Modules development under *NSF CCLI EMD project DUE-0088904*.

The topics for the modules listed below have been chosen to help achieve one or more of the following goals:

1) enhancing conceptual understanding of fundamental concepts (1, 2, 10, 11, 12, 14),
2) providing an interactive tool for a widely used technique (3, 4, 13), or
3) providing additional focus on often poorly understood topics (5, 6, 7, 8, 9).

While only one goal is matched to each module, it is clear that many of the modules listed below also help with one or more of the other goals.

Please feel free to suggest any changes or modifications which improve the modules!

List of Modules

Module 1	Parallel and series in simple DC circuit (voltage source)
Module 2	Parallel and series in simple DC circuit (current source)
Module 3	Nodal analysis (DC)
Module 4	Nodal analysis (AC)
Module 5	Voltage regulation (VR) and efficiency (η) in simple AC circuit
Module 6	Power factor correction in simple AC circuit
Module 7	Using transformers to lower VR and η in simple AC circuit
Module 8	Balanced 3ϕ systems (Y-Y)
Module 9	Balanced 3ϕ systems (Y-Δ)
Module 10	1^{st}-order systems: step, ramp, and sinusoidal response
Module 11*	2^{nd}-order systems: Step response, sinusoidal steady-state response
Module 12*	Dynamical systems and sinusoidal steady-state response
Module 13	Sketching Bode diagrams ***(may be the most challenging module)***
Module 14*	Simple feedback control system

The purpose of the conceptual questions (the ones beginning with ***True or false?)*** accompanying some of the modules is to help students assess their level of understanding.

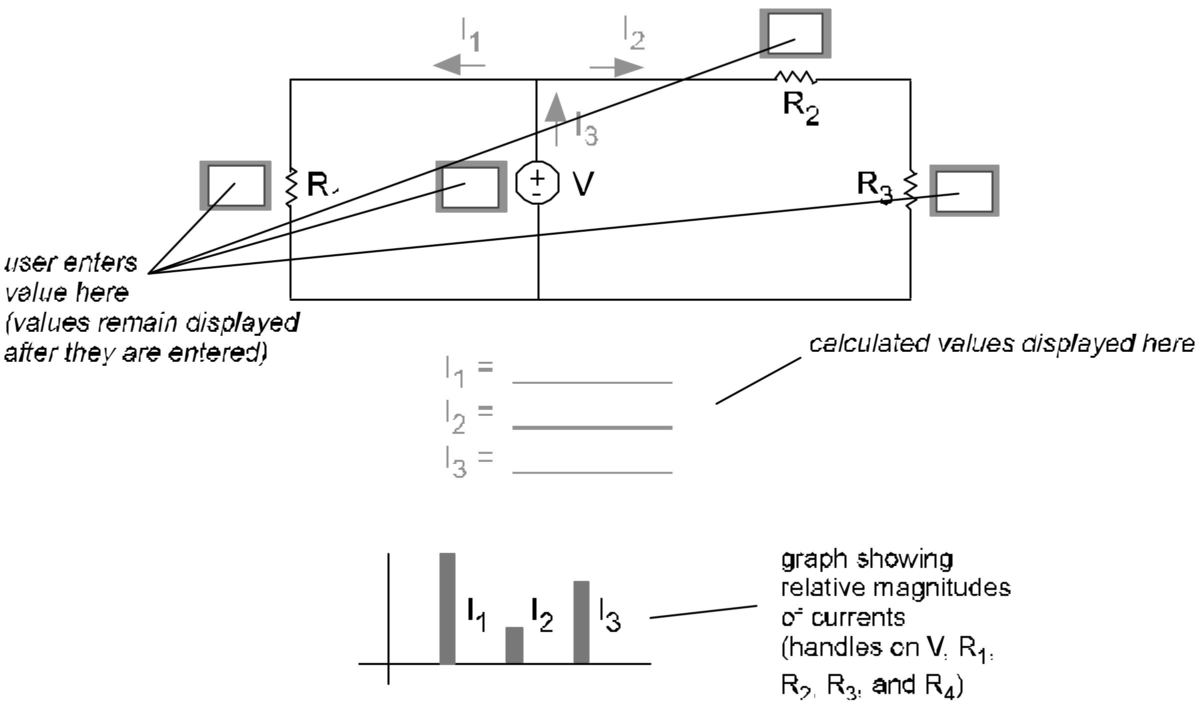
Note 1: In modules involving electric power, phasor voltages and currents are assumed RMS.

Note 2: Allowing parameters to have “handles” that allow them to be continuously varied will be useful in some of the modules, especially with those modules (1, 2, 5, 6, 7) having graphs showing relative variations.

** Not completed.*

Module 1

Module 1 is interactive and consists of a simple DC circuit. The user inputs values for the voltage source and resistances. The purpose of the module is to allow students to explore the consequences of elements (in this case resistances) in parallel and series.



True or false?

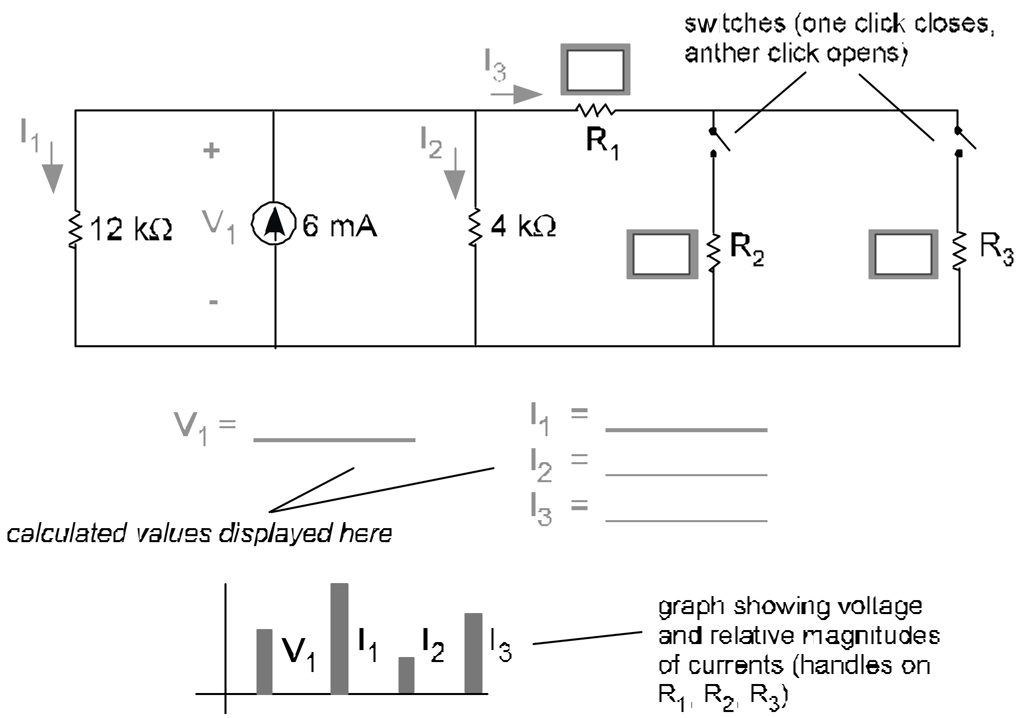
1. If the resistance of R_3 decreases, the power absorbed by R_2 will decrease. *Why or why not*?

2. If the resistance of R_1 decreases, the power absorbed by R_2 will remain the same, and the power delivered by the voltage source will increase. *Why or why not?*

Note: $R_1 = 0$ results in invalid model and does $R_2 + R_3 = 0$.

Module 2

Module 2 is interactive and consists of a simple DC circuit. The user inputs values for the resistances and can close and open the switches. The purpose of the module is to allow students to explore the consequences of elements (in this case resistances) in parallel and series.



True or false?

