Working Active Power Concept in a Three Phase System

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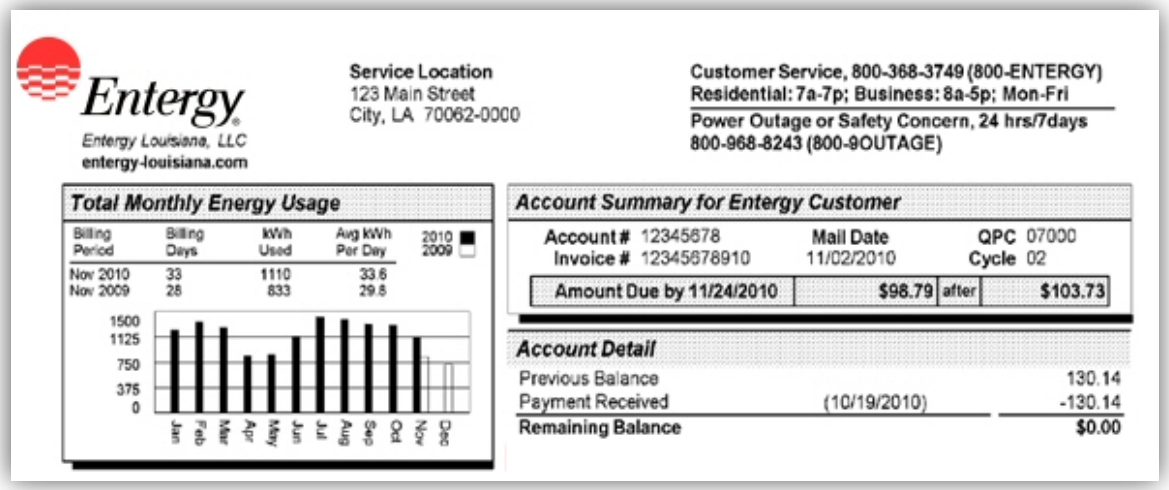
Outline

- Introduction
- Working Active Power Concept
- Measurement of Working Active Power
- Detrimental Active Power Concept
- Conclusion of Working Active Power Concept
- Future Research Plans

Introduction

- Everyone pays their power bill
- How is this bill calculated?
- How do we know it's fair?



Entergy

Entergy Louisiana, LLC
entergy-louisiana.com

Service Location
123 Main Street
City, LA 70062-0000

Customer Service, 800-368-3749 (800-ENTERGY)
Residential: 7a-7p; Business: 8a-5p; Mon-Fri
Power Outage or Safety Concern, 24 hrs/7days
800-968-8243 (800-9OUTAGE)

Total Monthly Energy Usage

Billing Period	Billing Days	kWh Used	Avg kWh Per Day
Nov 2010	33	1110	33.6
Nov 2009	28	833	29.8

2010 ■ 2009

1500
1125
750
375
0

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Account Summary for Entergy Customer

Account # 12345678 Mail Date QPC 07000
Invoice # 12345678910 11/02/2010 Cycle 02

Amount Due by 11/24/2010	$98.79	after	$103.73

Account Detail

Previous Balance		130.14
Payment Received	(10/19/2010)	-130.14
Remaining Balance		$0.00

Introduction

- Main component of energy bills

$$W_a = \int_0^{month} P dt$$

- W_a (kWh) is the active energy.
- P (kW) is the traditional active power.
- Analog revenue meters are based upon this principle.

Introduction

- Economics of power system is important.
- Current billing standards are outdated.
- Can these standard still be used?

Introduction

- New technologies bring new challenges
  - Additional distortion and asymmetry.
  - Causes extra, unaccounted for power losses.

Introduction

- Active power concept needs further decomposition.
- One party is not being accurately compensated, financially.
- New concept of ***working active power***
  - Pinpoints the source of degradation.
  - Everyone is accurately compensated.

Working Active Power Concept

- Active power consist of several quantities

$$P = P_{\mathrm{w}} - P_{\mathrm{r}} + P_{\mathrm{d}}$$

Power needed for load operation

Load distortion and unbalance

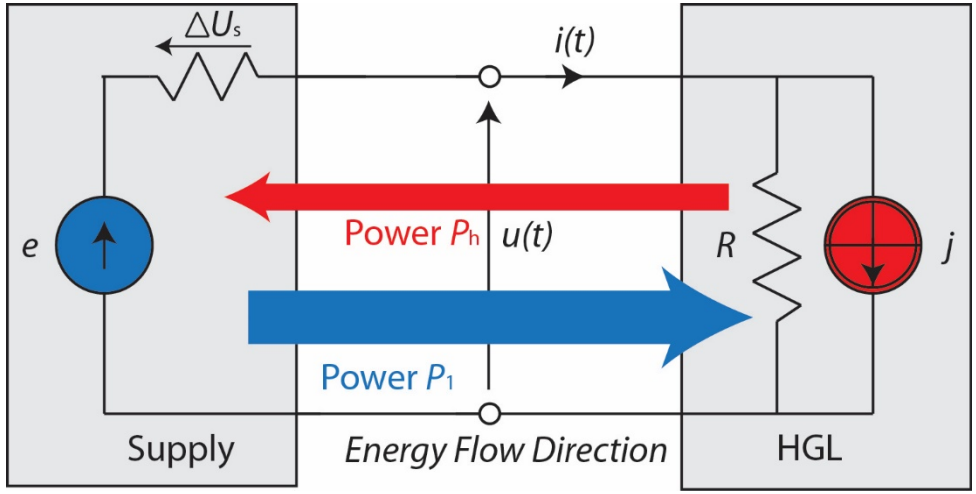
Supply distortion & asymmetry

- Reflected Power, P_r refers to revenue loss of utility.
- Detrimental Power, P_d refers to customer overpayment.

Working Active Power Concept

$$i(t) = \sum_{0}^{\infty} i_n(t) = i_1(t) + i_h(t)$$

$$u(t) = \sum_{0}^{\infty} u_n(t) = u_1(t) + u_h(t)$$

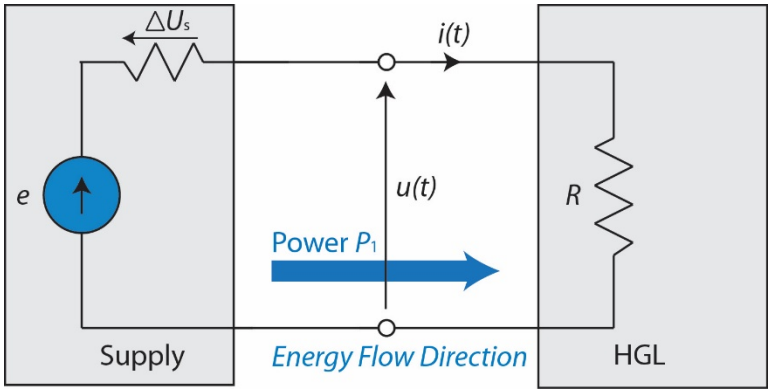


Fundamental & higher harmonics

- Voltage supply is 1Φ and sinusoidal.
- Load is a resistive harmonic generating load (HGL).

