Hardening Power Supplies to Line Voltage Transients

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Abstract

The power line transient environment is described. Transient voltages on the DC output of off-line rectifier/filter designs are shown. Protection schemes are discussed. An integrated rectifier/transient suppressor circuit is suggested as a cost-effective means of rendering the DC bus virtually immune to line transients.

INTRODUCTION

Unexpected line voltage transients are finally being recognized as a significant factor in the failure of Switching Mode Power Supplies (SMPS). As stated in a recent Navy publication (1): “The most predominant power supply failure modes are caused by peak instantaneous transients and subtle factors within and external to the power supply...
The following is a list of key points to consider when designing and evaluating a switching-mode power supply design: (1) Put voltage transient protection on the input power lines”.

Until the publication of IEEE Standard 587-1980 (2), now ANSI-IEEE C62.41, the designer of off-line SMPS was unsure of the AC line transient environment. Now switching power supplies can be designed to meet this standard and pulse generators are available which produce the waveform specified. The standard specifies that low impedances across the line in commercial and industrial environments should handle an 8/20 current waveshape (double exponential, 8 ms rise time, 20 ms decay to half of peak) having a peak amplitude of 3000 A.

It should be understood that lightning induced transients propagate through a system as a current source looking for a low impedance path to ground. It is unlikely that most designers make provision for the rectifier and filter system to handle pulse currents up to 3000 A, but a conservation design philosophy indicates that this should be done. The task is not easy, because component manufacturers do not generally consider this problem either.

A rectifier diode having a single-cycle 60 Hz surge current rating exceeding 300 A would most probably handle the 3000 A, 8/20 ms impulse specified in the standard, but the capability of rectifiers with lower ratings is questionable and needs to be verified. Rectifier diode surge capability will not be further addressed in this paper but clearly the rectifier must handle surge currents; the amount depends upon the protection scheme used.

In most off-line SMPS, the element which prevents excessive transient voltages from appearing across the DC bus and also bears the brunt of carrying the line to neutral transient pulse current is the filter capacitor. However, the charge delivered by the input transient and the voltage drop across the capacitor’s ESL and ESR combine to develop a large overshoot voltage. This overshoot usually shorts the power switches connected to the DC output from the rectifier system.

Providing a network to limit voltage to a predetermined maximum rather than using higher voltage power switches offers a number of advantages to the power supply designer, independent of the choice of switching transistor (i.e., bipolar or FET). For a bipolar transistor of a given die area, lowering the breakdown voltage raises current gain and reduces all switching times. Reducing the breakdown voltage of a FET chip causes a marked decrease in on-state voltage - the principle determinant of power loss - because of the relationship $r_{DS(on)}$ of VB2.5. Alternately, a smaller size power switch chip could be used to achieve the same performance while realizing a significant cost savings (3).

CONDITIONS IN AN UNPROTECTED SYSTEM

Most SMPS have an input network as shown in Figure 1. The impedance is used to limit start-up inrush current without causing excessive power loss. The series impedance may be a thermistor or a resistor which is often shunted by a triac to reduce power loss after start-up.

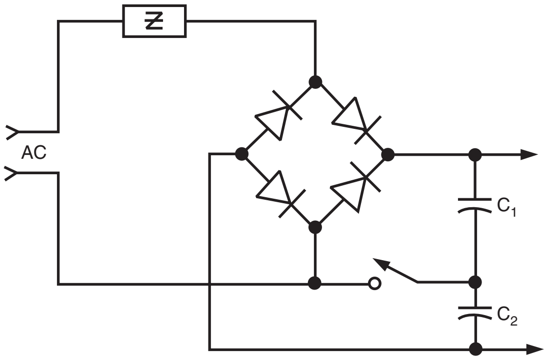

Figure 1. Basic Line Rectifier and Filter for SMPS Operating from 120/240 V Lines

It is not unusual to allow for a 20 % tolerance on a 120/240 V AC power line which puts the voltage crest at about 400 V. Added to the DC level is the overshoot caused by the 3000 A impulse. The usual switching power supply which operates from 120/240 V inputs has two capacitors as part of the voltage double arrangement. The capacitors are connected in series when used on 240 V.

