Power Conversion Design Guide

by Raoji Patel

Topic 7

Power Conversion Design Guide

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APPENDICES

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Introduction

This guide presents an overview of power conversion technology and lists the major features of the most popular topologies. Basic guidance in selecting the proper topology and its associated components is provided, first through listing the advantages and disadvantages for each topology and secondly through component selection tables which are based on topology, output power and other significant factors.

Clarification of some of the basic questions related to power conversion technology are presented in Appendix I; furthermore, the task of designing of a power supply is made easier by providing some important design equations and related information in Appendix II.

Overview of Power Supply Technology

In recent years, there have been many significant technological changes in power supply design. These became possible with advances in power transistors, integrated circuits, capacitors, and design techniques. This has resulted in lower cost per watt with improved performance.

Techniques for conversion of unregulated DC voltage into the desired DC level continue to center around linear and switching regulators. Linears continue to be heavier, larger, and less efficient than switchers, but they are still less expensive, less complex, and offer better ripple, noise and EMI/RFI specs. Advances affecting linear regulators have been in capacitors with greater "CV" product in small sizes, three terminal regulators with better regulation specs, (like the UC7800A and UC7900A) and control integrated circuits like the UC3834 which offer the ability to build a high efficiency linear using PNP transistors.

Switching regulators continue to incorporate the most changes with many innovations and improvements in technology. Multiple output switchers (40 to 150 watts) are used in high volume for home computers and games. Their cost is setting new record lows, at 40 to 60 cents per watt. Large multiple output switchers (150 to 500 watts) are benefiting from lower cost bipolar switching transistors, such as Unitrode TO220 UMT13000 series transistors, Schottky rectifiers, like the USD TO220 series rectifiers, and broader selection of UC integrated circuits designed to replace large quantities of discrete parts needed to control pulse width modulation, current limit, over-voltage protection, and a variety of other control and monitor functions.

Conventional pulse width modulation (PWM) techniques are being challenged by two major innovations. One is the current mode control integrated circuit, like the UC3842 and UC3846, offering faster and more predictable response than conventional PWM techniques. Another is the voltage feed forward PWM technique which provides faster correction for input voltage changes. A third innovation allows an order of magnitude upward change in switching frequency. The latest technique, the series resonant power supply, operates from 100KHz to several megahertz. Using a sine wave instead of a square wave, this results in lower EMI, lower switching losses and practical reverse recovery requirements.

Unitrode's power MOSFET's are prime contributors to new designs, including the series resonant technique. MOSFET's and high speed bipolar transistors like the UMT2003 are enabling power supply designers to raise PWM switching frequencies from 25KHz to 80KHz and up. This results in a reduction in size of the magnetic and capacitive components.

DC to DC converters continue to find applications in a variety of systems. New functional blocks, such as the PIC910, make the converter easier to build. This is a hybrid circuit with the switching transistors and related components conveniently matched and mounted in a single package including the control integrated circuit.

Designers are continuing to advance the state of the art in switching regulator technology by using new products which help to reduce the size and weight of power packages. Power MOSFET's, Integrated Circuits, high speed platinum and Schottky rectifiers are such examples.

In an Uninterruptible Power Supply (UPS), some interesting advances are taking place. Small UPS products are emerging to serve the home and office computer market. Another new concept is Direct UPS (DUPS). Only a few small computers have incorporated this option, but its simplicity should attract widespread attention in the years to come. DUPS simply connects battery storage to the DC bus in the system power supply, instead of having to regenerate AC power. To make this a usable concept, designers will need to plan ahead for it in the early stages of system and power supply development.

How to use this "Guide"

The most common power sources and output voltages in a switching regulated power supply are shown in table I. The output voltage and its load current will depend upon the application. The power supply designs are tailored for each individual application.

There is no simple procedure in selecting the right topology for a given application; however, the factors which influence the selection of topology are identified in detail in the next section. One or more of the factors, listed in order of importance for a given application, will help to select the best topology.

1) Efficiency
2) Single vs. multiple output
3) Power output
4) Input voltage source
5) Maximum output current from each output
6) Performance
   - RFI
   - transient response
   - output ripple etc...
7) Size, weight & volume
8) Cost
9) Reliability

The chart shown in figure II provides an overview of most commonly used topologies, and lists the most important characteristics, in brief, for each topology. These characteristics are matched against applications needs for a proper choice of the topology. Further details for the selected topology should be evaluated for the final choice. Guidance for this evaluation is provided in section IV.

Most commonly used topologies in various applications are listed below:

A. Computer Main Frames
   - full-bridge switching regulator
   - current fed followed with a full-bridge
   - step-down or linears in secondary outputs

B. Personal computer, Word processor, Point of sale terminals
   - flyback switching regulator
   - half-bridge switching regulator
   - single transistor or two transistor forward converter
   - step-down or linears in secondary outputs

C. Home computer
   - linear regulator
   - low cost flyback regulator

D. Printer
   - linear regulator
   - step-down regulator
   - flyback regulator

E. PBX systems (switching station)
   - two transistor forward converter
   - half and full bridge regulator
   - step-down or linears in secondary outputs

F. CATV
   - step-down
   - linear regulator
   - flyback regulator

G. Video games
   - linear regulator
   - step-down regulator
   - flyback regulator
   - half-bridge regulator

H. Portable equipment (medical)
   - buck regulator
   - linear regulator

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The component selection tables for the switching transistor are developed based on topology, input voltage and output power. The rectifier selection table uses the output voltage and output load current to determine the proper rectifier. The component selection table includes the effect of PWM regulation with 2:1 variation of input voltage.

The next section contains guidelines for selecting the appropriate PWM control circuit for a selected topology. It also describes features for various power supply supervisory circuits, support and monitoring circuits.

Appendices include answers to most often asked questions about power conversion technology and some design equations which will be helpful in the design of a switching regulated power supply.

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MOST COMMON POWER SOURCES FOR SWITCHING POWER SUPPLIES

VOLTAGE	DC RANGE USED FOR WORST CASE DESIGN	WHERE USED
A. A.C. Lines		
100V, 60Hz	90–165V	Japanese Power Lines
117V, 60Hz	100–190V	U.S. Power Lines
220/230V, 50Hz	200–380V	European Power Lines
B. Transformer Secondary	Output Voltage:	
25V AC	20–40V	From AC lines in small equipment
C. DC Source		
+12V	7–15V	Automotive batteries
+24V	14–30V	Truck, etc., batteries
+28V	18–36V	Aircraft
+48V	42–56V	Telecommunications
+400V	300–450V	Mines

COMMON OUTPUT VOLTAGE FROM POWER SUPPLIES

VOLTAGE	TYPICAL APPLICATION
A. −5V, 2.5V	ECL Logic
B. 3 to 18V, [Typical 12V]	CMOS
C. +5V	Bipolar Logic
D. −5 to −12V	PMOS
E. +5 to +12V	NMOS
F. ±12V, ±15V, +30V	Operational Amplifier, Commercial Aircraft
G. +28V	Aerospace, IC Regulators, DC Motors
H. +48V	Telephone
I. 1.5KV to 8KV	Focus Voltage CRT
J. 7KV to 30KV	Anode Voltage CRT

Table I. *Possible input-output requirements of a switching regulated power supply.*

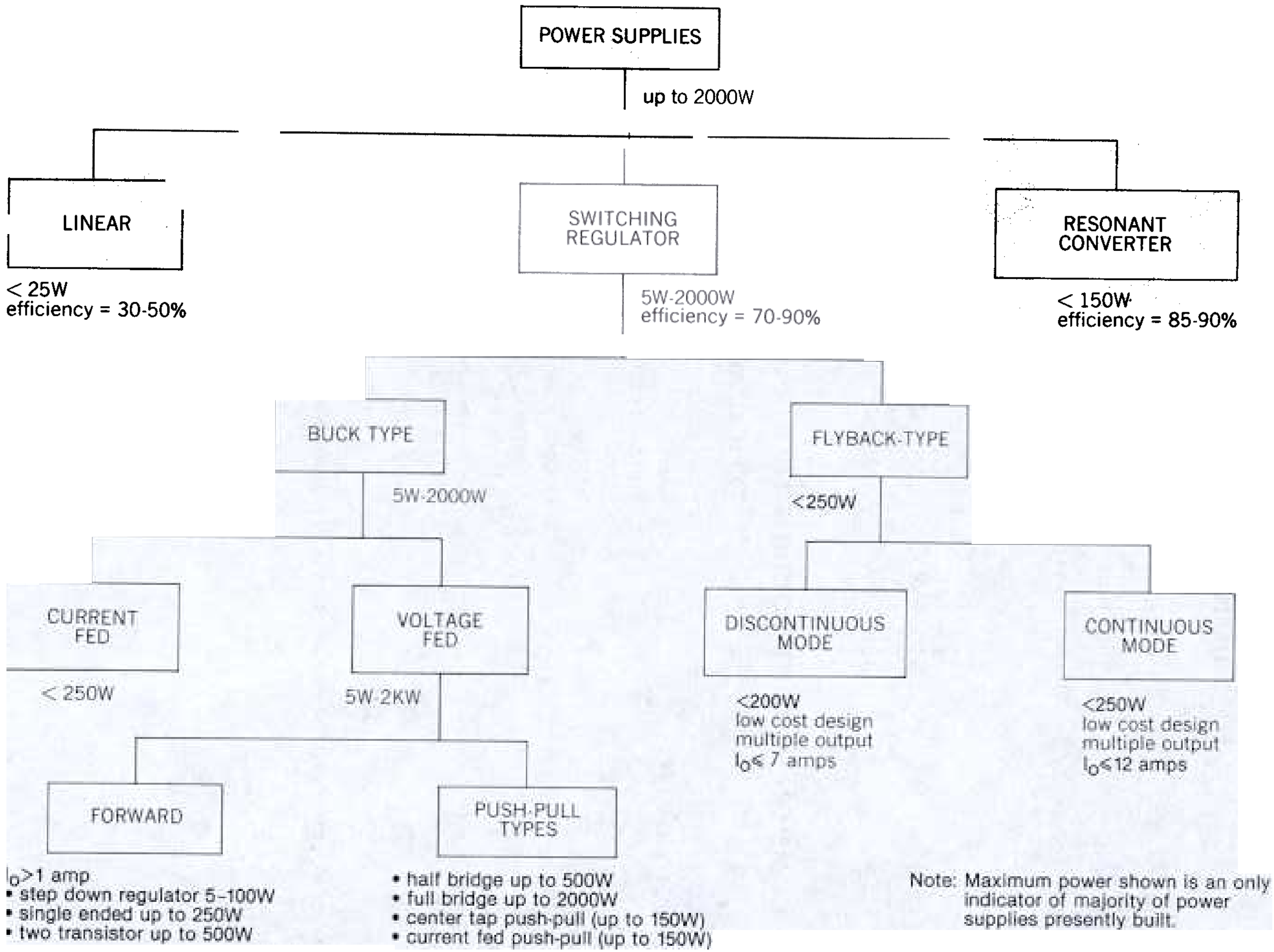

Figure II. *Overview of Power Supply Technology*

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Power Conversion Technology

This section considers advantages, disadvantages and component selection for various topologies which are commonly used for power conversion.

