TECH NOTE

Switching vs Linear Regulators

MicroPower Direct

MPD, a leading worldwide provider of power conversion products, was founded by a group of industry veterans in 1999. Located in Easton, MA, we are committed to delivering innovative, high quality power converters at the lowest possible prices.

We currently offer over 5,000 low cost standard "off-the-shelf" high performance power converters. Our product lines include DC/DC converters, AC/DC power supplies, high brightness LED drivers, IGBT drivers & controllers, and switching POL regulators.

Component selection and layout are carefully considered at the design stage to optimize product reliability. All manufacturing is in ISO9000 registered factories under strict quality control system guidelines. All products are supported worldwide, and carry a standard three year warranty.

MPD power products have been designed into a wide variety of products and systems by a very diverse customer base. End products range from computer peripherals to test instrumentation to telecommunications equipment to process/industrial controls to medical devices and more.

Even small electronic systems often require a wide variety of DC voltage levels to operate correctly. A system of any complexity will require a power distribution system to insure that all required voltage levels are available for system components. Low power voltage regulators are an important part of these systems.

A Typical Power Distribution System

A simplified power distribution system for a small system is shown in Fig 1. The AC supply provides the AC-DC conversion, power factor correction, and some protection from power line spikes, surges and sags.

The choice of a power bus voltage level is system dependent. Some of the concerns would include:

1. System Backplane: A backplane is typically used to rout power & signals to feature cards and in some systems, provide mechanical support for feature cards. Power lines must be of sufficient size to minimize losses.
2. Backup System: Many systems will use an uninterruptible power source to insure continuous service. This will typically involve the use of a standby battery system. Using a bus voltage that is compatible with the battery system could simplify connection to the backup system.
3. Regulatory requirements: The voltage levels that can safely be used in systems (where human contact is possible) are set by safety agencies. The most common standard is the European norm EN 60950. This standard sets the upper limit on a safe voltage (called the Safety Extra Low Voltage) at 60 VDC. Over 60 VDC is considered hazardous and requires minimum spacing requirements be met.

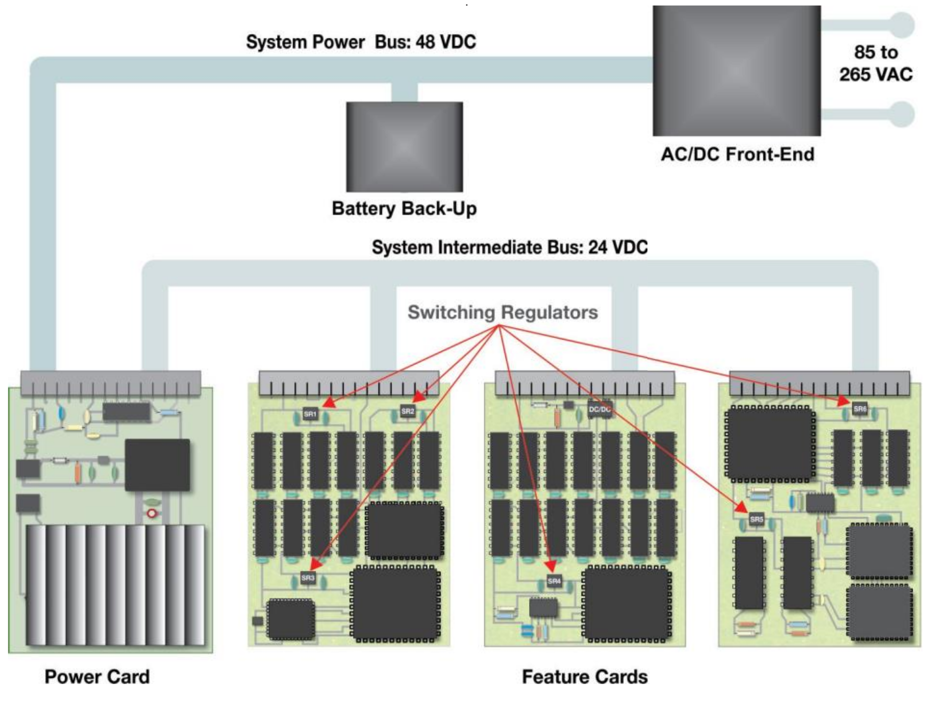
For our example, we are using a system power bus of 48 VDC. This feeds into a power card that has a high power, high efficiency, isolated DC/DC converter, the Intermediate Bus Converter. The IBC provides bus isolation, a regulated output, and the conversion to the system intermediate bus level. In our case, the bus voltage is 24 VDC.

