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Introduction

This Student Workbook provides a unit-by-unit outline of the Fault Assisted Circuits for Electronics Training (F.A.C.E.T.) curriculum.

The following information is included together with space to take notes as you move through the curriculum.

♦ The unit objective
♦ Unit fundamentals
♦ A list of new terms and words for the unit
♦ Equipment required for the unit
♦ The exercise objectives
♦ Exercise discussion
♦ Exercise notes

The Appendix includes safety information.
UNIT 1 – CIRCUIT BOARD FAMILIARIZATION

UNIT OBJECTIVE
At the completion of this unit, you will be able to identify the circuit blocks and major components on the POWER SUPPLY REGULATION CIRCUITS circuit board.

UNIT FUNDAMENTALS
Most electronic devices require power supply regulation circuits.

A power supply regulation circuit provides a constant voltage or current to a system when changes in the line voltage or load resistance occur.

NEW TERMS AND WORDS
*integrated circuit (IC)* - any electronic device in which active and passive elements are contained in a single package.
*discrete* - an individual circuit component, complete in itself, such as a resistor, diode, capacitor, or transistor, used as an individual and separable circuit element.

EQUIPMENT REQUIRED
F.A.C.E.T. base unit
Multimeter
POWER SUPPLY REGULATION CIRCUITS circuit board
NOTES
Exercise 1 – Circuit Location and Identification

EXERCISE OBJECTIVE
When you have completed this exercise, you will be familiar with the functional circuit blocks on the POWER SUPPLY REGULATION CIRCUITS circuit board. You will use the circuit board to locate and identify circuit components.

DISCUSSION
• The six power supply regulation circuits on the POWER SUPPLY REGULATION CIRCUITS circuit board are:
  - Shunt Voltage Regulator
  - Series Voltage Regulator
  - Current Regulator
  - Voltage Feedback Regulation
  - IC Regulator
  - DC to DC Converter

• The SHUNT VOLTAGE REGULATOR consists of a transistor in parallel with the load. Two-post connectors are used to energize the input and select the load resistor.
• The SERIES VOLTAGE REGULATOR consists of a transistor in series with the load. Two-post connectors are used to energize the input and select the load resistor.
• The CURRENT REGULATOR requires a two-post connector to energize the circuit, and a second two-post connector to provide a series connection between the PNP transistor and the circuit load.
• The VOLTAGE FEEDBACK REGULATOR is an enhanced version of a series voltage regulator. This regulator has circuits which provide overload protection and output voltage adjustment.
• The IC REGULATOR has an adjustable three-pin regulator which can be configured as a fixed or an adjustable voltage or current regulator.
• The DC to DC CONVERTER utilizes a switching regulator IC. The IC uses an inductor to increase the applied voltage.
• Both the IC REGULATOR and the DC to DC CONVERTER require a two-post connector to energize the input circuits.
Exercise 2 – Power Supply Regulator Introduction

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to configure and operate two power supply regulation circuits. You will verify your results by measuring circuit voltages.

DISCUSSION
- Power supply regulators provide a constant output voltage or current independent of variations in the line voltage and/or load resistance.
- Regulator feedback circuits control the accuracy of the output regulation.

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UNIT 2 – SHUNT VOLTAGE REGULATOR

UNIT OBJECTIVE
At the completion of this unit, you will be able to describe the operation, line regulation, and load regulation of a shunt voltage regulator.

UNIT FUNDAMENTALS

A shunt regulator is designed to maintain a nearly constant load voltage for changes in line (input) voltage or load resistance.

A shunt voltage regulator uses a regulating device, usually a transistor, in parallel (or in shunt) with the circuit output.

The transistor forces more or less current through $R_S$ as a means to control the load, or output, voltage ($V_O$).

Transistor current is added to the load current. Total circuit current flows through $R_S$.

The performance of a shunt regulator is determined by its ability to maintain a constant load voltage.

