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).

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

$$P_{Loss} = |I_{Line}|^2 R_{Line} = \underbrace{\left(\frac{\sqrt{P_{Trans}^2 + Q_{Trans}^2}}{|\vec{V}_{Send}|} \right)^2}_{\text{losses may be reduced by minimizing magnitude of line current flow}} R_{Line} \tag{1}$$

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).

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

$$\text{dc transmission effects: } \underbrace{\frac{\sqrt{P_{Line}^2}}{\left|V_{Sending}-V_{Receiving}\right|}}_{|I_{Line}| \text{ when reactive power flow is eliminated}} < \underbrace{\frac{\sqrt{P_{Line}^2+Q_{Line}^2}}{\left|V_{Sending}-V_{Receiving}\right|}}_{\text{"normal" } |I_{Line}|} \tag{3}$$

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 60*Hz* waveforms into dc.
- *transmission line* – which conducts power from sending-end to receiving-end of line.
- *inverter* – which converts dc to 60*Hz* 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.

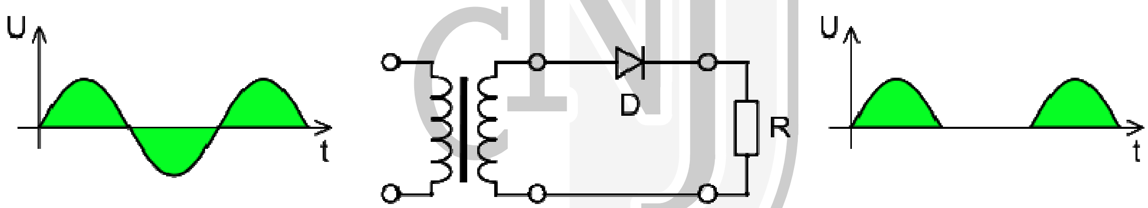

Figure 1: Half-Wave Rectifier with Input Waveform (left), Circuit (middle), and Output Waveform (right)

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.

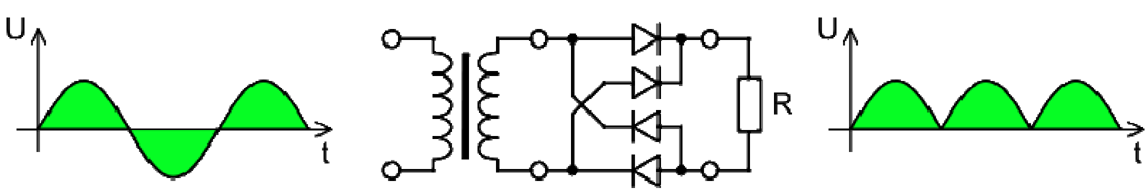

Figure 2: Full-Wave Rectifier with Input Waveform (left), Circuit (middle), and Output Waveform (right)

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).

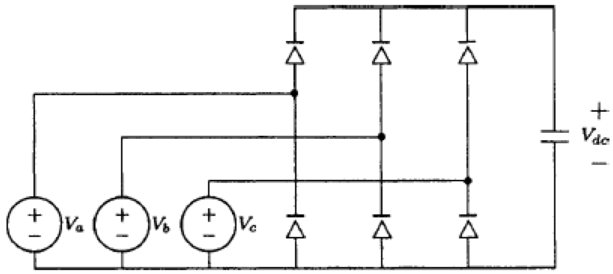

Figure 3: Three-Phase Rectifier (V_{abc} to V_{dc})

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).

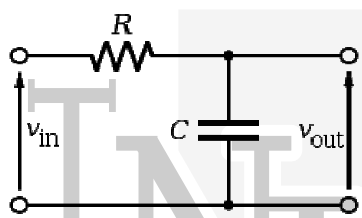

Figure 4: Low-Pass Filter

$$f_c = \frac{1}{2\pi RC} \tag{4}$$

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.

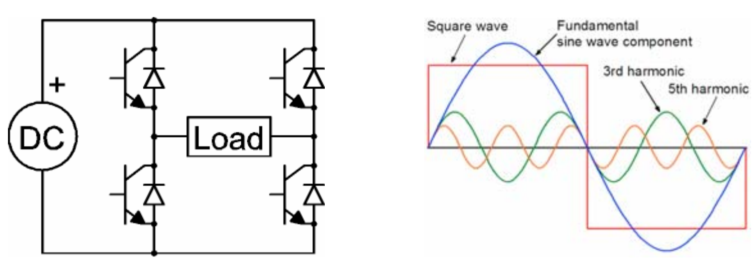

Figure 5: Single-Phase H-Bridge Inverter (left) and Sample Output (right)

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.