Using isolated DC/DC converters for every different voltage required on the feature cards would add too much expense to the system. To provide a variety of voltage levels, we use voltage regulators (often called regulators, non-isolated DC/DC converters or point of load (POL) regulators. These are available with linear and switching regulation designs.

Linear Voltage Regulators

Linear regulators have been in use for many years. By varying the resistance of a regulating component, they provide a constant output voltage for varying

Figure 1: Simplified Power Distribution System



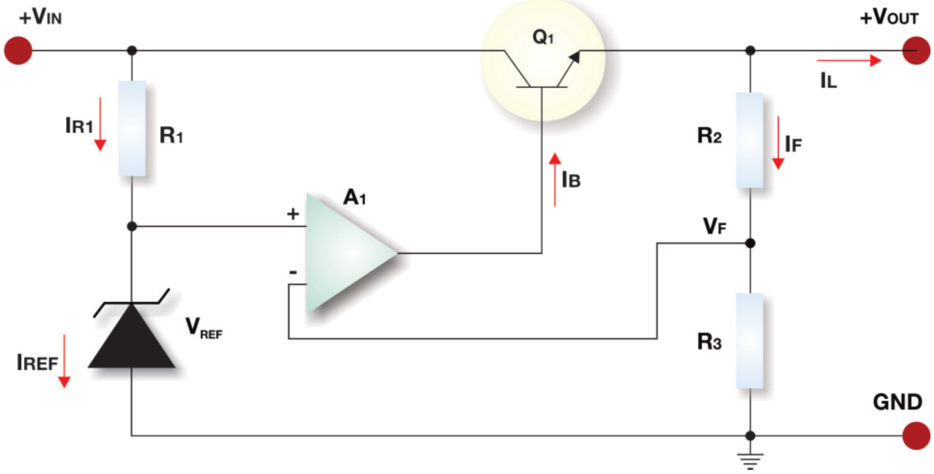


Figure 2: Linear Series Regulator

input line and output load levels. The regulating component is either in parallel with the output (shunt) or in series with the output.

Series Linear Regulator

A simplified series linear voltage regulator is shown in figure 2. As stated, the regulating component is the transistor Q_1. Without the feedback components, the output of the circuit would be:

$$V_{OUT} = V_{REF} - V_{BE}$$

Where: V_{REF} = The zener reference voltage
V_{BE} = The Q_1 base/emitter Voltage

Feedback is added to the circuit to improve regulation. Our simple example circuit operates as follows:

1. A stable reference voltage is provided by V_{REF} and R_1. The value of R_1 is calculated by the following formula:

$$R_1 = \frac{V_{IN} - V_{REF}}{I_{REF} + \frac{I_L}{J3 + 1} + I_F}$$

Where: V_{IN} = The circuit input voltage
V_{REF} = The zener reference voltage
I_{REF} = The current through the zener
I_L = The circuit output current
� = The gain of Q_1
I_F = The current through R_2

The reference voltage is fed into the positive input of the amplifier (A_1).

2. The voltage divider network, R_2 and R_3, feeds an error voltage (V_F) to the negative input of the amplifier (A_1). The output of A_1 in turn adjusts the base current (I_B) of Q_1 to keep the circuit output within regulation. The output current is equal to:

$$I_L = (J3 + 1)\ I_B - I_F$$

Where: � = The Q_1 gain
I_B = The Q_1 base current
I_F = The current through R_2

3. The values of R_2 and R_3 must be sufficiently high enough to minimize power loss. It's not unusual to see values of 100 KΩ plus for R_2. The regulator output voltage is equal to:

$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_3}\right)$$

Where: V_{REF} = The zener reference voltage
R_2 = The value of R_2 in ohms
R_3 = The value of R_3 in ohms

Series Linear regulators are the most common type now in use. They are inexpensive and easy to use. However, under some typical operating conditions, the voltage drop across Q_1 could be high, resulting in a substantial temperature rise. For this reason, series linear regulators are often attached to heat sinks. This increases their cost and the amount of board space required. The internal heat generated could also reduce the expected operating life of the component.

