Non - Isolated Flyback Supplies Using *TOPSwitch*®

Design Note DN-12

Introduction

Many applications require a regulated low voltage DC output derived from AC mains (or high voltage DC rail) input but do not need safety isolation between input and output. These applications arise in systems where the output load is itself isolated from the user. Typical applications include motor drives where the power supply output feeds logic/display electronics and output half bridge drivers. Examples include industrial and domestic pumps, air conditioning and general purpose variable speed drives. In white goods applications such as frost-free refrigerators and microwave ovens, a non-isolated supply may power a low voltage DC fan motor to circulate cooling air.

A simple flyback power supply effectively converts from rectified AC mains voltage (normally 100 to 400 V DC) to low output voltages typically between 5 and 15 VDC. The flyback topology is superior to the buck converter which, due to the wide conversion ratio between input and output voltage, requires very small duty cycles, generates high peak and RMS currents, and suffers from low efficiency. The flyback converter, however, enables the designer to utilize the full duty cycle range to maximize efficiency by appropriate choice of primary and secondary transformer turns.

Most non-isolated power supplies operate from fixed mains voltages of 100, 110, 220, 230, 240, or 277 VAC. Wide range or universal input operation is normally not required. Circuit examples include both 230 VAC and 110 VAC designs for the following non-isolated power supplies:

DC Motor Supply (Figure 1, 2)
DC Motor Supply with 5V auxiliary output (Figure 4, 5, 7)
Low Cost Single Output 5V supply (Figure 8, 9)

DC Motor Supply

Figure 1 shows a 10 Watt supply operating from 230 VAC input and delivering a single 12V output to a low voltage DC motor.

The EMI filter (C6 and L2) and the bridge rectifier (BR1) are shown here but will be dropped from the remaining examples

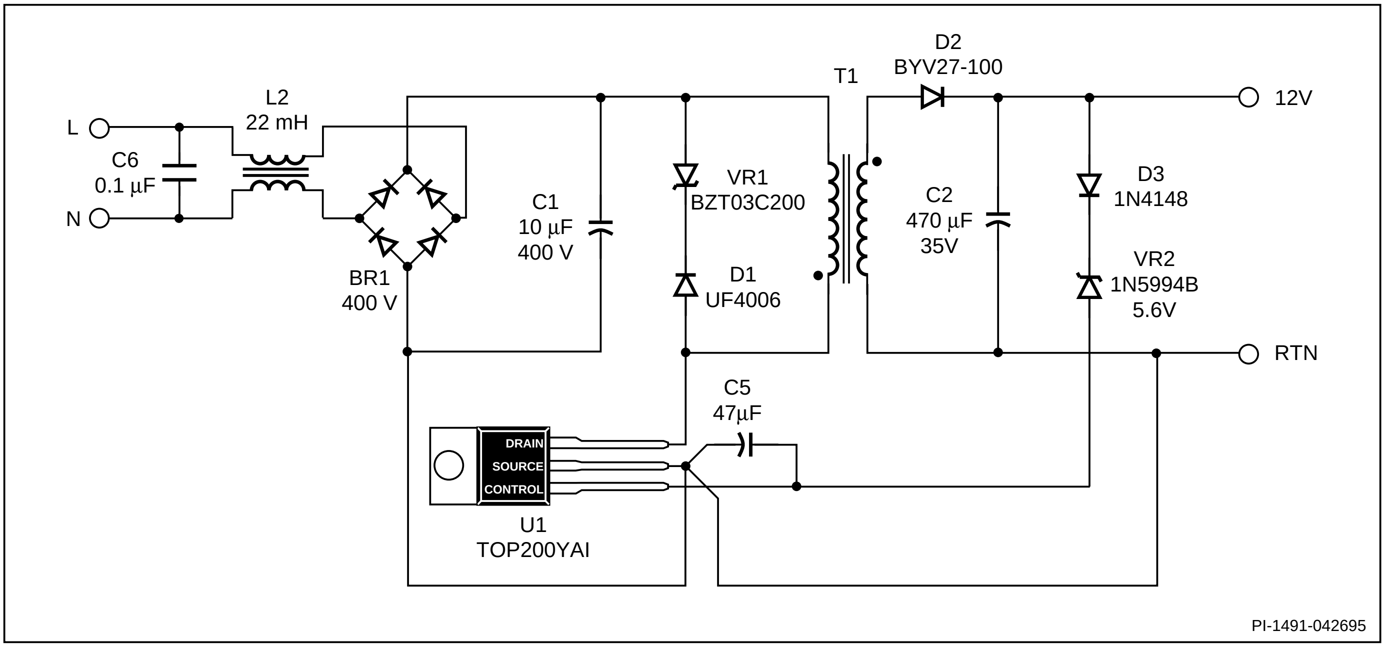

Figure 1. Non-Isolated Motor Power Supply.

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DC Motor Supply (continued)

for clarity. C1 charges to the peak of the AC mains voltage. Full wave rectification generates a ripple voltage on C1 occurring at twice the line frequency with peak to peak voltage of typically 10 to 40 Volts (depending on the size of C1). BR1 can be four discrete diodes to reduce cost or an integrated, four terminal device to save printed circuit board area. Half wave rectification is generally not recommended for size and cost reasons because C1 must be doubled in value for the same AC ripple voltage.

VR1 and D1 clamp voltage spikes and reduce Drain voltage ringing when *TOPSwitch* turns off. D2 and C2 rectify and filter the output power winding of T1. The output voltage is directly sensed by Zener diode VR2. Blocking diode D3 prevents the motor from loading the Control pin during start-up.

