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Mitigating the Effects of Temporary Overvoltage on Electronic Devices

Solutions Guide

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EPRI Project Manager
B. Fortenbery

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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Electric Power Research Institute (EPRI)
942 Corridor Park Blvd
Knoxville, TN 37932

Principal Investigators
D. Nastasi
M. Young
F. Khan

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PRODUCT DESCRIPTION

Temporary overvoltage (TOV) is a power system phenomenon that can disrupt the normal operation of electronic equipment connected to a distribution system and, in some instances, can cause damage to electrical components. Electronic devices generally operate using dc power via an internal or external power supply that converts ac 120 V at 60 Hz to the needed dc operating level. These power supplies exist in a variety of types that range widely in terms of complexity and costs. When exposed to TOV, the electrical components within these power supplies may be prone to failure or poor operation depending on the magnitude and/or duration of the event and ratings of the exposed electrical components.

While the causes of TOV events are well documented, there is little information available to make devices more robust. This report seeks to bridge the TOV information gap by providing a technical summary of the causes of TOV events, outlining the relative magnitude and duration of such events and providing guidelines for increasing the immunity of equipment to them. The approach employs a classification system that groups power supplies typically used in residential and commercial applications by relative cost and complexity. Investigators analyzed each group to find its inherent weaknesses to TOV and used these findings to identify ways to reduce these vulnerabilities.

Results and Findings

The study investigates two methods to mitigate the effects of TOV on electronic devices operating in North America (120 V, 60 Hz). The first method involves the use of additional protection equipment to interface user equipment to the distribution grid. Such protection equipment may include online uninterruptible power supplies (UPS) systems that can detect a TOV and perform a seamless transition to back-up battery so that the user device never sees the TOV. The second method focuses on power supply design modifications/improvements that include component upgrades or extended use of switch-mode power supplies.

Challenges and Objectives

The effects of power anomalies are not often considered during the design of power supplies. Priority is given to marketable features or to minimizing manufacturing cost. EPRI has a record of influencing product manufacturers to consider their products' performance in the non-ideal electrical environment of the real grid. The overarching challenge is to improve the compatibility between the ac power grid and the products that are connected to the grid.

Applications, Values, and Use

The intended use of this document is to provide solutions for power supply designers who want to enhance their products robustness to survive most TOV events. The information in this report will eventually feed into a larger and more comprehensive design guide for manufacturers, which will cover a broader range of ac power quality issues.

EPRI Perspective

EPRI has performed laboratory experiments in previous studies to determine the effect of TOV on several types of electronic devices and has also collected data from distribution systems to determine the cause, likelihood, and effect of TOV events on actual customer loads. With this information at hand, researchers could devise solutions for mitigating the effects of TOV in an analytical manner.

Approach

The project team developed guidelines for cost effectively mitigating TOV effects on electronic devices. For load-side protection devices, the team considered both the level of protection attainable along with the relative cost. For design-level modifications, they estimated the relative costs for more robust components for multiple levels of protection. To accomplish these analyses, the team sorted various types of power supplies indigenous to residential and commercial electronic devices into four categories according to their complexity and relative cost. They then analyzed the power supplies in each category by reviewing typical design features as a means to target vulnerabilities to TOV. Based on this analysis, the team devised an optimal method for mitigating the effects of TOV on residential electronic devices.

Keywords

Temporary overvoltage
TOV
Power quality
Power supply

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

Background

Residential and commercial electronic devices are susceptible to impaired operation or damage when exposed to voltage magnitudes greater than their rated design values. One such overvoltage condition, classified in terms of its duration, is commonly called temporary overvoltage (TOV), having durations on the order of several cycles to minutes. This is in contrast to transient overvoltages, having sub-cycle duration.

To protect electronic equipment from TOV, external power conditioning or internal power supply design solutions can be implemented. The cost-effectiveness of any mitigating solution is related to the desired level of protection. Such issues along with a brief tutorial and quantification of overvoltage events are discussed throughout this report.

Preliminary Materials

This document follows work performed in previous EPRI projects to identify the causes and effects of TOV with regard to residential electronic equipment. This report seeks to present suggestions for mitigating the effects of TOV on residential electronic equipment. More specific information about TOV has been published in previous EPRI reports that address its causes and its effects on electrical equipment. For further information about TOV beyond the contents of this document, the authors refer the reader to the EPRI reports outlined in Table 1-1.

Table 1-1
Previously Published EPRI Documents Relevant for Superconducting Power Cables

Title	Document	Description
Effects of Temporary Overvoltage on Residential Products	1008540	Provides a comprehensive overview of the causes of TOV Provides survey data Presents laboratory testing in which various residential electronic devices were subjected to various levels of TOV
Effects of Temporary Overvoltage on Residential Products, Part II	1010892	Provides more testing of residential electronic devices for susceptibility to TOV Provides post mortem analysis of failed/damaged test subjects

Report Organization

The content in this report is presented in five chapters. It is recommended that those with limited knowledge of overvoltage phenomena read the report in its entirety. However, those who have knowledge of the subject may wish to move ahead to the subject matter found in chapters 3, 4, and 5 that addresses mitigation of TOV effects. The progression of the report is described below:

- **Chapter 2** provides a brief tutorial on the causes of TOV in a power system along with the voltage levels and durations typically associated with each event.
- **Chapter 3** presents ways to mitigate the effects of TOV to user equipment through the use of protection devices that interface such equipment to the utility.
- **Chapter 4** investigates design level solutions to mitigate TOV through the analysis of power supply topology and presents incremental levels of protection based on relative costs.
- **Chapter 5** summarizes the findings of the report and provides suggestions for choosing the appropriate level of protection.

2

TOV: A BRIEF TECHNICAL SYNOPSIS

Overview

Power system events, including overvoltage events can be classified by their duration. For example, a swell (overvoltage) lasting between 0.5 and 30 cycles is called an "instantaneous" swell, one lasting between 30 cycles and 3 seconds is called a "momentary" swell, one lasting between 3 seconds and 1 minute is a "temporary" swell, and one lasting longer than 1 minute is a long term overvoltage according to IEEE Std 1159.[1]

For purposes of this study, a temporary overvoltage is an overvoltage condition that has durations greater than a tenth of a second (6 cycles @ 60 Hz) and lasting up to a few minutes. Depending on the cause of the overvoltage, durations can be indefinite, subsiding only when the circuit is isolated. Technically, these events are referred to as long term overvoltages.

This chapter seeks to inform the reader about the causes of TOV events and how each of these events correlates to a particular magnitude and duration. Five TOV scenarios are summarized in this chapter along their associated magnitudes and durations. These events are summarized to provide a better understanding of the phenomenon and to realize its possible effect on end-user equipment.

Causes of TOV

The five most commonly known types of TOV events are listed in Table 2-1.

Table 2-1
Magnitudes and Durations for Common TOV Events

Cause of TOV	Typical Magnitudes (pu)	Worst Case Magnitudes (pu)	Typical Durations (seconds)	Worst Case Durations (seconds)
Power System Faults	1.2 to 1.3	1.5	0.1 to 2	10
Impaired Secondary Neutral	1.3 to 1.5	2	Hours (sustained)	
Ferroresonance	1.5 to 2	3	Several seconds to minutes	
Poor Voltage Regulation	1.1-1.15	1.2	Hours (sustained)	
Contact with High Voltage Circuits	Unknown	Several per unit	0.1-1	

Power System Faults

Faults on a power system present an array of problems in addition to current magnitudes that can exceed nominal values by several per unit. One side-effect of power system faults is the possibility of voltage rise on any un-faulted phase due to shifts in the ground potential. For instance, a single line-to-ground fault shifts the ground potential at the location of the fault. The severity of shift in ground potential is directly dependent on the utilized grounding configuration. A worst case scenario occurs in an ungrounded system where the ground potential assumes the same value of the faulted phase. This worst case scenario can lead to an increase in the line-to-line voltage to levels approaching 1.73 pu. Likewise, single line-to-ground fault on a perfectly grounded system results in no change in the ground potential and thus no rise in voltage on the unfaulted phases.

The overvoltage levels caused by single line-to-ground faults are presented in Figure 2-1 according to grounding scheme. While double line-to-ground faults can cause overvoltages that are slightly higher than that of single line-to-ground, single line-to-ground faults occur more frequently. Therefore, 1.73 pu is sufficient as a design criteria for residential electronic equipment.

Impaired Secondary Neutral

In the United States, electricity is provided to residential customers via a split-phase configuration located at the utility transformer. This utility transformer steps-down the distribution voltage to 240 V_{rms} which is then split into two 120 V_{rms} terminals through the use of a neutral connection. TOV can occur if this neutral becomes loose or disconnected anywhere between the utility transformer and the service entrance of a residence. The diagram presented in Figure 2-2 represents a split-phase set-up with a broken or loose neutral. In the worst case scenario, the neutral is open and the output voltage can be as high as 2.0 pu (240 V_{rms}). However, the amount of overvoltage on each of the branches is dependent on the relative loading of the two branches. This concept introduces a voltage divider relationship that is dependant on the relative load levels of the two branch circuits.