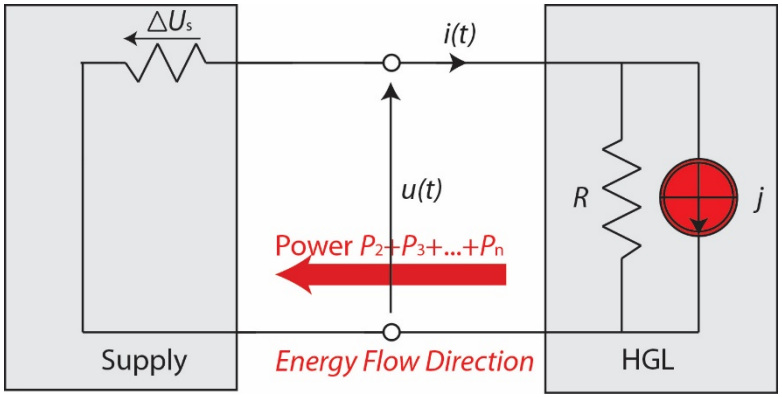
Working Active Power Concept

Fundamental harmonic



Supply e is sinusoidal (e_1)

Higher harmonics



HGL, $j = j_2 + j_3 + \ldots + j_n$

- Circuit analyzed per harmonic order

Working Active Power Concept

- The harmonic power components are considered negative.

$$P_2, P_3, P_4, \ldots, P_n < 0$$

- The active power at the load terminals is equal to

$$P = \underbrace{P_1}_{\text{Load Power}} + \underbrace{P_2 + P_3 + \ldots + P_n}_{\text{HGL sends back energy}}$$

Working Active Power Concept

- Harmonic powers are referred as ***reflected active power***

$$P_r = -(P_2 + P_3 + P_4 + \ldots + P_n)$$

- Fundamental power is referred as ***working active power***

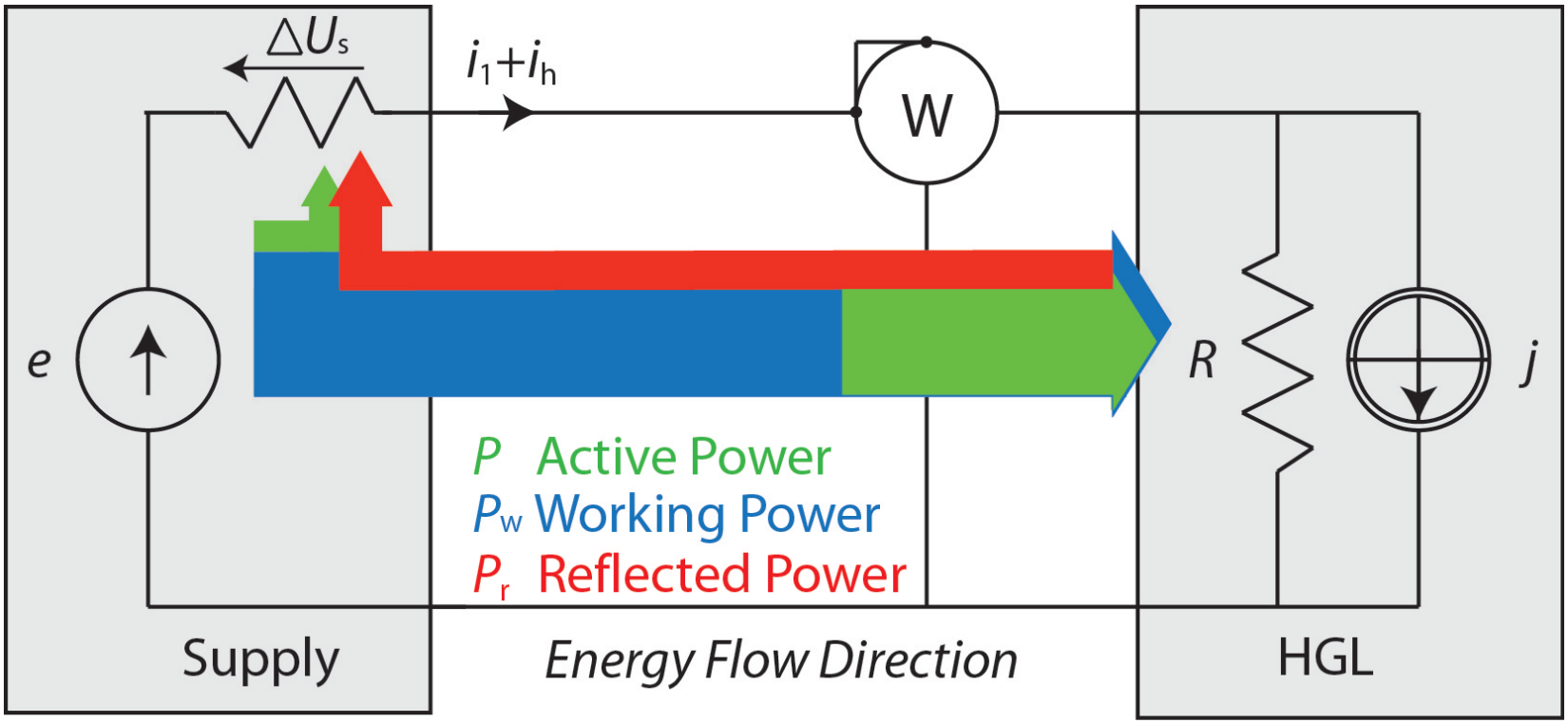
$$P = P_w - P_r$$

Active Power (Metered Power)

Working Power (Load Power)

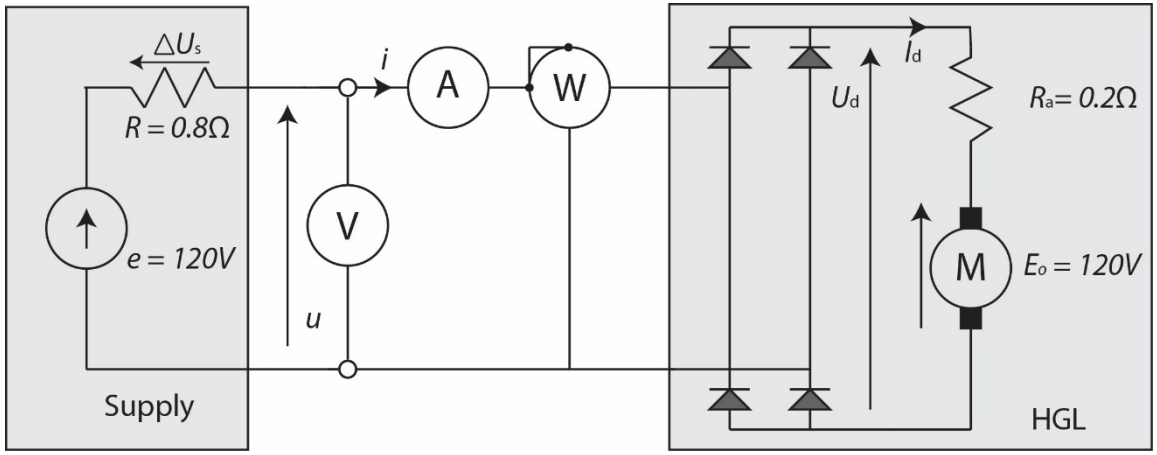
Reflected Power (Harmonic Generating)

