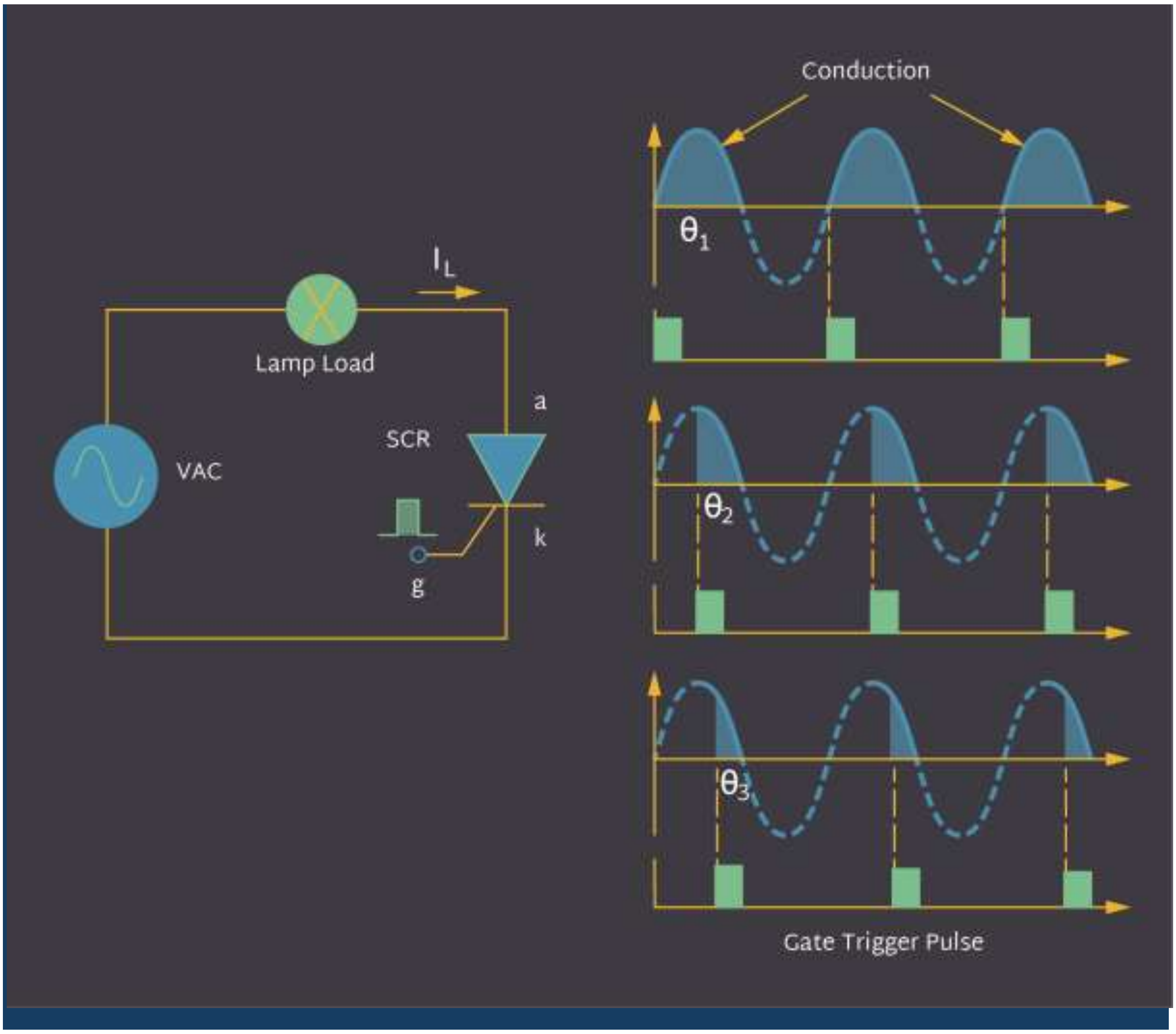

AC/DC Converters

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Circuits often require an integrated AC power source as the optimum strategy to reduce size, cost or due to application specific needs. Understanding the key concepts associated with conversion and the practical alternatives available is a good start towards a successful design.

Safety First!
When the AC source is a mains power socket, great care must be taken to ensure an implementation is safe to use. Without exception, this subsystem should be designed and implemented by a qualified expert. If possible, use a preapproved off-the-shelf plug pack.

Compliance is Compulsory!
When you plug in anything to a mains plug socket, it must comply with legal certification standards in the country it will be used in. More than this, it must have been tested and certified to do so – an expensive process. This is to ensure it is safe, does not interfere with other people or contribute noise to the AC main power lines.