Loss of a neutral is not uncommon in power distribution systems. However, TOV due to loss of a neutral is more likely and can last for long periods of time.

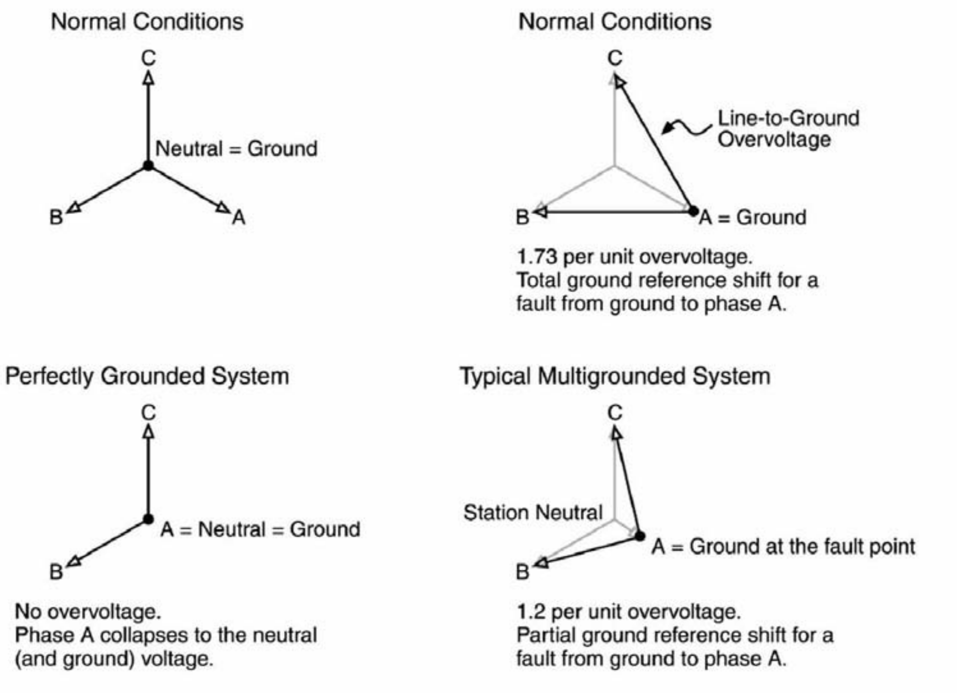

Figure 2-1
Ground Potential Shifts and Overvoltages Due to Grounding Configuration

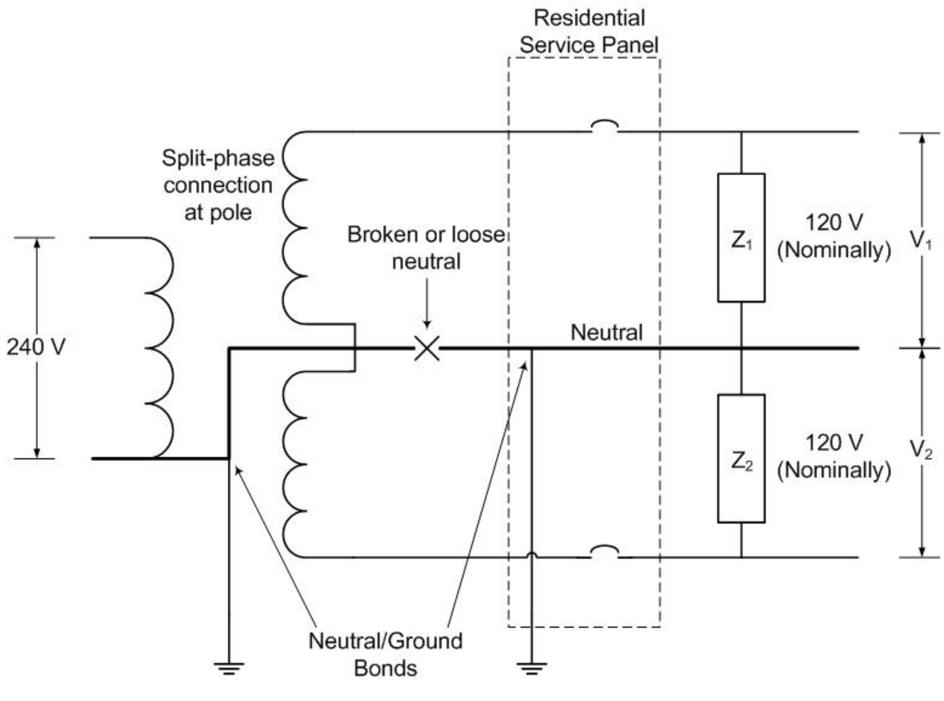

Figure 2-2
Voltage Divider During Broken or Loose Neutral

Ferroresonance

Ferroresonance on a distribution system refers to a complex phenomenon that involves a series resonance between the magnetizing reactance of a transformer and the inherent system capacitance. It is characterized by the sudden onset of very high and sustained overvoltages with concurrent high levels of harmonic distortion as shown in Figure 2-3. Ferroresonance can occur in both overhead and underground systems.

Underground systems or cable-fed transformers are particularly susceptible to ferroresonance because long cables introduce a high capacitance to a circuit cable-fed circuits are particularly susceptible to ferroresonance. The transformer connection is also a critical factor.

Typical values of overvoltage during ferroresonance are between 1.5 and 2.0 pu on the residential side, although values as high as 3.0 can occur. TOV events due to ferroresonance are fairly rare but can result in overvoltage magnitudes that are quite large and last indefinitely or until the problem is resolved.

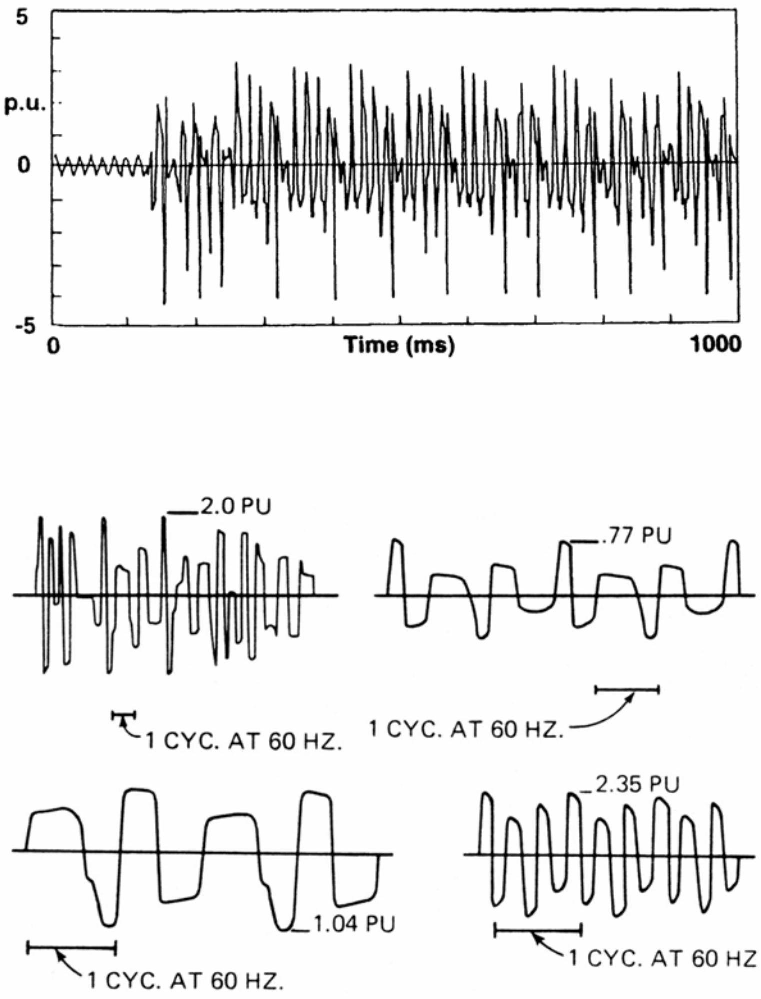

Figure 2-3
Examples of Ferroresonance [2] [3]

Poor Voltage Regulation

The misapplication or malfunction of utility voltage regulation equipment can lead to the onset of an overvoltage event. Improper installation or incorrect settings are examples of misapplication that can cause TOVs. Malfunction of the voltage regulator or capacity capacitor bank controller can also result in overvoltage events that fall in the TOV realm.

An onset of TOV can also occur due to time lag of the voltage regulator. In the case of an overvoltage due to tripping of a downstream recloser, the regulator may require some finite time to react and respond appropriately, during which time the system experiences an overvoltage.

Overvoltages due to voltage regulator issues are usually not that high (1.1 to 1.2 pu), however they can last for long periods of time.

Contact with High Voltage Circuits

Faults that occur between transmission and distribution circuits can result in dangerously high overvoltage conditions that will likely cause equipment damage. While overvoltage may not be too high when the distribution circuit is online, when it is isolated from the rest of the system the faulted distribution system becomes the same potential as the transmission line.

Contact with HV circuits presents one of the worst case scenarios for TOV as it can lead to magnitudes to several per unit. Duration, however, is very short due to the activation of utility circuit protection.

