Analog Circuits and Systems
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Lecture 20: DC Voltage Regulators
DC Voltage Power Supply

Diagram:
- AC to DC Converter
- Voltage Regulator
- Unregulated DC Voltage
- Regulated DC Voltage
- $V_{ac}$
AC to DC converter

Full wave rectifier with capacitive filter

\[
\text{Peak - to - peak ripple at the output} = \frac{I_i}{C} \left( \frac{T}{2} \right)
\]

where \(I_i\) is the average current delivered by AC to DC converter and \(T = 20\, \text{ms}\)
Voltage Regulator

![Voltage Regulator Diagram](image)
Characteristics of a Power Supply

Input Power = $P_i = V_i I_i$

Output Power = $P_o = V_o I_o$

Efficiency = $\eta = \frac{V_o I_o}{V_i I_i}$

Power dissipated in the voltage regulator

$P_i - P_o = P_d = V_i I_i - V_o I_o$

$= (V_i - V_o) I_o$ as $I_o$; $I_i$ except for bias current

$(V_i - V_o)$ should be kept to minimum (known as dropout voltage) in order to improve the efficiency.
Line regulation : Percentage change in $V_o$ as the input voltage $V_i$ changes from its maximum to minimum $\frac{\partial V_o}{V_o} \times 100$

Load regulation : Percentage change in $V_o$ as the output current $I_o$ is changed from its minimum to maximum $\frac{\partial V_o}{V_o} \times 100$

Temperature coefficient of the output voltage : Change in output voltage for a small change in input voltage at a specified output voltage expressed in terms of parts per million $= \left( \frac{\partial V_o}{\partial T} \right) \frac{ppm}{^\circ C}$
Characteristics of a Power Supply (contd.,)

Output impedance : Change in output voltage for a small change in output current at a given load current $I_o \left( \frac{\partial V_o}{\partial I_o} \right)$

Ripple rejection factor : Percentage change in output voltage for a small change in input voltage around the nominal value of input voltage. $\left( \frac{\partial V_o}{\partial V_i} V_i \right) V_o – PSRR (Power Supply Rejection Ratio)$
Load/Line Transient Regulation

- Voltage at the output terminal is likely to have undesirable transients at the time of switching on the input power or when step load changes occur.
- The output impedance of the voltage regulator is complex.
- The presence of feedback loop with large loop gain and the multiple poles associated with this loop makes the output impedance complex.
- Compensation has to be provided to make the output impedance resistive.
VCVS as voltage regulator

\[ V_{\text{reg}} = \left(1 + \frac{R_2}{R_1}\right)V_Z \]
Voltage regulator as a feedback system

VCVS as voltage regulator

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Voltage regulator as a feedback system (contd.,)

Forward path \( G_1 = \frac{G_{10}}{1 + \frac{s}{\omega_1}} \left( 1 + \frac{s}{\omega_2} \right) \); \( \frac{G_{10} \omega_1}{s \left( 1 + \frac{s}{\omega_2} \right)} \) for \( \omega_1 \ll \omega_2 \)

In internally compensated Op Amps \( \omega_1 \); \( \frac{\omega_2}{G_{10}} \)

Hence \( G_1 ; \frac{GB}{s \left( 1 + \frac{s}{\omega_2} \right)} \)

Feedback path \( G_2 ; \frac{R_1}{R_1 + R_2} \)
Voltage regulator as a feedback system (contd.,)
Voltage regulator as a feedback system (contd.,)

\[
\frac{V_o}{V_i} = \left(1 + \frac{R_2}{R_1}\right) \left(1 + \frac{1}{G_i}\right) \left(1 + \frac{R_2}{R_1}\right) \left(1 + \frac{s}{\omega_2}\right) = \frac{s\left(1 + \frac{R_2}{R_1}\right)}{1 + \frac{GB}{\omega_2}} + \frac{s^2\left(1 + \frac{R_2}{R_1}\right)}{\omega_2GB} = \frac{1 + \frac{R_2}{R_1}}{1 + \frac{s}{\omega_nQ} + \frac{s^2}{\omega_n^2}}
\]

where \(Q = \sqrt{\frac{GB}{\omega_n^2}}\)
Voltage regulator as a feedback system (contd.,)

- High rate of rise and least amount of ringing occurs at $Q = 1$
- $G_2 = \frac{V_Z}{V_o} = \frac{R_1}{R_1 + R_2}$ is determined by the required output voltage
- As $w_2$ and $G_{10}$ are fixed for a given Op Amp $w_1$ is chosen to make $Q = 1$
  
  $$\omega_1 = \frac{\omega_2}{G_{10}} \left(1 + \frac{R_2}{R_1}\right)$$
- In internally compensated Op Amps like 741 and TL081 $w_1$ is already chosen to make $Q = 1$ for $V_o = V_Z$, i.e., $G_2 = 1$
  
  $$\omega_1 = \frac{\omega_2}{G_{10}}$$
Voltage regulator as a feedback system (contd.,)

- For any other \( G_2 < 1 \); \( Q \) will always be correspondingly less than 1 resulting in unsatisfactory transient response.
- It is therefore necessary to use uncompensated Op Amps like LM748 to design voltage regulators with good transient response.
Design of Voltage Regulator using 741/TL081

- Design voltage regulator with a reference of 1.2 V for a regulated output of 10 V for a maximum load current 15 mA.
Design of Voltage Regulator using 741/TL081 (contd.)

- Voltage Regulator using Voltage reference IC for 1.2 V: REF3012

\[
\left(1 + \frac{R_1}{R_2}\right)10 = 1.2V
\]

\[R_1 = 1.2 \text{ k}\Omega \quad \text{and} \quad R_2 = 8.8 \text{ k}\Omega\]

The Op Amp used is 741
Simulation

[Graph and schematic diagram of a circuit with labels: 18V, 741, 9 to 9.1 Step]
Simulation
Current boosting pass transistor

- Super Transistor using opamp
Current boosting pass transistor (contd.,)

- using n-channel pass transistor
- using p-channel pass transistor
  - Load Dropout Regulator (LDO)
Voltage Regulator with Current Boosting
LM 2940: 1 Amp Low Drop Out Regulator

- Input Voltage Range = 6 V to 26 V
- Output Current in Excess of 1 A
- Dropout Voltage Typically 0.5 V at $I_{\text{OUT}} = 1$ A
- Output Voltage Trimmed before Assembly (5, 8, 9, 10, 12 and 15 volts)
- Load regulation: 80 to 130 mV from $I_o = 50$ mA to 1 amp
- Line regulation: 50 to 80 mV for $V_i = 2$ V to 26 V
- Output impedance: 35 to 55 mW at $I_o = 100$ mA $V_o = 5$ and 8 V
- Ripple rejection: 72 to 66 dB for $I_o = 100$ mA $V_o = 5$ and 8 V
- Temperature coefficient of the output voltage: 33 ppm $V_o = 5$
Schematic diagram of LM 2940

It uses a PNP transistor for current boosting
Using LM2940

* C1 is needed if regulator is located far (more than a few inches) from power supply filter

** C_{OUT} must be at least 22 \mu F to maintain stability. It may be increased without bound to maintain regulation during transients. Locate as close as possible to the regulator. This capacitor must be rated over the same operating temperature range as the regulator and the ESR (Equivalent Series Resistance) is critical.
Conclusion