## AC Power



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## AC Power

## Voltage Waveform

Consider the following AC circuit driven by a source with voltage waveform;

$$
V(t)=V_{\max } \cos w t
$$

Phasor representation of this voltage waveform will then be

$$
V_{\max } \angle 0^{\circ}
$$



$$
\text { Load }=R+j X
$$

$$
=Z / \theta \quad+\cdots \cdots Z=\sqrt{R^{2}+X^{2}}, \theta=\operatorname{Tan}^{-1}(X / R)
$$

## AC Power

## Phase Shift in Voltage Waveform

Consider now, the following AC circuit driven by a a source with an AC voltage waveform;

$$
V(t)=V_{\max } \cos \left(w t-\theta_{v}\right)
$$

Phasor representation of the shifted voltage waveform will then be

$$
V_{\max } /-\theta_{v}
$$



$$
\begin{aligned}
& \theta_{v} / w=t_{1} \\
& t_{1}=3 \mathrm{msec}
\end{aligned}
$$



## AC Power

## Current Waveform

## Relation Between Voltage and Gurrent Phasors

$\theta_{v} / w=t_{1}$
$t_{1}=3 \mathrm{msec}$



$$
Z=\sqrt{R^{2}+X^{2}}, \theta=\operatorname{Tan}^{-1}(X / R)
$$

$1(t)$


$$
\theta=\theta_{v}-\theta_{1}=\operatorname{Tan}^{-1}(X / R)
$$

$\square$

## AC Power

## Current Waveform

Phasor representation of this current will then be

$$
I_{\max } /-\theta_{1}
$$

Waveform representation of this current will then be

$$
I(t)=I_{\max } \cos \left(w t-\theta_{1}\right)
$$

$$
I(t)=I_{\max } \cos \left(\overrightarrow{w t}-\theta_{1}\right)
$$

$$
\text { Load }=R+j X
$$

$$
=Z \angle \theta
$$

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## AC Power

## Voltage and Current Waveforms

Please note that the angle difference $\theta_{v}-\theta_{l}$ depends only on the resistance $R$ and reactance $X$ of the load



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## AC Power

## AC Power - Power Expression

Voltage and current waveforms are
$V(t)=V_{\text {max }} \cos w t$
$I(t)=I_{\text {max }} \cos (w t-\theta)$

Power waveform will then be

$$
\begin{aligned}
S(t) & =V(t) \times I(t)^{*} \\
& =V_{\max } \cos w t \times I_{\max } \cos (w t+\theta)
\end{aligned}
$$

Please note that; "G:" sign here has been altered due to the conjugation operation in the definition of power:

$$
S=V x I^{*}
$$



$$
\theta / w=\left(\theta_{v}-\theta_{1}\right) / w
$$



| $I^{*}$ | $\hat{I} \cos (w t+\theta)$ |
| :--- | :--- |
| $v$ | $\hat{V} \cos (w t)$ |



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## AC Power

## AC Power - Power Expression

Power waveform is the product of the voltage and conjugate of the current waveforms

$$
S(t)=V_{\max } I_{\max } \cos w t \times \cos (w t+\theta)
$$

$$
\cos a x \cos b=1 / 2[\cos (a+b)+\cos (a-b)]
$$

$$
S(t)=1 / 2 V_{\max } I_{\max }[\cos (w t+w t+\theta)+
$$

$$
\cos (w t-w t-\theta)]
$$

$$
=1 / 2 V_{\max } I_{\max }[\cos (2 w t+\theta)+\cos \theta]
$$

$$
=\left(V_{\max } / \sqrt{2}\right)\left(I_{\max } / \sqrt{2}\right)[\cos (2 w t+\theta)+
$$

$$
\cos \theta]
$$

$$
=V_{r m s} I_{r m s}[\cos (2 w t+\theta)+\cos \theta]
$$

$$
V_{r m s}=V_{\max } / \sqrt{2}
$$

$$
\theta=\theta_{v}-\theta_{I}=\operatorname{Tan}^{-1}(X / R)
$$



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## AC Power

## AC Power - Decomposition of Power Expression

Power expression may be decomposed into two components
$S(t)=V_{r m s} I_{r m s} \cos (2 w t+\theta)+V_{r m s} I_{r m s} \cos \theta$

