Designing Power Supplies Intended For TEMPEST Equipment

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Introduction

Power supply design is the least often considered part of TEMPEST engineering work, and is also most often the cause of schedule delays and other major containment related problems. The effects of feedback control and load isolation on the containment problem are seldom discussed when designing to achieve constant ripple free outputs with changing loads for meeting box or system level requirements. From the power supply industry perspective, commercial designers ask themselves II When was the last time anyone designing a box felt less efficiency was more desirable?"

Why do these factors seem less important? The answer most often given is “We plan to use filtering to prevent the TEMPEST signals from getting out of our box." This single statement has probably caused more budget over-runs and delayed delivery schedules then any other single item in the entire inventory of the TEMPEST industry.

This paper presents a review of power supply design from the perspective of the TEMPEST design engineer. While all power design types are discussed, there are probably as many different methods of achieving the required TEMPEST isolation in a specific application, as there are different designs to meet any specific power generation requirements.

A Hierarchal Approach

TEMPEST power supply design is based on a hierarchal approach that less efficiency and less noise is better. However, the practicality of this approach cannot easily be supported. Commercial supplies are designed on the basis of greatest efficiency with the least number of parts, period. Unless a large number of supplies are to be built, a special supply incorporating all the best suppression and isolation techniques is impractical. The best a designer can usually do is look at the, general layout of the pc board should also be considered.

In a great many cases, when the TEMPEST engineer is faced with redesigning an existing box that already contains a power supply, a few simple changes to the supply will greatly enhance its isolation characteristics. To automatically choose the approach of adding filters to the AC input lines is the worst (and often most expensive) approach a TEMPEST designer can take.

To summarize the hierarchal approach, look at the efficiency first, the design type second, the cost third, the output characteristics last. All these must be considered in terms of circuit load requirements, and ease of incorporating additional isolation into the design.
Power supply Classifications

When power supplies are classified by the technique they use for voltage regulation, they form the family tree shown in Figure 1. The major division between supply types is linear or switcher, with ferro-regulated supplies best described as unswitchers. Most switcher variations are in switcher resonant- mode-converter or pulse-width-modulated types, while linears are either series, shunt, or a combination of both. Most commercial linear regulators are series pass transistor with controlled feedback base current. Shunt type supplies are virtually unavailable commercially, even though they offer the best isolation from a TEMPEST applications viewpoint. Resonant-mode converter circuits vary switching frequency, while pulse-width- modulated (PWM) circuits change the pulse width while keeping the switching frequency constant.

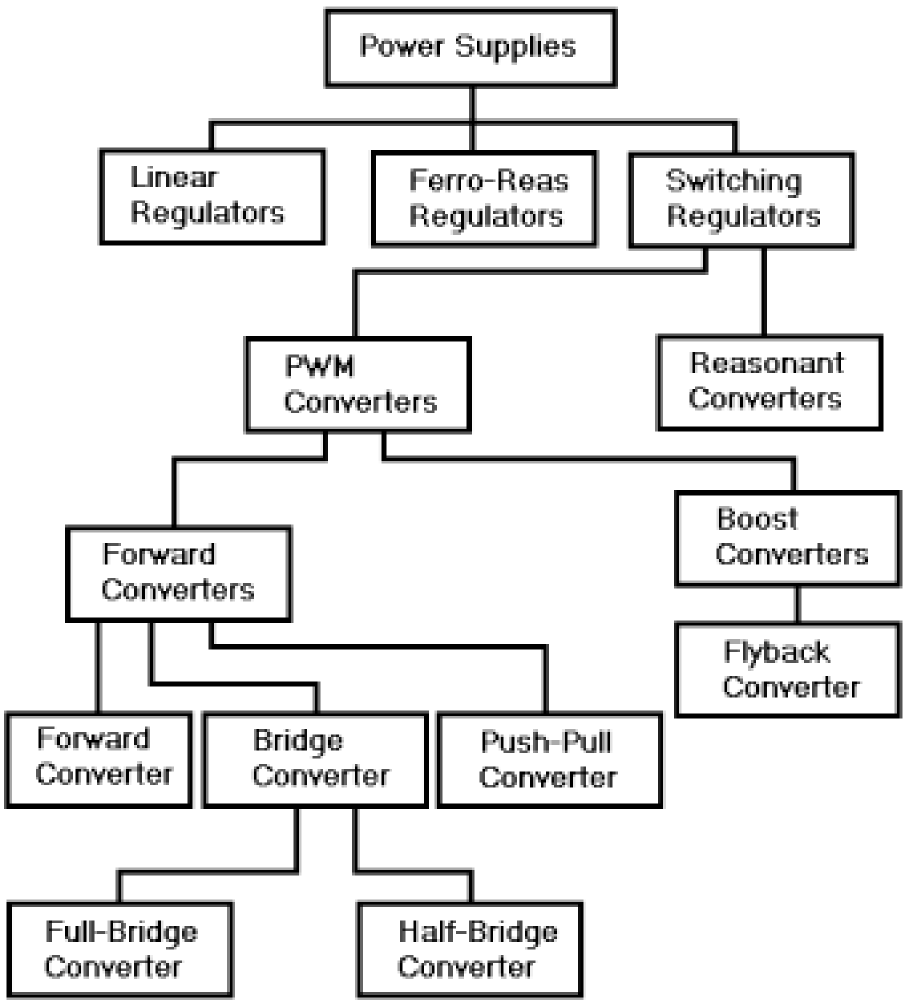

Figure 1 - Power Supply Family Tree

PWM supplies are subdivided into buck or boost type regulator circuits. These types are generally chosen based on power requirements. Boost type regulators are normally used for lower power (20 to 100 watts) applications while buck type forward converters are used for medium power (100 to 400 watts) applications. High power requirements demand half or full bridge type converters.

Efficiency also relates directly to supply type. Obviously, a supply with a dissipative series pass element is less efficient then a supply relying on transistors that simply turn on and off. The penalty you pay for higher efficiency is increased regulation and less noise generation. Linear series regulated supplies provide efficiency levels as low as 30% depending on the output voltage. Shunt regulators offer 20% efficiencies, while switchers provide as high as 85% efficiencies at voltage levels above 40 volts. At low voltage levels, the efficiency of switchers drops to around 70%. Ferro-resonant supplies achieve 70% efficiencies and have few parts, but are sensitive to powerline frequency changes, plus they are exceedingly heavy.

