EE 330
Lecture 28

Thyristor Circuits
Amplifier Biasing (precursor)
Two-Port Amplifier Model
Review from Last Lecture

The ideal Triac

Consider the basic Triac circuit
The Basic Triac Circuit

Assume ideal Triac

Load Line: \[ V_{AC} = I_T R_L + V_{TR} \]

Analysis: \[ I_I = f(V_{TR}, V_{GT1}) \]

The solution of these two equations is at the intersection of the load line and the device characteristics

Two stable operating points for both positive and negative \( V_{AC} \)

If \( V_{AC} \) is a sinusoidal signal, will stay OFF
The Basic Triac Circuit

Review from Last Lecture
Assume ideal Triac

Load Line: \( V_{CC} = I_T R_L + V_{TR} \)

Analysis:
\[
V_{AC} = I_T R_L + V_{TR} \quad \quad I_{FI} = f(V_{TR}, V_{GT2})
\]

Single solution for both positive and negative \( V_{AC} \)

If \( V_{AC} \) is a sinusoidal signal will stay ON

(except for small time when \( I_T = 0 \) but then ON and OFF state of Triac do not alter current in circuit)
The Actual Triac in Basic Circuit

Can turn on for either positive or negative $V_{AC}$ with single gate signal
Quadrants of Operation Defined in $V_{M21}-V_{GT1}$ plane

(not in the $I_T-V_{M21}$ plane)

But for any specific circuit, can map quadrants from the $V_{M21}-V_{GT1}$ plane to $I_T-V_{M21}$ plane
Review from Last Lecture

Identification of Quadrants of Operation in $I_T-V_{M21}$ plane

Curves may not be symmetric between $Q_1$ and $Q_3$ in the $I_T-V_{M21}$ plane

Turn on current may be large and variable in $Q_4$ (of the $V_{M21}-V_{GT1}$)

Generally avoid operation in $Q_4$ (of the $V_{M21}-V_{GT1}$ plane)

Most common to operate in $Q2$-$Q3$ quadrants or $Q1$-$Q3$ quadrants (of the $V_{M21}-V_{GT1}$ plane)
Some Basic Triac Application Circuits

(\(V_{GG}\) often from logic/control circuit)

Quad 1 : Quad 4
(not attractive because of Quad 4)

Quad 2 : Quad 3
Some Basic Triac Application Circuits

Limitations?

If \( V_{AC} \) is the standard 120VAC line voltage, where do we get the dc power supply?

Direct digital control of trigger voltage/current with dedicated IC
Some Basic Triac Application Circuits

Quad 1 : Quad 3

Quad 1 : Quad 3

Quad 1 : Quad 3
Some Basic Triac Application Circuits

Quad 1/Quad 2 : Quad 3/Quad 4

Not real popular

Quad 1

Logic and/or Interface Circuit

Real popular
Thyristor Types

Some of the more major types:

• SCR
• Triac
• Bidirectional Phase-controlled thyristors (BCT)
• LASCR (Light activated SCR)
• Gate Turn-off thyristors (GTO)
• FET-controlled thyristors (FET-CTH)
• MOS Turn-off thyristors (MTO)
• MOS-controlled thyristors (MCT)
Thyristor Applications

Thyristors are available for working at very low current levels in electronic circuits to moderate current levels such is in incandescent light dimmers to very high current levels

$I_{TRIAC}$ from under $1\text{mA}$ to $10000\text{A}$

Applications most prevalent for moderate to high current thyristors
SCR, rated about 100 amperes, 1200 volts, 1/2 inch stud, photographed by C J Cowie. Uploaded on 4 April 2006.
Thanks to Prof. Ajjarapu for providing the following slides:

**PT40QPx45**

**Pulse Power Thyristor Switch**

Preliminary Information

Replaces November 1999 version, DS5267-1.1

**KEY PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{DRM}$</td>
<td>4500V</td>
</tr>
<tr>
<td>$I_{T(AV)}$</td>
<td>760A</td>
</tr>
<tr>
<td>$I_{TSM}$</td>
<td>13000A</td>
</tr>
<tr>
<td>$dl/dt$</td>
<td>5000A/μs</td>
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</tbody>
</table>

**APPLICATIONS**

- Pulse Power
- Crowbars
- Ignitron Replacement
**Bi-Directional Control Thyristor**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>$V_{RM}$</td>
<td>6500 V</td>
</tr>
<tr>
<td>$I_{T(\text{AV})M}$</td>
<td>1405 A</td>
</tr>
<tr>
<td>$I_{T(\text{RMS})}$</td>
<td>2205 A</td>
</tr>
<tr>
<td>$I_{TSM}$</td>
<td>$22 \times 10^3$ A</td>
</tr>
<tr>
<td>$V_{TO}$</td>
<td>1.2 V</td>
</tr>
<tr>
<td>$r_T$</td>
<td>0.6 mΩ</td>
</tr>
</tbody>
</table>

