Electronic circuits require a wide variety of voltage levels to operate correctly. A DC/DC converter (DC/DC) is an electronic circuit used either to transform one voltage level to a different level; or to provide an isolation barrier for a voltage bus. DC/DCs are typically used in power distribution systems to provide a local voltage conversion, point of load voltage regulation or power bus isolation.

**Unregulated Converters**

Many low power or low cost DC/DC converters are unregulated circuits. They provide a voltage conversion and in some cases an isolation barrier, but the output level will vary with changes in the input level (line regulation is specified as a % change in $V_{OUT}$/% change in $V_{IN}$).

A typical unregulated DC/DC converter will use two transistor switches connected in a push-pull configuration (see page 4) with a center-tapped transformer. The free running oscillator (also called a classical or Royer) type converter, as shown in Figure 1 below, illustrates this. The circuit operates as follows:

1. One of the transistor switches ($Q_1$, $Q_2$) will start to turn on when an input voltage is applied. Positive feedback, applied to the base of the transistor by the transformer ($T_1$), will then turn the switch on hard.

2. The switch will remain turned on until the transformer saturates. This causes the transformer voltages to reverse, turning off the first transistor switch and turning on the second. The circuit will self oscillate in this way, producing a high speed square wave.

3. The square wave is full-wave rectified and filtered to provide an unregulated DC output.

This circuit is widely used for low power applications (<5W). It provides a low cost method of achieving an isolated voltage conversion, good performance envelope and reliable field operation in a small package.

The main drawback to free-running converters is the lack of output regulation. For applications requiring tight regulation, this can be provided by adding a linear regulator to the output circuit., as shown in Figure 1.

**Linear Voltage Regulation**

A linear voltage regulator provides a constant output voltage for varying input voltage and output load levels. It achieves this by controlling a series regulating element ($Q_1$). As illustrated in Figure 2 above, our simple example circuit operates as follows:

1. The zener diode ($Z_1$) provides a voltage reference input ($V_{REF}$) to the input of the error amplifier ($A_1$). This reference input is compared to the output voltage, which is fed back from the voltage divider network, $R_5$ and $R_6$. Any variation in the output voltage level produces an amplified error signal that is used to drive $Q_1$. The output is equal to:

$$V_{OUT} = V_{REF} \left( \frac{R_4 + R_5}{R_5} \right)$$

2. Output short circuit protection is provided by $Q_2$. The increased current drawn by an output short will increase the voltage drop across the sense resistor ($R_S$). If the voltage drop across $R_S$ rises sufficiently, $Q_2$ will turn on, pulling the error amplifier into saturation, allowing the output voltage to drop. The input voltage must be higher than the output to maintain regulation.

Low cost linear regulator IC’s are very common. Most have added circuitry to improve stability, limit high currents and prevent thermal damage. Linear regulators provide:

**Plus**
- Tight Regulation
- Low Noise & Ripple
- Fast Transient Response

**Minus**
- Low Efficiency
- Limited Input Range
- Low Power Density

When added to the free-running circuit as shown in Figure 1, a linear regulator will provide good output regulation. Because
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Theory Of DC/DC Converter Operation

Theory Of DC/DC Converter Operation

Most DC/DCs available as standard products use switch-mode regulation to improve performance features (efficiency, input range, etc) while maintaining small circuit size and economic production cost levels. 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.

In switching circuits, Pulse Width Modulation (PWM) is used to control the chopper or switch. A PWM circuit typically includes a reference voltage source, error amplifier, and 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. Illustrated in Figure 3 above, it operates as follows:

1. The converter output is monitored via the voltage divider R1 and R2. This sense voltage (VST) is compared to a reference voltage (VREF). Any difference in these two voltages produces an output from the error amplifier. This error level is fed through an isolation barrier (typically an opto-isolator) to a PWM IC. This isolation barrier insures the integrity of the converters input/output galvanic isolation.