Sinusoidal (AC) Term



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## ( <br> AC Power

## AC Power - Average Power Expression

## Average Power

$S(t)=V_{r m s} I_{\text {mss }}[\cos (2 w t+\theta)+\cos \theta]$
$S(t)_{\text {avg }}=(1 / T) \int_{0}^{T} S(t) d t$
$S(t)_{\mathrm{arg}}=(1 / T) \int P(t) d t$

$$
\begin{aligned}
& =(1 / T) \int V_{\text {rms }} I_{\text {rms }}[\cos (2 w t+\theta)+\cos \theta] d t \\
& =(1 / T) \int V_{\text {rms }} I_{\text {rms }} \cos (2 w t+\theta) d t+(1 / T) \int V_{\text {rms }} I_{\text {rms }} \cos \theta d t
\end{aligned}
$$

Average is zero
(

Sum of these areas is zero


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## AC Power

## AC Power - Average Power Expression

## Average Power

$$
\begin{aligned}
S(t)_{\text {avg }} & =(1 / T) \int P(t) d t \\
& =(1 / T) V_{\text {ms }} I_{m s} \int \cos \theta d t \\
& =(1 / T) V_{m s} I_{m s} \cos \theta\left(\int d t\right) \ldots \ldots \ldots . . . . . . \int_{0}^{T} d t=T \\
& =(1 / T) T V_{\text {rms }} I_{\text {rms }} \cos \theta \\
& =V_{r m s} I_{r m s} \cos \theta
\end{aligned}
$$

$S(t)_{\text {avg }}=V_{r m s} I_{r m s} \cos \theta$


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## AC Power

## Example

## Question

Calculate the average and instantaneous powers dissipated in the load shown below

## Parameters:

$V_{\text {rms }}=100$ Volts
$Z_{\text {load }}=3+j 4$ Ohms $=5 / 53.13^{\circ} 0 \mathrm{hms}$


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AC Power

## Example

## Solution

$$
\begin{aligned}
& V_{\max }=100 \times \sqrt{2}=144.4 \text { Volts } \\
& \begin{aligned}
I & =V_{\max } \angle 0^{\circ} / Z \angle \theta \\
& =144.4 \angle 0^{\circ} / 5 \angle 53.13^{\circ} \\
& =28.8 /-53.13^{\circ} \mathrm{Amp} \\
I_{r m s} & =I_{\max } / \sqrt{2}=28.8 / \sqrt{2}=20 \mathrm{Amp}
\end{aligned}
\end{aligned}
$$




## AC Power

## Example

## Solution

| $S(t)_{\text {avg }}$ | $=V_{\text {rms }} I_{\text {rms }} \cos \theta$ |
| ---: | :--- |
|  | $=100 \times 20 \cos 53.13=1200$ Watt |

$S(t)=V(t) I(t)$
$=\sqrt{2} \times 100 \cos w t \times \sqrt{2} \times 20 \cos \left(w t+53.13^{\circ}\right)$
$=4000 \cos w t x \cos \left(w t+53.13^{\circ}\right)$
$V(t)=V_{\text {max }} \cos w t$
$=\sqrt{2} \mathrm{~V}_{\mathrm{rms}} \cos \mathrm{wt}$
$=100 \sqrt{2} \cos \mathrm{wt}$
$=144.4 \cos \mathrm{wt}$
$\xrightarrow[I(t)]{\longrightarrow}$


Please note that;
"-" sign here has been changed to " + " due to the conjugate operation in the definition of power: $S=V \times I^{*}$

## AC Power

## Example



## AC Power

## Complex Power

## Active Power Expression

Expanding the first term in the power expression; $S(t)=V_{r m s} I_{r m s}[\cos (2 w t+\theta)+\cos \theta]$
$=V_{r m s} I_{r m s}(\cos 2 w t \cos \theta-\sin 2 w t \sin \theta+\cos \theta)$

$$
\cos (a+b)=\cos a \cos b-\sin a \sin b
$$

and recombining the cosine terms;

$$
=V_{r m s} I_{r m s}[\cos \theta(1+\cos 2 w t)-\sin 2 w t \sin \theta]
$$




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## AC Power

## Complex Power

$S(t)=V_{\text {rms }} I_{\text {rms }}[\cos \theta(1+\cos 2 w t)-\sin 2 w t \sin \theta]$
$=V_{r m s} I_{m s} \cos \theta(1+\cos 2 w t)-V_{m s} I_{m s} \sin \theta \sin 2 w t$

$$
=V_{r m s} I_{m s} \cos \theta(1+\cos 2 w t)-Q_{m a x} \sin 2 w t
$$



$$
400
$$

$$
Q_{m a x}=V_{m m s} I_{r m s} \sin \theta
$$

$$
Q(t)=\text { Reactive power }
$$



## AC Power

## Active and Reactive Powers - Summary



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## AC Power <br> Active and Reactive Power Waveforms



