harmonics creates other problems which also results in considerable losses
- Alternating current passing though a conductor sets up alternating magnetic field.
- Create varying magnetic field around the conductor

HARMONICS AND ENERGY LOSS
SKIN EFFECT

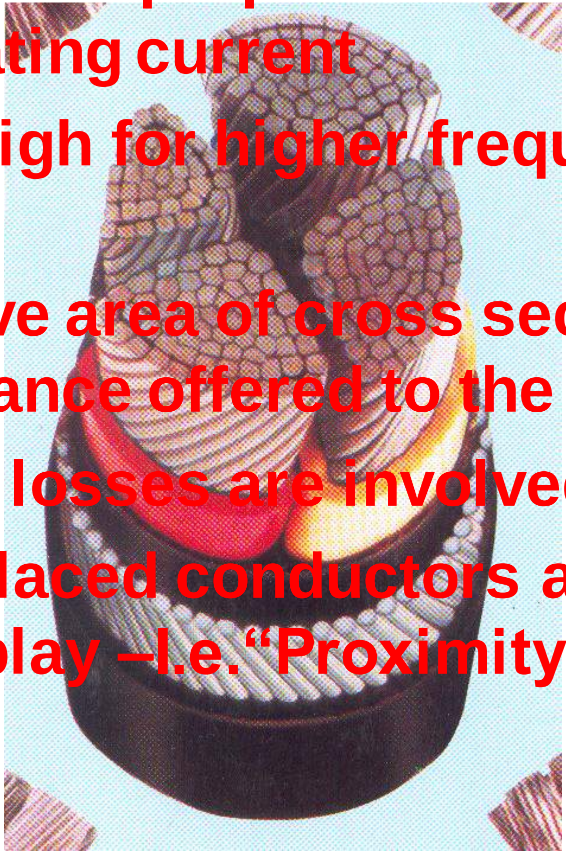
- Center of the conductor enveloped by more varying magnetic flux than on the outside.
- They push the current to the periphery of the conductor as the center is subjected to higher intensity of magnetic field
- This concentration at surface is “the skin Effect”

  Increases conductor effective resistance
- This is more pronounced if the conductors are associated with magnetic material as the flux density is much higher

HARMONICS AND ENERGY LOSS CONDUCTORS, CABLES ETC.

SKIN EFFECT

- These effects are proportional to the frequency of the alternating current
- Hence very high for higher frequency harmonic currents
- Since effective area of cross section is reduced, higher resistance offered to the current flow
- Very high I^2R losses are involved
- For closely placed conductors another factor comes in to play –I.e."Proximity Effects"



HARMONICS AND ENERGY LOSS CONDUCTORS, CABLES ETC. PROXIMITY EFFECT

Conductor halves in close proximity cut by more

Flux than the remote halves.

Current distribution not even throughout the

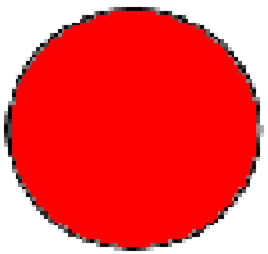
Cross-section,

Greater portion carried by remote halves.

When currents are in opposite directions,halves in closer proximity carry more current.

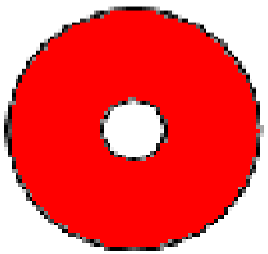
Overall effect- increase in effective resistance.

EFFECTIVE AREA OF CONDUCTORS FOR HARMONIC CURRENTS



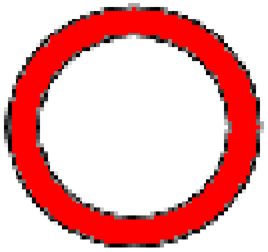
Cross – sectional area of a round conductor available for conducting DC current

“DC resistance”



Cross sectional area of the same conductor available for conducting normal-frequency AC

“AC resistance”



Cross sectional area of the same conductor available for conducting high-frequency AC

“AC resistance”

HARMONICS AND ENERGY LOSS CONDUCTORS, CABLES ETC.