2. Within the PWM, the amplified error voltage (VST) provides one input to a voltage comparator. The other input is a sawtooth waveform (VPWM). The sawtooth waveform has a period (T) that is equal to the reciprocal of the converter switching frequency. The comparator will provide a rectangular waveform (VOUT) that is proportional to the output voltage level of the error amplifier.

3. The rectangular waveform is amplified and applied to the base of the semiconductor switch (Q1). This signal controls the “On Time” of the switch. The “On Time” of the switch will adjust the input to the error amplifier (VST) to a level equal to the reference voltage (VREF). The level of VST is determined by:

\[ V_s = \frac{V_{OUT} \times V_{ST}}{R_1 + R_2} \]

Where:
- \( V_{OUT} \) = Output Voltage Level in VDC
- \( V_{ST} \) = Voltage Drop Across R1 in VDC
- \( R_1 \) = Value of R1 Expressed in Ω
- \( R_2 \) = Value of R2 Expressed in Ω

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

The use of switching regulation circuits offer a number of advantages over older linear controllers. The much higher efficiencies achieved and switching frequencies used allow the use of much smaller components, substantially reducing circuit size and improving circuit performance and reliability. The economy and flexibility of switching regulator circuits make them suitable for a wide variety of common topologies used in the design of DC/DC converters.

Non-Isolated Topologies

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 4, it operates as follows:

1. When the shunt switch (Q) is “ON”, the output rectifier (D) is reverse biased. During the “ON” period, energy is stored in the input inductor (L) and current to the output load is supplied by the capacitor (C).

2. When Q is “OFF”, the energy field in L begins to collapse, reversing the voltage polarity on the input inductor. This forward biases the output rectifier, allowing current to flow through D, to the load. This current flow will also “Boost” the charge on C to a value higher than the input level.

3. The output voltage is equal to:

\[ V_{OUT} = \frac{V_{IN} \times T_{ON}}{R_1 / 2L_1} \]

Where:
- \( T \) = Switching Period of Q
- \( T_{ON} \) = On Time of Q
- \( L_1 \) = Value of L, Expressed in Henries
- \( R_1 \) = Output Load Expressed in Ω
- \( V_{IN} \) = Input Voltage Level in VDC

Simple Boost regulators are not typically used in the design of DC/DC converters. However, derivative circuits such as the “Flyback converter” are very popular.
Buck Regulator: A buck regulator will take an unregulated voltage input and produce a regulated output voltage at a lower level. A simple buck regulator circuit is illustrated in Figure 5 below. It operates as follows:

1. When the series switch (Q₁) is "ON", the "flywheel" diode (D₃) is reverse biased. During this period current is supplied to the load through the output inductor (L₁).

2. When Q₁ is "OFF", the energy field in L₁ begins to collapse. This forward biases D₁, allowing current flow through the output capacitor (C₁). Thus, L₁ supplies energy to the load during both halves of the switching cycle resulting in lower output ripple than boost regulators.

3. The output voltage is equal to:

\[ V_{OUT} = V_{IN} \left( \frac{TON}{T} \right) \]

Where:
- \( T \) = Switching Period of Q₁
- \( TON \) = On time of Q₁
- \( V_{IN} \) = Input Voltage Level in VDC

From this it can be seen that the output voltage level will always be lower than the input voltage level.

Simple Buck regulators are often used in low cost, high efficiency point-of-load regulators. Like the Boost regulator however, more complex derivatives of the circuit (see Forward Converter) are more often chosen for standard DC/DC converter designs.

Isolated Topologies

For many applications the performance levels achieved with simple Buck or Boost regulators is not sufficient. For circuits requiring multiple outputs, extended input ranges, input/output isolation, etc., more complex topologies are required.