Defining a Desired Level of Immunity

Now that the main causes of TOV events have been summarized along with their signature magnitudes and durations, we can begin the process of protecting user equipment from such phenomena by establishing a desired immunity level. There are three important pieces of information that will aid in this process:

- The ITIC curve that describes the level of protection suggested for Information Technology equipment,
- Analysis of overvoltage survey data acquired from previous EPRI studies.
- Manufacturing cost of employing the techniques. Any proposed embedded solution should not significantly add to the cost of the product.

Together, these pieces of information will aid in identifying the level of protection already offered in most electronic devices and give insight as to what TOV events are prevalent on distribution systems.

The approach will be to first propose an immunity level, then research to find cost break points. The result should be an improved immunity level that will prevent equipment damage at an acceptable (ideally negligible) increase in manufacturing cost.

ITIC Curve

Currently, there are standards available that define what source voltage is acceptable for a 120/240 V_{rms} applications. Outside a narrow tolerance band is a region in which equipment might misoperate or be damaged. A general curve for computer equipment is the ITIC curve shown in Figure 2-4, named after the Information Technology Industry Council who developed the curve. The ITIC curve was not intended to define an immunity level for equipment. Instead, it was created to represent the current design goals for IT equipment manufacturers. Here, we use the ITIC curve as a reference for perspective.

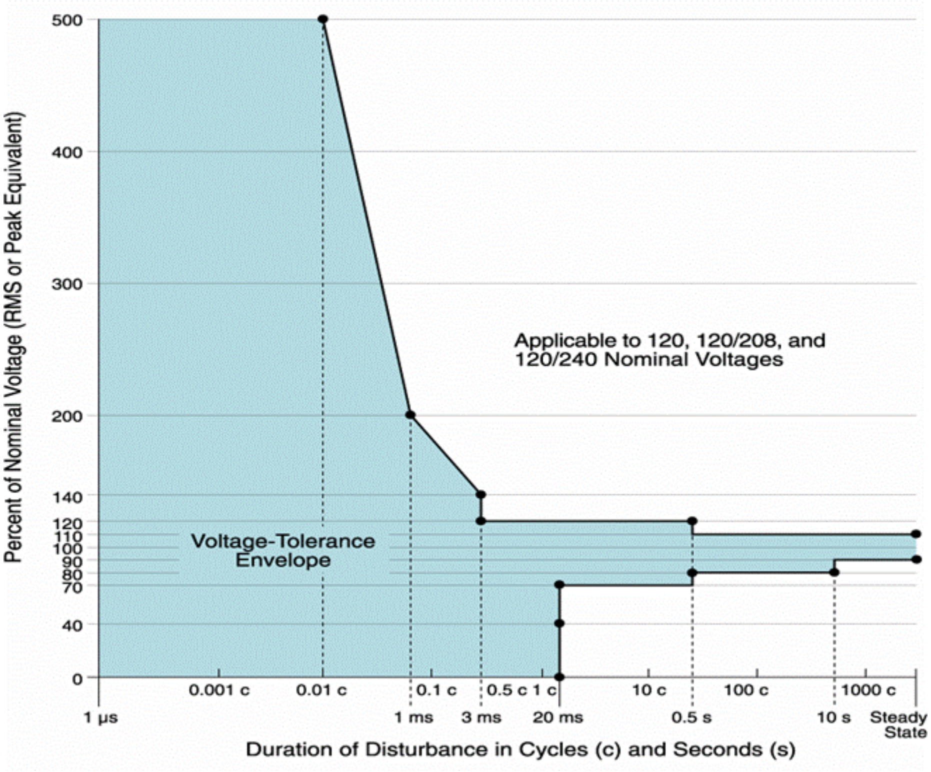

Figure 2-4
Information Technology Industry Council (ITIC) Curve

Analysis of Field Data

Since 1993, EPRI has conducted two power quality surveys in which power-line monitors were installed within distribution feeders at hundreds of locations across the United States. The event data recorded from these monitors was uploaded into a database where it could be queried and polled in a variety of ways. Using data recorded between March-June of 1995, a search was performed on the data for voltage swell events that fell within the TOV specifications listed in Table 2-1. Since some of the specifications listed in Table 2-1 are open-ended, the boundaries for the database query listed in Table 2-2 were generated with somewhat arbitrary endpoints.

Table 2-2
Boundaries Chosen for Database Query on TOV Events

Magnitude	Duration	Represented Event
1.2 to 1.3 pu	0.1 to 2 s	Overvoltages during a fault
1.3 to 1.5 pu	0.1 s to 1000 s	Loss of secondary neutral
1.1 to 1.15 pu	0.1 s to 1000 s	Overvoltages due to poor voltage regulation
1.5 to 2.0 pu	0.1 to 180 s	Ferroresonance
2.0 to 5.0 pu	0.1 to 1 s	Contact to high voltage circuits

Results of the TOV query on the survey data and the bounding boxes defined in Table 2-2 are combined into the scatter plot shown in Figure 2-5. It should be noted that the causes of the events in the scatter plot are unknown. They are represented on the graph because their magnitudes and durations fall within the boundaries listed in Table 2-2. Boxes have been placed around the magnitude and duration zones that correspond to the boundaries used to represent to a particular type of TOV event, not necessarily because those events inside the box are know to be caused by that event. Because of this identification method, the number of occurrences for each type of event should be disregarded. For example, because the power monitors were installed at substations, it is not possible to detect events caused by a loose neutral or by local faults, although events appear in those boxes.

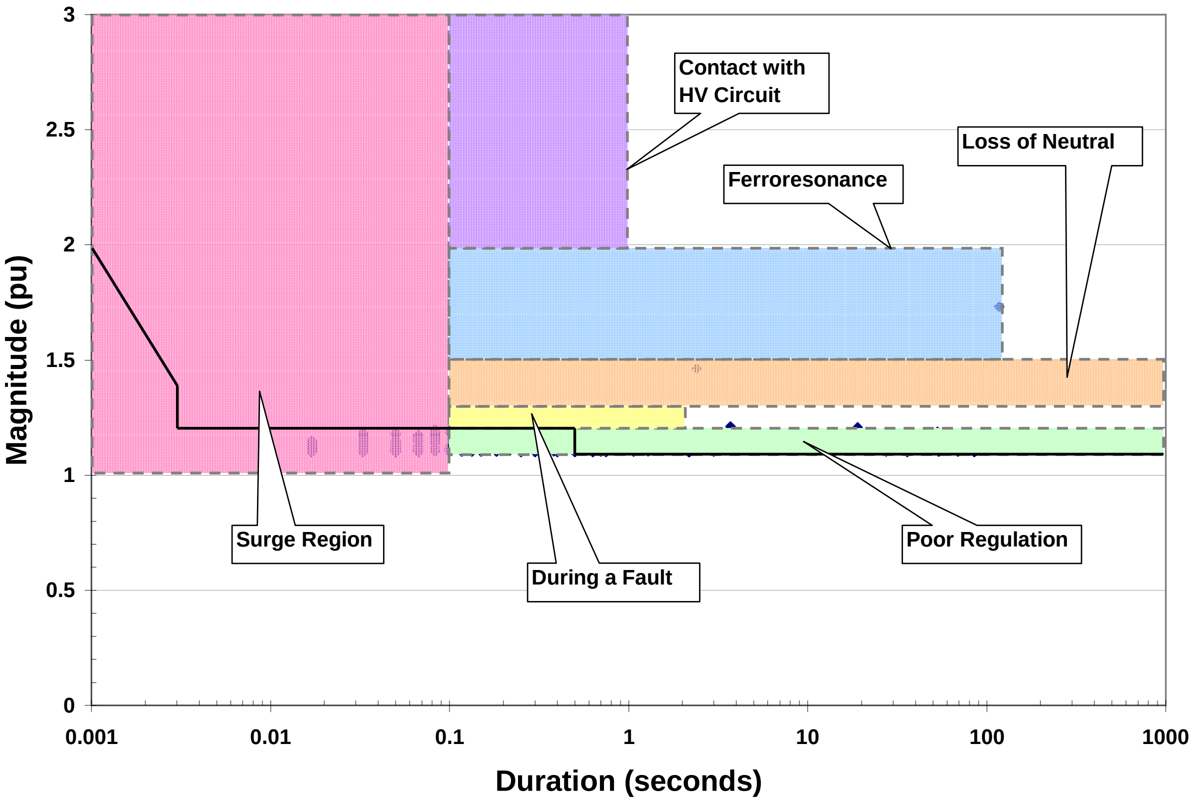

Figure 2-5
TOV Events Grouped by Query Results

Postulate a New Immunity Level

A goal of the present research is to help to define a new immunity level to TOV for electronic equipment. Using the ITIC curve as a guide, we observe that equipment is expected to operate during a 1.2 PU overvoltage for as long as ½ second. For events longer than ½ second, the equipment should operate without interruption during TOV events of 1.1 PU for any duration. This curve is very conservative. We see in the scatter plot that many events exceed these limits. That is not to say that equipment is damaged every time an event occurs outside the ITIC curve, but it does mean that a realistic immunity curve could be drawn to embody the present immunity of electronic equipment to TOV. Further, the envelope can be pushed to include an even greater immunity level than presently exists. The question is, would suggesting a greater immunity level become cost prohibitive? The balance of this report gives supporting information to suggest that electronic appliances can be built to withstand a greater temporary overvoltage than they do presently, and without adding significantly to their cost. Below are some observations on the limited amount of monitoring data.

