Flat Transformer Technology Corp.

FT3510-0002
FWD-12x2A-1B
FWD KIT #1

APPLICATION NOTE AN02

100 W Forward Converter

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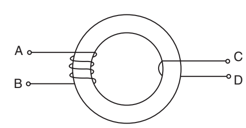
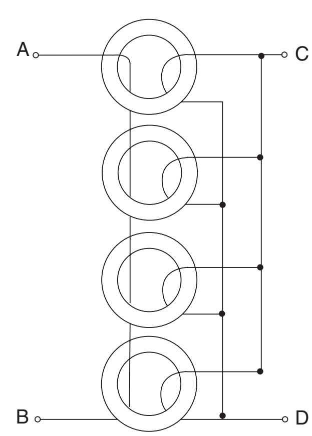
TAKE THE PAIN OUT OF FORWARD CONVERTER DESIGN

If you have ever designed a 50+ Watt converter, you would probably agree the transformer design and verification takes a considerable amount of time and prudent attention. Parasitic effects such as the leakage inductance and the inter-winding capacitance, size constraint, primary to secondary isolation as well as heat management and, last but not least cost. All these factors form a multi-variable optimization problem to be solved within a time constraint. While low loss, high saturation flux density and high current handling are all important, perhaps the key advantage can be gained is by reducing the number of turns on the higher voltage side. Hot spots, parasitic inductance and capacitance, are the primary causes of re-iterating your design. These steps can virtually be eliminated when there are few primary turns.

Flat Transformer Technology has simplified the process of power transformer design. The Flat Transformer is a distributed approach to handling power. The transformer is essentially a low profile structure with cubical cores whose secondary is a patented copper foil wrapped uniquely on the inside wall of the core, forming a high current single turn (with built-in center-tap, when used for push-pull, half-bridge and full-bridge converters). As the need for output current is increased, more cores are utilized in parallel. Similarly, as the number of primary turns are decreased, more cores are used in series. For example, in a 2 modules design, the primary sides add in series, which means each core sees only half the voltage, while the secondary windings add in parallel, thus the current capacity (compared with a single core) is doubled. For a 3 modules design, each core on the primary side sees 1/3 of the applied voltage, and the secondary side current capacity is tripled, and so on. This primary problem of high input voltages and high output currents, which inspired the invention of the Flat Transformers, is thus solved in a most elegant manner.



Conventional Transformer



Flat Transformer

The modules for the Flat Transformer are optimized for minimum loss operation in the frequency range of 150-250KHz. The secondary conductor thickness has the proper skin depth for the design frequencies. This frequency range coincides with the latest advances in the power semiconductor technology. Lower gate charge and lower ON resistance power MOSFETs and ultra fast recovery diodes are now available, rendering operation at these frequencies quite practical and cost effective. Also, the selected switching frequencies lead to reduced component sizes, resulting in cost-savings not possible with other transformers.

The circuit described herein makes use of the Flat Transformer in a 100 Watt forward converter transformer. A two-core module is used and configured to have a two-turn secondary. The turns ratio is determined by the number of turns of wire divided by two. The number of primary turns was selected to be 7 to achieve a compromise in maximum duty cycle, output current ripple and transient response. As can be seen, the primary advantage of the transformer is derived from the few primary turns. Leakage inductance and the associated voltage drops are reduced dramatically. The number of primary turns may be adjusted by +/- 1 turn, yielding an inductance of :

$$A_L \times N^2 = 9000 nh/T^2 \times 49 = 441 \mu h$$

The Leakage inductance, also proportional to turns squared is:

$$8 \ nh/T^2 \times 49 = 392 \ nh$$

which is less than 0.1% of primary inductance, quite a challenge for conventional transformers!

The fewer turns also reduce proximity effect and winding capacitance within the transformer windings, since all turns are partially exposed, permitting heat transfer by convection.

Design Example:

A step-by-step design procedure is shown below for designing the transformer and the output inductor.