Thus, the total DC bus voltage spikes up to twice the individual capacitor transients when used on 240 V. The voltage waveform of Figure 2 reveals the presence of three components of overshoot: 1) a fast rising step caused the di/dt of the wave flowing through the capacitors ESL, 2) an in-phase component caused by the current flow through capacitor ESL, and 3) a charge placed on the capacitor. Obviously, the transient voltage can be reduced by using a large valued capacitor having low ESL and ESR. The relationship is given in below Equation.

$$V_C = \frac{I}{C}\int idt + iRs + LS\frac{di}{dt}$$

where
C = Input filter capacitance
i = Pulse current
Rs = Capacitor equivalent series resistance (ESR)
Ls = Capacitor equivalent series inductance (ES)
di/dt = Rate of rise of transient current

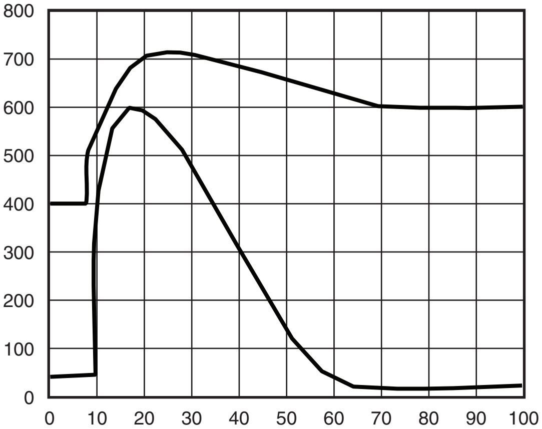

Figure 2. Capacitor Waveform Showing Spike Caused by Current, and Charge Placed on Capacitor ($C_1 = C_2 = 60$ mF; Upper: 10 V/div; Lower: 100 A/div; Time: 10 ms/div)

Measured voltage transients for some different capacitors when pulsed with 500 A in the circuit of Figure 1 are shown in Table 1. With a 3000 A pulse, overshoots of 6 times the values shown would occur. In all cases of 240 V input, the transient voltage exceeds the typical 250 V surge rating of a 200 V capacitor. Even worse, the DC bus - possibly at about 400 V because of high line, low load condition - is now up to at least 560 V! No wonder power switch failures occur in seemingly well designed systems.

TABLE 1 - TRANSIENT PERFORMANCE OF THE CIRCUIT OF FIGURE 1
(Peak Pulse Current = 500 A)

C_1, C_2	TYPE	INPUT	PEAK TRANSIENT VOLTAGE	CHARGE VOLTAGE
540 µF	Mepco/Electra 319DA541T250AMA1	120 V	39 V	30 V
		240 V	75 V	58 V
650 µF	Mepco/Electra 3120EA651T200BHA1	120 V	33 V	23 V
		240 V	65 V	46 V
2100 µF	General Electric 44A417052M21	120 V	12 V	7 V
		240 V	27 V	16 V

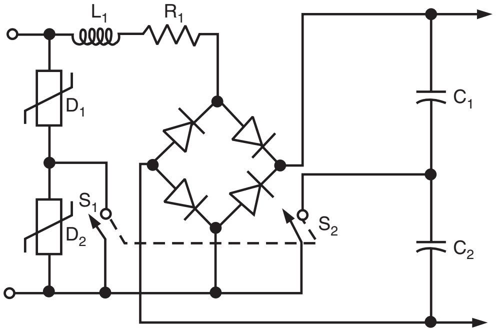

Figure 3. Basic Circuit with MOV Protection

The spike could be clipped by a suitable TVS device but the charge voltage persists for too long and is not easily eliminated. The best solution is to minimize the amount of transient current being fed to the capacitor.

TRANSIENT PROTECTION TECHNIQUES

General principles of powerline transient protection have been described in a paper by Jacobus (4). Almost concurrently, a specific module designed using these same principles, which meets the 3000 A specification of ANSI-IEEE C62.41, was described by Roehr and Clark (5). Both papers deal with providing transient protection downstream from susceptible equipment. However, in a power supply, components which must be present for rectification and filtering may be used as part of the transient suppression network.

TABLE 2 - TRANSIENT PERFORMANCE OF THE CIRCUIT OF FIGURE 3
(R_1 = 0.05 Ω, C_1 = C_2 = 540 µF, Peak Pulse Current = 2000 A)

R_1 - L_1	INPUT	S_1	PEAK TRANSIENT VOLTAGE	CHARGE VOLTAGE	PEAK CAPACITOR CURRENT
0.5 Ω - 0 µH	120 V	Open	77 V	54 V	1080 A
		Closed	24 V	21 V	440 A
	240 V	Open	106 V	78 V	780 A
0.5 Ω - 100 µH	120 V	Closed	18 V	10 V	190 A
	240 V	Open	74 V	47 V	440 A
1.0 Ω - 100 µH	120 V	Closed	12 V	7 V	130 A
	240 V	Open	53 V	34 V	300 A

When transient protection is used in a SMPS, it most often is nothing more than a single MOV across the line as shown in Figure 3. Table 2 shows test results taken in the circuit of Figure 3. Note that the worst transients occur in the 240 V position when both switches are open. However, unless the MOV voltage is adjusted to fit the lower line voltage when used on 120 V ac, (i.e., S_1 is closed), a very large capacitor current flows. For example, with only 0.5 Ω impedance the 77 V spike appears across only one capacitor; with 3000 A of input current the spike would increase to 115 V which could exceed the surge voltage rating of the capacitor. The 106 V transient increases to about 150 V when 3000 A is applied, bringing the bus voltage to 550 V.