## AC Power

## AC Power Active and Reactive Power Waveforms

One revolution = 10 msec Hence, $2.5 \mathrm{msec}=360^{\circ} / 4=90^{\circ}$

Please note that Q leads P by $90^{\circ}$



## AC Power

METU

## AC Power Active Power Waveform

```
P(t)= V vms }\mp@subsup{I}{rms}{}\operatorname{cos}0(1+\operatorname{cos}2wt
    = V Vrms Ims 
```



Active Power (P)
$\longrightarrow$


$$
P(t)_{\text {avg }}=150 \mathrm{~W}
$$



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## AC Power

METU

## AC Power Reactive Power Waveform

$Q(t)=V_{r m s} I_{r m s} \sin \theta \times \sin 2 w t$
$=Q_{\text {max }} \sin 2 w t$

$Q(t)_{\text {sinusoidal }} \quad Q_{\max }$


Q(t), Reactive Power (VAR)
$1 / 4$ Period $=2.5 \mathrm{msec}$
$200 \square$


## AC Power

METU

## AC Power <br> Reactive Power Waveform (During the first 5 mseconds)



## AC Power

## AC Power Reactive Power Waveform (During the next 5 mseconds)

## AC Power

## Phosors Representation of Active and Reactive Powers

Mean of $P(t)$ is called active power Peak of $\mathrm{Q}(\mathrm{t})$ is called reactive power

$$
\mathrm{P}(\mathrm{t})=\text { Active Power (Watt) }
$$




Q(t), Reactive Power (VAR)


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## AC Power

## Phosors Representation of Active and Reactive Powers

## Voltage and Current

Angular speed: $w=2 \pi f$

$$
=2 \times 3.14 \times 50=314 \mathrm{rad} / \mathrm{sec}
$$

Time for one revolution $=1 / f=1 / 50=0.020$ sec $=20 \mathrm{msec}$
Hence,
Angle for $1 / 4$ revolution $=360^{\circ} / 4=90^{\circ}$
Time for $1 / 4$ revolution $=20 \mathrm{msec} / 4=5 \mathrm{msec}$

## Active and Reactive Power

Angular speed: $w^{\prime}=2 w=4 \pi f$

$$
=2 \times 314=628 \mathrm{rad} / \mathrm{sec}
$$

Time for one revolution $=10 \mathrm{msec}$
Time for $1 / 4$ revolution $=10 \mathrm{msec} / 4=2.5 \mathrm{msec}$

Angle $=90^{\circ}$, Time for $1 / 4$ revolution $=20 / 4=5 \mathrm{msec}$


AC Power

## Phosors Representation of Active and Reactive Powers



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## Phosors Representation of Active and Reactive Powers



## Phosors Representation of Active and Reactive Powers

| S - Total power | (k) VA (kVA) |
| :--- | :--- |
| P- Active power | (k) Watt (kW) |
| Q - Reactive power | (k) VAR (kVAR) |

Please note that this angle depends only on the resistance R and reactance X of the load, i.e.

$$
\begin{aligned}
\theta & =\operatorname{Tan}^{-1} X / R \\
& =\operatorname{Tan}^{-1} Q / P
\end{aligned}
$$



## © <br> AC Power

## Basic Conversions

## Polar Representation

$$
P=S \cos \theta, \quad Q=S \sin \theta
$$

## Rectangular

 Representation$P+j Q$
$P=S \cos \theta$

$$
\begin{aligned}
& X / R=Q / P \\
& \text { i.e. if } X=0 \quad \Rightarrow Q=0
\end{aligned}
$$



## AC Power

## AC Power <br> Active Reactive Powers (in the first 5 mseconds)



## AC Power

## AC Power Active Reactive Powers (in the next 5 mseconds)



## AC Power

## AC Power Active Reactive Powers



## AC Power

## Active-Reactive Powers

$$
P=S \cos \theta, \quad Q=S \sin \theta
$$

$$
S=\sqrt{P^{2}+Q^{2}}, \quad \theta=\operatorname{Tan}^{-1}(Q / P)
$$

4..........

