LECTURE 10

LECTURE NOTES: FEBRUARY 5, 2003

OUTLINE

REVIEW

1. Introduction to Operational Amplifiers
   - Application: Magnetic Storage Disk Drive Read Channel
2. Operational Amplifier Characteristics
3. Negative Feedback Principles
4. Ideal Operational Amplifier Circuits
5. Non-Ideal Operational Amplifier Circuits

HOMEWORK DUE FEBRUARY 17, 2003 BEFORE CLASS:

1. PSPice Problem 1:
   a. Complete the PSpice Tutorial I (on our Web site). Please use PSpice Version 9.2 if possible (PSpice CDs have been provided and more are available). Also, as noted, PSpice 9.2 is available on all SEASnet PCs.
   b. Solve for the power absorbed (dissipated) by the sources in the circuit shown below. Note that the currents in the sources are i_a = 0.1A, i_b = 1A, and i_c = 10A.
   c. Submit your problem by providing a hardcopy of the power dissipation data. This would be just as shown in Figures 32 and 33 of the PSpice Tutorial I.
   d. This is a small variant of the problem solved in the Tutorial I. The intent of this exercise is to familiarize you with the PSpice tool. Next week we will have homework assignments for PSpice directed to other problems.

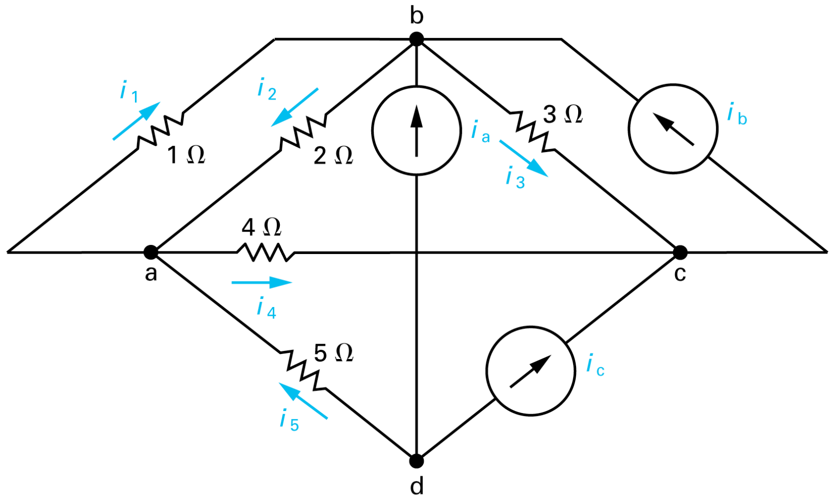

Figure 1. Circuit for PSpice Problem 1. Note: i_a = 0.1A, i_b = 1A, and i_c = 10A.

2. Textbook Problem 4.58 V_{TH} = 45V, R_{TH} = 30Ω
3. Textbook Problem 4.70 V_{TH} = 0 (note there are no independent sources, R_{TH} = 20Ω
4. Textbook Problem 4.74 There are two solutions arising from the two roots of a quadratic equation that you will encounter, R_O = 2.5Ω and 22.5Ω. Hint: for this problem, solve for the Thevinin voltage and resistance for the circuit *connected* to R_O. The Thevinin numerical values are: V_{TH} = 100V, R_{TH} = 7.5Ω Then, use this source equivalent to compute power dissipation in R_O as a function of the R_O value.
5. Textbook Problem 4.87 i_o = 2A , v_O = -136V