Flyback Converter: The Flyback topology is very popular for low power DC/DC converters. Illustrated in Figure 6, it operates as follows:

1. When the switch (Q₁) is "ON", current flows through the input (primary side) circuit. During this period, energy is stored in the primary windings of the transformer (T₁), which acts as an inductor. The longer the "ON" time of Q₁, the higher the peak current value stored in T₁ (see waveform diagram). The peak current value is given by:

\[ I_{PEAK} = (V_{IN} - 1) \left( \frac{TON}{Lp} \right) \]

Where:
- \( V_{IN} \) = Input Voltage Level in VDC
- \( TON \) = On time of Q₁
- \( L_p \) = Inductance of the Transformer Primary Expressed in Henries

During this period, the output rectifier (D₃) is reverse biased, blocking the energy stored in the transformer from the output. Current to the output load is supplied by the capacitor (C₁).

2. When Q₁ is "OFF", the energy field in T₁ begins to collapse, reversing the polarity of the transformer windings. This forward biases D₁, allowing current to flow through the transformer secondary to the output circuit. This current recharges the capacitor (C₂) as well as supplying the output load. This period is called the "Flyback Period".

The waveforms shown in Figure 7 illustrate a Flyback converter operating in discontinuous mode. Simply put, in discontinuous mode the secondary current will ramp down to zero (period T₃) before Q₂ returns to an "ON" state. To prevent the circuit instability that could be caused by saturation of the transformer core, a minimum period of dead time (T₄) must be maintained. Discontinuous mode is the most popular Flyback technique in use today.

Additional outputs can be added to the circuit quite simply. In low power, low cost converters, a center-tapped transformer secondary is used to produce a second output, as shown in Figure 8. For applications requiring higher performance or more than two outputs, auxiliary (or Slave) outputs can be added. As shown in Figure 8, in a slave configuration the feedback loop is connected to the primary output only. This results in looser regulation for the auxiliary outputs, but the performance level is acceptable for most applications.

The Flyback topology is popular because of its economy and versatility. It has fewer components which decreases material and manufacturing costs. Its performance level is acceptable for a wide variety of applications. On the negative side, Flyback circuits typically have higher levels of output ripple & noise than other topologies. Also, output components are subjected to higher stress levels (especially output capacitors) and must be chosen very conservatively.

Forward Converter: The forward converter is popular for moderate and high power converters. As illustrated in Figure 9, it operates as follows:

1. When the switch (Q₁) is "ON", the output rectifier (D₂) is forward biased and current flows "forward" from the transformer (T₂) secondary to the output inductor (L₂) and the load. During this period, the fly-wheel diode (D₃) is reverse biased.

2. When Q₁ turns "Off", the voltage across T₂ reverses polarity, reverse biasing D₂. The energy field in L₂ then begins to collapse, forward biasing D₃. Current will now flow in the output circuit through D₃ and C₂.
Theory Of DC/DC Converter Operation

Other Topologies - With this note, we have briefly discussed the most popular circuits used for standard DC/DC converters. Many other circuits (or variations of those already discussed) are used to meet specific application requirements. These would include resonant converters, bridge topologies, Cuk converters, etc.

Circuit Enhancements

The basic converter topology, once chosen, does not provide the performance envelope or feature set required by most applications. A number of circuit enhancements must be added to meet the demands of most applications. These would include:

Input Filter: The switching action of a DC/DC converter produces ripple and noise that is fed back onto the input DC power bus. The AC current component of this noise is called "Input Reflected Ripple Current" (or Back Ripple Current). It is typically specified as a mA Pk to Pk value.

Input filters are used to suppress this EMI. The type of filtering used depends upon the size, power level and cost of the converter as well as the application requirements it is designed to meet. Common filter configurations used include a simple capacitor, LC filters, Pi (P) filters and common mode filters (such as the Balun filter shown in figure 12). Some converters with more robust input filtering may be tested to insure compliance to specified limits such as EN522.