1. If one or more of the switches are closed, the power delivered by the current source will increase from that delivered when all switches are open. *Why or why not?*

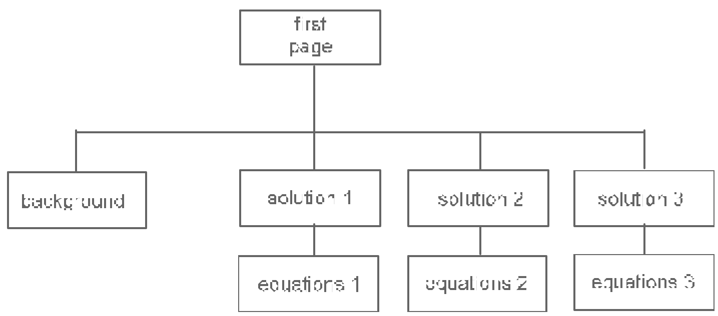
2. If one or more of the switches are closed, V_1 will decrease from that present when all switches are open. *Why or why not?*

3. If one or more of the switches are closed, the current through I_1 and I_2 will increase from that present when all switches are open. *Why or why not?*

Module 3

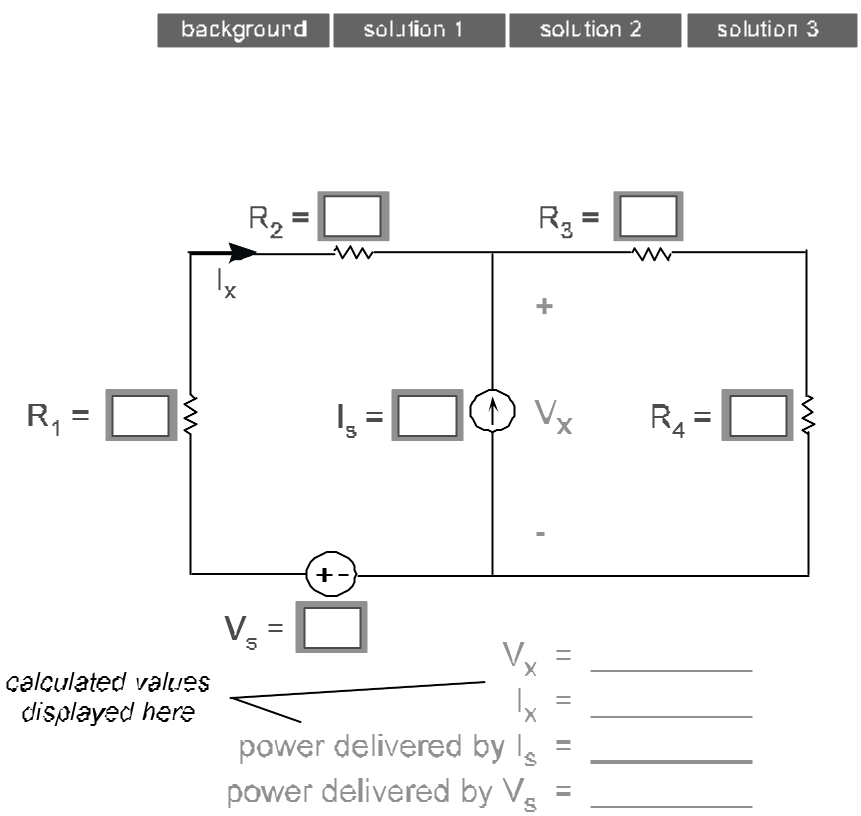
The purpose of module 3 is to illustrate the use of nodal analysis for a DC circuit. It is interactive with multiple pages. The first page will consist of an interactive unlabeled circuit. The user can work on this first page, entering numbers in for the circuit elements to check their own work.

Those just learning can click on ***background***, ***solution 1***, ***solution 2***, or ***solution 3***. ***Background*** is a static page describing the nodal technique. ***Solution 1*** page is an interactive circuit with a particular labeling. The user can click on **equations** to show the equations involved. ***Solution 2*** page is another interactive circuit with a particular labeling. The user can click on **equations** to show the equations involved. ***Solution 3*** page is another interactive circuit with a particular labeling. The user can click on **equations** to show the equations involved.



---

first page



background

first page | solution 1 | solution 2 | solution 3

General

A. Writing node voltage equations

1. Choose a reference node.
2. Label node voltages.
3. If dependent sources are present, express control variables in terms of node voltages
4. Circle all voltage sources by supernodes
5. Write KCL equations for all nodes or supernodes not associated with the reference node.
6. Write element relations for voltage sources in terms of node voltages.

B. Solve for node voltages.

The result should be n-1 independent equations in the n-1 node voltages.

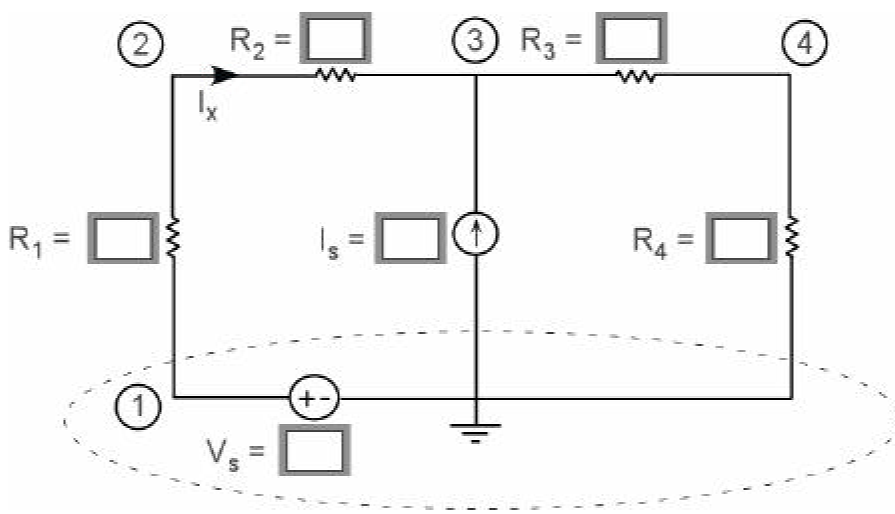
7. Solve equations for node voltages.

C. Use node voltages to find the variable in which you're interested.

Any quantity of interest can be expressed in terms of node voltages.

8. Express quantity of interest in terms of node voltages and solve.

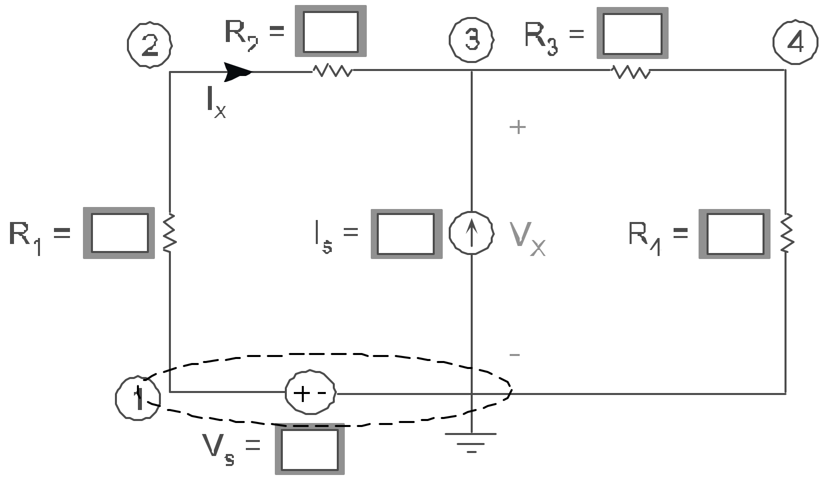
For this circuit



1. Assign Nodes. (one choice is shown)
2. Circle all voltage sources with supernodes.
3. Write KCL at all nodes except the reference and all supernodes that do not include the reference node. In the circuit above the supernode includes the reference node; the supernode circles the reference node.
4. Write KCL at node 1, at node 2, and at node 3.
5. Write the element relation for V_s.
6. The result is 4 equations in 4 unknowns (V_1, V_2, V_3, V_4).

solution 1

first page | equations | solution 2 | solution 3



V_x = ______________ V_1 = ______________

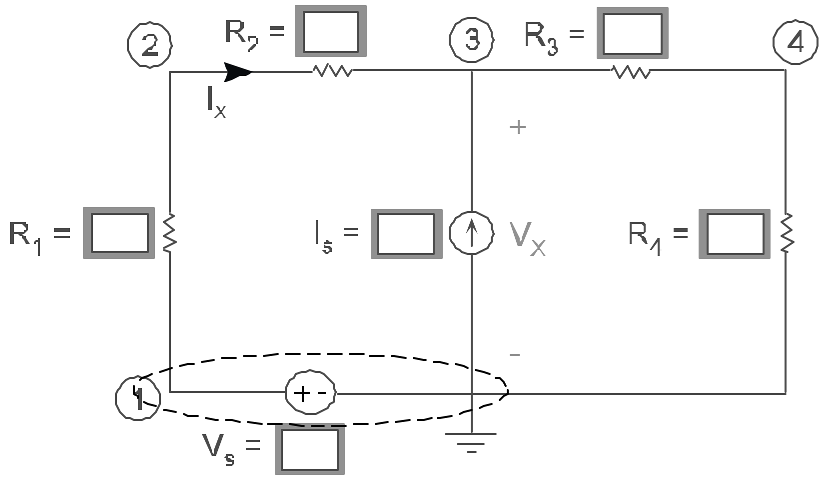
I_x = ______________ V_2 = ______________

power delivered by I_s = ______________ V_3 = ______________

power delivered by V_s = ______________ V_4 = ______________

equations (from solution 1)