Proximity effect decreases with increase

In spacing between cables.

- **At certain harmonics the combined effect results in twice the I^2R loss**

A.C/D.C resistance ratio	Frequency	Harmonic of 50 Hz
1.01	50	1
1.21	250	5
1.35	350	7
1.65	550	11

DIELECTRIC LOSSES

- Apart from the conductor copper loss, in the case of long cables, the dielectric loss of the insulation becomes a matter of concern.
- The dielectric loss in watts per kilometer per phase is given by the equation:
- $D = 2\pi \; f \; C \; U02 \tan \delta \; 10^{-6}$ (watt/km per phase)

- from this equation , for a specified design of cable with values of C and U_0 are fixed,
- the dielectric loss is proportional to the frequency,
- does not depend upon the current passing through the cable.
- Hence, higher the harmonics higher the dielectric losses will be.

HARMONICS AND INDUCTION MOTOR

When the power supplied to the stator of the motor contains harmonics,

- The stator winding affected by skin effect
- The rotor is severely affected, as the conductors are subjected to magnetic field of varying frequencies.
- 1.5 Hz to 300 Hz.
- In the motor the rotating magnetic field developed by the fundamental frequency voltage only develop necessary torque – delivers shaft power

HARMONICS AND INDUCTION MOTOR

- With motor designed for 3% slip, the rotor currents have a frequency of 1.5Hz;
- The rotor is designed to have the reactance and DC resistance nearly equal at this frequency to get optimum efficiency.
- But, different types of Rotating Magnetic fields are setup by individual harmonic currents
- While fields created by forward magnetic fields subtract on the rotor field, negative ones added up to the rotor field

HARMONICS AND INDUCTION MOTOR

- 5^{th} harmonic creates 250 Hz frequency while 11^{th} and 13^{th} pair together to induce 500 Hz in the rotor
- These high frequency harmonics snow balls the skin effect and the rotor I^2R loss becomes very high
- The rotor have currents at 6,12,18,12 etc times the stator frequency
- High frequency means higher eddy current and hysterisis loss
- The negative torques will affect the shaft horse power; some times create very bad vibration
- At certain level the efficiency drops down about 10%

HARMONICS AND INDUCTION MOTOR

- Harmonic fields rotating relative to each other produce torque pulsations
- Needs re-examination of torsional characteristics of entire shaft system
- Leakage flux set up in stator and rotor end windings added to the losses
- With skewed rotor bars, high frequency produce substantial iron loss;
- Depends upon amount of skew and iron loss characteristics

HARMONICS AND INDUCTION MOTOR

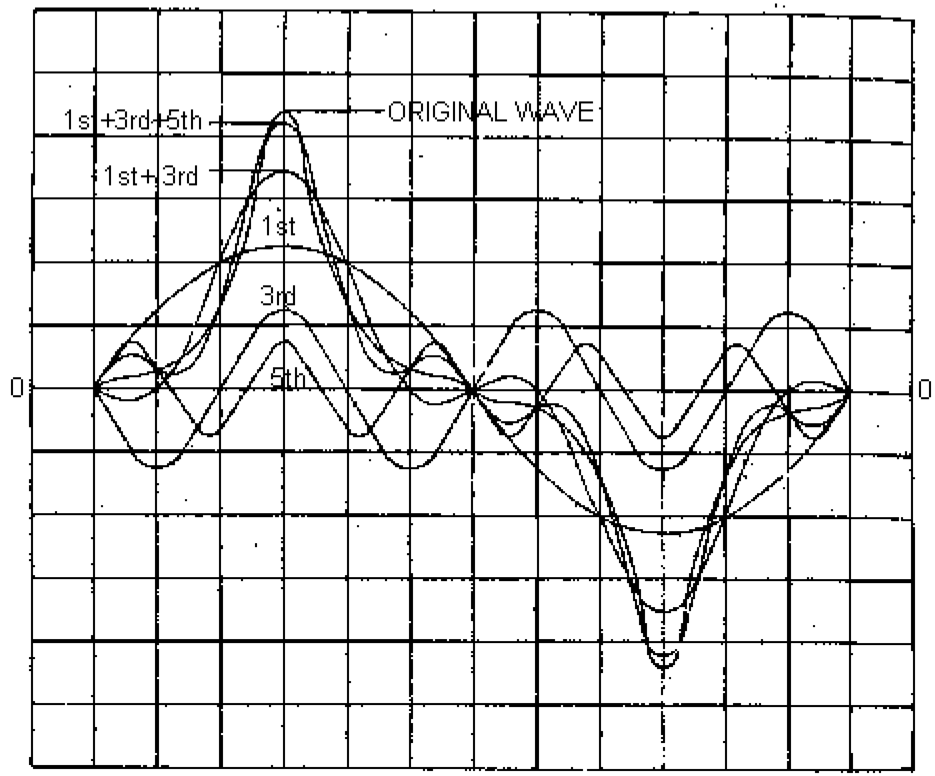
Case Study:

- Test on a 15 kW motor at full out put
- With 50 Hz fundamental sinusoidal voltage loss at full load = 1303 Watts
- With Quasi-square wave voltage 1600 Watts
- Losses up by 23%

HARMONICS AND TRANSFORMER

- Transformers essentially comprises of current carrying conductors encircled by iron core
- Hence harmonics effects results in:
- Higher eddy current and hysterisis losses
- Skin effects due to harmonic current
- High copper losses
- This effect more important for converter transformers
- Filters do not neutralize harmonic current in these transformers; due to higher losses develop unexpected hot spot in tanks

NO LOAD CURRENT OF A STAR/STAR TRANSFORMER
HARMONIC RESOLUTION

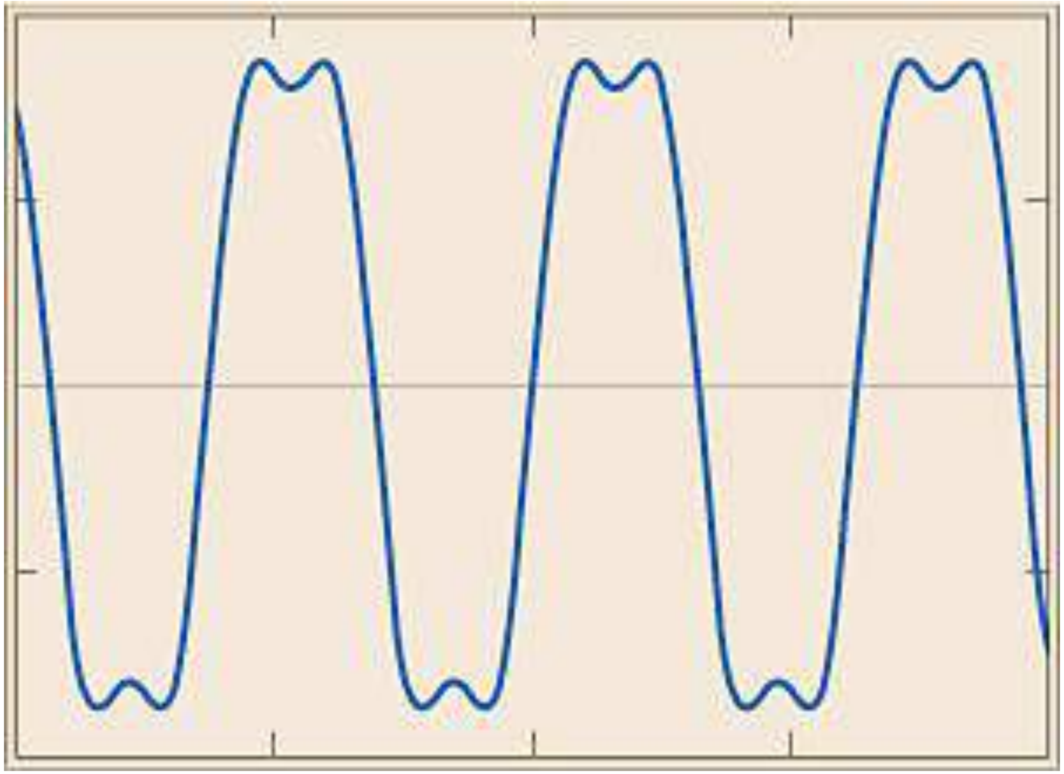


Harmonic analysis of peaked no load current wave of i_0 = 100 sin θ + 31.5 sin 5θ+…

