Equipment Immunity Performance Guidelines

2010 Activities

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Technical Update, December 2010

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REPORT SUMMARY

This report details EPRI's 2010 efforts for improved equipment-immunity standards and performance in the electrical environment.

Background

EPRI has an important role to play in advising standards committees and in challenging industry to develop more compatible end-use devices. The 2010 equipment-immunity work included both advising standards-development groups and promoting concepts of more robust end-use equipment within industry. In the standards arena, EPRI participated in development of Institute of Electrical and Electronics Engineers (IEEE) equipment-immunity standards and a Society of Automotive Engineers (SAE) standard for electric vehicle car chargers. System-compatibility concepts were promoted through a workshop and industry challenge.

Objectives

- To help influence change in existing standards leading to creation of new or revised standards that will improve equipment compatibility with the electrical environment.
- To promote development of end-use equipment that is more compatible with the intended electrical environment.

Approach

To inform future revisions of standards, EPRI continues to play an active role in helping to advise standards committees. The efforts of one of the major activities from 2006 through 2010 reached a pinnacle in 2010 when the CIGRE/CIRED/UIE C4.110 joint working group issued its final report titled *Voltage Dip Immunity of Equipment Used in Installations.* The knowledge gained from this work has been incorporated into a draft IEEE P1668 document titled *Recommended Practice for Voltage Sag and Interruption Ride-Through Testing for End-Use Electrical Equipment Less than 1,000 Volts.* Furthermore, the International Electrotechnical Commission (IEC) is now considering the C4.110 work in future revisions of IEC standards regarding voltage sags. EPRI also joined the SAE J2894 working group and provided key testing and data input to the draft standard titled *Power Quality Requirements for Plug-In Vehicle Chargers.* Furthermore, EPRI initiated a call to improve the design of the general-purpose ac "ice cube" relay through a white paper, magazine articles, and presentations.

Results

Continued involvement in the standards arena is expected to lead to more robust voltage-sag standards and improved system compatibility between equipment and the actual electrical environment. EPRI and member utilities agreed in 2006 on a 10-year plan that would include success statements—one of which is to achieve cost-effective power quality compatibility between the electrical system and its loads. Because the IEEE P1668 work is now well underway and the CIGRE/CIRED/UIE group work has produced recommendations for testing methods such as those detailed in this report, EPRI has made significant progress towards the goal.

EPRI Perspective

EPRI's role is to bring together members, participants, the Institute's scientists and engineers, and other leading experts to work collaboratively on solutions to the challenges of electric power. In the area of power quality and system compatibility, EPRI is working collaboratively with the standards community to lead industry towards more robust equipment designs that push further the limits of improved system compatibility. At the same time, their joint efforts balance these future requirements with what is technically feasible and cost-effective for those who must build equipment to meet power quality standards. EPRI believes that continued involvement in this work is required to help bridge the gap between equipment performance and the electrical environment.

Keywords

Voltage sags
SEMI F47
IEC 61000-4-34
IEEE P1668
SAE J2894
Ice cube relay

ABSTRACT

The 2010 equipment immunity work included both advising standards-development groups and promoting concepts of more robust end-use equipment within industry. In the standards arena, EPRI participated in the development of IEEE equipment-immunity standards and a Society of Automotive Engineers (SAE) standard for electric vehicle car chargers. System-compatibility concepts were promoted through a workshop and industry challenge. Furthermore, EPRI wrote a seminal white paper on the need to develop more robust relays. This report describes the details of each of these efforts and the forward path in this research arena.

CONTENTS

1
INTRODUCTION

This year's equipment immunity activities have contributed to the completion of one working group's activities and its final report, as well as continued support of an IEEE effort. Furthermore, EPRI joined an important Society of Automotive Engineers (SAE) standards effort. New ground was also charted with a call to action for the development of a more robust common industrial component—the "ice cube" relay. EPRI remains involved in these activities to ensure that the end result of the emerging standards work is improved system compatibility. The 2010 efforts have resulted in substantial work to move the electric utility and customer end-use equipment further toward compatibility.

