PROGRAM RUN

DIELECTRIC CONSTANT = 2.7
DIELECTRIC THICKNESS(INCHES)=0.0625
TRACK THICKNESS(INCHES)=0.0015

Z (OHMS)	TRACK WIDTH (INCHES)
42.9	0.170
44.2	0.165
45.5	0.160
46.8	0.155
48.2	0.150
49.7	0.145
51.1	0.140
52.7	0.135
54.3	0.130
55.9	0.125
57.7	0.120
59.5	0.115

END OF WIDTH RANGE FOR Z SPECIFIED IN PROGRAM LN 230,240.

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This article was written for ITEM by Edward E. Wetherhold, Signal Analysis Center, Honeywell Inc., Annapolis, MD.

FILTERING FOR SWITCHING POWER SUPPLIES

General

In order to supply electronic equipment with energy from the line supply, components are needed which transform the AC current into various DC voltages. In most cases when transforming and rectifying a voltage, stabilization and a galvanic separation is required.

Conventional equipment fulfills this task with a power line transformer, a rectifier and a regulated adjustable element. The transformer converts the voltage and separates galvanically the secondary voltage from the line. The rectifier delivers a DC voltage, which is stabilized by the adjustable element (generally a series transistor) independently from the load conditions.

Using this principle, neither the volume nor the weight can be reduced in the manner required with modern construction techniques for miniaturization of equipment. Particular disadvantages are the large and heavy line transformer and the lossy voltage stabilizer. The high losses produce heat which again must be conducted away via large heat sinks or blowers.

These disadvantages can be removed by increasing the operating frequency and substituting the series transistor with a regulated switch. The principle of switching power supplies is based on these two measures.

Switching power supplies have a higher efficiency, lower weight, and lower volume than conventional line components. These advantages are based mainly on the fact that switched operations of the adjustable element lead to lower losses and smaller heat sink volume and weight, and a higher operating frequency enables the transformer and the secondary side filter elements to be easily miniaturized.

These great advantages have to be seen in the light of a disadvantage which cannot be ignored. In order to obtain a high efficiency, the operating frequency must be high and the switching time of the adjustable element must be chosen as short as possible. Due to the high frequency, a wide interference spectrum is produced in the frequency domain with high amplitude values, which is caused by the fast switching flank of the adjustable element. To better understand the interference voltages produced, we will investigate the causes of this phenomenon more closely.

Cause of the Interference Voltage

In a line switching regulator, the rectified line voltage is converted into a rectangular square wave with a pair of transistors (half bridge forward converter) or two pairs of transistors (full bridge forward converter). The transistors are driven so that positive and negative voltages are alternately applied across the primary winding of the transformer. Due to the transistor switch, this voltage change cannot suddenly occur, but is time-delayed by the rise time ($T_f \sim 500$ns)of fall time ($T_r \sim 1000$ns). As a consequence, a trapezoidal wave is applied to the transformer.

Due to the periodical amplitude changes in the time domain, discrete frequencies are produced in the frequency domain. This occurrence can be deduced with the help of the Fourier analysis. To simplify, we assume identical rise and fall times ($T_r = T_g = T$). We thereby obtain the symmetrical triangular wave and can write the Fourier coefficients:

$$C_n = \frac{V}{2}\left[\frac{1}{n^2 f \cdot \pi^2 \tau} \cdot \sin\left(n \cdot \frac{\pi}{2}\right) \cdot \sin\left(n \cdot \pi \cdot \frac{\tau}{T}\right) - \frac{\sin(n\pi)}{n \cdot \pi}\right]$$

for values of $n = 0,1,2,3$ . . . . . .

The Fourier coefficients are a function of the voltage amplitude V, the fundamental frequency f and its harmonics n, as well as rise and fall times τ respectively.