Input Current Limiting: Many DC/DC converters include circuitry that protects the internal components from damage in the event there is an output short circuit caused by a system fault. These circuits generally fall into three categories:

Power Limiting: Also called Constant Current Limiting, these circuits will hold the output current at a constant value under a fault condition. This set point is typically 110% to 120% of the full rated output current for the design. This is illustrated in Figure 13.

While it is typically the least expensive method to limit input current, power limiting, is not the most popular method. This is because of the stress that extended operation at 120% of rated output can place on the circuit components.

Foldback Current Limiting: As illustrated in figure 13, In a foldback protected circuit, the setpoint is again set at about 120% of rated output load. However, with this method, the output current is reduced back to a much lower level (typically 20% to 40%) of output current until the fault

Push Pull Converter: The basic push-Pull circuit is very similar in operation to the Forward converter. Illustrated in figure 11 (at right), it operates as follows:

1. Two semiconductor switches (Q1 & Q2) are connected to either end of the center tapped primary of a transformer (L1). The switches are operated 180° out of phase, so current flows first in one half of the primary winding and then in the other half.

2. The operation of the output circuit is very similar to that described for the Forward converter. The current waveform across the output inductor (L2) is very close to that shown for the Forward topology (figure 10).

The Push-Pull topology is still very popular for the design of DC/DC converters. It offers the designer good performance (efficiency, regulation, etc.) and is easily adaptable for varying application needs. It is more expensive than other topologies because of the increased complexity.

More components are required for a Forward converter circuit, so material and manufacturing costs tend to be higher than the Flyback type circuit. However, the Forward converter generally exhibits lower output noise and ripple, improved transient response and lower stress levels (on the output components) than comparable Flyback circuits.

Push Pull Converter: The basic push-Pull circuit is very similar in operation to the Forward converter. Illustrated in figure 11 (at right), it operates as follows:

3. For the single output unit shown, the output voltage is equal to approximately:

\[ V_{OUT} = (((V_{IN} - 1)N) - V_{DX}) \times \frac{T_{ON}}{T} \]

Where:  
- \( V_{IN} = \) Input Voltage Level in VDC
- \( N = \) Primary/Secondary Turns Ratio of T1
- \( V_{DX} = \) Voltage Drop Across the Rectifying Diode D2
- \( T_{ON} = \) On Time Of Q1
- \( T = \) Switching Period of Q1

Similar to the Buck regulator, the output inductor in the Forward converter provides current to the load during both halves of the switching cycle, as illustrated in the waveforms of figure 10. The current in the output inductor is approximately equal to the sum of the current flowing through the fly-wheel diode \( (I_{F1}) \) and the transformer secondary current \( (I_{C2}) \).

The diode \( D_2 \) is a "Catch" diode. The voltage across the \( T_1 \) primary reverses polarity when \( Q_1 \) turns "OFF". The end of \( T_1 \) identified with an "A" try to swing negative. If this is allowed to go too far, it could cause \( Q_1 \) to fail. \( D_1 \) will hold this point to one diode drop above ground, effectively limiting the voltage at the collector of \( Q_1 \) to about two times the value of \( V_{IN} \).

Like the Flyback converter, additional outputs can be added to the Forward topology very easily. Again, the typical way to achieve this is with a center-tapped secondary for low cost designs or quasi-regulated slave outputs.

The switching action of a DC/DC converter produces ripple and noise that is fed back onto the input DC power bus. The AC current component of this noise is called "Input Reflected Ripple Current" (or Back Ripple Current). It is typically specified as a mA Pk to Pk value.

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Foldback Current Limiting: As illustrated in figure 13, In a foldback protected circuit, the setpoint is again set at about 120% of rated output load. However, with this method, the output current is reduced back to a much lower level (typically 20% to 40%) of output current until the fault
condition is removed. A typical circuit is shown in figure 14. This circuit operates as follows:

1. The voltage drop across the sense resistor ($R_s$) provides one input into the "Current Sense Comparator" (within the PWM chip). The sense resistor is normally a very low value (<1Ω)

2. In the event of a fault condition such as an output short circuit, the current flowing through the input circuit of the converter will increase significantly. In turn, this will increase the voltage drop across $R_s$ ($V_{RS}$). When $V_{RS}$ exceeds the activating threshold of the current sense comparator, an error output occurs.

