**EE 5200 - Lecture 1** Tuesday Aug 26, 2003

**Topics for Today**:

- Introductions
  - 6 students on campus
  - 10 students at “remote” sites, including:
    - B&V (Ann Arbor, plus?), ITC, Minn Power (Duluth), more.
- Startup
  - Web page: http://www.ee.mtu.edu/faculty/bamork/ee5200/
  - Book, references
  - Software - Matlab, ASPEN, ATP
  - EE5200-L@mtu.edu (participation “strongly” encouraged)
  - Daily lecture notes scanned and .pdf file archived
  - Exercises usually sent out via e-mail, 1-2 each week.
  - Grading:

| | | |
|---|---|---|
| ≥ 90 | A | 4.0 |
| ≥ 95 | AB | 3.5 |
| ≥ 80 | B | 3.0 |

- Quick Review of circuit basics:
  - Active vs. passive sign convention
  - Dual-subscript notation, single-subscript (implied reference)
  - Closure of subscripts in mesh equation
  - Euler's Identity - basis for phasor analysis! See handout.
  - Drawing phasor diagrams, arrowheads
  - Three-phase, "open" vs. "closed" voltage phasor diagrams
  - Errata in text book - Figs. 1.16, 1.17.

- Study Chapters 1 and 2 for Thursday

  Do Practices Exercises at end of Chapter!

# EE 5200
# Advanced Methods in Power Systems Analysis

Fall Semester 2003
EERC 216 - T,R 9:35-10:50 am

**Dr. Bruce Mork | Office Hours**

Course Syllabus | Pre-Req Material | Text & References | Useful Web Links | Grades to Date

Schedule and Coverage (Subject to Change Depending on Learning Needs of Students):

| **Week - Coverage *(Read Material Before Class)*** | **Lecture Date** | **Material Coverage** |
|---|---|---|
| 1 - Ch. 1 | L1 - Aug 26th<br>L2 - Aug 28th | Three-Phase phasor analysis, good circuit analysis habits, Errata in Ch.1<br>Pre-req exercises - rate your foundational skills |
| 2 - Ch. 1,2 | L3 - Sep 2nd<br>L4 - Sep 4th | Proper Use of "Closed" Voltage Phasor Diagrams for Graphical Analysis<br>Three-Phase network analysis, transformer basics |
| 3 - Ch. 2<br>L6-Prep | L5 - Sep 9th<br>L6 - Sep 11th | Transformer connections (Delta, Y, auto, zig-zag), core structure<br>IEEE/IEC Phase Shifts, 3-Winding Transformers, LTCs, PSs, etc. |
| 4 - Ch.2,4,5 | L7 - Sep 16th<br>L8 - Sep 18th | Transmission Lines, Line Constants |
| 5 - Ch. 4,5,6 | L9 - Sep 23th<br>L10 - Sep 25th | Transmission Lines in system calculations |
| 6 - Ch. 6 | L11 - Sep 30th<br>L12 - Oct 2nd | No Lecture - Dr. Mork is attending IPST , (coauthor of 2 papers)<br>Transmission Lines - compensation, traveling waves, etc. |
| 7 - Ch. 3 | L13 - Oct 7th<br>L14 - Oct 9th | Synchronous Machines - salient, non-salient, d-q-0<br>Test 1 (Midterm), takehome, approx date |
| 8 - Ch. 3,7 | L15 - Oct 14th<br>L16 - Oct 16th | Synchronous Machines<br>Admittance Formulations |
| 9 - Ch. 7,8 | L17 - Oct 21st<br>L18 - Oct 23rd | Network Calculations with [Y] and [Z] |

| | | |
|---|---|---|
| 10 - Ch. 9,14 NR Details | L19 - Oct 28th<br>L20 - Oct 30th | Loadflow, contingencies |
| 11 - Ch. 10,11,12 | L21 - Nov 4th<br>L22 - Nov 6th | Review of Fault Calculations - balanced 3-phase<br>Sequence Networks, unsymmetrical faults |
| 12 - Ch. 13 Gen/Grid Operation Intro to Dispatch | L23 - Nov 11th<br>L24 - Nov 12th | Economic Dispatch - lossless, lossy (B-coefficients)<br>Frequency control, droop, AGC, unit commitment |
| 13 - Ch. 16 System Stability | L25 - Nov 18th<br>L26 - Nov 20th | System Stability, Swing Equation, Out-of-Step problem<br>Considerations for Distributed Generation |
| Fall Break | Nov 22nd - 30th | Thanksgiving Recess - Enjoy. Come back refreshed and ready. |
| 14 - Ch. 6 Transients | L27 - Dec 2nd<br>L28 - Dec 4th | Intro to Transients<br>Test 2, takehome, approx date |
| 15 - Glover (Ch.12) | L29 - Dec 9th<br>L30 - Dec 11th<br>Makeup - Dec 12th | Transient Simulation - Quick Overview of RL, RC, RLC<br>RLC Transients using $Z_0$ , Cap Bank Switching (time permitting)<br>Makeup/Wrapup |
| Finals Week | Dec 16th, 8:30-11am | Presentation of Term Project |

## Course Description and Learning Goals:

EE 5200 is the lead-off graduate course in Electrical Power Systems. The main goal of the course is to quickly review and then advance the student's existing knowledge of power systems analysis. Emphasis is on foundation theories, advanced analysis methods, developing conceptual insights, and gaining experience with applicable software simulation and analysis packages. Although today's software is quite advanced, in order to properly apply the software and interpret the results we must have both a good analytical understanding and a practical/conceptual "big picture" understanding of how the system behaves and of all of the interactions between the equipment and components that make up the system. Power systems consist of hundreds or thousands of "buses" or nodes, and the network equations dealt with may have thousands of variables. New operational complexities imposed by deregulation of the power industry, installation of distributed generation, and application of FACTS and other state-of-the-art equipment has renewed the need for sound analysis, simulation, and design skills. This course provides the foundation for the remaining power area graduate courses. Computer simulation methods, formerly combined with this course, are now taught in EE5240 .