Specifications:

$V_{in} = 36 \ V_{dc}$ to $60 \ V_{dc}$

$V_{aut} = 5 \ V_{dc}$

Output Current = 20 Amps

A two core module (FTI series –12mm high PN: FWD 12x2A-1B or FTI-3510-0002) is used as the main power transformer. The secondary is a two-turn winding.

The turns ratio is set as follows:

$$\frac{N_{sec.}}{N_{prim.}} = \frac{V_{out} + V_{diode} + V_{inductor}}{V_{in\_min} \times D_{max}}$$

Where:

N_{sec} = number of secondary turns = 2
N_{prim} = number of primary turns
D_{max} = Maximum allowable duty cycle = 0.68
V_{diode} = Secondary Shottkey diode drop + secondary wire losses = ~1volt
$V_{inductor}$ = Voltage allotted on the secondary Inductor to assure proper transient response at low line = 1.5V
V_{in_min} = Minimum input line voltage = 36 volts

$$N_{primary} = \frac{V_{in\ min} \times D_{max} \times N_{sec}}{V_{out} + V_{diode} + V_{inductor}}$$

Primary inductance = $A_L \times (N_{prim})^2 = 9000 \times 49 = 441 \mu H$
Secondary Inductance = $9000 \ nh \times 2^2 = 36 \mu h$

Primary Leakage Inductance = ***8nh x 36 = 392 nh,*** less than 0.1% of primary inductance, quite negligible.

$$B_{max} = \textit{Maximum Flux Density} = \frac{V_{in\ min} \times D_{max} \times 10^8}{A_e \times N \times freq.}$$

Frequency is selected at 200 kHz.

$$B_{max} = \frac{36 \times 0.680 \times 10^8}{0.68 \times 7 \times 200 \times 10^3} = 2571 \text{ Gauss}$$

B_{max} = 2571 gauss, well under 3700 gauss max limit.

The core reset is accomplished by resonant reset method. During switch turn-off, the magnetization current stored in the primary inductance charges the drain to source capacitance and reverses the voltage applied to the transformer thus resetting the transformer. Care must be taken to ensure that the drain voltage settles at around V_{in} by the end of the transformer reset period. This will keep switching losses to a minimum. The frequency of resonance must be greater than the switching frequency to allow enough time for the transformer to be reset. The resonant frequency is determined by:

$$F_{resonance} = \frac{1}{(2 \times \pi \times \sqrt{L_{prim} \times C})}$$

Where C is the drain to source capacitance of the switching MOSFET = 650pf Max

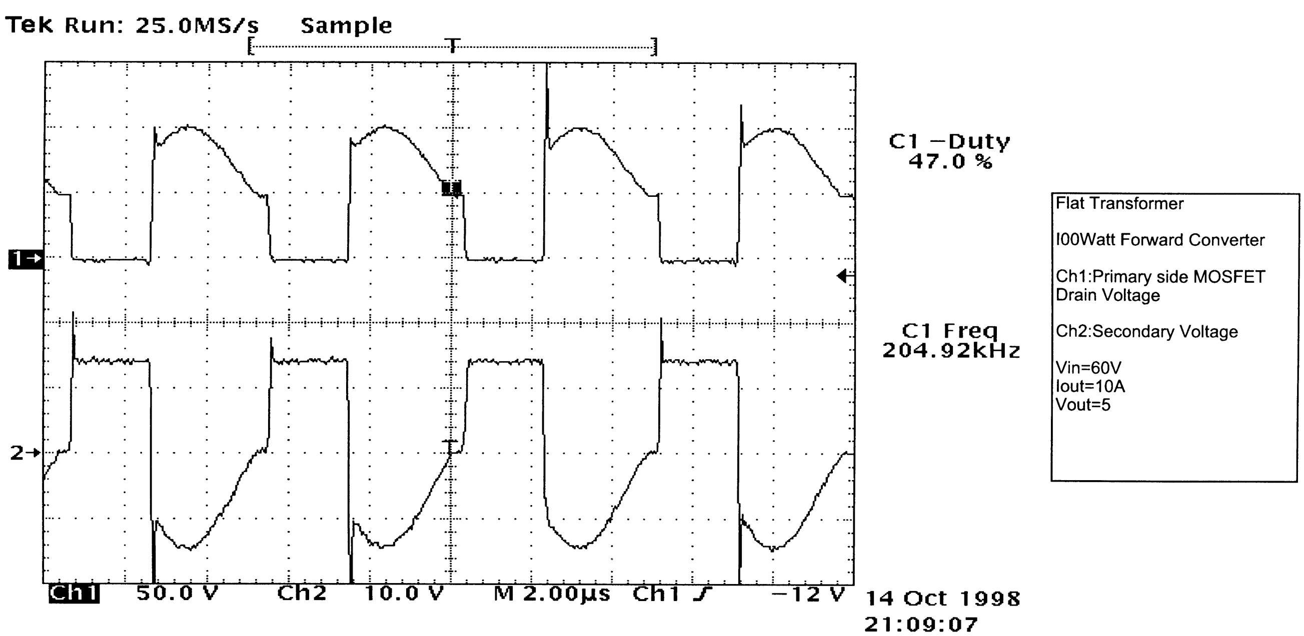
$F_{resonance} = 297\ kHz$

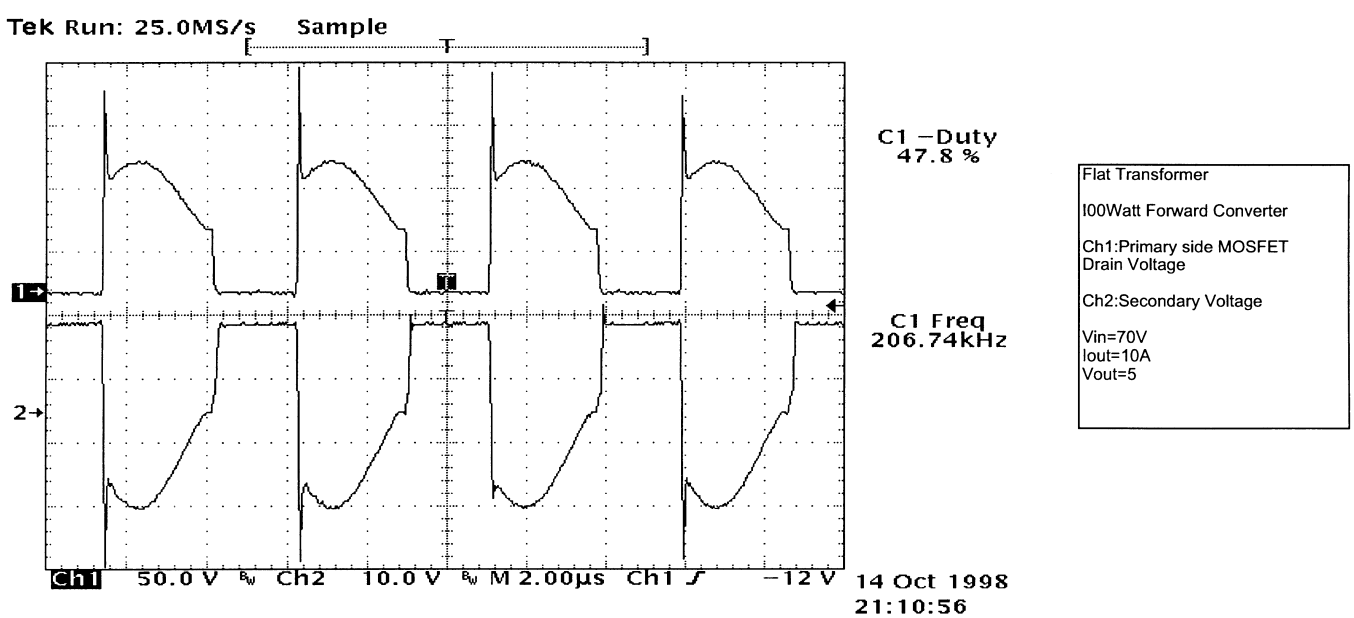
Which meets the requirement under worst case conditions. The peak MOSFET drain voltage is measured at around 90-100 Volts, so it is safe to use a 150-Volt MOSFET.

