APPLICATION NOTE

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An overview of switched-mode power supplies

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Conceptually, three basic approaches exist for obtaining regulated DC voltage from an AC power source. These are:

- Shunt regulation

- Series linear regulation

- Series switched-mode regulation

All require AC power line rectification.

The series switched-mode regulators will be referred to as switched-mode power supplies or SMPS during the course of this article

Briefly stated, if all three types of regulation can perform the same function, the following are some of the key parameters to be addressed:

- From an economical point of view, cost of the system is paramount.

- From an operations point of view, weight of the system is critical.

- From a design criteria, system efficiency is the first order of business

The series and shunt regulators operate on the same principle of sensing the DC output voltage, comparing to an internal reference level and varying a resistor (active device) to maintain the output levels within pre-specified limits.

Switched-mode power supplies (SMPS) are basically DC-to-DC converters, operating at frequencies in the 20kHz and higher region. Basically, the SMPS is a power source which utilizes the energy stored during one portion of its operating cycle to supply power during the remaining segment of its operating cycle.

Linear regulators, both shunt and series, suffer when required to supply large currents with resultant high dissipation across the regulating device. Efficiency suffers tremendously. (Efficiencies less than 40% are typical.)

Switched-mode power supplies operate at much higher levels of efficiency (generally in the order of 75% to 80%), thereby reducing significantly the energy wasted in the regulated supply. The SMPS does, however, suffer significantly in the ripple regulation it is able to maintain, as opposed to a much higher degree of regulation available in series (or shunt) linear regulators.

The linear regulators obtain improved regulation by virtue of the series pass elements always conducting, as opposed to SMPS devices having their active devices operative only during a portion of the overall operating period.

Some definitions and comparisons between linear regulators and switched-mode power supplies follow for reference.

REGULATION

Line Regulation — (Sometimes referred to as static regulation) refers to the changes in the output (as a percent of nominal or actual value) as the input AC is varied slowly from its rated minimum value to its rated maximum value (e.g., from 105VAC$_{RMS}$ to 125VAC$_{RMS}$).

Load Regulation — (Sometimes referred to as dynamic regulation) refers to changes in output (as a percent of nominal or actual value) when the load conditions are suddenly changed (e.g., minimum load to full load.)

NOTES: The combination of static and dynamic regulation are cumulative care should be taken when referring to the regulation characteristics of a power supply

Thermal Regulation — Referred to as changes due to ambient variations or thermal drift.

TRANSIENT RESPONSE

The ability of the regulator to respond to rapid changes in either line variations, load variations, or intermittent transient input conditions. (This parameter is often referred to as "recovery time".)

AC PARAMETERS

Voltage Limiting — The regulator's ability to "shut down" in the event that the internal control elements fail to function properly.

Current Limiting — Often referred to as "fold-back", where the amplifier segment of the regulator folds back the output current of the device when safe operating limits are exceeded.

Thermal Shutdown — The regulator's ability to shut itself down when the maximum die temperature is exceeded.

GENERAL PARAMETERS

Power Dissipation — The maximum power the regulator can tolerate and still maintain operation within the safe operating area of its active devices.