In 2010, EPRI remained engaged in important standards and system-compatibility efforts in the industry. Efforts related to the IEEE, SAE, and International Electrotechnical Commission (IEC) were at the forefront of the work. Activities discussed in this update include:

- Completion of the final report from the CIGRE/CIRED/UIE joint working group JWG C4.110 *Voltage Dip Immunity of Equipment Used in Installations.* This seminal work has laid the ground for future standardization.
- Major updates to the draft IEEE 1668 document titled *Recommended Practice for Voltage Sag and Interruption Ride-through Testing for End-use Electrical Equipment Less than 1,000 Volts.* Building on the work from the JWGC4.110 report, this draft recommended practice is moving toward completion.
- Involvement in the development of the SAE J2894 standard for electric vehicle battery chargers. This is a timely and important standard that will help set the requirements for the mass premier of this new class of automobiles.
- The call to action from a white paper titled "AC Ice Cube Relays Applied for Improved Power Quality." A challenge that sounds like an oxymoron to those who are in the power quality profession, this paper and related efforts have made the case to industry for improved designs of this common component.

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COMPLETION OF THE JWG C4.110 WORKING GROUP EFFORTS

A joint effort of CIGRE[1], CIRED[2], and UIE[3], the JWG C4.110 Working Group disbanded in 2010 as the final report was issued. The purpose of this working group was to gather technical knowledge on the immunity of equipment, installations and processes against voltage dips[4], and to use this knowledge in the further development of methods and standards.

Issued in April of 2010 through CIGRE and UIE, the final report represents findings from an exhaustive three-year effort to better characterize voltage sags, their impacts, how voltage-sag testing should be conducted, and how end users can best specify equipment to match their power quality requirements. In order to disseminate the results of the work, several efforts were undertaken, including a workshop and continued "get the word out" efforts by UEI Working Group 2. This section details the basic conclusions of the work and the follow-up activities.

Obtaining the Final Report

The final report, shown in Figure 2-1, is posted at both the CIGRE and UIE web sites. It is available for free at the UIE site at the following URL: http://www.uie.org/node/401

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[1] CIGRE (International Council on Large Electric Systems) is one of the leading worldwide organizations on electric power systems, covering their technical, economic, environmental, organizational, and regulatory aspects.
[2] CIRED is the Congrès International des Réseaux Electriques de Distribution, or, in English, the International Conference on Electricity Distribution. CIRED is set up as an international association. Since October 2004, it has taken the legal form of a *de facto* association (association de fait) under Belgian law.
[3] The UIE, the International Union for Electricity Applications, is a non-governmental and non-profit organization founded in 1953. The objective of the UIE is to promote and develop the applications of electricity while respecting demands in the fields of protection of the environment, energy efficiency, economic viability, and social acceptance.
[4] *Voltage dip,* in the new IEC standards, is used in the same context as *voltage sag.* This eliminates the confusion that previously existed between standards and terminology.