Common Inputs

Regardless of regulator type, the vast majority of power supplies use an input filter and decoupling capacitors to protect the supply from external noise, and to reduce internally generated noise for FCC certification. Linear supplies are "in-line" devices and require a step down transformer to reduce the voltage drop that would otherwise be required across the linear transistor for the supply to meet its output needs. The step down transformer is followed by a rectifier (full or half wave) for dc conversion. The design for a typical power supply input is shown in Figure 2.

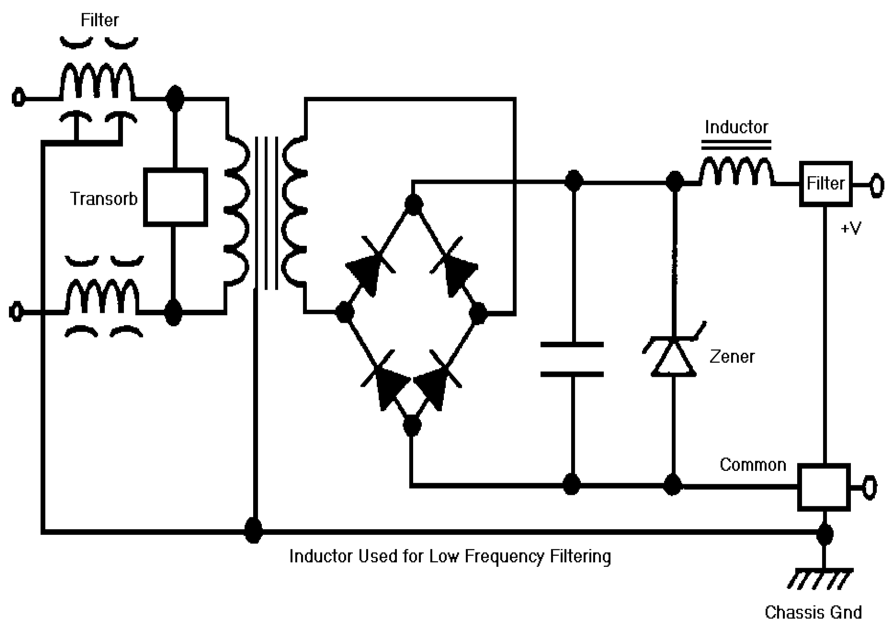

Figure 2 - Typical Input Design of an AC/DC Supply

Switchers are considered "off-line" devices, and can be used in either dc to dc converters or can be used to directly rectify and filter the ac line voltage without using a heavy 50-60 Hz transformer. Since transformers are expensive, and since switchers achieve good input noise isolation and get higher efficiency levels from higher voltages, a common commercial practice is to provide ac directly to the switching devices, then use a small high frequency transformer before rectifying. From the rectifier, a capacitor is then used as a filtering device for the small high frequency ripple. This capacitor is much smaller then the traditional 60 Hz high voltage power supply variety.

From the TEMPEST perspective, using capacitor regulated rectifier voltage directly provides the least isolation between output and input since you must have a discontinuous secondary current flow (high peak-to-average ratio of forward diode current). Current is drawn in short, high amplitude pulses to replace the charge of the filter capacitor which discharges to the load during diode off times. It should also be obvious that since the capacity available from the small capacitor provides much less isolation in the reverse direction then would a much larger capacitor connected directly across the powerline at the ac to dc rectifier.

Another common powerline input is to use an adjustable diode setting at the bridge circuit to set the supply for 110 VAC or 220 VAC. As shown in Figure 3, this condition presents an interesting situation for TEMPEST powerline conducted tests. Since only the diode's reference configuration effects operation at 110 VAC or 220 VAC, one TEMPEST conducted test on the high side at one power level, and one test on the neutral side of the supply input line should be sufficient to TEMPEST accredit the equipment under test.

Series Regulator Design

Series regulators are basically structured with a series transistor that represents variable impedance in the powerline that changes its characteristics with changing load requirements. The physical reason for the 220/230VAC improvement in voltage regulation using a series element is because a large fraction of the increase in input voltage due to load variations appears across the pass element, such that the output voltage tries to remain constant. If the input increases, the output must also increase, but to a much smaller extent, since the output increase will directly change the bias on the series transistor towards less current. However, note that in the reverse direction, a change in load current 110/115VAC directly changes the transistor bias, and thus also transferred directly to the transistors input. The condition is shown in Figure 4.