A single small, low cost output capacitor (C2) is used because DC motors can accept higher output ripple voltage when compared to logic or display circuitry. Switching frequency output ripple voltage is typically 450 mV (peak to peak).

Figure 2 shows the same circuit with the addition of a low cost post filter (L1, C3) to reduce the switching frequency ripple voltage to typically 30 mV (peak to peak).

Line frequency output voltage ripple can be reduced to less than 30 mV by increasing C1 to 22 uF.

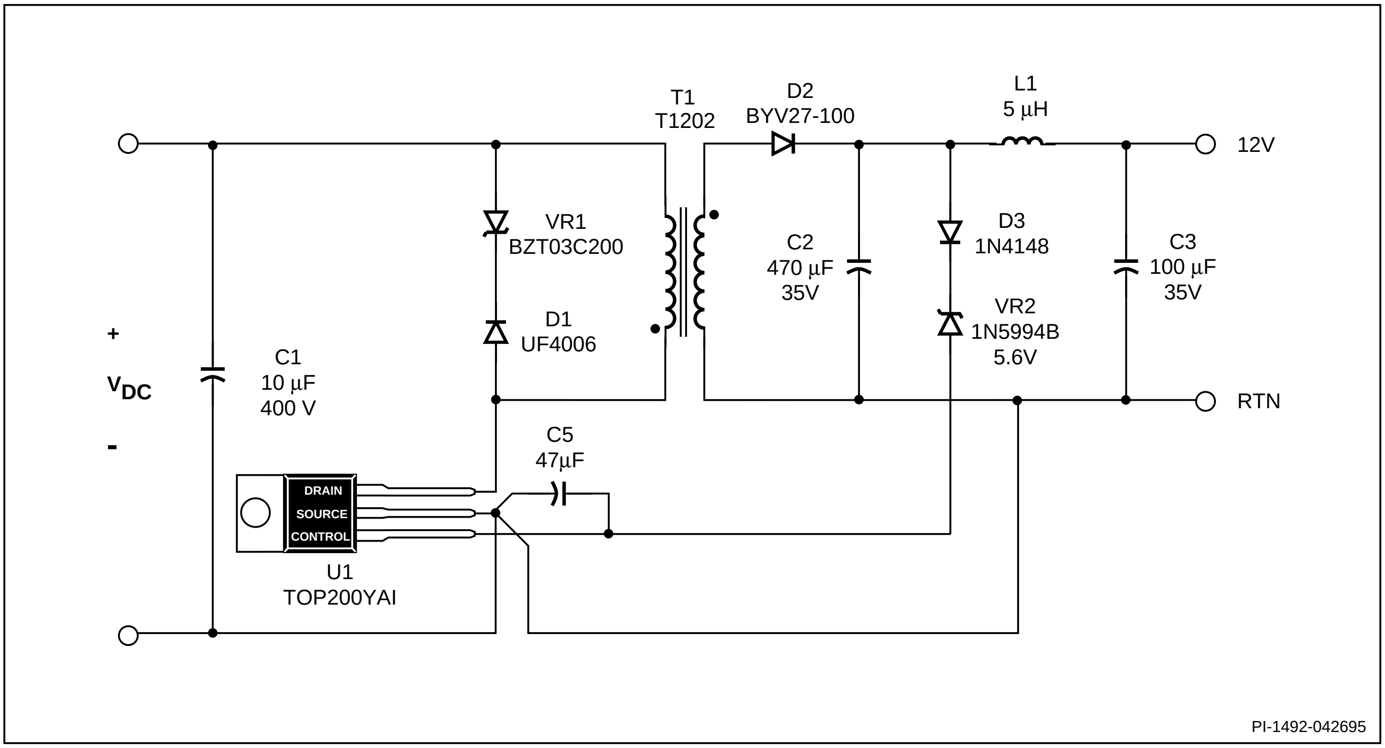

Figure 2. Non-Isolated Motor Supply with Post Filter.

Selecting Components to Determine Output Voltage

The output voltage (V_{OUT}) is a function of the regulated *TOPSwitch* Control pin voltage V_C (typically 5.7 Volts), Control pin dynamic impedance Z_C (typically 15 Ω), Zener diode voltage V_{VR2}, Zener dynamic impedance Z_{VR2}, *TOPSwitch* Control pin current I_C, and diode D3 forward voltage drop V_{D3}:

$$V_{OUT} = ((Z_C + Z_{VR2}) \times I_C) + V_C + V_{VR2} + V_{D3} \quad (1)$$

The *TOPSwitch* data sheet specifies the tolerance of both the Control pin dynamic impedance (Z_C) and the Shunt regulator voltage (V_C) at a control pin current (Ic) of 4mA. Unit to unit output voltage tolerance is subject to the combined tolerances of all variables in Equation (1). The major factors will be the Zener voltage tolerance (generally +/-2% to +/- 5% for low cost devices) and the *TOPSwitch* shunt regulator voltage tolerance (worst case +/-5% including the effects of temperature). Control pin current I_C will have a second order effect due to tolerances of each series impedance (Z_C and Z_{VR2}).