Topics typically covered in this 15-week course and the software used are as follows (textbook, instructor, and priorities may alter coverage):

- Good habits in circuit analysis: double subscript notation, active/passive sign convention, visualization via phasor diagrams
- Three phase circuit calculations: source, transformers, transformer design/application,

and loads - wye, delta, & zig-zag.

- Synchronous machines
- Transmission lines and cables.
- Advanced System Analysis, Operation, Design:
  - Load Flow, Planning Studies, System Operation (Aspen) Load Flow, Planning Studies, System Operation (Aspen)
  - State Estimation, System Operation, Frequency Control (MatLab, Matlab Power Block Set)
  - Symmetrical Components and Short-Circuit Analysis (Aspen)
  - System-Level Stability Analysis (MatLab, T2000, PSS/E?)
  - Introduction to Transient Analysis (ATP, MatLab)

## Prerequisite Material, Useful References

- Euler's Identity - The foundation of phasor analysis, hyperbolic functions (used for long transmission lines)
- Transformers 101 - Everything you wanted (or need to now) know about transformers but were afraid to ask...

## Course Text and other Useful References:

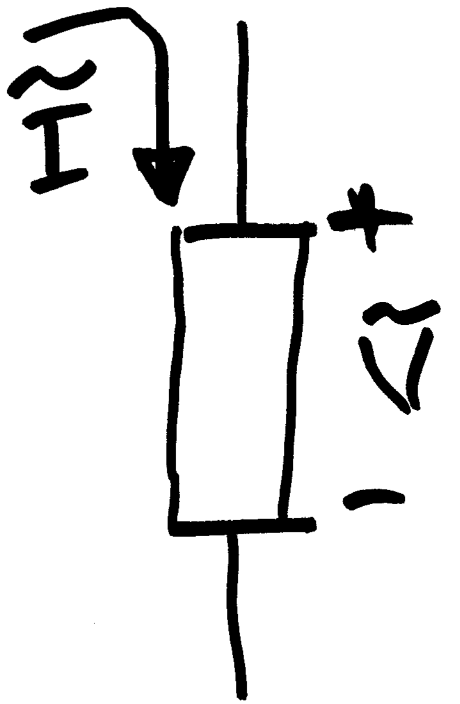
- **Course Text (REQUIRED)**: *Power Systems Analysis*, J.J. Grainger, W.D. Stevenson, McGraw-Hill, © 1994 . ISBN 0-07-061293-5.
- *Power System Analysis and Design*, J.D. Glover & M. Sarma, 3rd Ed, Brooks/Cole Publishing, © 2002. Used in EE4221/4222, this is an excellent introductino and reference for power system analysis basics, and for understanding overall power system behavior.
- Protective Relaying Principles and Applications, J. Lewis Blackburn, 2nd Ed, Marcel Dekker, ©1998.
- Power System Stability and Control (Stability Swings and Out-of-Step Relaying: Sections 13.5 & 13.6), P. Kundur, McGraw-Hill/EPRI, © 1994.
- Symmetrical Components for Power Systems Engineering, J.L. Blackburn, Marcel Dekker, © 1993.

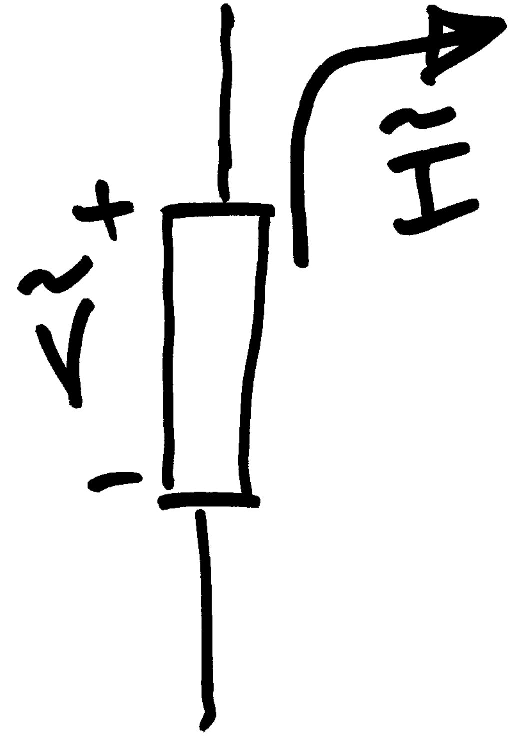
## Useful Web links and other resources:

- Lots of Interesting Photos, or "What those squiggles on the blackboard really represent."
  - Six Consumers Energy Substations - A plethora of high voltage substation equipment, relays, controls.
  - Hoover Dam - One of the world's first truly huge hydro stations, built in 1930s and still quite amazing (during my visit, Jan 2003).
  - Tiny vs. Huge Hydros - Contrast of our local Victoria Hydro (12.5 MW) with Hoover Dam (2.1 GW) .
  - Storm Damage of 345-kV Transmission Lines - four lines out of Powerton Station, Exelon, May 2003.
  - Transformer Explosion Caught on Video - Details unknown, rumors say it is alongside a golf course, somewhere in Florida.
- Example System Data Cases
  - IEEE Loadflow and Stability Cases and Standard Data File Formats (CDF, PTI, PECO) - Univ of Washington