Efficiency — The ratio (in percent) of the usable versus total power being dissipated in a regulated supply. (The losses can be AC as well as DC losses.)
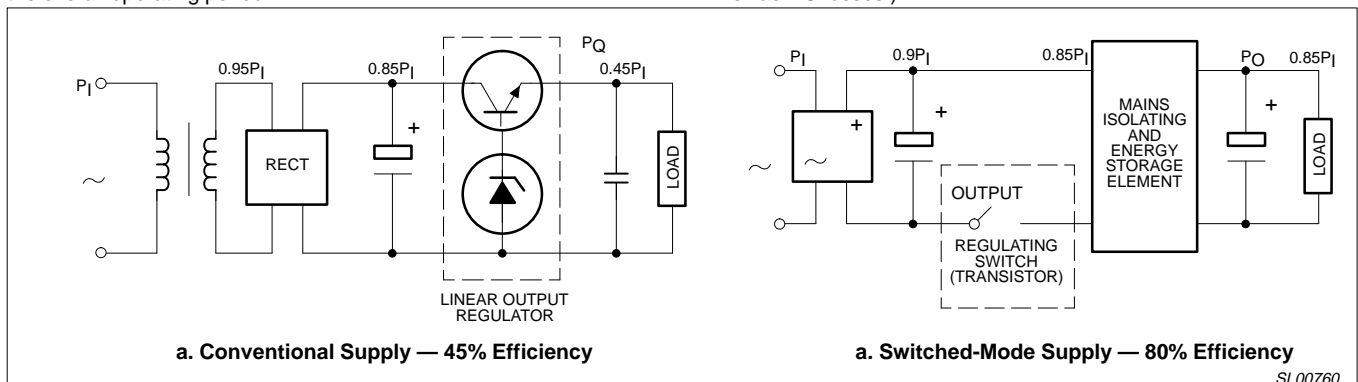

a. Conventional Supply — 45% Efficiency

a. Switched-Mode Supply — 80% Efficiency

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Figure 1. Losses in Regulated Power Supplies

EMI/RFI — Generation of ElectroMagnetic/Radio Frequency Interference signals and magnetic field disturbance in SMPS devices. (Transformer and choke design are available which reduce both RFI & EMI to safe acceptance regions.)

The balance of this section will be dedicated to the discussion of the general operation of Switched-Mode Power Supplies (SMPS) with emphasis on the Philips Semiconductors NE5560 Control and Protection Module.

Switched-mode power supplies (SMPS) have gained much popularity in recent years because of the benefits they offer. They are now used on a large scale in desk calculators, computers, instrumentation, etc., and it is confidently expected that the market for this type of supply will grow.

The advantages of SMPS are low weight and small size, high efficiency, wide AC input voltage range, and low cost.

- Low weight and small size are possible because operation occurs at a frequency beyond the audible range; the inductive elements are small.

- High efficiency because, for output regulation, the power transistor is switched rapidly between saturation and cut-off and therefore has little dissipation. This eases heatsink requirements, which contributes to weight and volume reduction. Conventional linear regulator supplies may have efficiencies as low as 50%, or less, but efficiencies of 80% are readily achievable with SMPS (see Figure 1).

- Wide AC input voltage range because the flexibility of varying the switching frequency in addition to the change in transistor duty cycle makes voltage adaptation unnecessary.

- Low overall cost, due to the reduced volume and power dissipation, means that less material is required and smaller semiconductor devices suffice.

Switched-mode power supplies also have slight disadvantages in comparison to linear regulators, namely, somewhat greater circuit complexity, tendency to RFI radiation, slower response to rapid load changes, and less ability to remove output ripple.
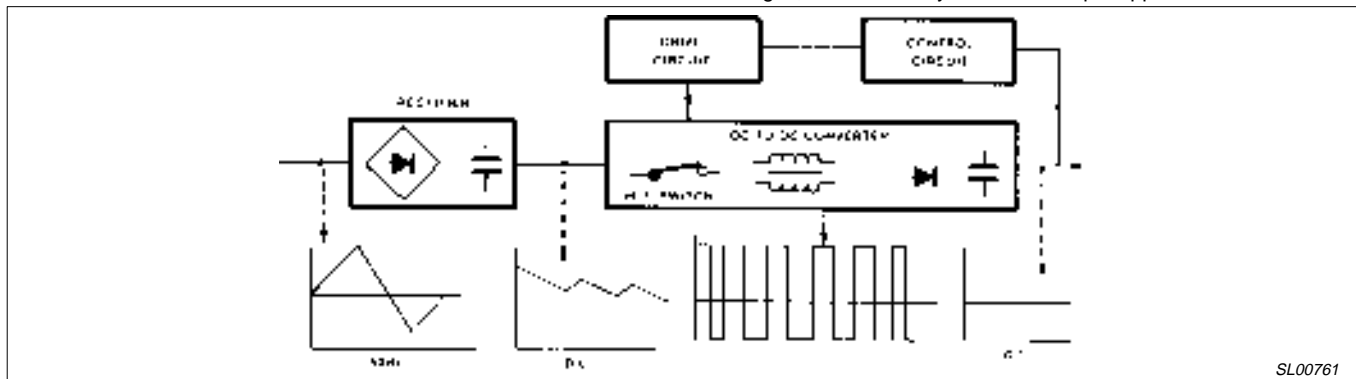