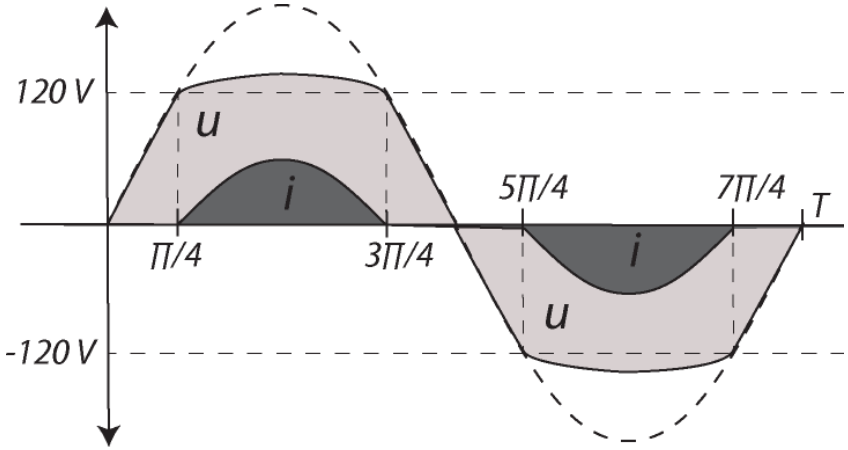
Working Active Power Concept



Working Active Power Concept

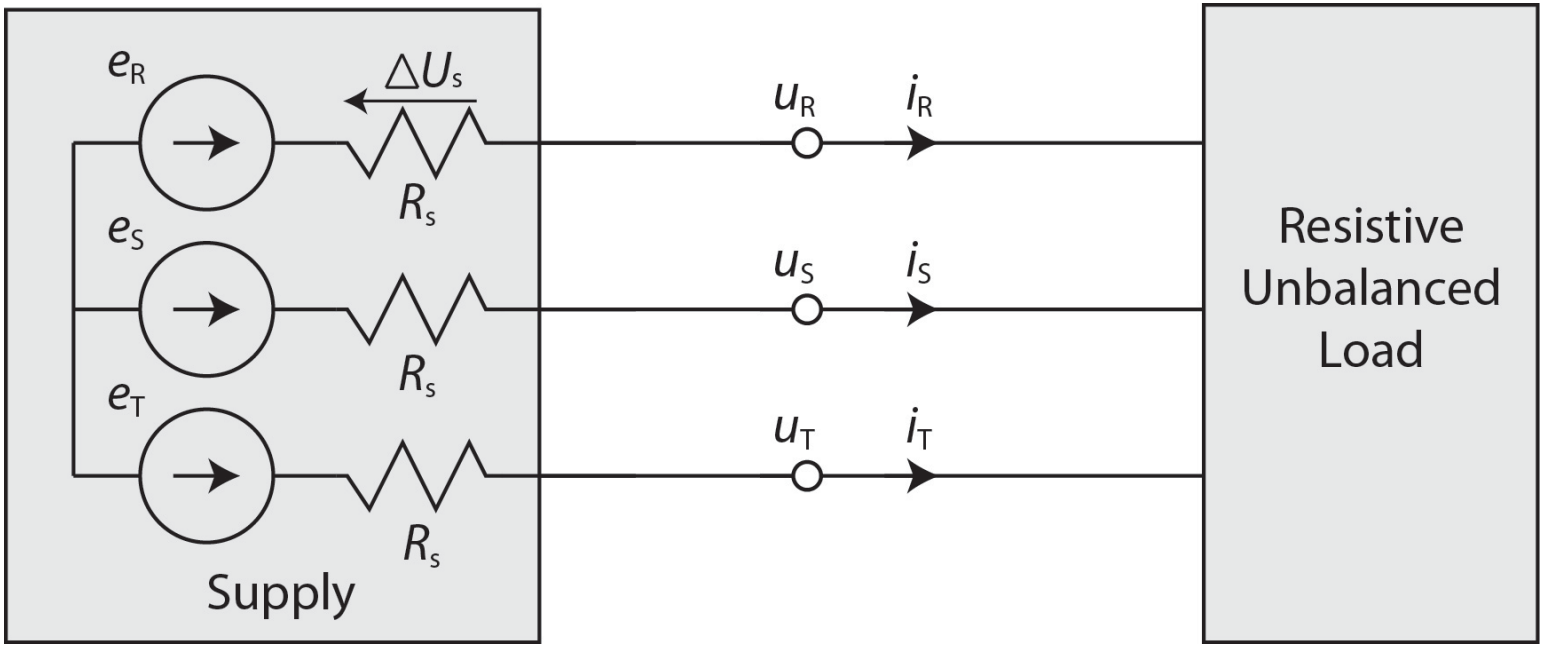
- Assumptions
  - Lossless rectifier
  - Neglect armature inductance
- Results
  - I_1 = 21.8 [A] and U_1 = 102.56 [V]
  - I_s = 25.47 [A]
  - P = 2097 [W]
  - P_w = 2235.8 [W]
  - $P_r = P_w - P$ = 138.8 [W]