first page | solution 1 | solution 2 | solution 3



V_x = ________ V_1 = ________

I_x = ________ V_2 = ________

power delivered by I_s = ________ V_3 = ________

power delivered by V_s = ________ V_4 = ________

node equations
$$\begin{cases} V_1 = V_s & \text{(voltage source)} \\ \dfrac{V_2 - V_1}{R_1} + \dfrac{V_2 - V_3}{R_2} = 0 & \text{(KCL at node 2)} \\ \dfrac{V_3 - V_2}{R_2} + \dfrac{V_3 - V_4}{R_3} - I_s = 0 & \text{(KCL at node 3)} \\ \dfrac{V_4 - V_3}{R_3} + \dfrac{V_4}{R_4} = 0 & \text{(KCL at node 3)} \end{cases}$$

$$V_x = V_3$$

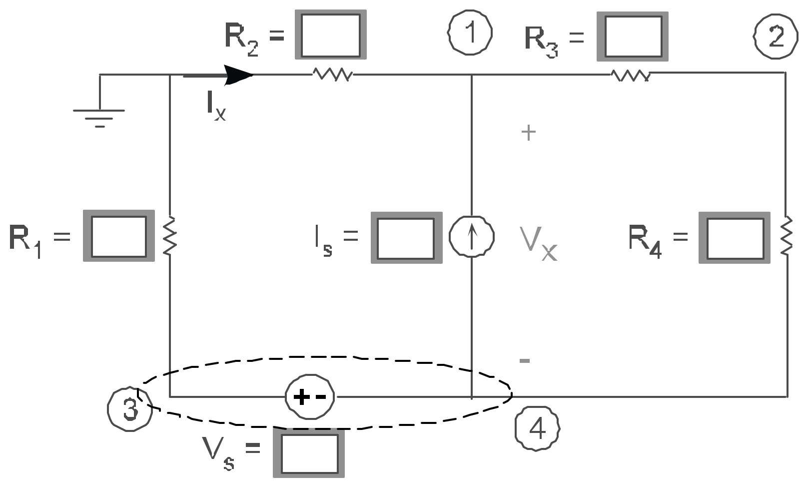
$$I_x = \frac{V_2 - V_3}{R_2}$$

power delivered by current source = $V_3 \; I_s$

power delivered by voltage source = $V_s \dfrac{V_1 - V_2}{R_1}$

solution 2

first page | solution 1 | equations | solution 3



V_x = ____________ V_1 = ____________

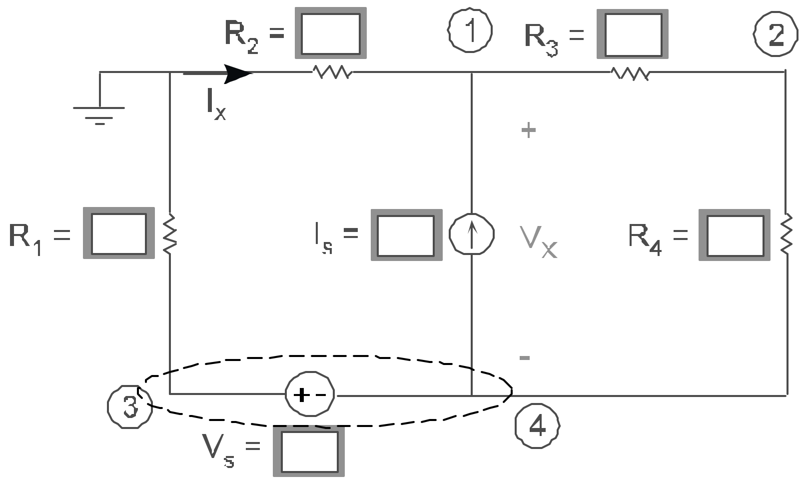
I_x = ____________ V_2 = ____________

power delivered by I_s = ____________ V_3 = ____________

power delivered by V_s = ____________ V_4 = ____________

equations (from solution 2)

first page | solution 1 | solution 2 | solution 3



V_x = ________ V_1 = ________

I_x = ________ V_2 = ________

power delivered by I_s = ________ V_3 = ________

power delivered by V_s = ________ V_4 = ________

node equations

$$\begin{cases} \dfrac{V_1}{R_2} + \dfrac{V_1 - V_2}{R_3} - I_s = 0 & \text{(KCL at node 1)} \\[2ex] \dfrac{V_2 - V_1}{R_3} + \dfrac{V_2 - V_4}{R_4} = 0 & \text{(KCL at node 2)} \\[2ex] V_3 - V_4 = V_s & \text{(voltage source)} \\[2ex] \dfrac{V_3}{R_1} + \dfrac{V_4 - V_2}{R_4} + I_s = 0 & \text{(KCL at supernode 3/4)} \end{cases}$$

$$V_x = V_1 - V_4$$

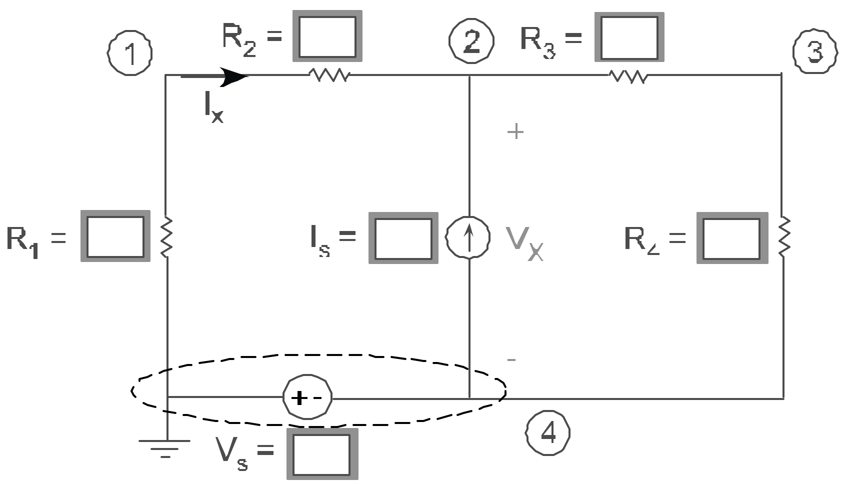
$$I_x = \frac{-V_1}{R_2}$$

power delivered by current source = $(V_1 - V_4)\ I_s$

power delivered by voltage source = $V_s \dfrac{V_3}{R_1}$

solution 3

first page | solution 1 | solution 2 | equations



V_x = ____________ V_1 = ____________

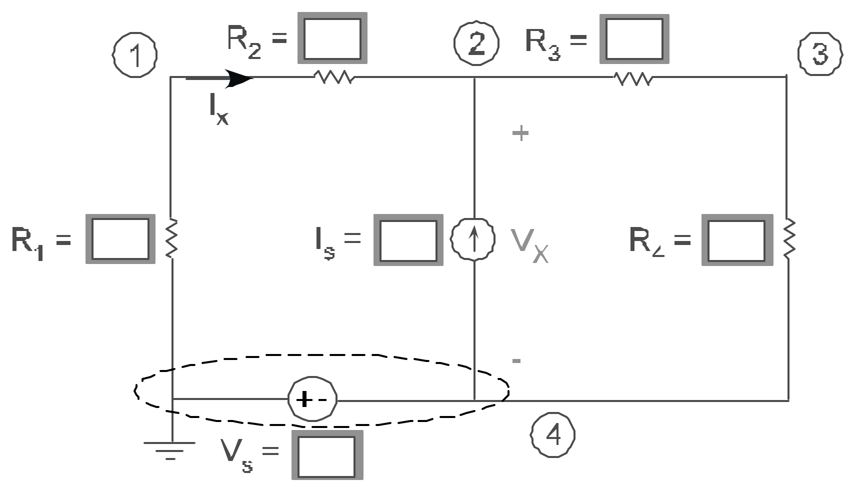
I_x = ____________ V_2 = ____________

power delivered by I_s = ____________ V_3 = ____________

power delivered by V_s = ____________ V_4 = ____________

equations (from solution 3)

first page | solution 1 | solution 2 | solution 3



V_X = ______ V_1 = ______

I_X = ______ V_2 = ______

power delivered by I_s = ______ V_3 = ______

power delivered by V_s = ______ V_4 = ______

node equations
$$\begin{cases} \dfrac{V_1}{R_1} + \dfrac{V_1 - V_2}{R_2} = 0 & \text{(KCL at node 1)} \\ \dfrac{V_2 - V_1}{R_2} + \dfrac{V_2 - V_3}{R_3} - I_s = 0 & \text{(KCL at node 2)} \\ \dfrac{V_3 - V_2}{R_3} + \dfrac{V_3 - V_4}{R_4} = 0 & \text{(KCL at node 3)} \\ -V_4 = V_s & \text{(voltage source)} \end{cases}$$

$$V_X = V_2 - V_4$$

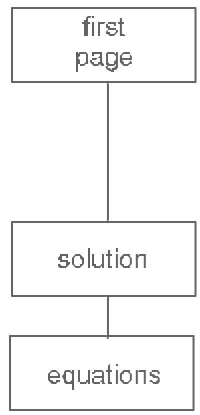
$$I_x = \frac{-V_1}{R_1} = \frac{V_1 - V_2}{R_2}$$