Line regulation expressed as a percentage, indicates the ability to maintain a constant load voltage for variations in circuit line (input) voltage.

Load regulation expressed as a percentage, indicates the ability to maintain a constant load voltage for variations in circuit load resistance.
NEW TERMS AND WORDS

shunt voltage regulator - a type of regulator that uses a parallel element to control output voltage when line voltage or load voltage changes.

Line regulation - the ability of a voltage regulator to maintain a constant output voltage for variations in line voltage.

Load regulation - the ability of a voltage regulator to maintain a constant output voltage for variations in load resistance.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
Multimeter
POWER SUPPLY REGULATION CIRCUITS circuit board

NOTES
Exercise 1 – Shunt Regulator Operation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to describe shunt voltage regulator operation by using a typical voltage regulator circuit. You will verify your results with a multimeter.

DISCUSSION
- A shunt regulator uses the current flow through $R_S$ to maintain a nearly constant output voltage.
- Output voltage of the shunt regulator is developed by the zener diode ($V_Z$) and the transistor base-emitter junction ($V_{BE}$).
- Changes in line voltage or load current cause a change in base current. This change forces a change in collector current which creates a change in the voltage drop across $R_S$. This change in $V_{RS}$ maintains the circuit output voltage.

NOTES
Exercise 2 – Line Regulation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to calculate the percentage of line regulation of a shunt voltage regulator. You will obtain the required data with a multimeter.

DISCUSSION
• Line regulation specifies the allowable change in circuit output voltage for a given change in line voltage.
• Line regulation is expressed as a percentage and is usually determined with the load resistance held constant.
• Line regulation percentage is calculated as follows:
  \[
  \% \text{ Line Regulation} = \frac{V_O \text{ at max line} - V_O \text{ at min line}}{V_O \text{ at min line}} \times 100
  \]

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Exercise 3 – Load Regulation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to describe and calculate load regulation. You will verify your results with a multimeter.

EXERCISE DISCUSSION
• Load regulation specifies the allowable change in circuit output voltage for a given change in load resistance.
• Load regulation is expressed as a percentage and is usually determined with the line voltage held constant.
• Load regulation percentage is calculated as follows:
  \[
  \% \text{ Load Regulation} = \frac{V_O \text{ at min load} - V_O \text{ at max load}}{V_O \text{ at max load}} \times 100
  \]

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UNIT 3 – SERIES VOLTAGE REGULATOR

UNIT OBJECTIVE
At the completion of this unit, you will be able to describe the operation, line regulation, and load regulation of a series voltage-regulating circuit.

UNIT FUNDAMENTALS

A series regulator has a regulating transistor (Q1) in series with the output (circuit load $R_L$).

Q1 is referred to as the series pass transistor because all of the load current must pass through the transistor.

The series regulating configuration shown is also referred to as an emitter follower circuit.

In the series regulator, the voltage drop across Q1 is varied to maintain a nearly constant output voltage.

$R_S$, in series with Q1, reduces the power dissipation of Q1.

R1 provides the base current for Q1 and the bias current for zener diode CR1.

CR1 provides the circuit reference voltage.
In typical applications, input and output bypass capacitors are used to provide stability (prevent undesired oscillations) to the circuit.

A **bleeder resistor** is used to maintain a minimum circuit load current.

The polarity of a specific voltage is determined by the reference point selected.

Unless noted, all voltages are with respect to circuit common.

Since the input (collector) of Q1 (an NPN transistor) is more positive than the output (emitter) of Q1, $V_{CE}$ of Q1 is measured as shown.
The voltage at the base of Q1 is more positive than the voltage at the emitter of Q1. $V_{BE}$ of Q1 is measured as shown.

**NEW TERMS AND WORDS**

*series regulator* - a voltage-regulating circuit that uses a series pass transistor.

*pass transistor* - a name commonly applied to a series regulating element because all output current must pass through this device.

*bleeder resistor* - a resistor that is connected across a circuit to provide a minimum circuit load.

