Module Introduction

PURPOSE:
• This module provides information about the Freescale regulated power supplies.

OBJECTIVES:
• Describe the the difference between series & shunt linear regulators
• Describe the the different types of switch converters
• Describe the the basic fundamentals of Integrated Circuit (IC) Power Supply devices

CONTENTS:
• 17 pages
• 2 questions

LEARNING TIME:
• 20 minutes

Welcome to this module on regulated power supplies. This module will describe regulator basics and the two types of linear regulators. Also it covers all of the different types of switching regulators including Buck, Boost and Buck/Boost converters. We will explain duty cycle control and compare linear to switch mode regulators. Finally, this module will describe the Integrated Circuit (IC) power supply devices and discuss some of the applications where IC power supply components can be used.
Let’s learn about the basics of the power supply regulator starting with this simple block diagram.

The reference voltage ($V_{ref}$) is the voltage standard to which all control of the regulator is referenced. Any variation in the reference is reflected in the output. The reference must therefore be stable at all voltages and temperatures.

The sampling element monitors the output and supplies a feedback voltage equal to $V_{ref}$ when the output voltage ($V_O$) is at the regulated set point. Any deviation in the output voltage from the set point causes the feedback voltage to vary above or below the $V_{ref}$ level. The variation represents the output error voltage.

The error amplifier provides gain of the feedback error voltage variation. In addition, the error amplifier monitors and compares the feedback voltage to $V_{ref}$. When the output voltage is above the set point, the error voltage will be greater than $V_{ref}$, and the error amplifier output will decrease. The opposite occurs when the output is below the set point.

The control element responds to the error amplifier output. When the output voltage increases, the feedback voltage increases, decreasing the error amplifier output, which in turn causes the control element to decrease the output voltage. The opposite occurs when the output is below the set point. This action is referred to as closed loop control.
Linear regulators utilize a series voltage divider principle to obtain the required output voltage. Current flowing through two resistors in series will create a voltage drop across each resistor that is proportional to the resistor’s value. The sum of the two resistor voltage drops equals the applied input voltage ($V_{in}$).

Series and the Shunt Regulators are two basic Linear Regulator configurations used in integrated circuits that utilize the voltage divider principle. For control purposes, one resistor element value is variable while the other is fixed.

The series regulator has the variable resistor element ($R_{series}$) in series with the load current ($I_{load}$) and thus the name series regulator. As the load resistance changes, $I_{load}$ changes, causing the output voltage ($V_O$) to change. By monitoring (sampling) $V_O$ and modulating (varying) $R_{series}$, the output voltage can be maintained at a constant (regulated) value.

The shunt regulator has the variable resistor element ($R_{shunt}$) in parallel with $I_{load}$ (shunting the $I_{load}$ ) thus the name shunt regulator. Again, as the load resistance changes, $I_{load}$ changes, causing $V_O$ to change. By monitoring (sampling) $V_O$ and modulating (varying) $R_{shunt}$, the output voltage can be maintained at a constant (regulated) value.

All linear regulators consume regulator current ($I_{reg}$) in their regulating the output voltage. $I_{reg}$ can be appreciable and represents lost energy that is not retrievable for delivery to the load. A transistor is usually used in ICs to provide the active variable resistor element function. The transistor’s conduction is modulated so as to produce the necessary resistance.
The circuit shown is a series regulator with the variable series resistor element replaced with a transistor. A resistor divider network $R_1$ and $R_2$ is used to sample the output voltage ($V_O$) and compare the sampled $V_O$ voltage to the reference voltage ($V_{ref}$) using the error amplifier (EA). The transistor functions as an active series resistor element. The error amplifier modulates the resistance of the transistor to maintain a constant output voltage.

The resistance sum of $R_1$ and $R_2$ is high to ensure that minimal power is consumed by the sampling element.

A change in the applied input voltage ($\Delta V_{in}$) results in a change in active series resistance. The product of the series resistance and the load current creates a changing input-to-output voltage differential ($V_{in} - V_O$) that compensates for the input voltage change.

