

Name \_\_\_\_\_

The College of New Jersey  
Department of Electrical and Computer Engineering (ECE)  
Power Systems and Renewability (ELC470)

## Experiment #2: High-Voltage dc Transmission Line (HVDC)

### Objective:

To familiarize students with simulation (in PSpice) of three-phase circuits as well as high-voltage dc transmission (HVDC) in power systems.

### Background:

A high-voltage direct-current (HVDC) line may be used for **long-distance, bulk** transmission of electrical power – a stark contrast to the more common alternating current (AC) line. For this purpose, HVDC may be:

- *less expensive*
- *more efficient*
- *more stable* – because it prevents cascading voltage collapse due to loss of synchronization (no need for synchronization of sending and receiving end).

Both high-voltage and direct-current transmission alone reduce resistive power loss (aka. heat dissipation) by reducing the magnitude of current  $|I_{Line}|$  flowing along the line. Refer to (1).

$$|I_{Line}| = \frac{|\vec{S}_{Trans}|}{|\vec{V}_{Send}|} = \frac{\sqrt{P_{Trans}^2 + Q_{Trans}^2}}{|\vec{V}_{Send}|}$$

$$P_{Loss} = |I_{Line}|^2 R_{Line} = \left( \frac{\sqrt{P_{Trans}^2 + Q_{Trans}^2}}{|\vec{V}_{Send}|} \right)^2 R_{Line} \quad (1)$$

losses may be reduced by minimizing magnitude of line current flow

However, they work in different ways:

- *high-voltage* – for a defined and constant apparent transmission power ( $\vec{S}_{Trans}$ ), a higher sending-end voltage ( $\vec{V}_{Send}$ ) corresponds to lower current flow, as dictated by Ohm's Law. This, in turn, corresponds to reduced  $I^2R$  losses. Refer to (2).
- *direct-current* – for a defined and constant real transmission power ( $P_{Trans}$ ), a direct-current implementation dramatically reduces reactive power flow (which does not exist in non-oscillating circuits) and reduces the magnitude of current flow, as dictated by  $\vec{S} = \vec{V}\vec{I}^*$ . This, in turn, corresponds to reduced  $I^2R$  losses. Refer to (3).

high-voltage effects:

$$\frac{\overbrace{|I_{Line}| \text{ when voltage is boosted by factor of } \alpha > 1}^{\sqrt{P_{Line}^2 + Q_{Line}^2}}}{\alpha |V_{Sending} - V_{Receiving}|} < \frac{\overbrace{\text{"normal"} |I_{Line}|}^{\sqrt{P_{Line}^2 + Q_{Line}^2}}}{|V_{Sending} - V_{Receiving}|} \quad (2)$$

dc transmission effects: 
$$\frac{\sqrt{P_{Line}^2}}{\left| V_{Sending} - V_{Receiving} \right|} < \frac{\sqrt{P_{Line}^2 + Q_{Line}^2}}{\left| V_{Sending} - V_{Receiving} \right|} \quad (3)$$

$\underbrace{\left| I_{Line} \right|}_{\text{"normal" } |I_{Line}|} \text{ when reactive power flow is eliminated}$

A high-voltage direct-current (HVDC) line is composed of several pieces including:

- *sending-end transformer* – which increases voltage levels at sending-end of transmission line and attenuates current flow.
- *rectifier* – which converts the 60Hz waveforms into dc.
- *transmission line* – which conducts power from sending-end to receiving-end of line.
- *inverter* – which converts dc to 60Hz waveform.
- *receiving-end transformer* – which decreases voltage levels at receiving-end of transmission line and facilitates interface with other transmission / distribution systems.
- *resonant and low-pass filters* – may be placed throughout the line to eliminate harmonics and generate purely sinusoidal ac and constant dc voltages.

### Rectifier

A rectifier is an electrical device that converts alternating-current (ac), which periodically reverses direction, to direct-current (dc) which flows in only one direction. Generally, it is composed of diodes which block undesirable reverse flows. The most basic rectifier is the single-phase half-wave diode rectifier which employs a single diode and simply blocks any reverse current. One drawback of this circuit is the fact that power transfer is reduced by one-half (one-half of the wave is blocked). Refer to Figure 1.

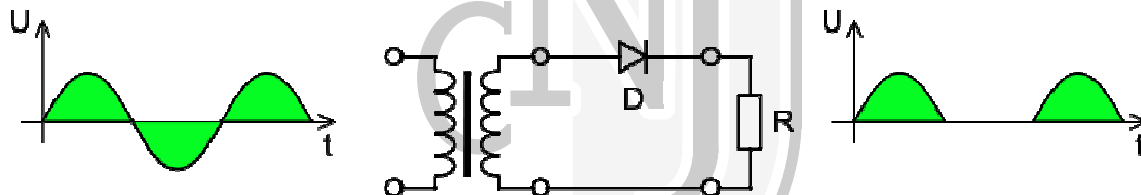


Figure 1: Half-Wave Rectifier with Input Waveform (left), Circuit (middle), and Output Waveform (right)

A more complex rectifier is the single-phase full-wave which employs two diodes. However, it has the ability to “flip” the negative half of the wave cycle to positive – ensuring maximum power transfer. Refer to Figure 2.