Shunt Linear Regulator

A linear shunt regulator is illustrated in Fig 3. The regulating device is again the transistor Q_1. This time though, Q_1 is placed across (or in shunt with) the load. The current across Q_1 is varied to compensate for changes in the load. Our example circuit operates as follows:

1. The input resistor (R_1) is sized to provide enough current to V_{REF} and Q_1. The value of R_1 is calculated as follows:

$$R_1 = \frac{V_{IN} - V_{OUT}}{I_{REF} + \frac{J3 + 1}{J3} I_C + I_F + I_L}$$

Where: V_{IN} = The circuit input voltage
V_{OUT} = The circuit output voltage
I_{REF} = The current through the zener
� = The gain of Q_1
I_C = The collector current of Q_1
I_F = The current through R_2
I_L = The circuit output current

2. Again, the divider network, R_2 & R_3, sets the voltage level (V_F) on the negative input of the amplifier A_1. The output of A_1 in turn adjusts the drive Q_1 to keep the regulator output within regulation. The output voltage is equal to:

$$V_{OUT} = V_{IN} - R_1 (I_{R2} + I_C + I_F + I_L)$$

Where: V_{IN} = The circuit input voltage
R_1 = The size of R_1 in ohms
I_{R2} = The current through R_2
I_C = The collector current of Q_1
I_L = The circuit output current
I_F = The current through R_3

Shunt regulators are less efficient than series regulators by nature of the design. A larger portion of the input current flows through the regulating device (Q_1) than a series regulator design. However, since they are inherently short circuit proof and are less sensitive to input voltage transients, a shunt regulator could be a better design choice in some applications.

Drop & Dropout Voltage

For linear series and shunt regulators, the output is always lower than the input voltage. This voltage differential is commonly referred to as the "drop voltage". The "dropout voltage" is the minimum value of this voltage differential that is required for the regulator to operate properly. The typical value for the dropout voltage is about 2.0 VDC.

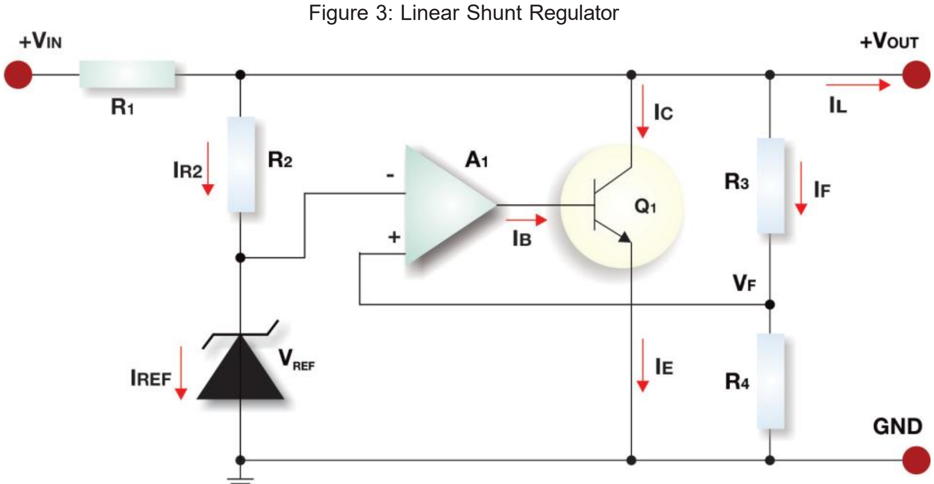
There are regulators available in which the dropout voltage has been reduced. These units are called low drop out or LDO regulators.

Switching Regulators

Switching regulators were once considered to be too big, too noisy and too expensive for use in most POL regulation applications. However, in recent years dramatic improvements have been made in the packaging and performance of switching regulators. In fact, switching regulators are now a viable alternative for most regulator applications. They not only meet most linear regulator performance specifications, they improve on efficiency, input range and no load input current. Due to their improved efficiency, they typically require significantly less board space than linear models with the similar output power specifications.