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Diameter = 140mm
Thanks to Prof. Ajjarapu for providing the following slides:

THE BIDIRECTIONAL CONTROL THYRISTOR (BCT)

by

Kenneth M. Thomas, Björn Backlund, Orhan Toker
ABB Semiconductors AG, CH5600 Lenzburg, Switzerland

Björn Thorvaldsson
ABB Power Systems AB, S-721 64 Västerås, Sweden

ABSTRACT

The Bidirectional Control Thyristor (BCT) is a new concept for high power thyristors integrated on a single silicon wafer with separate gate contacts. This unique design, based on free-floating silicon technology, successfully overcomes the traditional problems of interference experienced by bidirectional thyristors during dynamic operation which previously prevented the use of such devices. Such components are suitable for applications at high voltages like a normal thyristor but where triacs can no longer be used.
Thanks to Prof. Ajjarapu for providing the following slides:

High Current, High Voltage Solid State Discharge Switches for Electromagnetic Launch Applications

A. Welleman, R. Leutwyler, J. Waldmeyer
ABB Switzerland Ltd, Semiconductors - CH-5600 Lenzburg

Abstract—This presentation is about the work done on design, built-up, production and test of ready-to-use solid state switch assemblies using Thyristor- or IGCT technology. The presented thyristor switch assemblies, using 120 mm wafer size, are made to switch 3MJ stored energy into a load. The maximum charge voltage of the assembly is 12 kVdc, current capability more than 260kA@tp=3.3ms and a pulse repetition rate of up to 6 shots per minute with convection air cooling. New very large thyristors with 150 mm wafer diameter will be available from fall 2008. As second a 70 kA/21kVdc switch using IGCT technology will be presented. The switch is designed for fast discharge in the micro-second range and has a very high di/dt capability. Because for adapted standard products which can fulfill the requirements for pulsed applications. Beside the semiconductor devices, ABB is also in the position to supply complete custom made ready-to-use solid state switch assemblies including clamping, triggering, cooling and with application oriented testing. The presentation describes both, the loose semiconductor components as well as some custom made solid state switches for single pulse or low repetition rate pulsing.

II. Device Technology

2008 Paper
Thanks to Prof. Ajjarapu for providing the following slides:

Fig. 3: Thyristor Switch Assembly A-STP 5742U-18-CC
Stud-Mounted SCR
110 Amp RMS Rating

Thanks to Prof. Ajjarapu for providing the following slides:

- **Auxiliary Cathode Lead (Red)**
  Extends cathode potential to the control circuit.

- **Gate Lead (White)**

- **Cathode Lead**

- **Stud Anode**
Cross-section of a BCT wafer showing the antiparallel arrangement of the A and B component thyristors. The arrows indicate the convention of forward blocking for A and B.
Thyristor Valve - 12 Pulse Converter (6.5kV, 1568 Amp, Water cooled)

Thanks to Prof. Ajjarapu for providing the following slides:
Thyristor Observations

Many different structures used to build thyristors

Range from low power devices to extremely high power devices

Often single-wafer solutions for high power applications

Usually formed by diffusions

Widely used throughout society but little visibility

Applications somewhat restricted
Thyristors

The good

SCRs
Triacs

The bad

Parasitic Device that can destroy integrated circuits
The Thyristor

A bipolar device in CMOS Processes

Consider a Bulk-CMOS Process

If this parasitic SCR turns on, either circuit will latch up or destroy itself

Guard rings must be included to prevent latchup

Design rules generally include provisions for guard rings
Amplifier Biasing (precursor)

Not convenient to have multiple dc power supplies

$V_{OUTQ}$ very sensitive to $V_{EE}$
Amplifier Biasing (precursor)

Not convenient to have multiple dc power supplies
$V_{OUTQ}$ very sensitive to $V_{EE}$

Compare the small-signal equivalent circuits of these two structures
Amplifier Biasing (precursor)

\[ \begin{align*}
V_{CC} & \quad R_1 \quad v_{out} \\
V_{in} & \quad B \quad C \quad E \quad Q_1 \\
V_{EE} & \\
\end{align*} \]

Compare the small-signal equivalent circuits of these two structures

\[ \begin{align*}
\text{Since Thevenin equivalent circuit in red circle is } V_{IN}, \text{ both circuits have same voltage gain} \\
\end{align*} \]
Amplifier Characterization (an example)