**EQUIPMENT REQUIRED**

F.A.C.E.T. base unit
Multimeter
POWER SUPPLY REGULATION CIRCUITS circuit board
Exercise 1 – Series Regulator Operation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to describe series voltage regulator operation. You will verify your results with a multimeter.

EXERCISE DISCUSSION
• Circuit output or load voltage is determined by $V_{CR1}$ and $V_{BE}$.
• Required transistor base current is typically less than the load current because of transistor gain.
• Zener diode current is selected to bias the zener beyond its knee (zener voltage breakdown region).
• Calculations of circuit component power dissipation utilize standard power formulas.

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Exercise 2 – Line Regulation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to calculate the percentage of line regulation for a series voltage regulator. You will verify your results with a multimeter.

DISCUSSION
• Line regulation specifies the allowable change in circuit output voltage for a given change in line voltage.
• Line regulation is expressed as a percentage and is usually determined with the load resistance held constant.
• Line regulation percentage is calculated as follows:
  \[ \% \text{ Line Regulation} = \frac{V_O \text{ at max line} - V_O \text{ at min line}}{V_O \text{ at min line}} \times 100 \]

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Exercise 3 – Load Regulation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to calculate the percentage of load regulation of your circuit. You will verify your results with a multimeter.

DISCUSSION
• Load regulation specifies the allowable change in circuit output voltage for a given change in load resistance.
• Load regulation is expressed as a percentage and is usually determined with the line voltage held constant.
• Load regulation percentage is calculated as follows:
  \[ \text{% Load Regulation} = \frac{V_O \text{ at min load} - V_O \text{ at max load}}{V_O \text{ at max load}} \times 100 \]

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UNIT 4 – VOLTAGE FEEDBACK REGULATION

UNIT OBJECTIVE
At the completion of this unit, you will be able to demonstrate the operation of a voltage feedback regulator circuit that uses active foldback current limiting.

UNIT FUNDAMENTALS

This is a block diagram of the series pass feedback voltage regulator used in this unit.

With exception to the error amplifier, output voltage sampling, and protection circuit, the regulator functions as an emitter follower (standard series pass regulator).

The circuit output voltage is controlled by varying the conduction of Q1, the series pass transistor.

The conduction of Q1 is controlled by the error amplifier circuit, which varies the base current of Q1.

Should an overload or short circuit occur, the active protection circuit reduces the output (load) current and voltage.

An activated foldback protection circuit draws current away from the base of the pass transistor to reduce its conduction.
NEW TERMS AND WORDS

d\textit{foldback} - a protective circuit that reduces output current and voltage below peak levels under overload conditions.
d\textit{feedback} - a signal coupled from the output of a circuit back to input.
d\textit{current-sensing resistor} - a resistor that develops a voltage drop that is proportional to the load current.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
Multimeter
POWER SUPPLY REGULATION CIRCUITS circuit board

NOTES
Exercise 1 – Voltage Feedback Regulator Operation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to demonstrate the operation of a voltage feedback regulator. You will verify your results with a multimeter.

DISCUSSION
• The major functions required by a voltage feedback regulator are feedback, error detection, and a series control element (pass transistor).
• Feedback voltage is generated by the series resistors R6, R7 (a potentiometer), and R8.
• The zener diode provides a reference voltage.
• The error detection amplifier (Q3) compares the feedback voltage against the reference voltage.
• Q1 is the circuit pass transistor. The base current of Q1 is controlled by Q3.
• The regulating mechanism of this circuit consists of the base current of Q1 and the collector current of Q3.
• If the output voltage increases, the collector current of Q3 increases causing a decrease in the base current of Q1. Q1 collector-emitter voltage increases and restores the output voltage to the initial value.

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Exercise 2 – Voltage Feedback Load Regulation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to determine the load regulation of a voltage feedback regulator by using measured values. You will verify your results with a multimeter.