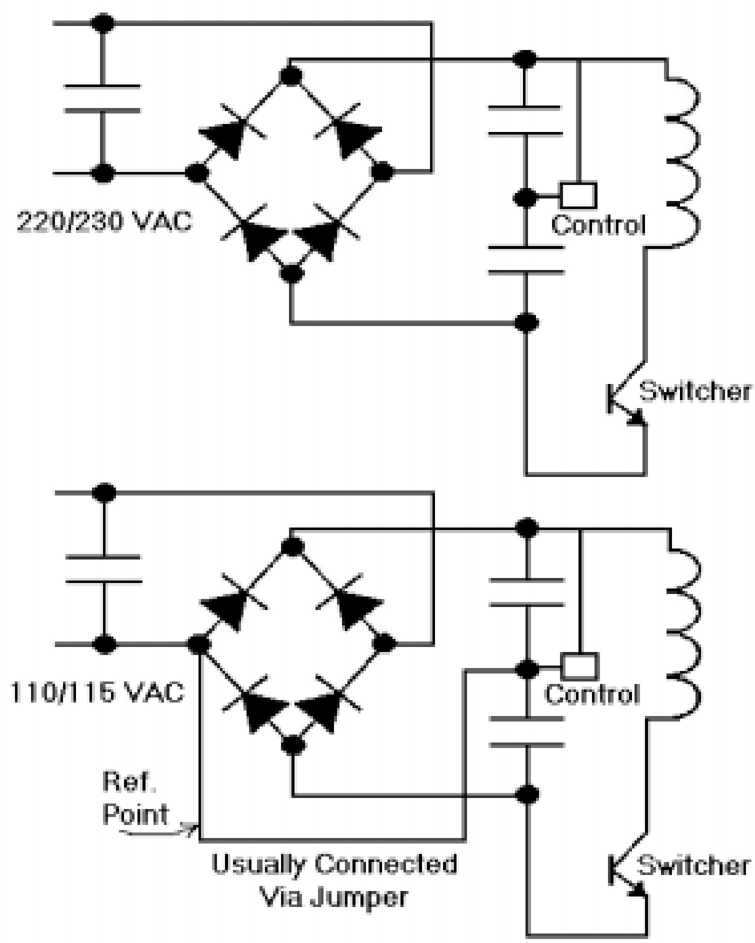

Figure 3 - Jumper Configuration for 110/220 VAC Operation

A second situation exists where series regulation, especially in the form of a three terminal regulator IC, is desirable. This condition occurs when there is the possibility of amplitude modulation of higher frequency signals that can appear on digital black outputs. Again, since the forward isolation is high for the regulator, the device works effectively as an output wave shaper. However, the output must be able to accommodate the resultant voltage loss due to the diode drop inside the regulator.

Shunt Regulator Design

Modern circuit design books seldom address even superficially the subject of shunt regulation. This is due to its extremely poor efficiency, heats generation, and the fact that regulators of this type are not commercially manufactured. Therefore, why would anyone even be interested in such a device?

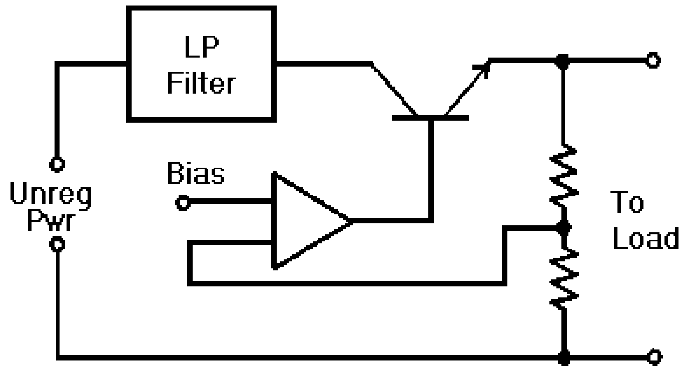

Figure 4 - Typical Series Regulator

Shunt R regulation involves sinking or using current at a constant level despite load requirements. Since voltage levels from a current source will vary without some type of voltage regulation incorporated, shunt regulation for greatly varying loads also requires some form of series regulation. A typical shunt regulator is shown in Figure 5, and a series shunt regulator is shown in Figure 6.

Considering the series-shunt regulator of Figure 6, certain factors must be accounted for when building the supply for its isolation characteristics to remain effective. These factors are listed below.

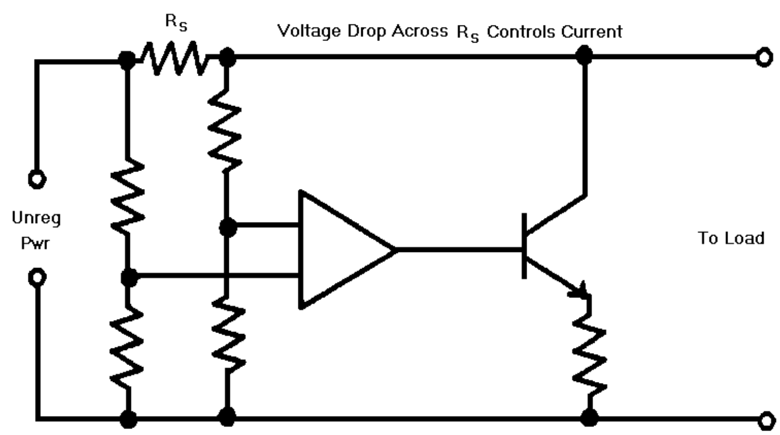

Figure 5 - Typical Shunt Regulator

1. When laying out the board, insure that IC2 and the ICl/IC3 set are physically isolated.
2. For a two-sided board, do not run traces in parallel on directly opposite sides.
3. Make sure that the 12 volt input and the regulated output are physically separated.
4. Cover all unused board space with a ground shield.
5. Use a split ground plane for the input and the output connected only at the interface connector.
6. Make sure that the IC pins are oriented for minimum distance to their opposite connection with no trace cross-overs.

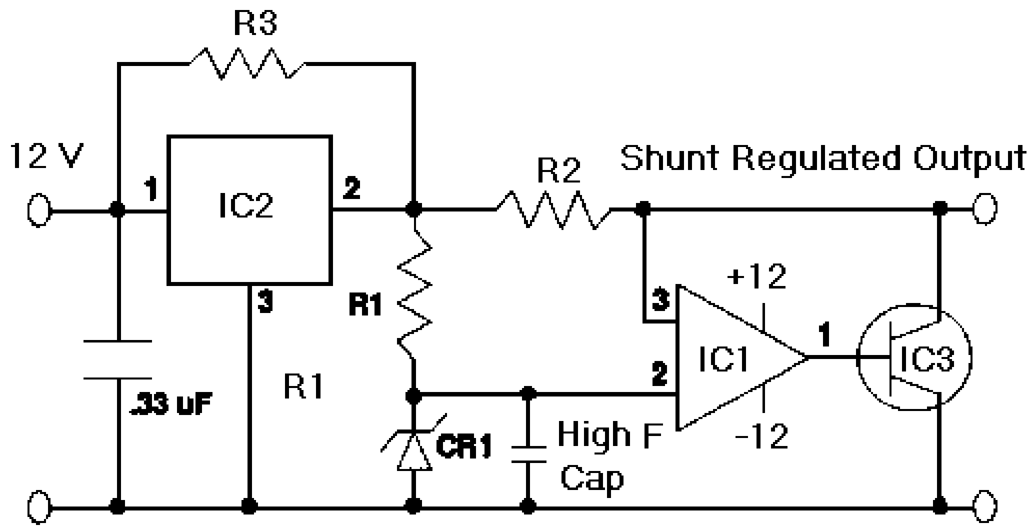

Figure 6 - Series-Shunt Regulator Design

Ferro-Resonant (Requlated) Power Supplies

Unswitchers, as they are sometimes called, are an inexpensive means of achieving high efficiency and good (0.4% load and 0.2% line) regulation. A typical ferro-resonant transformer design is shown in Figure 7. High efficiency supplies, such as shown in Figure 8, apply basic ferro-resonant techniques, and then add a simple feedback circuit that essentially tunes the transformer core in a way so as to prevent large core saturation losses. Ferro-resonance here refers to the hysteresis or elastic after effects resulting from the interaction of magnetic fields with iron based transformer material. It is possible to select material which almost, but not quite, saturates when eiposed to a specified power level at 60 Hz ac. Tuning the transformer core allows the saturation point to be adjusted based on variable loads. Most unswitchers use two separate secondary windings, one with the capacitor, rather then the tapped approach shown here.