Check Web Site for general update and hints on homework

OPERATIONAL AMPLIFIER IMPORTANT DEFINITIONS

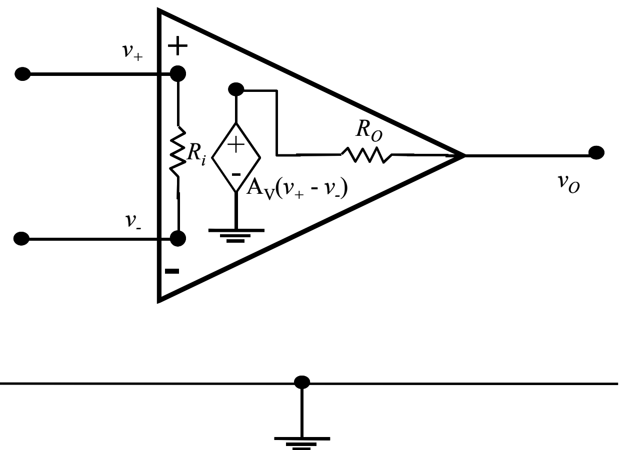

Figure 2. Operational Amplifier Equivalent Circuit

- Before proceeding further, we must list key definitions for the Operational Amplifier:

Non-Ideal Operational Amplifier

1.	A_V:	Open Loop Gain	Value is Finite
2.	R_i :	Open Loop Input Resistance	Value is Finite
3.	R_O :	Open Loop Output Resistance	Value is Finite

Ideal Operational Amplifier

1.	A_V:	Open Loop Gain	Value is Infinite
2.	R_i :	Open Loop Input Resistance	Value is Infinite
3.	R_O :	Open Loop Output Resistance	Value is Zero

- These quantities are termed Open Loop values since they will prevail in the case where the Operational Amplifier were to operate without negative feedback. In the event that negative feedback is properly included, the *system* values of gain and input and output resistance may be very different.

OPERATIONAL AMPLIFIER CIRCUIT ANALYTICAL PROBLEM SOLVING METHODS

- There are two fundamental classes of problems that we will encounter in solving operational amplifier circuit problems.
- The first class concerns the case where we assume ***Ideal Operational Amplifier*** behavior
- The second class concerns the case where we assume ***Non-Ideal Operational Amplifier*** behavior
- In both cases, with some care, we will be able to easily use our straightforward node-voltage approaches to solve our problem.
- In the ***Ideal Operational Amplifier*** case, we will be able to simplify our problem solving procedures with an assumption made regarding the equivalence of the inverting and non-inverting amplifier inputs.
- In the ***Non-Ideal Operational Amplifier*** we will introduce the Dependent Voltage source model for the Operational Amplifier including the appropriate values.
- The goal for solving Operational Amplifier Circuit problems at this stage of EE10 will be to:
    - Solve for the system ***Transfer Function.*** The ratio of output signal to input signal where these signals are current or voltage values. This is generally defines as a ***Gain*** value.
    - Solve for the *system closed loop input resistance* associated with defined ***input terminals.***
    - Solve for the *system closed loop output resistance* associated with defined ***output terminals.***
    - Our problem requirements may include that we must consider 1) the Operational Amplifier internal *open loop input resistance* and/or *open loop ouput resistance.*
    - Determine if the operational amplifier component is operating with its output voltage within its ***linear region*** as determined by its voltage supplies.

OPERATIONAL AMPLIFIER CIRCUIT ANALYTICAL PROBLEM SOLVING PROCEDURE FOR NON-IDEAL OPERATIONAL AMPLIFIER CIRCUITS

1) Consider the problem statement and determine whether the problem requires a non-ideal or ideal operational amplifier.

2) If non-ideal, then determine if *input or output resistance* values, R_i and R_O, must be considered and what *open loop gain,* A_V values must be considered.

3) Then, draw the operational amplifier circuit according to the problem statement using the operational amplifier symbol as in Figure 1, above.

4) Then, draw a new circuit using the appropriate Operational Amplifier model with Dependent Source, and R_i and R_O, as required.

5) Perform any available circuit simplifications with resistor equivalents.

6) Write down the Node Voltage equation using the Ground symbols as the common reference nodes. Note that *all Ground Symbols* ***are part of the same node***. As always, the Node Voltages are defined positive and defined relative to the Ground references.

7) Solve the Node Voltage equations.

8) Use the Dependent source voltage value of $A_V(v_+ - v_-)$

9) Note very carefully the circuit components connected to the Non-Inverting (+) and Inverting (-) terminals.