DISCUSSION
• Load regulation determines the ability of the voltage regulator to maintain a constant output voltage with changes in circuit load.
• The voltage feedback regulator has two principal control loops. The primary control loop uses the variation in $V_{CE}$ to maintain a near-constant load voltage while the secondary control loop applies feedback to Q3 causing control over the conduction of the pass transistor.
• Load regulation percentage is calculated as follows:
  \[
  \text{% Load Regulation} = \frac{V_O \text{ at min load} - V_O \text{ at max load}}{V_O \text{ at max load}} \times 100
  \]

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Exercise 3 – Active Foldback Current Limiting

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to demonstrate the foldback current limiting protection circuit of a series voltage feedback regulator. You will verify your results with a multimeter.

EXERCISE DISCUSSION
• Active foldback current protection requires a sensing transistor and current-sensing resistor to detect a current overload.
• The sensing transistor is cut off (does not conduct) when no overload exist and conducts when a current overload occurs.
• Exceeding specified load current causes the circuit output voltage and current to decrease.
• On the VOLTAGE FEEDBACK REGULATION circuit block, transistor Q2 and resistors R3, R4, and R5 create the foldback network.
• During normal operating conditions, Q2 is reverse-biased and does not conduct.
• When the load current through R5 (a current sensing resistor) is large enough to generate a voltage drop that forward biases Q2, the circuit enters the foldback current-limiting mode.

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UNIT 5 – CURRENT REGULATOR

UNIT OBJECTIVE
At the completion of this unit, you will be able to demonstrate the operation of a current regulator.

UNIT FUNDAMENTALS
An ideal current source provides a constant load (output) current regardless of line (input) or load changes.

Based on Ohm's law (E = I x R), a constant current through a variable load resistance generates a load voltage directly related to the value of the resistance.

Transistors can be configured to generate a constant current output.

Within design limits, practical current sources can provide line regulation and load regulation (maintain a near constant output current).

NEW TERMS AND WORDS
current source - a power source whose output is stated in terms of current. A current source provides a fixed value of current independent of the load.

EQUIPMENT REQUIRED
F.A.C.E.T. base unit
Multimeter
POWER SUPPLY REGULATION CIRCUITS circuit board
Exercise 1 – Current Regulator Operation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to demonstrate the operation of a transistor current regulator. You will verify your results with a multimeter.

DISCUSSION
- A PNP transistor configured as a common base circuit is used as a current regulator.
- A zener diode is used to provide a constant voltage, and resistor R1 provides a fixed resistance.
- Proper bias current for CR1 and base current for Q1 are provided by R2. Transistor Q1 is used to isolate the input circuit from the output circuit.
- The voltage across R1 is equal to the zener voltage minus the base-emitter voltage of Q1.
- Output current regulation is due to the constant value of the zener and the base-emitter voltages.
- Current regulation is lost if the load voltage increases to the point where Q1 saturates.

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Exercise 2 – Current Regulator Line Regulation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to calculate the percentage of current regulator line regulation. You will verify your results with a multimeter.

DISCUSSION
• A current regulator with good line regulation maintains nearly constant load current when variations of input voltage occur.
• Determine line regulation by maintaining a constant load resistance as the input voltage is varied between specific limits.
• This equation is used to calculate percentage line regulation:
  \[
  \text{Line regulation} = \frac{I_{L(max)} - I_{L(min)}}{I_{L(min)}} \times 100
  \]
• The constant current is determined by the voltage drop across R1.
• Variations in line voltage affect the current and voltage of CR1. Zener diode voltage variations affect the voltage across R1 and \( V_{BE} \) of Q1.
• \( V_{BE} \) is nearly constant; therefore, it is the voltage drop across R1 that varies and determines whether circuit current increases or decreases.
Exercise 3 – Current Regulator Load Regulation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to calculate the percentage of load regulation of a current regulator. You will verify your results with a multimeter.