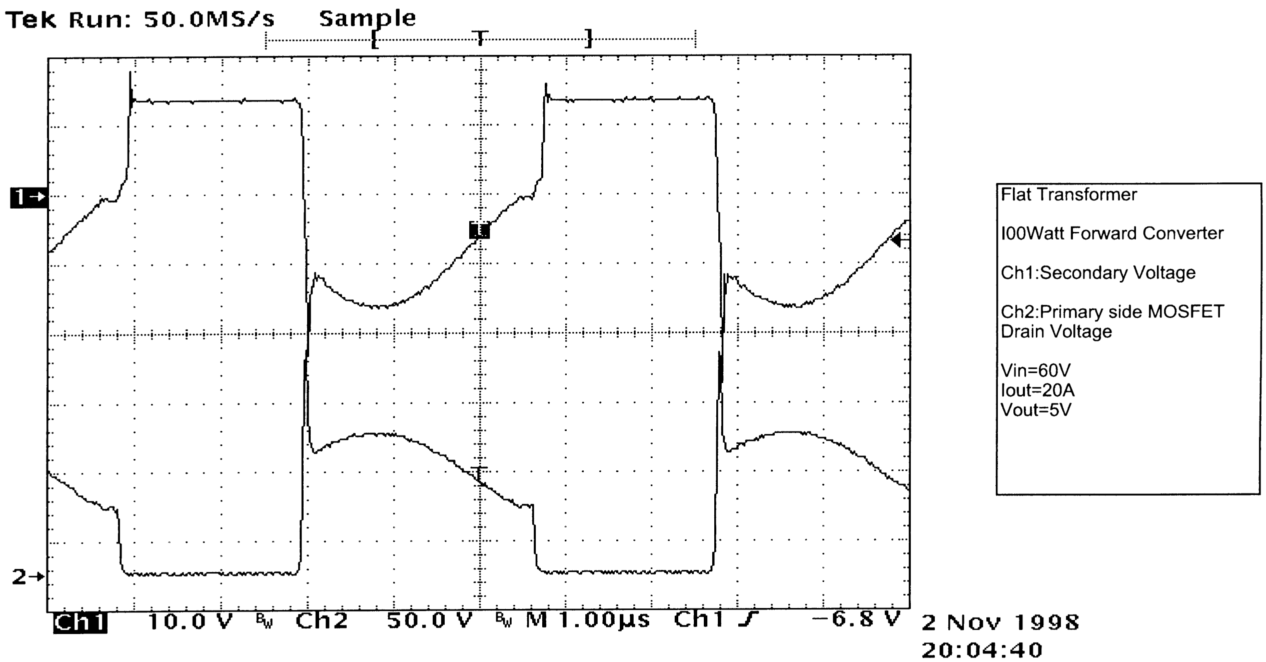
Figure 1. shows the scope waveforms of the drain voltage of the MOSFET (primary) and the transformer secondary for