10) Note very carefully how the *system* input voltage (V_i) or input current (I_i) is applied.

11) Solve for the requested values. This may require computing

    a. For amplifier system voltage gain: the ratio of system output voltage to input voltage

    b. For amplifier system voltage to current gain: the ratio of system output current to input voltage

    c. For amplifier system current to voltage gain: the ratio of system output voltage to input current

    d. For amplifier system current to current gain: the ratio of system output current to input current

    e. For amplifier system input resistance: the ratio of system input voltage to input current

    f. For amplifier system output resistance: the Thevenin resistance at the output terminals (of course, computed without an input signal applied).

OPERATIONAL AMPLIFIER CIRCUIT ANALYTICAL PROBLEM SOLVING PROCEDURE FOR NON-IDEAL OPERATIONAL AMPLIFIER CIRCUITS: REVIEW

- Lets return to a problem that we have previously discussed and examine a specific feature of operational amplifier feedback circuit characteristics.
- The first circuit we will reexamine will the Non-Inverting Voltage amplifier.
- Our problem statement is:

> *Determine Voltage Gain for the Non-Inverting Voltage Amplifier, for an Operational Amplifier having an* Open Loop Output Resistance, R_O. *Compute for finite open loop gain and infinite open loop gain.*

- The circuit is shown below.

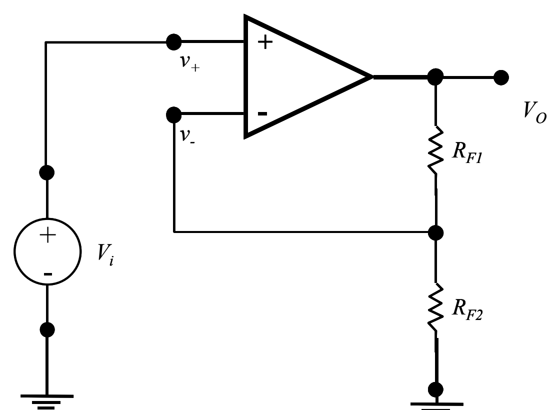

Figure 3. The Non Inverting Operational Voltage Amplifier

- We first drew our circuit model.
- We had included one non-ideal feature to this Operational Amplifier. This will be its output resistance, R_O.
- So, lets insert the true model elements for the Operational Amplifier. The new circuit appears below.
- We use Node Voltage methods to solve for output voltage. For the node at the output, where v_O is measured, we have.

$$\frac{A_V(v_+ - v_-) - V_O}{R_O} - \frac{V_O}{R_{F1} + R_{F2}} = 0$$

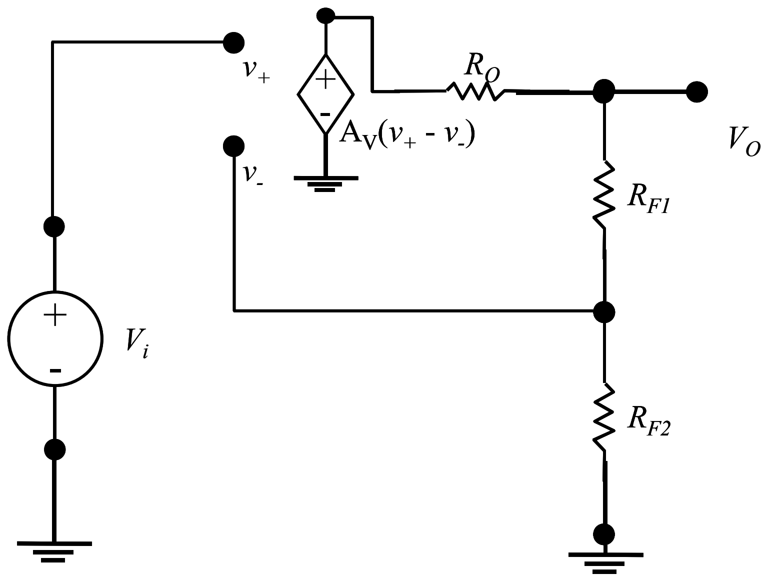

Figure 4. The Non Inverting Voltage Amplifier model including Output Resistance, R_O.