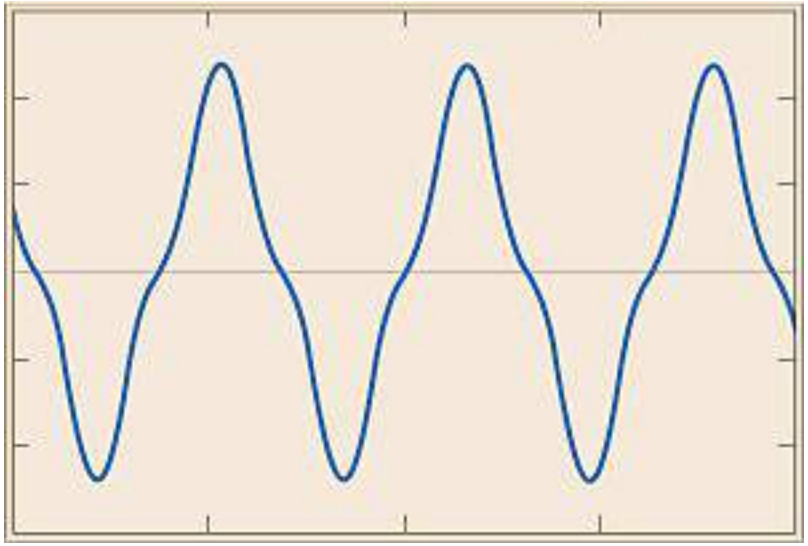
HARMONICS AND TRANSFORMER

- Third harmonics-Important for power transformers; circulation of triplen zero sequence current in delta windings
- These extra currents over heat the windings
- The RMS value of pure sine wave is 0.707 of peak value
- 340 V peak value has an RMS voltage of 240
- But this ratio is not true for a distorted waveform
- RMS value is the measure of the heat generated by an equivalent DC current
- Hence, heat produced by harmonics are much higher

THIRD HARMONICS IN PHASE WITH FUNDAMENTAL



THIRD HARMONICS OUT OF PHASE WITH FUNDAMENTAL



Phase currents add in neutral

	*Phase sequence = **A-B-C***		
Fundamental	**A** 0°	**B** 120°	**C** 240°
3rd harmonic	**A'** $3 \times 0^\circ$ (0°)	**B'** $3 \times 120^\circ$ ($360^\circ = 0^\circ$)	**C'** $3 \times 240^\circ$ ($720^\circ = 0^\circ$)

HARMONICS AND TRANSFORMER

- Since harmonic currents are neither in phase nor follow supplied voltage they do not deliver any power
- In a pure sinusoidal waveform the displacement angle between the current and the voltage decides the power factor, known as displacement power factor or apparent power factor
- This does not hold good in case of harmonic currents as they do not have any such angular relation
- Hence power factor is kW/Volts X Ampere
- ***Actually this is the true power factor in a circuit which has harmonic currents***