In high load current conditions, the voltage drop across the active series element results in a substantial power loss lowering the regulator's efficiency. Series regulators are designed to minimize the voltage drop to improve efficiency.

Important series regulator parameters are: voltage drop, output voltage regulation, output load regulation, and input regulation (line regulation). Voltage drop is the voltage developed across the active series element and is usually expressed as the drop-out voltage measured at the maximum load current. Load regulation measures the regulator's ability to maintain $V_O$ constant under varying load current conditions. Line regulation is the regulator's ability to maintain $V_O$ constant under varying $V_{in}$.
The basic shunt regulator is shown here. The current (I) is the sum of the currents flowing through the shunt element (transistor), the current flowing through the R₁R₂ sampling network, plus the current delivered to the load. The output voltage (V₀) is equal to the input voltage (Vin) minus the IR voltage drop developed across the series resistor R. V₀ is held constant by modulating the resistance of the NPN shunt transistor.

The shunt regulator is less sensitive to input voltage variations and does not reflect load current transients back to the input source. This is as a result of the “buffering” or “absorbing” effect due to the shunt element’s action. The shunt regulator is inherently protected from an output short circuit. An output short will cause the shunt transistor to turn-OFF and the output current is inherently limited by resistor R.

Percentage wise, shunt regulators deliver less current to the output and are therefore less efficient than series regulators. A considerable amount of the input current is diverted through the shunt element with a lesser amount through the R₁R₂ sampling element.
The Buck converter is used in DC-to-DC step-down voltage control applications where the input voltage is greater than the output voltage. The basic Buck converter circuit is shown here.

When the switch is CLOSED, current flows through the switch, inductor, and to the output load. As the inductor (L) current flow increases, energy is built up in the inductor’s magnetic field. In addition, the capacitor charges with the indicated polarity.

When the switch is OPENED, the inductor’s magnetic field collapses, returning it’s energy back to the inductor. The collapsing magnetic field reverses the polarity across the inductor. With the inductor polarity reversed, the freewheeling diode (D1) becomes forward biased, keeping the now negative terminal of the inductor clamped to ground while allowing the positive inductor terminal to continue supplying energy to the load. The action is for the inductor to resist or “buck” output current flow turn-OFF, thus the name Buck converter. The capacitor working in conjunction with the inductor provides output voltage filtering by smoothing out or averaging the applied pulses of input voltage.

In this diagram, the mechanical switch has been replaced with a more efficient and controllable transistor switch. The output voltage is a direct function of the switch’s duty cycle \([D = \frac{t_{on}}{t_{on} + t_{off}}]\) times the input voltage \(V_{in}\) or simply \(\frac{V_O}{V_{in}} = D\). Neglecting circuit losses, a 50% duty cycle would produce an output voltage of one-half the input voltage. By monitoring the output voltage and controlling the duty cycle accordingly, accurate step-down DC voltages are very efficiently generated and maintained.
The Boost converter is used in DC-to-DC step-up voltage control applications where an output voltage greater than the input voltage is required. The initial boost converter state has the input voltage (Vin) applied with the switch OPEN and a load connected, the diode (D1) is forward biased causing low level current to flow through the inductor creating a low energy magnetic field. The output capacitor (CO) will charge to a voltage near Vin.

When the switch is CLOSED, the full Vin voltage is applied across the inductor L storing energy in the inductor’s magnetic field. The diode D1 is back biased and any continued current flow through the load will be due to prior energy stored in the output capacitor (CO) discharging through the load.

When the switch is OPENED again the magnetic field collapses and the stored inductor energy is recovered by the inductor. The collapsing field inductor polarity voltage adds to the applied Vin voltage and the diode D1 is forward biased to deliver the higher voltage to the load. Voltage “pump-up” or boost occurs only during inductor field collapses thus the name Boost converter. The step-up boost current is not continuous and a large CO is required to provide adequate output voltage filtering of the energy pulses from the inductor.