- Also, for the node at the inverting input,

$$1)\ \frac{V_O - v_-}{R_{F1}} - \frac{v_-}{R_{F2}} = 0$$

- And, further we can note that the input voltage is connected to the non-inverting input, so,

$$2)\ V_i = v_+$$

- Note that all the voltages are node voltages measured relative to the reference and ther terminals at the node are defined as positive (as usual).

- Now, from the second equation, we have just the voltage divider expression resulting from this:

$$3)\ v_- = V_O \frac{R_{F2}}{R_{F1} + R_{F2}}$$

- So, manipulating our first equation, and substituting for V_i,

$$4)\ \frac{A_V V_i}{R_O} - \frac{A_V v_-}{R_O} - \frac{V_o}{R_O} = \frac{V_O}{R_{F1} + R_{F2}}$$

- Now, we want an equation in terms of output and input voltage only. But, we have the voltage divider system providing our feedback signal and definition of v_-

- So,

$$5)\ \frac{A_V V_i}{R_O} - \frac{A_V V_O R_{F2}}{R_O\left(R_{F1}+R_{F2}\right)} - \frac{V_o}{R_O} = \frac{V_O}{R_{F1}+R_{F2}}$$

- Manipulating,

$$6)\ \frac{A_V V_i}{R_O} = V_o\left[\frac{A_V R_{F2}}{R_O\left(R_{F1}+R_{F2}\right)} + \frac{1}{R_{F1}+R_{F2}} + \frac{1}{R_O}\right]$$

- Finally, we obtain our output voltage in terms of input voltage:

$$7)\ V_o = \frac{\dfrac{A_V V_i}{R_O}}{\left[\dfrac{A_V R_{F2}}{R_O\left(R_{F1}+R_{F2}\right)} + \dfrac{1}{R_{F1}+R_{F2}} + \dfrac{1}{R_O}\right]}$$

- Now, at this stage, note which terms in the denominator contain the open loop gain factor.

- We can multiply through by the factor of R_O/A_V. This yields

$$8)\ \frac{V_o}{V_i} = \frac{1}{\left[\dfrac{R_{F2}}{\left(R_{F1}+R_{F2}\right)} + \left(\dfrac{1}{A_V}\right)\left(1+\dfrac{R_O}{R_{F1}+R_{F2}}\right)\right]}$$

- This expression is characteristic of Negative Feedback Operational Amplifier *transfer functions* that express the output signal of a circuit in terms of an input signal.

- Note, that in the limit of infinite open loop gain, we have,

$$9)\ \frac{V_o}{V_i} = \frac{\left(R_{F1}+R_{F2}\right)}{R_{F2}}$$

OPERATIONAL AMPLIFIER CIRCUIT ANALYTICAL PROBLEM SOLVING PROCEDURE FOR IDEAL OPERATIONAL AMPLIFIER CIRCUITS

- Some problems will be stated in terms of the Ideal Amplifier problem class.

- Lets consider the case of Ideal Operational Amplifiers. This is the specific case where open loop gain, A_V is assumed to be infinite.

- Now, lets examine a very important circuit property, the voltage difference at the Operational Amplifier inputs. Lets solve for (v_+ - v_-) in the above circuit.

- Previously, we had developed Equation (4):

$$\frac{A_V V_i}{R_O} - \frac{A_V v_-}{R_O} - \frac{V_o}{R_O} = \frac{V_O}{R_{F1} + R_{F2}}$$

- But, $V_i = v_+$, so,

$$\frac{A_V v_+}{R_O} - \frac{A_V v_-}{R_O} - \frac{V_o}{R_O} = \frac{V_O}{R_{F1} + R_{F2}}$$

- or

$$v_+ - v_- = \frac{-V_O}{A_V}\left(1 + \frac{R_O}{R_{F1} + R_{F2}}\right)$$

- Now, consider this in the limit where A_V tends towards infinite value.