- TOVs greater than 1.3 pu and less than 2.0 pu are rare, but can occur
- In very rare occasions, TOVs can reach magnitudes of 3.0 pu or greater
- In the majority of TOV occurrences, magnitudes are less than 1.2 pu

From this information, it can be postulated that the effects resulting from a majority of TOV events can be mitigated if 2.0 pu is used as a design or protection criteria. Therefore, the solutions sought throughout this report will concentrate on mitigation/protection from TOV events bearing in mind this 2.0 pu threshold.

Figure 2-6 shows the proposed threshold superimposed on the same graph with the scatter plot and the bounding boxes for perspective. Note that the proposed immunity level is defined only for the range of temporary overvoltage and does not reach into the surge domain. The realm of surge is a phenomenon of its own and is discussed separately from this report. As a future exercise, a surge immunity level should be defined for events having duration less than 100 ms.

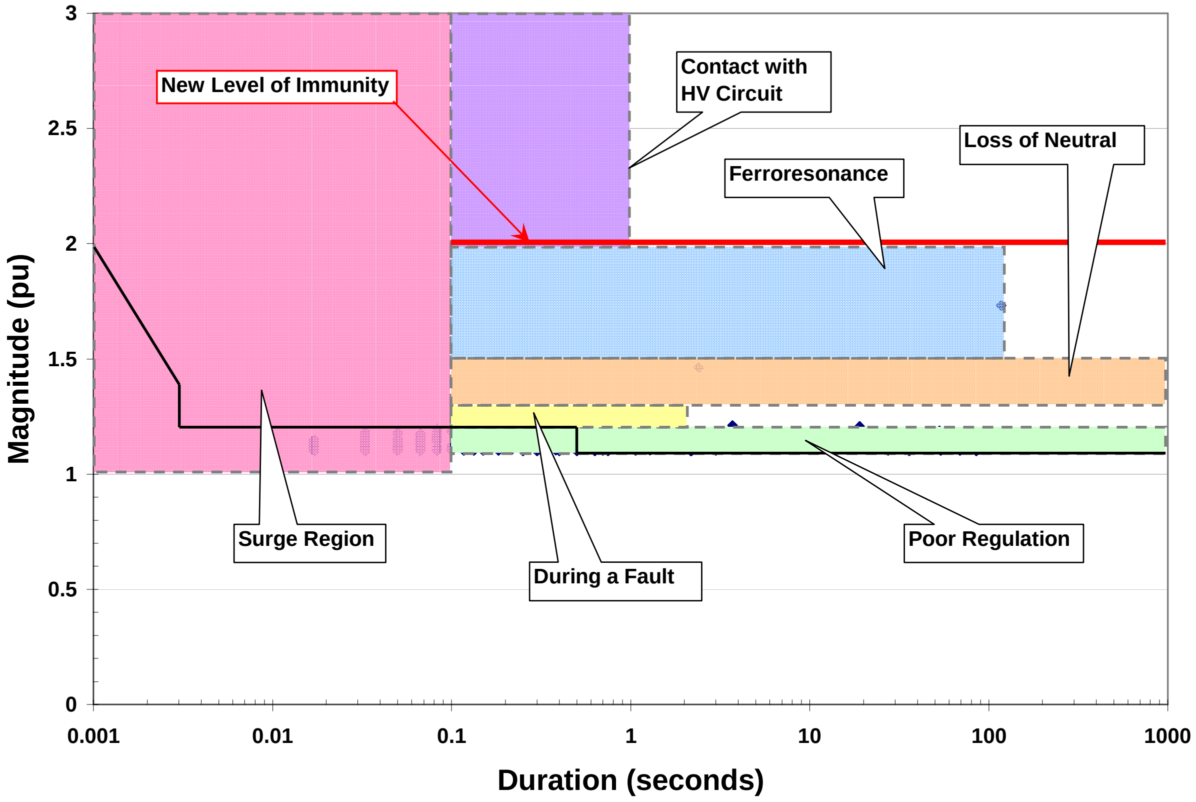

Figure 2-6
Proposed Level of Immunity

3

POWER CONDITIONING DEVICES

Existing Protection Products

Note that for the purpose of this discussion, surge protection, although important, addresses transient rather than temporary overvoltage. Some surge protection schemes are themselves vulnerable to temporary overvoltage. The protection scheme employed by most surge suppressors is to clamp the voltage at a certain maximum level, beyond which, the surge suppressor will dissipate energy for the duration of the transient event. The amount of energy dissipated by a surge protector during a transient overvoltage (such as that produced by lightning) is on the order of a few hundred joules and is dissipated in a matter of microseconds. However, these protectors are not capable of dissipating the enormous amount of energy available during a TOV and will fail very quickly if the TOV has sufficient magnitude to exceed the clamping voltage of the surge protector.

Because of the nature of temporary overvoltage, the best approach is not to attempt to dissipate its energy, but rather to either withstand the voltage or to quickly open the circuit and avoid the overvoltage altogether. Power conditioners are built to withstand the overvoltage, to a certain limit, and act as a buffer to protect their loads. A few examples are the constant voltage transformer (CVT) also known as the ferro-resonant transformer, the automatic tap-changing transformer, and the battery-based uninterruptible power supply (UPS).

An alternate strategy is to detect the TOV condition and quickly open the circuit to protect the sensitive electronic load. This is the role of an overvoltage relay, available as a commercial product or possibly as a built-in solution. A brief discussion of the benefits and limitations of each technology follows.

An overvoltage relay can protect loads during an overvoltage, by simply disconnecting the load (and possibly reconnecting it). Figure 3-1 shows how a circuit with an overvoltage relay is configured to protect the load from TOV.

Protection by avoidance is effective and cost effective. However, the main disadvantage of the overvoltage relay is the sudden loss of AC power when the protection circuit operates. To properly employ this technique, the overvoltage sensitivity would need to be set at the upper withstand limit of the equipment that it is protecting. This will minimize the interruptions, acting only in extreme overvoltage conditions where potential damage could occur. Perhaps the overvoltage relay scheme would be best coupled with other TOV protection methods.

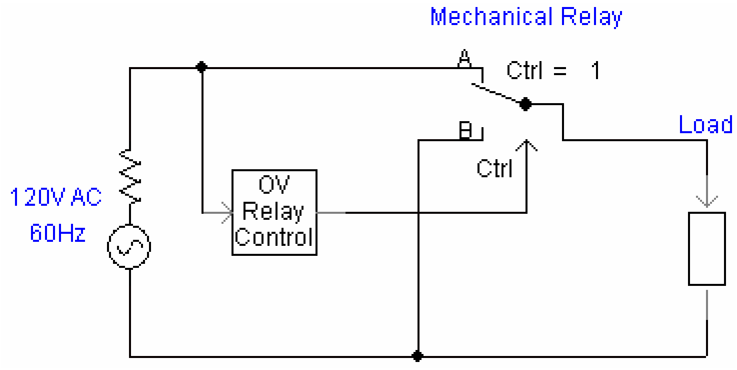

Figure 3-1
Circuit with an Overvoltage Relay

The remaining load side solutions to voltage swells require much larger and more expensive hardware. This is due to the fact that the remaining solutions all require that all the load power be conditioned in some way. These devices include constant voltage transformers (ferroresonant transformers), tap changing transformers, and uninterruptible power supplies.

Ferroresonant Transformers

A simple CVT circuit is shown in Figure 3-2. A ferroresonant transformer is a device designed to transform the voltage from an overvoltage or undervoltage condition to the appropriate steady state level by limiting the flux to a constant value. Ferroresonant transformers keep the secondary side in saturation to limit the amount of flux, and thereby reduce the current passing from the primary to the secondary side of the transformer. Ferroresonant transformers have in the past been notorious for having a lot of harmonic distortion. The sine wave was generally distorted to almost a square wave, but recent advances in ferroresonant transformer technology have improved this to about 3% THD in some models (assuming the input voltage is within the rating range) using advanced resonant LC filters.

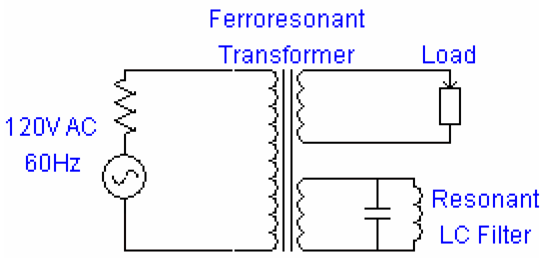

Figure 3-2
Circuit Utilizing a Constant Voltage Transformer

Ferroresonant transformers are limited on how much overvoltage and how much undervoltage they can input and still provide the rated output. Generally, they are better suited for correcting voltage sags than temporary overvoltage. Most ferroresonant transformers have a steady state range and a short duration range that allow for inputs much further from the desired output. Due to their operation in the saturation region, ferroresonant transformers are quite inefficient and expend energy in the form of dissipated heat. Their use for overvoltage protection is not feasible in many applications due to their size, weight, generated noise, and dissipated heat.