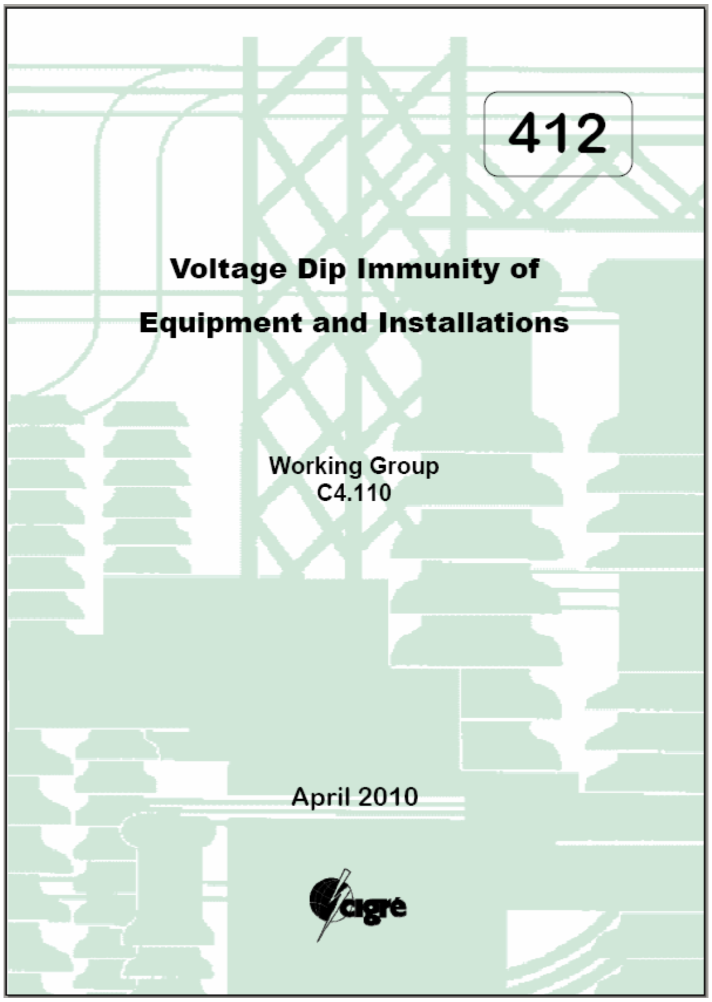


Figure 2-1
C4.110 Working-Group Report Available for Download

Major Conclusions from the Report

The conclusions of the working-group report are presented on a chapter-by-chapter basis.

Conclusions Related to Describing Voltage Dips

The working group has created a detailed description of the different properties and characteristics of voltage dips (called *sags* elsewhere in this report). The description of voltage dips divides the voltage waveform into pre-dip, during-dip, and recovery segments. The report focuses special emphasis on the three-phase character and the occasional non-rectangular character of voltage dips. Based on this detailed description, a summary of voltage-dip characteristics was created that may be used by equipment manufacturers and researchers as a checklist when they develop new equipment. For voltage dips in three-phase systems, the working group accepted a classification that is based on the number of phase-to-neutral voltages that show a significant drop in magnitude. The three types of dips (Type I, Type II, and Type III) correspond to a significant drop in magnitude for one-, two-, or three-phase-to-neutral voltages, respectively, as shown in Figure 2-2 [1]. It should be noted that the measurement of phase-to-neutral voltages provides more information but that the phase-to-phase voltages are more relevant for voltage-dip statistics on medium-voltage and high-voltage networks. Only for low-voltage networks with loads connected phase-to-neutral (as are common in most countries) should the phase-to-neutral voltages form the basis for voltage-dip statistics.

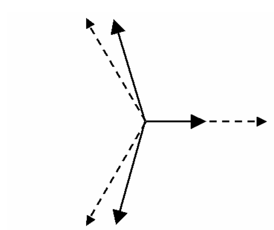
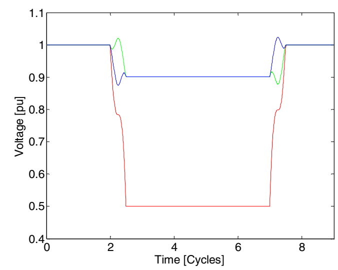
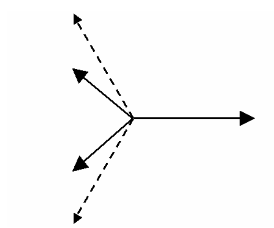
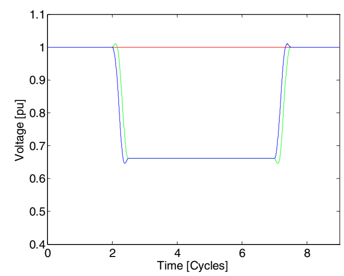
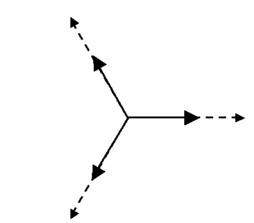
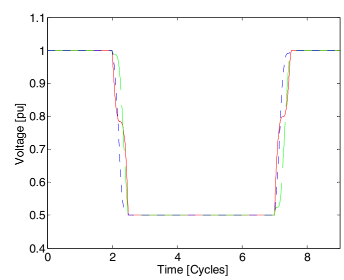
Basic Types of Voltage Dips	**Vector**	RMS Plot
Type I: Single-Phase Voltage Dip		
Type II: Two-Phase Voltage Dip		
Type III: Three-Phase Voltage Dip		