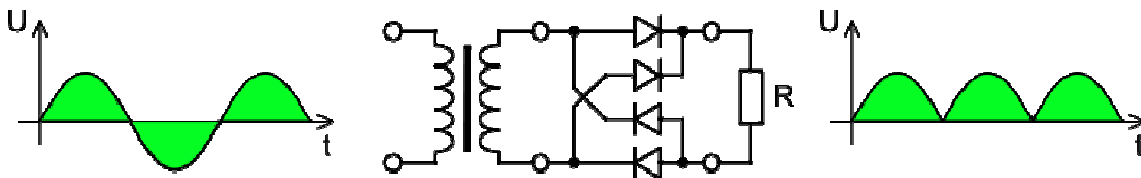


Figure 2: Full-Wave Rectifier with Input Waveform (left), Circuit (middle), and Output Waveform (right)

In HVDC transmission, however, one requires the ability to rectify three ac waves and generate a single dc voltage. For this task, a three-phase full-wave rectifier is employed. Intentionally, the expected output for this three-phase rectifier is not shown (students will examine this behavior).

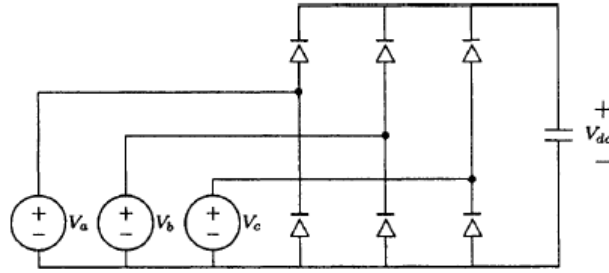


Figure 3: Three-Phase Rectifier ( $V_{abc}$  to  $V_{dc}$ )

### Filtering

The output of the rectifier shown in Figure 2 is direct-current, although it is by no means constant with respect to time (straight line). Remember, a dc waveform is one which does not cross the  $x$ -axis (aka. reverse direction). However, it may still exhibit periodic changing behavior. A low-pass filter may be used to eliminate higher-frequency harmonics in the dc waveform. Refer to Figure 4. The corner frequency of this filter is defined in (4).

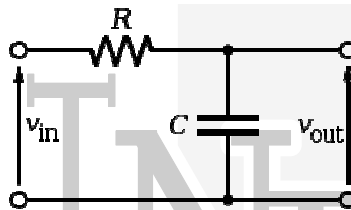


Figure 4: Low-Pass Filter

$$f_c = \frac{1}{2\pi RC} \quad (4)$$

### Inverter

An inverter is an electrical device which converts direct-current (dc) to alternating-current (ac). Generally, it is composed of controllable switches which allow synchronized reversal of voltages and currents. The most basic inverter is the **single-phase ideal-switch type** which employs two switches (assumed to be ideal for purposes of analysis) to apply the dc voltage across a load with both positive and negative polarity. Note, however, that this inverter will not generate purely sinusoidal voltage / current waveforms. For a purely resistive load, the output will take on the shape of a square-wave.

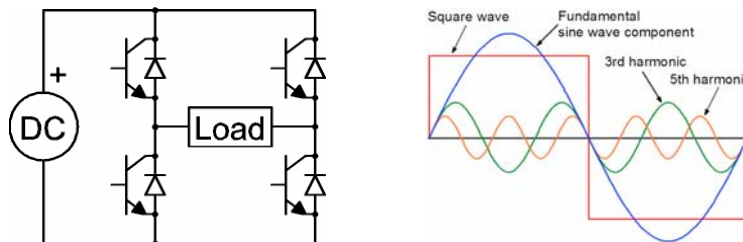


Figure 5: Single-Phase H-Bridge Inverter (left) and Sample Output (right)

In HVDC transmission, however, one requires the ability to invert one dc voltage and generate **three 60Hz ac waveforms**. Although a perfect sinusoidal shape is preferable, it is not always

practically realizable. A three-phase inverter is constructed, essentially, as three single-phase inverters in parallel – all drawing from the same dc supply.