Figure 2. Block Diagram of Switched-Mode Power Supply
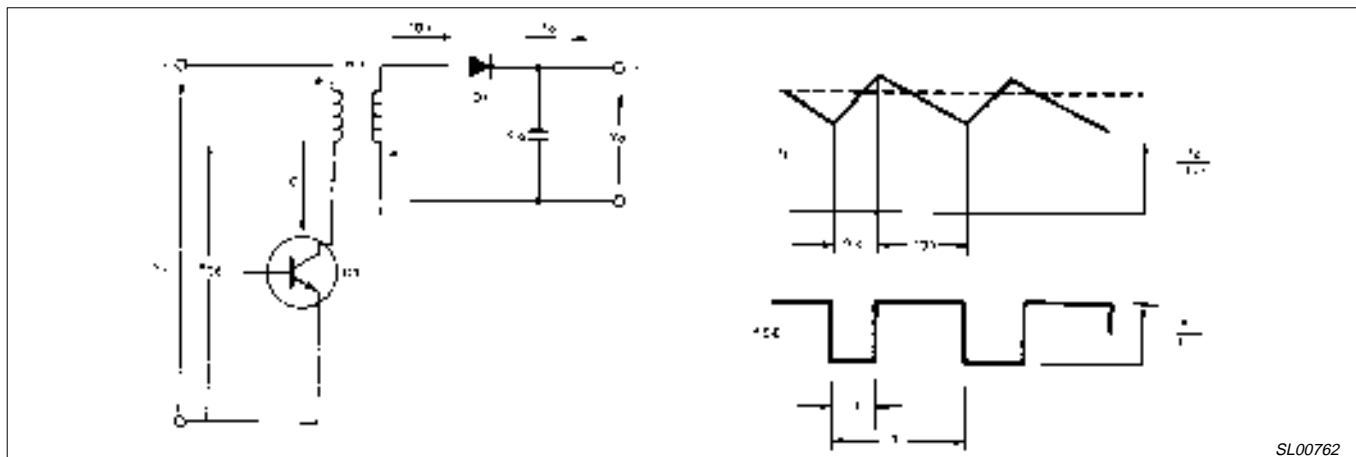

Figure 3. Flyback Converter Circuit Diagram and Waveforms

HOW SWITCHED-MODE POWER SUPPLIES OPERATE

The switched-mode power supply is a modern version of its forerunner, the electromechanical vibrator, used in the past to supply car radios. But the new concept is much more reliable because of the far greater lifetime of the transistor switch. Figure 2 shows the principle of the AC fed SMPS. In this system, the AC voltage is rectified, smoothed, and supplied to the electronic chopper, which

operates at a frequency above the audible range to prevent noise. The chopped DC voltage is applied to the primary of a transformer, and the secondary voltage is rectified and smoothed to give the required DC output. The transformer is necessary to isolate the output from the input. Output voltage is sensed by a control circuit, which adjusts the duty cycle of the switching transistor, via the drive circuit, to keep the output voltage constant irrespective of load and

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line voltage changes. Without the input rectifier, this system can be operated from a battery or other DC source.

Depending on the requirements of the application, the DC-to-DC converter can be one of the three basic types: flyback converter, forward converter, or push-pull (balanced) converter.