A switching regulator uses high speed semiconductor switches to chop the DC input voltage into a high frequency square wave. Switching frequencies range from 20 kHz to over 20 MHz. Pulse width modulation (PWM) is used to control the semiconductor chopper or switch. A PWM circuit typically includes a reference voltage source, error amplifier, and a pulse width modulator IC. By varying the duty cycle of the switch, the PWM circuit controls the average DC voltage that is delivered to the output circuit.

Figure 3: Linear Shunt Regulator



Switching Regulator Terminology

AC Front-End: Part of a distributed power system that will convert AC line voltage to a semiregulated DC voltage level. An AC front-end will typically provide power factor correction and universal (~85 VAC to 265 VAC) AC input compatibility.
Battery Backup: An electronic equipment subsystem that provides temporary power in case input power to the system is lost. Battery backed systems range from short term options for AC/DC power supplies to high VA Uninterruptible Power Systems.
Boost Regulator: A basic switching regulator topology wherein energy is stored in an input inductor. When the shunt switch is turned off, this energy is transferred to the output. Boost regulators take an unregulated input voltage, and produce a higher, regulated output voltage.
Buck Regulator: A basic regulator topology with a series switch. In a linear circuit, the regulating component's resistance to current is varied. In a switching regulator it is turned on/off at high speed. Buck regulators will only produce an output voltage lower than the input voltage level.
Bus Converter: A DC/DC converter that provides the isolated intermediate bus voltage in a distributed power system. The intermediate bus is used to power non-isolated point of load (POL) converters. Typically it will be a "brick" type package with a 48 VDC input and a 5 to 12 VDC output.
DC/DC Converter (DC/DC): A device that accepts a regulated or unregulated DC input voltage and produces an isolated DC output that is the same or possibly at a different voltage level.
Drop Out Voltage: The minimum input voltage level required to operate a voltage regulator to within specified operating limits.
Efficiency (,): The ratio of total output power to input power expressed as a percentage.
Linear Power Supply: A power supply that utilizes linear regulation. Linear's provide excellent regulation, low output noise and fast transient response. However, they are typically much heavier, larger and less efficient than "switchers", which are now much more popular.
Linear Regulation: A regulation technique in which the regulating device (typically a transistor) is placed in series or parallel with the load. Voltage variations across the load are then controlled by changing the effective resistance of the regulating device to dissipate unused power.
Linear Regulator: A voltage regulator that utilizes a transistor or other device (zener diode, etc) to control the output voltage. This method is inherently inefficient, as the regulating component is dropping the difference between the input voltage and the regulated output voltage. For moderate to high power applications, this power loss can be significant.
Regulation: The ability of a regulator to maintain an output voltage to within specified limits under varying conditions of input line and output load.
Regulator: A circuit or component with a varying input voltage that maintains a tightly controlled output voltage. They are often used to provide tighter regulation on power lines to critical portions of a circuit or to components sensitive to power line fluctuations. They are sometimes called point of load (POL) regulators.
Regulator Diode: A semiconductor diode, typically a zener, used as a two-terminal voltage regulator.
Series Regulator: A circuit in which the regulating device is placed in series with the load to achieve a constant voltage across the load. This is the most popular method of linear regulation.
Shunt Regulator: A circuit in which the regulating device is placed in parallel with the load to achieve a constant voltage across the load.
Switching Regulator: A circuit (typically a pulse width modulator) that uses a closed loop design to regulate the output voltage.
Three Terminal Regulator: A regulator packaged in a standard 3-terminal package.
Voltage Regulator: A circuit or device that provides a steady output voltage despite variations in the output load or the input line. They are readily available as linear or switching regulators.
Zener Diode: A diode specially fabricated to conduct in both directions. It conducts in the forward direction like a normal diode, and once a set voltage level is met, it will conduct in reverse. In power supply circuits they are typically used as voltage regulating devices. Also called an Avalanche Diode or Zener.