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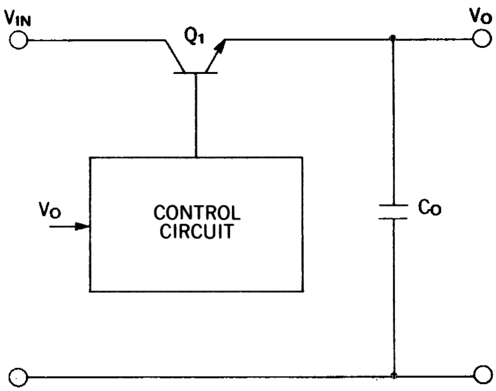
LINEAR REGULATOR

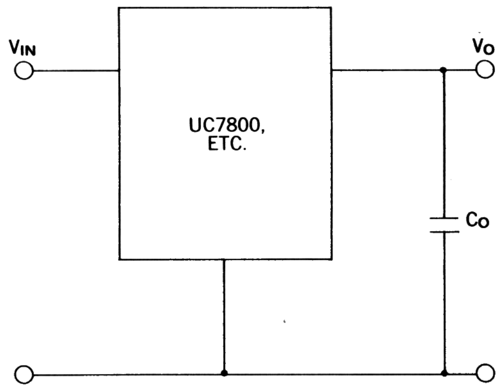
Output Power: Up To 25 Watts

TYPE 1



LINEAR REGULATOR

TYPE 2 (3 Terminal Regulator)



LINEAR REGULATOR

IT'S USED FOR:

- Extremely low ripple and noise.
- Low input to output voltage difference.
- Tight regulation.
- Fast transient response.

ADVANTAGES

- Low output ripple and noise
- Fast transient response
- Low cost under 1.0 amp of output current
- No RFI or EMI
- No need for high speed switching transistor

TRANSISTOR SELECTION (Type 1)

BV_{CEO} or $BV_{DSS} \geq 1.2\ V_{in(max)}$

$I_{c(max)}$ or $I_{D\ (max)} \geq I_{o(max)}$

$I_{S/B} \geq I_{o(max)}$ at $V_{in(max)}$ at 125 °C junction.

DISADVANTAGES

- Efficiency
  Main Regulator ≈ 45%,
  Post Regulator ≈ 65%,
  (with ± 5% line).
- Large heat sink needed to remove the heat, bulky in size
- In a 25 watt off line power supply, bulky 60Hz transformer is required
- Lower watt per cubic inch compared to switching regulator

Linear Regulator

A. DEVICE SELECTION (Type 1)

IC control circuit (used for both positive and negative regulators)

UC3834 High Efficiency Linear Regulator Low Input-Output Differential

Output transistor:

Q_1 Positive Regulator (>200mA)
2N2907 and 2N4150, GE D44
Negative Regulator (>200mA)
2N4150

- Minimum V_{IN}—V_{OUT} less than 0.5V at 5A Load with External Pass Device
- No additional pass device required for $I_O \leq 200mA$
- Adjustable Low Threshold Current Sense Amplifier
- Under- and Over-Voltage Fault Alert with Programmable Delay
- Over-Voltage Fault Latch with 100mA Crowbar Drive Output

B. DEVICE SELECTION (Type 2)

Positive Linear Regulator

Output Current	Output Voltages*			
	+5V	+12V	+15V	adjustable +1.2 to 37V
1.0A	UC340-05K UC340-05T	UC340-12K UC340-12T	UC340-15K UC340-15T	
1.5A	UC7805CK UC7805CT 5V±4%	UC7812CK UC7812CT 12V±4%	UC7815CK UC7815CT 15V±4%	UC317T ±0.1%
1.5A	UC7805ACK UC7805ACT 5V±1%	UC7812ACK UC7812ACT 12V±1%	UC7815ACK UC7815ACT 15V±1%	
3.0A				UC350K

*Max. Input Voltage≈ +40V

Negative Linear Regulator

Output Current	Output Voltages*			
	−5V	−12V	−15V	adjustable −1.2 to −37V
1.0A	UC320-05K UC320-05T	UC320-12K UC320-12T	UC320-15K UC320-15T	
+1.5A	UC7905CK UC7905CT −5V±4%	UC7912CK UC7912CT −12V±4%	UC7915CK UC7915CT −15V±4%	UC337T ±3%
+1.5A	UC7905ACK UC7905ACT −5V±1%	UC7912ACK UC7912ACT −12V±1%	UC7915ACK UC7915ACT −15V±1%	

*Max. Input Voltage≈ −40V

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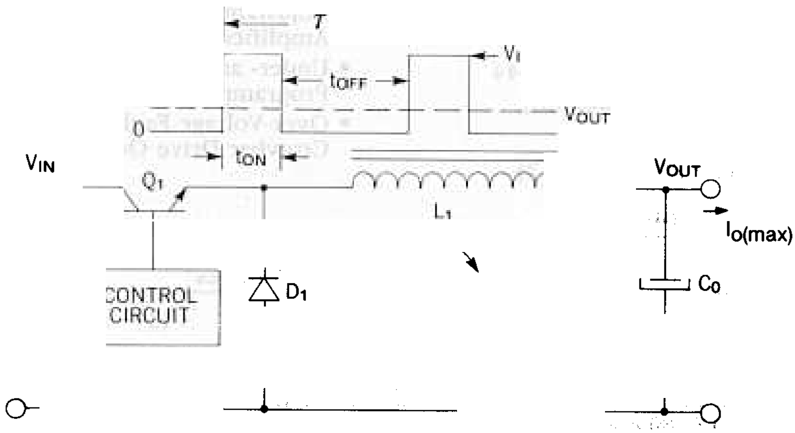
SWITCHING REGULATOR

BUCK REGULATOR—(Step Down Regulator)

Output Power: 5 Watts And Up



IT'S USED FOR:
- High efficiency
- Ease of thermal management
- When only one or two outputs are required
- Large input to output voltage difference
- Spot regulation/point of load
- Battery operated portable equipment

ADVANTAGES
- Provides high efficiency
- Lower cost, size and weight
- Tolerant of line input variations

DISADVANTAGES
- No DC isolation between input and output (to protect output load: it requires a crow-bar and fuse).
- Provides only one output per circuit
- Output ripple higher than Linear
- Slow transient response compared to Linear
- Power circuit has 2 pole roll-off characteristics

TRANSISTOR SELECTION

BV_{CEO} or $BV_{DSS} \geq 1.2\ V_{in\ (max)}$

I_c (max) or I_D (max) $\geq 1.2\ I_{o(max)}$

$R_{DS\ (on)} \approx \frac{75}{I_D}\Omega$ for $V_{in} \leq 100V$

$R_{DS\ (on)} \approx \frac{2}{I_D}\Omega$ for $V_{in} \geq 100V$

RECTIFIER SELECTION

Catch Diode

$V_R \geq 1.2V_{in(max)}$

$I_F \geq I_{O(max)}$; $I_{F(avg)} = I_O\ (max)\ (1-D_{min})$

Reverse recovery of diode should be at least 3 times faster than the current rise time of the transistor.

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Buck Regulator (Step Down Regulator)
Semiconductor Component Selection

Max. Output Load Current	Max. Input Voltage 40V	60V	80V	100V	190V	380V
2A	Hybrid: PIC910 or PIC660	PIC601	PIC602		PIC800	PIC801
	Transistor: UFN523	— UFN522	— UFN522	UMT13006 or UFN631	UMT13006 or UFN733	UMT13007 or UFN833
	Rectifier: USD645* or UES1401 or UES1301 (axial)	UES1402 or UES1302	UES1402 or UES1302	UES1403 UES1303	UES1305 UES1411	UES1412
5A	Hybrid: PIC910 or PIC660	PIC661	PIC662		PIC800	
	Transistor: UFN531	— UFN530	— UFN530	UMT13008 or UFN641	UMT13008 or UFN743	UMT13009 or UFN841
	Rectifier: USD645* UES1401	UES1402	UES1402	UES1403	UES705 or UES1411	UES1412
10A	Hybrid: PIC625	PIC626				
	Transistor: 2N5038 or UFN541	2N5038 or UFN540	2N5038 or UFN540	2N5672 or UFN251	2N6676 or UFN351	2N6678 or UFN451.
	Rectifier: USD845* or UES1501	UES1502	UES1502	UES1503	UES705	
15A	Hybrid: PIC645	PIC646	PIC647			
	Transistor: 2N5671 or UFN151	2N5671 or UFN150	2N5672 or UFN150	2N5672 or UFN251	2N6676 —	2N6678 —
	Rectifier: UES701	UES702	UES702	UES703	UES705	
20A	Transistor: 2N5671 or UFN151	2N5671 or UFN150	2N5672 or UFN150	UMT2003 or UFN251 (x2)	UMT2003 —	UMT2003 —
	Rectifier: UES701	UES702	UES702	UES703	UES805	
50A	Rectifier: USD545* or UES801	UES802	UES802	UES803	UES805	

PIC600 and 800 series are power output stages for buck regulators which contain switching transistors and catch diodes.

PIC910 is a complete buck regulator except for the filter components (includes transistor, catch diode, and PWM control circuit).