Working Active Power Concept

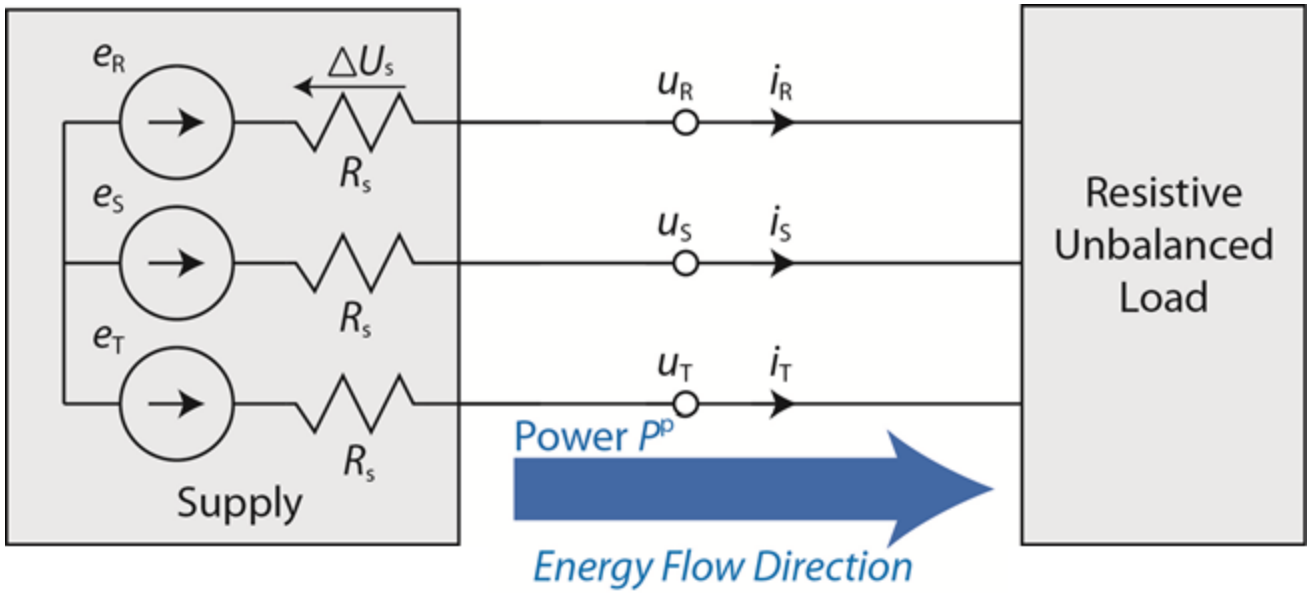
- Three phase, three wire system with a sinusoidal, symmetrical voltage supply.



Working Active Power Concept

- Positive sequence components produce the positive sequence power.

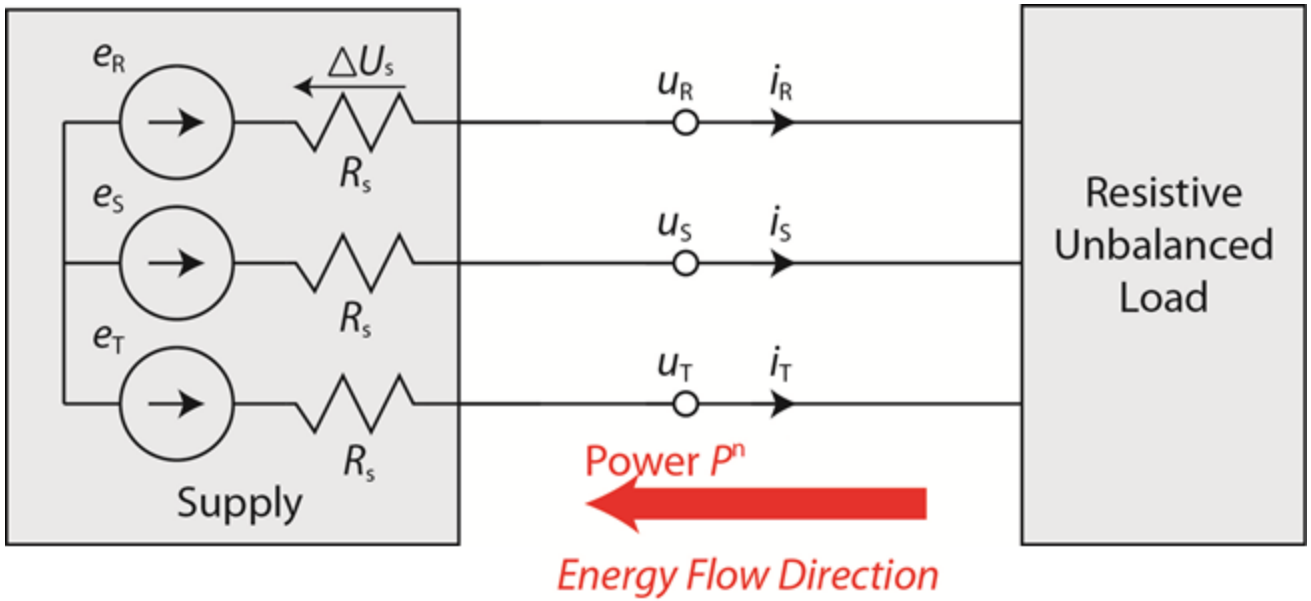
$$P^{\mathrm{p}} = 3U^{\mathrm{p}} I^{\mathrm{p}} \cos\theta^{\mathrm{p}}$$



Working Active Power Concept

- Negative sequence components produce the negative sequence power.