  - Example 17-Bus New Zealand System - from Arillaga text
  - 15 Loadflow Cases (CDF, EUROSTAG, BPA) - Tsinghua University
- Useful References, Journals, Publications
  - Research Journals and Transactions
    - IEEE Transactions on Power Systems
    - IEEE Transactions on Power Delivery
    - IEEE Transactions on Industrical Applications
    - IEEE Transactions on Power Electronics
    - IEE Proceedings - Generation, Transmission and Distribution
    - IEE Proceedings - Electric Power Applications
    - European Transactions on Electric Power
  - Magazines on Computer Methods and Engineering Applications
    - IEEE Computer Applications in Power (CAPS)
    - IEEE Industry Applications Magazine
    - IEEE Power Engineering Review
  - Engineering Applications Magazines
    - Transmission & Distribution World - "T&D Magazine"
    - Power Quality Magazine
    - Power Technology International
    - Power Engineering International
- Public Domain or Royalty-Free Software
  - ATP - Alternative Transients Program (Royalty Free, Licensing Required)
  - PCFLOW, PCFLOWH - Load Flow and Harmonic Load Flow, Univ of Texas Austin, Prof. Mack Grady (Public Domain)
  - Educational Software - List of Links Provided by IEEE Power Engineering Education Committee
- Available Commercial Software
  - Aspen - Loadflow, Short-Circuit, Relay Coordination (Academic Version Available)
  - MatLab with Simulink and Power System Toolbox - Full spectrum of power system analysis and controls (Academic Versions Available)
  - PSS/E - Loadflow, Short-Circuit, Dynamic Stability (Academic Pricing Available)
  - CAPE - Loadflow, Short-Circuit, and Relay Coordination (Academic Pricing Available)
  - V-Flow, V-Net, V-Pro, V-Harm, V-Cap, etc . - Power Verdict Series: Suite of programs by Cooper Power Systems
  - ETAP PowerStation - Full suite for power system analysis and design
  - Transmission 2000 - Loadflow, Short Circuit, Dynamic Stability, and Relay Coordination (Academic Version Available)
  - EDSA - Loadflow, Short Circuit, Relaying, AC and DC systems (mostly industrial, auto, shipboard)

# SIGN CONVENTION




PASSIVE

"Motor Convention"

"Load Convention"

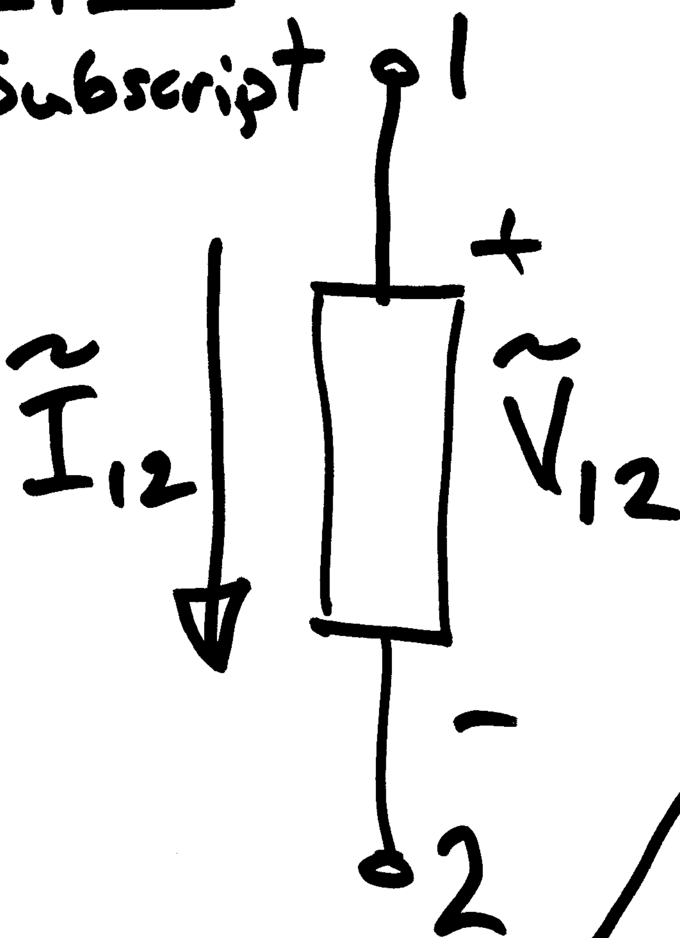
ACTIVE

"Generator Convention"

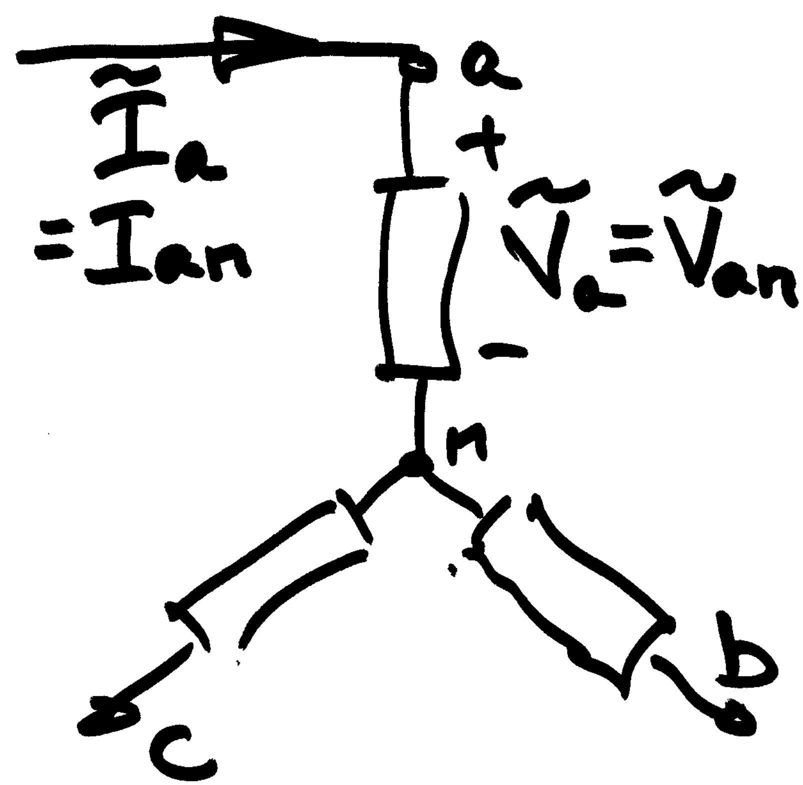
"Source Convention"