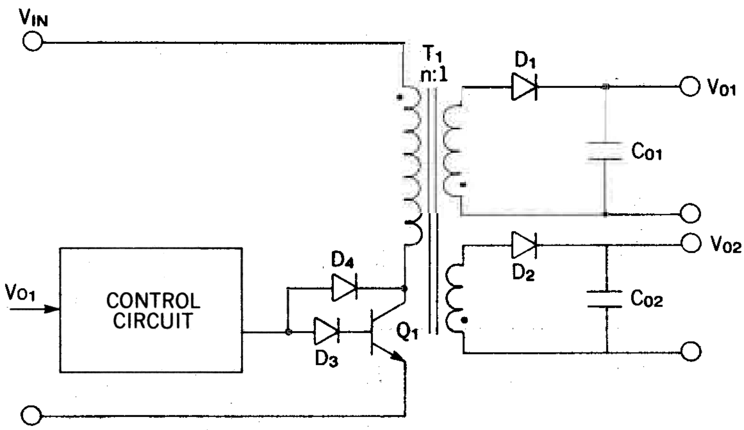
*Input voltage 35 volts max.

RECOMMENDED PWM CONTROL CIRCUIT: Refer to section "Selection of PWM control circuit"

Nomenclature: UFN: Power MOSFET; USD: Schottky Rectifier; UES: $t_r = 20–50ns$ Rectifier; SES: $t_r = 100ns$ Rectifier; PIC: Hybrid Circuit.

DISCONTINUOUS MODE FLYBACK REGULATOR

Power Output: Up To 200 Watts



FLYBACK REGULATOR

IT'S USED FOR:
- Low cost
- Multiple outputs
- Wide variations in output load currents
- Providing input to output isolation
- Output current less than 7 Amps for any given output
- Good voltage tracking between outputs

ADVANTAGES
- All the output voltages track each other
- Output voltage can be sensed through power transformer
- Fast transient response
- Slow (trr) rectifier is acceptable in outputs
- Only one diode in secondary per output
- No filter inductor in secondary
- Easy to stabilize the closed loop. (single pole)

DISADVANTAGES
- Large peak current in the switching diodes and transistors.
- Output capacitor must be twice as large (to obtain lower ESR) when it is compared with continuous mode.
- Transformer is 3 times larger than continuous mode flyback regulator.
- In some cases V_F matching is required to obtain proper output DC level for multiple outputs.

TRANSISTOR SELECTION

$$BV_{CEO} \geq 1.2 V_{in(max)}$$

$$BV_{CER} \text{ or } BV_{DSS} \geq V_{in(max)} + nV_O + \left\{\begin{matrix}\text{leakage}\\\text{inductance}\\\text{spike}\end{matrix}\right\}$$

$$I_{cpk} \text{ or } I_{Dpk} \geq \frac{2\,Po}{\eta\, V_{in(min)} D_{max}}$$

$$R_{DS(on)} \approx \frac{2}{I_D}\Omega$$

RECTIFIER SELECTION

$$V_R \geq V_O + \frac{V_{in(max)}}{n}$$

$$I_{Fpk} \geq \frac{2\,P_O}{(1-D_{max})\,V_O} \qquad I_{F(avg)} = 0.4 I_{Fpk}$$

Slow diode (100-400ns) is acceptable due to low di/dt during turn-off.

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DISCONTINUOUS MODE FLYBACK REGULATOR

A. TRANSISTOR SELECTION

Output Power	Input voltage 117/ 220V AC line input	Input voltage 117V AC line input
50W	UMT13005	UMT13006 UFN742
100W	UMT13007-9	UMT13008 UFN740
150W	UMT13009 2N6545	UMT1011 UFN740
200W	2N6547	2N6546 UFN350

B. RECTIFIER SELECTION

I_O = Output Current	V_O = Output Voltage				
	+5V	+12V	+15V	+28V	+48V
0.5A	USD1130	SES5001	SES5002	SES5003	UES1104
1.0A	USD1130	SES5002	SES5002	SES5003	UES1304
3.0A	USD635 IN5821 (axial)	SES5402 SES5301 (axial)	SES5302 (axial) SES5402	SES5303 (axial) SES5403	SES5404
5.0A	USD835	SES5401	SES5402	SES5403	SES5404
10A	USD935	UES1402 SES5501	SES5502	SES5503	SES5404
15A	USD935	UES701	UES702	UES703	

Snubber Diode —1N3613, 1N3614

Clamp Diode —1N3613

Baker Clamp Diode —1N4946

C. CONTROL CIRCUIT SELECTION

Refer to section "Selection of PWM Control Circuits'

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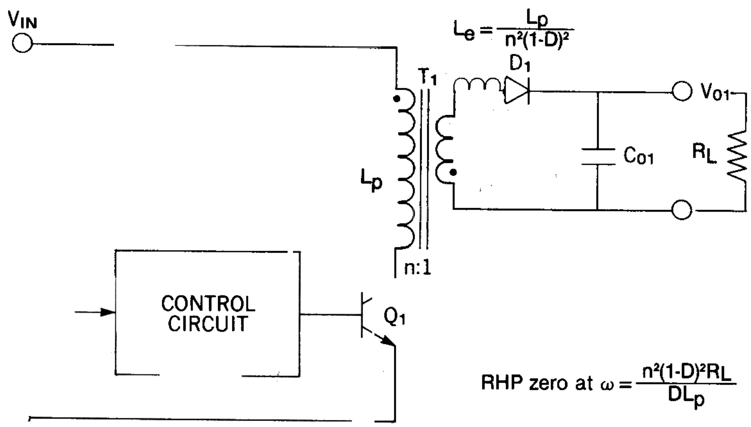
CONTINUOUS MODE FLYBACK REGULATOR

Power Output: Up To 250 Watts



FLYBACK REGULATOR

IT'S USED FOR:

- Low cost
- Multiple outputs
- Wide variation in output load current
- Output current is less than 15A per output
- Providing input to output isolation

ADVANTAGES

- Output filter cap is half the size when it is compared with discontinuous mode flyback
- Peak diode and transistor current is approximately ½ times discontinuous mode

DISADVANTAGES

- Rectifier diodes should be 4 times faster than discontinuous mode flyback ($t_{rr} \cong$ 25-100 ns)
- Transformer T_1 is larger than discontinuous mode flyback regulator
- Difficult to stabilize the loop because the power circuit has 2 poles and RHP zero

TRANSISTOR SELECTION

$BV_{CEO} \geqslant 1.2\ V_{in(max)}$

BV_{CER} or $BV_{DSS} \geqslant V_{in(max)} + n\ V_O + \left\{\begin{array}{l}\text{leakage}\\ \text{inductance}\\ \text{spike}\end{array}\right\}$

$$I_{c(max)} \text{ or } I_{D(max)} \approx \frac{(1.2)\ P_O}{\eta\ V_{in(min)}\ D_{(max)}}$$

$$R_{DS(on)} \approx \frac{2}{I_D}\Omega$$

RECTIFIER SELECTION

$$V_R \geqslant V_O + \frac{V_{in(max)}}{n}$$

$$I_{Fpk} \geqslant \frac{1.2\ P_O}{(1-D_{max})V_O} \qquad I_{F(avg)} = 0.7 I_{Fpk}$$

Rectifiers with fast reverse recovery are required.

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A. TRANSISTOR SELECTION

Output Power	Input voltage 220V AC line or 117V line with doubler	Input voltage 117V AC line
50W	UMT13005	UMT13004 UFN732
100W	UMT13007	UMT13006 UFN742
150W	UMT13009 2N6545	UMT13008 UFN740 2N6675
250W	2N6547	UMT1011 UFN350

B. RECTIFIER SELECTION

I_O = Output Current	V_O = Output Voltage				
	+5V	+12V	+15V	+28V	+48V
0.5A	USD1130	UES1001	UES1002	UES1003	UES1104
1.0A	USD1130	UES1001	UES1102	UES1103	UES1304
3.0A	USD635 1N5821 (axial)	UES1401 UES1301 (axial)	UES1402 UES1302 (axial)	UES1403 UES1303 (axial)	UES1404 UES1304 (axial)
5.0A	USD835	UES1401	UES1402	UES1403	UES1404
10A	USD935	UES1501	UES1502	UES1503	UES1504
15A	USD935	UES1501 UES701	UES1502 UES702	UES1503 UES703	

Snubber Diode —1N3613, 1N3614

Clamp Diode —1N3613

Baker Clamp Diode —1N4946

C. CONTROL CIRCUIT SELECTION

Refer to section "Selection of PWM Control Circuits'

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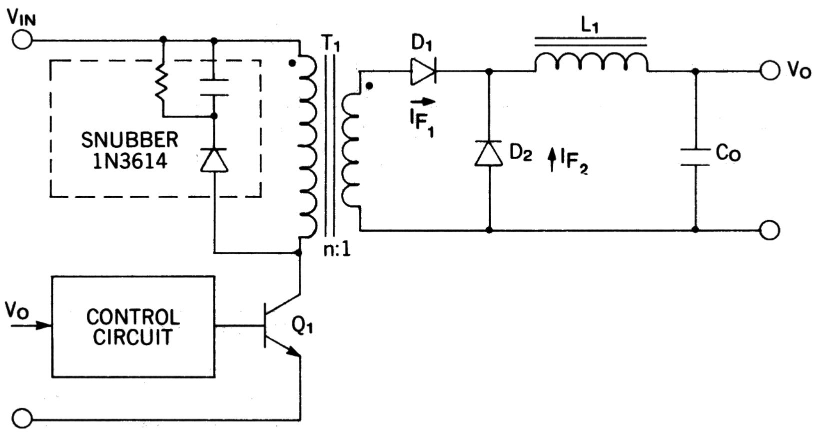
SINGLE ENDED FORWARD CONVERTER

Power Output: Up To 250 Watts



FORWARD CONVERTER

IT'S USED FOR:

- Low output noise and ripple voltage
- Avoiding flux symmetry problems

ADVANTAGES

- Drive circuit is simpler compared to other forward converters
- Only one switching transistor is required

DISADVANTAGES

- Higher cost than flyback design
- Inefficient use of power Transformer T_1 ($D_{max} \leq 50\%$) compared to bridge or push-pull topology
- Blocking voltage of transistor Q1 is 2 times input voltage
- Regulation problem at light load for multiple output
- Power circuit has 2 pole small signal characteristic

TRANSISTOR SELECTION

$V_{CEO} \geq 1.2\ V_{in(max)}$

$$BV_{CER} \text{ or } BV_{DSS} \geq V_{in(max)} \frac{1}{1-D_{max}} \left\{ \begin{matrix} \text{leakage} \\ \text{inductance} \\ \text{spike} \end{matrix} \right\}$$

$$I_{c(max)} \text{ or } I_{D(max)} \geq \frac{1.2\ P_O}{\eta\ V_{in(min)} D_{max}}$$

$$R_{DS(on)} \approx \frac{2}{I_{D(max)}} \Omega$$

RECTIFIER SELECTION

Output rectifier D1

$$V_R \geq \frac{1.2\ (V_O + V_F)\ V_{in(max)}}{V_{in(min)}\ D_{max}} + \left\{ \begin{matrix} \text{leakage} \\ \text{inductance} \\ \text{spike} \end{matrix} \right\}$$