Figure 2-2
Type I, II, and III Voltage Dips

Conclusions Related to an Assessment of Equipment and Process Immunity

The final report from the C4.110 Working Group presents an overview of the immunity of different types of equipment against voltage dips. The impact of voltage-dip characteristics (magnitude, duration, and others) on equipment immunity is illustrated in a quantitative way. The working group introduced a useful new concept, “process-immunity time.” Starting with the nominal process parameter value P_{nom} (controlled by the device), an interruption in the supply voltage is assumed to occur at time t_1. As a result, the process parameter starts to deviate from its nominal value. This may happen instantaneously or, as depicted in Figure 2-3 [1], after a time interval •t. This delay might be associated with the tripping of the equipment •t seconds after the actual interruption in the supply voltage, or with a “dead time” in the process response. At time t_2, the process parameter value crosses the lower boundary P_{limit}, below which normal operation of the process cannot be maintained. Starting from t_2 onwards, the process no longer operates as intended and must be shut down, restarted, or otherwise corrected. The PIT is defined as the time interval between the start of the voltage interruption and the moment when the process parameter goes out of the allowed tolerance limit (below the limit).

$$PIT = t_2 - t_1$$

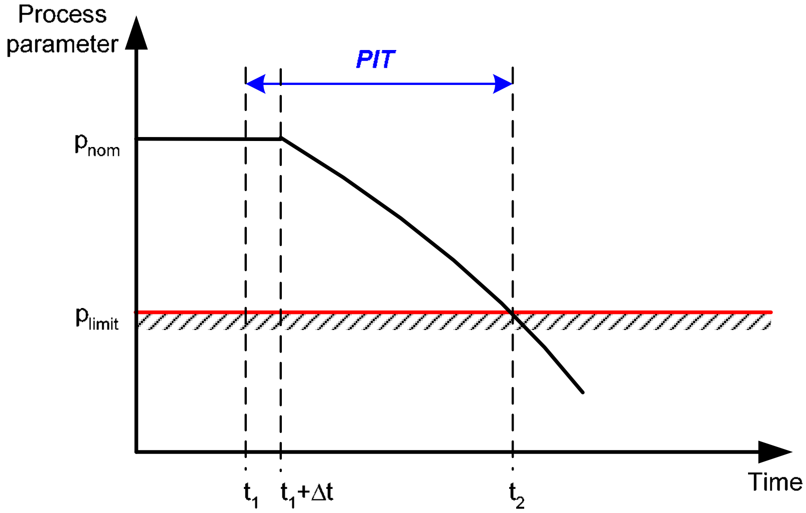


Figure 2-3
Definition of the Process Immunity Time (PIT) for Equipment within the Process

In the CIGRE report, a distinction is made between equipment failure and process failure. This new characterization is expected to allow for a better economic assessment of the impact of dips on industrial installations. The report also methodically presents a way for analyzing an entire process and finding a process-immunity time for each individual device or section of that process.

Conclusions Related to Immunity Testing and Characterization

The authors of the final report worked to make careful distinctions between characterization testing and compliance testing. The working group established guidelines for characterizing dip immunity of equipment. The working group proposed that the immunity of equipment be presented as a "voltage tolerance curve," which is one simple way for equipment manufacturers and users of their equipment to communicate about dip immunity. This is in contrast to the current versions of the IEC 61000-4-11 and IEC 61000-4-34 standards that require only specific test points [2, 3].

The working group recommended that compliance testing include only two characteristics: residual voltage (magnitude) and duration. Based on knowledge available at the present time, the working group did not see sufficient justification to perform additional tests covering characteristics such as phase-angle jump and point-on-wave.

For characterization testing of three-phase equipment, the working group recommended that the equipment immunity be described by voltage-tolerance curves for each of the three types of dips. The working group recognized that it may not be practical to exactly reproduce the unbalanced voltage dips. In many cases, approximations need to be made to allow the use of available test equipment. The working group did not specifically argue for or against any of the methods due to lack of information that any of the methods is significantly less likely to accurately assess the compatibility between the equipment and the system.

With regards to compliance testing of three-phase equipment, the working group recommended that tests for Type I, Type II, and Type III dips be included. Statistical data gathered by the working group showed that a significant number of voltage dips are of the Type III designation. However, due to a lack of data about the economic consequences of requiring such dips in compliance testing, the working group could not reach consensus and collectively gave no recommendations regarding the form in which Type III dips should be included in compliance testing [1].

Conclusions Related to the Economics of Voltage-Dip Immunity

The working group described the economics of dip immunity in a qualitative way in the report. A distinction was drawn between dip immunity of individual installations and dip-immunity requirements placed on all equipment through standards. While the economics of making equipment more immune at individual installations is well-understood, the cost of installation versus payback at a specific site may not be readily available. Therefore, the report lays out the steps for quantifying the economics of dip immunity at individual installations. The working group was not able to quantitatively determine the economics of setting global standards for equipment dip immunity. Many high-level discussions on this topic were discussed from the cost of new testing equipment for standards testing as well as the cost per machine to make the equipment robust to any new voltage-dip testing requirements. The working group concluded that economics play an important role in selecting the appropriate voltage-dip immunity, both for individual installations and for immunity requirements that impact all equipment.