Let us put the following values into this expression for a practical case. Viz for:

$V = 150$ Volt

$f = \frac{1}{T} = 50$ k Hz

$\tau = 500$ ns

$n = 1$ to 1000

If this result is presented in double logarithmic form, then we obtain the following picture:

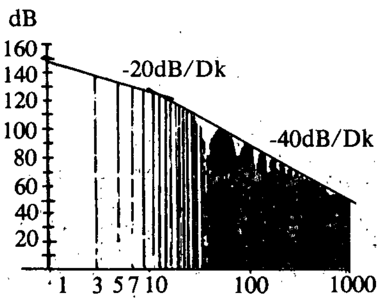


Figure 1. Spectrum of a Symmetrical Triangular Wave ($f_1 = 50$ kHz, $\tau = 500$ ns and $V = 150$ Volt)

Since the calculated triangular wave is a symmetrical signal with reference to the time axis, the DC component is zero (at $n = 0$), and the lines appear in the spectrum only at the odd whole multiples of $n = 1,3,5,7$ etc.

The presentation in Figure 1 is remarkable, in that up to the 13th harmonic, the harmonic amplitudes in the spectrum fall at -20 db/decade and above this at -40 dB/decade. This critical frequency follows the condition

$$n = \frac{1}{\pi \cdot f \cdot \tau}$$

and is dependent on the pulse frequency and the rise time. Using the values from Figure 1, we obtain for $n = 13$, a critical frequency which corresponds to 650 kHz.

In summary, we can establish that, with a switching power supply, the interference voltage observed is produced by the switching sequence. The switched voltage, the switching frequency and the switching time (flank slope of pulse) determine the values in the interference spectrum. These values fall linearly with increasing frequency ($1/n \cdot f \triangleq$ -20 dB/decade) up to a critical frequency, and above this as the square with increasing frequency ($1/n^2 \cdot f \triangleq$ -40 dB/decade).

The shorter the switching time, the steeper the switching flank and the more the critical frequency will be displaced in the spectrum towards higher frequencies. Thus, the amplitude values of the interference voltages will be increased and the interference worsened. On the other hand, the short switching times are a requirement for a high efficiency for the line regulator, since the power losses of the switch increase with greater switching times. The Fourier analysis enables any desired signal to be dissected into a number of pure sinewaves at definite frequencies and amplitudes.

Used on our example (see Figure 2), we can therefore transform the triangular wave into the frequency domain and at 150 kHz and 7.885 Volt amplitude (7.885 $V \triangleq 138$ dB/μV).

Supposition: $f = 150$ kHz
$n = 3$
$\tau = 500$ ns
$V = 150$ Volt

We can therefore assume an equivalent circuit diagram for the switching element for the above supposition in the frequency domain a sinewave voltage source with $f = n \cdot 50$ kHz and a voltage amplitude, which corresponds to the Fourier coefficients. The sum of all these voltage sources is the interference spectrum with the interference voltages. At this point, the question arises as to how the interference voltage gets from the switching element into the line cable and how it can be measured there.

Propagation of the Interference Voltages

In order to explain the phenomenon of the conducted interference voltage propagation, we will look at the switching stage of a switching regulator, as shown in Figure 2.

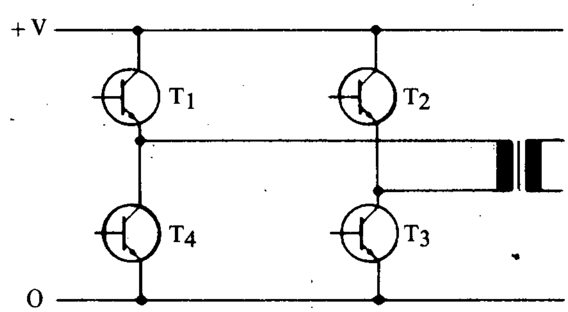


Figure 2. Switching Stage of a Switching Regulator

It must be noted that the collectors of the transistors T_1 and T_2 are always at potential $+V$ and their emitters, depending on the switching position, alternate between the potential 0 and $+V$. On the other hand, the emitters of transistors T_3 and T_4 are always at potential 0 and the collectors oscillate between 0 and $+V$. Transistors in T0-3 cases have the collector connected to the case. For this reason, such transistors must be insulated from the heat sink. As insulating material, ceramic, plastic or mica can be considered (materials whicn on one hand show a good heat conduction, and on the other a good voltage insulation strength with a relatively large E_r). This insulating washer can be regarded as a capacity, whose value is in the main determined by the geometry and the dielectric constant E_r.

$$C = E_0 \cdot E_r \cdot \frac{\text{Area}}{\text{distance}} \text{ (pF)}$$

in which $E_0 = 8.855$ pF/m.