## Rectangular

 Representation$P+j Q$
active Power (kVAR)

Q


S, Total Power (kVA)

P, Active Power (kW)

## AC Power

## Active-Reactive Powers


Q, Reactive Power (kVAR)

S, Total (Complex) Power (kVA)


P, Active Power (kW)


## (1) <br> AC Power

## Power Meters



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## AC Power

## Reactive Power Compensation

## Definition

Reactive power compensation is partial or full cancellation of the reactive component of complex power by introducing a negative (compensation) component

Q, Reactive Power
(kVAR)


## AC Power

## Power Factor

## Definition

Cosine of the angle between S and P is called Power Factor of the load

$$
\begin{aligned}
\text { Power Factor } & =\text { p.f. }=\cos \theta \\
& =\cos \left(\text { Tan }^{-1} Q / P\right)
\end{aligned}
$$

## Please note that reducing Q means reducing the angle $\theta$, and hence increasing power factor

Hence, reactive power compensation is sometimes called as "Power Factor Correction", i.e. correcting power factor to a value near unity

Q, Reactive Power (kVAR)


- Compensation (kVAR)
$Q_{\text {new }}$
Reactive Power
(kVAR)


S, Total Power (kVA)

P, Active Power (kW)
$\mathrm{S}_{\text {new, }}$ Total Power (kVA)

P, Active Power (kW)

## AC Power

## Full or Partial Compensation

## Partial Compensation

Partial compensation is the case, where Power Factor is raised to a value not reaching unity


$$
\begin{aligned}
\text { Power Factor }_{\text {new }} & =p . f_{\text {new }}=\cos \theta_{\text {new }} \\
& =\cos \left(\text { Tan }^{-1} Q_{\text {new }} / P\right)
\end{aligned}
$$

## Full Gompensation

Full compensation is the case, where Power Factor is unity

$$
\begin{aligned}
\text { Power Factor }_{\text {new }} & =p . f_{\text {new }}=\cos \theta_{\text {new }} \\
& =\cos \left(\text { Tan }^{-1} 0 / P\right)=1
\end{aligned}
$$



$$
Q_{\text {new }}=0 \quad \theta_{\text {new }}=0 \quad S_{\text {new }}=P
$$

P, Active Power (kW)

## AC Power

## Charging Principle Applied by TEDAS

If

$$
|Q / P|>1 / 3
$$

Then, reactive power is charged
If

$$
|Q / P|<1 / 3
$$

Then, reactive power is free


Please note that

$$
/ Q / P />1 / 3
$$

means;

$$
\begin{aligned}
& \operatorname{Tan}^{-1}(1 / 3)=18.435^{\circ} \\
& \cos 18.435^{\circ}=0.949 \cong 0.95
\end{aligned}
$$

## AC Power

## Why Partial Compensation is Preferred?

## Partial Compensation

Due to economic reasons, full compensation is rarely implemented


Reactive power needed to raise p.f. from 0.95 to 1 is the same as that for raising p.f. from 0.83 to 0.95 (not worthwhile)


## AC Power

## Application of Reactive Power Compensation

## Reduction of Equipment Loading

- Transformers
- Lines
- Cables
are priced with respect to the power rating (kVA)
Prices of these equipments on the other hand, are determined by the cross-section ( $\mathrm{mm}^{2}$ ) of the equipment

| Cross <br> Section | Current <br> Capacity |
| ---: | ---: |
| $\left(\mathrm{mm}^{2}\right)$ | (Amp) |
| 1.0 | 12.0 |
| 1.5 | 16.0 |
| 2.5 | 21.0 |
| 4.0 | 27.0 |
| 6.0 | 35.0 |
| 10.0 | 48.0 |
| 16.0 | 65.0 |
| 25.0 | 88.0 |
| 35.0 | 110.0 |
| 50.0 | 140.0 |
| 70.0 | 175.0 |
| 95.0 | 215.0 |
| 120.0 | 225.0 |