Conclusions Related to Voltage-Dip Statistics

In order to determine what percentage of voltage dips were Type I, II, and III, the working group created a global database of voltage-dip statistics. This database included statistics from several countries on several continents. The database permitted the working group to reach new insights about the ratio between balanced and unbalanced dips, about the variation in number of dips between different sites, about the appropriateness of different equipment-immunity requirements, and about the characteristics of three-phase test vectors, among other dip-related questions. The results of the database analysis are presented as a set of contour charts for Type I, Type II, and Type III dips. One of the major findings was that Type III made up as much as 20 percent of the total number of recorded voltage dips. From this finding and as mentioned earlier in this section, the working group concluded that three phase (Type III) events should be included in testing and compliance standards.

Conclusions Related to Voltage-Dip Immunity Classes and Their Application

The working group created a number of classes concerning voltage-dip immunity and their associated immunity curves. The use of these classes should simplify communication between equipment manufacturers and equipment end users about voltage-dip immunity. Furthermore, this effort should allow equipment end users to have more information when selecting or specifying equipment for their facilities. The test levels (combinations of duration and voltage magnitude for each of the three types of dips) for each class were proposed.

The working group emphasized that performance criteria (how the equipment recovers after a dip-induced trip) were a critical concept next to the immunity requirement. Three performance criteria were proposed: "full operation," "self-recovery," and "assisted recovery." A "voltage-dip immunity label" was introduced that combines the immunity class with the performance criterion for a specific device. Finally, a systematic methodology, based on the voltage-dip immunity label, was introduced for selecting electrical equipment to ensure a required level of dip immunity for an industrial process.

Report Dissemination

The working group conducted several activities in 2010 to get the word out on the C4.110 final report. The first of these activities was the presentation of the results in a tutorial at the annual EPRI Power Quality and Smart Distribution Conference. Held in on June 14th, 2010 in Quebec City, about 20 individuals attended this important tutorial. Members of the working group presented the concepts from the report. The tutorial agenda is shown in Figure 2-4.

Voltage Dip Immunity of Equipment Used in Installations: CIGRE/CIRED/ UIE C4.110 Tutorial

Voltage DIP Characteristics
Math Bollen, STRI

Equipment and Processes
Kurt Stockman, University College West Flanders, Ghent University Association

Immunity Testing
Bill Brumsickle, SoftSwitching Technologies

Voltage DIP Economics
Alex McEachern, Power Standards Lab

Voltage DIP Statistics and Classification
Robert Neumann, Qualitrol

Immunity Objectives
Gaetan Ethier, Hydro-Québec

Figure 2-4
Voltage-Dip Immunity Tutorial Agenda from 2010 PQ and SD Conference

After the completion of the C4.110 working group efforts, UIE Working Group 2 took on the responsibility of getting the word out related to the report's findings and recommendations. Among the responsibilities of UIE Working Group 2 was sending letters to stakeholders. The summarized content to various stakeholders is shown below:

The key messages issued to regulators are the following:

- The occurrence of voltage dips is part of the normal operation of any power system.
- Monitoring and recording of voltage dips is needed.
- Regulators should provide the incentives to facilitate voltage-dip monitoring by network operators.

The main messages from to the network operators (electric utilities) are:

- Voltage dips are a main concern for industrial customers after reliability.
- Voltage dips may result in serious economic loss for many industrial customers.
- Mutual understanding of the origin and consequences of voltage dips is an essential basis for jointly addressing the compatibility between the network and the industrial installation. Furthermore, customers need data on number and severity of voltage dips to improve immunity.

The key messages conveyed in a letter to equipment manufacturers contained the following ideas:

- Manufacturers should consider voltage-dip immunity of their equipment at an early stage in the process of developing new equipment.

- Customers need to know the immunity of equipment against voltage dips in order to choose equipment for use in their installations. Voltage-tolerance curves are a suitable method for this.
- The voltage-dip immunity label concept simplifies communication between equipment manufacturers and their customers.
- Equipment manufacturers should get involved in the further development of voltage-dip immunity labels.