Load and Line Regulation and Temperature Effects

The series impedance terms in Equation (1) will lead to slight output voltage variations due to changing Control pin current I_C. I_C has a dynamic range of 4 mA (typically from 2.5 to 6.5 mA) as the duty cycle changes from maximum to minimum value, respectively. Operating the power supply in the continuous mode will minimize these effects because the duty cycle is relatively constant with output load. A worst case estimate of the load regulation due to the series impedance can be calculated from Equation (1) by considering the minimum to maximum duty cycle extremes in I_C. Taking a worst case Zener dynamic impedance of 30 Ω:

$$\Delta V = (15\Omega + 30\Omega) \times (6.5mA - 2.5mA) = 0.18V \tag{2}$$

With 12 Volt output, this represents a 1.5% variation between minimum and maximum duty cycle. Figure 3 shows load regulation data from the Figure 1 circuit and demonstrates a 1.2% change in output voltage V_{OUT} as the load changes from 10 to 100% (1 to 10 Watts). Directly sensing the output voltage as shown in the circuits of Figures 1 and 2 yields excellent line regulation (less than 1%) from 180 to 265 VAC.

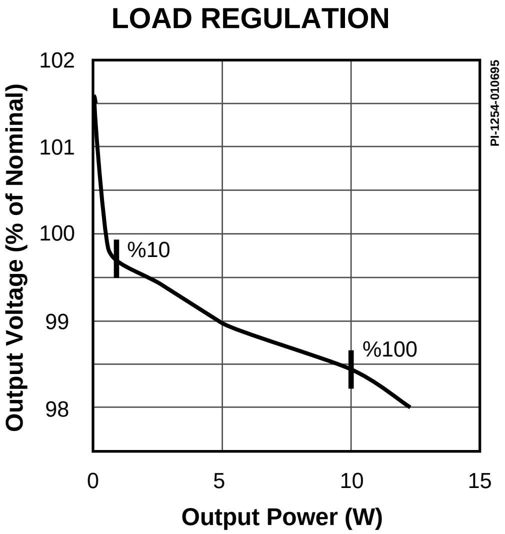

Figure 3. Load Regulation of Circuit Shown in Figure 1.

The positive temperature coefficient of the 5.6 V Zener (VR2) (typically 1.5 to 2.0mV/°C at currents between 2.5 to 6.5mA) tends to cancel the negative temperature coefficient of D3 (-2.1mV/°C). In applications requiring a different output voltage, the characteristics of the chosen Zener should be taken into account to determine the effects of both impedance and temperature coefficient on load and temperature regulation.

Control Pin and Feedback Components

The circuits shown in Figures 1 and 2 have a DC gain determined by two series impedance terms: the Control pin dynamic impedance Z_C and Zener diode dynamic impedance Z_{VR2}. Circuit stability under all conditions of line and load may require increasing effective Control pin impedance with an external series resistor. If circuit instability is observed, start with 47 Ω in series with the Control pin. Values from 15 Ω to 200 Ω should be tested. Equations 1 and 2 should be modified to include this additional series resistance to determine the effects on output voltage and load regulation.

The single capacitor, C5, on the control pin performs a number of functions. C5 determines the auto-restart frequency during start up and output short circuit conditions, filters internal MOSFET gate charge currents flowing into the control pin, and provides loop compensation. See AN-14 for further information on component choice and layout considerations.

DC Motor Supply with 5V Auxiliary Output

An additional 5V auxiliary output is necessary in some applications such as motor drive systems where a 12 or 15 Volt output supplies the output inverter half bridge drivers and an additional 5V supply is required for microcontroller and associated logic circuitry. Figure 4 shows a simple circuit adding an LM7805 type linear regulator to the main output voltage. As with the previous circuits, the output post filter (L1, C3) is optional depending on the output ripple specification required. The LM7805 is a low cost solution when an accurate 5V is required. Linear regulator power dissipation limits the use of this circuit to lower power levels.