$$P^{n} = 3U^{n} I^{n} \cos\theta^{n}$$



Working Active Power Concept

- The active power at the load terminals consist of

$$\underbrace{P} = \underbrace{P^{\mathrm{p}}} + \underbrace{P^{\mathrm{n}}}$$

Metered Power

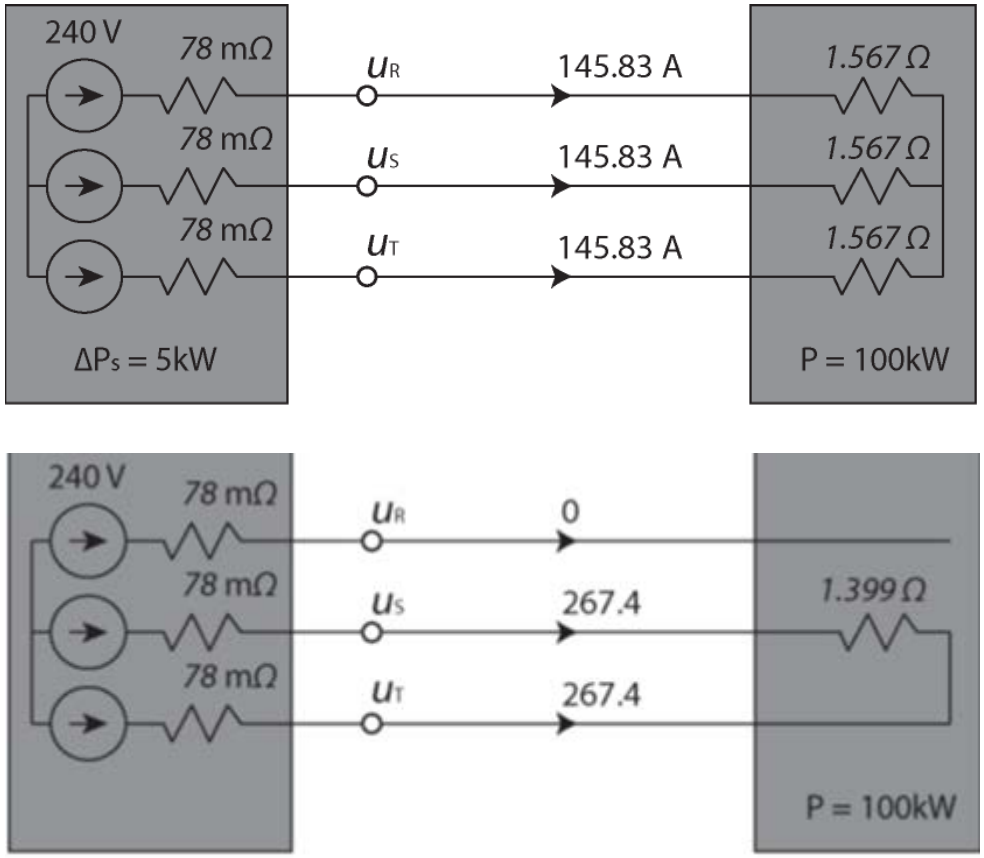
Pos. Seq. Power

Negative sequence sends energy back

$$\overbrace{P} = \overbrace{P_{\mathrm{w}}} - \overbrace{P_{\mathrm{r}}}$$

Working Active Power Concept

- Assumptions
  - Loads have equal 3Φ Power
  - Symmetrical Voltage Supply
- Results for unbalanced
  - U^P = 228 and U^N = 11.8 [V]
  - I^P = 154.4 and I^N = -154.4 [A]
  - P = 100k [W]
  - P_w = 105.6k [W]
  - $P_r = P_w - P$ = 5.6k [W]



Working Active Power Concept

- HGLs requires more power than equivalent linear time invariant (LTI) loads from generators.

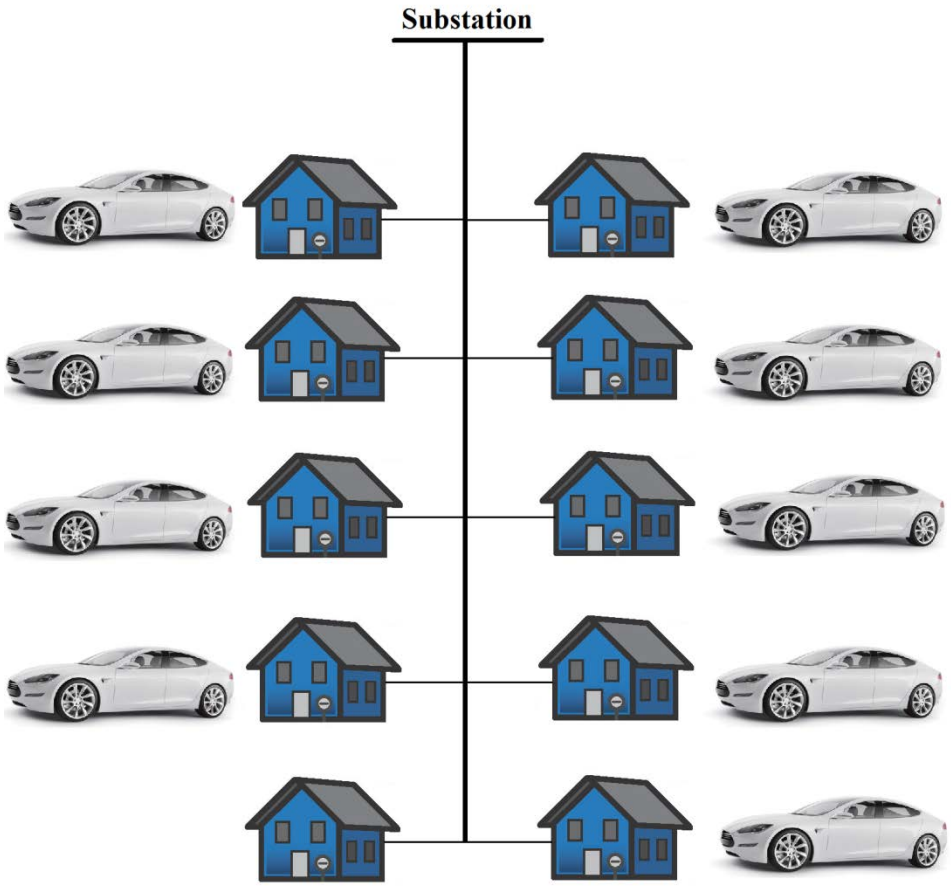
$$P_{W_{(HGL)}} > P_{W_{(LTI)}}$$

- Extra power is automatically included in energy bills.

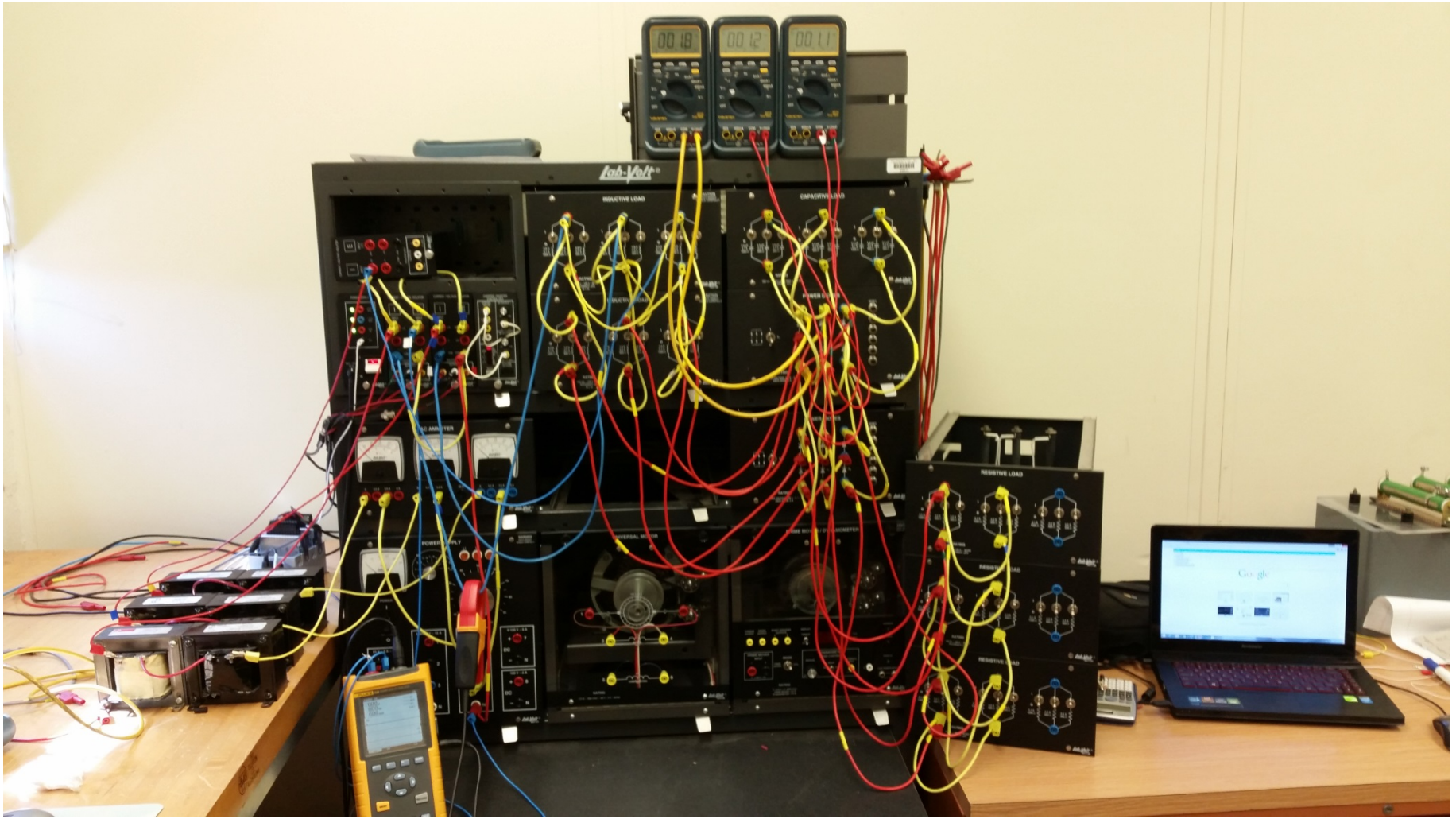
- Without pinpointing the specific customer at fault, this power loss is spread across the entire customer base.