What is an AC/DC Converter?
Electric power is transported on wires either as a direct current (DC) flowing in one direction

at a non-oscillating *constant* voltage, or as an alternating current (AC) flowing backwards and forwards due to an oscillating voltage. AC is the dominant method of transporting power because it offers several advantages over DC, including lower distribution costs and simple way of converting between voltage levels thanks to the invention of the transformer. AC power that is sent at high voltage over long distances and then converted down to a lower voltage is a more efficient and safer source of power in homes. Depending on the location, high voltage can range from 4kV (kilo-volts) up to 765kV. As a reminder, AC mains in homes range from 110V to 250V, depending on which part of the world you live it. In the U.S., the typical AC main line is 120V.

Converters steer an alternating current, as its voltage also alternates, into reactive impedance elements, such as inductors (L) and capacitors (C), where it is stored and integrated. This process separates the power associated with the positive and negative potentials. Filters are used to smooth out the energy stored, resulting in creation of a DC source for other circuits. This circuit can take many forms but always comprises of the same essential elements, and may have one or more stages of conversion. The converter depicted in figure 1 is called a ‘forward converter”, which is a higher efficiency than a slightly simpler architecture; a ‘flyback converter’. Although not discuss in detail, a flyback converter differs from a forward converter in that its operation depends upon energy stored in the airgap of the transformer in the circuit. Apart from this difference, they can utilize the same essential blocks.

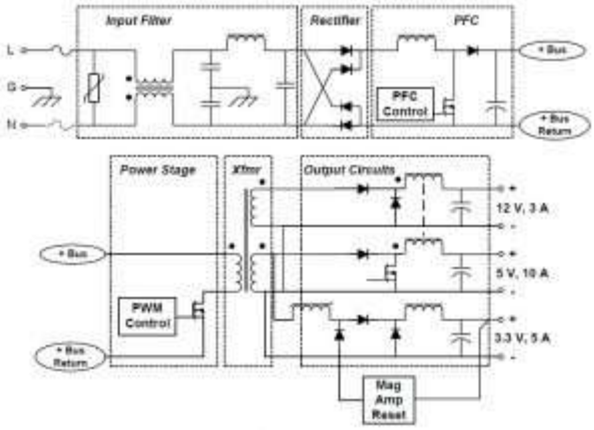

Figure 1: Functional Block Diagram of a Forward Converter AC/DC Power Supply

Input Filtering Block

An input filter is important as it prevents noise produced in the power supply switching elements from getting back onto the mains power supply. It also prevents noise that may be on the mains power supply getting into subsequent circuits. The filter passes through 50/60Hz mains frequency, and attenuates higher frequency noise and harmonics that might be present. As with other parts of an AC to DC converter, reactive elements like capacitors and inductors perform the important role of frequency – selective suppression. Capacitors do not pass DC, and can be used in series (as DC blocking ‘high pass filter’ elements), or parallel (to shunt high frequencies to ground preventing them from getting through to the converter). More information on filtering can be found here.

The input filtering block will also typically include a voltage dependent resistor, or varistor to prevent high voltage spikes on the electrical power grid from damaging the power supply. This is the rectangular box with the diagonal line through it on the input in Figure 1. The most common type of varistor is a metal-oxide varistor (MOV). Any voltage over the devices ‘clamping voltage’ causes the MOV to become conductive, shunting the high voltage spike and suppressing the surge.

Rectification

The simplest AC/DC converters comprise of a transformer following the input filtering, which then passes onto a rectifier to produce DC. In this case, rectification occurs after the transformer because transformers do not pass DC. However, many AC/DC converters use more sophisticated, multi-stage conversion topologies as depicted in figure 1 due to advantages of smaller transformer requirements and lower noise referred back to the mains power supply.

Rectifiers are implemented using semiconductor devices that conditionally conduct current in one direction only, like diodes. More sophisticated semiconductor rectifiers include thyristors. Silicon controlled rectifiers (SCR) and triode for alternating current (TRIAC) are analogous to a relay in that a small amount of voltage can control the flow of a larger voltage and current. The way these work is they only conduct when a controlling ‘gate’ is triggered by an input signal. By switching the device on or off at the right time as the AC waveform flows – current is steered to create a DC separation. There are many circuits for doing this, with signals tapped off the AC waveform used as control signals that set the phase quadrants thyristors are on or off. This is *commutation*, and can be either *natural* (in the case of a simple diode) or *forced*, as in the case of devices that are more sophisticated.