Tap-Changing Transformers

Much like the automatic tap-changing voltage regulators used by utilities, taps are switched using feedback to control the turns-ratio and the effective output voltage.

Although tap-changing transformers are much more efficient than ferroresonant transformers and they produce much less harmonic distortion, many have mechanical relays inside, limiting the life expectancy in comparison to ferroresonant transformers. Tap-changing transformers also take longer to react to a change in voltage due to the mechanical delay. Typically requiring 3 – 5 cycles to switch, compared to about 1 cycle for most ferroresonant transformers [4].

Uninterruptible Power Supplies

Uninterruptible power supplies (UPS) are designed to protect loads during a variety of power quality issues, including complete power loss. The UPS generally has a battery that is charged from the line voltage using a rectifier. If a loss of power occurs, or a sag or swell occurs that is out of the acceptable range, the UPS will invert the DC battery power to an AC signal that can be used to power whatever device(s) are attached to the UPS. In the process of rectifying and then inverting the DC voltage to AC, the voltage is effectively filtered, remedying any issues with overvoltages or undervoltages. A UPS can be a good solution to overvoltage problems, but it is generally a very expensive solution and can only supply power to the system for as long as the UPS's battery remains charged. Additionally the UPS can only protect to a level to which its own power supply can withstand.

Summary

While the power conditioning solutions are fairly expensive, they provide protection from a variety of power system events including TOV (although not their primary purpose). The pros and cons of each technology are summarized in Table 3-1.

Table 3-1
Non-Semiconductor Load-Side TOV Solutions: Pros & Cons

Device	Pros	Cons
Overvoltage Relay	• Inexpensive • Prevents equipment damage	• Loss of power during events • Nuisance tripping
Ferroresonant Transformers	• Simple operation • Durable; no moving parts • Fairly large input range	• Produces THD • Expensive & bulky • Inefficient: produces heat & noise
Tap-Changing Transformers	• Cheaper than ferroresonant transformers • High efficiency & signal filtering • Variable input range	• Reliability issues: moving parts • Shorter life expectancy • Slow acting 3-5 cycles
Uninterruptible Power Supplies	• Protects against many types of disturbances • Filters: Rectification & Inversion	• Very expensive • Limited battery life

4

DESIGN LEVEL SOLUTIONS

Overview

Power supplies in electronic devices are crucial components as they convert the mains ac power to useful dc power for device operation. For a wide range of devices, power supplies may vary greatly by design, architecture, and topology. This section will investigate the behavior of power supplies used in consumer electronic products under TOV situations in an effort to pinpoint likely causes of failure. Based on failure modes, design level guidelines for mitigation of TOV are prescribed to increase immunity. The study will consider both the use of universal SMPS (switch-mode power supplies) and/or upgrades to components of increased robustness. The study will also provide some guidelines pertaining to cost effectiveness of the solution for each case. It is the hope of the authors that manufactures who desire increased protection or ride-through capability of their equipment during TOV events can use this information as an effective starting point.

Analytical Methodology

There are likely as many different power supply designs in existing residential electronic equipment as there are pieces of residential electronic equipment. However, the internal power supplies can be divided into the four main categories listed in Table 4-1. In general, the four categories are: linear with voltage regulation, linear without voltage regulation, switch-mode with active power factor correction, and switch-mode without active power factor correction. What distinguishes these power supplies in order to arrive at this logical grouping is their design complexity, which, in turn relates to cost, and is dictated by their function.

For example, consider a digital alarm clock that retails for about ten dollars. The power supply is likely to be a simple linear design without voltage regulation. Contrast that design with a high-wattage power supply designed for a desktop computer or server. This design would include a variety of advanced features such as active power factor correction, inrush current limiter, PWM (pulse width modulation) controller and multiple DC output voltages.

The power supply type in each classification was investigated through analysis of circuit design schematics and dissection of several residential devices. Major failure-modes of these power supply types were then summarized along with guidelines to increasing robustness in order to mitigate the effects of TOV at 1.5, 2.0, and 3.0 per unit. It is important to note that the observations made in this report regarding component retrofits and additional costs are marginal approximations that were made using resources that were readily available based on budget and time constraints. Therefore, additional analysis and testing may be necessary to verify the findings provided in this chapter.

Table 4-1
Grouping of Power Supplies Typically Used in Residential Electronic Devices

Group	Power Supply Type	Active PFC	Relative Cost	Typical Devices
1	Linear, no voltage regulation	No	Low	• Clock radios • Wall chargers • Portable CD players • Microwave oven control
2	Linear with voltage regulation	No	Moderate	• Home theater components • High-end audio & video devices
3	Switched-mode power supply	No	Low	• Cell phone chargers • CFLs (compact fluorescent lights) • Laptop adapter • Low-cost DVD players • Low cost VCRs • Satellite receivers (set-top-box)
4	Switched-mode power supply	Yes	High	• Computer power supplies

Linear Power Supplies

The linear power supply is the basic form of an ac-dc converter. AC mains voltage is stepped down using a transformer and rectified by rectifier diodes and capacitors to achieve useful dc voltage. The transformer provides the necessary galvanic isolation and steps down the input ac voltage to the appropriate level. A filter capacitor located in the final stage smoothes out the pulsating 120 Hz dc voltage in order to achieve minimal ripple in the output dc voltage waveform. Figure 4-1 shows two different kinds of linear power supply circuits.

Group 1 – Linear without Voltage Regulation

Overview

A linear power supply without a voltage regulation circuit represents a more simple form of the topology. With this arrangement, the output voltage varies with input ac voltage variation or load variation. In addition, the ripple component present at the output will also change with any load variation. For this reason, basic power supplies of this type are used in inexpensive electronic devices such as clock radios, power adapters, microwave oven displays, inexpensive audio gadgets, and other inexpensive devices found throughout the home. The no-load dc output of these power supplies can be expressed using the following equation:

$$Vout\,(dc) = \frac{Vin\,(ac)|_{RMS}}{Transformer\ turn\ ratio} \bullet \sqrt{2}$$

Analysis

Linear power supplies without voltage regulation are susceptible to damage during temporary over voltage situations. If there is any voltage variation on the input side, it is directly experienced at the low voltage side of the transformer and propagates into the main circuit of the device. Usually, these circuits contain a low power step-down transformer that is typically rated at 5-15 watts. Ideally a transformer should withstand an over voltage for a short time if the windings are designed to carry the added current. However, the transformers are selected based on a cost criteria, minimizing any margin for withstanding an overvoltage. As a result, the transformer's primary is subjected to excessive heating that can lead to failure during temporary or sustained overvoltage. The power supply circuits shown in Figure 4-1 represent linear power supplies without a voltage regulation scheme at the output.

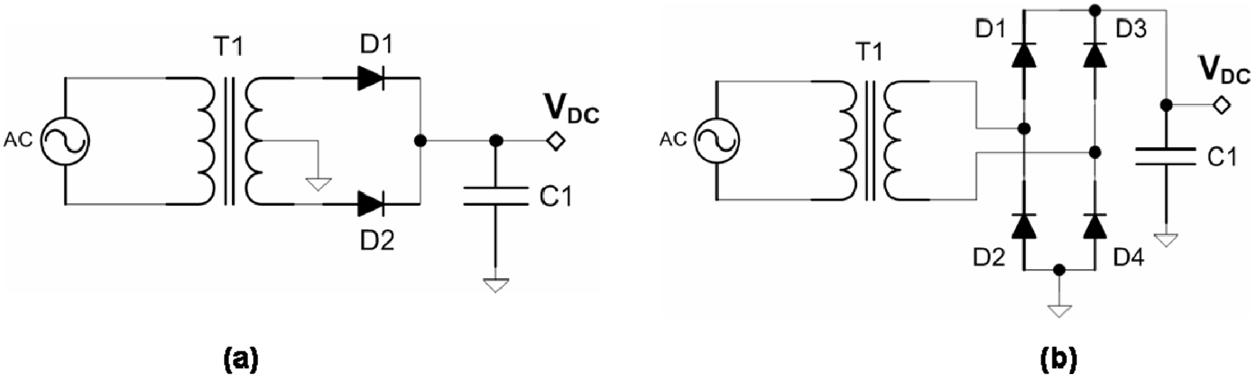

Figure 4-1
Schematic Diagrams of Linear Power Supply Circuits without Voltage Regulation

The diodes used in the circuit are usually rated at several hundred volts although they never experience that. The capacitor (C1) connected at the low voltage dc bus may be affected by the TOV situation. If the transformer can withstand the overvoltage, the elevated dc voltage is experienced by the capacitor, and the capacitor may fail if its voltage rating is close to the normal voltage of the dc bus.