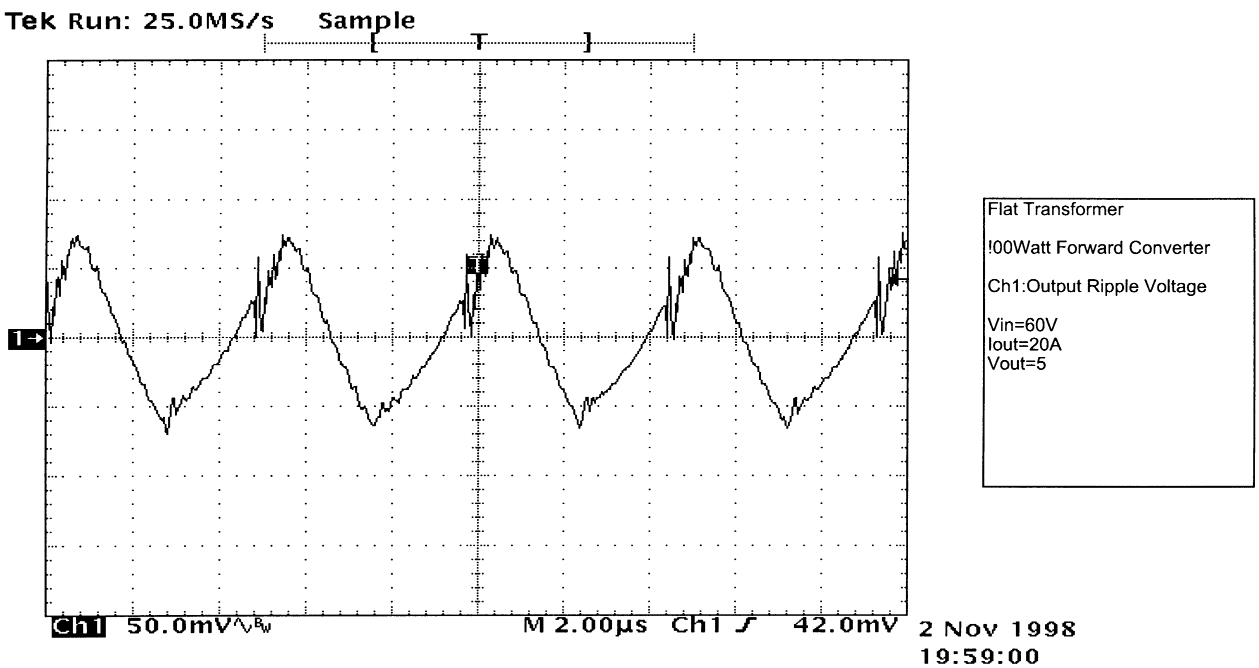
$V_{in} = 48 Volts$ and $I_{out} = 20\ Amps$.

Figure 1: Drain Voltage Of The MOSFET









The controller selected is the UCC3580-3 manufactured by Unitrode. The features that make this controller attractive are:

1. Line voltage feed forward, thus improving line regulation, or making the output insensitive to line voltage variations.

2. Programmable Maximum Duty cycle limit allows sufficient time for transformer reset.

3. Volt-second product limitation. This feature prevents the transformer from saturation under high current transients or sudden drops in input voltage by limiting the maximum Volt-Seconds applied to the transformer.

4. Under-voltage lock-out on both the line voltage and the supply pin, preventing the converter from drawing excessive current when there is insufficient voltage to operate as intended.

5. Internal wide bandwidth error amplifier.

6. Low start-up current.

Any other controller with similar features may also be used.

This controller operates from a supply voltage of 9 volts. An auxiliary winding with 3 turns on the power transformer will supply this voltage. Resistor R1 supplies sufficient current to kick-start the controller, after which time the supply and gate drive current is obtained from the auxiliary winding via D1, R10 and capacitor C14.

The frequency of operation and the maximum duty cycles are set as follows:

$$\textit{Freq.} = \frac{1.44}{(R21 + 1.25 \times R\,23) \times C18}$$

$$D_{max} = \frac{R\,21}{(R21 + 1.25 \times R\,23)}$$

With the values shown (see schematic), the frequency is 210 kHz.

The values of R20 and R24 are selected such that at minimum input voltage of 36 Volts, the line under-voltage lock-out, which is activated (thus prohibiting operation) at 5Volts, is near the trip point.