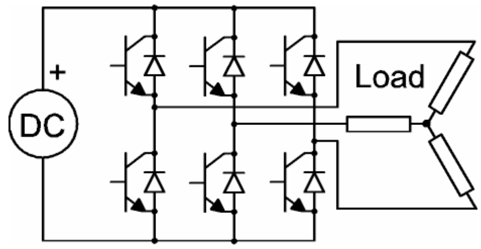

Figure 6: Three-Phase H-Bridge Inverter

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 $E_i = |E_i| \angle 0^O$.

$$\begin{aligned} L_S &= 2.7656mH \\ M_S &= 1.3828mH \end{aligned} \tag{5}$$

- 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.

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

- 3 single-phase loads – modeled as Y-connected impedances of 5Ω.

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

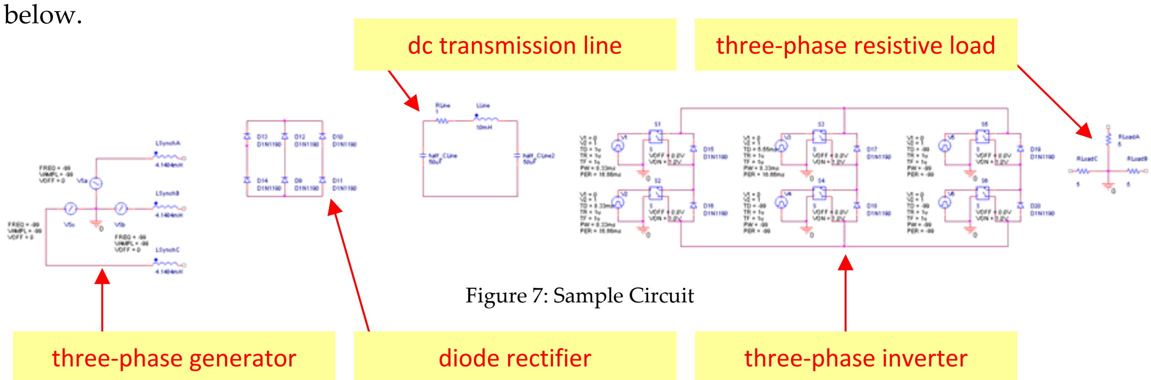

Figure 7: Sample Circuit

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 (VSa, VSb, VSc)
- 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 = 0*V*: sets the source's "off" value
- V2 = 1*V*: 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 = 1us: defines the rise-time of the pulse. Normally, it is set to a very small value.
- TF = 1us: 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 60*Hz* waveform.

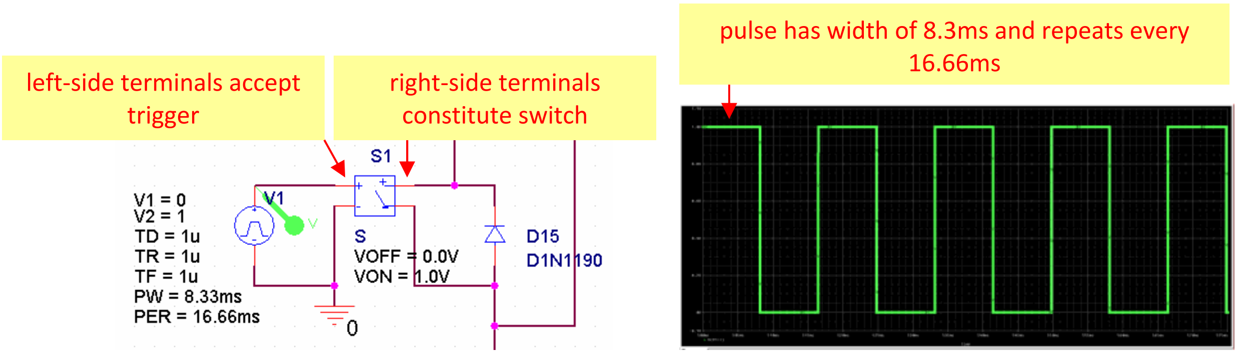

Figure 8: Example of VPULSE and Utilization to Trigger Ideal Switch

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.