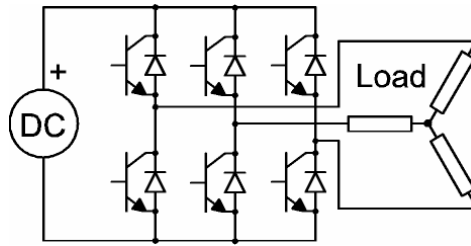


Figure 6: Three-Phase H-Bridge Inverter

### Introduction (pts):

INSERT INTRODUCTION HERE

### Procedure Part #1: Transient Analysis

The circuit used in this lab is similar to that of lab #1, consisting of:

- **1 three-phase generator** – modeled by armature equivalent circuit presented in Figure 3.5 of Grainger. Assume that the synchronous machine operates at a rated internal electromotive force of  $110V_{LL}$  (aka.  $|E_i| = 110V_{LL}$ ) in positive sequence, has negligible internal resistance, and has synchronous resistance as defined below. Set  $E_i = |E_i| \angle 0^\circ$ .

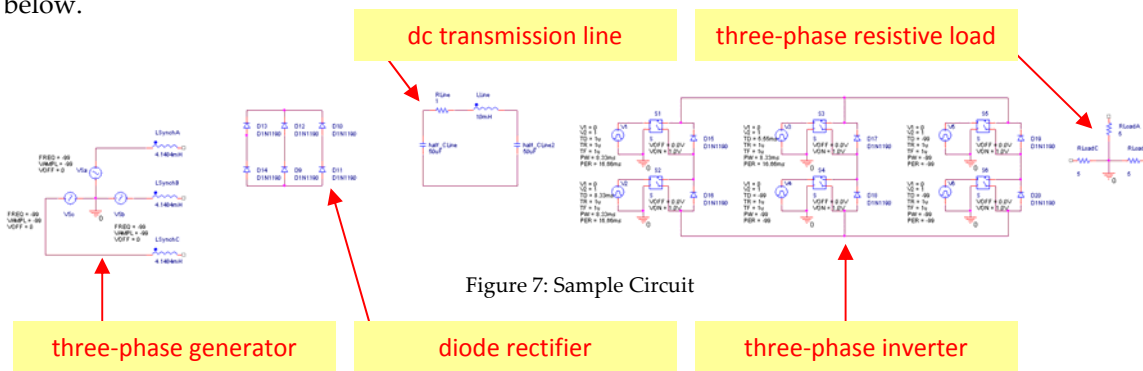
$$\begin{aligned} L_s &= 2.7656mH \\ M_s &= 1.3828mH \end{aligned} \quad (5)$$

- **1 three-phase ideal transformer** – with turns ratio of 1:1 and connection of Y-Y.
- **3 single-phase medium-length transmission lines** – modeled with “PI” equivalent circuit presented in Figure 4.2. of Grainger. Assume that the line impedances are defined as below.

$$\begin{aligned} R_{Line} &= 2.5\Omega \\ X_{Line} &= \omega(10mH) \\ C_{Line} &= 100\mu F \text{ (aka. } 50\mu F \text{ per side of x-line)} \end{aligned} \quad (6)$$

- **3 single-phase loads** – modeled as Y-connected impedances of  $5\Omega$ .

**Step #1:** Load the main circuit provided to you by instructor. A sample screen-capture is shown below.



**Step #2:** This schematic provides the components and incomplete structure for a three-phase high-voltage direct-current transmission system, based on the system from lab #1 – same generator and load behavior. The student, however, must:

- define generator internal electromotive forces ( $V_{Sa}$ ,  $V_{Sb}$ ,  $V_{Sc}$ )
- place missing connection between “pieces” of the system
- define pulsed voltage sources which trigger ideal switches within inverter

**Note:** Missing values, within the schematic, are denoted with value of -99.

**Note:** The VPULSE voltage source triggers the ideal switches. When  $VPULSE = 1V$ , the switch is on. When  $VPULSE = 0V$ , the switch is off. The parameters of this source are listed below.

- $V1 = 0V$ : sets the source’s “off” value
- $V2 = 1V$ : sets the source’s “on” value
- $TD = ???$ : defines the delay of the pulse. If this value is set to zero, then the pulse (with value of  $V2$ ) is applied at the beginning of each cycle. If this value is set to  $T/2$ , then the pulse is applied half-way through each cycle.
- $TR = 1\mu s$ : defines the rise-time of the pulse. Normally, it is set to a very small value.
- $TF = 1\mu s$ : defines the fall-time of the pulse. Normally, it is set to a very small value.
- $PW = ???$ : defines the width of the pulse, or length of time  $V2$  is applied. For the rest of the cycle,  $V1$  is applied.
- $PER = :$  defines the period ( $T$ ) of the pulsed waveform. Remember, the objective is to generate a 60Hz waveform.