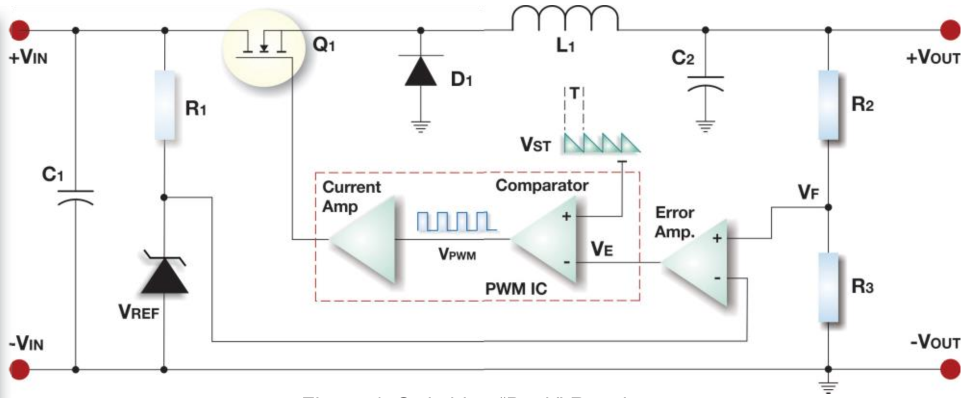


Figure 4: Switching "Buck" Regulator

Switching Buck Regulator

Illustrated in figure 4 above is a buck regulator. In a buck regulator circuit, the output is always lower than the input. It operates as follows:

1. When the series switch (Q_1, a high speed MOSFET) is "ON", the "flywheel" (or "Free-Wheeling") diode (D_1) is reverse biased. During this period current is supplied to the load through the output inductor (L_1).
2. When Q_1 is "OFF", the energy field in L_1 begins to collapse. This will forward bias D_1, allowing current flow through the output capacitor (C_2). Thus, L_1 supplies energy to the load during both halves of the switching cycle resulting in lower output ripple than boost regulators (see Switching Boost Regulator).

   The output voltage is equal to:

$$V_{OUT} = V_{IN} \left(\frac{T_{ON}}{T} \right)$$

Where: V_{IN} = The input voltage level in VDC
T = The switching period of Q_1
T_{ON} = The on time of Q_1

From this it can be seen that the output of the buck regulator circuit cannot exceed the input voltage level.

3. The output voltage is kept within specified regulation limits by the feedback circuit that controls the on/off time of Q_1. The output is monitored via the voltage divider R_2 and R_3. The feedback voltage (V_F) is connected to the positive input of the error amplifier where it is compared to a reference voltage (V_{REF}). Any difference in these two voltages produces an output from the error amplifier. This error level is one input into a PWM IC.
4. Within the PWM, the amplified error voltage (V_E) provides one input to a voltage comparator. The other input is a sawtooth waveform (V_{ST}). The waveform has a period (T) that is equal to the reciprocal of the converter switching frequency. The voltage comparator produces a rectangular waveform (V_{PWM}). This waveform is proportional to the output voltage level of the error amplifier.

3. The rectangular waveform is amplified and then applied to the base of the semiconductor switch (Q_1). This signal will control the Q_1 "On Time". The "On Time" of the switch will adjust the feedback voltage to the error amplifier (V_F) to a level equal to the reference voltage (V_{REF}). The level of V_F is determined by:

$$V_F = \left(\frac{V_{Out} \times V_{R3}}{R_2 + R_3} \right)$$

Where: V_{OUT} = The output voltage level in VDC
V_{R3} = The voltage drop across R_3 in VDC
R_2 = The value of R_2 in ohms
R_3 = The value of R_3 in ohms

Filtering in the output section will minimize the voltage ripple caused by the switching action of the circuit.

Switching Boost Regulator

A Boost regulator (sometimes called a "Ringing Choke Circuit") will take an unregulated voltage input and produce a regulated output voltage at a higher level. Illustrated in figure 5, it operates as follows:

1. When the shunt switch (Q_1) is "ON", the output rectifier (D_1) is reverse biased. During the "ON" period, energy is stored in the input inductor (L_1) and current to the output load is supplied by the capacitor (C_2).
2. When Q_1 is "OFF", the energy field in L_1 begins to collapse, reversing the voltage polarity on the input inductor. This forward biases the output rectifier, allowing current to flow through D_1 to the load. This current flow will also "Boost" the charge on C_2 to a value higher than the input level. The value of C_2