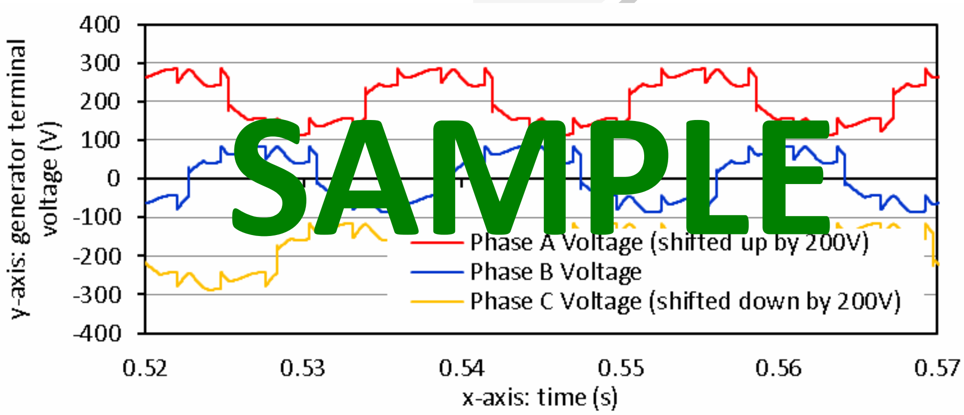

Figure 9: SAMPLE RESULTS – Three-Phase Generator Terminal Voltages (Phases A, B, and C) vs. Time for HVDC Transmission System of ELC470 Laboratory #2. Note that these values (and their shapes) may not be correct!!!

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.

$$V_{RMS} = \overbrace{\sqrt{\frac{1}{T}\int_0^T \left[\mathbf{v}^2(t)\right]dt}}^{T=\text{period of waveform}} = \overbrace{\sqrt{\frac{1}{T}\sum_{k=0}^{K}\left(\mathbf{v}^2[k]\right)\underbrace{\Delta\mathbf{t}[k]}_{\text{size of kth time-step}}}}^{K=\text{period of waveform in discrete time-steps}} \tag{7}$$

Note: To obtain the best results from (7), choose the window of integration to be equal to the fundamental waveform period (16.66*ms*) or a multiple of the this period (e.g. 0.05*ms*).
Note: Also, try shifting the waveforms by a constant value (e.g. 200*V*) for purposes of comparison. However, remember to note this in the legend.

(pts) $\mathbf{RMS}\left(\mathbf{v}_{GenA}(t)\right) =$
= ____

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 60*Hz*). 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})

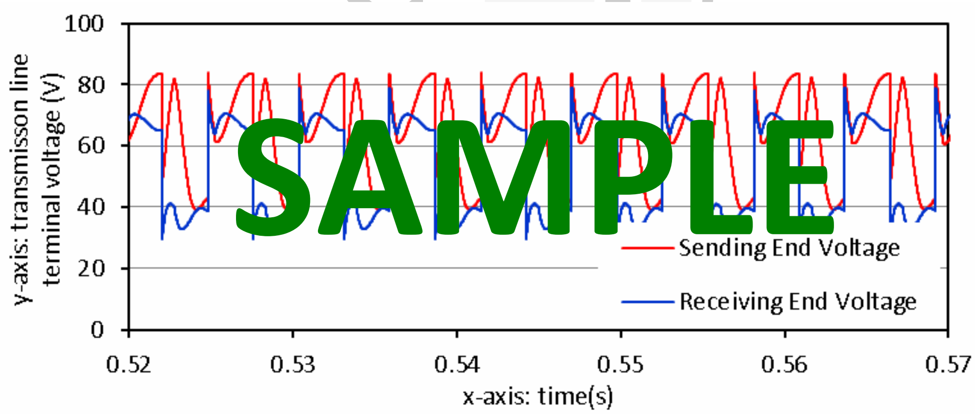

Figure 10: SAMPLE RESULTS – Sending and Receiving-End Line Terminal Voltages (dc) vs. Time for HVDC Transmission System of ELC470 Laboratory #2. Note that these values (and their shapes) may not be correct!!!