$I_{Fpk} \geq I_{o(max)}$

$I_{F1(avg)} = D_{(max)}\ I_{o(max)}$

$I_{F2(avg)} \approx (1-D_{min}) I_{o(max)}$

D_1 Reverse recovery≈100–200 ns

D_2 Reverse recovery≈25–100 ns

SINGLE ENDED FORWARD CONVERTER

A. TRANSISTOR SELECTION

Output Power	Input voltage 220V AC line or 117V line with doubler	Input voltage 117V AC line
75W	UMT13005	UMT13006 UFN732
150W	UMT13007-9 2N6545	UMT13008 UFN740
250W	2N6547	UMT1011

B. RECTIFIER SELECTION

I_O = Output Current	V_O = Output Voltage			
	±5V	±12, ±15V	±28V	±48V
1A, 2A	USD640C 1N5819 (axial)	UES2402 UES1002	UES2404 UES1104 (axial)	UES1105
5A	USD640C 1N5822 (axial)	UES2402	UES2404	UES1305
10A	USD740C	UES2402	UES2404	UES2605
20A	USD345C	UES2602 UES1502		
40A	USM145C USD545 (DO-5)			
70A	USM145C USD545 (DO-5)			

Snubber Diode 1N3613, 1N3614

Clamp Diode 1N3614

Baker Clamp Diode 1N4946

C. IC SELECTION

Refer to section "Selection of PWM Control Circuits"

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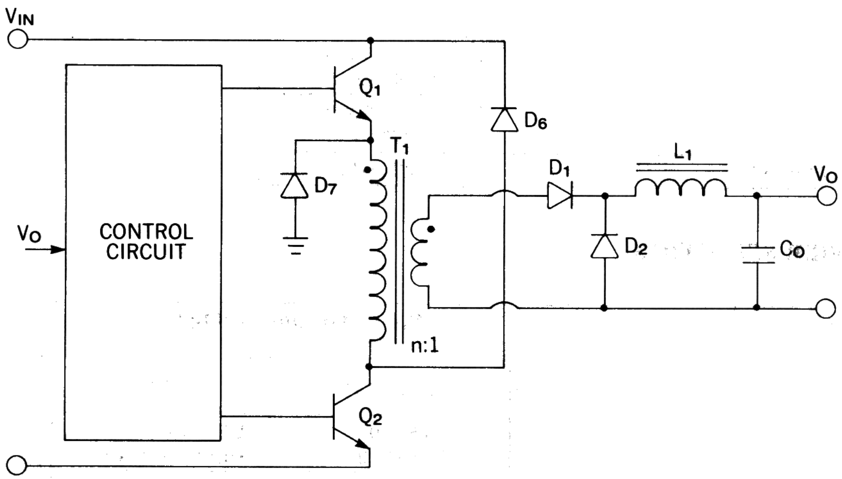
B. TWO TRANSISTOR FORWARD CONVERTER

Power Output: Up To 500 Watts



FORWARD CONVERTER

IT'S USED FOR:
- High input and transient voltage
- High efficiency and reliability
- Low output ripple and noise

ADVANTAGES
- Lower transistor voltage rating compared to single ended circuit
- High efficiency because of simple non-dissipative snubber and clamp
- Larger input transient capability

DISADVANTAGES
- Dual output drive circuits required
- Poor transformer utilization compared to push-pull and half bridge topology
- Other disadvantages are same as for single ended circuit
- Power circuit has 2 pole small signal characteristics

TRANSISTOR SELECTION

BV_{CEO} or $BV_{DSS} \geq 1.1 V_{in(max)}$

$$I_{D(max)} \text{ or } I_{C(max)} \geq \frac{1.2\, P_O}{\eta\, V_{in(min)}\, D_{max}}$$

Reasonable switching time is required at $I_{C(max)}$

$$R_{DS(on)} \approx \frac{2}{I_D}(max)$$

RECTIFIER SELECTION

Output rectifier

$$V_{R(min)} \geq \frac{1.2(V_O + V_F)V_{in(max)}}{V_{in(min)}\, D_{max}} + \begin{Bmatrix}\text{leakage} \\ \text{inductance} \\ \text{spike}\end{Bmatrix}$$

$I_{F_{pk}} \geq I_{O(max)}$

$I_{F_1}(avg) = D(max)\, I_O(max)$

I_{F_2} (avg) = $(1\text{-}D_{min})\, I_O(max)$

D_1 Reverse Recovery: 100–200 ns

D_2 Reverse Recovery: 25–100 ns

Clamp diodes D_6-D_7 reverse recovery: 200–400 ns

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A. TRANSISTOR SELECTION

Output Power	Input voltage 220V AC line or 117V line with doubler	Input voltage 117V AC line
75W	UMT13005 UFN833	UMT13006 UFN731
150W	UMT13007-9 2N6673 2N6545 UFN843 UFN742 2N6768	UMT13008 UFN741
250W	2N6675 UFN841	2N6674 UFN351
500W	2N6678 UFN451	2N6676

B. OUTPUT RECTIFIER—DIODE D_1 and D_2 SELECTION

I_O = Output Current	V_O = Output Voltage			
	±5V	±12, ±15V	±28V	±48V
1A, 2A	USD640C 1N5819 (axial)	UES2402 UES1002	UES2404 UES1104 (axial)	UES1105
5A	USD640C 1N5822 (axial)	UES2402	UES2404	UES1305
10A	USD740C	UES2402	UES2404	UES2605
20A	USD345C	UES2602 UES1502		
40A	USM145C USD545 (DO-5)			
70A	USM145C USD545 (DO-5)			

Snubber Diode 1N3613 (2A-800V)

Clamp Diode D_6, D_7 1N5420
1N4946

Baker Clamp Diode 1N4946

C. IC SELECTION

Refer to section "Selection of PWM Control Circuits'

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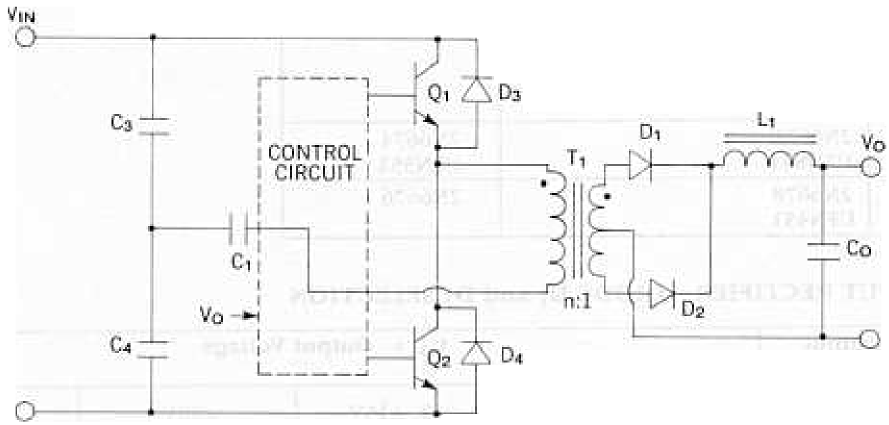
HALF-BRIDGE CIRCUIT

Power Level: Up To 500 Watts



HALF-BRIDGE CIRCUIT

IT'S USED FOR:

- Providing high output power
- Optimizing transformer utilization by operating in 1st and 3rd quadrant
- To provide efficient design

ADVANTAGES

- Flux symmetry problems are corrected with capacitor C1
- Leakage inductance and magnetizing energy are pumped into input and output filter caps thus improving efficiency
- Transformer utilization is better than forward converter

DISADVANTAGES

- It requires two 60cps filter caps
- Transistor's storage time should have tight tolerances to avoid gross imbalance in operating flux level
- Power circuit has 2 pole small signal characteristics
- Can't use current-mode PWM control

TRANSISTOR SELECTION

BV_{CEO} or $BV_{DSS} \geq 1.1\ V_{in(max)}$

$$I_{c(max)} \text{ or } I_{D(max)} \geq \frac{2\ P_O}{\eta\ V_{in(min)}}$$

$$R_{DS(on)} \approx \frac{2}{I_{D(max)}} \Omega$$

RECTIFIER SELECTION

$$V_R \geq 2.2 \frac{[V_O + V_F]\ V_{in(max)}}{V_{in(min)}} + \left\{ \begin{array}{l} \text{Voltage} \\ \text{spike due} \\ \text{to leakage} \\ \text{inductance} \end{array} \right\}$$

$I_{Fpk} \geq I_{O(max)}$; $I_{F(avg)} = 0.5\ I_{O(max)}$

D_1 and D_2 should be fast (20-100ns)

A. TRANSISTOR SELECTION

Output Power	Input voltage 220V AC line or 117V line with doubler	Input voltage 117V AC line
50W	UMT13005 UFN821	UMT13006 UFN733
100W	UMT13007 2N6543 UFN831	UMT13008 2N6671 UFN743
150W	UMT13007 2N6673 UFN843	UMT13008 2N6671 UFN741
250W	UMT13009 2N6673 UFN841	2N6674 UFN353
500W	2N6675 UFN451	UMT2003 UFN351

B. RECTIFIER SELECTION

I_O = Output Current	V_O = Output Voltage			
	±5V	±12, ±15V	±28V	±48V
1A, 2A	USD640C 1N5819 (axial)	UES2402 UES1002	UES2404 UES1104 (axial)	UES1105
5A	USD640C 1N5822 (axial)	UES2402	UES2404	UES1305
10A	USD740C	UES2402	UES2402	UES2605
20A	USD345C	UES2602 UES1502		
40A	USM145C USD545 (DO-5)			
70A	USM145C USD545 (DO-5)			
100A	USM20045C 2xUSD545			
250A	3xUES801			

Snubber Diode 2N3613

Clamp Diode—D_3, D_4 1N4946, 1N5420

Baker Clamp Diode 1N4946

C. IC SELECTION

Refer to section "Selection of PWM Control Circuits

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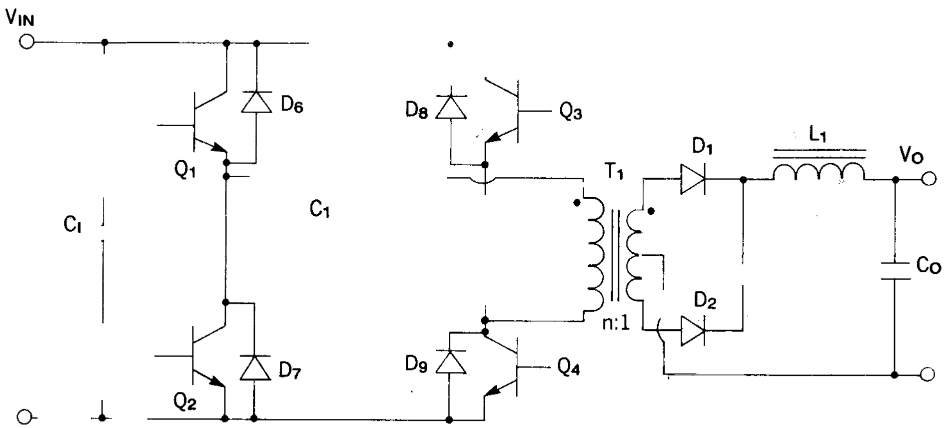
FULL BRIDGE—SWITCHING REGULATOR

Power Level: 500–2000 Watts



FULL-BRIDGE SWITCHING REGULATOR

IT'S USED FOR:

- Providing over 500 watts of output power. Sometimes transformers are paralleled to provide higher power output.