Determine $V_{OUTQ}$, $A_v$, $R_{IN}$

Determine $v_{OUT}$ and $V_{OUT}(t)$ if $v_{IN}=.002\sin(400t)$

In the following slides we will analyze this circuit
Amplifier Characterization (an example)

Several different biasing circuits can be used

(biasing components: C, R\textsubscript{B}, V\textsubscript{CC} in this case, all disappear in small-signal gain circuit)
Amplifier Characterization (an example)

Determine $V_{OUTQ}$ and the SS voltage gain, assume $\beta=100$
Amplifier Characterization (an example)

Determine \( V_{OUTQ} \)

\[
\begin{align*}
I_C &= \beta I_B = 100 \left( \frac{12V - 0.6V}{500K} \right) = 2.3mA \\
V_{OUTQ} &= 12V - I_C R_1 = 12V - 2.3mA \cdot 2K = 7.4V
\end{align*}
\]
Amplifier Characterization (an example)

Determine the SS voltage gain

\[ \beta = 100 \]

\[ V_{CC} = 12V \]

\[ R_B = 500K \]

\[ R_1 = 2K \]

\[ C = 1\mu F \]

\[ V_{IN}(t) \]

\[ V_{OUT} \]

\[ \beta = 100 \]

**ss equivalent circuit**

\[ V_{OUT} = -g_m v_{BE} R_1 \]

\[ V_{IN} = v_{BE} \]

\[ A_V = -R_1 g_m \]

\[ A_V \approx -\frac{I_{CQ} R_1}{V_t} \]

\[ A_V \approx -\frac{2.3mA \cdot 2K}{26mV} \approx -177 \]

This basic amplifier structure is widely used and repeated analysis serves no useful purpose.

Have seen this circuit before but will repeat for review purposes.
Amplifier Characterization (an example)

Determine $R_{IN}$

$$R_{in} = \frac{V_{IN}}{i_{IN}}$$

$$R_{in} = R_B // r_\pi$$

Usually $R_B >> r_\pi$

$$R_{in} \approx R_B // r_\pi \approx r_\pi$$

$$R_{in} \approx r_\pi = \frac{I_{CQ}}{\beta V_t}$$
Examples

Determine $v_{out}$ and $V_{OUT}(t)$ if $v_{in} = .002\sin(400t)$

$$v_{OUT} = A_v v_{IN}$$

$$v_{OUT} = -177 \cdot .002 \sin(400t) = -0.354 \sin(400t)$$

$$V_{OUT}(t) \approx V_{OUTQ} + A_v v_{IN}$$

$$V_{OUT} \approx 7.4V - 0.35 \cdot \sin(400t)$$
End of Lecture 28
Two-Port Representation of Amplifiers

- Two-port model representation of amplifiers useful for insight into operation and analysis
- Internal components to the two-port can be quite complicated but equivalent two-port model is quite simple
Two-port representation of amplifiers

Amplifiers can be modeled as a two-port

• Amplifier often unilateral (signal propagates in only one direction: wlog $y_{12}=0$)
• One terminal is often common
Two-port representation of amplifiers

- Thevenin equivalent output port often more standard
- $R_{IN}$, $A_V$, and $R_{OUT}$ often used to characterize the two-port of amplifiers
Amplifier input impedance, output impedance and gain are usually of interest.

**Why?**

Example 1: Assume amplifier is **unilateral**

Can get gain without reconsidering details about components internal to the Amplifier !!!

Analysis more involved when not unilateral
Amplifier input impedance, output impedance and gain are usually of interest.

Why?

Example 2: Assume amplifiers are unilateral

Can get gain without reconsidering details about components internal to the Amplifier !!!

Analysis more involved when not unilateral
Two-port representation of amplifiers

- **Amplifier usually unilaterial** (signal propagates in only one direction: wlog $y_{12}=0$)
- One terminal is often common
- “Amplifier” parameters often used

### y parameters

- Amplifier parameters can also be used if not **unilaterial**
- One terminal is often common

### Amplifier parameters
Determination of small-signal model parameters:

In the past, we have determined small-signal model parameters from the nonlinear port characteristics

\[
\begin{align*}
I_1 &= f_1(V_1, V_2) \\
I_2 &= f_2(V_1, V_2)
\end{align*}
\]

\[
y_{ij} = \left. \frac{\partial f_i(V_1, V_2)}{\partial V_j} \right|_{V=V_Q}
\]

• Will now determine small-signal model parameters for two-port comprised of linear networks
• Results are identical but latter approach is often much easier
Two-Port Equivalents of Interconnected Two-ports