Now, the mechanical switch has been replaced with a more efficient and controllable transistor switch. For a repetitive switching mode, the output voltage is a function of the switch duty cycle and can be expressed mathematically as: \( V_O / V_{in} = [1 / (1 - D)] \) where D is the switching duty cycle. By monitoring \( V_O \) and controlling the duty cycle, very accurate step-up voltages can be very efficiently generated and maintained. Boost converters find application in battery chargers and photo-flashers.
The Buck-Boost converter is used in DC-to-DC step-up and step down voltage control applications.

This diagram shows us that the switch is CLOSED, the full $V_{in}$ voltage is applied across the inductor (L) causing energy to be stored in the inductor’s magnetic field. The diode ($D_1$) is back biased preventing positive current flow to the output load.

In the next phase, the switch is OPENED, the inductor current ceases, causing the magnetic field to collapse and $D_1$ to be forward biased returning stored energy back to the circuit. Notice the polarity of the output voltage relative to that of the input. The polarity inversion is characteristic of this type of converter. It is only during inductor fly-back (magnetic field collapse) that energy is delivered to the output filtering capacitor and the load. Both $V_{in}$ and $V_{o}$ currents are pulsed and low output voltage ripple is difficult to obtain. As a result a very large output filter capacitor is required. The $V_{o}$ to $V_{in}$ voltage transfer function can be expressed as: $V_o / V_{in} = D / (1 – D)$ where D is the duty cycle. By selecting a duty cycle that is either greater or less than 0.5, the output voltage can be made to be lower or higher (respectively) than the applied input voltage.

The mechanical switch is replaced with a more efficient and controllable transistor switch. By monitoring the output and adjusting the duty cycle accordingly, the step-up or step-down voltage can be maintained.
Switching - Duty Cycle Control Types

Duty Cycle:
\[ D = \frac{t_{on}}{t_{on} + t_{off}} \]

Duty cycle is a measure of turn-ON time \( (t_{on}) \) relative to the period of the frequency time \( (t_{on} + t_{off}) \) such that \( D = \frac{t_{on}}{t_{on} + t_{off}} \).

The three basic types of duty cycle control are; fixed frequency variable duty cycle, fixed ON-time variable frequency, and fixed OFF-time variable frequency.

- **Fixed frequency variable duty cycle** is commonly referred to as pulse width modulated (PWM) duty cycle control. PWM duty cycle control is frequently used in ICs. Output noise filtering is made somewhat simpler as a result of the fixed frequency.

- **With fixed ON-time variable frequency**, the OFF-time decreases and the frequency increases directly as the load current increases. The use of a fixed ON-time makes the inductor design calculations simpler. A fixed ON-time also makes the stored energy per cycle predictable which helps in defining the operating area of the inductor.

- **Using fixed OFF-time variable frequency control**, the ON-time varies with load current. As the demand for load current increases, the ON-time decreases and the frequency increases.
Linear vs Switch Mode Summary

- **Linear Regulators (Series & Shunt)**
  - Are a more direct means of regulation
  - Are the easiest to implement in applications
  - Series regulators are more efficient than the shunt regulators
  - No radiated Electro-Magnetic Interference (EMI) since no high current switching or inductors are involved
  - Are less efficient than switching regulators and generate greater amounts of heat than do switching regulators for the same delivered output current
  - Find application in lower power applications or where efficiency is of lesser concern

- **Switching Regulators**
  - Are more efficient than linear regulators
  - Switching regulators transform power while linear regulators consume power to regulate.
  - Switching regulators store-up energy in a magnetic field and recover the energy when the magnetic field collapses
  - Radiate considerable EMI as a result of inductor high current switching
  - Most used in applications where high power and efficiency are of primary concern.

Linear regulators, both series and shunt, are a more direct means of regulation and are the easiest to implement in applications. Series regulators are more efficient than the shunt regulators. Linear regulators have no radiated electro-magnetic interference (EMI) since no high current switching or inductors are involved. They are less efficient than switching regulators, and generate greater amounts of heat for the same delivered output current. These regulators are better suited for lower power applications or where efficiency is of lesser concern.