ADVANTAGES

- Provides same advantages as listed for half-bridge regulator
- Only one 60 cps filter cap is required except in doubler configurations
- Provides 2 times the output power of the half-bridge circuit with the same type switching transistor

DISADVANTAGES

- 4 switching transistors and clamp diodes are required
- Power circuit has 2 pole small signal characteristics

TRANSISTOR SELECTION

BV_{CEO} or $BV_{DSS} \geqslant 1.1\ V_{in(max)}$

$$I_{c(max)} \text{ or } I_{D(max)} \geqslant \frac{P_O}{\eta\ V_{in(min)}}$$

$$R_{DS(on)} \approx \frac{2}{I_D}\Omega$$

RECTIFIER SELECTION

$$V_{R(min)} \geqslant 2.2 \frac{[V_O + V_F] V_{in(max)}}{V_{in(min)}} + \left\{\begin{array}{l}\text{Voltage} \\ \text{spike due} \\ \text{to leakage} \\ \text{inductance}\end{array}\right\}$$

$I_{F(max)} \geqslant I_{O(max)}$

$I_{F_{1,2}}(avg) = 0.5\ I_O$

D_1 and D_2 should be fast (20-100ns)

A. TRANSISTOR SELECTION

Output Power	Input voltage 220V AC line or 117 V line with doubler	Input voltage 117V AC line
200W	UMT13007 2N6543 UFN831	UMT13008 2N6671 UFN743
300W	UMT13009 2N6673 UFN843	UMT13008 2N6671 UFN741
500W	UMT13009 2N6673 UFN841	2N6674 UFN353
1000W	2N6675 UFN451	UMT2003 2N6676 UFN351
2000W	UMT2003 2N6678 UFN451(x2)	

B. RECTIFIER SELECTION

I_O = Output Current	V_O = Output Voltage			
	±5V	±12, ±15V	±28V	±48V
1A, 2A	USD640C 1N5819 (axial)	UES2402 UES1002	UES2404 UES1104 (axial)	UES1105
5A	USD640C 1N5822 (axial)	UES2402	UES2404	UES1305
10A	USD740C	UES2402	UES2404	UES2605
20A	USD345C	UES2602 UES1502		
40A	USM145C USD545 (DO-5)			
70A	USM145C USD545 (DO-5)			
100A	USM20045C 2xUSD545(DO-5)			
250A	4xUSD545			

Snubber Diode	1N3613, 1N3614
Clamp Diode—D_6, D_7, D_8, D_9	1N4946, 1N5420
Baker Clamp Diode	1N4946

C. IC SELECTION

Refer to section "Selection of PWM Control Circuits

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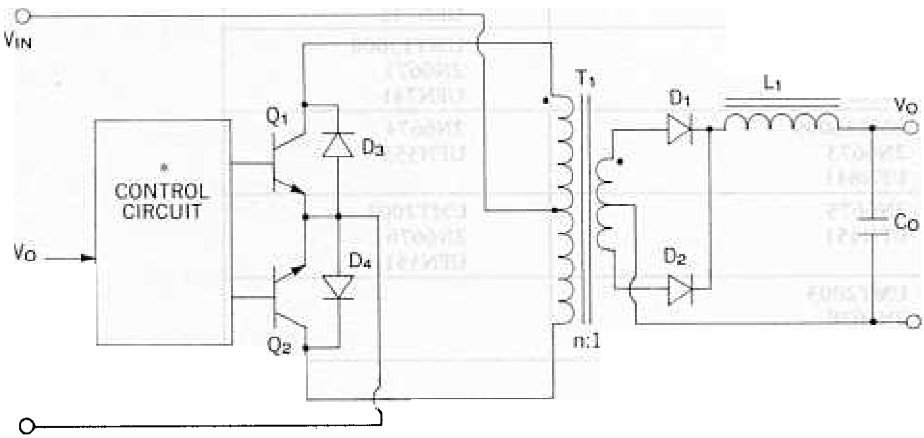
CENTER TAPPED PUSH-PULL SWITCHING REGULATOR

Power Level: Up To 150 Watts



PUSH-PULL REGULATOR

IT'S USED FOR:

- Small size and weight

*New control chip UC1846 solves flux symmetry problems associated with push-pull switching regulator.

ADVANTAGES

- Smaller size, weight and cost
- Efficient design
- Easier base drive (both referenced to ground)

DISADVANTAGES

- Inherent flux symmetry problems can be corrected with current-mode PWM control circuit
- Transformer must be slightly over-designed
- Transistor rating twice the input supply voltage
- Power circuit has 2 pole small signal characteristics
- Power circuit has 1 pole small signal characteristics with current-mode control

TRANSISTOR SELECTION

$BV_{CEO(min)} \geq 1.1\ V_{in(max)}$

$BV_{CER(min)}$ or $BV_{DSS} \geq 2V_{in(max)} + \begin{Bmatrix}\text{leakage}\\ \text{inductance}\\ \text{spike}\end{Bmatrix}$

$I_{c(max)}$ or $I_{D(max)} \geq \dfrac{P_O}{\eta\ V_{in(min)}}$

$R_{DS(on)} \approx \dfrac{0.75}{I_{D(max)}}$

RECTIFIER SELECTION

$V_R \geq 2.2 \dfrac{[V_O + V_F]V_{in(max)}}{V_{in(min)}} + \{\text{Voltage spike}\}$

$I_{Fpk} \geq I_{O(max)}$

$I_{F\,1,2}(avg) = 0.5\ I_{O(max)}$

D_1 and D_2 should be fast reverse recovery rectifiers.

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A. TRANSISTOR SELECTION

Output Power	12V DC Input	28V DC Input	117 VAC	220 VAC
20W	PIC610 UFN531	PIC612 UFN522		
50W	PIC635 UFN541	PIC637 2N5038 UFN530	UMT13005 UFN821	
100W		2N5038 UFN542	UMT13005 UFN831	
150W			UMT13007 UFN841	2N6543

B. RECTIFIER SELECTION

I_O = Output Current	V_O = Output Voltage			
	±5V	±12, ±15V	±28V	±48V
1A-2A	USD640C 1N5819 (axial)	UES2402 UES1002	UES2404 UES1104 (axial)	UES1105
5A	USD640C 1N5822 (axial)	UES2402	UES2404	UES1305
10A	USD740C	UES2402	UES2404	UES2605
20A	USD345C	UES2602 UES1502		
40A	USM145C USD545 (DO-4)			

Snubber Diode	1N3613
Clamp Diode—D_3, D_4	1N3613
Baker Clamp Diode	1N4946 (600V) trr 250ns.

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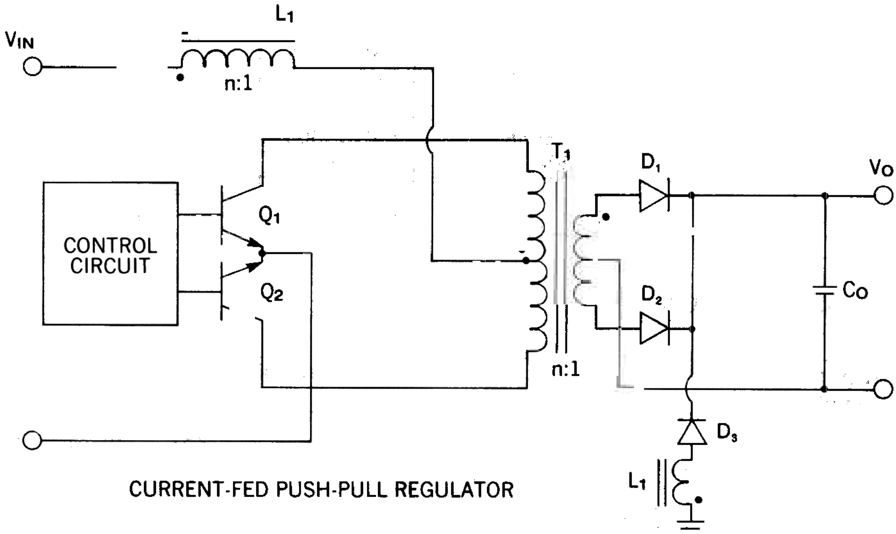
CURRENT-FED PUSH-PULL SWITCHING REGULATOR

Power Level: Under 150 Watts



CURRENT-FED PUSH-PULL REGULATOR

IT'S USED FOR:

- Multiple outputs
- Low output ripple and noise
- Large input transient voltage
- Good voltage tracking between multiple outputs
- Providing good transient response to all multiple outputs.