# Subscripts

Double-Subscript

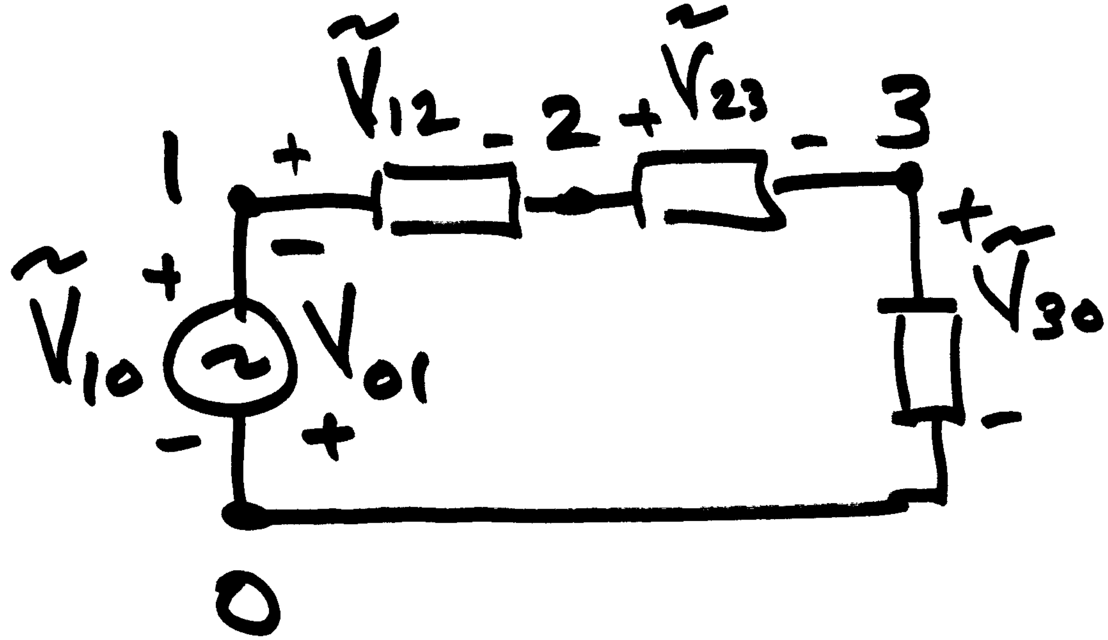



Always use voltage drops! (Voltage rises seen in old texts).




Single subscript notation: Second subscript is assumed.

## Closure in subscripts:




KVL: $\Sigma V_s = 0$ (Sum of V drops!)

starting at node 0:

$$-\tilde{V}_{10} + \tilde{V}_{12} + \tilde{V}_{23} + V_{30} = 0$$

$$\tilde{V}_{10} = \tilde{V}_{12} + \tilde{V}_{23} + \tilde{V}_{30}$$

or:

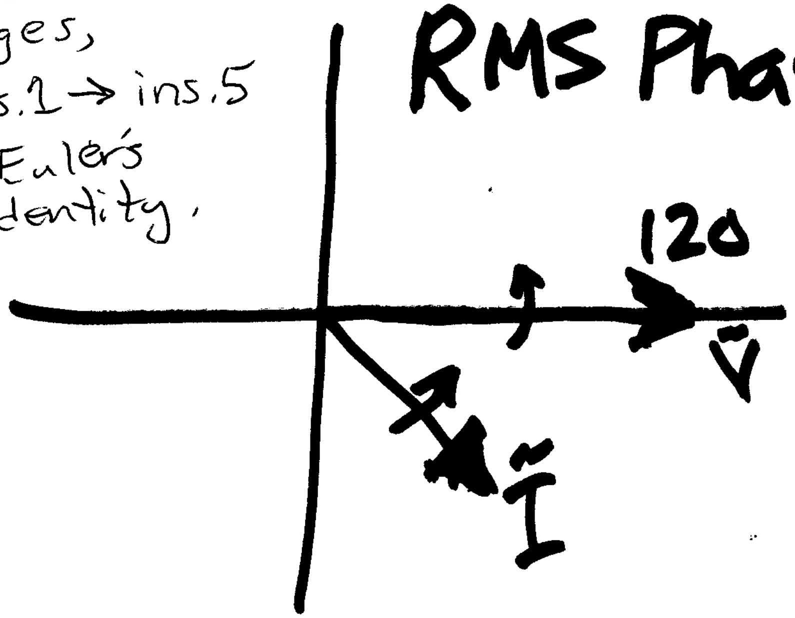
$$0 = V_{01} + V_{12} + V_{23} + V_{30}$$

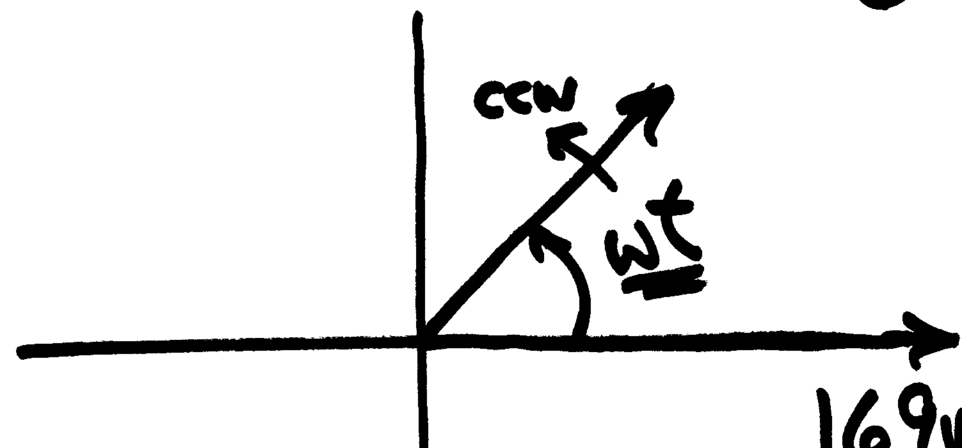
# Phasor Analysis (use "cos reference")



see next 5 pages, ins.1 → ins.5 for Euler's Identity.

RMS Phasors



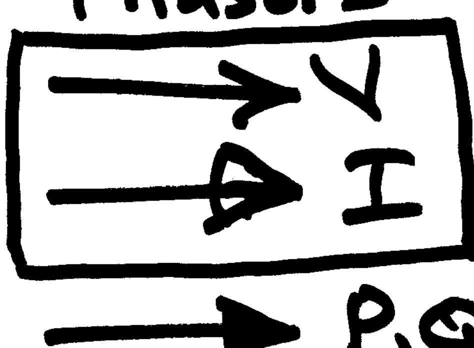

Peak, time-domain phasors.