The design shown is similar to a saturated magnetic regulator, but wi thout attendant core losses. It provides inherent spike suppression on the output, and total control over output voltage and current, without the need for a series regulator. The one massive drawback to the supply is weight, since physically enough core material is needed to achieve the non-saturation level for the power output required.

Ferro-resonant transformers use two secondary windings, flui density to the saturation level. Once saturation occurs, output voltage will be virtually constant despite large line surges on the input. From the TEMPEST perspective, large short duration load surges suffer the same fate from output to input since energy is virtually drawn from core flui rather then directly from the input power.

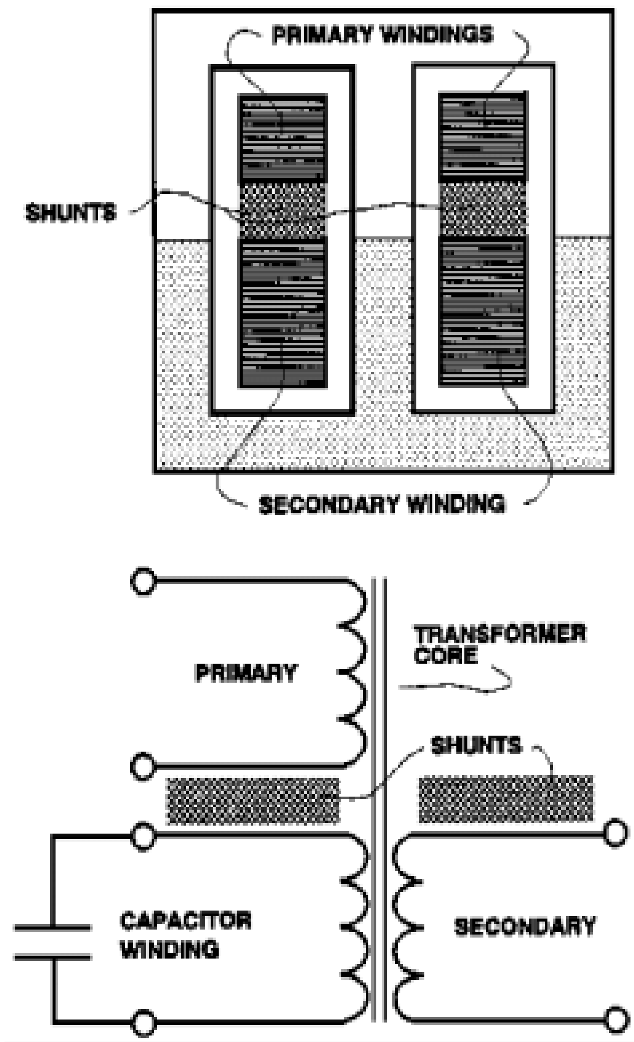

Figure 7 - Ferro-Resonant Transformer Design

Results of attenuation measurements made on a ferro- resonant supply at Rockwell Collins (1) show values of 72 dB attenuation at 10 KHz, 90 dB at 100 KHz, and a break point where attenuation begins to drop below 90 dB at approximately 2 MHz. As in the case with shunt circuits, high frequency problems can be controlled with filters on dc output lines that can handle the signals at the frequencies where the supply starts to break down.

Switching Regulator Design

Switchers were developed as a means of increasing efficiency and power density. While linear regulation is not only quieter, cheaper, and better for precision regulation, switchers often use linear regulation on their outputs to improve their regulation characteristics. A number of different configurations are possible, each with advantages and disadvantages for TEMPEST isolation. Before discussing each regulator type, general switching techniques will be reviewed.

A typical flyback n converter is shown in Figure 9. Flyback regulators are considered boost (voltage step-up) circuits because when the switch is closed, current flows through the inductor and switch, causing energy to be stored in the inductor's flux prior to load delivery. When the switch opens, the inductor discharges, delivering a current pulse to the load. The longer the on- time compared to the off-time, the more energy storage and transfer.

Using pulse-width modulation, the length of time the switching transistor remains on is easily controlled by directly comparing input to output voltages. Good high efficiency flyback regulators use low loss transistors (sometimes MOSFETS), low loss diodes, and low loss transformers. Ideally, the circuit itself is lossless since at any one time the switching element is controlling either zero current or zero voltage.