power delivered by current source = $\left(V_2 - V_4\right) I_s$

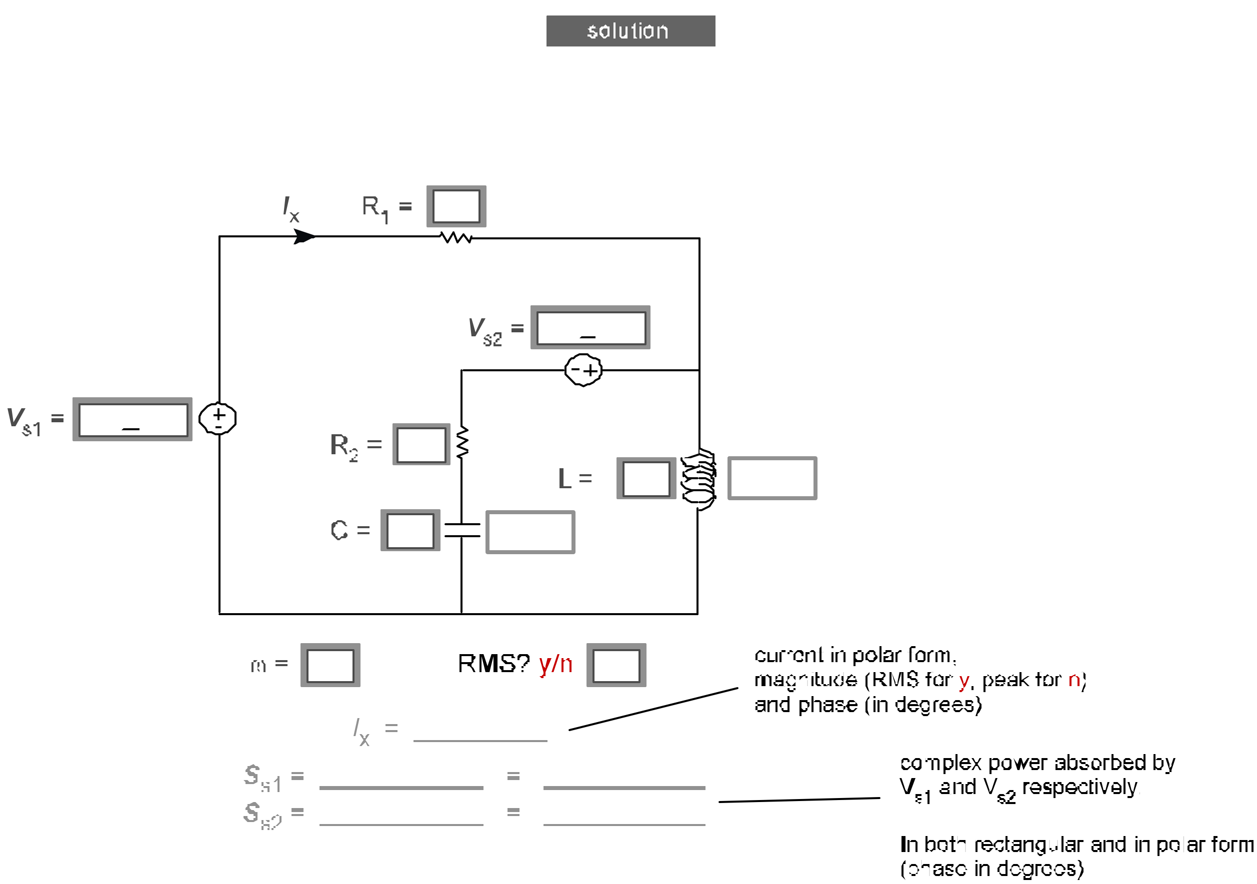
power delivered by voltage source = $V_s \dfrac{-V_1}{R_1}$

Module 4
The purpose of module 4 is to illustrate the use of sinusoidal steady-state analysis using nodal analysis. The first page will consist of an interactive unlabeled phasor circuit. The user can work on this first page, entering numbers in for the circuit elements to check their own work.

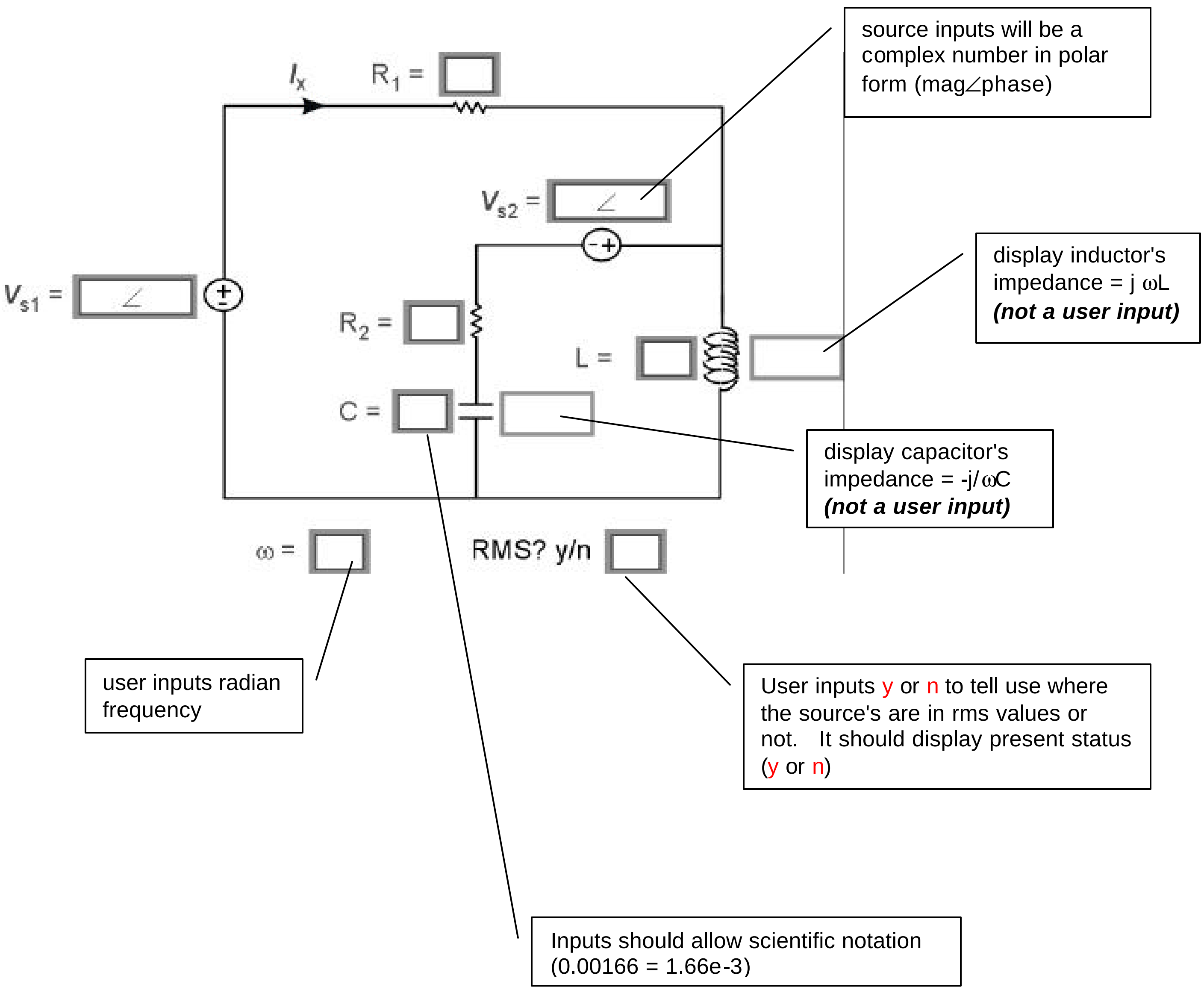
Those learning can click on ***solution*** and can then click on **equations** to show the equations involved.