Proposed Solution

The above analysis suggests that the most sensitive element to TOV events is the transformer. For residential devices, the transformer is rated for 115-120 V_{rms} input voltage. In order to achieve a target of 2.0 pu overvoltage, the transformer's primary as well as secondary windings need to be modified to withstand 240 V_{rms} or higher voltage. This higher rating will ensure a safe operation of the transformer at higher voltages even as high as 2.5 pu of higher for short durations. However, the increase in input voltage will have a direct effect on the secondary side of the transformer because it will increase the dc voltage to the electronic circuit beyond the safe range. Therefore, the secondary effect caused by the transformer retrofit winding will add additional costs in more robust rectifier components and the addition of a voltage regulator circuit.

The components of linear power supplies most sensitive to TOV are summarized in Table 4-2 along with possible retrofit options to increase robustness. The additional costs associated with the incremental increase of TOV mitigation are shown in Figure 4-2.

Table 4-2
Components Susceptible to Damage During a TOV Event for a Linear Power Supply Without Voltage Regulation

Voltage Level	1.0 pu	1.5 pu	2.0 pu	2.5 pu	3.0 pu
Affected Components	None	Transformer	Transformer Main Circuit*	Transformer Main Circuit* Filter Capacitor	Transformer Main Circuit* Filter Capacitor
Additional Cost (U.S. Dollars)	None	1.00	1.50	2.00	2.50

*main circuit refers to the electronics which receive their power from the power supply

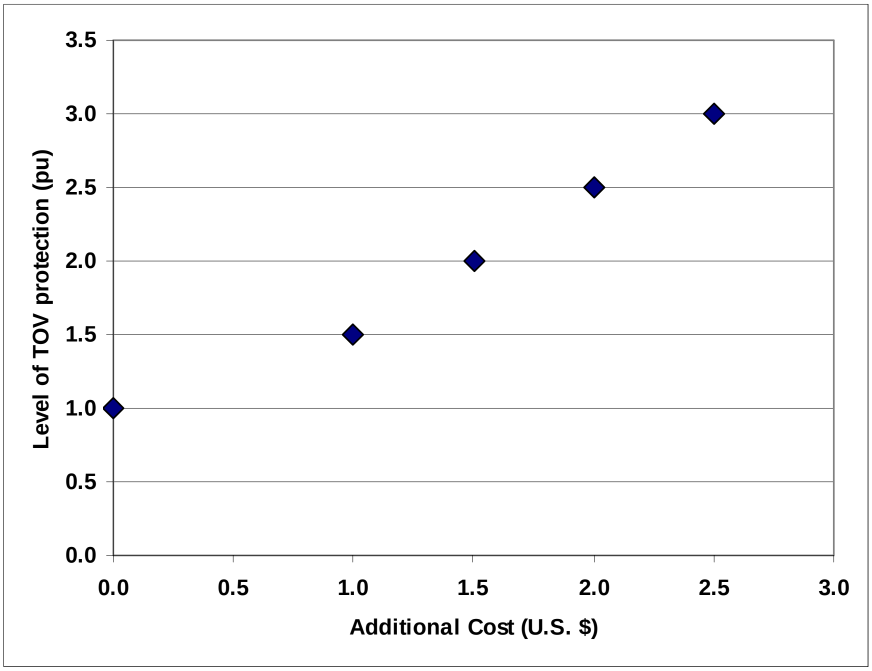

Figure 4-2
Approximate Additional Cost of TOV Mitigation for Linear Power Supplies without Voltage Regulation

Group 2 – Linear with Voltage Regulation

Overview

In many applications, linear power supplies are equipped with a voltage regulator circuit to provide constant voltage output as required by many electronic circuits. A typical linear regulated ac-dc circuit is shown in Figure 4-3. In this circuit, a transformer based ac-dc circuit acts as the input of the voltage regulator circuit. The voltage regulator IC keeps the voltage constant during variation in the input voltage (within a specific range) or load variation. For proper operation of the circuit, the input dc voltage of the regulator should typically be 1.5 to 2.0 volts higher than the output voltage.

In achieving a constant voltage output, the overall efficiency of the circuit is penalized. The voltage regulator, or linear regulator, bears a power loss across the regulator IC that is equal to the product of load current and the voltage across the regulator (V_{in}-V_{out}).

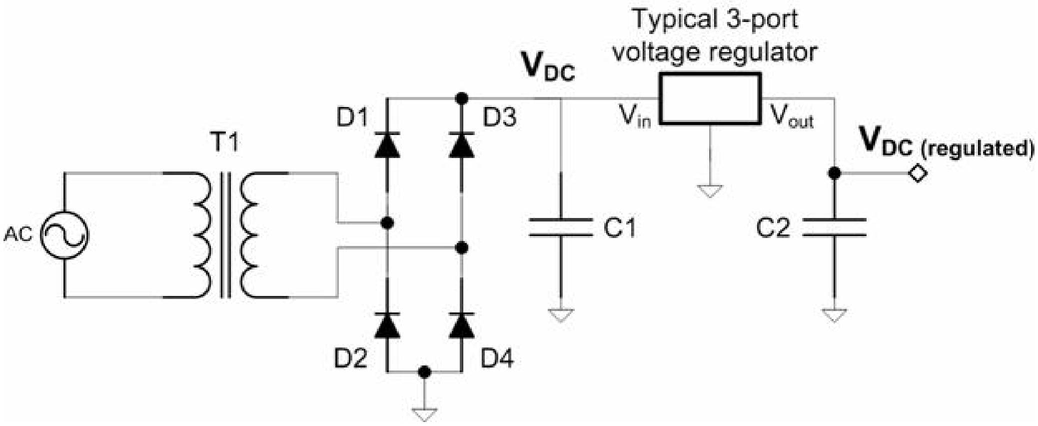

Figure 4-3
A Typical AC-DC Circuit with Constant Output Voltage

Analysis

Regulated ac-dc converter circuits are primarily used for devices that are susceptible to input voltage variation and harmonics present on the ac mains. Like the unregulated linear ac-dc converter circuit, this circuit also suffers from the limitation that prevents it from operating safely during a TOV situation. The voltage regulator IC typically has a wide input voltage range and should be able to withstand 2.0 pu voltage if the transformer passes the voltage. However, the power loss in the circuit will increase substantially due to the increase in the voltage drop across the regulator and can cause excessive heating in the regulator circuit.

Proposed Solution

Similar to linear power supplies without voltage regulation, the primary weakness to TOV phenomena of these power supplies is the input transformer. The presence of the voltage regulator means that fewer additional components will be required to upgrade these power supplies for TOV survival for values of up to 2.0 pu, but a more robust transformer is required to handle overvoltages of this magnitude. Therefore, the only additional costs required for TOV protection are the transformer and filter capacitor modifications. The included voltage regulator circuit should temporarily withstand the TOV situation.

The components of linear power supplies most sensitive to TOV are summarized in along with possible retrofit fit options to increase robustness. The additional costs associated with the incremental increase of TOV mitigation are shown in Figure 4-4.

Table 4-3
Components Susceptible to Damage During a TOV Event for a Linear Power Supply with Voltage Regulation

Voltage Level	1.0 pu	1.5 pu	2.0 pu	2.5 pu	3.0 pu
Affected Components	None	Transformer	Transformer	Transformer Filter Capacitor	Transformer Filter Capacitor
Additional Cost (U.S. Dollars)	None	1.00	1.00	1.50	2.00

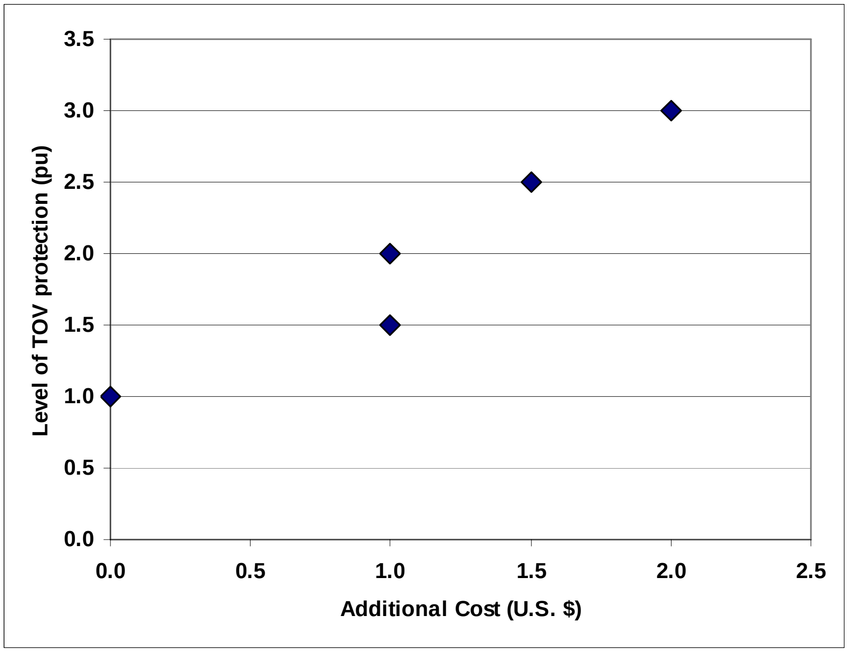

Figure 4-4
Approximate Additional Cost of TOV Mitigation for Linear Power Supplies with Voltage Regulation

Switch-Mode Power Supplies

Switch-mode power supplies (SMPS) are usually best-known for high efficiency operation and greater power to volume ratio. These days, SMPS circuits are being used in many residential applications starting from low cost CFL drivers to 1000 W computer power supplies. Commercial and industrial devices may use kW and MW range SMPS circuits.