The Flyback Converter

Figure 3 shows the flyback converter circuit, and the waveforms of transistor voltage, V_{CE}, and choke current, I_L, reflected to the primary (choke double-wound for line isolation). Cycle time and transistor duty cycle are denoted T and δ, respectively. While Q1 conducts, energy is accumulated in the choke magnetic field (I_L rising and D_1 reverse-biased), and it is discharged into the output capacitor and the load during the flyback period, that is, while Q1 is off (I_L falling and D_1 forward-biased). During Q1 conduction, C_O continues delivering energy to the load, so providing smoothing action. It will be noted that only one inductive element is needed, in

distinction to the converter types discussed below, which require two. As the V_{CE} waveform shows, the peak collector voltage is twice the input voltage, V_I, for δ equal to 0.5.

The Forward Converter

A major advantage of the forward converter, particularly for low output voltage applications, is that the high frequency output ripple is limited by the choke in series with the output. Figure 4 illustrates the circuit. During the transistor-on (or forward) period, energy is simultaneously stored in the choke L_O and passed via D_1 to the load. While Q1 is off, part of the energy accumulated in L_O is transferred to the load through free-wheeling diode D_2. Output capacitor C_O smoothes the ripple due to transistor switching. After transistor turn-off, the magnetic energy built up in the transformer core is returned to the DC input via the demagnetizing winding (closely coupled with the primary) and D_3, so limiting the peak collector voltage to twice the input voltage, V_I.
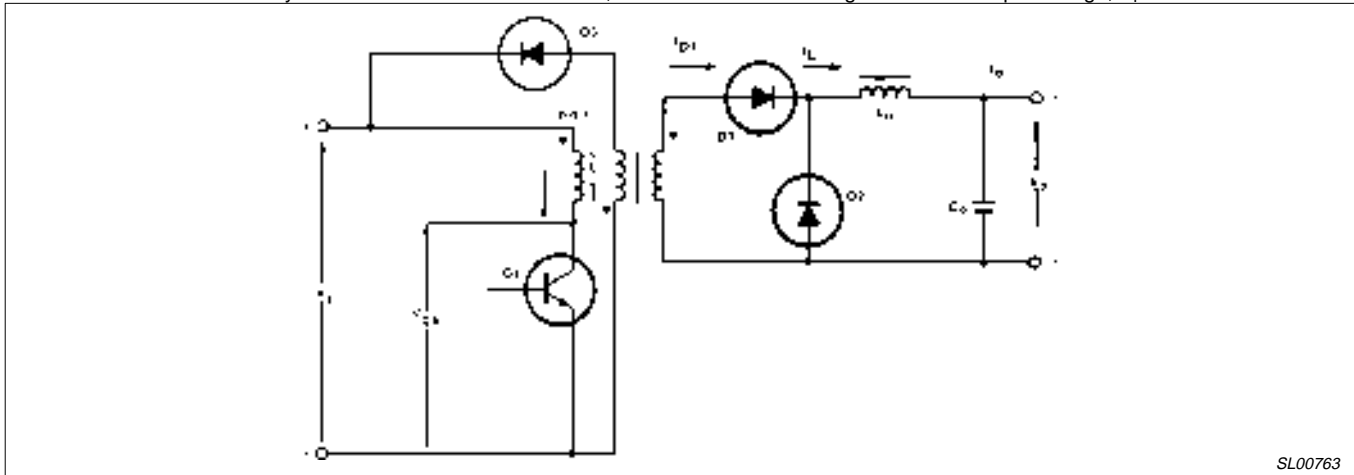