- Then, the voltage difference at the amplifier input becomes zero. We can see this analytically here, and also observe this in our PSpice Simulation.

- This suggests a problem solving method where we set

$$v_+ = v_-$$

- Also, we set the current that flows into the Operational Amplifier at the Inverting and Non-Inverting inputs to zero.

- We then use these rules in writing our Node Voltage equations.

- In the Ideal Amplifier case, we have a new set of Procedures:

OPERATIONAL AMPLIFIER CIRCUIT ANALYTICAL PROBLEM SOLVING PROCEDURE FOR NON-IDEAL OPERATIONAL AMPLIFIER CIRCUITS

1) Consider the problem statement and determine whether the problem requires a non-ideal or ideal operational amplifier.

2) If Ideal, we will follow this procedure

3) Then, draw the operational amplifier circuit according to the problem statement using the *simplified* operational amplifier symbol as in Figure 2, above.

4) Perform any available circuit simplifications with resistor equivalents.

5) Write down the Node Voltage equation using the Ground symbols as the common reference nodes. Note that *all Ground Symbols* ***are part of the same node***. As always, the Node Voltages are defined positive and defined relative to the Ground references.

6) Solve the Node Voltage equations.

7) If Ideal, then note that we will assume that

$$v_+ = v_-$$

8) Also, we set the current that flows into the Operational Amplifier at the Inverting and Non-Inverting inputs to zero.

9) Note very carefully the circuit components connected to the Non-Inverting (+) and Inverting (-) terminals.

10) Note very carefully how the *system* input voltage (V_i) or input current (I_i) is applied.

11) Solve for the requested values. This may require computing

    a. For amplifier system voltage gain: the ratio of system output voltage to input voltage

    b. For amplifier system voltage to current gain: the ratio of system output current to input voltage

    c. For amplifier system current to voltage gain: the ratio of system output voltage to input current

    d. For amplifier system current to current gain: the ratio of system output current to input current

    e. For amplifier system input resistance: the ratio of system input voltage to input current

    f. For amplifier system output resistance: the Thevenin resistance at the output terminals (of course, computed without an input signal applied).

OPERATIONAL AMPLIFIER CIRCUIT ANALYTICAL PROBLEM SOLVING PROCEDURE FOR IDEAL OPERATIONAL AMPLIFIER CIRCUITS: REVIEW

- Lets return to the problem that we have previously discussed
- Our problem statement is:

Determine Voltage Gain for the Non-Inverting Voltage Amplifier, for an ideal Operational Amplifier.

- The circuit is shown below.

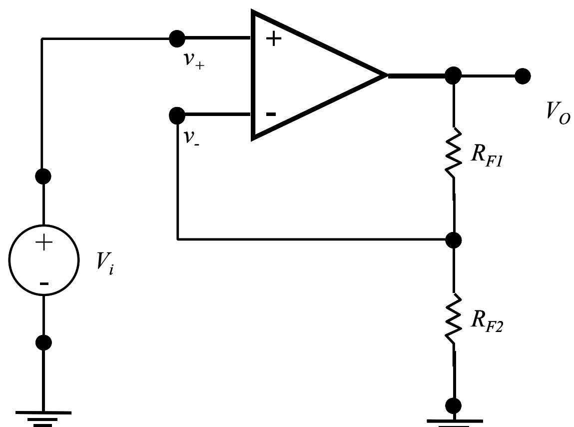

Figure 5. The Non Inverting Operational Voltage Amplifier

- Our circuit model.
- We note that

$$1)\ v_+ = v_-$$

- We use Node Voltage methods to solve for output voltage. There are two Essential Nodes. One is at the Inverting Input. One is the ground potential reference. For the node at the Inverting Input, we have the following Node Voltage Equation.