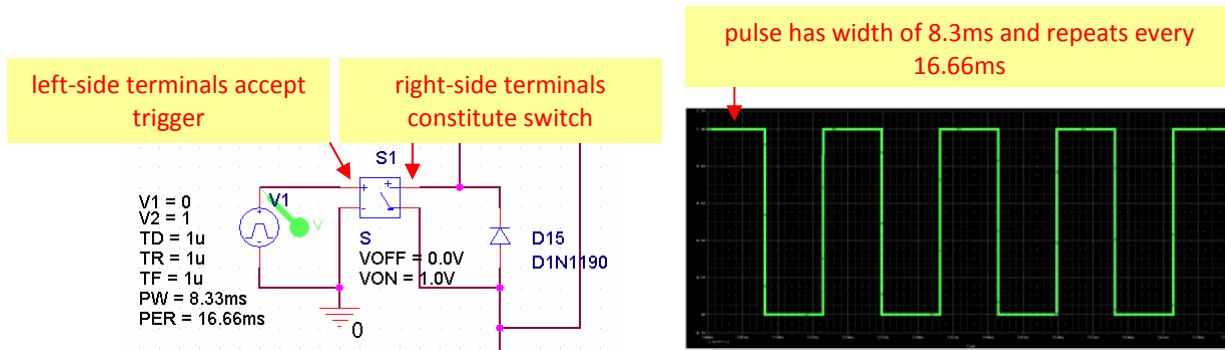


Figure 8: Example of VPULSE and Utilization to Trigger Ideal Switch

**Step #3:** Complete this circuit in PSpice. Copy and paste the schematic below.

- (pts) is figure present?
- (pts) proper title and labels
- (pts) circuit structure
- (pts) definition of VAMPL (for VSIN)
- (pts) definition of FREQ (for VSIN)
- (pts) definition of switch trigger times

INSERT SCHEMATIC HERE

**Step #4:** Simulate this circuit (transient analysis). Copy and paste below, in Excel (not PSpice), the instantaneous terminal voltage of the generator over 3 cycles. Make sure simulation results begin from  $t = 1s$  and end with  $t = 1.05s$  to avoid any transients which may exist.

- (pts) is graph present?
- (pts) proper title, axes labels, and legend
- (pts) clearly labeled waveforms
- (pts) appropriate data ( $v_{GenA}$ ,  $v_{GenB}$ ,  $v_{GenC}$ )

**Note:** Try shifting the waveforms by a constant value (e.g. 200V) for purposes of comparison. However, remember to note this in the legend.

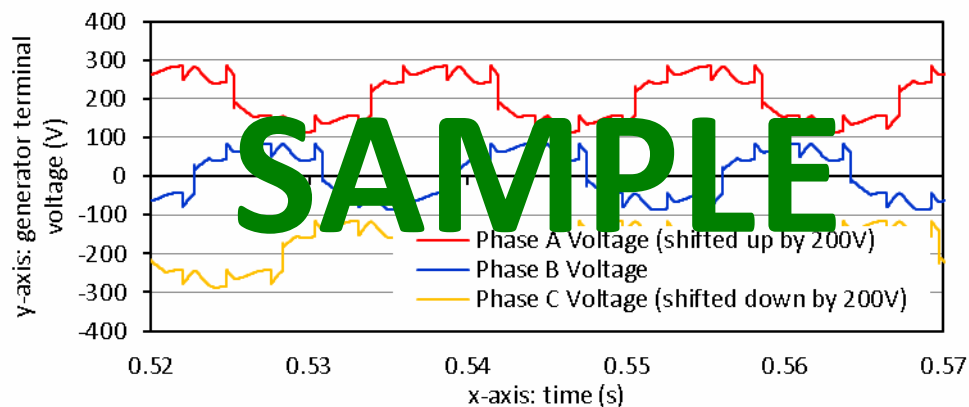


Figure 9: SAMPLE RESULTS – Three-Phase Generator Terminal Voltages (Phases A, B, and C) vs. Time for HVDC Transmission System of ELC470 Laboratory #2. Note that these values (and their shapes) may not be correct!!!

INSERT PLOT HERE

**Step #5:** Calculate the RMS magnitude of the phase A generator terminal voltage in Excel. Use the definition of root-mean square magnitude below.

$$V_{RMS} = \sqrt{\frac{1}{T} \int_0^T [v^2(t)] dt} = \sqrt{\frac{1}{T} \sum_{k=0}^K (v^2[k]) \Delta t[k]} \quad (7)$$

$T$  = period of waveform  
 $K$  = period of waveform in discrete time-steps  
 $\Delta t[k]$  = size of kth time-step

**Note:** To obtain the best results from (7), choose the window of integration to be equal to the fundamental waveform period (16.66ms) or a multiple of this period (e.g. 0.05ms).

**Note:** Also, try shifting the waveforms by a constant value (e.g. 200V) for purposes of comparison. However, remember to note this in the legend.