The ramp voltage for the PWM controller is made proportional to the input voltage by converting it into a charging current for capacitor C17 through R18. The volt-second limit operates at 3.3 V, thus the ramp slope is:

$$\textit{Slope} = V_{in}\,(R18 \times C17)$$

The charging current of 1.415 ma is obtained by setting R18 to 42.4 KΩ for an input voltage of 60 volts. At low line (36 volts), the maximum duty cycle is 0.7. The maximum ramp voltage is set at 3 volts (to prevent the volt-second limit of 3.3V from interfering with normal operation) the capacitor value is selected as follows:

$$V_{ramp\_max} = \frac{V_{in} \times T_{on}}{R18 \times C17}$$

Where:

V_{ramp_max} = maximum ramp vltage = 3.0V
$V_{in} = 36V$
$R18 = 42K$
$T_{on} = D_{max}/Freq. = 0.7/210$ kHz

Output Inductor Selection:

The inductor ripple current is equal to

$$\textit{Delta\_I} = \frac{\{V_{sec} - (V_o + V_d)\} \times D_{max}}{L \times Freq.}$$

Where:

V_{sec} = Secondary voltage=$N_{sec/Nprim}$ x V_{in_min} = 10.3V
$V_{out} + V_d$ = 5+1 = 6V
L = Output Inductor

To set the ripple current equal to 10 - 15% of output current, the inductor value of 5uH is selected.

$$\textit{Delta\_I} = \frac{(10.3 - 6) \times 0.7}{5u \times 210K} = 2.87\ \textit{Amps}$$

The Inductor must be capable of sustaining 80% of its initial inductance at 20Amps. It also must be able to store an amount of energy equivalent to:

$$\textit{Energy} = \frac{1}{2} L I^2$$

Where:

$I = Idc + 0.5 \times Delta\_I = 20 + 0.5 \times 2.87 = 21.43$

And the energy in Joules is:

$$E = 0.5 \times 21.43^2 \times 5\mu h = 2 \text{ milli-joules}$$

Core :

Use the MPP or Sendust core that are built into the module or use coroidal core: American Cores & Electronics PN: AS090125 or Magnetics 77310-A7. Use 8 turns of AWG # 16 gauge wire.

Output Capacitor Selection:

The initial attempt at selecting the output capacitor is originated from output voltage ripple requirements. The ESR of the output capacitor is calculated by dividing the desired voltage ripple by the inductor ripple current. A safety margin should be allowed for the fact that the inductance will drop at full load (if not determined exactly at full load) and thus the ripple current will increase. A safety margin of 80% is used here:
For a 1% output ripple:

$$ESR = \frac{V_{o\_ripple} \times 80}{\textit{Delta\_I}}$$

$V_{o\_ripple} = 50mv$

$$ESR = \frac{0.04}{2.87} = 14 \text{ milliohms}$$

Three pieces of 1000uf, 25V capacitors (UPL1E series from Nichicon) are selected. The ESR of each capacitor is 36 milli-ohms and thus the combined parallel ESR is 12 milli-ohms.

Stability and Frequency Compensation Considerations:

Since the above converter is based on a voltage mode controller, a double pole is introduced at the output LC corner frequency:

$$Wp = \frac{1}{\sqrt{LC}}$$

Where:

L = output inductor = 5uh
C = Output Capacitor = 3000uf

$$Wp = 2\pi \text{ Freq.} = 8165 \text{ Rad}$$
$$\text{Frequency of Double Pole} = \frac{8165}{2\pi} = 1.3 \text{ kHz}$$

The zero introduced by the output capacitor ands its ESR is :

$$F_z = \frac{1}{2\pi C \times ESR} = \frac{1}{2\pi \times 3000\mu \times 0.12} = 4.42 \text{ kHz}$$

Since there is isolation requirements between input and output voltages, an opto-coupler is used to transfer the feedback information from the secondary to the primary. A linear shunt reference, SC431, by Semtech Corporation, is used to achieve the frequency compensation as well as provide the opto-coupling with the proportional drive current it requires. The output of the opto-coupler is fed to the inverting input of the error amplifier, with a gain of –1. The input to output transfer ratio resistors are set so as to set the opto-coupler gain to 1 and have the output of the error amplifier at a nominal voltage of 2.5V. The frequency compensation is implemented via the SC431 shunt regulator feedback network.