Cross section (size) of the cable ( $\mathrm{mm}^{2}$ )


## AC Power

## Application of Reactive Power Compensation

## Reduction of Equipment Loading

Hence, the power rating S (kVA) of a cable is merely determined by the cross section, which must be minimized in order to reduce the investment to be made for the cable


## AC Power

## Application of Reactive Power Compensation

## Reduction of Equipment Loading

Hence, the power rating S (kVA) of a cable is merely determined by the cross section, which must be minimized in order to reduce the investment to be made for the cable

Hence, S (kVA) must be minimized


## AC Power

## Alternative Ways of Reducing S (kVA)

## Alternative Ways of Reducing $\mathbf{S}(\mathbf{k V A})$

a) Reducing the overall loading;

P + jQ (kW + jkVAR) (Overall comsumption)
Unreasonable, since the active consumption $P$ is determined by the needs of the comsumer, who consumes electricity
a) Reducing only Q (kVAR) Possible, reasonable


Please note that active power does not change after compensation


## AC Power

## Example

## Question

The factory shown on the RHS draws a load at 6300 V nominal voltage

$$
P+j Q=120 k W+j 140 k V A R
$$

Calculate the amount of reactive power needed in order to raise the power factor of the factory to 0.95

$P+j Q=120 \mathrm{~kW}+j 140 \mathrm{kVAR}$

$$
Q_{\text {comp }}=\Delta Q=Q-Q_{\text {new }}
$$

## AC Power

## Example

## Answer

## Uncompensated (Given) Case

$\operatorname{Tan} \theta=Q / P$

$$
=140 / 120=1.1667
$$

$\theta=\operatorname{Tan}^{-1} 1.167=49.40^{\circ}$
p.f.: $\cos \theta=0.65$ (lagging)

$Q_{\text {new }}=39.43$ (kVAR)

$Q_{\text {comp }}=\Delta Q=Q-Q_{\text {new }}=140-39.43=100.57 \mathrm{kVAR}$
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## AC Power

## Example

## Question

Now, for the previous problem, calculate the reduction in line losses as a result of this compensation by assuming that line impedance is

$$
R+j X=10+j 20 \text { Ohms }
$$

## TEDAŞ 6300 V Mains



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## AC Power

## Example

$S=V I^{*} \rightarrow I=S / V=\sqrt{140^{2}+120^{2}} / 6300$

$$
=184.39 \times 1000 / 6300=29.268 \mathrm{Amp}
$$

$$
\begin{aligned}
S_{\text {new }}=V I_{\text {new }}{ }^{*} \rightarrow I_{\text {new }} & =\sqrt{39.43^{2}+120^{2}} / 6300 \\
& =126.312 \times 1000 / 6300=20.049 \mathrm{Amp}
\end{aligned}
$$

$$
P_{\text {loss }}=R I^{2}=10 \times 29.268^{2}=8566.39 \text { Watts }
$$

$$
P_{\text {loss.new }}=R I_{\text {new }}{ }^{2}=10 \times 20.495^{2}=4019.84 \text { Watts }
$$

$$
\begin{aligned}
\Delta P_{\text {loss }} & =8566.39-4019.84 \\
& =4546.55 \text { Watts }
\end{aligned}
$$

3 km O/H line


$P+j Q=120 \mathrm{~kW}+j 140 \mathrm{kVAR}$
$Q_{\text {comp }}=\Delta Q=Q-Q n e w$

## AC Power

## Example

> Now, calculate the return rate of the investment to be made for the compensator, by assuming that the retail price of electricity is 16 Cents/kWh and price of capacitor is 184.41 USD/kVAR

$$
\begin{aligned}
& \Delta P_{\text {loss }}=8566.39-4019.84=4546.55 \text { Watts } \\
& \text { Investment }
\end{aligned}=100.57 \mathrm{kVAR} * 184.41 \text { USD/kVAR }
$$

LV-ACB ${ }^{\text {TM }}$ List Price
Low Voltage Automatic Capacitor Banks

480 VOLT AUTOMATIC CAPACITOR BANKS

| BANK | STEP |  | MODEL |
| :--- | :--- | :--- | :--- |
| RATING | KVAR | NOMBER | LIST |
| (KVAR) |  |  |  |
| PRICE |  |  |  |