Figure 5: Switching "Boost" Regulator

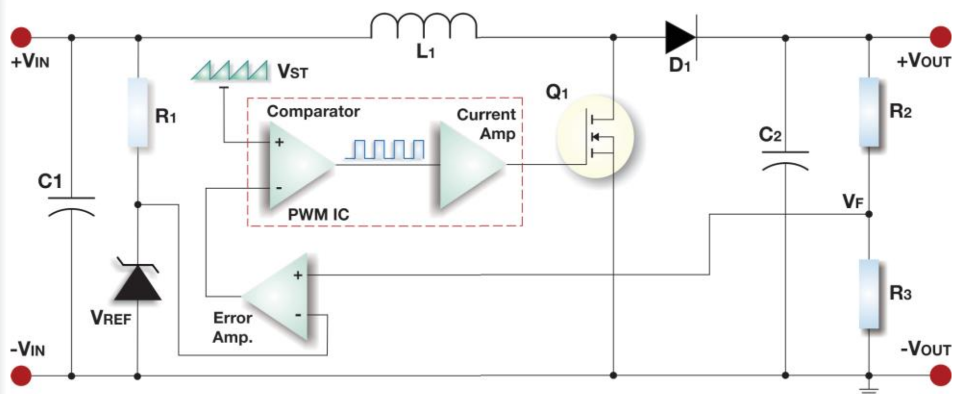
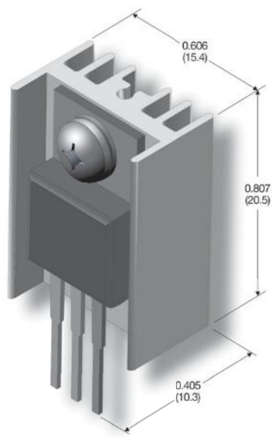
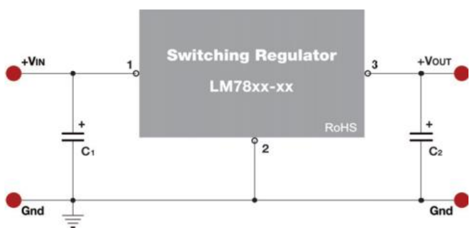


Figure 6: Linear and Switching Regulator Comparison

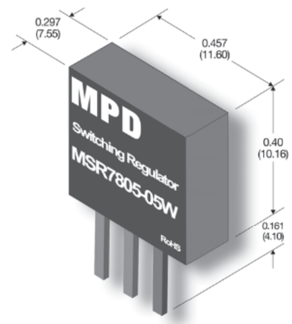


LM78XX Type Linear Regulator (With Heatsink)

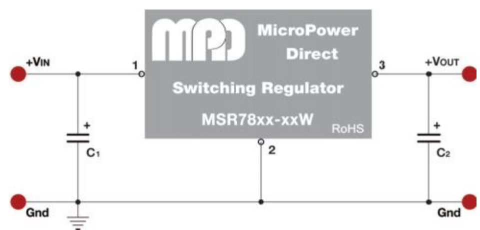


LM78XX Connection Diagram)

Parameter	Linear
Input Range	Narrow
Circuit Complexity	Low
Efficiency	40 - 60%
Noise	Low
Neg. Output Capability	No
No Load Input Current	6 - 8 mA
Safety Approval	No
Size	Large (With A Heatsink)
Cost	Low

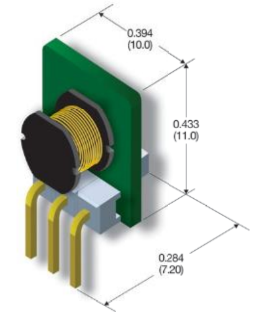


MSR7805W Switching Regulator

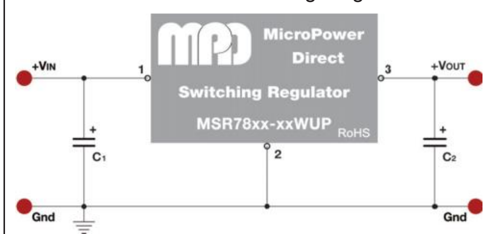


MSR7805W Connection Diagram)

Parameter	Switching
Input Range	Very Wide
Circuit Complexity	Low
Efficiency	80 - 95%
Noise	Low - Med
Neg. Output Capability	Yes
No Load Input Current	1.5 mA
Safety Approval	Yes
Size	Small
Cost	Med - Low



MSR7805WUP Switching Regulator



MSR7805WUP Connection Diagram)