To improve the transient suppression, the capacitor and/or the series impedance must be larger. The data in Table 2 taken with higher series impedances shows some improvement in lowering the transient levels, but the transients are still higher than desired. For very low power supplies, the circuit of Figure 3 would be satisfactory, if an appropriate series impedance and capacitor were chosen. For example, the data of Table 1 shows that the 2100 mF capacitor allowed only 27 V of overshoot with a 500 A pulse. This capacitor would be satisfactory if used in Figure 3 with the 0.5 Ω - 100 mH input network.

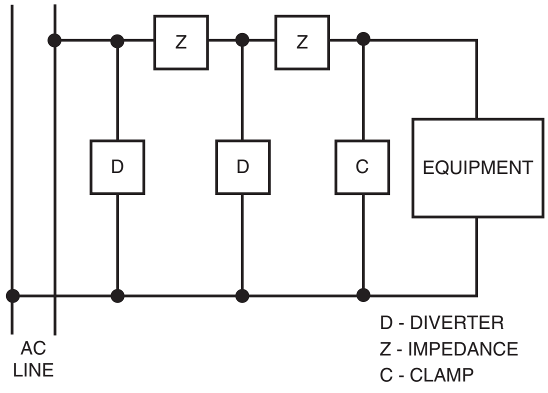

Figure 4. General Topology for a Protection Network

A general topology for transient protectors is shown in Figure 4 using the notations of Jacobus. The diverter devices handle high currents but do not offer a precise control of voltage; gas tubes and metal oxide varistors (MOVs) are typical diverting elements. The clamp devices have lower impedance than the diverters but have lower energy handling capabilities. A TRANSZORB™ Transient Voltage Suppressor (TVS) Diode is a typical clamping device. The series impedances shown semi-isolate the various diverter and clamp stages by causing a voltage drop between them. To meet the requirements of ANSI-IEEE C62.41, Category B, and provide low output voltage clamping, the topology of Figure 4 has proven to be quite effective.

AN INTEGRATED RECTIFIER/SUPPRESSOR CIRCUIT

After some experimentation, the network of Figure 4 has been found to work quite well when the first diverter is a MOV, the first impedance is composed of the inrush current limiting resistance and an inductor, the second diverter is a silicon Transient Voltage Suppressor and capacitor network, the second impedance is a series R - L circuit, and the clamping device is the filter capacitor.

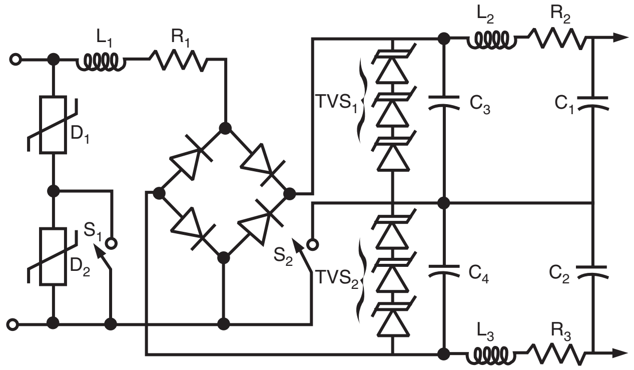

Figure 5. Circuit Providing a High Level of Protection

Figure 5 (patent pending) shows a practical implementation of the circuit of Figure 4, which is virtually immune to transients. The resulting T filter network also attenuates high frequency noise in both directions, thus easing EMI filter requirements. Performance is shown in Table 3 when pulsed with 2500 A. The resulting 25 V peak transient appearing at the output is low enough to allow the use of 450 V rated transistors in the power switching section.

TABLE 3 - TRANSIENT PERFORMANCE OF THE CIRCUIT OF FIGURE 5

(Pulse Current ≈ 2500 A, $L_1 = L_2 = L_3 = 100\ \mu H$, $R_1 = R_2 = R_3 = 0.5\ \Omega$ TVS Stack, 5KP60)

INPUT	PEAK TRANSIENT VOLTAGE	CHARGE VOLTAGE	PEAK CAPACITOR CURRENT
120 V	9 V	5 V	103 A
240 V	25 V	16 V	163 A

CONCLUSION

Only by ensuring a clean dc bus can a switching power supply be a reliable piece of equipment. Attention must be given to the lowly line rectifier and filter system to dramatically reduce line voltage transients. The circuit of Figure 5 provides a satisfactory clean DC level.

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