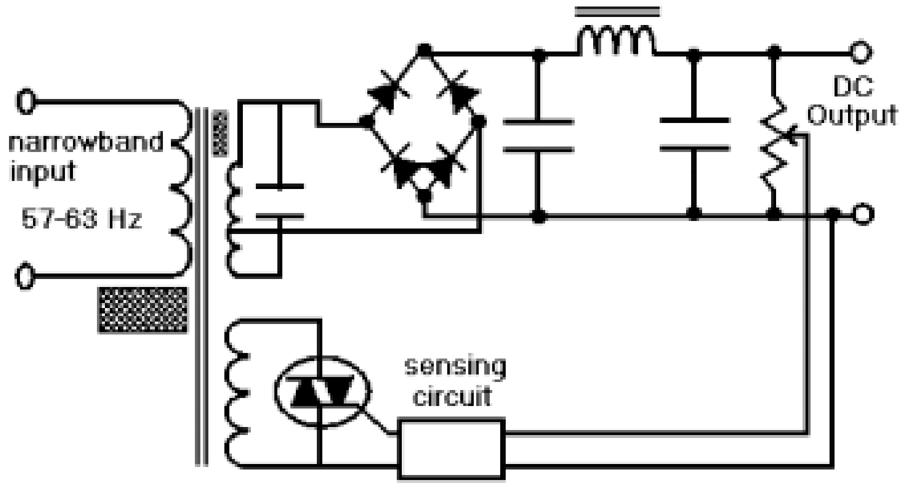

Figure 8 - Ferro-Resonant Power Supply

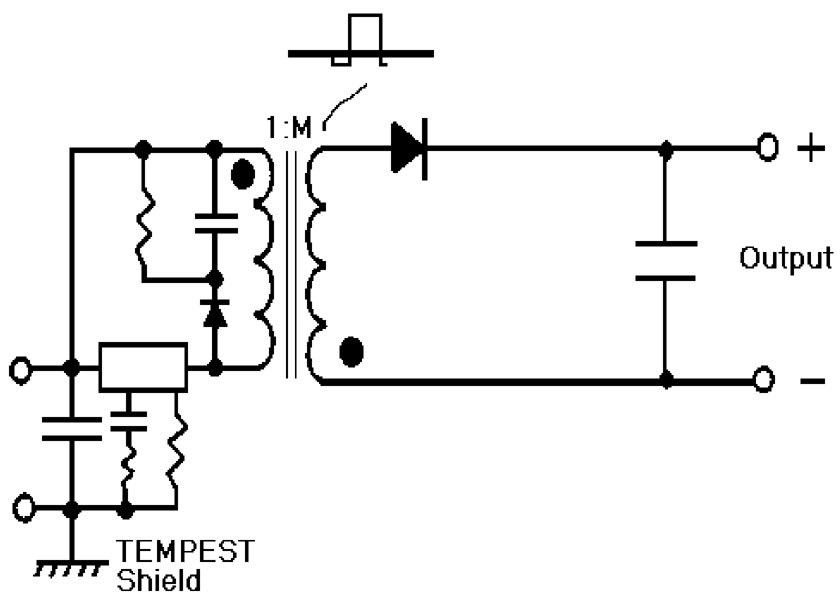

Figure 9 - Typical Flyback Regulator

A TEMPEST application for a low power isolated flyback type regulator is shown in. Figure 10. Notice both the ground isolation and the TEMPEST shield. The shield is normally the RED/BLACK interface.

Buck Converters

A typical buck converter is shown in Figure 11. This type of converter acts as a step-down regulator because the output voltage is always less then the input voltage. When the switching transistor is closed, energy flows through the inductor directly to the load. When the switch opens, energy stored in the inductor flui maintains the load current requirements. The load sees a constant current source, while the line source sees fluxuations in load current directly.

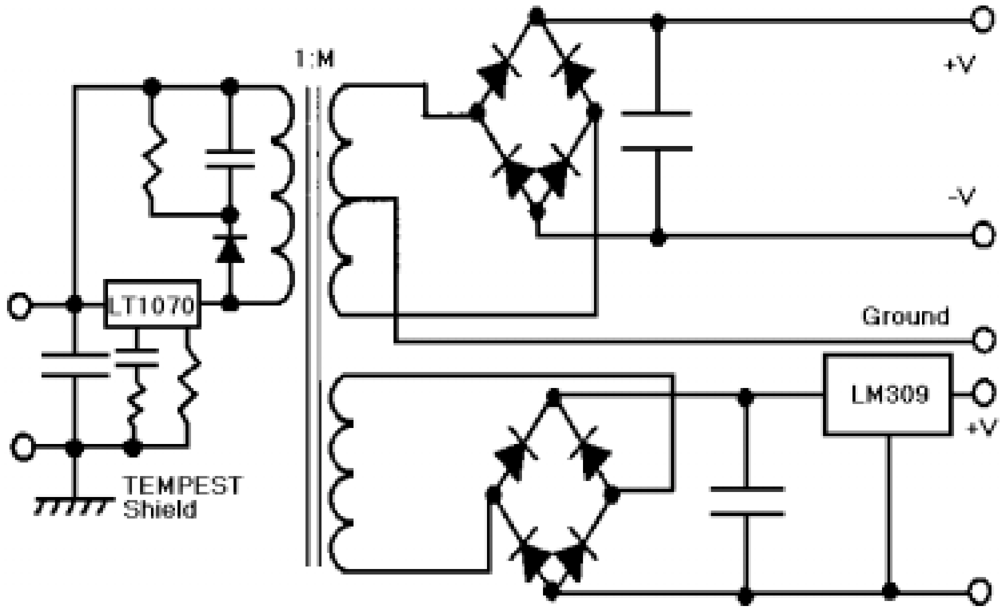

Figure 10 - Isolated TEMPEST Controlled Flyback Regulator

Buck type regulators include forward converters, push/pull converters, half bridge converters, and full bridge converters. The sections below briefly describe each of these devices, including their relevant TEMPEST characteristics.

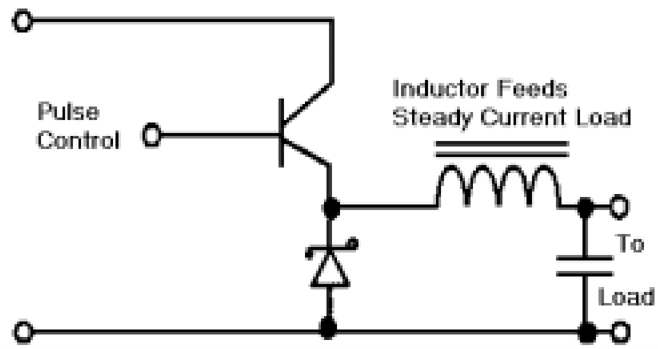

Figure 11 - Buck Type Circuit

Forward converter

A forward converter is shown in Figure 12. Although it looks like a flyback regulator, the forward converter stores energy in the output rather then in its transformer. Noticing the direction of the transformer windings, when the transistor switch is on, output voltage is generated in the secondary and flows through the diode to the inductor and load. The longer (the switch stays on, the higher the average output voltage. When the switch turns off, current continues to flow through the diode since current cannot change direct1on instantaneously. Thus, at higher switching frequencies, ripple reduction improves over what occurs with a flyback dev1ce.