(pts)  $RMS(v_{GenA}(t)) =$  \_\_\_\_\_  
 = \_\_\_\_\_

**Step #6:** Copy and paste below, in Excel (not PSpice), the instantaneous voltage at the sending and receiving ends of the transmission line over 3 cycles (assuming 60Hz). Make sure simulation results begin from  $t = 1s$  and end with  $t = 1.05s$  to avoid any transients which may exist.

- (pts) is graph present?
- (pts) proper title, axes labels, and legend
- (pts) clearly labeled waveforms
- (pts) appropriate data ( $v_{Send}$ ,  $v_{Rec}$ )

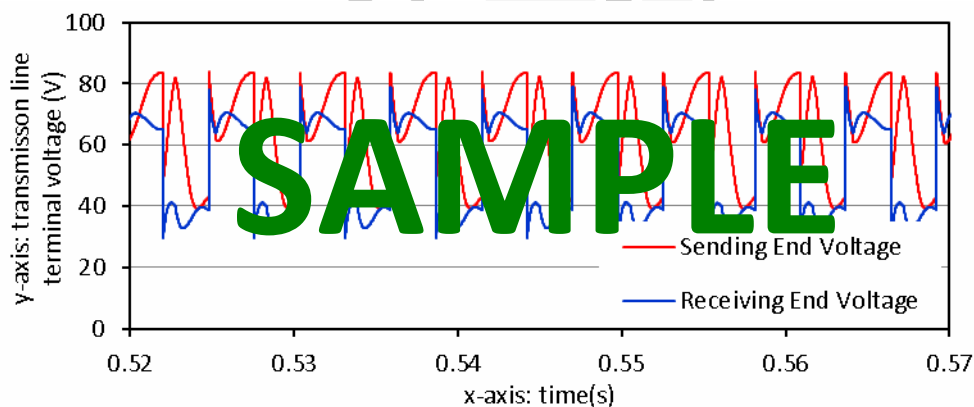


Figure 10: SAMPLE RESULTS – Sending and Receiving-End Line Terminal Voltages (dc) vs. Time for HVDC Transmission System of ELC470 Laboratory #2. Note that these values (and their shapes) may not be correct!!!

INSERT PLOT HERE

**Step #7:** Calculate the ripple in the sending and receiving-end transmission line voltages (for the case above). Refer to (8).

$$\Delta V = \max(v(t)) - \min(v(t)) \quad (8)$$

(pts)  $\Delta V_{Send} =$   
 $=$  \_\_\_\_\_

(pts)  $\Delta V_{Rec} =$   
 $=$  \_\_\_\_\_

**Step #8:** Calculate the average sending and receiving-end dc transmission line voltages (for the case above).

$$\text{avg}(v(t)) = \overbrace{\frac{1}{T} \int_0^T v(t) dt}^{\text{continuous average}} = \overbrace{\frac{1}{T} \sum_0^K v[k] \Delta t[k]}^{\text{discrete average}} \quad (9)$$

size of kth time-step

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<http://anthony.deese.googlepages.com>

**Note:** To obtain the best results from (7), choose the window of integration to be equal to the fundamental waveform period (16.66ms) or a multiple of the this period (e.g. 0.05ms).

(pts)  $\text{avg}(v_{Send}(t)) =$   
 $=$  \_\_\_\_\_

(pts)  $\text{avg}(v_{Rec}(t)) =$   
 $=$  \_\_\_\_\_

**Step #9:** Increase the resistance of the three-phase load from 5  $\Omega$  per phase to 500 k $\Omega$  per phase.

**Step #10:** Copy and paste below, in Excel (not PSpice), the three-phase instantaneous voltages at generator terminal as well as the sending and receiving ends of the transmission line over 3 cycles (assuming 60Hz). **Make sure simulation results begin from  $t = 1s$  and end with  $t = 1.05s$  to avoid any transients which may exist.**

- (pts) is graph present?
- (pts) proper title, axes labels, and legend
- (pts) clearly labeled waveforms
- (pts) appropriate data (  $v_{GenA}, v_{GenB}, v_{GenC}, v_{Send}, v_{Rec}$  )

INSERT PLOT HERE

**Step #11:** (pts) From the results above, answer the following question. What effect does loading have on the system? Why? Compare the plot from Steps#10 to those from Steps #4 and 6.

**Step #12:** Decrease the resistance of the three-phase load from 500 k $\Omega$  per phase back to 5  $\Omega$  per phase.



**Step #13:** Simulate this circuit (transient analysis with  $R_{Load} = 5\ \Omega$ ). Copy and paste below, in Excel (not PSpice), the three-phase instantaneous voltages at the load terminals over 3 cycles (assuming 60Hz). Make sure simulation results begin from  $t = 1s$  and end with  $t = 1.05s$  to avoid any transients which may exist.