R6 and R12 set the low frequency gain (before Fp) to about 2.5 with R6/C11 combination introducing a zero at approximately 30 Hz, thus providing a flat gain up to the output LC break frequency. At 1600 Hz, C12, R8 and R12 create a zero in the transfer function at 1600 Hz, thus combating the double pole roll-off introduced by the output L-C filter. C12 and R8 flatten the mid-band gain at around 17 kHz, which is higher than the highest expected zero frequency, Fz, introduced by output filter capacitor. The R6/C9 combination rolls off the gain at around 32 kHz.

Additional Information

For more information or other design examples, please contact our technical support at ***jlau@flattransformer.com*** or visit our web site at ***www.flattransformer.com***.

Disclaimer

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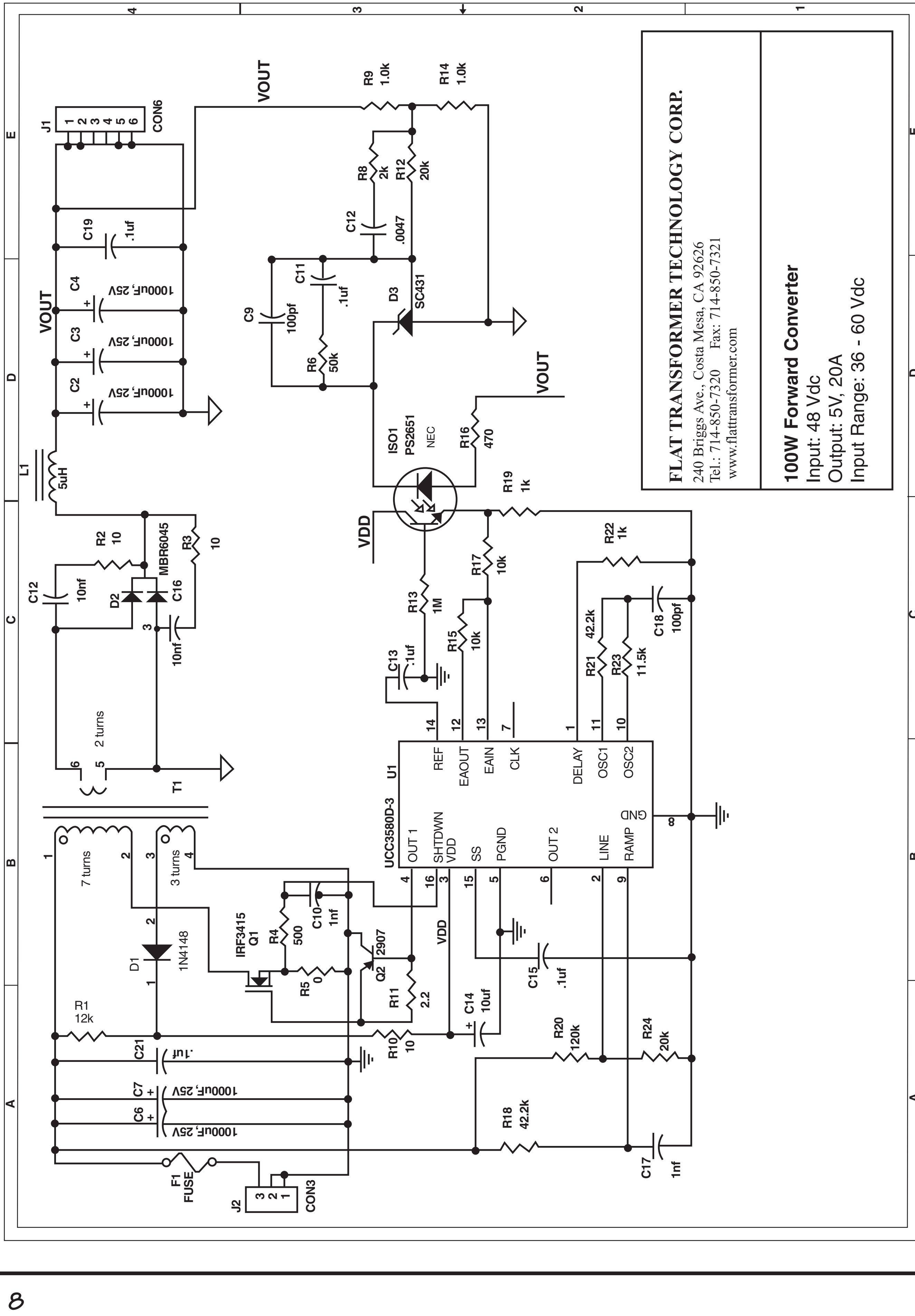
Bill Of Materials