Parameter	Switching
Input Range	Very Wide
Circuit Complexity	Low
Efficiency	80 - 96%
Noise	Low - Med
Neg. Output Capability	Yes
No Load Input Current	1.5 mA
Safety Approval	Yes
Size	Very Small
Cost	Med - Low

must be sufficiently high enough to provide adequate filtering of the inductor pulses. The output voltage is equal to:

$$V_{OUT} = V_{IN} \times T_{ON} \sqrt{\frac{R_L}{2T\,L_1}}$$

Where: V_{IN} = The input voltage level in VDC
T = The switching period of Q_1
T_{ON} = The on time of Q_1
R_L = The output load in ohms
L_1 = The inductor size in Henries
V_{IN} = The circuit input voltage

The boost topology is not as popular in switching regulator designs as buck circuits are. This is primarily due to their lower operating efficiency levels. However, they can be useful in applications where a higher output voltage is desired. One such area might be charging circuits for battery banks.

Switching vs Linear Regulators

As stated, advances in manufacturing and component technology have resulted in the release of switching regulators that are viable alternatives to their linear counterparts. The tables and diagrams above give an overview of the LM78xx type linear regulator and two new switching regulators available from MPD. These are the MSR7805-xxW (a potted regulator with a 0.5A output) and the MSR7805WUP (an unpotted regulator with a 0.5A output).

The top drawings illustrate the relative size of a typical of a typical operating installation. As can be seen, the need for a heatsink increases the space required for the linear model increases substantially.

The middle diagram shows the recommended connection from the individual datasheets. For all three regulators an input capacitor is added to improve stability and an output capacitor is added to improve transient response. The units will operate without these capacitors installed.

The chart reviews some of the important attributes of each unit. Traditionally, linear regulators have appealed to designers due to their low noise, simple connection and low cost. The major issue has typically been the low efficiency of linear devices. This will cause a significant loss of power for a load of any size. The power lost is equal to:

$$P_{Lost} = (V_{IN} - V_{OUT}) \times I_L$$

Where: V_{IN} = The circuit input voltage
V_{OUT} = The circuit output voltage
I_L = The circuit output current

This wasted power is dissipated as heat within the regulator. For many applications, the addition of a heatsink is required to prevent damage to the regulator. A typical heatsink assembly is shown above.

The addition of a heatsink increases the linear regulator footprint to approximately 40% larger than the equivalent switching regulator which does not need a heatsink. It also adds roughly 25% to the cost of using a linear regulator. This puts the cost into a range where switching regulators are more competitive.

Another common low cost regulator type is the switching regulator LM2575. This unit requires the two capacitors, a reference diode and an output inductor to complete the circuit. The incomplete LM2575 is offered at low cost by itself. However, if the required components are added in, the purchase cost is about the same as the MSR7805WUP.

When comparing the merits of these or other devices, consideration should be given to the added labor cost incurred for the installation of any external components. Other considerations would include the board space required to mount these components and the effect (if any) that the increased component count (or heat radiation) has on board reliability.

If you have any questions or comments on this note or the MSR78xx regulators, please contact technical sales at 781-344-8226.

MPD: Switching Regulator Products

Model No.	Input (VDC)	Output Voltage (VDC)	Output Current (mA)	Efficiency (typ %)	Safety Approval	Negative Output	Package Type	Package Dimensions
MSR7805W	4.75 - 36	3.3, 5, 9, 12, 15	500	To 95	Yes	Yes	Potted SIP	0.457 x 0.297 x 0.40 In 11.60 x 7.55 x 10.16 mm
MSR7805WUP	4.75 - 36	3.3, 5, 12, 15	500	To 95	Yes	Yes	Unpotted SIP	0.394 x 0.284 x 0.433 In 10.00 x 7.20 x 11.00 mm
MSR7810W(L)	6.0 - 36	3.3, 5, 9, 12, 15	1,000	To 96	Yes	Yes	Potted SIP	0.453 x 0.689 x 0.354 In 11.50 x 17.50 x 9.00 mm
MSR7810WUP	6.0 - 36	3.3, 5, 12, 15	1,000	To 96	Yes	Yes	Unpotted SIP	0.453 x 0.295 x 0.689 In 11.50 x 7.50 x 17.50 mm
LSR7805	4.5 - 28	3.3, 5, 9, 12, 15	500	To 96	No	No	SMT	0.60 x 0.476 x 0.285 In 15.24 x 12.10 x 7.25 mm
LSR7810	4.75 - 18	1.5, 1.8, 2.5, 3.3, 5, 6.5	1,000	To 93	No	No	SMT	0.60 x 0.476 x 0.285 In 15.24 x 12.10 x 7.25 mm
SR7810(L)	4.75 - 32	1.5, 1.8, 2.5, 3.3, 5, 6.5, 9, 12, 15	1,000	To 97	No	No	Potted SIP	0.45 x 0.35 x 0.69 In 11.50 x 9.00 x 17.50 mm
SR7815W(L)	4.75 - 18	1.5, 1.8, 2.5, 3.3, 5, 6.5	1,500	To 95	No	No	Potted SIP	0.45 x 0.35 x 0.69 In 11.50 x 9.00 x 17.50 mm
SR7820W(L)	4.75 - 32	1.5, 1.8, 2.5, 3.3, 5, 6.5	2,000	To 92	No	No	Potted SIP	0.45 x 0.35 x 0.69 In 11.50 x 9.00 x 17.50 mm