The key messages conveyed in a letter to industrial customers are:

- The occurrence of voltage dips is part of the normal operation of a power system. The number of dips varies strongly between locations. Network operators can provide indicative information on this.
- Improving the immunity of installations against voltage dips should be based on economic considerations.
- Dips should be considered during the design of an installation using the new methodology of Process Immunity Time.
- Cooperation between process and electrical engineers is essential to solve problems due to voltage dips.

The key messages to manufacturers of power quality monitors are:

- In a three-phase system, distinguish between Type I, Type II, and Type III voltage dips. Monitoring equipment should begin to classify voltage dips in these categories as described in the working group report.
- Monitor manufacturers should contribute to the development of suitable additional voltage-dip characteristics. There are other characteristics such as phase-angle jump and point-on-wave that would be helpful to capture with a PQ monitor.
- Monitor manufacturers are encouraged to have their systems present statistical results in the form of contour charts and percentiles. When information from voltage dips over a longer period is available, this should be presented in the form of a voltage-dip contour chart or a similar method. It is thereby essential that the number of dips be given separately as a function of residual voltage, as well as duration, for Type I, Type II and Type III dips. Providing the number of dips only as a function of the residual voltage is insufficient.

3
IEEE P1668 WORKING GROUP

Background

The IEEE P1668 Working Group got underway in 2007 and continued in 2010. This is a working group under the Power System Engineering Subcommittee of the IEEE Industrial Applications Society. Meetings are formally held at the IEEE Industrial and Commercial Power Systems annual meeting and at the Industrial Applications Society annual meeting (when in the U.S.). This working group is expected to determine the basis for new testing standards for commercial and industrial equipment in a manner similar to those efforts that produced the SEMI F47 [4] and the IEC 61000-4-11 and 34 standards.

The plan of the working group is to gain consensus on a two-year guide for trial use that will serve as the testing standard for performing the system-compatibility assessment of industrial and commercial equipment. Should the two-year trial guide be accepted by consensus, it will then become an approved guide that will serve for five years. After this five-year period, there exists a possibility of developing either a test standard or a recommended-practice document, depending upon the interest.

It is anticipated that the recommended practice could form the basis of the proof or certification that the equipment so tested may meet various curves or tolerance envelopes. The intended result will be that equipment manufacturers would likely provide a line on their data sheets indicating that the equipment meets IEEE 1668. As EPRI participates in both the IEEE P1668 work as well as the JWG C4.110 activities described in the previous section of this report, efforts will be made to coordinate the activities and outcomes of these two efforts where possible. If done successfully, the IEEE P1668 recommended practice and the future IEC and SEMI voltage-sag standards would be harmonious.

It is also envisioned that this document could provide additional voltage-tolerance profiles for various equipment categories into two existing IEEE documents that are in preparation for the revision process: IEEE Std. 1346 and IEEE Std. 1000.

P1668 Working Group on the Web

The P1668 standard working group includes ten manufacturer participants, seven utility participants, and four participants from EPRI. The membership as well as working group information can be found at http://grouper.ieee.org/groups/ias/1668/index.html.

Overview of Scope

The scope of the IEEE P1668 is to provide a non-industry-specific recommended practice for voltage-sag ride-through performance and compliance testing regarding all electrical and electronic equipment connected to low-voltage power systems that may experience malfunction or shutdown as a result of reductions in supply voltage lasting less than one minute. The recommended practice will include the definition of minimum voltage-sag immunity requirements based on actual voltage-sag data rather than the capabilities of a given test fixture or platform. An included section, dedicated to the detailed analysis of voltage sags experienced by end users, provides insight into real-world voltage sags. The goal of this document is to clearly define the required testing procedures and test equipment requirements to reflect this electrical environment including single-phase, phase-to-phase, three-phase, and unbalanced voltage sags. The recommended practice also defines certification and test-reporting requirements, including voltage sag ride-through equipment characterization.

The working group has also determined that the purpose of the recommended practice is to clearly define test methods and ride-through performance for determining the sensitivity of electrical and electronic equipment to voltage sags. Analysis of real-world sags provides the foundation for both the test methods and the criteria, aligning themselves as closely as possible to the end user's electrical environment. The standard will define the characteristics of voltage-sag depth, duration, phase angle, and vectors required to relate to voltage-sag events actually experienced in the field. The recommended practice will show how different voltage-sag testing methods can be used to simulate these "real world" sags. End users will be able to use the standard in their purchase specifications to ensure the required level of performance. In addition, end users can use the voltage-sag criteria as a performance benchmark for existing equipment [5].