Switching Regulators are more efficient than linear regulators because they transform power while linear regulators consume power to regulate. They store-up energy in a magnetic field and recover the energy when the magnetic field collapses. Switching regulators radiate considerable EMI as a result of inductor high current switching. It is used mostly in applications involving high power and where efficiency is of primary concern.
Power Management Products

Power Management products are used in systems...
- that are embedded and require high levels of integration
- requiring multiple voltages, functions, or outputs
- requiring network control
- which benefit from supervisory and reset functions

Note: Freescale does not produce “regulators”; the power management products are designed to support system level development.

Now that we have a better understanding of regulator basics, let’s take a look at Power Management products. They can be used in embedded systems that require high levels of integration or can be used where multiple voltages, functions, or outputs are needed. They would also be useful if the design requires network control, supervisory or reset functions.

Features supported include:
- Input operating voltage between 5.0 V to 27 V
- Multiple outputs 2.6 V / 12 mA to 5.5 V / 1.5A
- Current and temperature protection
- Normal, stand-by and sleep, operations
- Transmission speeds to 1.0 Mbps
- CAN and SPI Interface to micro-controllers
- Reset, Watch-Dog and Wake-Up support
- Status Reporting and diagnostics and,
- Communications bus protection
Power management products are designed to complement controllers such as the PowerPC, HC08/12, and DSP. They support many applications including industrial, computer networking, automotive and marine electronics. Many features are available including multi-output low drop-out linear, step-down / step-up switching power supplies incorporating SPI and CAN interface control.

Typical Markets/Applications include:

- Automotive / Marine Electronics which include Engine ECU, Depth Finders, RADAR, Autopilots, Navigation Consoles and Communications Consoles.
- Computer Networking which includes, Network equipment, Cable modems and DSL
- Industrial uses include the 3-Phase Motors, DC Motors, test chambers, Robotics, and Controls

We call our family of linear regulators "system base chips" because they provide the power supply base for embedded systems. They communicate with the microprocessor directly via SPI, and to a network via CAN.
The MC33394 Basic Regulator Concept

Providing the voltage levels and sequencing necessary to allow plug & play use of the PowerPC processor family.

Any designs that have an embedded micro-controller are in need of our micro-dedicated power supply chips. You can help the customer complete his silicon system solution by powering the micro-controller with one of them!

The Analog Products Division (APD) has developed switching regulator capability as part of our portfolio. The first switching regulator introduced is the MC33394. This product is designed to support the MPC555/565 products and is also ideal for the MPC824x family of communications processors.

If the customer is using one of these PowerPC products, they need this IC! The PowerPC family of microprocessors require multiple voltages with specific power-up and power-down sequencing. The required output voltages as well as the sequencing of those voltages are built into the MC33394 and is a key differentiator between our power supply chips and competitor's generic chips.
Additional Resources

• For qualified products go to the Freescale web site at http://www.freescale.com

• For products in development go to: http://www.freescale.com/webapp/sps/library/prod_lib.jsp

• Order the Analog Products Pitch Pak (APDPAK/D) from LDC. The pitch pak contains information about analog technology, packaging, and each product in the portfolio.

• Contact APD marketing
  – US: Jennifer Chen 480 413 8119

For the latest released product information go to the web site listed here on this page.

For information on products that are still in development there is a different web site available.

An information package is available in hard copy and is available from LDC.

For additional inquiries contact our marketing department at the phone number listed here.
Which of the following is **NOT** an example of duty cycle control? Click on your choice.

a) Fixed OFF-Time variable frequency  
b) Fixed ON-Time variable frequency  
c) Fixed frequency variable duty cycle  
d) Fixed frequency fixed duty cycle

Here’s a question about duty cycle.

Correct:

Fixed frequency fixed duty cycle is not an example of duty cycle control.
Question

Complete the following statement. The Freescale MC33394_________________
Click on your choice.

a) is a complete power supply regulator
b) provides voltage levels and sequencing
c) supports only PowerPC microprocessors
d) does not support PowerPC microprocessors

Here’s a question about mixers.

Correct:
The Freescale MC 33394 does provide voltage levels and sequencing
This concludes our discussion of regulated power supplies. We have discussed regulator basics, defined series and shunt linear regulators. We also covered the switching regulators including Buck, Boost and Buck/Boost converters. Finally we introduced the power management products and discussed their features and applications.