- (pts) is graph present?
- (pts) proper title, axes labels, and legend
- (pts) clearly labeled waveforms
- (pts) appropriate data ( $v_{LoadA}$ ,  $v_{LoadB}$ ,  $v_{LoadC}$ )

**Note:** Try shifting the waveforms by a constant value (e.g. 200V) for purposes of comparison. However, remember to note this in the legend.

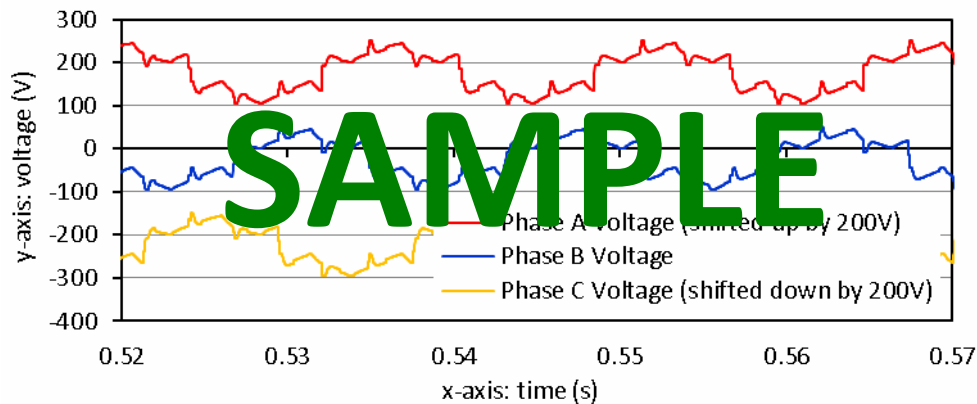


Figure 11: SAMPLE RESULTS – Load Voltages (abc) vs. Time for HVDC Transmission System of ELC470 Laboratory #2.  
Note that these values (and their shapes) may not be correct!!!

INSERT PLOT HERE

**Step #14:** Simulate the circuit in question (again transient analysis with  $R_{Load} = 5\ \Omega$ ). Copy and paste below, in Excel (not PSpice), the single-phase (aka. phase A) generator and load terminal voltages as well as currents over 3 cycles (assuming 60Hz). Make sure simulation results begin from  $t = 1s$  and end with  $t = 1.05s$  to avoid any transients which may exist.

- (pts) is graph present?
- (pts) proper title, axes labels, and legend
- (pts) clearly labeled waveforms
- (pts) appropriate data ( $v_{GenA}$ ,  $v_{LoadA}$ ,  $i_{GenA}$ ,  $i_{LoadA}$ )

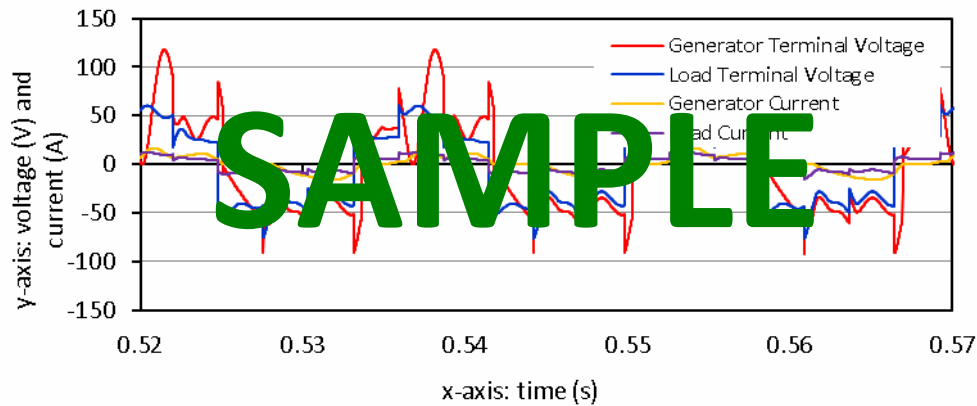


Figure 12: SAMPLE RESULTS – Generator and Load Terminal Voltages and Currents for Phase A vs. Time for HVDC Transmission System of ELC470 Laboratory #2. **Note that these values (and their shapes) may not be correct!!!**

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<http://anthony.deese.googlepages.com>

**Step #15:** Calculate the RMS magnitude of the voltages and currents below.

(pts)  $\text{RMS}(\mathbf{v}_{\text{GenA}}(t)) =$   
 $=$  \_\_\_\_\_

(pts)  $\text{RMS}(\mathbf{v}_{\text{LoadA}}(t)) =$   
 $=$  \_\_\_\_\_

(pts)  $\text{RMS}(\mathbf{i}_{\text{GenA}}(t)) =$   
 $=$  \_\_\_\_\_

(pts)  $\text{RMS}(\mathbf{i}_{\text{LoadA}}(t)) =$   
 $=$  \_\_\_\_\_

**Step #16:** Calculate the single-phase real power output of the generator and consumption of the load from the instantaneous voltage and current waveforms, as defined below. Refer to (10).

$$\text{average (aka. real) power } P = \frac{1}{T} \int_0^T \mathbf{v}(t) \mathbf{i}(t) dt = \frac{1}{T} \sum_{k=0}^K \mathbf{v}[k] \mathbf{i}[k] \Delta t \quad (10)$$



**Note:** To obtain the best results from (7), choose the window of integration to be equal to the fundamental waveform period (16.66ms) or a multiple of the this period (e.g. 0.05ms).