Example:

- could obtain two-port in any form
- often obtain equivalent circuit w/o identifying independent variables
- Unilateral iff $A_{VR}=0$
- Thevenin-Norton transformations can be made on either or both ports
Two-Port Equivalents of Interconnected Two-ports

Example:
Determination of two-port model parameters
(One method will be discussed here)

A method of obtaining $R_{in}$

$$R_{in} = \frac{V_{test}}{i_{test}}$$

Terminate the output in a short-circuit

$$i_1 = v_1 \left( \frac{1}{R_{in}} \right) + v_2 \left( \frac{-A_{VR}}{R_{in}} \right)$$
$$i_2 = v_1 \left( \frac{-A_{V0}}{R_0} \right) + v_2 \left( \frac{1}{R_0} \right)$$

$v_2 = 0$

$R_{in} = \frac{V_{test}}{i_{test}}$
Determination of two-port model parameters

A method of obtaining $A_{V0}$

<table>
<thead>
<tr>
<th>Test voltage $V_{test}$</th>
<th>$i_1$</th>
<th>$i_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{VR}V_2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$A_{V0}V_1$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Terminate the output in an open-circuit

$$i_1 = V_1 \left( \frac{1}{R_{in}} \right) + V_2 \left( -\frac{A_{VR}}{R_{in}} \right)$$

$$i_2 = V_1 \left( -\frac{A_{V0}}{R_0} \right) + V_2 \left( \frac{1}{R_0} \right)$$

$$i_2 = 0$$

$$A_{V0} = \frac{V_{out-test}}{V_{test}}$$
Determination of two-port model parameters

A method of obtaining $R_0$

\[
\begin{align*}
\mathbf{A} &= A_{vR} \mathbf{v}_2 + A_{v0} \mathbf{v}_1 \\
\mathbf{i}_1 &= \mathbf{v}_1 \left( \frac{1}{\mathbf{R}_{in}} \right) + \mathbf{v}_2 \left( - \frac{A_{vR}}{\mathbf{R}_{in}} \right) \quad \mathbf{v}_1 = 0 \\
\mathbf{i}_2 &= \mathbf{v}_1 \left( - \frac{A_{v0}}{\mathbf{R}_{0}} \right) + \mathbf{v}_2 \left( \frac{1}{\mathbf{R}_{0}} \right) \\
R_0 &= \frac{\mathbf{v}_{\text{test}}}{\mathbf{i}_{\text{test}}}
\end{align*}
\]

Terminate the input in a short-circuit
Determination of two-port model parameters

A method of obtaining $A_{VR}$

\begin{align*}
  i_1 &= v_1 \left( \frac{1}{R_{in}} \right) - v_2 \left( \frac{A_{VR}}{R_{in}} \right) \\
  i_2 &= v_1 \left( \frac{-A_{V0}}{R_0} \right) + v_2 \left( \frac{1}{R_0} \right)
\end{align*}

\[ i_1 = 0 \quad \Rightarrow \quad A_{VR} = \frac{v_{out-test}}{v_{test}} \]
Determination of Amplifier Two-Port Parameters

• Input and output parameters are obtained in exactly the same way, only distinction is in the notation used for the ports.

• Methods given for obtaining amplifier parameters $R_{in}$, $R_{OUT}$ and $A_V$ for unilateral networks are a special case of the non-unilateral analysis by observing that $A_{VR}=0$.

• In some cases, other methods for obtaining the amplifier parameters are easier than what was just discussed
Examples

Biasing Circuit

\[ V_{CC} = 12V \]

\[ R_{B1} = 50K \]

\[ C = 1uF \]

\[ R_{B2} = 10K \]

\[ R_2 = 2K \]

\[ Q_1 \]

\[ V_{OUT} \]

\[ V_{IN}(t) \]

\[ R_1 = 0.5K \]

Determine \( V_{OUTQ} \) and the SS voltage gain (\( A_V \)), assume \( \beta = 100 \)

(\( A_V \) is one of the small-signal model parameters for this circuit)
Determine $V_{OUTQ}$ and the SS voltage gain ($A_V$), assume $\beta=100$

($A_V$ is one of the small-signal model parameters for this circuit)
Determine $V_{OUTQ}$

This circuit is most practical when $I_B \ll I_{BB}$

With this assumption,

$$V_B = \left( \frac{R_{B2}}{R_{B1} + R_{B2}} \right) 12V$$

$$I_{CQ} = I_{EQ} = \left( \frac{V_B - 0.6V}{R_1} \right) = \frac{1.4V}{0.5K} = 2.8mA$$

$$V_{OUTQ} = 12V - I_{CQ} R_1 = 6.4V$$

Note: This Q-point is nearly independent of the characteristics of the nonlinear BJT!
Examples

Determine SS voltage gain

This voltage gain is nearly independent of the characteristics of the nonlinear BJT!