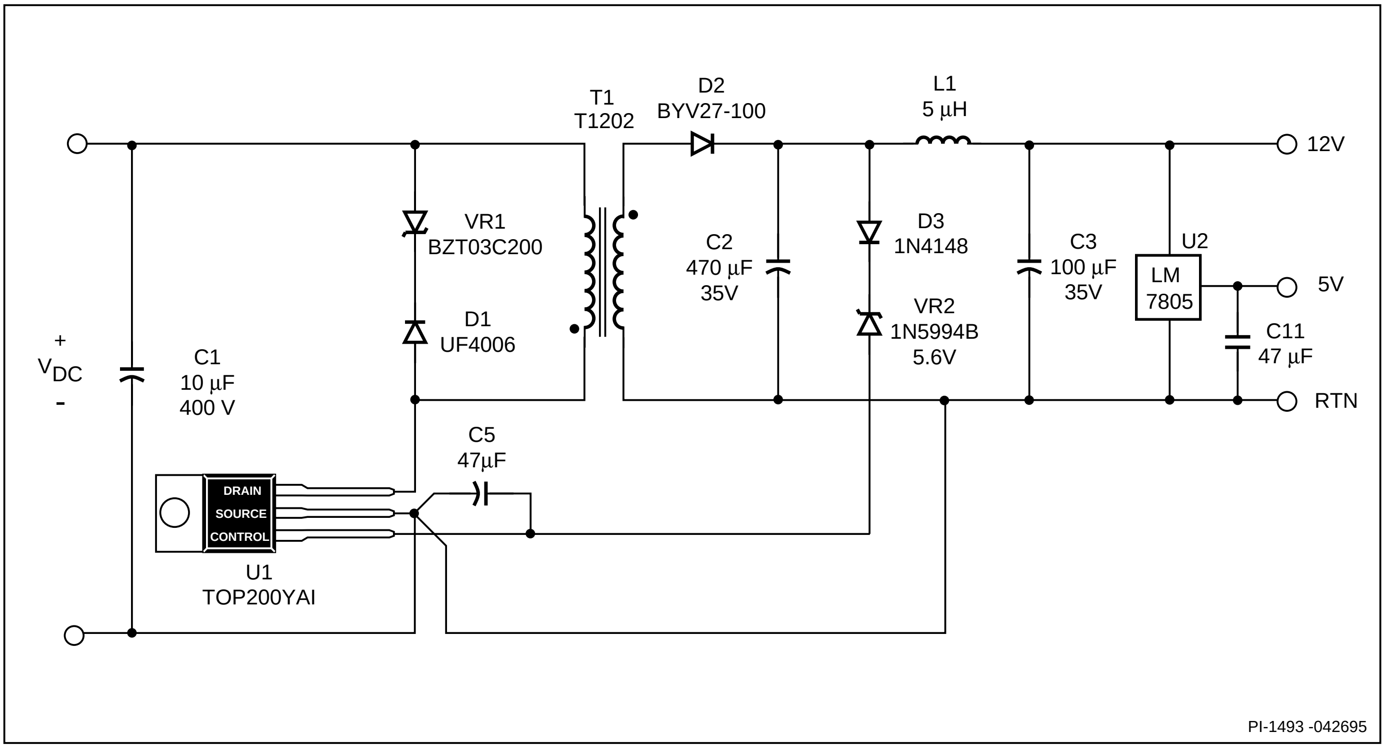

Figure 4. Non-Isolated 12 V Supply with 5 V Auxiliary Output.

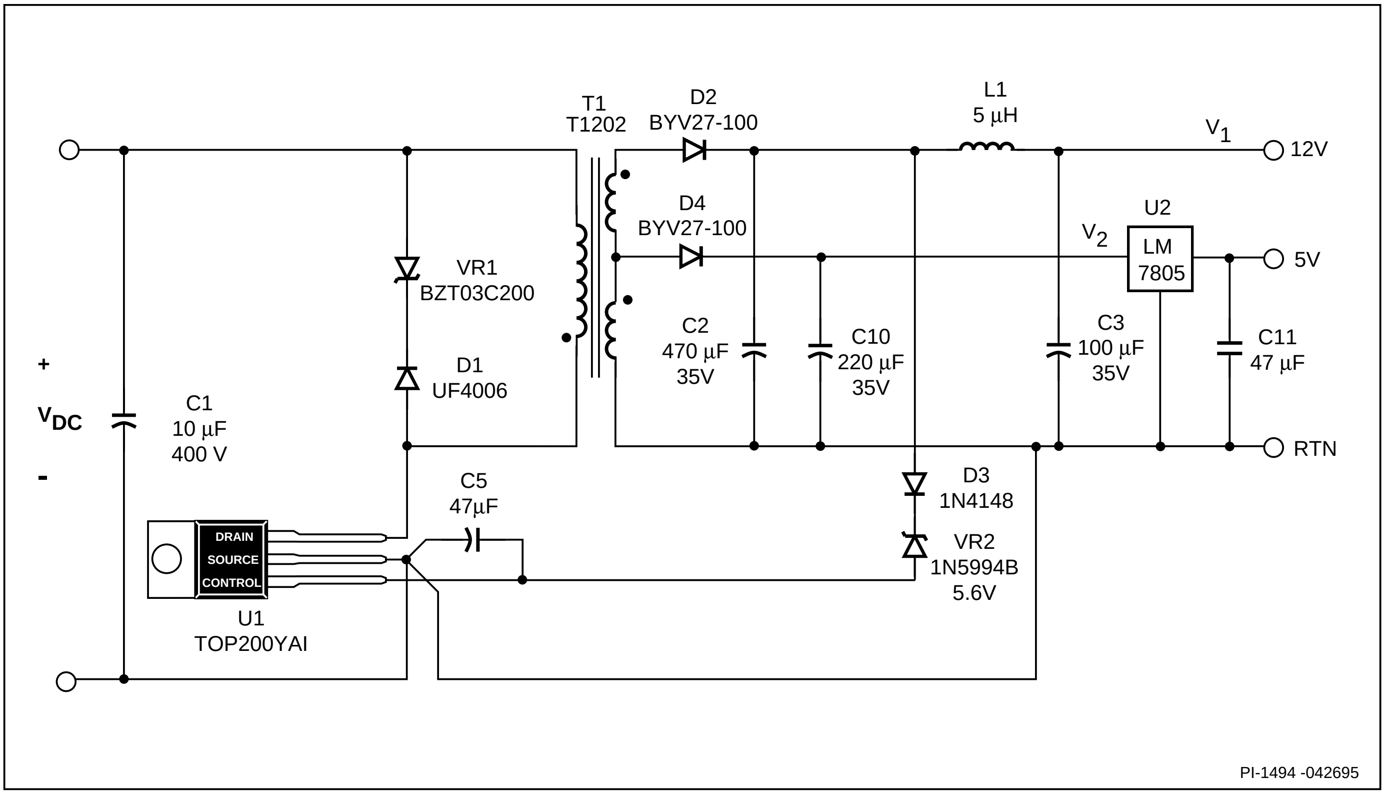

Figure 5. Non-Isolated 12 V Supply with 5 V Auxiliary Output with Improved Efficiency.

DC Motor Supply with 5V Auxiliary Output (continued)

Reduced linear power dissipation and increased output power capability can be achieved by tapping the main output winding as shown in Figure 5 to provide the LM7805 with a lower input voltage. The tapped winding should provide between 7.2 to 7.5 Volts for the LM7805 (or at least 6.5V if a low dropout regulator is used).