$$2)\ \frac{V_O - v_-}{R_{F1}} - \frac{v_-}{R_{F2}} = 0$$

- We also have the definition that:

$$3)\ V_i = v_+$$

- So, substituting for v_- with v_+ from 1) we have

$$\frac{V_O - v_+}{R_{F1}} - \frac{v_+}{R_{F2}} = 0$$

- and using that v_+ is just V_i we have,

$$\frac{V_O - V_i}{R_{F1}} - \frac{V_i}{R_{F2}} = 0$$

- We merely rearrange this to obtain the *Transfer Function* of V_O/V_i

$$\frac{V_O}{V_i} = \frac{(R_{F1} + R_{F2})}{R_{F2}}$$

- And, this is the *same* result we obtained before, in the limit of infinite open loop gain, A_V

- Lets review the results of our PSpice Simulation of the Non-Inverting Voltage Amplifier using the Transient Analysis method and plotting the Operational Amplifier Input Voltage difference.

OPERATIONAL AMPLIFIER CIRCUIT PSPICE SIMULATION PROBLEM SOLVING METHODS

- PSpice simulation of the Operational Amplifier and Operational Amplifier circuits will follow our analytical methods.

- We will use the Voltage Dependent Voltage Source, labeled as an "E" source in PSpice.

- This source contains four terminals. Two form inputs and two form outputs. The difference in input voltage between terminals 1 and 2 is amplified by the Gain factor and applied to the output terminals, 3 and 4.

- Thus, the constraint equation for the E Source is:

$$V_3 - V_4 = Gain(V_1 - V_2)$$

- This Gain value will correspond to the Open Loop Gain, A_V.

- Selection of the E Source from the Parts menu is shown below.

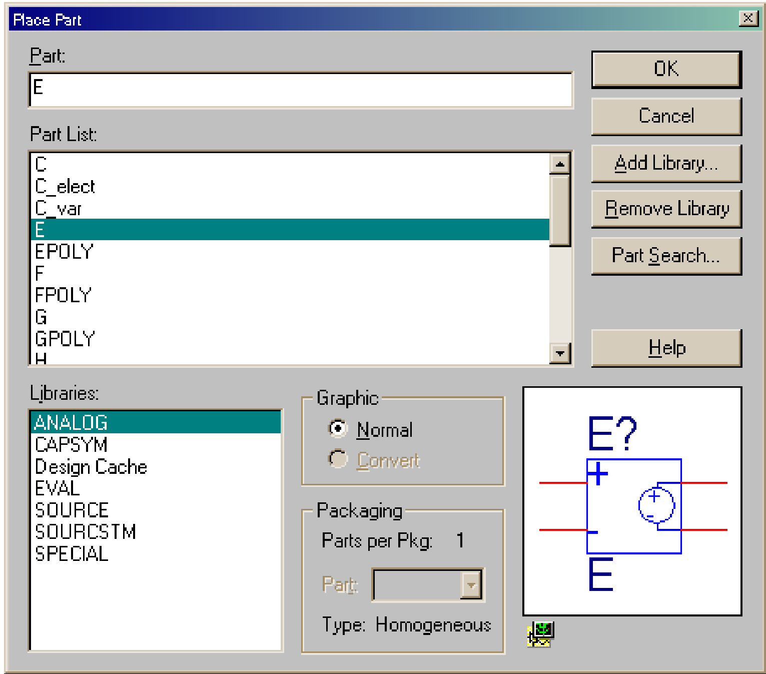

Figure 6. The E Source selected from the Parts Menu. Note this is located in the Analog Library