* Units with an (L) can be ordered with right angle pins

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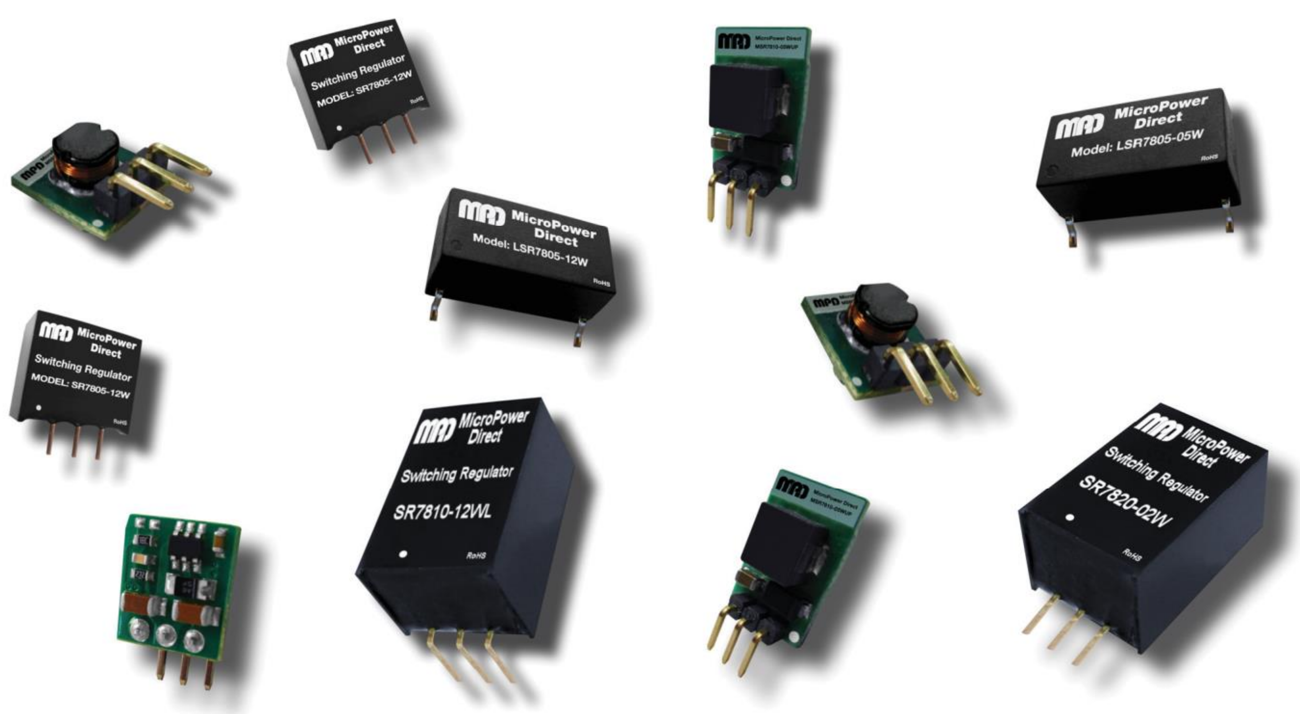

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