first page

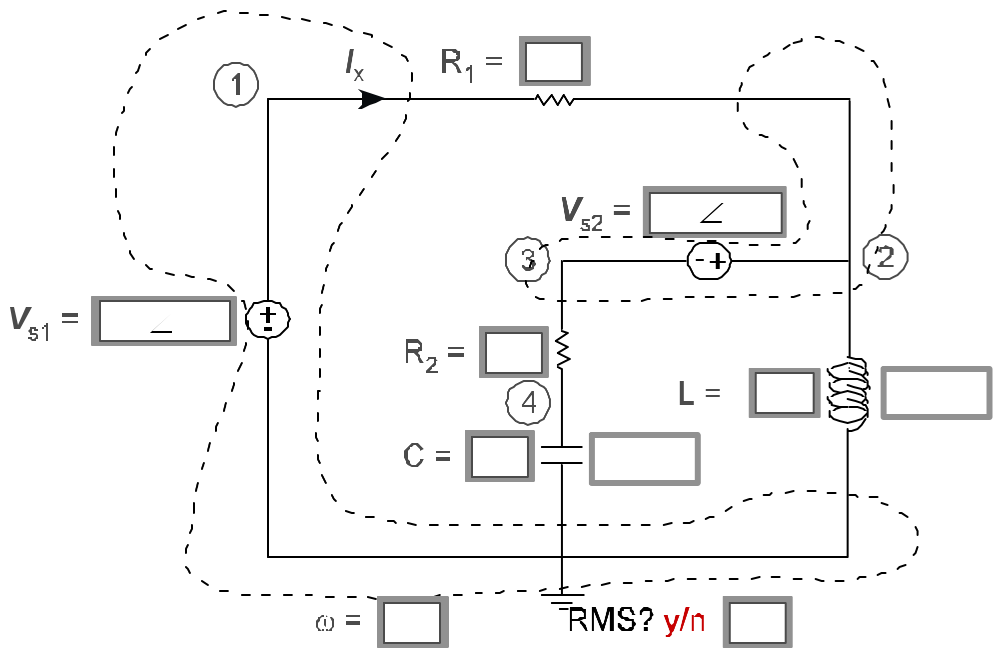


Informational page to aid in module design



solution

first page | equations



V_1 = __________

V_2 = __________

V_3 = __________

V_4 = __________

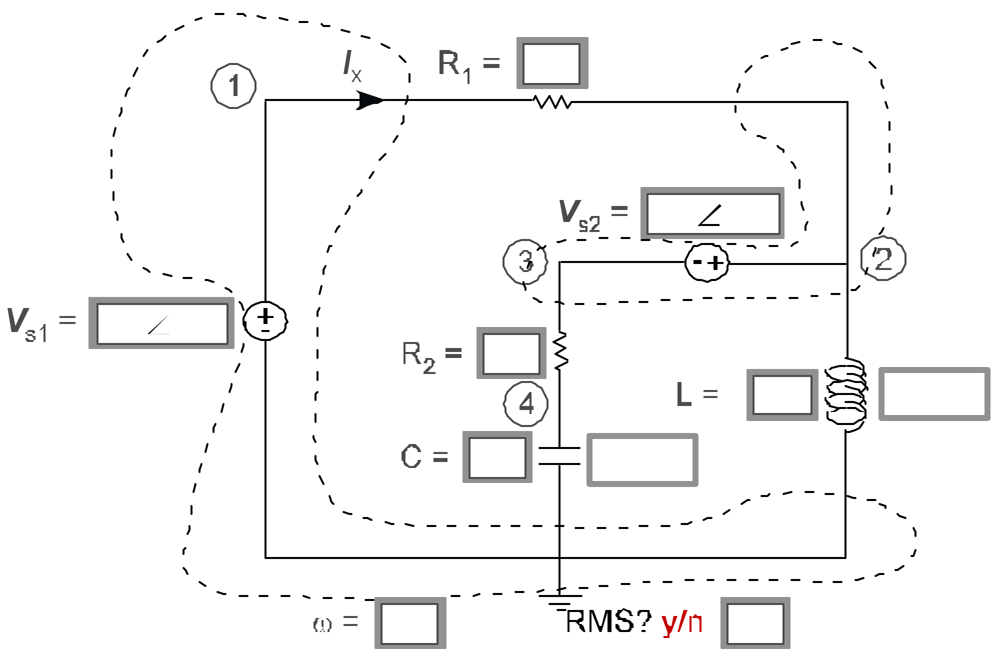
I_x = __________

S_{s1} = __________ = __________

S_{s2} = __________ = __________

equations

first page | solution



V_1 = ______

V_2 = ______

V_3 = ______

V_4 = ______

I_x = ______

S_{s1} = ______ = ______

S_{s2} = ______ = ______

nodal equations

$$\begin{cases} V_1 = V_{s1} & \text{(voltage source equation)} \\ V_2 - V_3 = V_{s2} & \text{(voltage source equation)} \\ \dfrac{V_4 - V_3}{R_2} + \dfrac{V_4}{-j/wC} = 0 & \text{(KCL at node 4)} \\ \dfrac{V_3 - V_4}{R_2} + \dfrac{V_2 - V_1}{R_1} + \dfrac{V_2}{jwL} = 0 & \text{(KCL at supernode 2/3)} \end{cases}$$

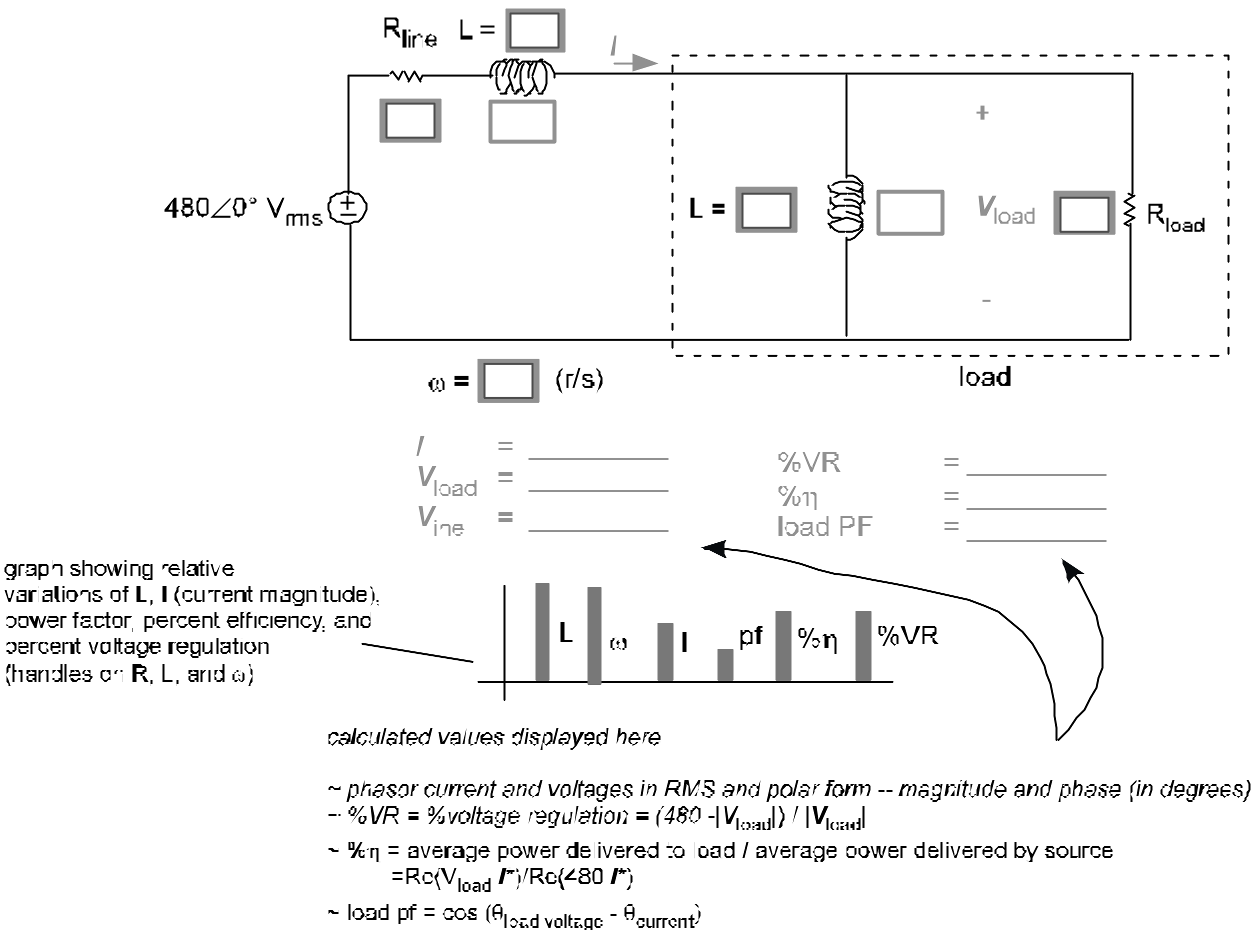
$$I_x = \frac{V_1 - V_2}{R_1}$$

$$S_{s1} = V_{s1}\left(\frac{V_1 - V_2}{R_1}\right)^* \quad \text{(using RMS values)} \qquad \left[= \frac{1}{2}V_{s1}\left(\frac{V_1 - V_2}{R_1}\right)^* \quad \text{(using peak values)} \right]$$

$$S_{s2} = V_{s2}\left(\frac{V_4 - V_3}{R_2}\right)^* \quad \text{(using RMS values)} \qquad \left[= \frac{1}{2}V_{s2}\left(\frac{V_4 - V_3}{R_2}\right)^* \quad \text{(using peak values)} \right]$$

Module 5

Module 5 is intended to demonstrate the effect of load inductance on voltage regulation and efficiency in power distribution systems.



True or false?