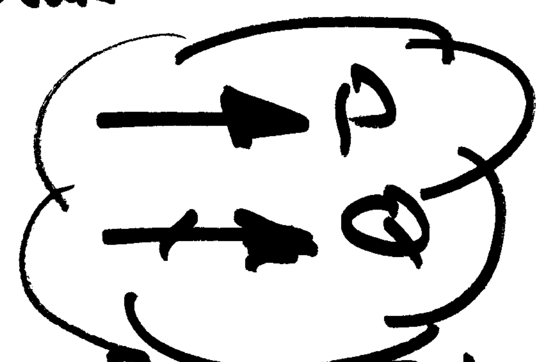
$\tilde{V}$ = ~~120 cos (ωt)~~ ?

$v(t) = \underbrace{120\sqrt{2}}_{V_{peak}} \cos \omega t$

$\underbrace{120}_{V_{RMS}} \angle 0° \; V_{RMS}$

Phasors

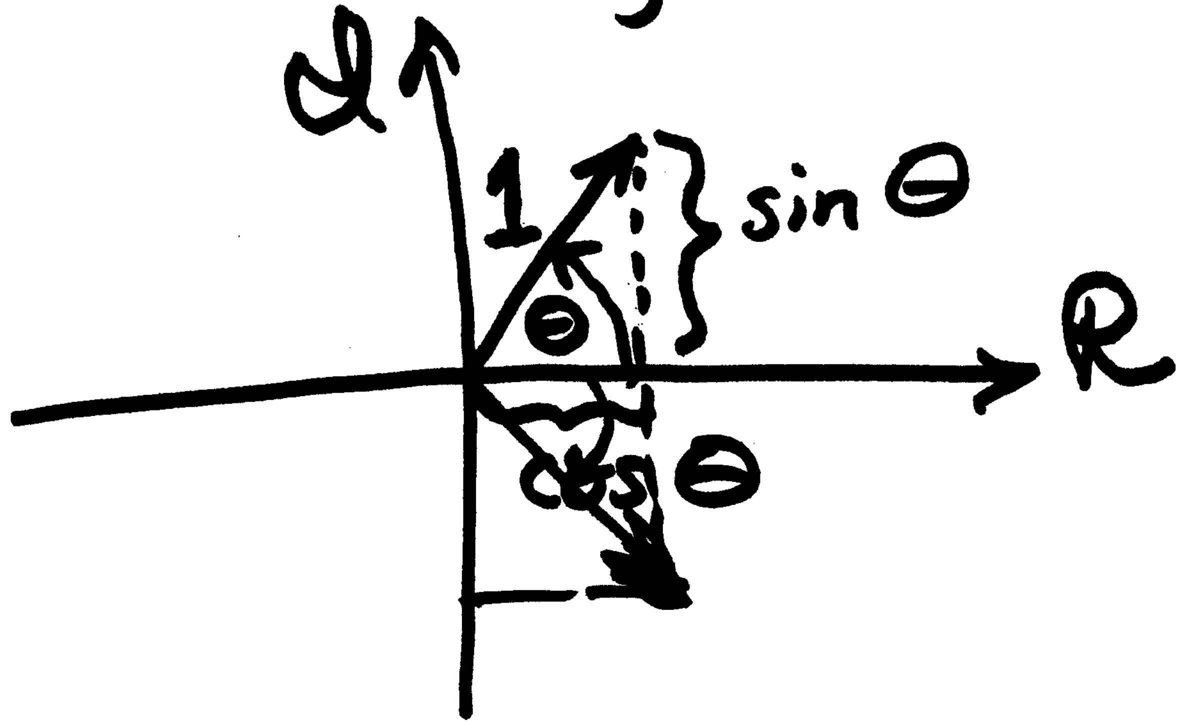


# Euler's Identity



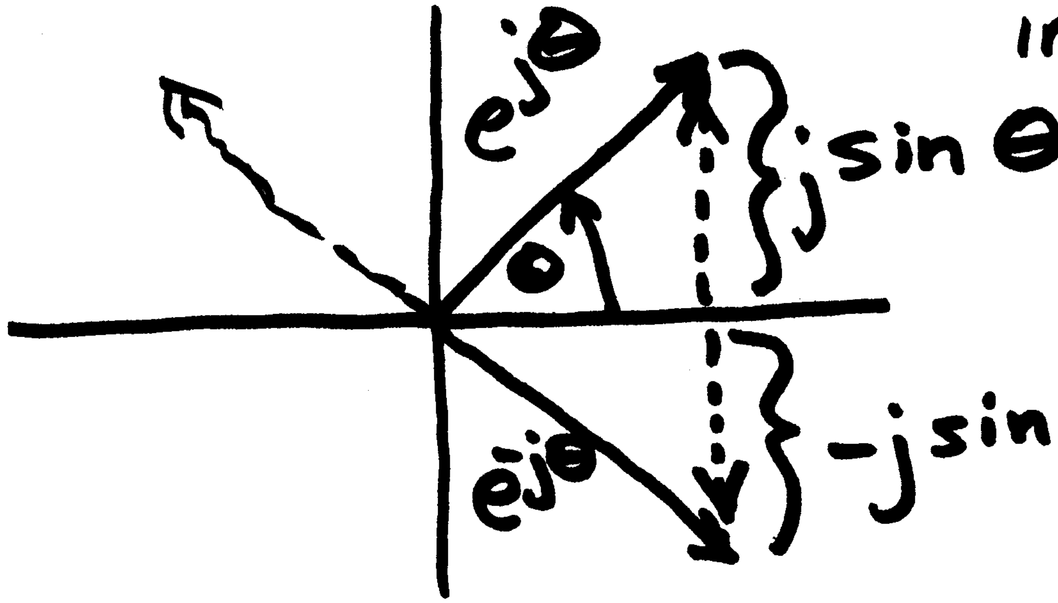
$e^{j\theta}$ = Unit vector at an angle $\theta$.




$$\therefore\ e^{j\theta} = \cos\theta + j\sin\theta \quad (1)$$

$$e^{-j\theta} = \cos\theta - j\sin\theta \quad (2)$$

ins. 2




If we <u>add</u> the 2 eqns

(1) + (2)