The circuit shown in Figure 5 was tested with 1 watt load on the 5V output and 10 Watts load on the 12V output. With no heatsink on the TO-220 package of the LM7805 regulator, a 29˚C case temperature rise was measured. Figure 6 shows load regulation for the V_2 output voltage (input to LM7805) with varying load on the 12V output and 1 Watt load on the 5V output. Figure 6 also shows that the V_2 voltage may be too low for the LM7805 to regulate if the 12V output is lightly loaded or unloaded. A preload resistor between 680 Ω and 1 kΩ should be applied to the 12V output if operation is required with light loading or no load.

Figure 7 shows a similar power supply designed to use a TOP100 and operate from the 110 VAC mains. Note that C1 has three times the capacitance and half the voltage rating compared with the 230 VAC circuit shown in Figure 5. VR1, D1, and D2 also have lower voltage ratings as shown.

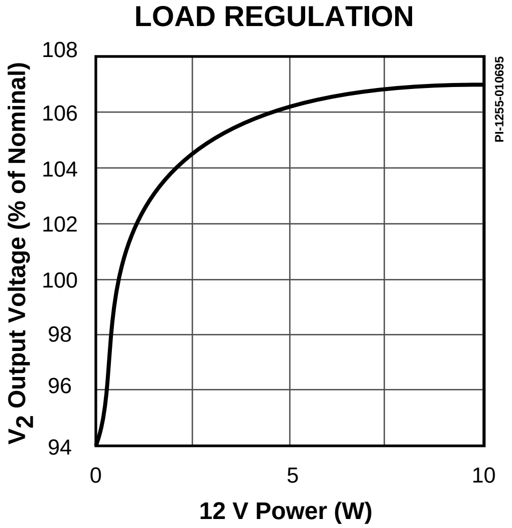

Figure 6. Regulation of 7.5 V (V_2) Output with Varying Load on 12 V (V_1) Output.

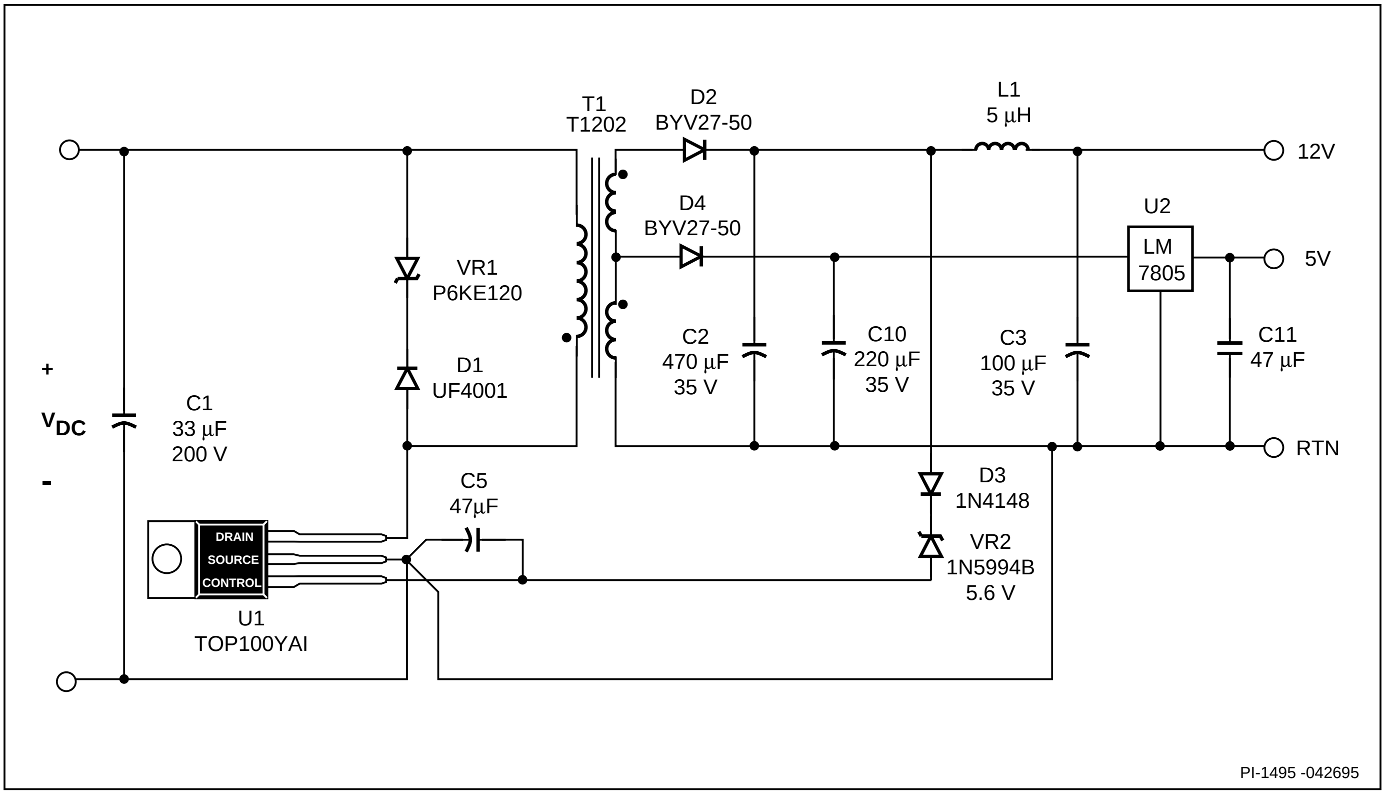

Figure 7. Non-Isolated 12 V Supply with 5 V Auxiliary Output for 110 VAC Input.