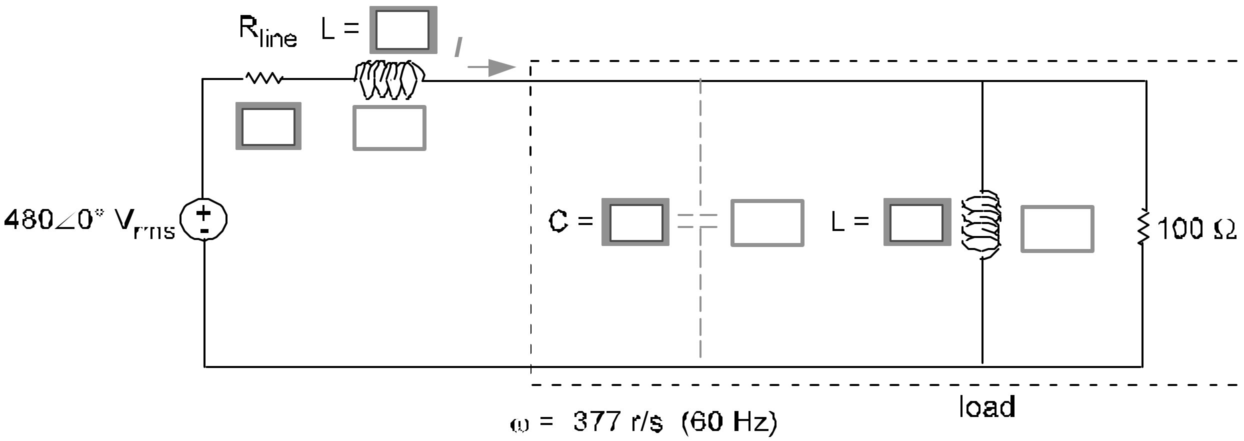
1. As L increases, the power absorbed by the 2 Ω line resistance will decrease.
   Why or why not?

2. As R_{load} increases, the pf will increase which will cause the efficiency to increase.
   Why or why not?

3. For a given R_{line} and R_{load}, η will be the maximum possible when L=0.
   Why or why not

Module 6

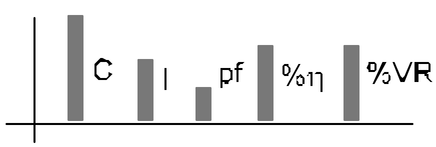
Module 6 is intended to demonstrate the effect of power factor correction on voltage regulation and efficiency in power distribution systems.



note: to avoid overcorrection, ωL should be less than 1/ωC

I = ________

%VR = ________
%η = ________
load PF = ________



graph showing relative variations of C, I (current magnitude), power factor, percent efficiency, and percent voltage regulation (handles on **R**, **L**, and **C**)

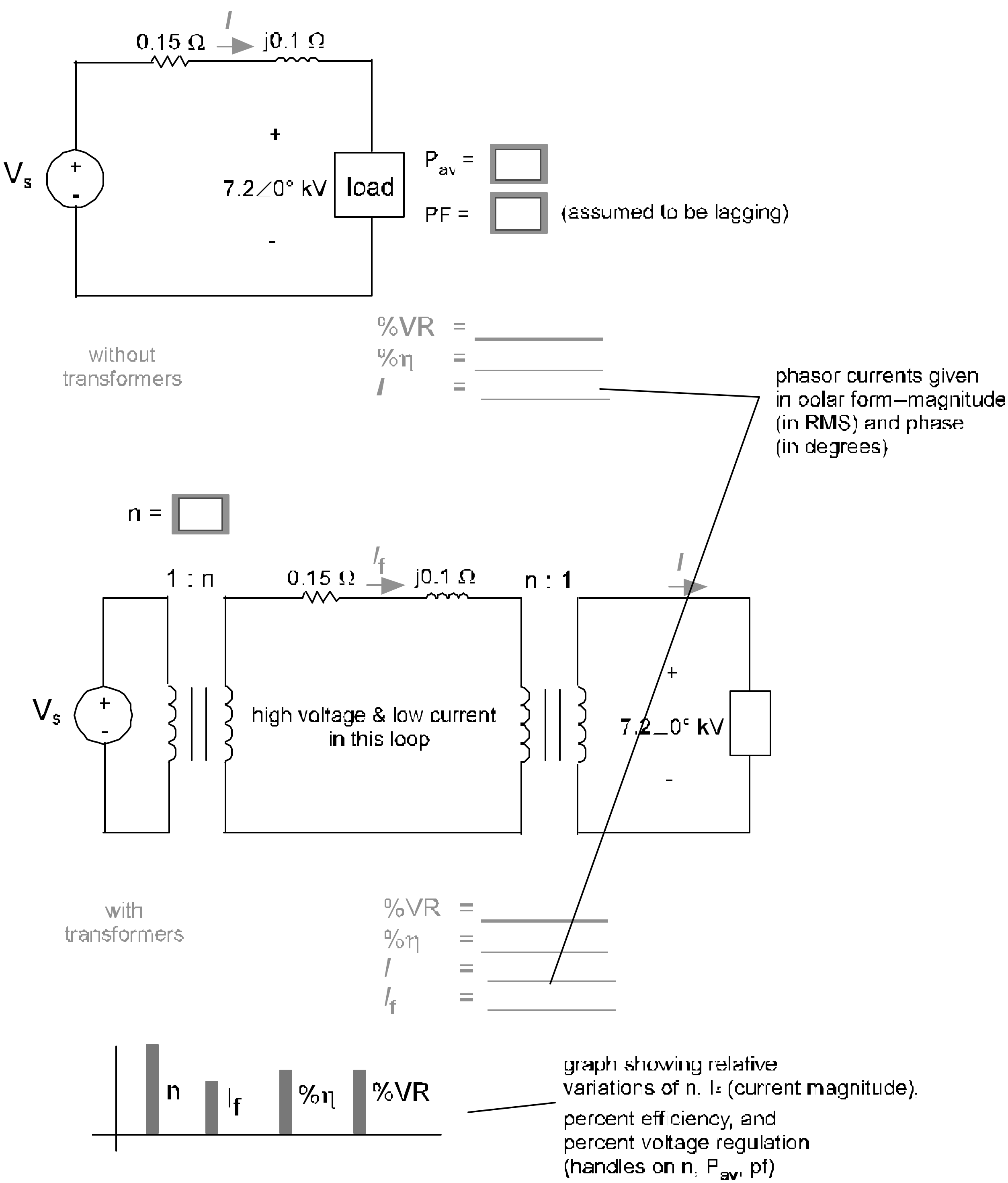
True or false?

1. The required C, in Farads, increases as the inductance, in Henries, increases.
   Why or why not?

2. As the pf is increased toward 1, |***I***| will decrease which will increase the %VR.
   Why or why not?

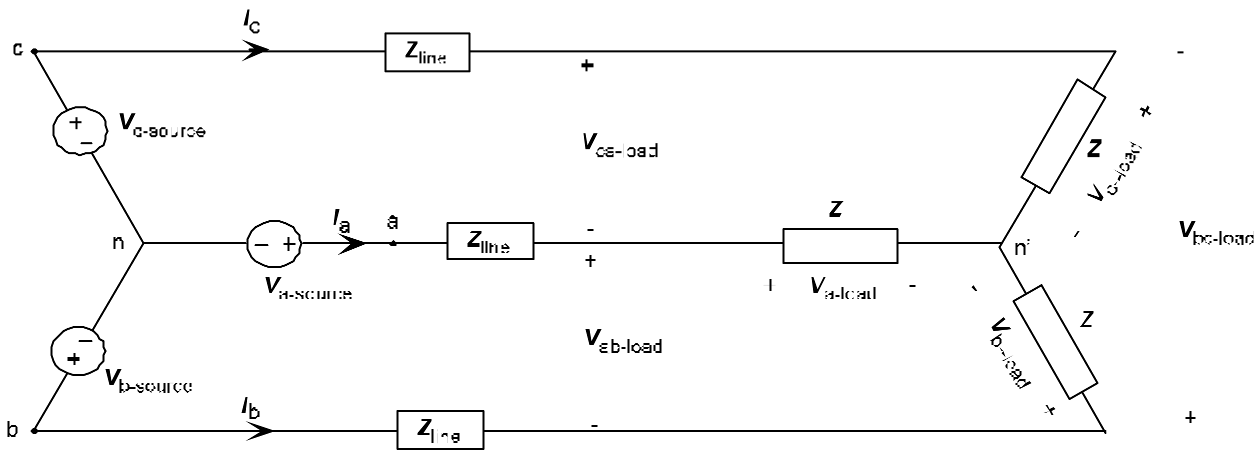
Module 7

Module 7 is intended to demonstrate the effect of using transformers on voltage regulation and efficiency.



Module 8

Module 8 is intended to allow the user to explore the relationships involved in a balanced 3ϕ Y-Y system.