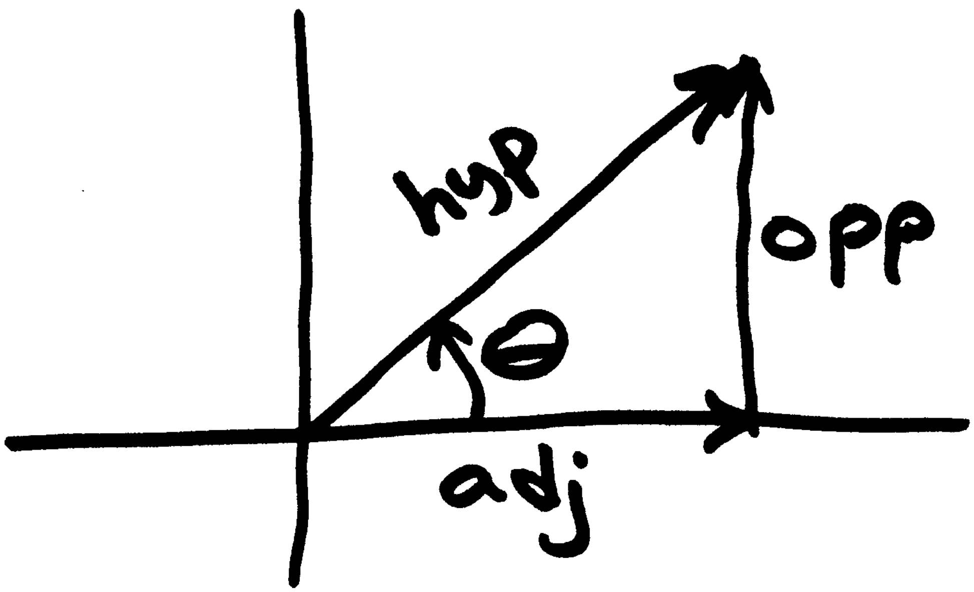
$$e^{j\theta} + e^{-j\theta} = 2\cos\theta$$

$$\Rightarrow \boxed{\cos\theta = \frac{e^{j\theta} + e^{-j\theta}}{2}}$$

Subtracting,

$$\boxed{\sin\theta = \frac{e^{j\theta} - e^{-j\theta}}{j2}}$$

Referring back to figure 3 on preceding page, this matches with the basic trig you learned:




$$\sin\theta = \frac{opp}{hyp} \qquad \cos\theta = \frac{adj}{hyp}$$

$$\tan = \frac{opp}{adj} = \frac{\sin\theta}{\cos\theta}$$

ins. 4

Hyperbolic Functions are similar exponential functions, where the exponent of e is, in general, a complex number, $z = a + jb$

$$\sinh(z) = \frac{e^{z} - e^{-z}}{2}$$

$$= \frac{e^{a}e^{jb} - e^{-a}e^{-jb}}{2}$$

$$\cosh(z) = \frac{e^{z} + e^{-z}}{2}$$

$$= \frac{e^{a}e^{jb} + e^{-a}e^{-jb}}{2}$$

Engineering Mathematics Handbook. ins. 5
© 1979 – Tuma, McGraw-Hill.



## (1) Definitions

A hyperbolic function is a combination of $e^x$ and $e^{-x}$ and is introduced as follows:

Hyperbolic sine of $x = \sinh x = \dfrac{e^x - e^{-x}}{2}$

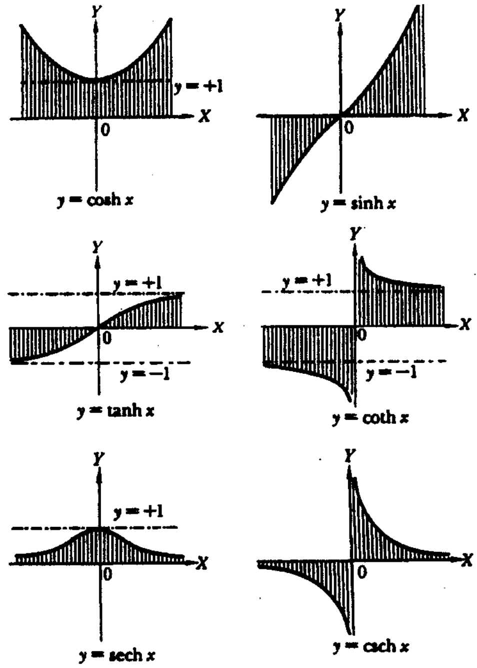
Hyperbolic cosine of $x = \cosh x = \dfrac{e^x + e^{-x}}{2}$

Hyperbolic tangent of $x = \tanh x = \dfrac{e^x - e^{-x}}{e^x + e^{-x}}$

Hyperbolic cotangent of $x = \coth x = \dfrac{e^x + e^{-x}}{e^x - e^{-x}}$

Hyperbolic secant of $x = \operatorname{sech} x = \dfrac{2}{e^x + e^{-x}}$

Hyperbolic cosecant of $x = \operatorname{csch} x = \dfrac{2}{e^x - e^{-x}}$




Examples for real values of Z:

[redacted]