With a T0-3 case the area is approximately 500 mm², as shown in Figure 3.

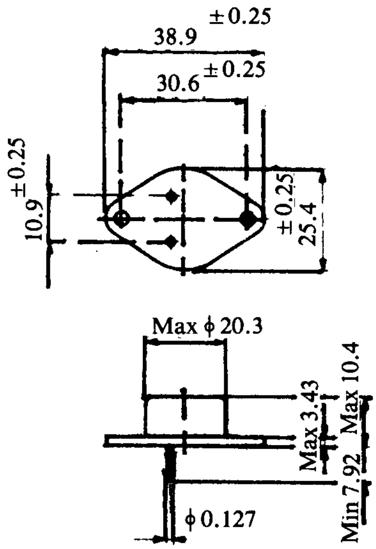


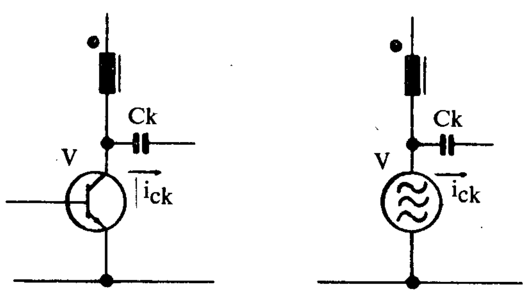
Figure 3. Geometric Dimensions of a Transistor with T0-3 Case

When various insulating materials are used for the washer, then the following values are determined for the capacities:

Insulating washer T0-3	Thickness mm	F/d mm	E_r	C calculated pF	C meas. pF
Mica	0.1	5000	3.5	155	160
Plastic	0.2	2500	4.2	93	96
A 10	2.0	250	9	20	23

Figure 4. Capacity Values of Various Insulating Materials for T0-3 Case

We have established that the collectors of the transistors T_3 and T_4 (see Figure 2) due to the insulated assembly show the following values of capacity above with respect to the heat sink.



Time Domain

for $V = 150$ V
$\tau = 500$ ns
$C_k = 150$ pF
$i_{ck} = 45$ma

Frequency Domain

for $V = 150$ V
$\tau = 500$ ns
$f = 50$ kHz
$n = 3$ (150 kHz)
$C_n = 7{,}885$ V
$C_K = 150$ pF
$i_{ck} = 1.1$ ma

Figure 5. Confrontation

A displacement current flows with each voltage jump when switching occurs with a peak value of 45 ma in the time domain and a sinewave current of 1.1 ma in the frequency domain. The difference between the two domains is that in the frequency domain only a single spectral line is effective, whereas in the time domain the whole spectrum is effective. As we will see later, measuring the interference voltage is an evaluation of the spectrum, thus a characterizing of the frequency domain. For this reason, it seems appropriate that we acquaint ourselves with the occurrences in this domain as follows.

In the example Figure 5, an interference current (i_{ck}) flows through the coupling capacity (C_K) via the heat sink to the case of the equipment. The latter is connected via earth connection to the guard line of the mains line supply, where the interference current can now flow by a conductive path.

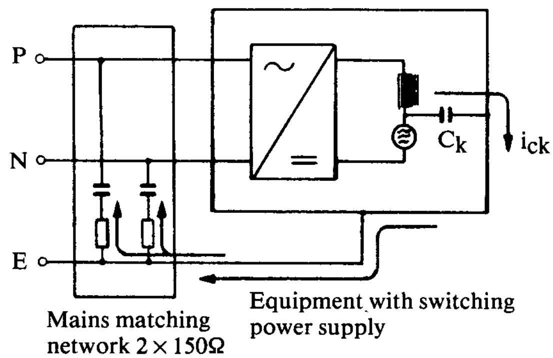


Figure 6. Asymmetrical Interference Current Path

Besides the resistors of the power line matching network, which represent the line impedance, the flow of the interference current (i_{ck}) causes a voltage drop. This is recorded by the measuring instrument and shown as dB/1μV. The recorded interference is designated common mode tension, since it is measured with respect to the earth potential.