EXERCISE DISCUSSION
- Current regulators with good load regulation maintain nearly constant load current with varying load resistance.
- Determine load regulation by maintaining a constant line voltage as the load resistance is varied between specific limits.
- This equation is used to calculate percentage load regulation:
  \[
  \text{Load regulation} = \frac{I_{L(\text{max})} - I_{L(\text{min})}}{I_{L(\text{min})}} \times 100
  \]
- The current through R2 is essentially constant and divides between the zener diode and the base of Q1.
- Changes in load resistance result in small changes in base current which cause a change in \(V_{R1}\).
- Changes in \(V_{R1}\) cause variations in load current.

NOTES
UNIT 6 – THREE-PIN IC REGULATOR

UNIT OBJECTIVE
At the completion of this unit, you will be able to demonstrate the operation of an adjustable three-pin integrated circuit power supply regulator.

UNIT FUNDAMENTALS

The LM317 adjustable three-pin integrated circuit (IC) regulator is designed to provide an adjustable positive output voltage.

The LM317 IC is housed in a TO-220 type plastic package. It can provide a maximum load current of 1.5A and dissipate 15W of power.

A heat sink, which is a metal tab attached to the internal chip, removes heat from the device.
The functional diagram of the regulator illustrates its similarity to the voltage feedback series pass regulator. Output voltage ($V_O$) is compared against the circuit reference voltage (zener diode) by the operational amplifier (error amplifier). The op amp output drives the base of the series pass transistor.

The internal reference zener diode current is provided by a constant current source. The current source buffers the zener diode from variations of line voltage. Protective circuits, which shut down the pass transistor, ensure that the regulator is not stressed beyond its maximum operating limits. The three-pin IC regulator can be configured as a voltage or current regulator with fixed or variable outputs.

Adjustability is derived from the application of Ohm's law to the voltage reference (ADJ terminal) of the IC.

Based on Ohm's law, a resistor in series with a voltage causes current to flow: $I = E/R$.

The programming current ($I_p$) required to operate the LM317 regulator is obtained from the IC ADJ voltage and an external resistance ($R_{REF}$).

$$I_p = \frac{V_{ADJ}}{R_{REF}}$$

For this regulator family, the programming current is essentially constant because $V_{ADJ}$ is constant.
NEW TERMS AND WORDS

integrated circuit (IC) - any electronic device in which passive and active elements are contained in a single package.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
Multimeter
POWER SUPPLY REGULATION CIRCUITS circuit board

NOTES
Exercise 1 – Regulator Operation & Voltage Regulation

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to demonstrate and measure the voltage regulation of a three-pin IC regulator. You will verify your results with a multimeter.

DISCUSSION
• The circuit configuration produces an adjustable output voltage.
• A specific programming current (I_p) is provided by the selection of R3.
• Circuit output voltage is varied by R2.
• At the desired output voltage, V+ and V- are equal. V_R3 equals V_REF, the zener diode voltage.
• Output voltage is defined by: \( V_O = 1.25 \times [1 + (R2/R3)] \)
• The value 1.25 is the nominal reference voltage and minimum output voltage for this regulator type.
• An opposing offset voltage (equal magnitude and opposite polarity), which cancels the circuit reference voltage is used to force the output voltage to zero.

NOTES
Exercise 2 – Current Regulation and Power Efficiency

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to demonstrate three-pin IC current regulation and determine IC power dissipation. You will verify your results with a multimeter.

DISCUSSION
• An LM317 can be configured as a constant current source (current regulator).
• RP is selected for a specific current output and the reference voltage of the IC is essentially constant.
• Current regulation is maintained by the combined internal reference voltage and op amp producing a constant voltage across RP.
• Current regulation and voltage regulation depend on a constant voltage across RP.
• Voltage regulator configuration uses the programming current flowing through R2 to set the circuit output voltage. Once set, the output voltage is constant and the output current varies depending on the load resistance.
• Current regulator configuration uses the programming current as the circuit constant current output and flows through R2. Output current is constant and the output voltage varies depending on the load resistance.
• Power is dissipated by the regulator. Power = \( V_D \times I_{RL} \) (where \( I_{RL} = V_{REF}/R_P \) or \( I_K \) of the circuit).
• Power consumed by the IC regulator is not available to the load. Therefore, power efficiency is less than 100%.
• Power efficiency is the power consumed divided by the line power. Multiply by 100 to obtain percentage. \( \%PE = \left( \frac{P_{LOAD}}{P_{LINE}} \right) \times 100. \)
UNIT 7 – DC TO DC CONVERTER

