**Circuit analysis with dependent sources (4.1-4.3)**

**A) Node Equations**

**B) Equivalent Sources**

**C) Amplifier Parameters:**
- Gain, $R_{IN}$, $R_{OUT}$
- Non-Ideal Op-Amp Model

**The 4 Basic Linear Dependent Sources**

- Voltage-controlled voltage source ... $V = A_v V_{cd}$
- Current-controlled voltage source ... $V = R_m I_2$
- Current-controlled current source ... $I = A_1 I_2$
- Voltage-controlled current source ... $I = G_m V_{cd}$

**EXAMPLE OF NODAL ANALYSIS WITH DEPENDENT SOURCES**

Standard technique, except an additional equation is needed if the dependent variable is an unknown current as here. Note $V_b$ is redundant.

$I = V_a / R_2 + (V_a - R_m I_2) / R_3$ and $I_2 = V_a / R_2$

Solving:

$V_a = I R_2 (R_3 - R_m)$

**THEVENIN EQUIVALENT WITH DEPENDENT SOURCES**

Method 1: Use $V_{oc}$ and $I_{sc}$ as usual to find $V_T$ and $R_T$ (and $I_{ss}$ as well)

Method 2: To find $R_T$ by the "ohmmeter method" turn off only the independent sources; let the dependent sources just do their thing.

See examples in text (such as Example 4.3).

This method also works when computing incremental signals such as a change in the source $V_S$ (given by $\Delta V_S$ or $v_S$) produces a change in $V_{IN}$ or $V_{OUT}$, (given by $\Delta V_{IN}$ or $\Delta V_{OUT}$) also written $v_{IN}$ and $v_{OUT}$), and their ratio called the small-signal gain ($\Delta V_{OUT} / \Delta V_S$) or ($v_{OUT} / v_S$)

**EXAMPLE CIRCUIT WITH MULTIPLE SOURCES**

Circuit with independent sources turned to zero

With method 2 we first find open circuit voltage $(V_v)$ and then we "measure" input resistance with source $I_{ss}$ turned off.

You verify the solution:

$V_{IN} = I_{ss} R_v (R_2 + R_3) / (R_2 + R_3 (1 - A))$

$R_m = R_v (R_2 + R_3) / (R_2 + R_3 (1 - A))$
EXAMPLE CIRCUIT: GAIN = \( \frac{\Delta V_{OUT}}{\Delta V_S} = \frac{V_{OUT}}{V_S} \)

\[ R_{IN} = \frac{R_s R_b}{R_s + R_b} \]
\[ V_{IN} = \frac{R_s}{R_s + R} V_s \]
\[ V_{OUT} = -G_m V_{IN} R_{OUT} = -G_m \left( \frac{R_s + R_{IN} + R_L}{R_s + R_L} \right) V_s \]

Input voltage divider and output current divider reduce the gain.

EXAMPLE CIRCUIT: INPUT/OUTPUT RESISTANCE

\[ R_{IN} = R_x \]
\[ R_{OUT} = \frac{R_x}{R_x + R} \]

Can circuit design improve \( R_{IN} \) and \( R_{OUT} \) or do we need better devices?

EXAMPLE CIRCUIT: INCREASED INPUT RESISTANCE

Add resistor \( R_x \)

Analysis: apply \( i_{\text{TEST}} \) and evaluate \( v_{\text{TEST}} \)

\[ V_{IN} = R_{IN} \text{TEST} + V_E \]

KCL \[ \frac{v}{R_x} + \frac{v_{\text{TEST}}}{R_x} - G_m R_{IN} \text{TEST} = 0 \]

Check for special case for \( R_x \) infinite

Outline your circuit analysis strategy here.

Hint: 1) Find \( V_x \) in terms of \( V_{\text{TEST}} \), 2) plug into expression for \( V_x \) and then 3) solve for \( V_x \) which appears on both sides of the equation.

Answer:

\[ V_x = V_{\text{TEST}} \left( \frac{A R_x + R_2}{A + R_1} \right) \]

\[ V_x = V_{\text{TEST}} \frac{R_x + R_2}{R_1} \]

Intuitive Explanation: \( G_m \) boops current which has to also go through \( R_x \). This raises \( v_{\text{TEST}} \) and the output impedance \( v_{\text{TEST}}/i_{\text{TEST}} \)

EXAMPLE CIRCUIT: INCREASED OUTPUT RESISTANCE

Add resistor \( R_x \)

The input has been assumed to be shorted

Analysis: apply \( i_{\text{TEST}} \) and evaluate \( v_{\text{TEST}} \)

Unknowns: \( i_{\text{TEST}} \), \( v_{\text{TEST}} \), \( v_{\text{IN}} \), \( v_E \)

Need 3 equations to find the ratio of \( i_{\text{TEST}}/v_{\text{TEST}} \)

Intuitive Explanation: \( G_m \) boops current which has to also go through \( R_x \). This raises \( v_{\text{TEST}} \) and the output impedance \( v_{\text{TEST}}/i_{\text{TEST}} \)

Try a bag. It is even easier

Finish this in the homework.

NON-IDEAL OP-AMPS

JUST ANOTHER CASE OF ANALYSIS WITH DEPENDENT SOURCES

Example:

Circuit (assume \( R_{IN} = 0 \))

Analysis:

Outline your circuit analysis strategy here.

Answer:

\[ V_x = V_{\text{TEST}} \left( \frac{A R_x + R_2}{A + R_1} \right) \]

\[ V_x = V_{\text{TEST}} \frac{R_x + R_2}{R_1} \]

if \( A \to \infty \)}