INSERT PLOT HERE

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

$$\Delta V = \mathbf{max}\left(\mathbf{v}(t)\right) - \mathbf{min}\left(\mathbf{v}(t)\right) \tag{8}$$

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

$= \underline{\hspace{10cm}}$

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

$= \underline{\hspace{10cm}}$

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

$$\mathbf{avg}\left(\mathbf{v}(t)\right) = \overbrace{\frac{1}{T}\int_0^T \mathbf{v}(t)\,dt}^{\text{continuous average}} = \overbrace{\frac{1}{T}\sum_0^K \mathbf{v}[k]\underbrace{\Delta\mathbf{t}[k]}_{\text{size of kth time-step}}}^{\text{discrete average}} \tag{9}$$

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

(pts) $\mathbf{avg}\left(\mathbf{v}_{Send}(t)\right) =$

$= \underline{\hspace{10cm}}$

(pts) $\mathbf{avg}\left(\mathbf{v}_{Rec}(t)\right) =$

$= \underline{\hspace{10cm}}$

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 60*Hz*). 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 60*Hz*). 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.

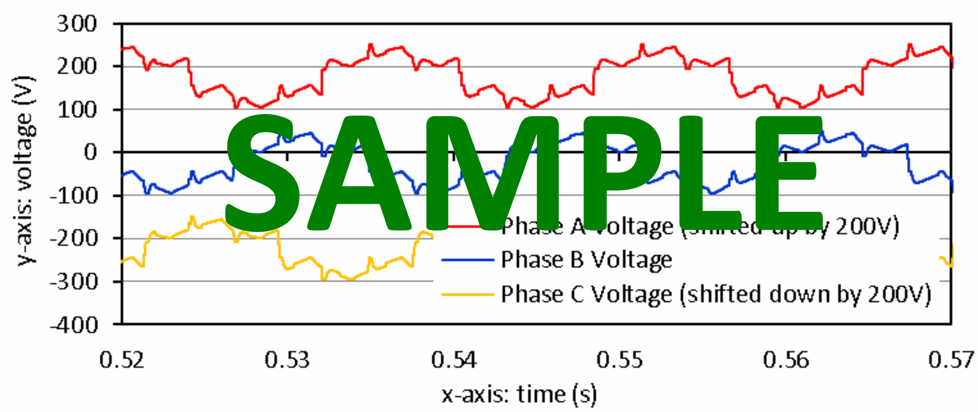

Figure 11: SAMPLE RESULTS – Load Voltages (abc) vs. Time for HVDC Transmission System of ELC470 Laboratory #2.
Note that these values (and their shapes) may not be correct!!!

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 60*Hz*). 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})

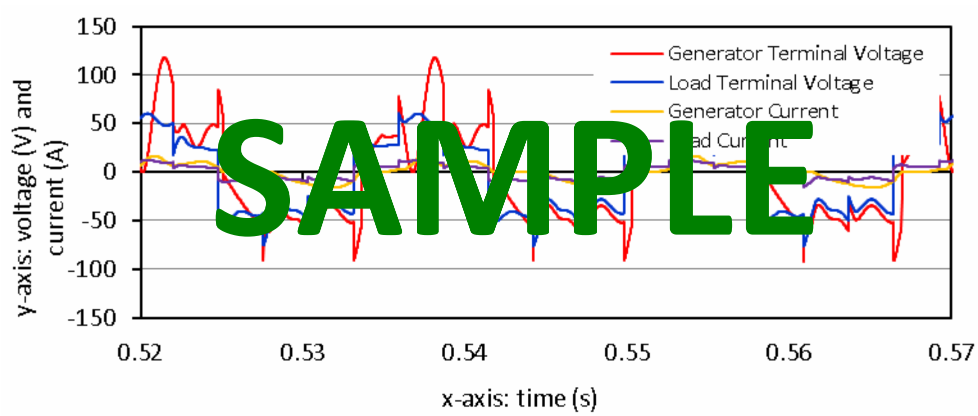

Figure 12: SAMPLE RESULTS – Generator and Load Terminal Voltages and Currents for Phase A vs. Time for HVDC Transmission System of ELC470 Laboratory #2. Note that these values (and their shapes) may not be correct!!!

INSERT PLOT HERE

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

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

= ____________________

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

= ____________________

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

= ____________________

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

= ____________________

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).

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

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

(pts) P_{GenA} =

= ____________________

(pts) P_{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.