The emergence of the universal switch-mode power supply (SMPS) in personal computers and other more expensive electronic devices may present an adequate solution for protection against many TOV events. These devices, which often provide power factor correction, use advanced switching technology to modulate the input waveform to the desired dc output value. It is this switching technology that allows the power supply to detect the TOV and adjust the modulation scheme accordingly to regulated the desired dc output and maintain uninterrupted operation of the electrical equipment. However, the power supply itself contains vulnerabilities to temporary overvoltage.

In order to facilitate utility environments in both the United States and Europe, universal SMPS can operate at 120 V_{rms} and 240 V_{rms} respectively; thereby providing at least 2.0 pu protection in the USA grid. However, universal SMPS are expensive and may not present the best solution in lower cost electronic equipment.

This report categorizes SMPS circuits in two groups based on price, complexity and usage. They are, (a) SMPS without active power factor correction, (b) SMPS with active power factor correction.

Group 3 – SMPS Without Active Power Factor Correction

Overview

A typical schematic of this class of SMPS is shown in Figure 4-5. The front end of the circuit is built from an electromagnetic interference (EMI) filter and a rectifier circuit. The rectified pulsating dc voltage is then filtered using C3 and fed to the main dc-dc converter circuit. These kinds of circuits can be made very inexpensively, and a self-oscillating circuit is used in the dc-dc converter section. Transformer T2 provides necessary isolation and is operated at very high frequency to reduce its overall size. In an SMPS circuit, active switches such as MOSFETs or IGBTs are operated in cut-off or linear mode. As a result, a substantial power savings can be achieved by reducing the loss associated with these switches.

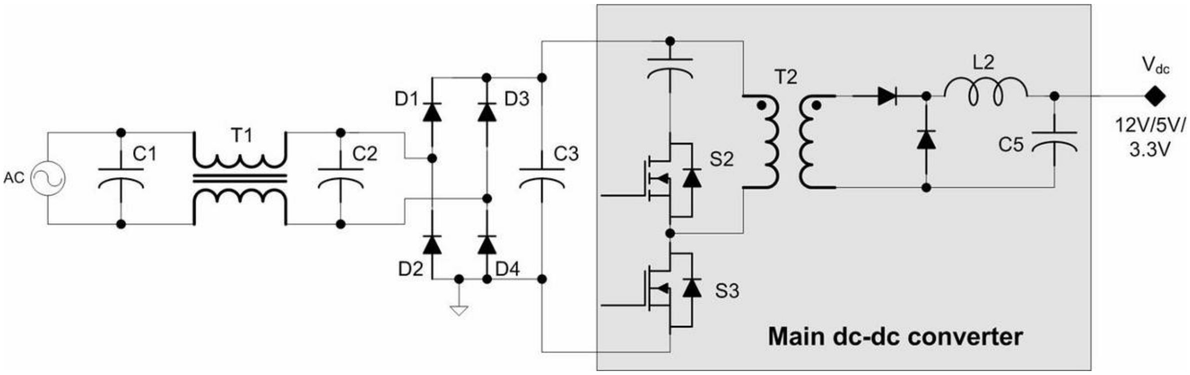

Figure 4-5
Typical Schematic Diagram of a SMPS Circuit Without Active Power Factor Correction

Analysis

The SMPS circuit shown in Figure 4-5 lacks the active PFC stage, and the resulting distortion power factor is much less than unity. In some cases, a passive PFC stage is used to elevate the power factor towards unity. However, an active PFC stage is required to achieve PF 0.9 or higher. Typical SMPS circuits are designed to operate in a wide voltage range from 85-265 V_{rms}. For this reason, these SMPS circuits do not experience any problems when operating up to 2.0 pu. However, when the input voltage is raised to levels beyond 265 V_{rms}, some components are affected by the overvoltage and may eventually suffer damage.

Proposed Solution

To achieve operation without failure for overvoltages beyond the 2.0 pu input voltage, component upgrades will be required as shown in Table 4-4. The primary component of concern is the MOSFET, which provides the switching needed to modulate the output signal to the desired level. Loss of this switching device will render the power supply useless. Upgraded filter capacitors will also be needed on the input side of the power supply. An estimation of the incremental costs associated with these upgrades is shown in Figure 4-6.

Table 4-4
Components Susceptible to Damage During a TOV Event for a SMPS Without Active PFC

Voltage Level	1.0 pu	1.5 pu	2.0 pu	2.5 pu	3.0 pu
Affected Components	None	None	None	• EMI filter capacitors • Filter capacitor in the front-end rectifier circuit • MOSFETs in the main dc-dc converter	• EMI filter capacitors • Filter capacitor in the front-end rectifier circuit • MOSFETs in the main dc-dc converter
Additional Cost (U.S. Dollars)	None	None	None	2.00	2.50

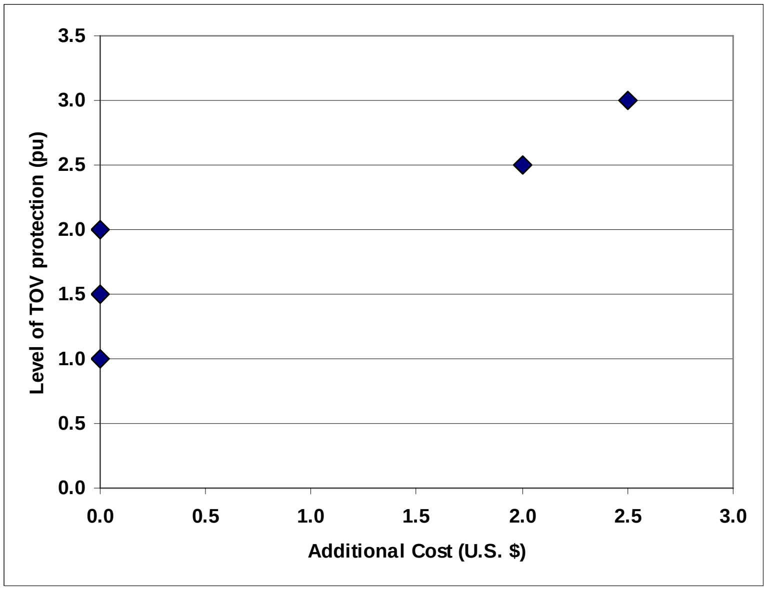

Figure 4-6
Approximate Additional Cost of TOV Mitigation for SMPS Without Active PFC

Group 4 – SMPS with Active Power Factor Correction

Overview

Often, it is desirable for larger power consumers such as computer power supplies capable of delivering 300W or more to have a power profile that is friendlier to the power system. This is accomplished by reducing crest factor and increasing power factor. To meet this requirement, SMPS are often equipped with an active PFC circuit that can provide power factor values greater than 0.9. To perform this function, the mains ac voltage is filtered and rectified using the EMI filter and bridge diode circuit. Unlike the SMPS circuit without active PFC, the rectified voltage is not heavily filtered using a bulk capacitor. Rather, it is fed to an active PFC circuit that is built from a non-isolated boost converter as shown in Figure 4-7. A control circuit instructs the active PFC to align the input current with the input voltage, thereby elevating the power factor to values approaching unity.

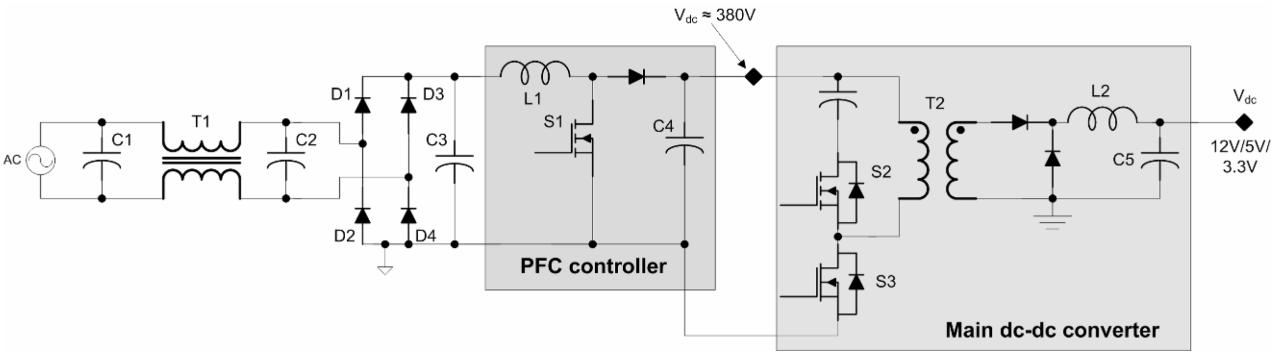

Figure 4-7
Typical Schematic Diagram of a SMPS Circuit With Active Power Factor Correction

Analysis

The output of the active PFC is filtered and fed to the main dc-dc converter circuit. Because of the additional PFC stage, this converter will have different weak points at high voltage input than SMPS without active PFC. The effect of TOV on the input EMI circuit is the same as before, however the active PFC circuit suffers from a design limitation that does not allow the circuit to operate beyond 268 V_{rms} with proper voltage regulation. The dc bus voltage at the output of the PFC circuit is maintained at 380 V, and the circuit's operating point will be at the extreme end if it is powered from a 268 V_{rms} ac source (because 268 V_{rms} ac input has an equivalent dc voltage of 380 V). Beyond 268 V_{rms}, the dc bus voltage cannot be regulated at 380 V, and the filter capacitor at this bus may fail. Moreover, the main dc-dc converter circuit connected at this bus will experience higher voltage also. Thus, the effect of TOV will eventually propagate to the various parts of the circuit.