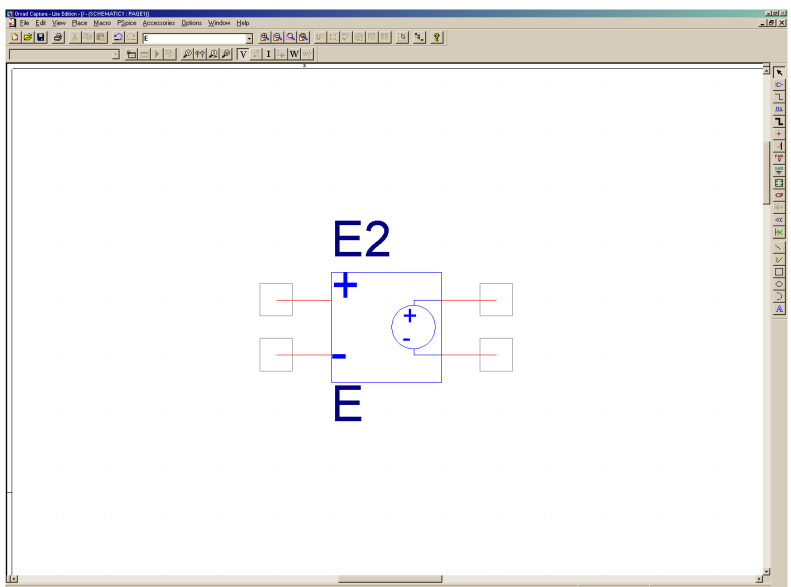

Figure 7. The E Source as it appears in a circuit.

- Now, the properties of the E Source, in particular its Gain, must be set by the Property Editor. Double click on the E Source to bring up the Property Editor.

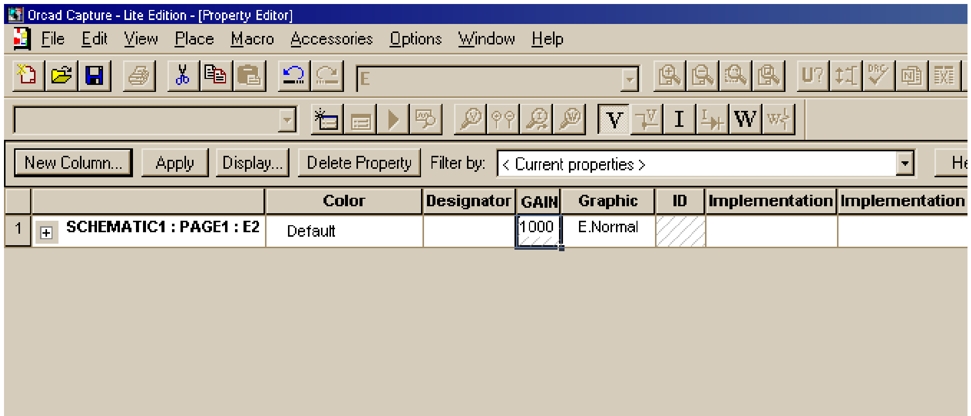

Figure 8. Double Click on the E-Source and this will bring up the Property Editor. Adjust Gain (or other parameters) and then press the Apply button. This is very important to allow the Property values to be set. Then, close this window by pressing on the "X" associated with this window – in the upper right – the standard Windows feature.

- Adjust Gain (or other parameters) and then press the Apply button. This is very important to allow the Property values to be set. Then, close this window by pressing on the "X" associated with this window – in the upper right – the standard Windows feature.

- **Be wary if the E Source Property Editor worksheet row above is expanded into two rows. It is best to collapse it into one row and make changes there. In any case, always check to ensure that the Gain values showing in both rows of the worksheet.**

- Let us proceed to examine the properties of a Non-Inverting Voltage Amplifier. This circuit will be used to investigate the characteristics of the input voltage difference versus open loop gain.