$V_{a\text{-load}}$ = [∠] *At load end. In polar form, magnitude in RMS, phase in degrees*

Z_{line} = [∠]

Z = [∠]

%VR = __________

%η = __________

at source

V_a = __________

V_b = __________

V_c = __________

$S_{delivered}$ = __________

= __________

line currents

I_a = __________

I_b = __________

I_c = __________

at load

V_a = __________

V_b = __________

V_c = __________

V_{ab} = __________

V_{bc} = __________

V_{ca} = __________

I_{ab} = __________

I_{bc} = __________

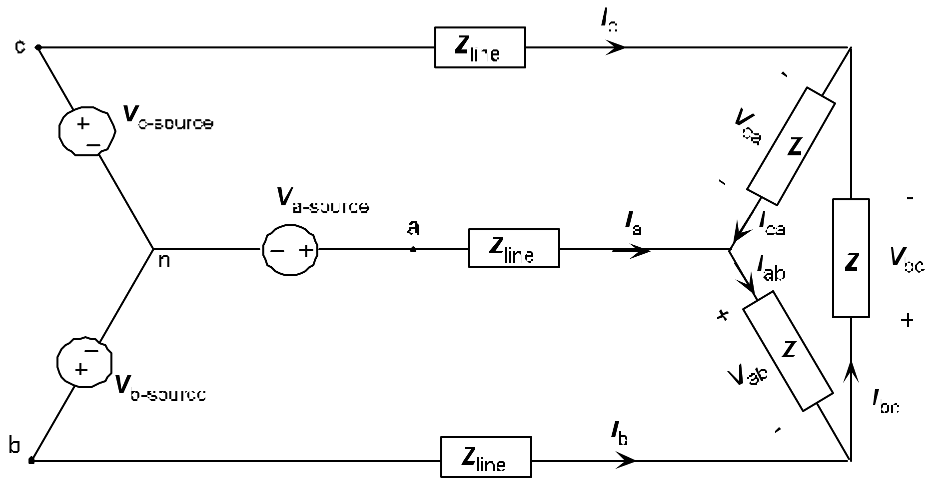
I_{ca} = __________

$S_{absorbed}$ = __________

= __________

Module 9

Module 9 is intended to allow the user to explore the relationships involved in a balanced 3ϕ Y-Δ system.



V_{ab} = [∠] *At load end. In polar form, magnitude in RMS, phase in degrees*

Z_{line} = [∠]

Z = [∠]

%VR = ________

%η = ________

at source

V_a = ________

V_b = ________

V_c = ________

$S_{delivered}$ = ________

= ________

line currents

I_a = ________

I_b = ________

I_c = ________

at load

V_{ab} = ________

V_{bc} = ________

V_{ca} = ________

I_{ab} = ________

I_{bc} = ________

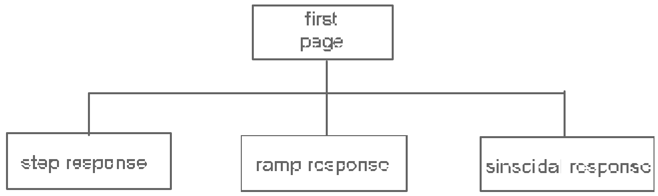
I_{ca} = ________

$S_{absorbed}$ = ________

= ________

Module 10

The purpose of module 10 is to allow the user to explore first-order systems via their step, ramp, and sinusoidal responses.



---

first page

$$t \frac{dx}{dt} + x = K\,f(t) \qquad \left\{ \begin{array}{l} f(t) = \text{system input (excitation)} \\ x = \text{system output (response)} \\ t = \text{time constant} \\ K = \text{static gain coefficient} \end{array} \right.$$

step input

first page | ramp input | sinusoidal input

$$t\frac{dx}{dt} + x = K\,f(t)$$

f(t) = system input (excitation)

x = system output (response)

t = time constant

K = static gain coefficient

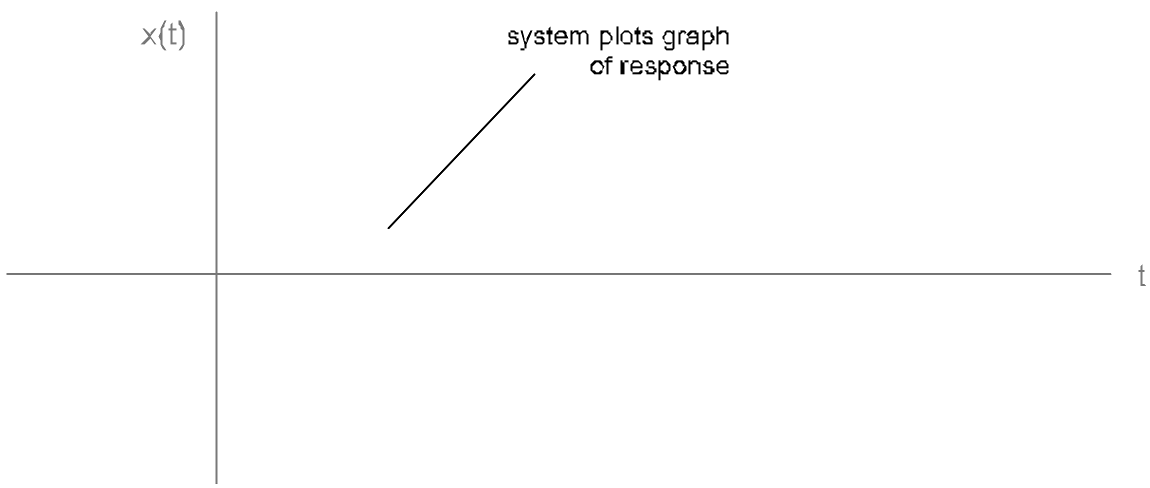
response for $f(t) = A\,u(t-t_o)$ and $x(t)\big|_{t=t_o} = x_o$,

$$x(t) = KA - (KA - x_o)e^{-(t-t_o)/t}$$

K = ☐ τ = ☐ t_o = ☐ x_o = ☐

system gives analytic form of response

$x(t)$ = ______________________________ $(t > t_o)$



ramp input

step input | first page | sinusoidal input

$$\tau \frac{dx}{dt} + x = K\,f(t) \qquad \begin{cases} f(t) = \text{system input (excitation)} \\ x = \text{system output (response)} \\ \tau = \text{time constant} \\ K = \text{static gain coefficient} \end{cases}$$

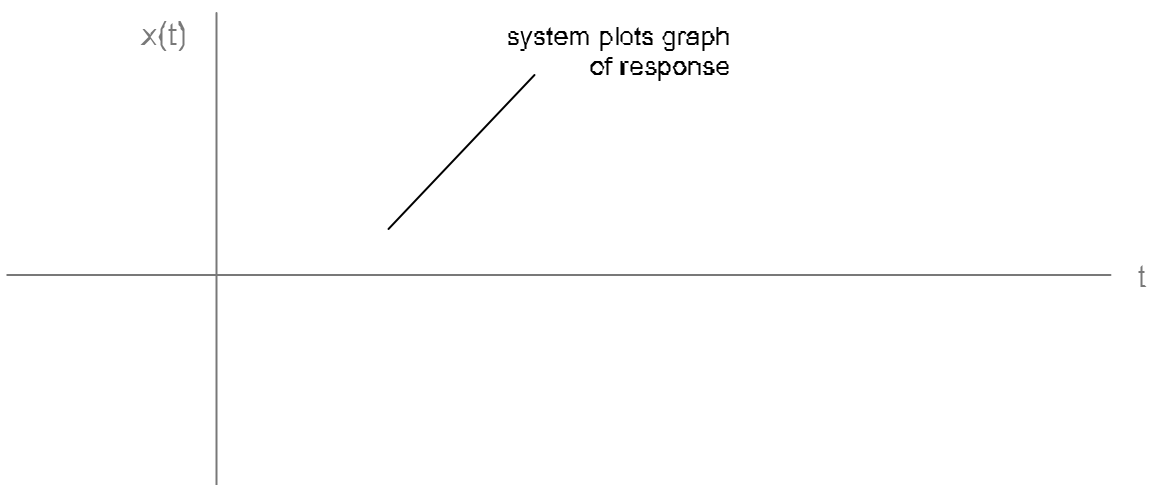
response for $f(t) = A\, r(t-t_o)$ and $x(t)\big|_{t=t_o} = x_o$,

$$x(t) = KA\left[(t - t_o) - \tau\right] - \left\{KA\left[-t_o - \tau\right] - x_o\right\} e^{-(t-t_o)/\tau}$$

K = ☐ τ = ☐ t_o = ☐ x_o = ☐

system gives analytic form of response

$x(t)$ = ______________________________ $(t > t_o)$



sinusoidal input

step input | ramp input | first page

$$\tau \frac{dx}{dt} + x = K\,f(t) \qquad \left\{ \begin{array}{l} f(t) = \text{system input (excitation)} \\ x = \text{system output (response)} \\ \tau = \text{time constant} \\ K = \text{static gain coefficient} \end{array} \right.$$