ADVANTAGES

- Input filter inductor L_1 prevents flux symmetry and cross conduction problem
- Low output ripple due to continuous conduction of current in the output filter cap
- Provides isolation to large input transient voltages
- Reduces the minimum output load requirements

DISADVANTAGES

- Input filter L_1 must have low leakage inductance to provide good current balance in T_1
- Three output filter rectifiers are required
- Power circuit has 2 pole small signal characteristics

TRANSISTOR SELECTION

BV_{CER} or $BV_{DSS} \geqslant V_{in} + n(V_O + V_F) + \{\text{Spike}\}$

$I_{C(max)}$ or $I_{D(max)} \approx 1.2 \frac{I_O}{n}$

$R_{DS(on)} \approx \frac{2}{I_{D(max)}} \Omega$

RECTIFIER SELECTION

Rectifier D_1 and D_2 could be a slow diode

voltage rating $\geqslant 2.2\,(V_O + V_F) + \left\{\begin{matrix}\text{leakage}\\ \text{inductance}\\ \text{spike}\end{matrix}\right\}$

Diode D_3 must be fast (20-100 ns)

$V_{R(min)} \geqslant V_O + \frac{(V_{in(max)} - nV_O)}{n}$

Forward current $I_{F_{pk}}$ is same as output current.

$I_{F(avg)} \approx 0.5\ I_{O(max)}$

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A. TRANSISTOR SELECTION

Output Power	Input voltage 220V AC line or 117V line with doubler	Input voltage 117V AC line
75W	UMT13005	UMT13004 UFN720
150W	UMT13005 2N6543	UMT13004 2N6542 UFN730
250W	UMT13007 2N6545	UMT13006 2N6544 UFN740

RECTIFIER SELECTION

Diode D_1, D_2 Selection:

Output Current I_O (max)	±5V	±12V	±15V, ±28V	±48V
1A, 2A	USD635C USD1130 (axial)	SES5401C SES5101 (axial)	SES5402C SES5002 (axial)	SES5403C SES5003 (axial)
3A	USD635C	SES5401C SES5301 (axial)	SES5402C SES5302 (axial)	SES5403C SES5303 (axial)
5A	USD635C	SES5401C	SES5402C	SES5403C
10A	USD635C	SES5401C	SES5402C	SES5403C
20A	USD835	SES5501	SES5502	
40A	USM140C USD6035	UES701	UES702	

Diode D_3 Selection:

±5V	±12V	±15V, ±28V	±48V
USD1130	UES1001	UES1002	UES1003
1N5821	UES1301	UES1302	UES1303
USD635	UES1401	UES1402	UES1403
USD835	UES1401	UES1402	UES1403
USD935	UES1501	UES1502	UES1503
USD935 (x2)	UES701 UES1501 (x2)	UES702 UES1502 (x2)	

Snubber Diode —1N3613 (2A-800V)
Clamp Diode —1N4946 (1A-600V)
Baker Clamp Diode —1N4946

D. IC SELECTION

Refer to section "Selection of PWM Control Circuits"

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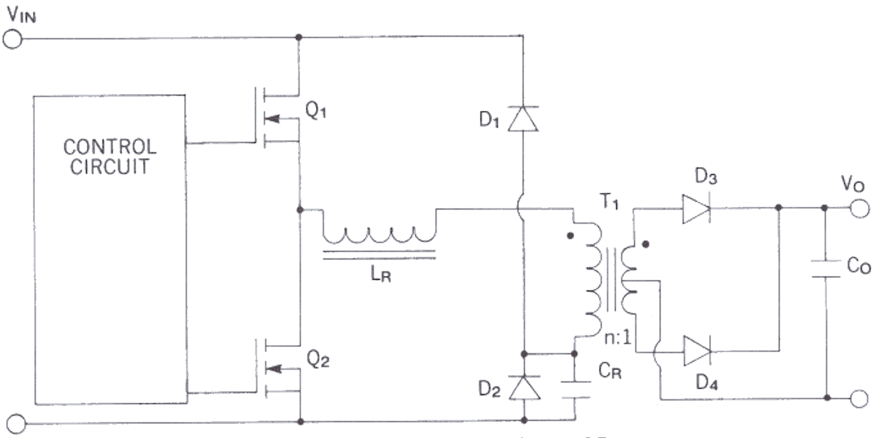
SERIES RESONANT SINE WAVE SWITCHING REGULATOR

Power Level: Less Than 150 Watts



SERIES RESONANT REGULATOR

IT'S USED FOR:

- Reduced size, weight and sometimes cost
- Low RFI and EMI
- Increased efficiency (85-90%)
- Higher frequency

ADVANTAGES

- Higher efficiency
- Smaller weight and volume
- Low switching losses allows high frequency operation. Thus reduced size of magnetics and heat sink.
- Reduced EMI—no trr related current spike, low di/dt current waveforms
- Increased reliability
  - —L_R acts as current limiter
  - —zero current switching, no heat generated
- Problem with leakage inductance is minimized.

DISADVANTAGES

- Requires additional resonant network, L_R and C_R
- Current rating of the switch is 3 to 4 times higher than conventional switching regulator
- Output filter cap carries high ripple current

TRANSISTOR SELECTION

$BV_{DSS} \geq 1.1\ V_{in(max)}$

$$I_{D(max)} \geq 3.5 \frac{2\ P_O}{V_{in(min)}}$$

$I_{D(rms)} = 0.5\ I_{D(max)}$

$$R_{DS(on)} \approx \frac{2V}{I_{D(rms)}}$$

RECTIFIER SELECTION

For D_3, D_4:

$V_R \geq 2.2\ V_O$ + Voltage Spike

$I_{Fpk} \geq \sqrt{2}\ I_{o(max)}$

$I_{F(avg)} = 0.35\ I_{Fpk}$

For D_1 and D_2; $V_R = 1.2\ V_{in(max)}$

For D_3 and D_4; slow reverse recovery diodes relative to frequency of operation can be used.

A. TRANSISTOR SELECTION

Output Power	Input voltage 220V AC line or 117V line with doubler	Input voltage 117V AC line
50W	UFN831	UFN743
100W	UFN841	UFN741
150W	UFN451	UFN351

B. OUTPUT RECTIFIER—DIODE D_3 or D_4 SELECTION

I_O = Output Current	V_O = Output Voltage			
	±5V	±12V	±15V, ±28V	±48V
1A, 2A	USD635C USD1130 (axial)	SES5401C SES5001 (axial)	SES5402C SES5002 (axial)	SES5403C SES5003 (axial)
3A	USD635C	SES5401C SES5301 (axial)	SES5402C SES5302 (axial)	SES5403C SES5303 (axial)
5A	USD635C	SES5401C	SES5402C	SES5403C
10A	USD635C	SES5401C	SES5402C	SES5403C
20A	USD835	SES5501	SES5502	
40A	USM140C USD6035	UES701	UES702	

Snubber Diode 1N4944, 1N4946

Clamp Diodes D_1, D_2 1N4944, 1N4946

C. IC SELECTION

Refer to section "Selection of PWM Control Circuits"

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SELECTION OF PWM CONTROL CIRCUITS

The important features of the PWM control circuit and their recommended applications are listed below. It should be used as a guideline for selecting the PWM control circuit.

Conventional PWM Circuits	Features	Recommended Applications
UC3524A	• pin to pin compatible with UC3524 • uncommitted push-pull with 200mA and 60V capability • under voltage lockout (8V) • ±1% reference • fast pulse by pulse current limit with wide common mode input range • double pulse suppression circuit • low stand-by current	• step-down regulator • flyback-type • single ended forward • two transistor forward
UC3525A/3527A	• push-pull totem pole output with 500mA peak current capability • oscillator range up to 500KHz • ±1% reference • under voltage lock out (8V)	• power MOSFET single ended flyback and forward • two transistor forward • half bridge • push-pull/full bridge
UC3526	• push-pull totem pole output with 200mA peak current capability • oscillator range up to 400KHz • ±1% reference • under voltage lock out (8V) • fast pulse by pulse current limit with wide common-mode input voltage • double pulse suppression circuit	• power MOSFET flyback regulator • power MOSFET single ended forward • two transistor forward • half bridge • push-pull/full bridge • current-fed
UC493A series	• uncommitted push-pull output with a 200mA capability • under voltage lock out (6.5V) • ±1% reference • two independent error amplifiers with a wide common-mode input voltage range • double pulse protection • 80mV internal threshold included in one of the error amplifiers forUC493A and UC495B • UC495A and B includes 39V zener for over 40V input supply	• single ended forward • two transistor forward • flyback-type

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SELECTION OF PWM CONTROL CIRCUITS (Cont'd)

Feed-Forward PWM control circuit	Features	Recommended Applications
UC3840	• single ended output with a 400mA output current capability • pulse by pulse and over current limiting amplifiers with a 3.0V common-mode input voltage range • ±1% reference • low stand-by current with a programmable start voltage • programmable under and over voltage protection circuit • intended for primary side control • UC3840 + UC3706 allows push-pull operation	• single ended forward • two transistor forward • flyback-type • current fed

Current-mode PWM Control Circuits	Features	Recommended Applications
UC3842	• low cost 8 pin IC circuit • single totem pole output circuit with a 200mA peak current capability • less than 1mA start-up current up to 16 volt • pre-set 16V start-up voltage and 10V under voltage lock-out • +1 volt internally set threshold for pulse by pulse current limiting	• single ended forward • two transistor forward • flyback-type • current-fed
UC3846/47	• push-pull totem pole output with 500mA peak current capability • ±1% reference • under voltage lock out (8V) • double pulse suppression • current sense amplifier with wide common-mode input voltages	• step-down regulators • push-pull/full bridge (*not* half bridge circuit)

POWER SUPPLY SUPPORT FUNCTIONS

Type	Description	Key Features
UC3543 UC3544	Power Supply Supervisory Circuit, Monitors and Controls Power Supply Output	• Over/Under-Voltage, and Current Sensing Circuits • Programmable Time Delays • SCR "Crowbar" Drive of 300mA • Optional Over-Voltage Latch • Internal 1% Accurate Reference • Remote Activation Capability • Uncommitted Comparator • Inputs for Low Voltage Sensing (UC3544 series only)
UC3706	Dual High Current MOSFET Compatible Output Driver	• Dual 1.5A Totem Pole Outputs • Parallel or Push-Pull Operations • Single-Ended to Push-Pull Conversion • Internal Overlap Protection • Analog, Latched Shutdown • High-Speed, Power MOSFET Compatible • Thermal Shutdown Protection • 5 to 40V Operation • Low Quiescent Current
UC3901	Isolated Feedback Generator Stable and Reliable Alternative to an Optical Coupler	• An Amplitude-Modulation System for Transformer Coupling an Isolated Feedback Error Signal • Internal 1% Reference and Error Amplifier • Loop Status Monitor • Low-Cost Alternative to Optical Couplers • Internal Carrier Oscillator Usable to 5MHz • Modulator Synchronizable to an External Clock
UC3903	Quad Supply and Line Monitor Precision System	• Monitor Four P wer Supply Output Voltage Levels • Both Over- and Un[illegible]r-Voltage Indicators • Internal Inverter for Negative Level Sense • Adjustable Fault Window • Additional Input for Early Line Fault Sense • On Chip, High-Current General Purpose OP-AMP

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APPENDIX I

QUESTIONS MOST OFTEN ASKED

1. *Define Topology.*
The circuit configuration by which power is transferred from the input power source to the output. Topology refers to the type of power transfer circuit.