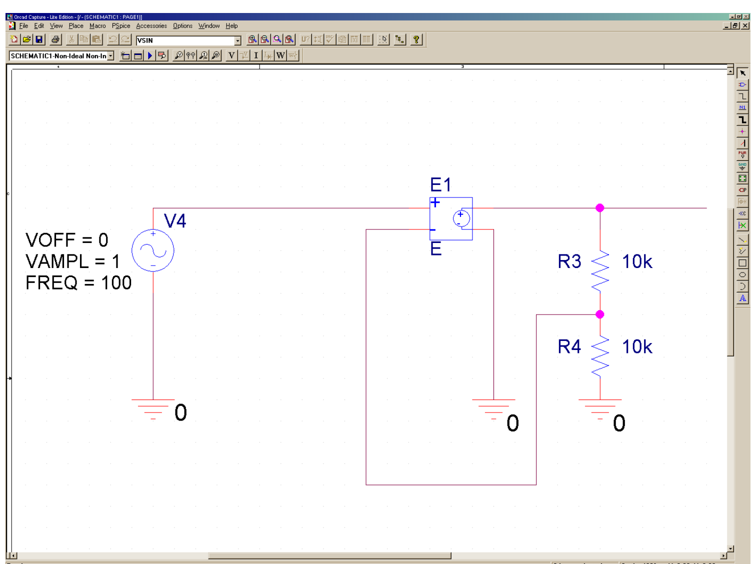

Figure 9. Circuit for demonstration of the dependence of Input Voltage Difference on Open Loop Voltage Gain. Here, A_V has a value of 1000

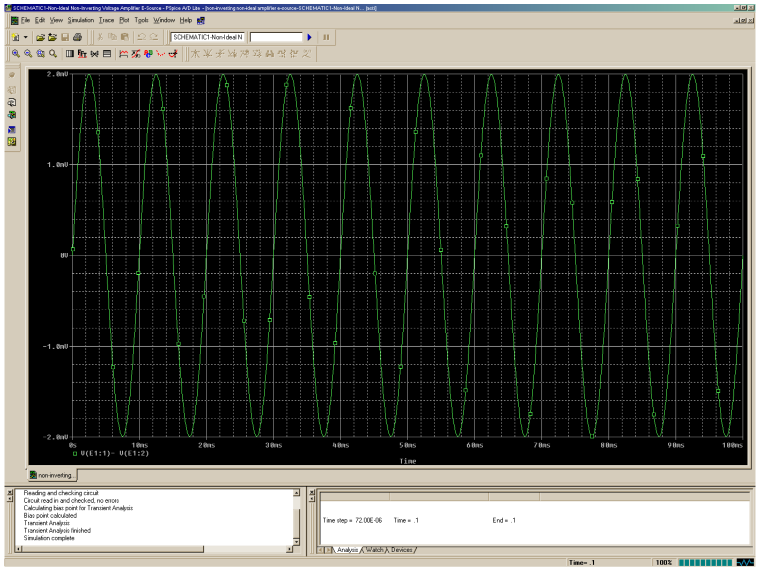

Figure 10. Results for demonstration of the dependence of Input Voltage Difference on Open Loop Voltage Gain. Here, AV has a value of 1000 Note this is the voltage difference at the inputs and its amplitude value is 2mV.

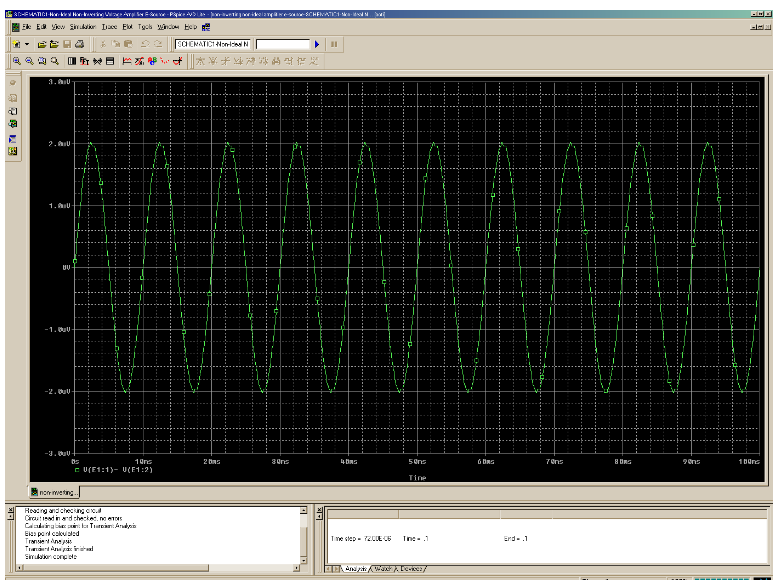

Figure 11. Results for demonstration of the dependence of Input Voltage Difference on Open Loop Voltage Gain. Here, AV has a value of 10^6 Note this is the voltage difference at the inputs and its amplitude value is 2μV.