3. The error output of the comparator will normally extend the "OFF" time of the switch Q1 or shutdown the PWM, reducing current flow in the input of the converter. This circuit is self recovering; once the fault condition is removed, the converter will return to normal operation.

Foldback circuits are very popular. Although they are more expensive to implement than power limiting circuits, they provide improved protection by lowering the stress levels on the converter components. However, for applications with high start up current levels, such as those with high capacitive loads, foldback circuits may be a potential problem. If the current demand at start-up exceeds the current-limit set point, the unit may not start (or will start and immediately shut down).

Hiccup Mode: Hiccup mode (also called "Cycle by Cycle" current limiting) is the most complex of the three methods. During a fault condition that causes the input current to exceed a predetermined threshold, the hiccup circuit will shut the converter down (via the PWM chip). After a set amount of time, the converter will try to start again. If the fault condition still exists, it will again be shut down. This cycle of attempting to start and shutting down, will be repeated until the fault condition is removed.

Hiccup protection is normally not found in low power converters because of the added expense (they are inherently more complex because they require a timing circuit). A typical design would turn off the hiccup protection during start up to prevent high inrush currents from triggering the protection circuit.

Remote ON/OFF Control: Many converters (especially those with >15W output power) include a logic input that can be used to turn the unit on or off. Sometimes called an "Enable" or "Inhibit" input, this feature typically utilizes the "Shutdown" input to the PWM controller IC. If this PWM function is pulled low, all PWM control outputs will shut down, effectively turning off the converter.

The Remote ON/OFF signal is typically TTL (open collector) and CMOS (open drain) compatible. Depending upon the design, it may be enabled by a logic high or low. This feature is particularly useful in mobile or remote/battery operated applications where power conservation is critical.

Synchronization: For some applications that use multiple converters, synchronization of the converter operating frequency may reduce overall system noise. Again, this feature takes advantage of the ability of some PWM chips to accept an external clock frequency. This feature is not generally available on low power, standard DC/DC converters.

Input Transient Protection: The addition of a suppression device such as an avalanche zener diode may prevent damage to the semiconductor switch caused by input transients. Connected across the input of the converter, the zener would present a high impedance to the input under normal operating conditions. In the event of an input transient, the impedance of the zener would drop rapidly. The energy contained within the transient would then be dissipated across the zener.

Input clamps are typically only provided on very specialized DC/DC converters or custom designs. For most standard converters, it is left to the user to add a transient suppression device externally.

Soft Start: A soft start circuit limits the inrush current to the converter at turn on. Typically, it consists of a timing network that ramps up the PWM control signal to the switching transistors at start-up. This limits high start-up currents and their potential problems (output overshoot, transformer saturation, etc). The start-up delay is typically less than 100 mSec.

Isolation: For a variety of reasons, most applications require the DC/DC converter include electrical isolation. Normally specified as Isolation Voltage, (or "Breakdown Voltage"), this is the maximum voltage (ac or dc) that can be continuously applied between isolated circuits without a breakdown occurring. For converters, it is normally specified as input-output or input-case isolation. Standard DC/DC converters typically offer isolation levels ranging from 500 VDC to 6,000 VDC. Minimum isolation voltage levels must be maintained to meet most safety regulations.

Figure 14: Simplified Input Current Limiting

Figure 15: Isolation

Input to output isolation is typically achieved with a transformer. Figure 15 illustrates some of the specifications normally included on a converter datasheet. Isolation Resistance is usually given in MΩ, and Isolation Capacitance is normally given in pF. These...
To maintain the integrity of the isolation barrier, regulated converters will need to insure the feedback loop is isolated also. In standard converters, this is often accomplished with an opto-isolator.