UNIT OBJECTIVE
When you have completed this unit, you will be able to demonstrate the operation of an IC switching regulator configured as a dc to dc converter.

UNIT FUNDAMENTALS

A dc to dc converter transforms a dc input voltage from one level to a different level.

The output voltage may be higher or lower than the input voltage, and the output polarity may be the same as or opposite to that of the input.

In general, dc to dc converter circuits control a transistor switch (Q1) that is used to charge an inductor (L1) with energy.

When transistor switch Q1 is turned on, energy is stored in the inductor, CR1 is reverse biased (off), and C1 supplies (discharges) energy to the load.
When transistor switch Q1 is turned off, energy from the inductor flows through CR1 (now forward biased) into C1 and the load.

A typical dc to dc converter circuit uses a transistor switch to chop up the dc line voltage into high frequency **pulses**. The pulses are rectified and filtered to provide a dc output voltage.

Due to the high frequency pulses (25 kHz or higher), the rectifier and filter components are generally smaller in size than required in conventional linear power supplies.

On your circuit board, a 78S40 type of universal switching regulator subsystem, housed in a 16-pin molded DIP package, is used for the dc to dc converter circuit block.

The 78S40 is a monolithic regulator subsystem consisting of the active building blocks required for a dc to dc converter circuit.
NEW TERMS AND WORDS

pulses - abrupt changes in voltage or current.
duty cycle - the amount of time a device operates as opposed to its idle time; the ratio of time on to total time.
ripple - a slight variation in the output voltage of a power supply related in frequency or input power frequency.

EQUIPMENT REQUIRED

F.A.C.E.T. base unit
Multimeter
Oscilloscope, dual trace
POWER SUPPLY REGULATION CIRCUITS circuit board

NOTES
Exercise 1 – Operating Characteristics

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to demonstrate the operating characteristics of a dc to dc converter. You will verify your results with an oscilloscope.

EXERCISE DISCUSSION
• The dc to dc converter on the circuit board has three sections:
  Switching regulator subsystem - controls the voltage switching action of Q1.
  Inductive storage element and rectifier/filter section - generates a dc output voltage
  Resistive divider - sample the output voltage and provide feedback control voltage
• The switching regulator subsystem comprises several active circuit blocks (the inductor is an external passive component).
• The oscillator block provides a free-running 25 kHz square wave that drives the transistor switch.
• An error amplifier (comparator) uses the reference voltage and feedback voltage to generate a control voltage.
• A control circuit block modifies the duty cycle of an oscillator circuit that provides the base drive for the transistor switch.
• If the on duty cycle of the free-running oscillator waveform were increased, the transistor switch would remain on longer and the inductor would charge proportionally longer.
• The two-transistor configuration of the transistor switch is referred to as a darlington stage.
• The IC provides a very stable internal band-gap voltage reference (1.25 Vdc nominal) at pin 8.
• Initial circuit output voltage ($V_O$) is determined by the ratio between R4 and R3 and is expressed by the following: $V_O = 1.25 \times [1 + (R4/R3)]$
• An IC SENSE voltage ($V_{R1}$) of about 0.3V limits the output current by modifying the switching regulator duty cycle.
• A capacitor connected to pin 12 is used to select the frequency of the internal free-running oscillator.
• R2 provides collector current for the IC driver transistor.
• Inductor L1 charges from $V_{CC}$ through R1 when the transistor switch is on and discharges into the load when the switch is off.
• CR1, a steering diode, ensures that the energy into and out of L1 is properly directed.
• The circuit output voltage appears across R5 and R6. C3 provides output voltage filtering (reduces ripple voltage).
• The R3/R4 voltage divider sets the output voltage by providing a sample (feedback) voltage.
• C2 bypasses the IC reference voltage. This action prevents stray pickup from the IC oscillator from disrupting the circuit regulation.
Exercise 2 – Voltage Regulation and Efficiency