(pts)  $P_{\text{GenA}} =$   
 $=$  \_\_\_\_\_

(pts)  $P_{\text{LoadA}} =$   
 $=$  \_\_\_\_\_

**Step #17:** Calculate the efficiency of this transmission system, in percent. Refer to (11).

$$efficiency(\%) = 100 \left( \frac{P_{Load}}{P_{Gen}} \right) \quad (11)$$

(pts) efficiency =

= \_\_\_\_\_

**Step #18: (pts)** How does this efficiency compare to that from Lab #1? Why is it the case? **Note** that, in that lab, the generator output 416.20W and load received 253.33W (per phase). Refer to Figure 13.

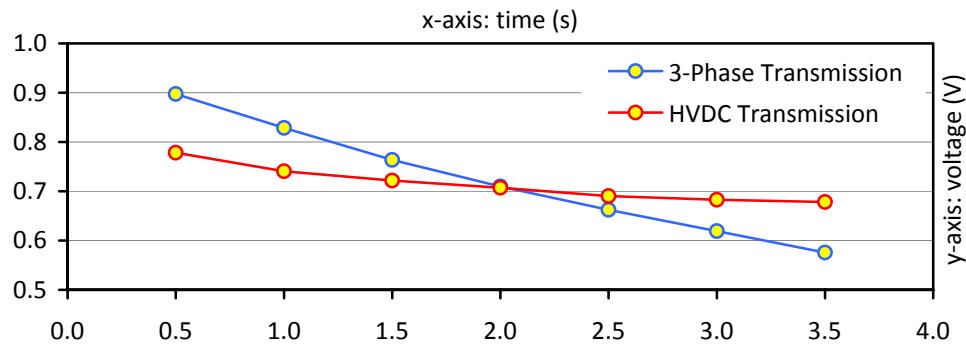


Figure 13: System Efficiency vs. Line Resistance for Three-Phase Systems in Lab #1 and #2 of ELC470

## Part #2: Harmonic Analysis

**Step #19:** Calculate the fundamental component of each waveform above via Fourier Analysis. Generate four graphs (corresponding to single-phase generator terminal voltage, load terminal voltage, generator current, and load current), each of which compares the observed waveform to the fundamental. Refer to the example below.

- (pts) is graph present?
- (pts) proper title, axes labels, and legend
- (pts) clearly labeled waveforms
- (pts) appropriate data (total instantaneous and fundamental components of  $V_{GenA}$ ,  $V_{LoadA}$ ,  $i_{GenA}$ ,  $i_{LoadA}$ )

**Note:** that any periodic waveform may be approximated by the sum of its dc, fundamental, and harmonic components as shown in (12). This is referred to as a Fourier Series.

the Fourier Series approximates any periodic waveform as the sum of its dc, fundamental, and harmonic components, as shown below

$$f(\omega t) = \underbrace{\frac{a_0}{2}}_{\text{dc}} + \underbrace{[a_1 \cos(\omega t) + b_1 \sin(\omega t)]}_{\text{fundamental component}} + \underbrace{[a_2 \cos(2\omega t) + b_2 \sin(2\omega t)]}_{\text{second harmonic component}} + \underbrace{[a_3 \cos(3\omega t) + b_3 \sin(3\omega t)]}_{\text{third harmonic component}} + \dots \quad (12)$$

Equation (12) may also be defined as below.

$$f(\omega t) = \frac{a_0}{2} + \sum_{k=1}^{\infty} a_k \cos(k\omega t) + b_k \sin(k\omega t) \quad (13)$$

The coefficients  $a$  and  $b$  are defined as below in continuous form. This lab presents discrete data. As such, the integrals of (14) must be converted to finite sums.

$$a_k = \frac{2}{T} \int_{-T/2}^{T/2} f(\omega t) \cos(k\omega t) dt \quad \text{for } k \geq 0$$

$$b_k = \frac{2}{T} \int_{-T/2}^{T/2} f(\omega t) \sin(k\omega t) dt \quad \text{for } k \geq 1 \quad (14)$$