Low Cost Single Output 5V Supply

Figure 8 shows a minimum parts count, highly accurate bias supply for 5V outputs. Again the use of a LM7805 linear regulator provides a low cost means of establishing a tight tolerance output. D3, D4 and D5 are connected in series to maintain sufficient input to the LM7805 (typically 7 Volts). The connection shown provides approximately 7.7 volts input to the LM7805 regulator at room temperature. Increasing temperature reduces this voltage slightly due to the combined temperature coefficients of D3, D4 and D5. With a temperature rise of 100 ˚C, the voltage will drop to approximately 7.1 Volts. Slightly higher LM7805 input voltage can be achieved by adding another diode in series with D5. A resistor can also be used in place of one or two diodes.

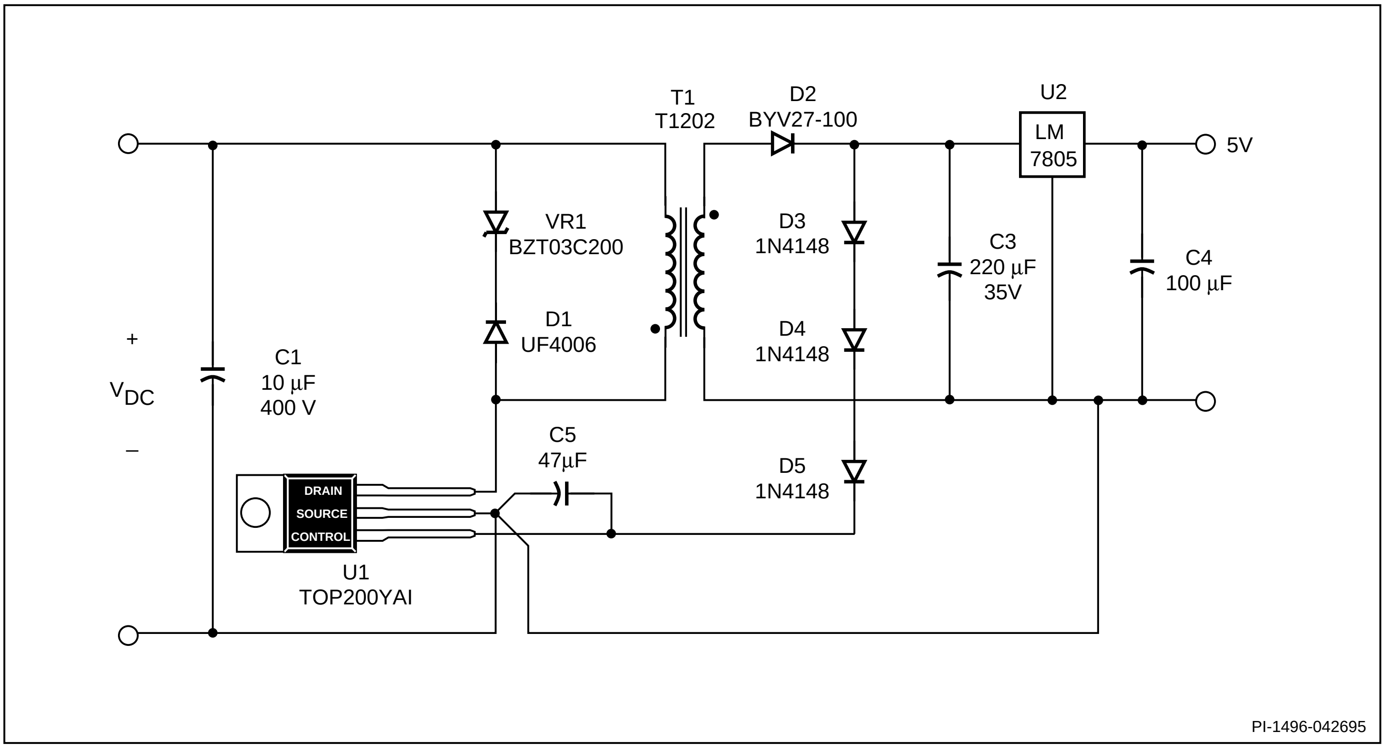

Figure 8. Non-Isolated 5 V Bias Supply with Minimum Parts Count.

Figure 9 shows a circuit for 5V output at higher power levels. The 5V output is sensed directly by a TL431 (U2) which combines an error amplifier, bandgap reference, and driver in a single package. Sensing output voltage directly with the TL431 greatly improves load regulation. The output voltage changes less than 1% as the output power changes from 1 to 10 Watts. U2 drives a PNP transistor (Q1) to provide a current proportional to the error signal. Q1 in turn drives the Control pin to establish the *TOPSwitch* duty cycle. A bias winding is necessary to provide Q1 with sufficient voltage to source the maximum required Control pin current. The bias winding output can also supply other circuitry but diode D3 and capacitor C4 ratings must be increased for the required output power. Power dissipation is minimized with Schottky rectifier D2. To reduce cost, a fast recovery diode such as the UG4A or UG-8AT from General Instrument are possible choices. A small preload resistor (R4) improves light or no load regulation.