When feedback control is necessary for this regulator type, it is generally optically coupled as shown in Figure 13. Optical coupling to control a power supply required that enough collector

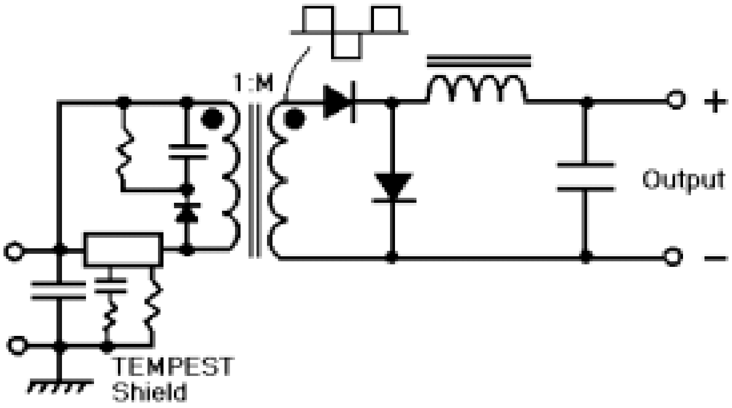

Figure 12 - Forward Converter

current be supplied to insure complete series regulator cutoff as shown in Figure 14. This means there is a possibility that a significant noise source may be located within the isolated power system. Therefore, to avoid the problem, buffer amps are used to increase to opto-isolator sourced current to the pass transistor.

Opto-isolators have a frequency response to 500 KHz, and provide 80 to 90 dB reverse isolation. They also have low coupling capacitance for increased common mode rejection. There normal application is as a digital interface between peripherals to eliminate ground loops, noise spikes, and other common impedance problems.

The primary area requiring increased isolation for the supply design is the transformer secondary. Although only practical using high voltage, low value capacitors, the high frequency isolation characteristics of the secondary can be improved by adding a high frequency capacitor to both sides of the inductor. The frequency response of the pi-filter can be calculated only when the high frequency response of the inductor are known, since the inductance for power components changes considerably as frequency increases.

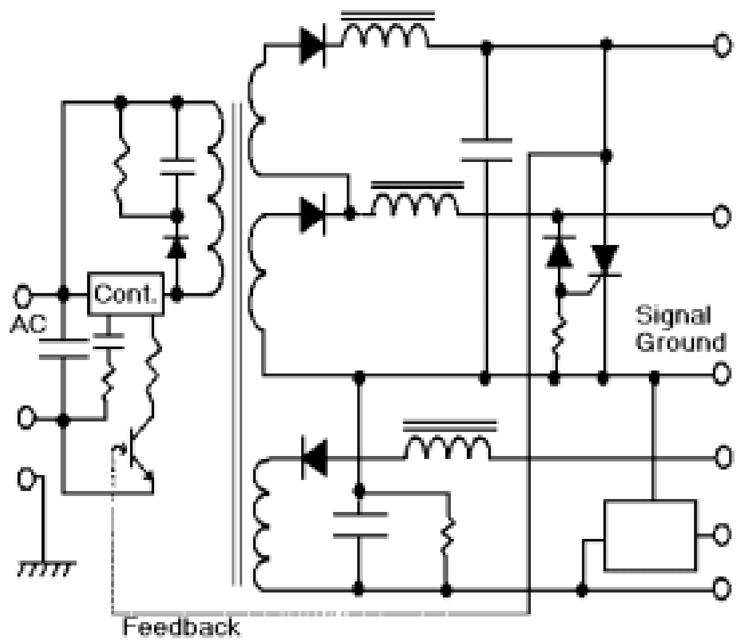

Figure 13 - Opto-Isolated Feedback Circuit

Finally, as with most other regulators of this type, the main TEMPEST isolation must be provided both common mode and differentially by Control separate filters, one in the high side, and one in the return side of the power output in a Balun configuration. Since Balun's are not always available, the usual approach is to use commercial off-the-shelf dc powerline filters. In this situation, care must be taken that a signal return path through chassis is not provided due to filter mounting. The best