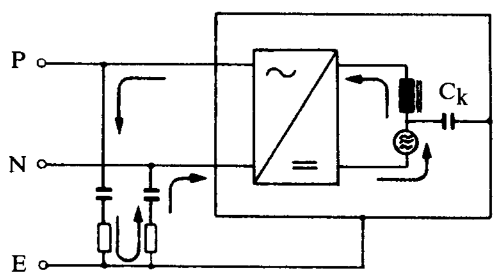


Figure 7. Symmetrical Interference Current Path

The portion of the interference current which wholly circulates in the phase and neutral lines causes a "Differential Mode Tension" in the power line matching network.

Measurement of the Interference Voltages

The HF interference currents which flow through the mains matching network cause a voltage drop across the 150 Ω resistors. This voltage is measured by means of a selective voltmeter in dB/1μV. A selective voltmeter is constructed in much the same way as a conventional radio receiver is constructed. The CISPR bandwidth, the frequency window, has a width of 9 kHz for the range from 150 kHz to 30 MHz. This window can be placed anywhere over the measuring range, in which spectral lines falling in the slot are measured and evaluated. From the CISPR, standards and maximum values have been laid down, which when measured in the manner indicated, may not be exceeded.

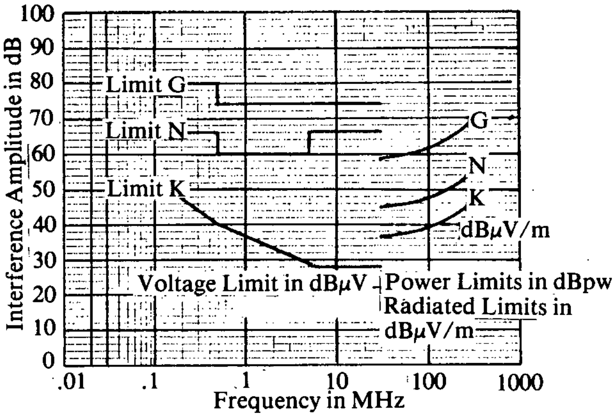


Figure 8. Maximum Permitted Interference Voltage Values (dB/uV)

Since in this measurement, an evaluation of the spectrum is of advantage, the events continue in the frequency domain. According to the example of Figure 5, an interference current of 1.1 ma flows at 150 kHz in the asymmetrical path. This current causes a voltage drop in the mains matching network of

$$U = R \cdot i_{ck} = 75 \cdot 1.1 \text{ ma} = 82.5 \text{ mV} \triangleq 98 \text{ dB.}$$

This is the indicated interference voltage of the measuring receiver. At 150 kHz, however, according to CISPR I-regulation, only 54 dB is allowed (interference limit N-12 dB). With suitable measures we must now attempt to reduce this interference voltage.

Measures to be Taken at the Interference Source

The most effective method for suppression is that which deals with the interference at its source. As we have seen, the source of the interference in a line switching regular are those transistors which have a very fast switching time and whose cases (collectors) oscillate between large potential differences. In the equivalent diagram the interference source is a voltage source, which generates sinewave voltages C_n as harmonics of the fundamental frequency. If we want to deal with this interference source at its origin, then the following measures are available:

$$C_n \cong \frac{V}{2 \cdot n^2 \cdot \pi^2 \cdot f \cdot \tau} \text{ (Volt)}$$

- Reduction of the voltage potential V
  Result: smaller convertible power.
- Increasing the switching time τ
  Result: higher losses and lower efficiency.
- Lowering the switching frequency f
  Result: larger transformer
  worse relationship Watt/Volume

Through such measures, the interference voltage would be reduced at its source, but the specific advantages of a line switching regulator would on the other hand be questionable. Who is surprised that the present development of modern line switching regulators with power MOSFET are going in the completely opposite direction? There are even shorter switching times and higher frequencies. We can, therefore, do nothing at the interference source to reduce the interference voltage. We must accept that even greater interference voltages will be generated in the future.

Reduction of the Coupling Capacity

In the next step, we will try to keep the coupling capacity as small as possible. The capacity is a function of the dielectric constant and the quotient of area/distance.

$$C_k = E_o \cdot E_r \cdot \frac{F}{d}$$

Should the capacity be kept small, a thick material which in addition is also a good heat conductor with a low E_r must be used. As in Figure 4, the disc insulator made of AlO shows the lowest capacity (20 pF). These discs are, however, very expensive and liable to breakage during operation or assembly, since the ceramic material is brittle.