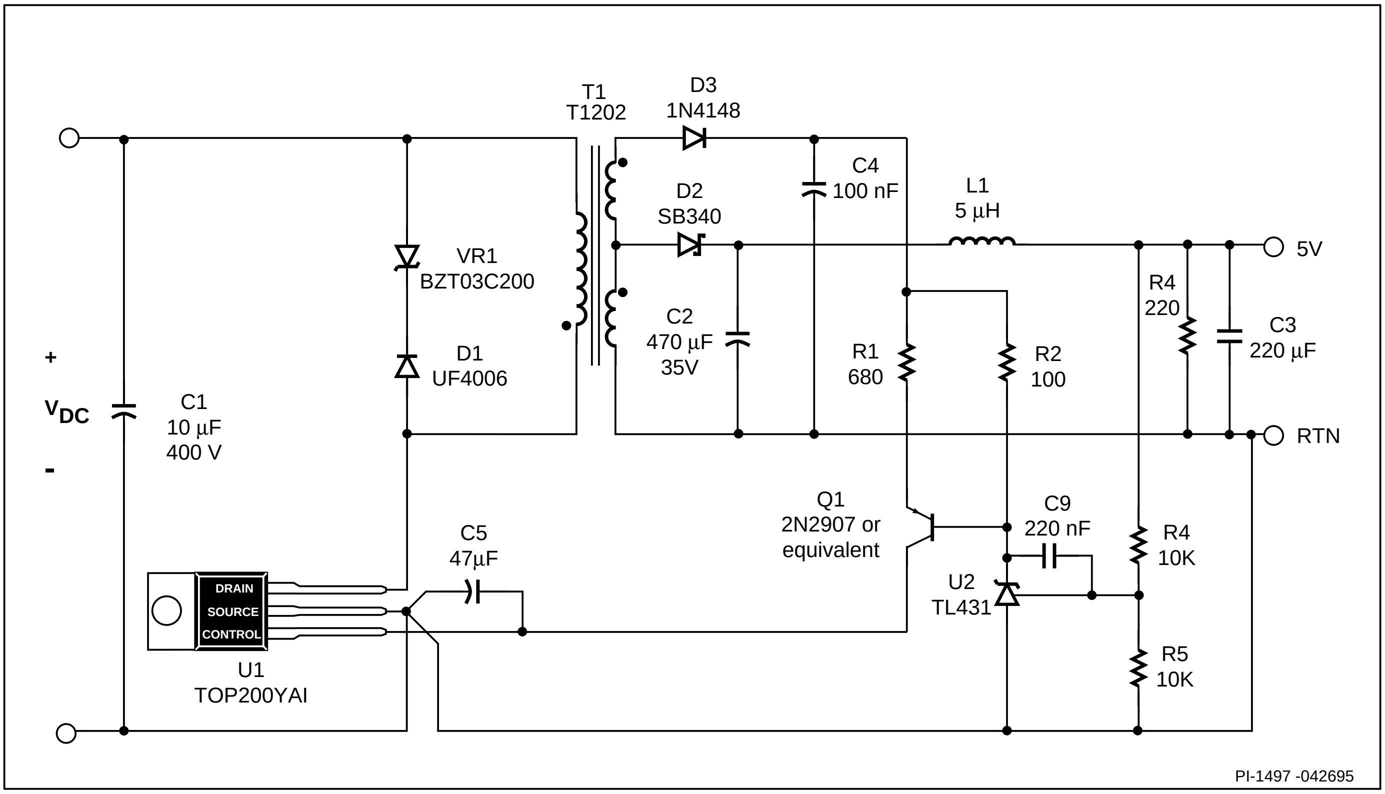

Figure 9. Non-Isolated 5 V Bias Supply with Improved Efficiency.

Transformer Design

Figures 10(a)-10(e) show five transformer designs used in the example circuits.

Each transformer is designed for approximately 0.79 Volts per turn on the output. Other output voltages are possible by using the following equation with number of turns N, output voltage V_{OUT}, and diode forward voltage drop V_D. For example: 12 Volt output with a diode forward voltage drop (V_D) of 0.7 Volts requires 16 secondary turns:

$$N = \frac{V_{OUT} + V_D}{0.79} = \frac{12 + 0.7}{0.79} \cong 16 \qquad (3)$$

The primaries and secondaries are interchangeable. For example, the transformer of Figure 10(e) can be converted from 230 VAC to 110 VAC input by simply using the primary from Figure 10(c).

Additional voltages can be created with windings scaled as shown where V_1 is the main output voltage with diode forward voltage drop V_{D1} and number of turns N_1. V_2 is the additional voltage with diode voltage V_{D2} and number of turns N_2.

$$N_2 = N_1 \times \frac{V_2 + V_{D2}}{V_1 + V_{D1}} \qquad (4)$$

For example: in the circuit of Fig 5, the input voltage for linear regulator U2 should be approximately 7.5 V. N_2 and N_1 are the number of turns of the 7.5 (V_2) and 12 (V_1) volt outputs respectively. V_{D2} and V_{D1} are the forward voltages (0.7V) of diodes D2 and D4 respectively.

$$N_2 = 16 \times \frac{7.5 + 0.7}{12 + 0.7} = 10.3 \qquad (5)$$

Increasing N_2 to the next higher integer multiple (11 turns) will increase V_2 slightly and ensures that the 7805 will not drop out of regulation.