2. *What is an error amplifier and error voltage?*
The voltage difference between the fixed reference and the regulated output is amplified by the error amplifier of the control circuit. The output of this amplifier is called the error voltage. The error voltage is used to change the on-time of the power output switch.

3. *What is the PWM technique?*
PWM is the abbreviation for Pulse Width Modulation. This technique translates the voltage level of an analog signal into the appropriate pulse width by comparison with a voltage ramp circuit. At the beginning of the cycle, the ramp voltage starts at zero and the output of the comparator is set high. Ramp voltage increases linearly through the entire cycle. When the ramp voltage is equal to the analog signal, the comparator output is set low (the analog signal represents the output of an error amplifier). The peak amplitude of the ramp voltage is fixed in a conventional PWM technique.

4. *Describe the input voltage feed-forward PWM technique & its advantages.*
It is a variation of the pulse width modulation technique. The output pulse-width of the control circuit is not only controlled by the error voltage but also the input supply voltage. The level of the error voltage remains fairly constant for several cycles. (Note that the ramp voltage starts from zero at the beginning of the cycle, and continues to increase linearly for the entire cycle.) The ramp slope is proportional to the input line voltage. Thus any change in input line voltage is immediately translated into a change of pulse width in the same cycle.
The main advantages of the PWM technique are:
   - Low input audio susceptibility
   - Smaller transformer
   - Less loop gain required

5. *What are the basic differences between current-fed converter (topology) and current-mode control (control method) converters, and what are the main advantages of the current-mode PWM technique?*
In a current-fed converter the power source used to power the post converter has constant current characteristics. Usually a filter inductor is used in the input line to achieve constant current source characteristics. With a current-mode control, the primary current is utilized to generate the ramp voltage, instead of the fixed ramp voltage which is used for the conventional PWM technique. This ramp voltage is needed to determine the output pulse width of the control chip. The major advantages of current-mode PWM techniques are:
   - Stable circuit
   - Fast transient response
   - Pulse by pulse current limiting

6. ***What is the main function of the compensation network?***
It provides stabilization necessary to avoid oscillation, with the higher loop gain necessary for good line and load regulation.

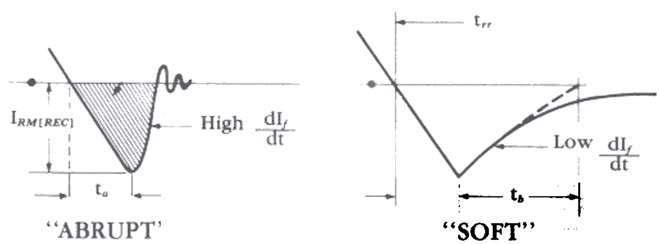
7. ***What is a right half plane (RHP) zero?***
The RHP zero is a particular characteristic of the closed loop system. A right half plane zero in a control loop occurs only in a continous-mode flyback topology rather than the control circuit. The continuous-mode flyback is an example. In a switching regulator, the on-time of the power switch increases when the output voltage drops below the desired level. This results in increased output power until output voltage reaches the desired level. However, in a continuous-mode flyback, this increase in on-time results in reduction of output power temporarily. (Note that power is delivered to output only during off-time.) This provides additional 90° phase lag in the control loop. This can result in unstable circuit operation at high frequency.

8. ***What is pulse by pulse current limiting?***
The pulse by pulse current limit circuit senses the switching current and if it exceeds the pre-set maximum current level, it terminates conduction of the output voltage control loop and switching transistor. The transistor turns on again at the beginning of the next cycle and if the switching current is over the current limit, the transistor immediately turns off.

9. ***What is ripple?***
The AC voltage across the output filter capacitor is referred to as the output ripple voltage. The peak to peak variation in current in an output filter inductor is also sometimes known as ripple current.

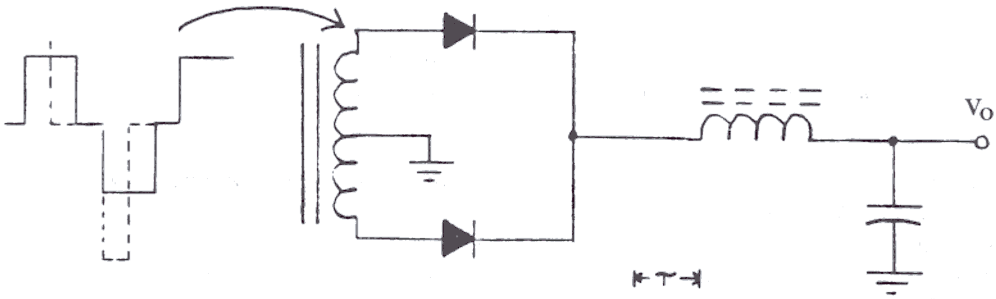
10. ***Why is minimum reverse recovery time desirable?***
To reduce current pulses which will result in;
- Reduced radio frequency interference (RFI)
- Reduced turn-on switching losses in transistor
- Reduced turn-off losses in the rectifier

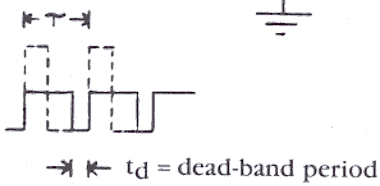
11. ***What is the difference between a soft and an abrupt reverse recovery characteristic?***
The rate at which reverse recovery current (di/dt) goes to zero determines the characteristic. Turn-off current waveforms for soft and abrupt reverse recoveries are shown below:



12. *List advantages of a soft reverse recovery characteristic over an abrupt one.*
Soft reverse recovery advantages are:
- Lower RFI
- Less voltage ringing

13. *Determine the reverse blocking voltage requirements for the output rectifiers in a +5V off-line PWM switching regulator.*
The voltage waveforms to determine voltage requirements of the rectifier at low line are shown below:





Reverse blocking voltage:

$$= 2R\left[\frac{V_O}{(T - t_d)/T} + V_F\right] + \text{leakage inductance spike} \qquad \frac{(T - t_d)}{T} = 0.9 \text{ to } 0.95$$

$$= 4\left[\frac{5}{0.9} + 0.8\right] + 7 = 32 \text{ volts}$$

Note that the ratio (R) between the maximum input DC voltage across 60cps input filter capacitor (just before capacitor recharges—at minimum input voltage with full load) to the maximum DC voltage (at high line with no load) is approximately two.

14. *What are the functional differences between clamp, catch and rectifier diodes?*
Clamp diode—Limits the maximum voltage excursions across device.
Catch diode—Provides current path for the inductor load current or transformer magnetizing current.
Rectifier diode—Directly converts AC voltage into pulsating DC voltage.

15. *What is the main function of a crow-bar circuit?*
The output voltage of the power supply provides power for many logic circuits. The voltage across these logic circuits must be limited to a safe value to prevent damage to these devices. The techniques used to limit excessive voltage are:

A. Zener clamp—
It is used to limit voltage due to short duration transient pulses. Voltage is clamped with a power zener.

B. Crow-bar circuit—
When output voltage exceeds pre-determined value, the silicon controlled rectifier (SCR) across the output turns on, and clamps the voltage by the forward drop of the SCR. Crow-bar needs to be reset to resume normal operation.

16. *What is a Synchronous rectifier?*
A power MOSFET or bipolar transistor can be used in place of a rectifier to improve the efficiency. Operating these devices in on-state, the developed voltage drop is considerably less than the low forward drop of a schottky rectifier. The device operates from the AC input voltage and conducts when input voltage is slightly greater than output voltage.

17. *What is the difference between a buck regulator and a step-down regulator?*
They are the same circuit. This circuit converts a high input voltage to a lower output voltage.

18. *What are the advantages and disadvantages of the single transistor forward converter compared to a buck regulator?*
Advantages:
Provides DC isolation between input supply voltage and the output voltage.
Provides multiple outputs.
Optimizes the switching transistor and rectifier utilization when there is a large difference between input and output voltage.
Disadvantages:
Needs transformer in addition to filter inductor.
Less efficient, it needs snubber network, switching losses are higher.
More expensive.

19. *Which is the lowest cost topology for multiple output power supply?*
Discontinuous-mode flyback.

20. *List the differences between a continuous-mode and a discontinuous-mode flyback.*

DISCONTINUOUS-MODE
- current in transformer drops to zero every cycle
- smaller transformer
- output filter caps 2 times larger
- single-pole

CONTINUOUS MODE
- it has RHP zero and 2 poles
- needs fast output rectifier
- approx. 2 times lower peak currents in transistor and rectifier

21. *What is the main difference between an inverter and a converter?*
Inverter has DC input and AC output;
converter has AC or DC input and DC output.

22. *What is proportional base drive?*
A base drive circuit where base current is always a certain fraction of the collector current. The ratio between these two currents is determined by the turns ratio of the current transformer used in the base drive circuit.

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23. *Define storage-time and why minimum storage-time is desirable.*
The time elapsed between the on-set of the turn-off signal to the instant when collector voltage starts to increase. It is important to have low storage-time to:
- control minimum pulse width
- reduce saturation losses during storage time
- prevent core saturation due to transformer asymmetry

24. *Give two main functions for the snubber network.*
- to reduce peak power dissipation during switching
- to reduce radiated noise

25. *What are the advantages of a power MOSFET over a bipolar device in a switching regulator application?*
A. Higher Efficiency
B. Faster Switching Characteristics
C. Lower System Cost
- drive circuit simpler
- no snubber circuit required
- smaller magnetics & filter capacitor
- in a high current application, devices can be paralleled easily

D. Improved Performance
- no cross conduction current in push-pull circuits (no storage time)

E. Allows the use of new topology—series resonant converter
F. Improved Reliability
- no forward or clamped reverse bias second breakdown problems
- uniform junction temperature
- integral diode can reduce component count

26. *Why is isolation necessary?*
When an output is derived from a 117V or 220V AC line input voltage, the output should have 3750V isolation (VDE requirements) from the 117V or 220V AC line for safety reasons.