HARMONICS AND TRANSFORMER

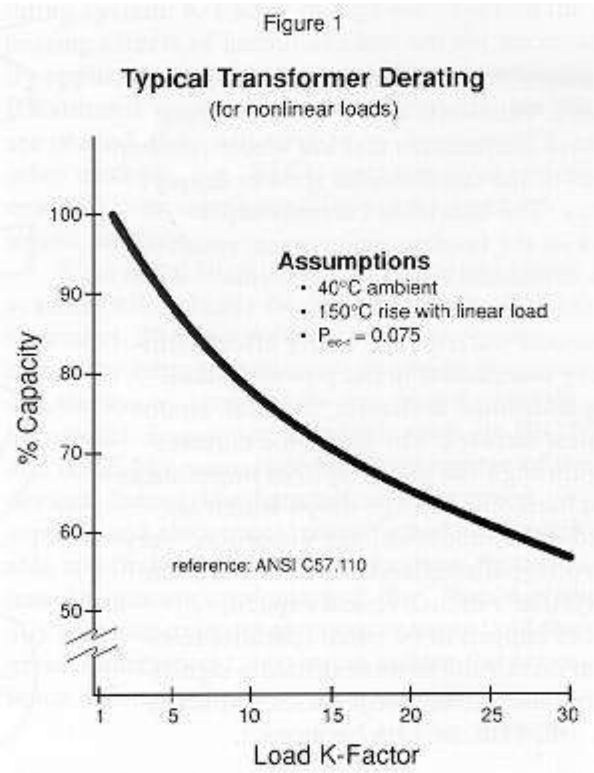
The losses in a transformer are a combination of

1. Excitation (No load loss) I.e. Eddy current, hysterisis, stray losses
2. Load losses mainly due to I^2R loss in the conductor
3. Both the losses increase as the square of the frequency but does not contribute to the power transfer
4. Heats transformer; increases the temperature resulting in premature failure apart from wasting energy!

TYPICAL EDDY CURRENT LOSS FACTORS FOR OIL-FILLED TRANSFORMERS

Transformer size oil filled transformer	Eddy current loss factor
Up to 1 MVA	1%
1 MVA TO 5 MVA	1 to 5 %
Greater than 5 MVA	9 to 15%

DERATING FACTOR FOR TRANSFORMERS



HARMONICS AND INSULATED CABLES

A cable is essentially a conductor surrounded by an insulation

These two components create losses;

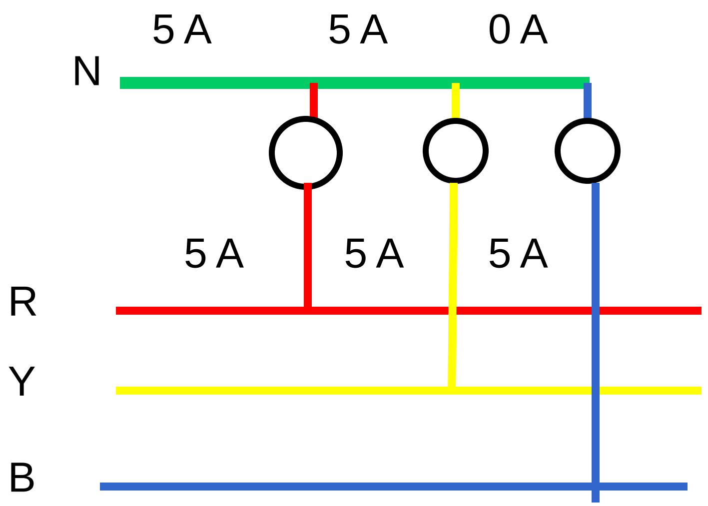
- The conductor develops I^2R loss due to the current flow
- If the current passing through contains higher harmonics this loss is increased due to the increased skin and proximity effects as shown earlier

HARMONICS AND INSULATED CABLES

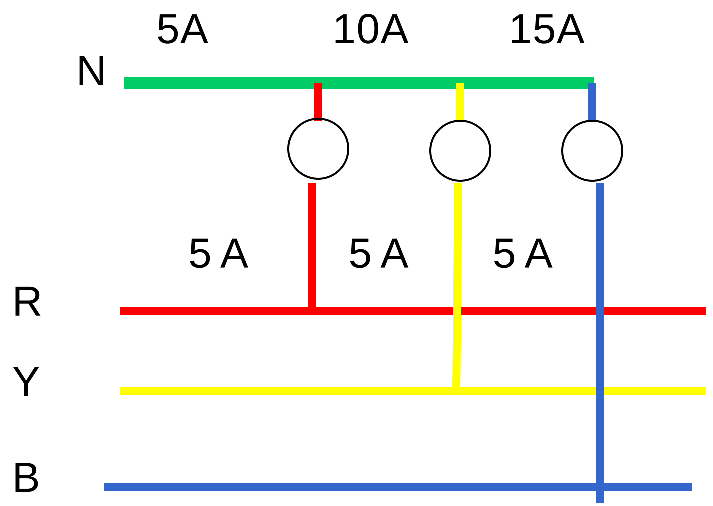
The insulation is subjected to dielectric loss