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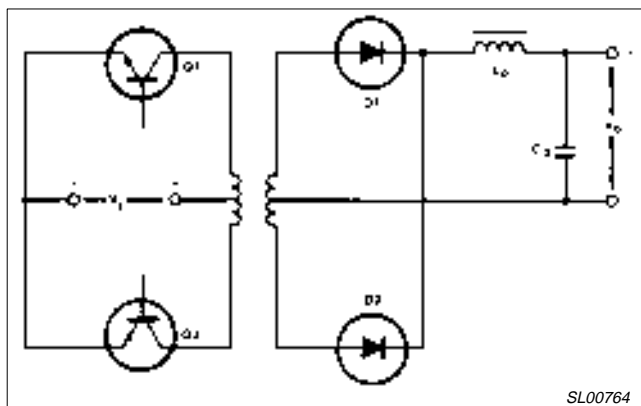**Figure 4. Forward Converter Circuit Diagram**

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Figure 5. Push-Pull Converter Circuit Diagram

The Push-Pull Converter

This converter type, given in Figure 5, consists of two forward converters operating in push-pull. Diodes D_1 and D_2 rectify the rectangular secondary voltage generated by Q1 and Q2 being turned on during alternate half cycles. Push-pull operation doubles the frequency of the ripple current in output filter L_OC_O and so reduces the output ripple voltage. The peak transistor voltage is $2V_I$.

MAKING THE BEST CONVERTER CHOICE

There exist several versions of the three fundamental circuits described earlier.

These are shown in Figure 6. Circuits IA, IIA and IIIA are the basic types. In the two transistor circuits IB and IIB, transistors Q1 and Q2 conduct simultaneously and diodes D_4 and D_5 limit the peak collector voltage to the level of DC input voltage, V_I. Similarly, in the push-pull circuits IIIB and IIIC, the collector voltage does not exceed V_I; in circuit IIIB, Q1 and Q2 are turned on during alternate half cycles, in circuit IIIC, Q1 and Q4 are turned on in one half cycle and Q2 and Q3 in the next.

Converter choice depends on application and performance requirements. The flyback converter is the simplest and least expensive; it is recommended for multi-output supplies because each output requires only one diode and one capacitor. However, smoothing may be a problem where ripple requirements are severe. The push-pull type has the most complex base drive circuit but it produces the lowest output ripple with given values of L_O and C_O.