FORWARD CONVERTER
Input: 48 Volts DC (36 to 60 Vdc)
Output: 5.0 Vdc at 20 amps.

Item	Qty	Reference	Part No.
1	5	C2, C3, C4, C6, C7	1000uF, 25V
2	2	C18, C9	100pf
3	2	C17, C10	1nf
4	5	C11, C13, C15, C19, C21	.1uf
5	1	C12	.0047
6	2	C12, C16	10nf
7	1	C14	10uf
8	1	D1	1N4148
9	1	D2	MBR6045 (International rectifier)
10	1	D3	SC431 (Semtech)
11	1	F1	FUSE
12	1	ISO1	PS2651
13	1	J1	CON6
14	1	J2	CON3
15	1	L1	5uH
16	1	Q1	IRF3415 (International rectifier)
17	1	Q2	2907
18	1	R1	12k
19	3	R2, R3, R10	10
20	1	R4	500
21	1	R5	0
22	1	R6	50k
23	1	R8	2k
24	2	R14, R9	1.0k
25	1	R11	2.2
26	2	R12, R24	20k
27	1	R13	1M
28	2	R17, R15	10k
29	1	R16	470
30	2	R18, R21	42.2k
31	2	R22, R19	1k
32	1	R20	120k
33	1	R23	11.5k
34	1	T1	Flat Transformer PN: FT-3510-0002 /FWD 12x2A-1B
35	1	U1	UCC3580D-3 (Unitrode)


FLAT TRANSFORMER TECHNOLOGY CORP.
240 Briggs Ave., Costa Mesa, CA 92626
Tel.: 714-850-7320 Fax: 714-850-7321
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100W Forward Converter
Input: 48 Vdc
Output: 5V, 20A
Input Range: 36 - 60 Vdc
VOUT
VDD
J1
CON6
J2
CON3
F1
FUSE
T1
7 turns
3 turns
2 turns
L1
5uH
D1
1N4148
D2
MBR6045
D3
SC431
Q1
IRF3415
Q2
2907
ISO1
PS2651
NEC
U1
UCC3580D-3
OUT 1
SHTDWN
VDD
SS
PGND
OUT 2
LINE
RAMP
GND
REF
EAOUT
EAIN
CLK
DELAY
OSC1
OSC2
R1 12k
R2 10
R3 10
R4 500
R5 0
R6 50k
R8 2k
R9 1.0k
R10 10
R11 2.2
R12 20k
R13 1M
R14 1.0k
R15 10k
R16 470
R17 10k
R18 42.2k
R19 1k
R20 120k
R21 42.2k
R22 1k
R23 11.5k
R24 20k
C2 1000uF, 25V
C3 1000uF, 25V
C4 1000uF, 25V
C6 1000uF, 25V
C7 1000uF, 25V
C9 100pf
C10 1nf
C11 .1uf
C12 .0047
C12 10nf
C13 .1uf
C14 10uf
C15 .1uf
C16 10nf
C17 1nf
C18 100pf
C19 .1uf
C21 .1uf