Working Active Power Concept

- There are 10 customers
- Relatively equal loading
- Then electric vehicle (EV) is introduced.
- Your electric bill goes up.

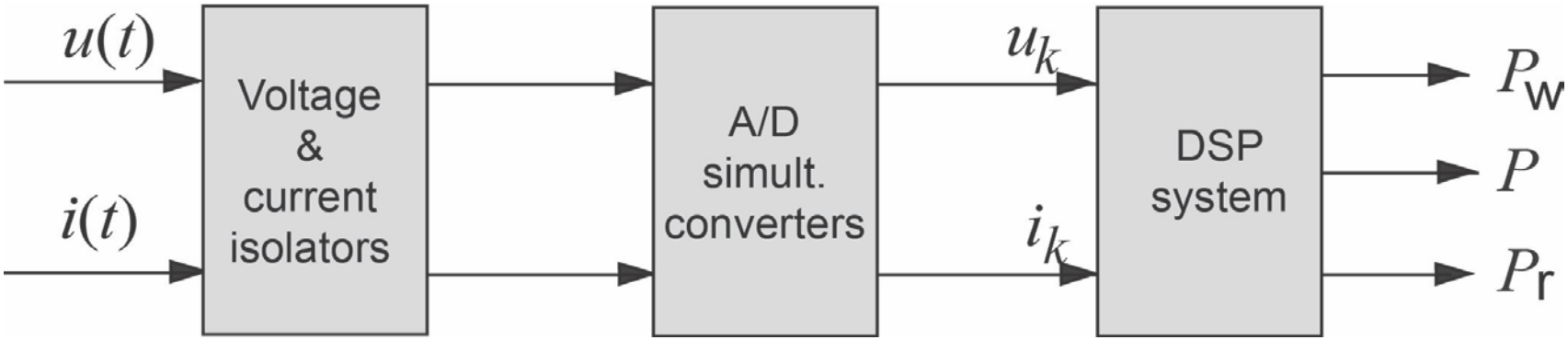


Measurement of Working Active Power



Measurement of Working Active Power

- Block diagram of the experimental setup



- A/D converters provides simultaneous 14 bit resolution.

Measurement of Working Active Power

- Accuracy was tested against Weston analog meters.

Measured Quantity	Analog meter (e_a)	DSP meter (e_d)	Combined Accuracy
Voltage	0.25%	0.12%	0.28%
Current	0.25%	0.15%	0.29%

Measurement of Working Active Power

- Experimental results for single phase

Experiment	P [W]	P_w [W]	P_w/P
Resistive Load	131.0	131.0	1.000
GE Microwave	1280	1310	1.015
10x CFL Bulbs	132.0	139.0	1.036
Xbox Console	74.0	78.0	1.039
Rectifier	178.0	185.0	1.032

Measurement of Working Active Power

- Experimental results for three phase loads

Experiment	P [kW]	P_w [kW]	P_w/P
Balanced Load	40.0	40.0	1.000
Unbalanced Load	37.3	38.0	1.019
3 Phase Rectifier	38.6	39.4	1.037

- Few percentages can add up to substantial losses over the entire power grid.

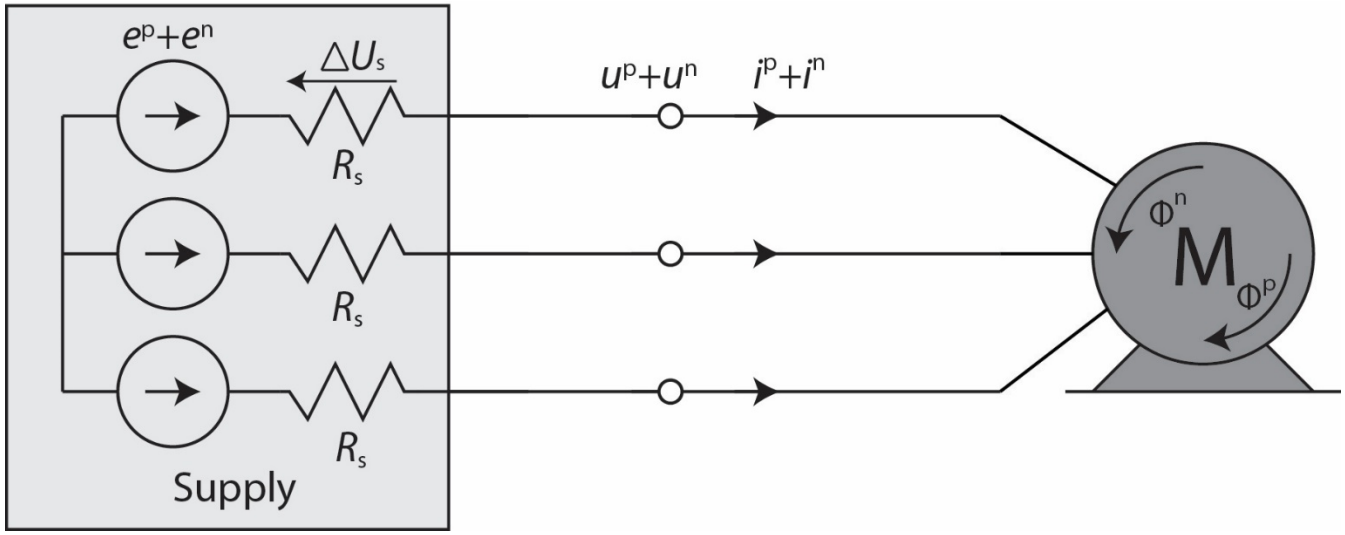
Measurement of Working Active Power

- Experimental results with varying supply impedance

S_{SC} / S_L	P [W]	P_W [W]	P_W/P
20	76.0	79.8	1.05
15	76.4	83.0	1.09
10	70.3	78.1	1.11
5	69.7	80.5	1.18
4	75.3	85.7	1.27
3	73.1	99.7	1.36
2	50.8	76.6	1.51