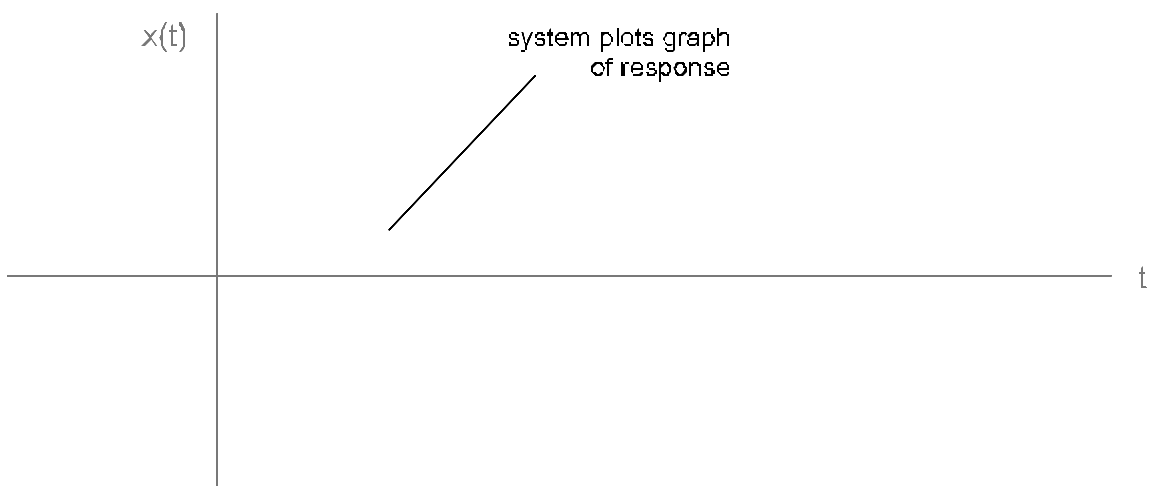
response for $f(t) = A\cos(\omega t + \theta)$ and $x(t)\big|_{t=t_o} = x_o$,

$$x(t) = \frac{KA}{\sqrt{1+(\omega\tau)^2}}\cos\left[\omega t + \theta - \tan^{-1}(\omega\tau)\right] - \left\{\frac{KA}{\sqrt{1+(\omega\tau)^2}}\cos\left[\theta - \tan^{-1}(\omega\tau)\right] - x_o\right\} e^{-(t-t_o)/\tau}$$

K = ☐ τ = ☐ t_o = ☐ x_o = ☐

system gives analytic form of response

$x(t)$ = ______________________________ $(t > t_o)$



Module 11 (to follow)
Module 12 (to follow)

Module 13

Module 13 is intended to help the user sketch Bode plots by hand. Understanding how Bode plots are sketched help students develop a deeper understanding of frequency domain analysis.

In the module, the user will enter a transfer function and the module provides

1) Factored transfer function in Bode form,
2) Straight line approximations for all individual factors (dotted lines) aand the overall straight line approximation for the transfer function (solid line) and the actual magnitude and phase curves

Example:

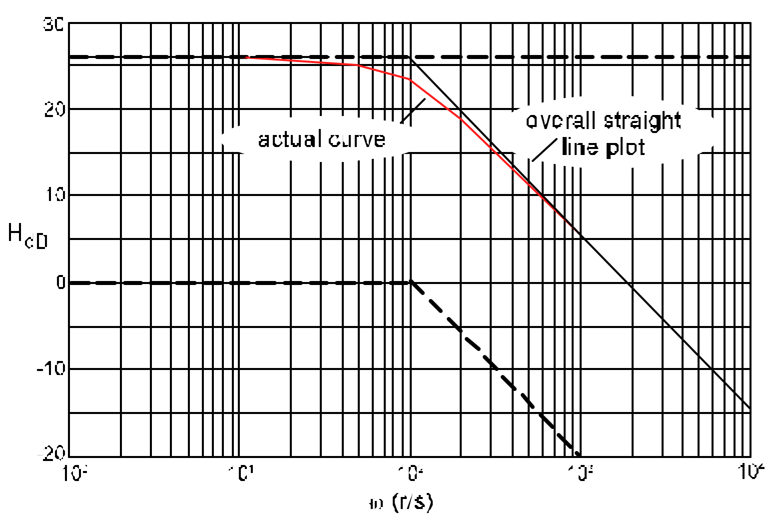
The user enters $H(s) = \dfrac{2000s}{s + 100}$

1) The system responds by providing the transfer function in factored Bode form.

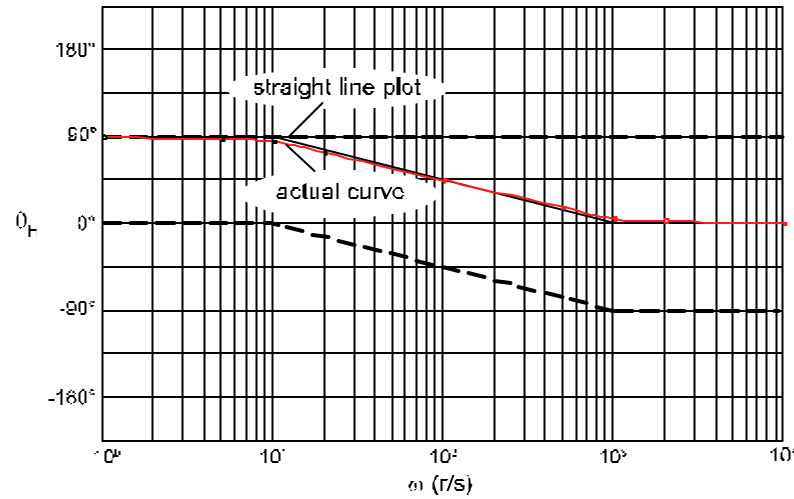
$$H = 20\,\frac{s}{\left(\dfrac{s}{100} + 1\right)}$$

2) Magnitude and phase plots

magnitude plot



phase plot



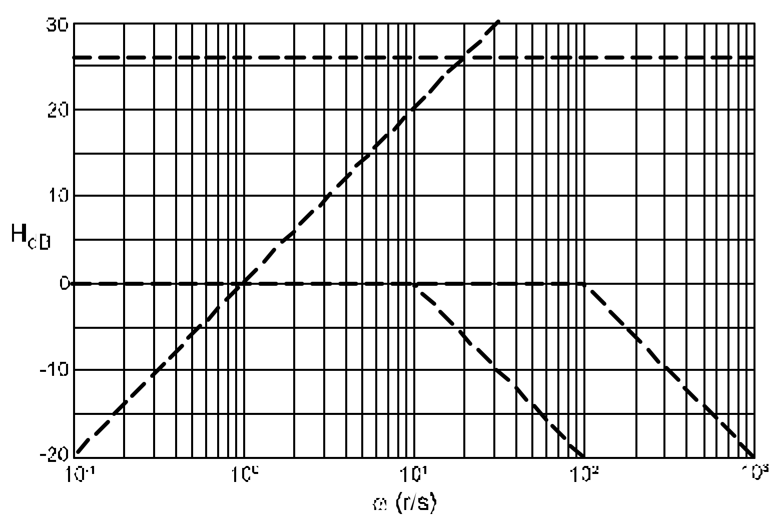
If it’s not too difficult, a meaningful enhancement would be to allow the user to choose only factors or only overall curves.

Below is an example, using another transfer function, to partially illustrate this for the magnitude curves.

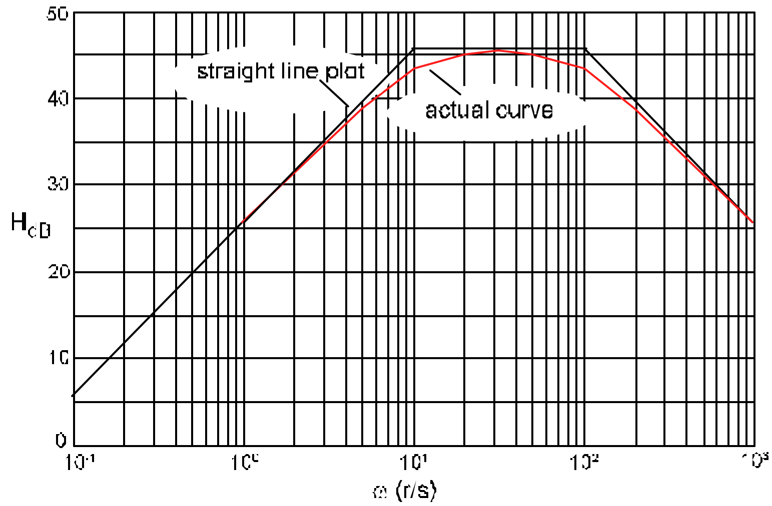
User enters $H(s) = -\dfrac{2(10^4)s}{s^2 + 110s + 10^3}$

System responses with H(s) in factored Bode form. $H(s) = -\dfrac{20s}{\left(\dfrac{s}{10}+1\right)\left(\dfrac{s}{100}+1\right)}$

User can choose a plot with only individual factors.



Or only the overall curves



Module 14 (to follow)