Figure 7 is a general guide for the choice of converter type, based on output voltage and power. In the case of the flyback converter, it becomes more and more difficult to keep the percentage output ripple below an acceptable level as the output power increases and the output voltage decreases. For reasons of circuit economy, however, the flyback converter is the best proposition if the output power does not exceed about 10W. For output powers higher than about 1kW, the push-pull converter is preferable.
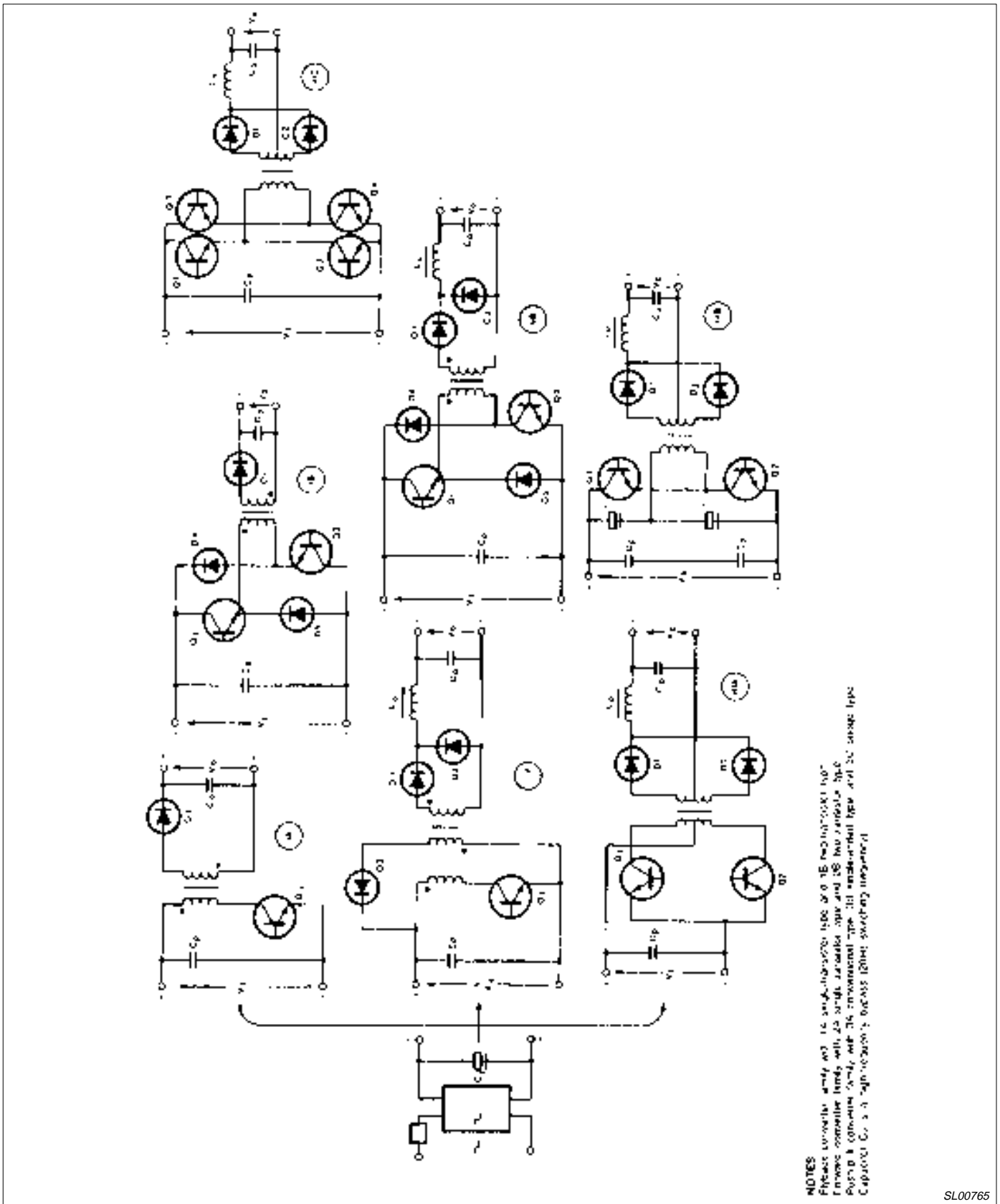
Figure 6. Various DC-to-DC Converter Types with Their Rectifier Supply

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THE CONTROL AND PROTECTION MODULE

In addition to providing adequate output voltage stabilization against line voltage and load changes, the control module must give fast protection against overload, equipment malfunction, and the effects of switch-on immediately following switch-off. In addition the following features are desirable:

- Soft-Start: a gradual increase of the transistor duty cycle after switch-on causing a slow rise of the output voltage, which prevents an excessive in-rush current due to a capacitive load or charging of the output capacitor.

- Synchronization: to prevent interference due to the difference in free-running frequencies (for example, in a system in which a low-power SMPS supplies the base drive circuit of the output switching transistor in a high-power SMPS).

- Remote switch-on and switch-off: essential for sequential switching of supply units in, for instance, a computer supply system.

The control and protection circuitry of a switched-mode power supply (SMPS) is a crucial and complicated part of the whole supply. Integration of this circuitry on a chip will therefore ease the design of an SMPS considerably.
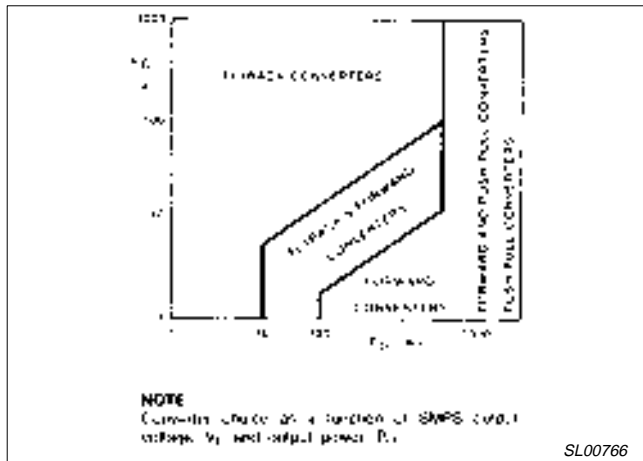

NOTE
Converter choice as a function of SMPS output voltage V_O and output power P_O.