Updated Layout of the Document

One major item that changed this year was that the P1668 document structure was re-organized to place the most relevant information in the body of the document. Sections that were previously chapters were moved to annex sections and are seen as informational to the main body of the document.

The IEEE P1668 draft recommended standard is now arranged as shown below.

Section 1 – Overview. This section will define the scope and purpose of the recommended practice.

Section 2 – Limitations. This section, basically, will outline that IEEE P1668 is a voltage-sag standard and will also outline what items that the standard does not address.

Section 3 – Normative References. This section will outline the ANSI and IEEE standards that are referenced and related to this recommended practice.

Section 4 – Definitions. The terms that are included in the standard are clearly defined, including items such as *ride-through capability* and *voltage sag*.

Section 5 – Electrical Environment. This section will define the causes of voltage sags, their typical characteristics, the effects of faults on the electric system, how voltage sags occur, how sags propegate throughout the system, how common sags are in the electrical system, and how voltage sags and phase currents are related. Particular focus is placed on how voltage sags appear at the point of connection (PCC) of the customer's equipment.

Section 6 – Recommend Voltage Sag Test Requirements. This section defines the requirements for voltage-sag testing for Type I, Type II, and Type III voltage sags.

Annex A: Test Procedures and Guidelines. This section describes how to conduct testing and provides guidance to the reader regarding which test methods are most relevant for the equipment types.

Annex B: Testing Equipment Requirements. The basic requirements of the voltage-sag generator will be defined in this section.

Annex C: Certification and Test Reports. The format of certification and test reports are defined in this section.

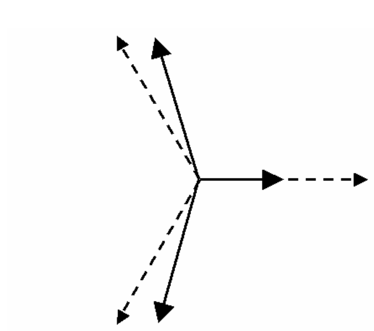
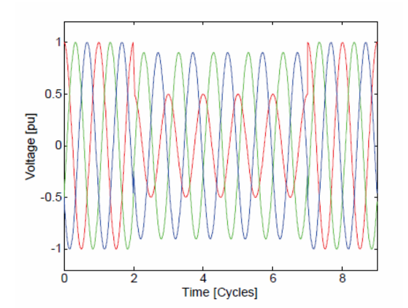
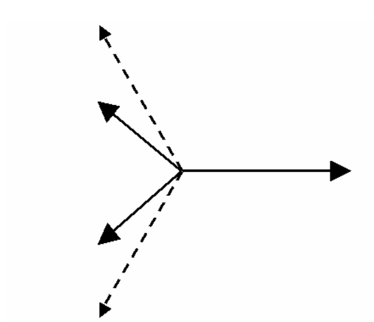
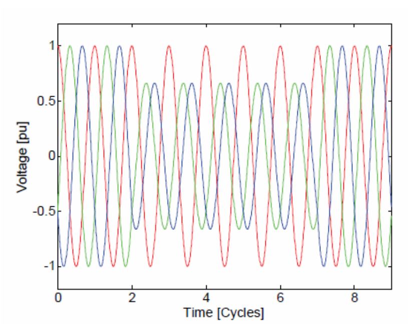
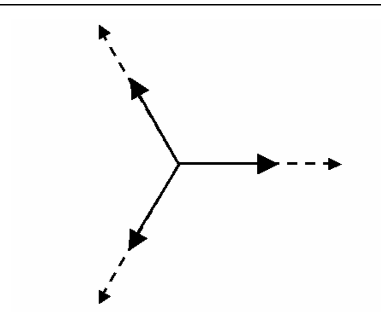
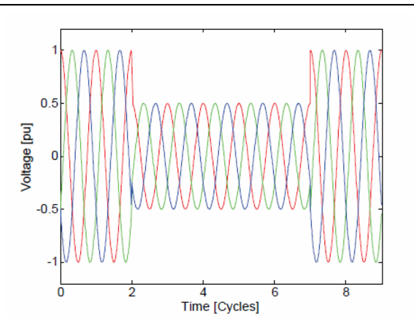
Recap of 2010 Efforts

The majority of work in the 2010 efforts focused around updating Section 5 to incorporate some of the C4.110 Working Group results and included a rewrite of Section 6. Furthermore, updates to the test procedures and guidelines, test equipment requirements, and certification and test reports were made. The following is a summary of the work in some of these areas.