High efficiency power supplies can use active devices like MOSFETs as switches in such circuits. The reason for using topologies that are more complex is usually for efficiency improvement, to lower noise or to act as a power control. Diodes have an intrinsic voltage drop across them when they conduct. This causes power to be dissipated in them, but other active elements may have much lower drop and therefore lower power loss. SCR and TRIAC circuits are particularly common in low cost power control circuits like the light dimmer example below – used to directly steer and control current delivered to the load as the input mains alternates. Note that these implementations are not galvanic when they do not have a transformer in the circuit – only useful in circuits that are appropriate like direct mains connected light control. They are also used in high power industrial and military power supplies where simplicity and robustness is essential

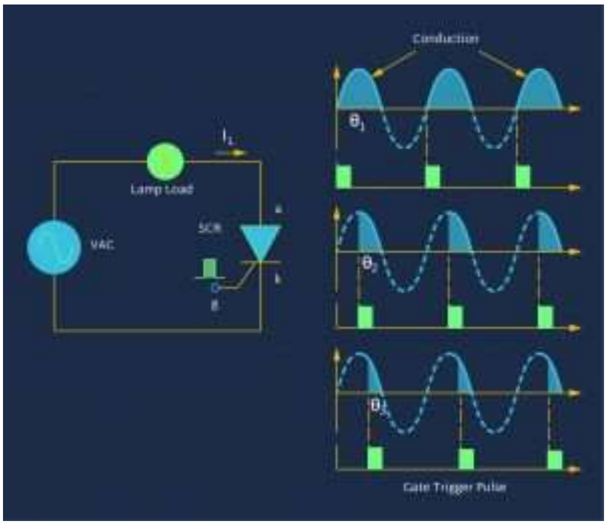

Figure 2: SCR Based Conversion

Power Factor Correction (PFC)

This is the most complicated aspect of a converter to understand. PFC is an essential element in improving the efficiency of a converter by correcting the relative phase of current being drawn to voltage waveform to maintain the optimum power factor. This reduces the ‘reactive load’ characteristics that the converter may otherwise present to the mains power supply. This is essential for maintaining high quality, efficient electrical networks and electrical supply companies can even impose special reactive current tariffs on customers that have poor power factors. Passive or active PFC refers to whether active elements or passive elements being used to correct the phase relationships. Semiconductor PFC can refer to special purpose ICs with integrated controllers tailored to actively monitor and adjust the PFC circuit, reducing the component count and simplifying the overall design while obtaining higher performance. They can incorporate other functions like over/under voltage protection, over current protection, soft start, and fault detection/response.

The converter depicted in figure 1 is a single stage PFC converter. The capacitor in this section is used to store the unbalanced energy between the pulsating input power and relatively constant output power of the stage. See the "Reactive Energy Storage" section for more details on this. Two stage PFC converters are commonly used as they don't have to handle as wide a voltage range across the storage capacitor you get in universal power supplies, which has a detrimental effect on conversion efficiency. They can also offer better trade-offs in the capacitor size, and this can help reduce cost.

Power Stage

The power stage controls the power delivered from the primary to the secondary side through the transformer. It comprises of an active switching device that switches at a high frequency that can be in the hundreds of kHz. The switch ON/OFF state is controlled by a pulse width modulation (PWM) input that changes depending upon the amount of power that needs to be dynamically delivered to the load. This information is obtained by a feedback path from the secondary side that may be communicated by a number of techniques that accommodate for the converter's isolation requirements. The higher frequency switching results in a smaller transformer requirement, reducing size and cost.

Transformer

A transformer is comprised of wires wound on a common core that couple into each other by electromagnetic induction. This is important when connecting to high voltage (mains) sources – referred to as 'off-line' conversion as the inductive coupling disconnects the mains from the subsequent circuit, a much safer scenario than direct connection. This coupling by an electromagnetic field, rather than a direct copper circuit, called 'galvanic isolation' restricts the maximum energy that can cause electric shock or dangerous sparking discharge to the stored energy in the transformers magnetic field flux lines. The ability (related to size and materials) of the transformer to store energy is an important consideration in converter design as it dictates how well the transformer can provide the energy to maintain the desired voltage potential under changing load conditions.

Details of transformer theory and operation can be found here and here.

Figure 1 has a block called 'Mag Amp Reset' associated with demagnetizing the transformer due to a magnetization current inherent in the architecture. Without this, the remanence of the core material would saturate it in a few cycles of the power stage PWM. Although too complex to cover in this tutorial, this additional circuit can be very confusing when reviewing converter circuit diagrams, and it is useful to know why it is required. There are a number of techniques to perform demagnetization, the simplest being when the power stage switch is off a demagnetizing current is fed back diode through a separate auxiliary winding. This circuit restricts the maximum PWM duty cycle to 50%, but more complex methods can be used to enable higher duty cycles.

Transformers or other galvanic isolation methods (like optocouplers) are frequently used to communicate information signals between primary and secondary sides. This is needed to facilitate more intricate control of the conversion process – enabling a primary side situated control circuit to respond to the state of the secondary side load and dynamically change how it steers current to get lower noise and higher efficiency.