$Z = a + jb$

$Z = a + X$

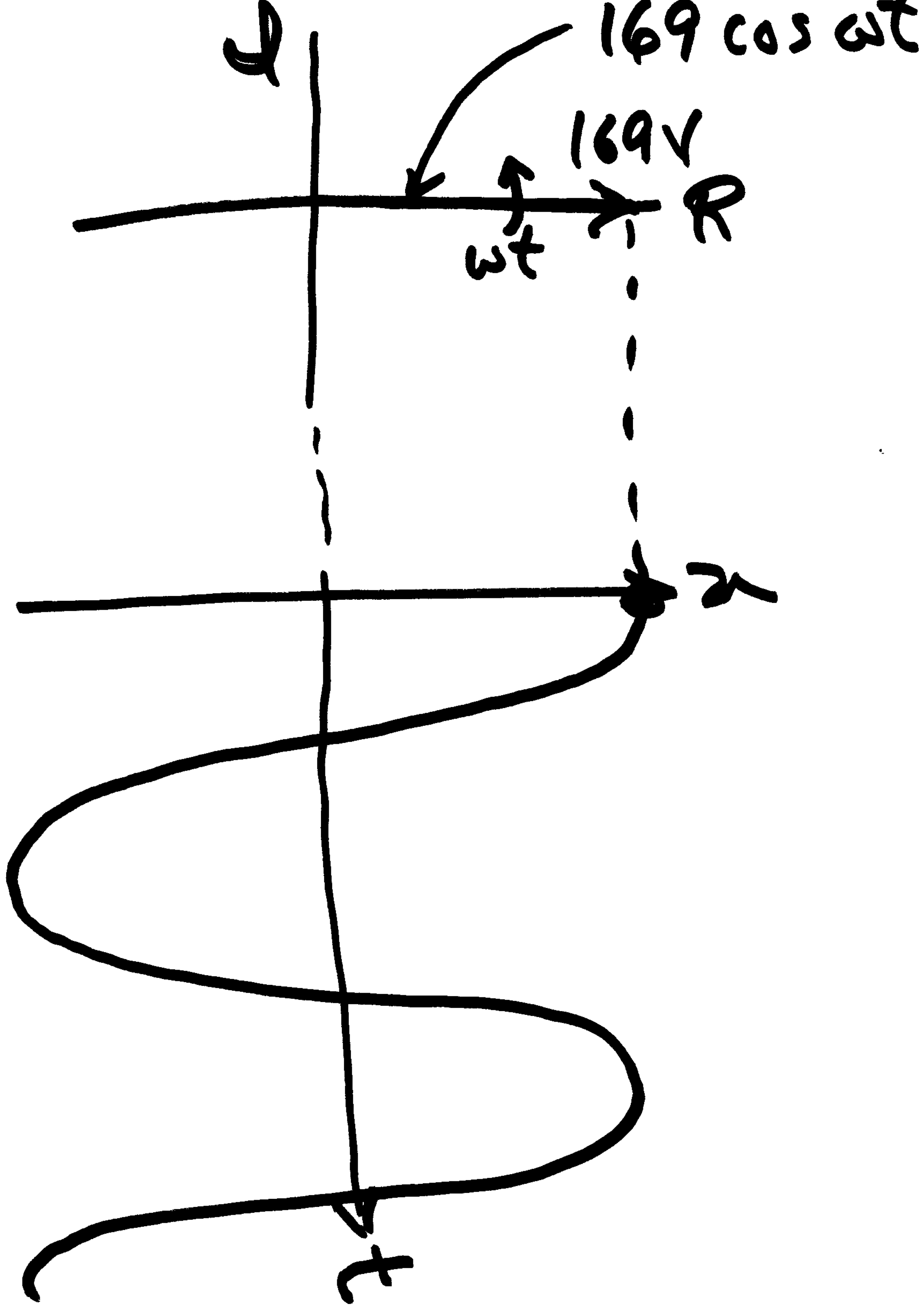
## (2) Relationships

| | | |
|---|---|---|
| $\cosh^2 x - \sinh^2 x = 1$ | $\tanh x = \dfrac{\sinh x}{\cosh x}$ | $\operatorname{sech} x \cosh x = 1$ |
| $\tanh^2 x + \operatorname{sech}^2 x = 1$ | $\coth x = \dfrac{\cosh x}{\sinh x}$ | $\operatorname{csch} x \sinh x = 1$ |
| $\coth^2 x - \operatorname{csch}^2 x = 1$ | | $\tanh x \coth x = 1$ |
| $\sinh(-x) = -\sinh x$ | $\tanh(-x) = -\tanh x$ | $\cosh(-x) = \cosh x$ |
| $\operatorname{sech}(-x) = \operatorname{sech} x$ | $\coth(-x) = -\coth x$ | $\operatorname{csch}(-x) = -\operatorname{csch} x$ |

## (3) Limit Values

| $x$ | $\sinh x$ | $\cosh x$ | $\tanh x$ | $\coth x$ | $\operatorname{sech} x$ | $\operatorname{csch} x$ |
|---|---|---|---|---|---|---|
| $-\infty$ | $-\infty$ | $+\infty$ | $-1$ | $-1$ | 0 | 0 |
| $-1$ | $-1.1752$ | $+1.5431$ | $-0.7616$ | $-1.3130$ | $+0.6480$ | $-0.8509$ |
| 0 | 0 | $+1$ | 0 | $\mp\infty$ | $+1$ | $\mp\infty$ |
| $+1$ | $+1.1752$ | $+1.5431$ | $+0.7616$ | $+1.3130$ | $+0.6480$ | $+0.8509$ |
| $+\infty$ | $+\infty$ | $+\infty$ | $+1$ | $+1$ | 0 | 0 |

7



# Three Phase Phasor Analysis



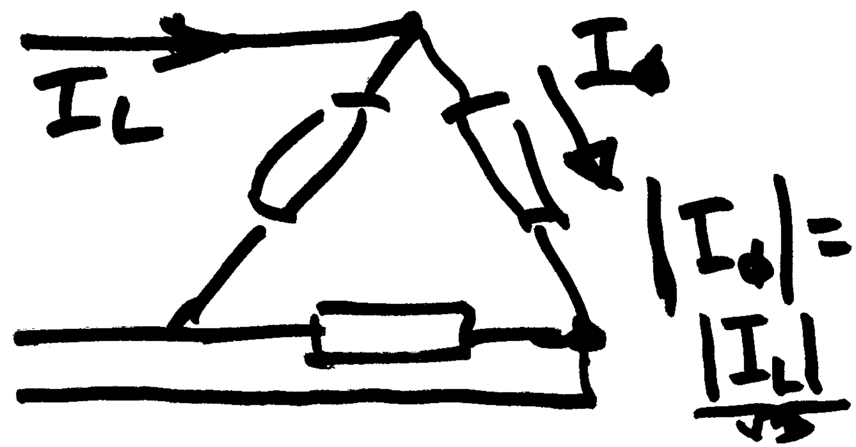
- Must deal with all V's & I's

**Don't!**

- Say "Line Voltage"
- Say "phase voltage" unless you also say whether it is <u>Δ or Y</u>.