Detrimental Active Power Concept

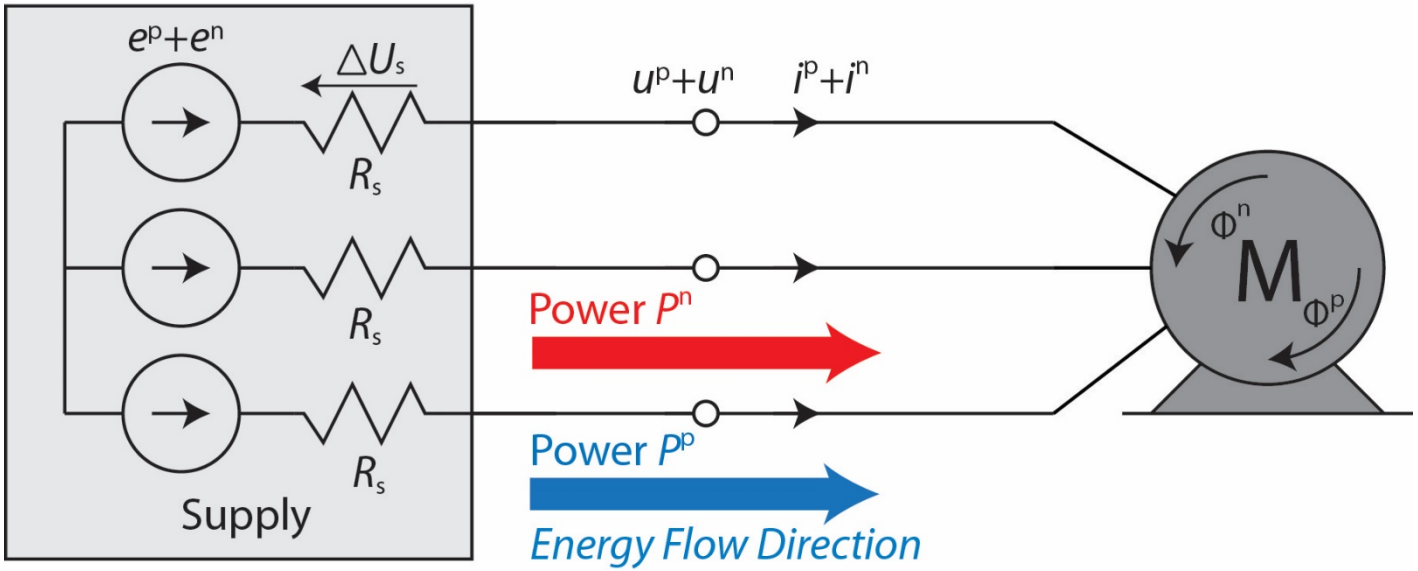
- Supply voltage with negative and positive sequence components



Detrimental Active Power Concept

- The active power measured at the motor terminals are

$$P = P^{\mathrm{p}} + P^{\mathrm{n}}$$



Detrimental Active Power Concept

- Motor current contains positive and negative sequence.

- The active power at the motor terminals consist of

$$P = P^{\mathrm{p}} + P^{\mathrm{n}}$$

Converts to output power*

Reduces motor torque
Increases heat & wear

**Minus losses of the motor*

Detrimental Active Power Concept

- P^{n} should be regarded as ***detrimental active power***

$$P_{d} = P^{n}$$

- P^{p} should be regarded as ***working active power***

$$P_{w} = P^{p}$$

Detrimental Active Power Concept

- Supply voltage harmonics harm the motor.

$$P_{\mathrm{h}} = P_2 + P_3 + P_4 + \ldots + P_n$$

- This harmonic power can be regarded as detrimental

$$P_{\mathrm{d}} = P^{\mathrm{n}} + P_{\mathrm{h}}$$

Detrimental Active Power Concept

- Refinery owns large motor ($1 million) for 25 years.
- Typical winding losses are 2~3%
- Detrimental power loss of 2% shortens lifespan ~5 yrs.

$$\frac{\$1,000,000}{25\text{yrs.}} = \$40,000 / \text{yr.}$$

$$5\text{yrs.} \times \$40,000 / \text{yr.} = \$200,000$$

- Plus detrimental power (P_d)
- Customers should only be billed for useful power (P_w).

Conclusion of Working Active Power Concept

$$P_{\mathrm{w}} = P + P_{\mathrm{r}} - P_{\mathrm{d}}$$

- ***Working active power*** is a fair way to bill customers.

$$If, P_{\mathrm{W}} - P > 0$$

- Reflected active power, customer underpays utility.

$$If, P_{\mathrm{W}} - P < 0$$

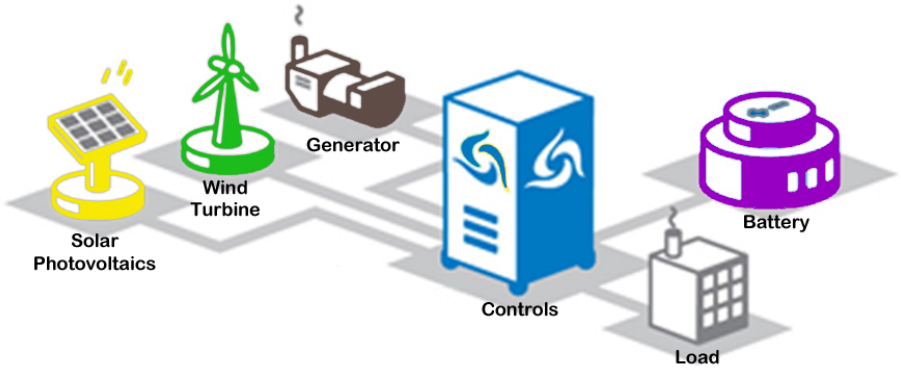
- Detrimental active power, utility overcharges customer.

Future Research Plans

- Experimentation on induction motors and power electronic loads.
- Experimentation on microgrids via advanced metering infrastructure (AMI).
- Create a realistic economic model.
- Push industry and regulatory bodies to standardize.