Measures to be Taken with the Heat Sink

Another effective method is to isolate and space the heat sink from the equipment case (guard earth). If, for example, a heat sink (profile WA 116 75 mm long) is spaced at a distance X from the casing, then the coupling capacity between the heat sink and the case is:

Distance X = 1 mm $\quad C_k = 80$ pF
X = 2 cm $\quad C_k = 4$ pF

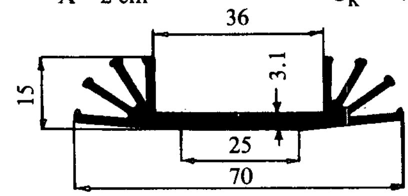


Figure 9. Dimensions of the Heat Sink WA 116

The resulting coupling capacity between collector and the case mass is still:

$$C_{k_{tot}} = 150 \text{ pF}/4 \text{ pF} = 3.98 \text{ pF}$$

Using the example of Figure 9, the displacement current through the reduced $C_{k_{tot}}$ capacity amounts to:

$$i_{ck} = |C_n| \cdot 2\pi n f \cdot C_{k_{tot}} = 29\mu A$$

This interference current causes a voltage drop across the resistors of the power line matching network of $U = R \cdot i_{ck} = 75 \cdot 29\mu A = 2.2 \text{ mV} \triangleq 67 \text{ dB}/(1\mu V)$.

The example makes apparent how with a relatively simple and cheap measure (mounting the heat sink on insulating distance pieces), the coupling capacity and the capacitive coupled interference current can be reduced by about 30 dB.

Incorporation of a Ground Line Choke

The high frequency asymmetrical interference current gets into the line supply via the ground line. If a ground line choke is placed immediately at the line entry point into the equipment, then the inductive reactance opposes the asymmetrical interference current. We obtain, together with the resistors of the power line matching network, the following voltage division:

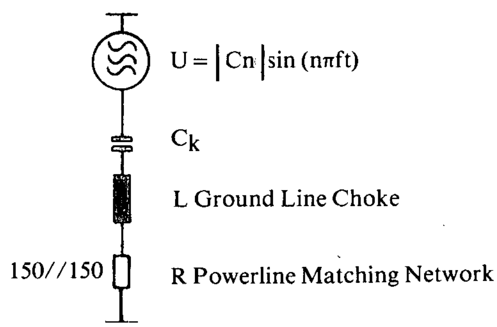


Figure 10. Power Line Matching Network

The division relationship is $A = 2nf\pi L/R + 1$.
For the case that $L = 250\mu H$
$n = 3$

$f = 50$ kHz
$R = 75\ \Omega$

then $A = \pi + 1 =$ dB.

Suppression with a Line Filter

By placing a line filter between the line supply and the equipment, the asymmetrical interference is effectively attenuated. The basic circuit of a single stage filter consists of a current compensated ring cored choke with a winding in each of the phase and neutral lines, as well as two drainage capacitors between phase, i.e., neutral to ground.

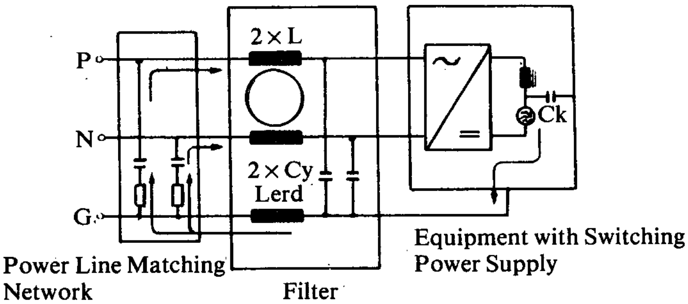


Figure 11. Filter for Suppression of Asymmetrical Interference Currents

According to requirement, the ground line choke can be integrated into the filter. The total inductance of the current compensated suppression choke acts against the asymmetrical interference current. Additionally, the Y capacitors form a capacitive shunt across the resistors of the power line matching network. The value of the Y capacitors is limited. Depending on the application of the equipment, the maximum permitted value of the leakage current is defined for mobile or fixed installation purposes and for EDP equipment. (0.75 mA for mobile, 3.5 A for fixed installations or EDP equipment, 40 μA for medical equipment etc.)