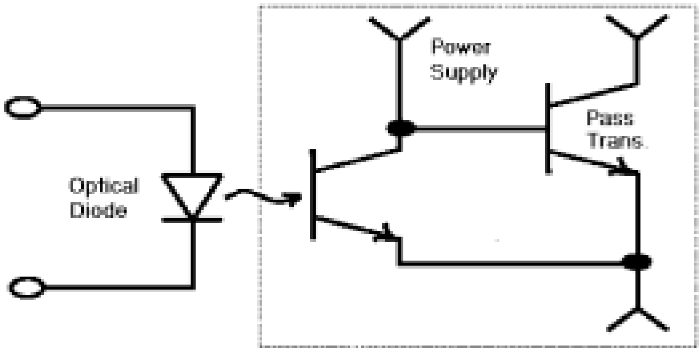

Figure 14 - Optical-Isolated Feedback Control

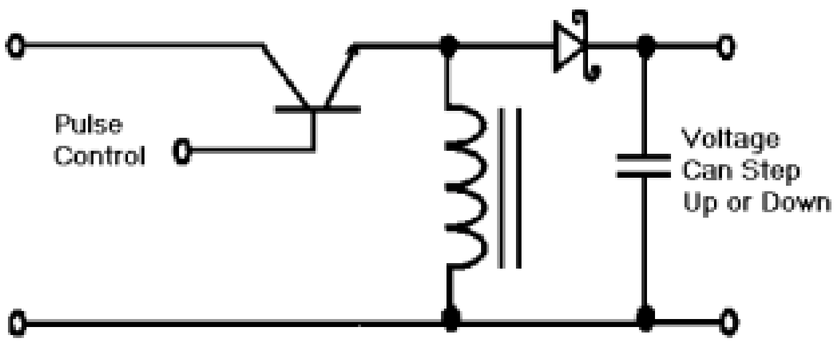

Figure 15 - Buck-Boost Circuit Design

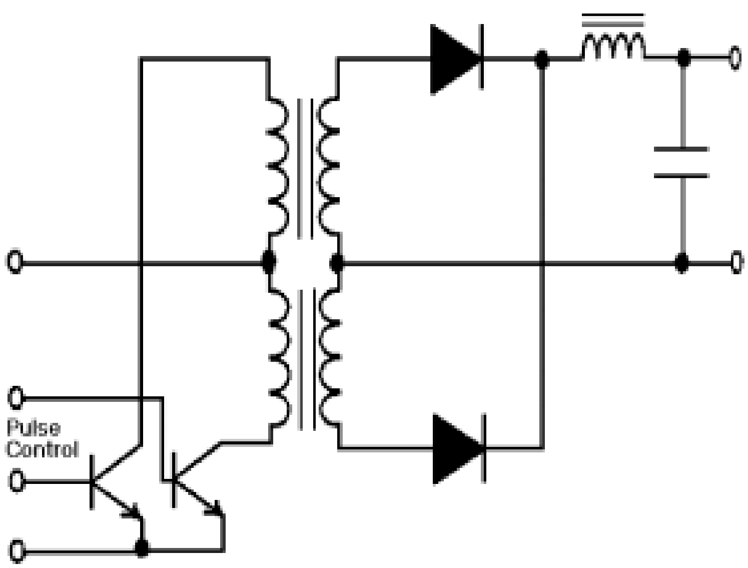

Figure 16 - Push/Pull Converter Circuit

approach is to mount the filters (pi preferably) directly to the center point ground on the chassis.

Inverter

An inverter, also called a buck-boost converter, is a combination of buck and boost technologies in that the circuit can step the voltage either up or down. When the transistor switches, the inductor in Figure 15 charges, but does not deliver current to the load due to reverse biasing on the diode. When the transistor turns off, the diode becomes forward biased, and energy is transferred from the inductor to the load.

Push-Pull Converter

Probably the most common forward converter type used, this configuration is shown in Figure 16. Operation and TEMPEST protection is virtually the same as the forward converter description, with energy storage in the output inductor while the switch is on. Since the two switches turn on at opposite times in this configuration, more efficient regulation, and less stress on the switch, is achievable with this approach at the expense of more noise.

The approach works since ringing is generated in the transformer primary with each switch changing the direction of the inductor fields in 1/2 the transformer inductor more often then in the single forward converter approach. Also, delay between turn on and turn off of each transistor must be carefully controlled in this configuration to insure excessive noise isn't created with both switch devices on at the same time.

System Design and Re-Regulation

Figure 17 shows a typical common input to an isolated RED and Black power system from an AC source. Notice that the input filters are primarily EMI related filters, while the supplies DC outputs are more severely TEMPEST filtered. Low frequency cut-off DC TEMPEST filters are considerably smaller and easier to apply then larger AC type filters. In this case, the TEMPEST filters are installed to actually cross the TEMPEST barrier.

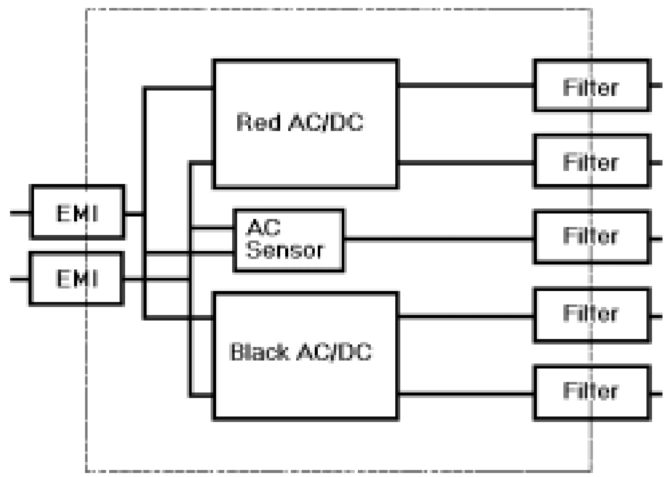

Figure 17 - Isolated RED/BLACK Power Input

Figure 18 shows RED power re-regulated from a common BLACK power system. Severe isolation from BLACK to RED is easy compared to the much more difficult problem of reverse isolation from RED to Black. In this case the RED regulator would provide the severe isolation.

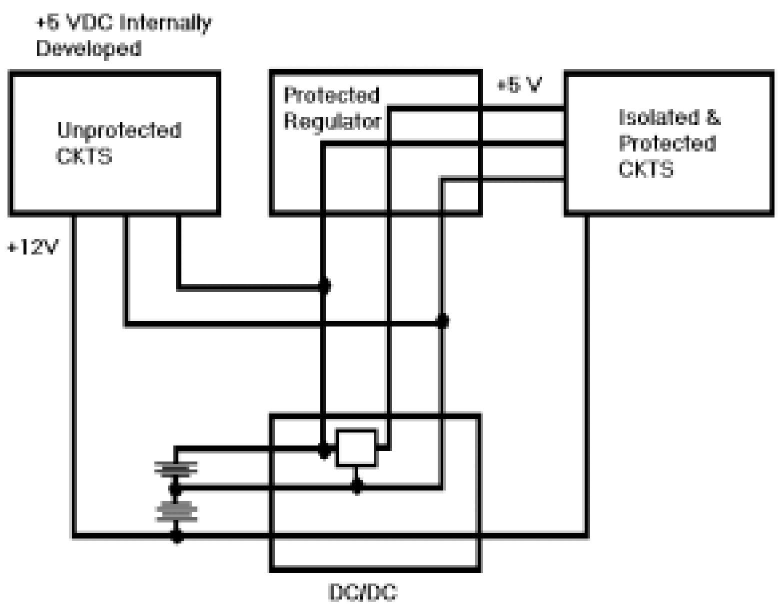

Figure 18 - +12 VDC Re-Regulated DC Power System

Generic Protection Techniques

A few other techniques are available to enhance TEMPEST protection in power systems that are generic in nature, since they are applicable regardless of the design used. Underlying all approaches however is the certainty that if power to the TEMPEST signal can be isolated at its source, the processing device itself, then additional measures located at the supply will not be necessary.

One technique which virtually eliminates transformer or inductor H-field radiated signals is the use of a torroid wound inductor. As shown in Figure 19, the air surrounding an air core inductor is part of the magnetic-flux path. Thus, it tends to radiate rf signals on the inductor windings.