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Figure 7. Converter Type

SMPS CONTROL LOOP

Figure 8 shows the principal control loop of a regulated SMPS. The output voltage V_O is sensed and, via a feedback network, fed to the input of an error amplifier where it is compared with a reference voltage.

The output of this amplifier is connected to an input of the pulse-width modulator, PWM.

The other input of this modulator is used for an oscillator signal, which can be a sawtooth or a triangle.

As a result, a rectangular waveform with the frequency of the oscillator is emerging at the output of the PWM.

The width of this pulse is dictated by the output voltage of the error amplifier.

After passing through an output stage, the pulse can be used to drive the power transistor of the SMPS.

When the width of the pulse is varied, the ontime of this transistor will also vary and consequently the amount of energy taken from the input voltage, V_I.

So, by controlling the duty cycle δ of the power transistor, one can stabilize the output of the SMPS against line and load variations. The duty cycle δ is defined as t_{ON}/T for the power transistor. Protections for overvoltage, overcurrent, etc., can be realized with additional inputs on the PWM or the output stage.

INITIAL TURN-ON

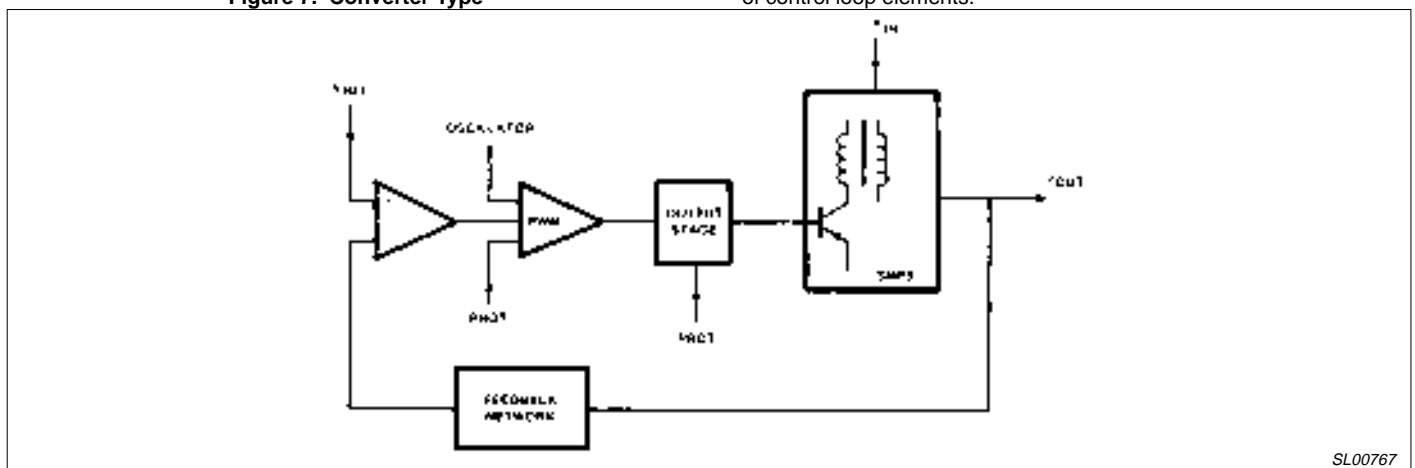It may be helpful to operate an SMPS open loop with reduced error amplifier gain. This provides an easy way to verify correct operation of control loop elements.

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Figure 8. SMPS Control Loop