27. *What is the function of a Baker Clamp?*
The collector current of the power transistor in a switching regulator is proportional to variable output load current. Normally, with bipolar transistors the fixed base drive current is optimized for a maximum output load current. This can result in unacceptably large storage time at light load, because the transistor will be driven into deep saturation. The baker clamp prevents deep transistor saturation by providing a path for excessive base drive current. Many applications, such as flyback and forward converters, are utilizing this technique. The baker clamp diode must have a fast reverse recovery time.

28. *Define power factor and why it is important to keep close to one.*
In an off-line switching regulator, the pulsating DC input voltage is derived through an input bridge rectifier. This pulsating DC voltage is utilized to charge the (60cps) input filter capacitor. The capacitor charges during the peak portion of the input pulsating DC voltage. The input AC voltage is isolated from the capacitor during the rest of the cycle.

When the capacitor charges from the input line voltage, it draws large peak currents, rather than continuous currents during the entire cycle. This large current drawn from the line, during a short period of the cycle, causes additional I^2R losses in the lines. The power factor can be defined by equation:

$$P.F. = \frac{\text{Output power}}{\text{Input AC voltage x RMS input current}}$$

29. ***Why does the input supply line see a negative input impedance when the output load is a switching regulator?***

With a fixed output load current, the peak current drawn from the input supply voltage remains the same even if input voltage is increased; however, the duty cycle is reduced to maintain output voltage regulation. Therefore average current drawn from the supply voltage is reduced while the input voltage increased to maintain constant power output. This negative change in current results in a line which sees a negative input impedance. Any inductance in the input line will cause oscillation if proper damping is not provided.

30. ***Is efficiency affected by the absolute value of the output voltage?***

$$\text{Efficiency} = \frac{\text{Output Power}}{} = \frac{\text{Output Power}}{\text{Output Power + Losses}}$$

Most of the power losses in a switching regulated power supply are due to the forward losses of the output rectifiers. For example, in a 5V supply, 20% of the output power will be lost in the rectifiers. This will limit the maximum efficiency to less than 80%. However, in a +12V supply only 8% of the output power will be lost in the rectifiers. This will result in maximum efficiency of approximately 92%.

APPENDIX II

ENGINEERING NOTE-BOOK "DESIGN EQUATIONS"

This section lists some of the important switching regulator design equations.

I. Input filter capacitor for 60 Hz rectification;

$$C_{in} = \frac{P_O}{\eta f_L \left(V_{PK}^2 - V_{min}^2\right)} \qquad \text{(EQ. 1)}$$

Where: V_{PK}—peak voltage at min. input line
V_{min}:V_{PK}—ripple across the capacitor
f_L—line frequency
P_O—output power
η—efficiency

with a line drop-out specification:

$$C_{in} \approx \frac{P_O\, N}{f_L\, \eta \left(V_{PK}^2 - V_{min}^2\right)} \qquad \text{(EQ.2)}$$

Where: N—number of drop-out cycles

II. The output filter capacitor:

$$c_O = \frac{\Delta I_L}{8\, f_S \Delta V_O} \qquad \text{(EQ. 3)}$$

Where: ΔV_O = output ripple voltage

The selected capacitor must have $ESR \leqslant \Delta V_O / \Delta I_L$

III. Magnetic design

Energy stored in the core material

$$W_c = \frac{1}{2}\, \frac{B\, Ae\, Hle}{.4\pi}\, 10^{-8} \qquad \text{(EQ.4)}$$

Where: B—magnetic flux density in gauss
H—magnetic field intensity in oersted
Ae—effective magnetic cross section area in cm. sq.
le—mean magnetic path length in cm.

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The required circuit energy

$$W_R = \tfrac{1}{2} L i_p^2 \qquad \text{(EQ. 5)}$$

Where: L— circuit inductance
i_p— peak current in inductor

Magnetic potential, from Ampere's law:

$$\frac{Hle}{.4\pi} = N_p i_p \qquad \text{(EQ. 6)}$$

lg = gap in the magnetic path in cm
le = lg
B = H for gapped inductor

The inductor value:

$$L = A_L N_p^2 \times 10^{-9} \text{ henries} \qquad \text{(EQ. 7)}$$

A_L inductance index
L henries

From Faraday's law, the minimum number of primary turns for the push-pull converter

$$N_{P_{min}} \geqslant \frac{V_{in(max)}\, 10^8}{4\, f_s\, B_{max}\, Ae} \qquad \text{(EQ. 8)}$$

Where: $V_{in(max)}$ = max. input DC voltage
f_s = switching frequency

For forward converter

$$N_{P_{min}} \geqslant \frac{V_{in(max)}\, 10^8}{2\, f_s\, B_{max}\, Ae} \qquad \text{(EQ. 9)}$$

The output filter inductor in PWM switching regulator:

$$L \approx \frac{V_O + V_F}{f_s\, \Delta I_L} \qquad \text{(EQ. 10)}$$

Where: V_O = output voltage
V_F = forward voltage drop in the rectifier
ΔI_L = peak to peak inductor current
$\approx 2\, I_{O(max)}$ or $I_{O(min)}$

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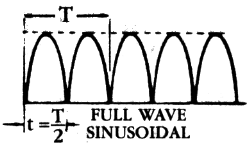
The temperature rise of the core with natural convection cooling:

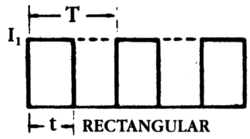
$$\Delta t = \frac{850 P_L}{A_S} \qquad \text{(EQ. 11)}$$

Where: P_L = power losses (copper and core losses)
A_S = core surface area in cm^2

IV. Equations for determining RMS current

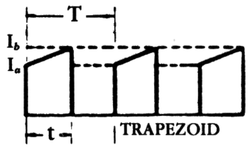


$$I_{RMS} = \frac{I_1}{\sqrt{2}}$$



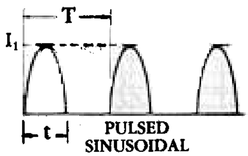
$$I_{RMS} = I_1\sqrt{D}$$

$$D = \frac{t}{T}$$



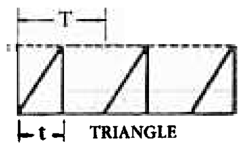
$$I_{RMS} = D\left[\frac{I_a^2 + I_aI_b + I_b^2}{3}\right]^{1/2}$$

$$D = \frac{t}{T}$$



$$I_{RMS} = I_1\sqrt{\frac{D}{2}}$$

$$D = \frac{t}{T}$$



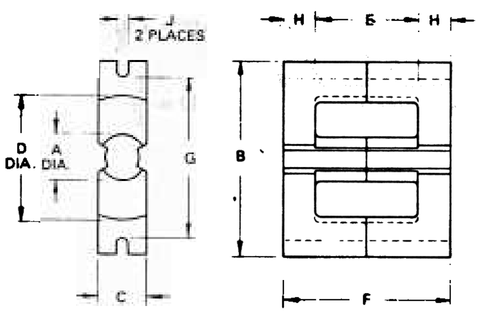
$$I_{RMS} = I_1\sqrt{\frac{D}{3}}$$

$$D = \frac{t}{T}$$

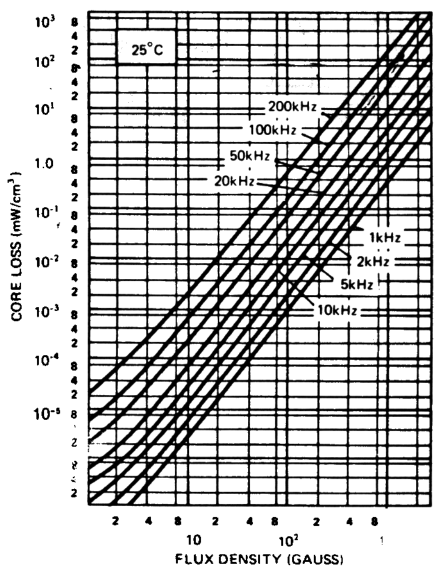
V. EC CORE DATA

EC core data is from Ferroxcube databook. There are many suppliers of this core series. Pregapped cores are available. All dimensions are in centimeters:

CORE	EC35	EC41	EC52	EC70
B	3.45	4.06	5.22	7.0
D	3.46	3.9	4.84	6.9
C	.95	1.16	1.34	1.64
A	.95	1.16	1.34	1.64
A_e	.843	1.25	1.83	2.83
l_e	7.74	8.8	10.3	14.1
V_e Core Volume	6.53	11.0	18.7	39.8
b_W (E)	2.45	2.78	3.18	5.55
h_W (H)	.66	.77	.98	1.22
A_W	1.65	2.15	3.12	6.39
Bobbin Cross Section Area	1.03	1.35	2.13	4.77
A_S	43.5	59	91	170
A_SA_W	1.39	2.69	5.71	18.1



CORE LOSS vs. FLUX DENSITY



WINDING DATA

WIRE TABLE—Copper Wire—Heavy Insulation:

AWG	DIAMETER Copper cm	AREA Copper cm^2	DIAMETER Insulated cm	AREA Ins. cm^2	OHMS/CM 20 C	OHMS/CM 100 C	AMPS for 450A/cm^2
16	.129	.013088	.139	.015207	.000132	.000176	5.890
17	.115	.010379	.124	.012164	.000166	.000222	4.671
18	.102	.008231	.111	.009735	.000209	.000280	3.704
19	.091	.006527	.100	.007794	.000264	.000353	2.937
20	.081	.005176	.089	.006244	.000333	.000445	2.329
21	.072	.004105	.080	.005004	.000420	.000561	1.847
22	.064	.003255	.071	.004013	.000530	.000708	1.465
23	.057	.002582	.064	.003221	.000668	.000892	1.162
24	.051	.002047	.057	.002586	.000842	.001125	.921
25	.045	.001624	.051	.002078	.001062	.001419	.731
26	.040	.001287	.046	.001671	.001339	.001789	.579
27	.036	.001021	.041	.001344	.001689	.002256	.459
28	.032	.000810	.037	.001083	.002129	.002845	.364
29	.029	.000642	.033	.000872	.002685	.003587	.289
30	.025	.000509	.030	.000704	.003386	.004523	.229
31	.023	.000404	.027	.000568	.004269	.005704	.182
32	.020	.000320	.024	.000459	.005384	.007192	.144
33	.018	.000254	.022	.000371	.006789	.009070	.114

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