**Output Filtering:** Filtering circuits on the converters output section will smooth the rectified pulses produced by the switching circuit. Like input filters, different filter configurations are used depending upon the converter design, component selection, circuit layout and application requirements.

**Overvoltage Protection (OVP):** A dramatic rise in the converter output voltage could cause damage to system components. Many converters include protection circuits to prevent this.

One common method is to connect a silicon controlled rectifier (SCR) between the converter output and ground. Called an overvoltage "Crowbar", this circuit clamps the output to ground when the SCR is triggered. Once triggered, the converter typically must be turned ON/OFF to reset the SCR.

**Figure 15: Overvoltage Protection (OVP)**

Another approach is shown in figure 15. Here, a zener diode ($D_2$) is used to sense the output. If the output level rises to the point that $D_2$ conducts, the PWM IC is shut down.

The threshold at which an OVP circuit will trigger varies according to the output being protected. Typical OVP setpoints are:

<table>
<thead>
<tr>
<th>Output Voltage</th>
<th>OVP Set-Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3 VDC</td>
<td>3.8 to 4.0 VDC</td>
</tr>
<tr>
<td>5.0 VDC</td>
<td>6.2 to 6.8 VDC</td>
</tr>
<tr>
<td>12.0 VDC</td>
<td>15.0 VDC</td>
</tr>
<tr>
<td>15.0 VDC</td>
<td>18.0 VDC</td>
</tr>
</tbody>
</table>

**Thermal Shutdown:** A thermal protection circuit will shut the converter off if a preset temperature level is exceeded. This temperature is normally measured at some point on the converter case (or baseplate) or near a sensitive component. Thermal protection is normally only provided on high power density converters where damaging internal temperature rises could occur if the unit is not properly cooled.

**In Summary:** This note is intended to be a brief overview of converter circuits. If you have specific technical questions on a DC/DC converter you are using or considering, please contact your vendor for detailed information.

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**Terms**

**Flyback Converter:** Sometimes called a "buck-boost" converter, this topology minimizes the required components by using a single transistor switch and eliminating the need for an output inductor. During the first half of the switching period, when the transistor switch is "ON", energy is stored in the transformer primary. During the second half or "flyback" period when the switch is "OFF", this energy is transferred to the transformer secondary and load.

**Forward Converter:** Like the flyback circuit, a forward converter uses a single transistor switch. However, in the forward converter, energy is transferred to the transformer secondary while the transistor switch is "ON", and stored in an output inductor.

**Full Bridge Converter:** A power supply topology, typically configured as a forward converter, that uses a bridge circuit, consisting of four switching transistors, to drive the transformer primary.

**Half Bridge Converter:** A power supply topology that uses a bridge circuit, consisting of two switching transistors, to drive the transformer primary. Half bridge converters are typically configured as a forward converter.

**Regulated Power Supply:** A power supply whose output is held to within a tight error band regardless of changes in line and load.

**Switching Power Supply:** A power supply that uses switching regulation. Switchers are typically smaller, more efficient & lighter than linear supplies.

**Switching Regulator:** A circuit (typically a pulse width modulator) that uses a closed loop design to regulate the output voltage.

**Three Terminal Regulator:** A linear regulator packaged in a standard 3-terminal transistor package. These devices can be configured as either a shunt or series regulator.

**Push Pull Converter:** A power supply circuit that uses two transistor switches and a center tapped transformer. Normally configured as a forward converter, the transistor switches turn on and off alternately.

**Quasi-Regulation:** Auxiliary outputs on a multiple output power supply that are regulated via the primary output (controlled by a direct feedback loop). Auxiliary output voltages are set by the turns ratio of the isolation transformer. Quasi-regulated outputs are significantly affected by variations in the primary output. Sometimes referred to as semi-regulation.