This is a fundamentally different amplifier structure

It can be shown that this is slightly non-unilateral

\[ V_{OUT} = -g_m V_{BE} R_2 \]
\[ V_{IN} = V_{BE} + R_1 \left( V_{BE} [g_\pi + g_m] \right) \]

\[ A_V = \frac{-R_2 g_m V_{BE}}{V_{BE} + R_1 \left( V_{BE} [g_\pi + g_m] \right)} = \frac{-R_2 g_m}{1 + R_1 \left( [g_\pi + g_m] \right)} \]

\[ A_V >> \frac{-R_2 g_m}{R_1 g_m} = \frac{-R_2}{R_1} \]
Examples

Determine $V_{OUTQ}$, $R_{IN}$, $R_{OUT}$, and the SS voltage gain, assume $\beta=100$
Examples

\[ R_2 = 2K \]
\[ Q_1 \]
\[ V_{OUT} \]
\[ V_{CC} = 12V \]
\[ V_{IN}(t) \]
\[ R_{B1} = 50K \]
\[ C_1 = 1uF \]
\[ R_1 = 0.5K \]
\[ R_{B2} = 10K \]
\[ C_2 = 100uF \]

Determine \( V_{OUT} \), \( R_{IN} \), \( R_{OUT} \), and the SS voltage gain, \( A_{VR} \); assume \( \beta = 100 \)

\( A_V \), \( R_{IN} \), \( R_{OUT} \), and \( A_{VR} \) are the small-signal model parameters for this circuit.
Examples

\[ R_2 = 2K \]
\[ Q1 \]
\[ V_{OUT} \]
\[ V_{CC} = 12V \]

\[ V_{IN}(t) \]
\[ R_{B1} = 50K \]
\[ C_1 = 1\mu F \]

This is the same as the previous circuit!

\[ V_{OUTQ} = 6.4V \]

\[ I_{CQ} = \frac{5.6V}{2K} = 2.8mA \]

Note: This Q-point is nearly independent of the characteristics of the nonlinear BJT!

The dc equivalent circuit
Examples

Determine the SS voltage gain

This is the same as the previous-previous circuit!

\[ A_V \approx -g_m R_2 \]

\[ A_V \approx -\frac{I_{CQ}R_2}{V_t} \]

\[ A_V \approx -\frac{5.6V}{26mV} = -215 \]

Note: This Gain is nearly independent of the characteristics of the nonlinear BJT!
Examples

Determine of $R_{IN}$

The SS equivalent circuit

$R_{IN} = R_{B1} // R_{B2} // r_\pi \quad \square \quad r_\pi$

$r_\pi = \left( \frac{I_{CQ}}{\beta V_t} \right)^{-1} = \left( \frac{2.8mA}{100 \cdot 26mV} \right)^{-1} = 928\Omega$

$R_{IN} = R_{B1} // R_{B2} // r_\pi \quad \square \quad r_\pi = 930\Omega$
Examples

Determine of $R_{OUT}$

The SS equivalent circuit

\[ R_{OUT} = \frac{V_{TEST}}{i_{TEST}} = R_2 // r_0 \]

\[ r_0 = \left( \frac{I_{CQ}}{V_{AF}} \right)^{-1} = \left( \frac{2.8\text{mA}}{200\text{V}} \right)^{-1} = (1.4\text{E}-5)^{-1} = 71\Omega \]

\[ R_{OUT} = R_2 // r_0 \square R_2 = 2\text{K} \]
Determine $A_{VR}$

The SS equivalent circuit

$\beta = 100$

$V_{OUT} = 0$

$A_{VR} = 0$
Determination of small-signal two-port representation

\[ V_{\text{IN}}(t) \]

\[ V_{\text{CC}} = 12\text{V} \]

\[ R_{B1} = 50\text{K} \]

\[ C_1 = 1\text{uF} \]

\[ R_{B2} = 10\text{K} \]

\[ R_1 = 0.5\text{K} \]

\[ R_2 = 2\text{K} \]

\[ C_2 = 100\text{uF} \]

\[ Q_1 \]

\[ V_{\text{OUT}} \]

\[ A_V = -215 \]

\[ R_{\text{IN}} \]

\[ r_{\pi} = 930\Omega \]

\[ R_{\text{OUT}} \]

\[ R_2 = 2\text{K} \]

This is the same basic amplifier that was considered many times
End of Lecture 28