Figure 11 shows a cross section of the transformer. The EF20 E core is available from Philips, Siemens, and Thomson. A two layer primary winding is used with three layers of tape (2.2 mils/ 0.9 mm thick) between primary layers to minimize capacitive coupling between the Drain connection and the dc rail end of the primary winding. The drain connection is made to the start of the primary winding so that the half of the winding which has the largest voltage excursion is furthest from the secondary winding. This minimizes the capacitive coupling between the primary and secondary windings. Three layers of tape are applied over the primary winding to reduce primary to secondary capacitance. The secondary is then wound covering approximately half the bobbin width as shown to reduce capacitance coupling to the primary winding. Parallel winding is used for lower output voltages to reduce leakage inductance. Three more layers of tape are added to secure the windings. To meet the specified primary inductance, a core gap length of approximately 11 mils/0.27 mm is created by grinding the center leg. The same gap length is used for both 230 VAC and 110 VAC designs. An alternative approach is to use spacers with thickness equal to half the gap length in each outside leg of the core. The gapped core halves are then secured with adhesives or clamps and the whole assembly varnished or epoxy impregnated.

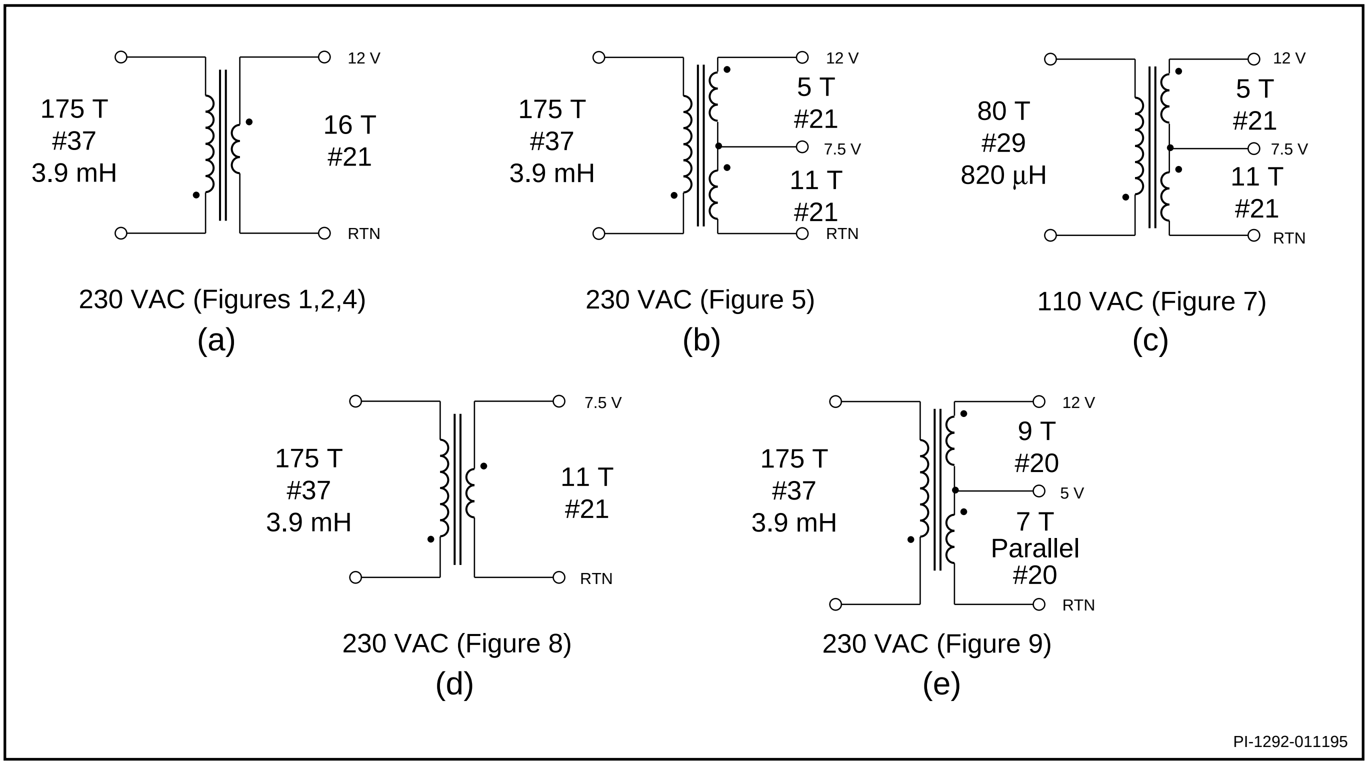

Figure 10. Transformer Schematics.

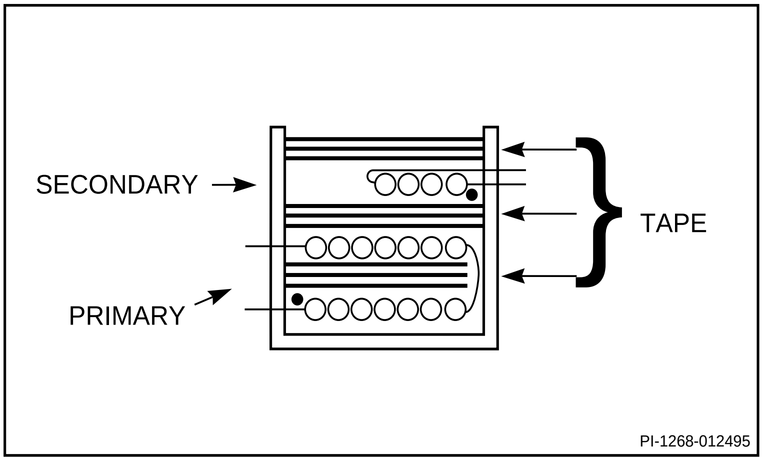

Figure 11. Transformer Construction.

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