Future Research Plans

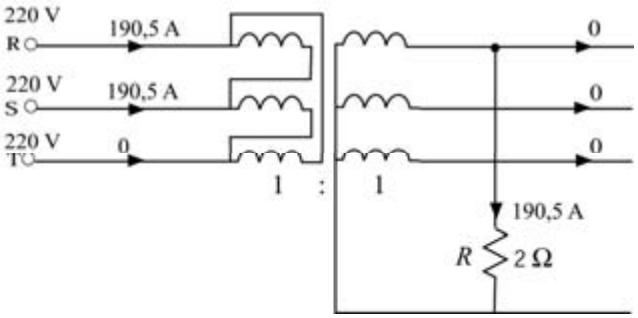
- Microgrid's power quality via AMI.



- Electric vehicle's impact on power quality

Future Research Plans

- Definition of apparent power “S.” $S = \sqrt{P^2 + Q^2} = S_G$



$$S = U_A I_A + U_B I_B + U_C I_C = S_A$$

$$S = \sqrt{U_A^2 + U_B^2 + U_C^2}\sqrt{I_A^2 + I_B^2 + I_C^2} = S_B$$

- Apparent power and power factor have different values.

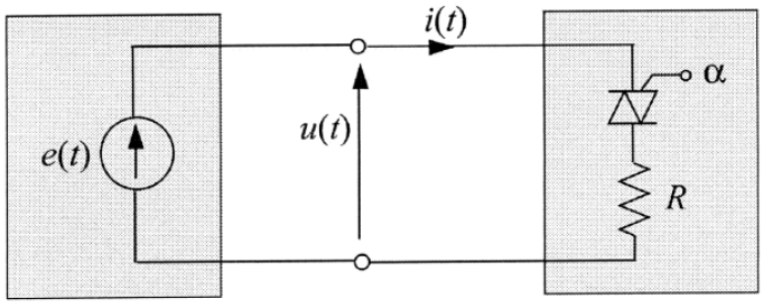
$S_G = 72.6\text{kVA}$ $\lambda_G = 1$ $P = 72.6\text{kW}$

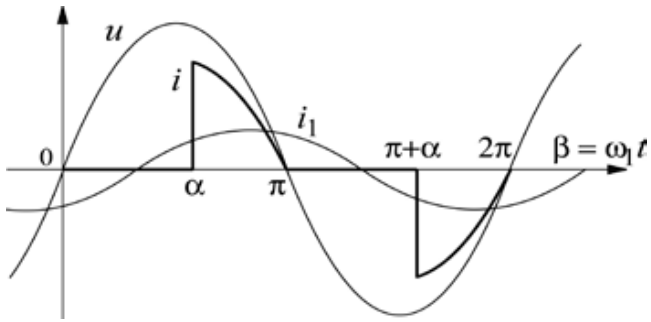
$S_A = 83.8\text{kVA}$ $\lambda_A = 0.86$

$S_B = 102.7\text{kVA}$ $\lambda_B = 0.71$

Future Research Plans

- What phenomena is responsible for reactive power "*Q*"?
- Common answer: magnetic fields and energy oscillation.





- Correct answer: phase shift

(even in non-reactive elements)

$$P = VI\cos(\theta)$$

$$Q = VI\sin(\theta)$$

Future Research Plans

- Active compensator (filter) for three phase systems.
- Injects negative current into the line.

$$i_{\text{Load}}(t) = i_{\text{a}}(t) + i_{\text{r}}(t) + i_{\text{s}}(t) + i_{\text{u}}(t)$$

$$j_{\text{Comp}}(t) = -i_{\text{r}}(t) - i_{\text{s}}(t) - i_{\text{u}}(t)$$

$$i_{\text{Supply}}(t) = i_{\text{Load}}(t) + j_{\text{Comp}}(t) = i_{\text{a}}(t)$$

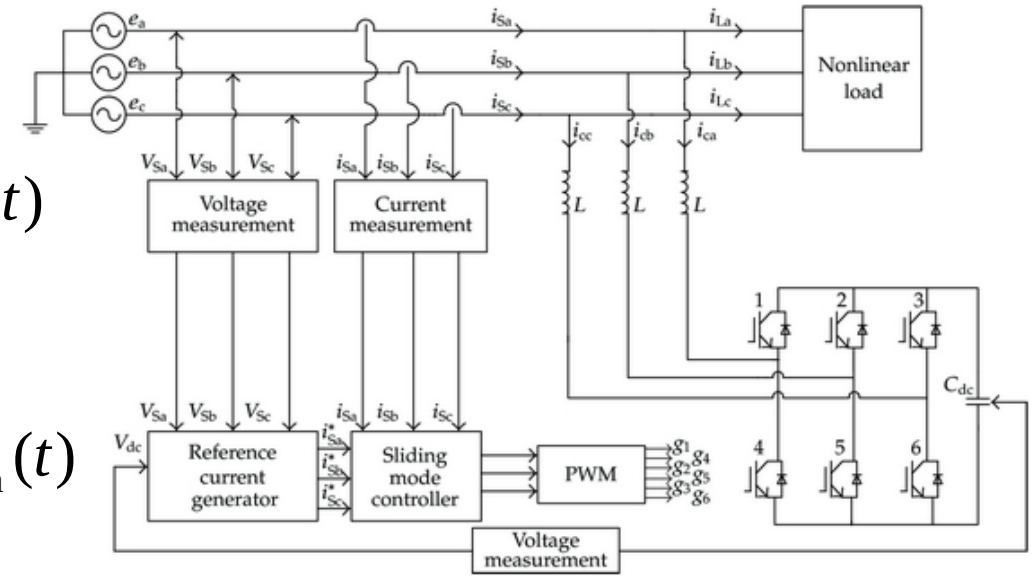


Image source: http://www.hindawi.com/journals/mpe/2012/549782/fig1/

Future Research Plans

- Target Journals
  - IEEE Transactions on Instrumentation & Measurement
  - IEEE Transactions on Power Delivery
  - IEEE Transactions on Power Electronics
  - Przegląd Elektrotechniczny (Polish journal started 1919)
- Target Conferences
  - ISNCC (Int'l School of Nonsinusodial Currents and Compensation)
  - IEEE Int'l Power & Energy Society Conference
  - IEEE Int'l Instrumentation and Measurement Conference
  - IEEE Innovative Smart Grid Technologies Conference

Future Research Plans

- Major Federal Agencies
  - Department of Defense (DoD): Young Investigator Program
  - Department of Energy (DoE): Early Career Research Program
  - National Science Foundation (NSF): Faculty Early Career Development
- Other Agencies
  - Nuclear Regulatory Commission (NRC)
  - Smart Grid Investment Grant (SGIG)
  - Private Industries (SEL, utilities and local consulting firms)

Future Research Plans

- Power protection laboratory
  - SEL (Schweitzer) Microprocessor based relays
  - Westinghouse mechanical relays
  - Omicron relay test sets
  - Beckwith Electric Co. relays

Future Research Plans

- Power electronics laboratory
  - LabVolt based laboratory center
  - Can also be used as electrical machine lab.

- Power quality & harmonics laboratory
  - LabVolt based laboratory center
  - Individual components are custom built

Thank You