- This loss is
- $= 2\pi \ f C \ U_0^2 \tan \delta \ 10^{-6}$ (watt/km per phase)
- For a specified design,
- C and U_0^2 are constant; therefore, loss is proportional to the frequency
- Higher the harmonics higher the losses

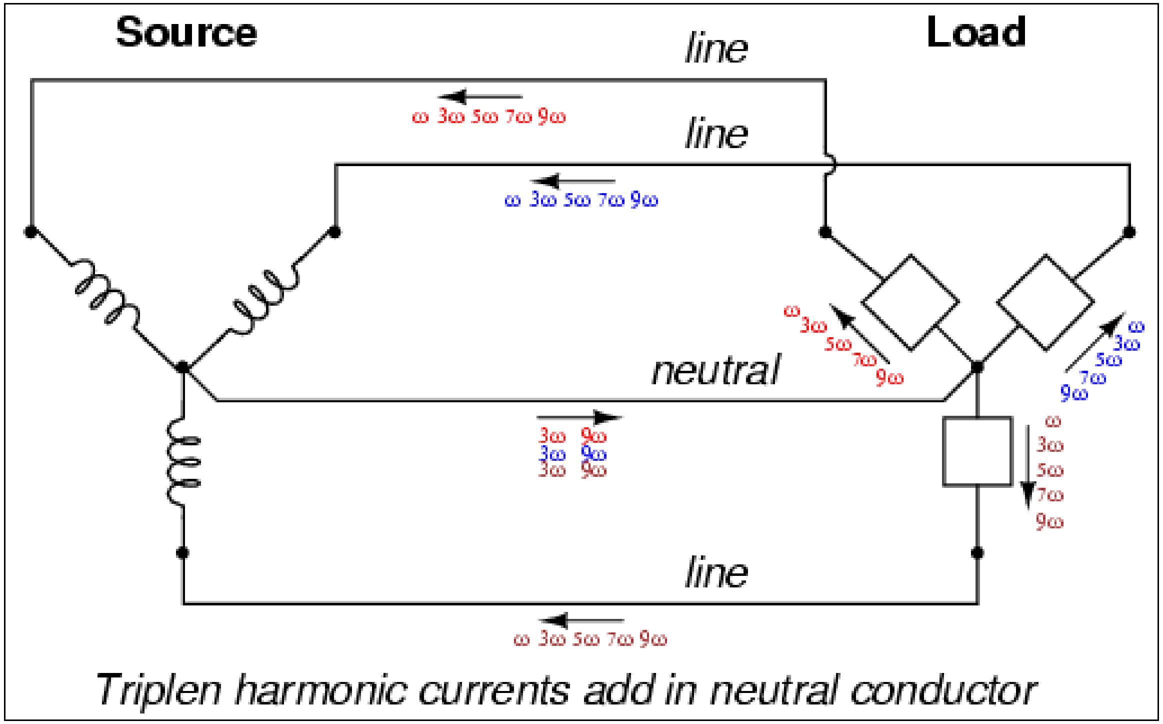
BALANCED LOAD
NEUTRAL CURRENT



BALANCED LOAD WITH THIRD HARMONICS
NEUTRAL CURRENT



THIRD HARMONICS AND NEUTRAL CURRENTS



CONCLUSION

- Harmonics are created in a power system by the consumer and also by the supplier
- But major portion by consumer
- Harmonics creates lot of problems, destroys equipments
- All energy efficient equipments essentially creates harmonics;
- These result in added energy losses
- Hence harmonics are to be limited
- ***While selecting energy efficient equipments these points are to be given greater attention***