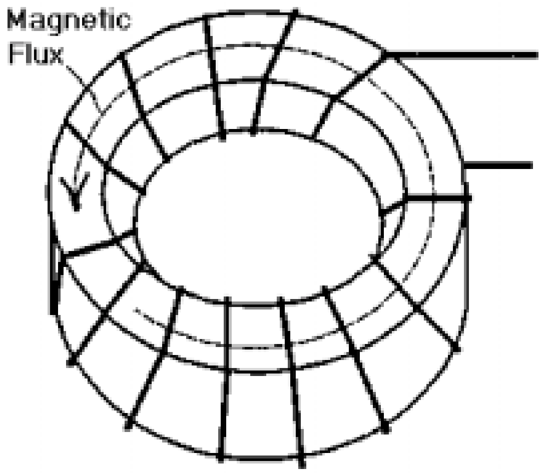

Figure 19 - Field Containment of Torroid Core

The magnetic-flux fields in the torroidal inductor are completely self contained BLACKCKTS within the inductor core material and do not radiate into space. However, an additional not so helpful byproduct of this approach is that, since there is less ac resistance in the device then in an air core inductor, there is a dramatic increase in the coil Q. Less windings are required for the same inductance at the frequency of interest in the supply design, but by the same token there is less inductance over the entire frequency range of interest to the TEMPEST engineer.

A second technique extremely useful when increased isolation is required on low power supply lines is the current limiter shown in Figure 20. Since the switching logic circuits require instantaneous current surges, using the limiter in conjunction with capacitance on selected power lines will force energy to be drawn from the capacitors rather then the line supply.

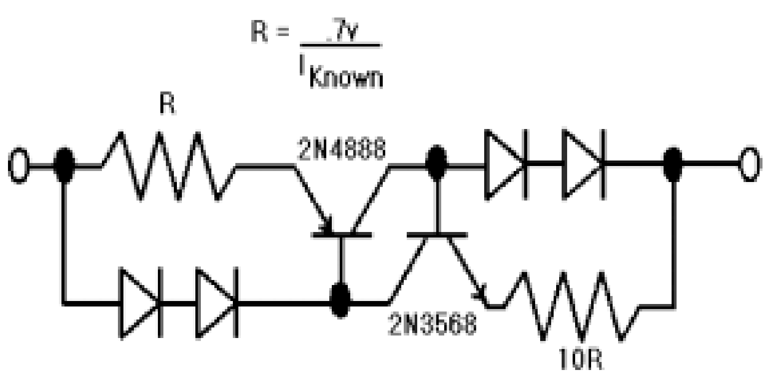

Figure 21 - Current Limiter

A third mechanical technique that reduces switching transistor noise is shown in Figure 21. Basically, a low impedance path through ground or the negat1ve supply line and back to the noise source R is provided via capacitance to the shield wire.

In addition to direct design approaches, time saving automated design and analysis tools such as SPICE will greatly enhance attenuation evaluation efforts. SPICE allows the power supply equivalent circuit to be modeled as a lattice network. Using lattice analysis techniques, the filter response of the network can be predicted - from output to input using the expected digital waveform as the stimulation source. Design changes can then be evaluated against both the expected outputs and the TEMPEST limit attenuation requ1rements virtually instantaneously.

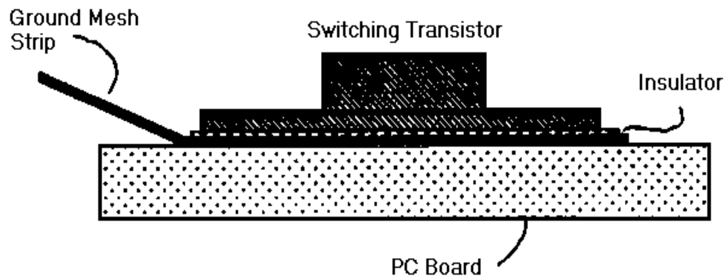

Figure 21 - Switching Transistor Noise Suppression

General TEMPEST Suppression Steps and Design Guidelines

1. Before buying filters and spending the time necessary to suppress noise from a switcher circuit, analyze the supply configuration in terms of a SPICE approach. Don't over filter if you don't need it.
2. Always design the supply for the lowest noise generation possible, even if the costs are a little higher.
3. Shunt regulation is preferred over series regulation since series regulation only isolates in one direction. Use a shunt or series shunt when lower frequency TEMPEST signals are present.
4. Concentrate on applying filtering on the dc output lines, not the ac input lines, and use Baluns if available.
5. Isolated battery power is preferred, but if DC power is supplied, it must be DC to DC converted.
6. Transformer coupling provides DC isolation between input and output power, but only isolation transformers isolate high frequency common mode coupling.
7. Tansformers, unless they are torroid wound, must be shielded for maximum isolation. Use a torroid wound inductor only when additional isolation has been provided at the TEMPEST envelope interface.
8. Separate transformer secondary power and power supplied to sensitive circuitry.
9. Isolated re-regulation is required from BLACK to RED. However, only standard forward regulation is required from RED to BLACK.
10. The easiest method of lowering the possibility of a high frequency PWM switcher indicating data transfers is to reduce the switchers efficiency.
11. Power supply circuits should be multipoint grounded to minimize the generation of ground noise and carriers.
12. Higher frequency switchers are easier to filter or otherwise noise suppress and are preferred over low frequency switchers.
13. Insure harmonics of the switcher,- and their cross modulation products, do not fall within the protected RF circuit bandwidths.
14. Reduce switching transistor noise problems by:
    a. Reduce collector to heat sink capacitance.

  b. Slow down turn on, prevent high frequency oscillation and reduce transformer saturation by adding delay capacitance to the transistors base.

15. Optically isolate when feedback loops are necessary.

Conclusions

This article describes the TEMPEST isolation techniques and operational characteristics of the most common power supply regulation circuits. If TEMPEST isolation is the objective, and you are working with an existing design, it is important to remember that efficiency and low cost, not isolation were the prime drivers for the original designer. Therefore, not only does a TEMPEST designer need to increase regulator circuit attenuation characteristics, but heat generation and component stress due to decreased efficiency will also me major areas of concern in the new design developed. Adequate TEMPEST isolation can usually be achieved without the addition of large, expensive ac filters. All that is needed is a little luck and a good feel for how power systems work.

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