EXERCISE OBJECTIVE
When you have completed this exercise, you will be able to demonstrate regulation and power efficiency of a dc to dc converter. You will verify your results with a voltmeter and an oscilloscope.

EXERCISE DISCUSSION
• Since \( V_{REF} \) is a constant reference voltage, the output voltage \( V_O \) is a function of the \( R4/R3 \) ratio.

• Initial output voltage is determined as follows: 
  \[ V_O = V_{REF} \times [(R4/R3) + 1] \]

• Output voltage is related to the energy transferred by the inductor. Therefore, \( V_O \) can also be expressed in terms of the switching transistor on/off ratio.

• Based on the transistor duty cycle, output voltage is determined as shown:
  \[ V_O = V_1 \times [(t_{on}/t_{off}) + 1] \] - 0.8. Where: \( V_1 \) is the circuit input \( (V_{CC}) \), and 0.8 V represents the voltage drop of diode CR1.

• Regulation occurs because output voltage variations cause proportional changes in the feedback voltage, \( V_{R3} \).

• A change in \( V_{R3} \) is detected by the comparator. The comparator modifies the on/off ratio of Q1, restoring the circuit output voltage.

• The output voltage of the converter varies between a maximum and minimum value. The peak-to-peak variation of the voltage is called ripple.

• There are two major operating areas for the switching regulator IC:
  Area A - the output is below a specified limit and must be boosted, or charged, to its proper level.
  Area B - the output voltage is above a specified limit and must be allowed to discharge to its proper level.

  Ripple voltage comprises two frequency components:
  1. - The high frequency component, which occurs during boost time, is generated by the switching action of the IC transistor.
  2. - The low frequency component, which occurs because of discharge time, equals the sum of the boost time and discharge time.

• The power efficiency (PE) of your circuit, expressed as a percentage, relates the power consumed by the load \( (P_L) \) to the total input power \( (P_I) \) required by your circuit.
  \[ \%PE = (P_L/P_I) \times 100 \]
NOTES
Safety is everyone’s responsibility. All must cooperate to create the safest possible working environment. Students must be reminded of the potential for harm, given common sense safety rules, and instructed to follow the electrical safety rules.

Any environment can be hazardous when it is unfamiliar. The F.A.C.E.T. computer-based laboratory may be a new environment to some students. Instruct students in the proper use of the F.A.C.E.T. equipment and explain what behavior is expected of them in this laboratory. It is up to the instructor to provide the necessary introduction to the learning environment and the equipment. This task will prevent injury to both student and equipment.

The voltage and current used in the F.A.C.E.T. Computer-Based Laboratory are, in themselves, harmless to the normal, healthy person. However, an electrical shock coming as a surprise will be uncomfortable and may cause a reaction that could create injury. The students should be made aware of the following electrical safety rules.

1. Turn off the power before working on a circuit.
2. Always confirm that the circuit is wired correctly before turning on the power. If required, have your instructor check your circuit wiring.
3. Perform the experiments as you are instructed: do not deviate from the documentation.
4. Never touch “live” wires with your bare hands or with tools.
5. Always hold test leads by their insulated areas.
6. Be aware that some components can become very hot during operation. (However, this is not a normal condition for your F.A.C.E.T. course equipment.) Always allow time for the components to cool before proceeding to touch or remove them from the circuit.
7. Do not work without supervision. Be sure someone is nearby to shut off the power and provide first aid in case of an accident.
8. Remove power cords by the plug, not by pulling on the cord. Check for cracked or broken insulation on the cord.