## AC Power

## Example

## Question

Now, for the previous problem, determine the minimum cross section of the line for the alternative cases, when line is compansated and uncompensated

$$
I_{\text {new }}=20.495 \mathrm{Amp}
$$

$I_{\text {initial }}=29.268 \mathrm{Amp}$

## TEDAŞ 6300 V

Mains
3 km O/H line $R+j X=10+j 20$ Ohm



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## AC Power

## Question

## Question

Now, for the previous problem, calculate the shunt capacitance in Farads needed for the amount of compensation found above

$$
\begin{aligned}
& Q_{\text {comp }}=\Delta Q=Q-Q_{\text {new }}=140-39.43=100.57 \mathrm{kVAR} \\
& Q_{\text {comp }}=V I_{\text {comp }}{ }^{*} \rightarrow I_{\text {comp }}=Q_{\text {comp }} / V=100570 \mathrm{VA} / 6300 \mathrm{~V}=15.963 \mathrm{Amp} \\
& X_{\text {comp }}=V / I_{\text {comp }}=6300 / 15.963=394.65 \text { Ohms } \\
& X_{\text {comp }}=1 /(j w C) \\
& C=1 /(j w X)=1 /(314.15 \times 394.65)=123.98 \mathrm{mF} \\
& \text { TEDAŞ } 6300 \mathrm{~V} \text { Mains } \\
& 3 \mathrm{~km} \text { O/H line } \\
& R+j X=10+j 20 \text { Ohms } \\
& \mathbf{Q}_{\text {new }}=\mathbf{Q}+\mathbf{Q}_{\text {comp }} \\
& Q_{\text {comp }}<0 \\
& P+j Q=120 k W+j 140 k V A R \\
& \mathbf{Q}_{\text {comp }}=\Delta \mathbf{Q}=\mathbf{Q}-\mathbf{Q n e w}
\end{aligned}
$$

## AC Power

## Medium Voltage Capacitor Banks

## Shunt connection of large capacity capacitors in power systems



## AC Power

## Installation of MV Capacitor Banks



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## AC Power

## Electronic Capacitors in a Motherboard



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## Another Example

- Early in the history or electricity, Thomas Edison's General Electric company was distributing DC electricity at 110 volts in the United States.
- Then Nikola Tesla the devised a system of three-phase AC electricity at 240 volts. Threephase meant that three alternating currents slightly out of phase were combined in order to even out the great variations in voltage occurring in AC electricity. He had calculated that 60 cycles per second or 60 Hz was the most effective frequency. Tesla later compromised to reduce the voltage to 110 volts for safety reasons.


## AC Power

## Another Example

- Europe goes to 50 Hz :
- With the backing of the Westinghouse Company, Tesla's AC system became the standard in the United States. Meanwhile, the German company AEG started generating electricity and became a virtual monopoly in Europe. They decided to use 50 Hz instead of 60 Hz to better fit their metric standards, but they kept the voltage at 110 V .
- Unfortunately,
- 50 Hz AC has greater losses and is not as efficient as 60 HZ .


## AC Power

- Due to the slower speed, 50 Hz electrical generators are 20 \% less effective than 60 Hz generators. Electrical transmission at 50 Hz is about $10-15 \%$ less efficient. 50 Hz transformers require larger windings and 50 Hz electric motors are less efficient than those meant to run at 60 Hz . They are more costly to make to handle the electrical losses and the extra heat generated at the lower frequency.
- Europe goes to 220 V
- Europe stayed at 110 V AC until the 1950 s, just after World War II. They then switched over to 220 V for better efficiency in electrical transmission. Great Britain not only switched to 220 V , but they also changed from 60 Hz to 50 Hz to follow the European lead. Since many people did not yet have electrical appliances in Europe after the war, the change-over was not that expensive for them.
- U.S. stays at $110 \mathrm{~V}, 60 \mathrm{~Hz}$


## AC Power

## Another Example

- The United States also considered converting to 220 V for home use but felt it would be too costly, due to all the 110 V electrical appliances people had. A compromise was made in the U.S. in that 220 V would come into the house where it would be split to 110 V to power most appliances. Certain household appliances such as the electric stove and electric clothes dryer would be powered at 220 V .


# Did everybody follow this part 

 carefully ?