Proposed Solution

Achieving operation without failure for overvoltages beyond the 2.0 pu input voltage involves component upgrades that result in higher costs that SMPS without active PFC. This result is due to the fact that the active PFC introduces additional components to the circuit. A list of susceptible components and approximate additional costs for upgrades are provided in Table 4-5. Again, the primary component of concern is the MOSFET, and upgraded filter capacitors will be needed on the input side of the power supply. An estimation of the incremental costs associated with these upgrades is shown in Figure 4-8.

Table 4-5
Components Susceptible to Damage During a TOV Event for a SMPS With Active PFC

Voltage Level	1.0 pu	1.5 pu	2.0 pu	2.5 pu	3.0 pu
Affected Components	None	None	None	• EMI filter capacitors • Filter capacitor in the front-end rectifier circuit • Output filter capacitor of the PFC circuit • MOSFETs in the main dc-dc converter	• EMI filter capacitors • Filter capacitor in the front-end rectifier circuit • Output filter capacitor of the PFC circuit • PFC circuit MOSFET • MOSFETs in the main dc-dc converter
Additional Cost (U.S. Dollars)	None	None	None	3.00	4.00

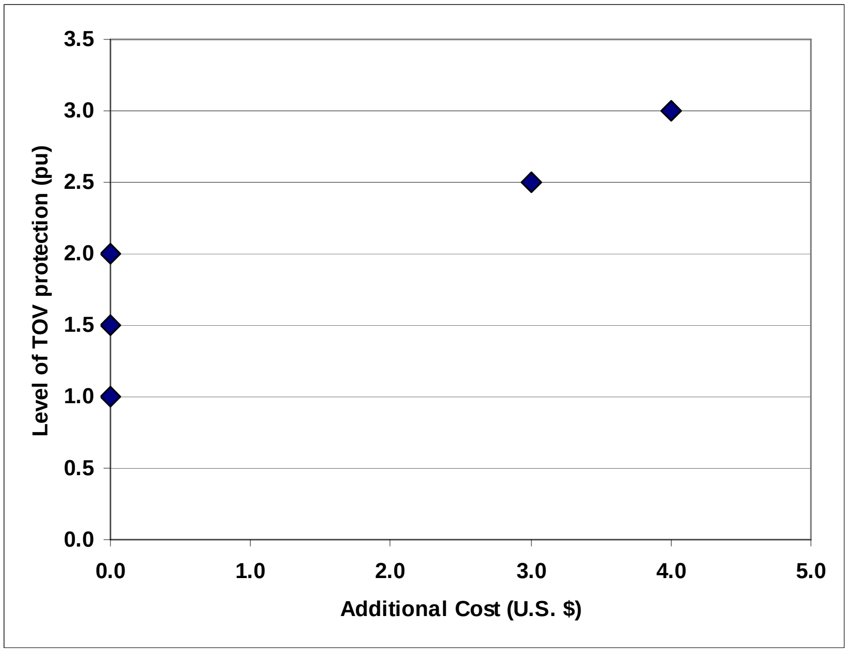

Figure 4-8
Approximate Additional Cost of TOV Mitigation for SMPS With Active PFC

5
CONCLUSIONS

The content of this report provides a review of the main causes of TOV and suggested solutions for mitigating the effects of such events on residential electronic devices. The study provides two sets of solutions based on empirical investigation. The first set of solutions encompasses load-side protection devices that are purchased by the consumers of the devices to be protected, while the second set of devices concentrates on design-level modifications to be performed by device manufacturers.

There are some viable load-side solutions that can provide adequate protection of residential electronic devices. UPS units provide various degrees of protection against TOV and can switch to a stored energy source for temporary uninterrupted operation. A major drawback to load-side protection devices that are effective against TOV is that they are relatively expensive, costing as much or more than the equipment they protect. Bearing this information, load-side protection devices may more justifiable from a cost standpoint for the protection of higher-end residential electronic equipment. Since such protection devices are typically purchased by the consumer of the device(s) to be protected, one must be careful to select protection devices with appropriate ratings and capabilities in order to achieve adequate protection.

Equipment manufacturers can provide an effective means for mitigating the effects of TOV by enhancement of their power supply designs. Such enhancement would incorporate the use of more robust circuit components or the use of universal SMPS. Based on the observation of typical power supply designs, key circuit components vulnerable to TOV events were identified and estimated wholesale costs for component upgrades were found. From this information, a new level of immunity of 2.0 pu for indefinite time durations is postulated as shown in Figure 5-1. Although the present research shows possible solutions to achieve up to 3.0 pu, a new immunity level of 2.0 pu can be suggested with greater confidence since SMPS are already rated for this condition.

It would be interesting to verify the observations and suggestions provided in this study with laboratory tests. Results of such testing could show the propagation of TOV throughout actual power supplies and the effectiveness of the design-level solutions. Also, a more complete TOV study with a larger dispersion of recording devices over a longer duration of time may help to further understand the frequency of such events and why they occur.

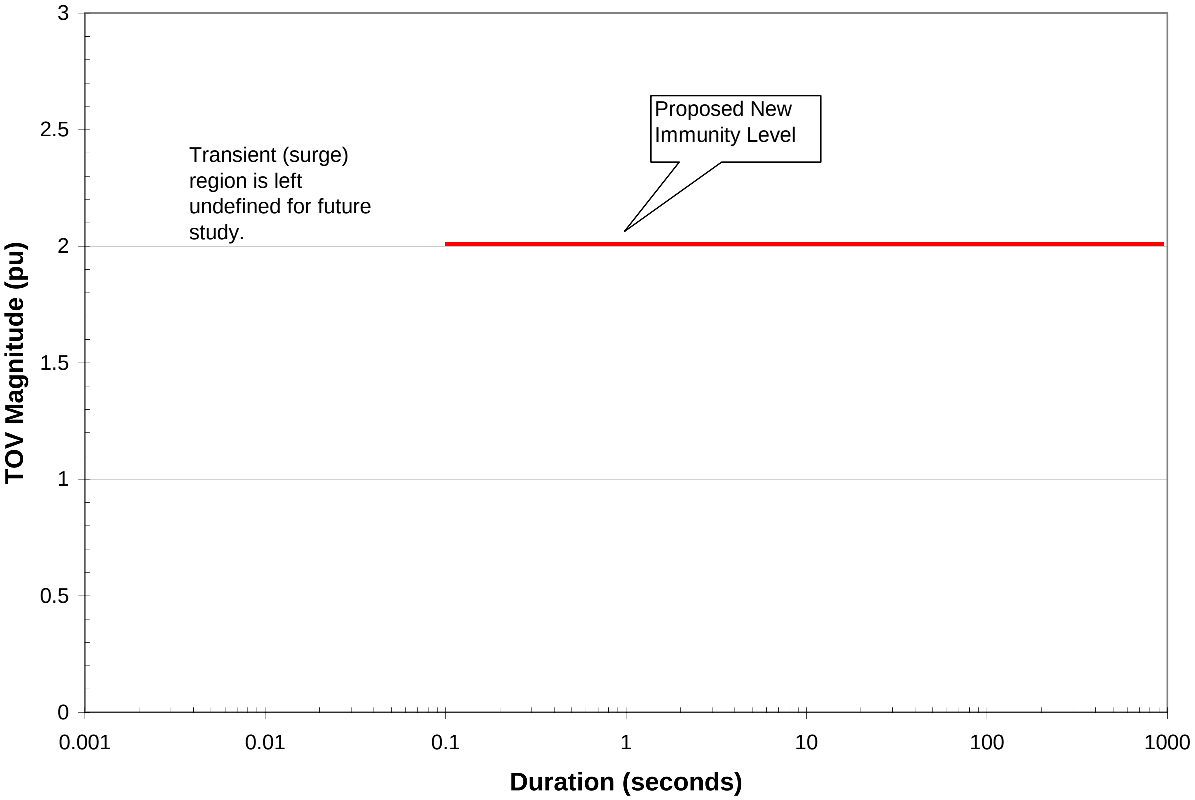

Figure 5-1
New Defined Level of Immunity

A

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