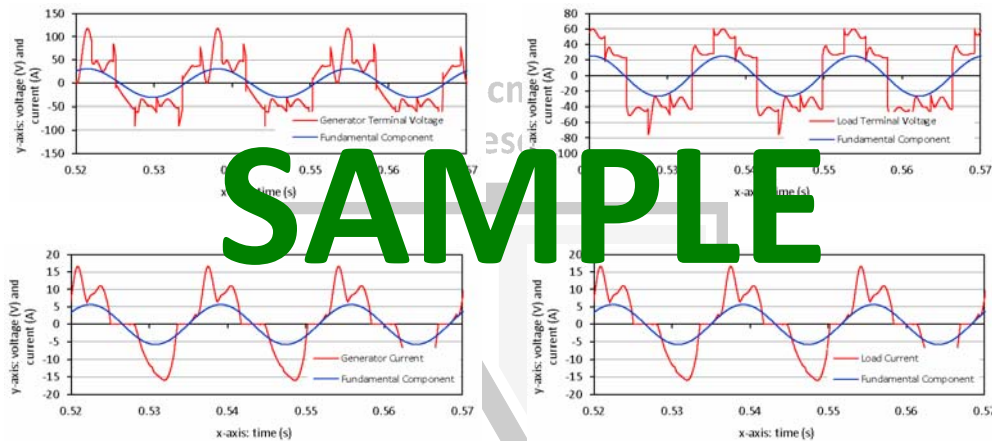


Figure 14: SAMPLE RESULTS – Comparison of Observed Waveforms and Fundamental Components of Generator and Load Terminal Voltages and Currents for Phase A vs. Time for HVDC Transmission System of ELC470 Laboratory #2. Note that generator terminal voltage is top-left, load terminal voltage is top-right, generator current is bottom-left, and load current is bottom-right. Note that these values (and their shapes) may not be correct!!!

INSERT PLOT HERE

**Step #20:** Define the fundamental waveforms above as phasors – using a process similar to that described in steps #9 and #10 of ELC470 lab #1. Equation (15) demonstrates how one may convert the Fourier function of (13) to phasor-form (neglect dc offset which should be small).

$$\underbrace{\left| \frac{\sqrt{a_k^2 + b_k^2}}{\sqrt{2}} \right|}_{\text{phasor form as function of RMS magnitude and phase angle}} \underbrace{\angle \tan^{-1} \left( \frac{b_k}{a_k} \right)}_{\text{sin-only representation of time-varying periodic waveform}} = \underbrace{\sqrt{a_k^2 + b_k^2} \sin \left( k\omega t + \tan^{-1} \left( \frac{b_k}{a_k} \right) \right)}_{\text{Fourier Series representation of time-varying periodic waveform}} = a_k \cos(k\omega t) + b_k \sin(k\omega t) \quad (15)$$

**Note:** Assume that the phase A terminal generator voltage has an angle of 0 degrees and shift all other phasors accordingly.

$$\begin{aligned} \text{(pts)} \quad \vec{V}_{GenA(1)} \text{ (phasor of fundamental component)} &= \\ &= \end{aligned}$$

(pts)  $\vec{V}_{LoadA(1)}$  (phasor of fundamental component) =  
= \_\_\_\_\_

(pts)  $\vec{I}_{GenA(1)}$  (phasor of fundamental component) =  
= \_\_\_\_\_

(pts)  $\vec{I}_{LoadA(1)}$  (phasor of fundamental component) =  
= \_\_\_\_\_

**Step #21:** Using the equation below, calculate the complex power supplied by the generator and absorbed by the load (considering fundamental waveform components only)

apparent power of fundmental waveforms:  $\vec{S}_{(1)} = \vec{V}_{(1)} \vec{I}_{(1)}^*$  (16)

(pts)  $P_{GenA(1)}$  (fundamental) =  
= \_\_\_\_\_

(pts)  $P_{LoadA(1)}$  (fundamental) =  
= \_\_\_\_\_

**Step #22: (pts)** Do the real power values calculated in Steps #16 and #21 match one another? Why or why not?

### Part #3: Filtering

**Step #23: (pts)** How may one use filtering to make the load voltage and current waveforms more sinusoid-like? Design a solution. Demonstrate, below, its affect on the waveforms as well as power loss along the transmission line?

**INSERT SCHEMATIC, PLOT, and LOSS CALCULATION HERE**

### Conclusion (pts):

In the conclusion section, you should answer the following questions.

- How would you evaluate your proposed solution / design? Does it operate as expected?
- Were there any significant discrepancies between theoretical, simulation, and hardware results? Can you offer an explanation?
- What lessons will you take away from this experiment? How do you feel this lab will help you in the future (classes as well as work environment)?
- What difficulties did you encounter from this experiment? For example, were any of the devices difficult to configure?