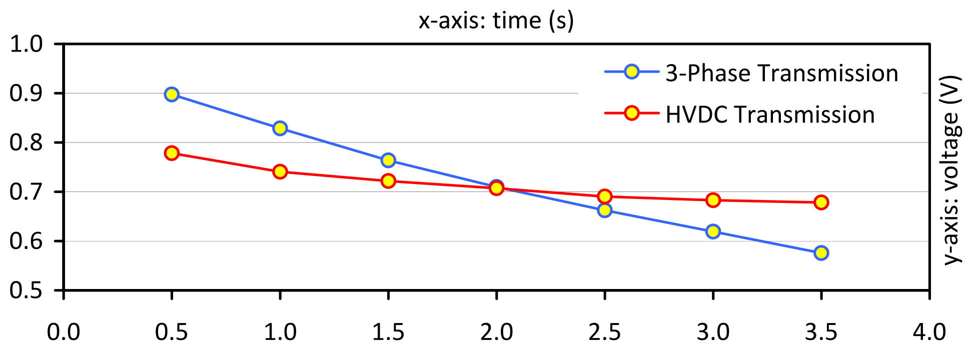

Figure 13: System Efficiency vs. Line Resistance for Three-Phase Systems in Lab #1 and #2 of ELC470

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.

$$\overbrace{\mathbf{f}(\omega t) = \underbrace{\frac{a_0}{2}}_{\text{dc}} + \underbrace{\left[a_1\mathbf{cos}(\omega t) + b_1\mathbf{sin}(\omega t)\right]}_{\text{fundamental component}} + \underbrace{\left[a_2\mathbf{cos}(2\omega t) + b_2\mathbf{sin}(2\omega t)\right]}_{\text{second harmonic component}} + \underbrace{\left[a_3\mathbf{cos}(3\omega t) + b_3\mathbf{sin}(3\omega t)\right]}_{\text{third harmonic component}} + \ldots}^{\text{the Fourier Series approximates any periodic waveform as the sum of its dc, fundamental, and harmonic components, as shown below}} \quad (12)$$

Equation (12) may also be defined as below.

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

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 converter to finite sums.

$$\begin{aligned} a_k &= \frac{2}{T}\int_{-T/2}^{T/2} \mathbf{f}(\omega t)\mathbf{cos}(k\omega t)\,dt \qquad \text{for } k \geq 0 \\ b_k &= \frac{2}{T}\int_{-T/2}^{T/2} \mathbf{f}(\omega t)\mathbf{sin}(k\omega t)\,dt \qquad \text{for } k \geq 1 \end{aligned} \tag{14}$$

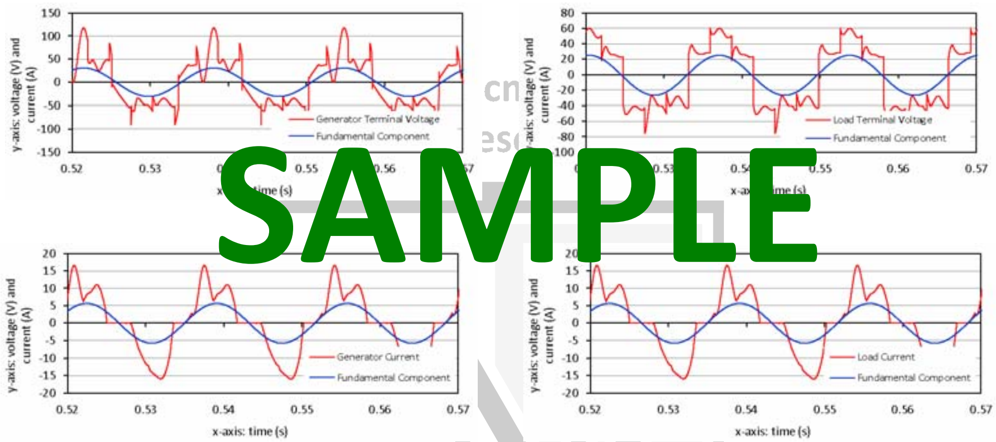

Figure 14: SAMPLE RESULTS – Comparison of Observed Waveforms and Fundamental Components of Generator and Load Terminal Voltages and Currents for Phase A vs. Time for HVDC Transmission System of ELC470 Laboratory #2. Note that generator terminal voltage is top-left, load terminal voltage is top-right, 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).

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

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

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

= ____

(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)

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

(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?