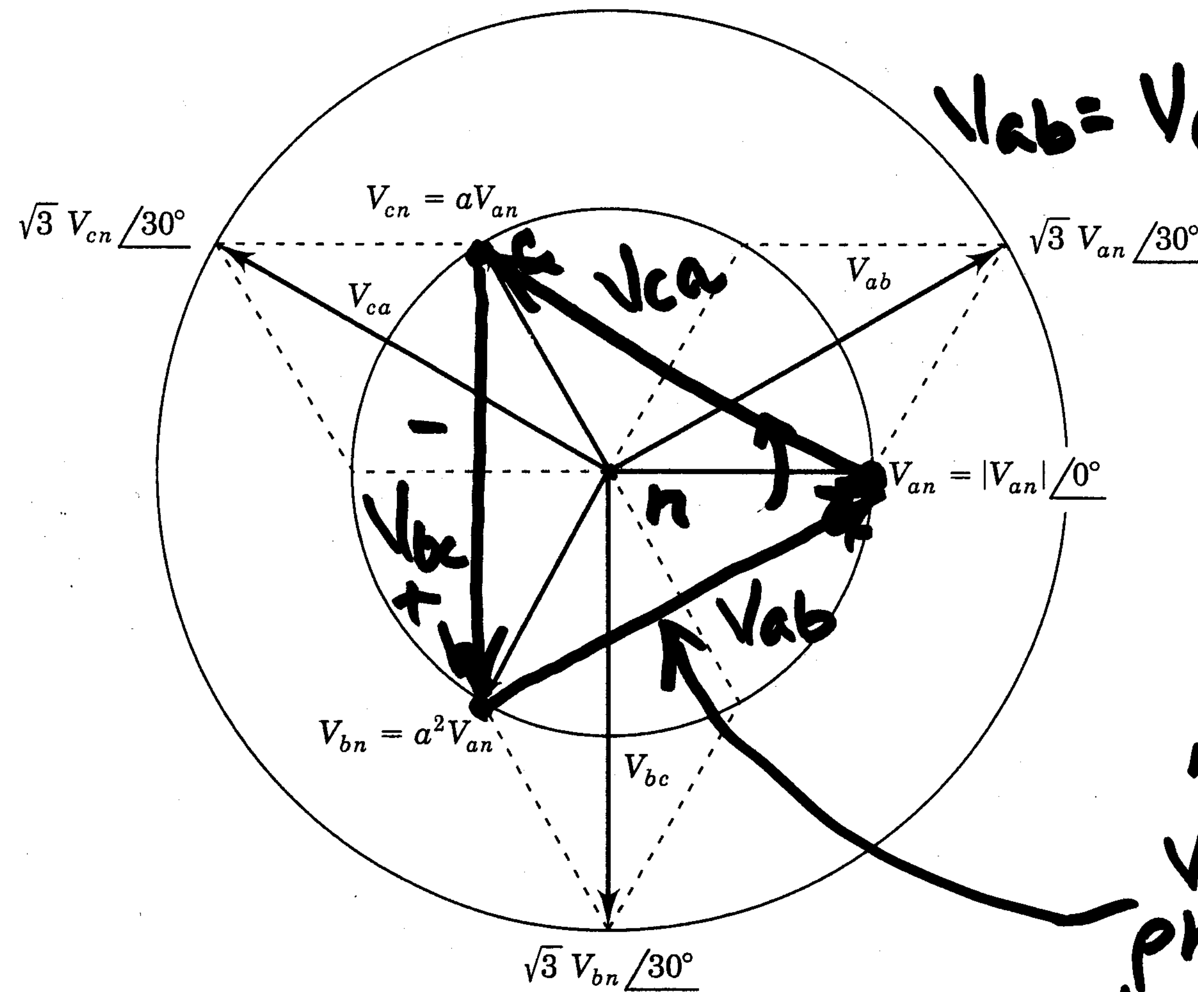
**ALWAYS!**

- Say $V_{LN}$ or $V_{LL}$
- say $I_{LINE}$ ($= I_\phi$ in Y)

9

$V_{ab} = V_{an} - V_{bn}$

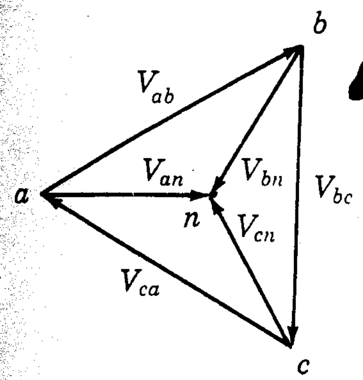



"closed voltage phasor diagram"

**FIGURE 1.15**
Phasor diagram of line-to-line voltages in relation to line-to-neutral voltages in a balanced three-phase circuit.

("open" voltage phasor diagram)

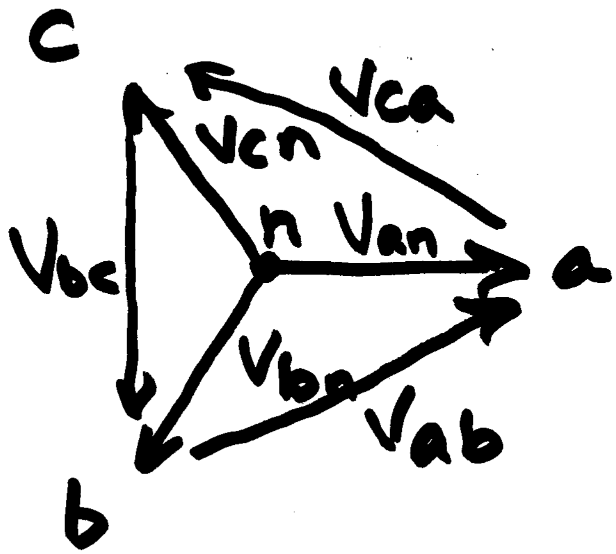
10




construction is mathematical correct, but not common practice!

**FIGURE 1.16**
Alternative method of drawing the phasors of Fig. 1.15.

also Fig 1.17




"Correct" common practice.