When dimensioning, the current compensated choke attention must be given to the high peak currents, as they often occur in line switching regulators on the line side, so that they do not saturate the magnetic material.

The result of saturation is a loss of inductance and, consequently, effectiveness of the choke against asymmetrical interference. The early saturation can be avoided if the current compensated choke is wound so that the stray field and winding differences are kept to a minimum. Bifilar windings exhibit about 1% of the powerline flux as stray flux. In contrast to the usual wound cores, a bifilar wound core saturates therefore at 3 to 4 times the current of the other core.

Suppression of a Symmetrical Interference Path

In contrast to the asymmetrical interference path, the symmetrical path is via the phase and neutral lines only.

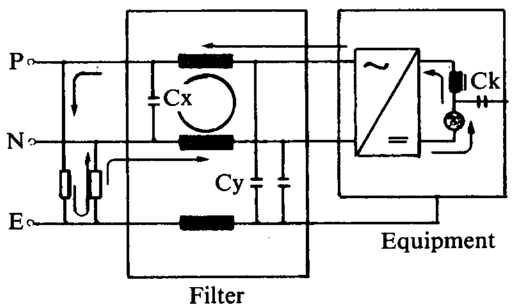


Figure 12. Symmetrical Interference Path

In the filter circuit of Figure 11, the X capacitors are mainly effective against the symmetrical interference as HF shunt across both of the resistors of the power line matching network. Since the symmetrical interference component only circulates in the phase and neutral lines, the fields in the ring core compensate each other. Only the stray inductance of the compensated choke acts to attenuate the symmetrical interference current.

As we previously saw, due to saturation, the core must be bifilar wound, whereby the advantage of the stray inductance is mainly lost. To achieve sufficient attenuation, a second non-bifilar wound current compensated choke must be placed after the first.

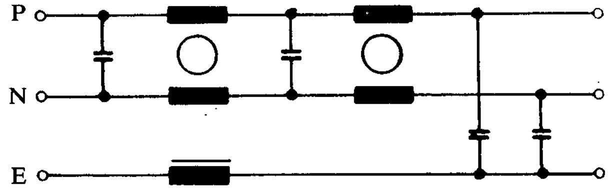


Figure 13. Two-Stage Filter

When mainly symmetrical interference is present, a rod cored choke must be used in the phase and neutral lines, which maintain their inductance and do not lose it through compensation or saturation.

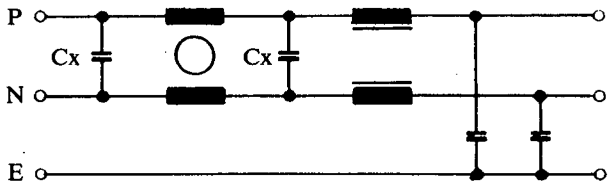


Figure 14. Stage Filter with Rod Cored Choke

The X-capacitor acts as a shunt for the power line matching network resistors.

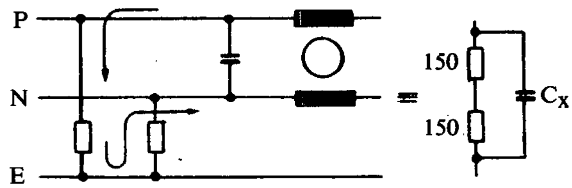


Figure 15. Effect of C_X

The result of impedance Z is:

$$Z = \frac{2R}{2R\omega \cdot C_X + 1}$$

The greater the X-capacitor, the smaller the impedance, and the smaller is the voltage drop across the power line matching network resistors.

Summary

Switching power supplies produce line interference. Without the necessary precautions, the resultant interference far exceeds the permitted limits. The higher the switching frequency and the faster the switching time, the wider the interference spectrum and the higher the interference amplitude. These spectral interference voltages couple via parasitic capacities to the case and get into the line supply over the guard line as asymmetrical interference currents. A reduction of the coupling capacity and a reactive impedance in the interference path attenuate these parasitic interference currents.

The above material was written for ITEM by J. Jordi, Schaffner Electronics, Switzerland.