Output Circuits

As mentioned in the filtering section, electric fields in passive reactive (storage) elements like capacitors and inductors store energy. When used after the charge steering rectification, they act as a *reservoir* of energy during the alternating input power cycle. This is a vital element in a convertor as this energy storage acts as a source – enabling a constant output voltage under varying load conditions. Active elements sense the voltage presented to the load and/or the current flowing into the load, and in a negative feedback control loop, use this information to adjust the energy *pumped* into these storage elements to maintain a constant output voltage level. This pumping process uses active elements to switch on and off the current flowing into the storage elements, referred to under the broad concept of *regulation*.

Regulation

We need a constant voltage presented to a load circuit, irrespective of the dynamic impedance of the load. Without this, over or under voltage conditions may occur, leading to spurious circuit behavior or even circuit damage. This is particular true with low voltage digital electronics where supply voltages must be tightly constrained within a window of a few percent of a nominal value. Reactive elements do not have any in-built control of this. The way an AC/DC converter achieves a tightly controlled window of output voltage is by conditionally controlling the energy stored in the low impedance reactive store *source*.

The voltage output will change over time as power drains from these elements and may also have variance caused by the non-ideal characteristics of the devices – like series resistance or parasitic capacitance. Some kind of dynamic control to *recharge* this source is required. This is called regulation. Loads like microprocessors change the power they demand as they perform different operations, and this exacerbates the need to have an active dynamic regulation.

Regulation control is a feedback circuit that controls the switching elements. In this case the switching element is on the primary side of the converter. For a switch to be efficient it has to be either hard ON (lowest impedance possible) or hard OFF (highest impedance possible) – as in between states lead to power traveling through the switch being dissipated and wasted. Semiconductor switches like MOSFETS are non-ideal and exhibit some impedance, they dissipate energy and this lowers conversion efficiency. There are only really two ways to control a switch , by varying the duty cycle a switch is on or off, called Pulse Width Modulation (PWM) or controlling the frequency of being ON or OFF. *Non-Resonant Mode* converters employ hard switching techniques, but *Resonant Mode* convertors employs a more intelligent soft-switching technique. Soft switching means switching on or off the alternating current waveforms at zero voltage or zero current points, eliminating switching losses and leading to very high efficiency architectures. Techniques like synchronous rectification replace the rectification diodes with active switching elements like MOSFETS. Controlling the switching synchronized to the input AC waveform enables the MOSFET to conduct with a very low ON resistance and less voltage drop at the right time – leading to higher efficiency when compared to diode rectification.

How does the regulation circuit know when to switch? There are two principle methods of control mode: voltage control and current control. Regulators utilize one or a combination of both methods to regulate the voltage presented to the load circuit.

Voltage Control Mode

The regulation circuit senses output voltage, compares it to a reference voltage to create an error function. The error signal modifies the switching ratio to bring the output closer to the desired level. This is the simplest method of control.

Current Control Mode

Both output voltage and inductor current sensed and the combination used to control the duty cycle. This inner ‘current sensing loop’ enables faster response time to load change, but is more complex than voltage control mode.

Further complicating the regulation element, over and above the method of control, the way a converter acts as a commutation cycle is called a *continuous* or *discontinuous* mode of operation. A continuous mode of operation is one where the inductor current never falls to zero (if the converter topology has one). This is a lower output ripple and therefore lower noise mode of operation, but as the inductor is always conducting, it is always dissipating some energy in its non-ideal series conduction losses. In discontinuous mode, the inductor current is allowed to go to zero, causing the load to obtain energy from the storage capacitors. This is a higher efficiency mode of operation but does potentially have more ripple and poorer regulation control.

Converter Types

As touched on briefly, there are several converter types relating to their topology, including flyback and buck- flyback architectures. These are common topologies as they incorporate transformers, have low component count and can be low cost relative to other options. Flyback converters are a buck-boost converter (step-up/step down) with the inductor replaced with a transformer. The stored energy inside the transformer is used to commutate the secondary through an active or passive rectification circuit. The most common type of flyback converter utilizes discontinuous mode (DCM) – with current flowing in the transformer getting to zero – as this typically has the simplest control loop and lowest cost. Continuous current mode (CCM) flyback convertors are required for higher power levels but result in higher transformer winding losses due to continuous conducting. Many power supplies switch between modes depending upon the load level. Quasi resonant (QR) and valley switching/variable frequency variations on the flyback topology are more complex circuits that optimize when and how switching occurs to improve efficiency. QR flyback achieve this by recycling energy of non-ideal leakage inductances, and valley switching reduces spikes caused by overshoot. They are typically used in low power applications.