Major Updates in the Document

Key changes to Section 6 are noted herein to help the reader understand the nature of the updates that have occurred. The new layout of Section 6 is less informational and more direct with respect to defining the requirements of the recommended practice. Section 6 now begins by classifying the types of voltage sags experienced in a three-phase system as Type I, Type II, and Type III. Table 3-1 shows the way in which types of voltage sags are presented in the document.

Table 3-1
Type I, II, and III Voltage Sag Classifications [5]

Voltage Sag Type	Description	Vector Diagram	Waveform
Type I[5]	This is a voltage sag in which the drop in voltage takes place mainly in one of the phase-to-ground voltages. $\overline{U}_a = \overline{V}$ $\overline{U}_b = -\frac{1}{2}\overline{V} - \frac{1}{2}j\overline{E}\sqrt{3}$ $\overline{U}_c = -\frac{1}{2}\overline{V} + \frac{1}{2}j\overline{E}\sqrt{3}$		
Type II	This is a voltage sag in which the drop in voltage magnitude takes place mainly in one of the phase-to-phase voltages. $\overline{U}_a = \overline{E}$ $\overline{U}_b = -\frac{1}{2}\overline{E} - \frac{1}{2}j\overline{V}\sqrt{3}$ $\overline{U}_c = -\frac{1}{2}\overline{E} + \frac{1}{2}j\overline{V}\sqrt{3}$		
Type III	This is a voltage sag in which the drop in voltage magnitude is equal for the three voltages. $\overline{U}_a = \overline{V}$ $\overline{U}_b = -\frac{1}{2}\overline{V} - \frac{1}{2}j\overline{V}\sqrt{3}$ $\overline{U}_c = -\frac{1}{2}\overline{V} + \frac{1}{2}j\overline{V}\sqrt{3}$		

The document then explains that the three basic voltage sag classifications can be used to understand how faults and voltage sags propagate through the electrical system.

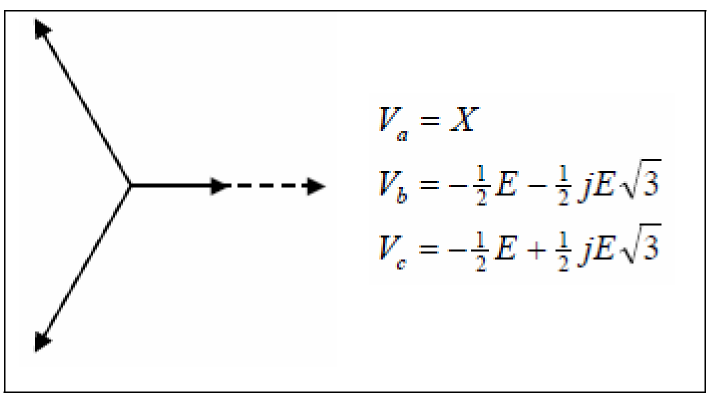
Table 3-2 shows an example of propagation of voltage sags and their resultant type based on the various transformation levels [5].

Table 3-2
Fault Propagation as Described by Type I, II, and III Voltage Sag Type Classifications

Type of Fault	Voltage Sag at Faulted Voltage Level	Voltage Sag after One Delta-Wye Transformer	Voltage Sag after Two Delta-Wye Transformers
Three-phase	Type III	Type III	Type III
Single-phase in a solidly-grounded network	Type I with a zero-sequence voltage	Type II	Type I
Single-phase in a non-solidly-grounded network	Zero-sequence voltage only	No voltage sag	No voltage sag
Two-phase	Type II	Type I	Type II
Two-phase-to-ground in a solidly-grounded network	Type II with a zero-sequence voltage	Type I, but with a bigger drop in magnitude in all phases than the common Type I	Type II, but with a bigger drop in magnitude in all phases than the common Type II
Two-phase-to-ground in a non-solidly-grounded network	Type II with a zero-sequence voltage	Type I	Type II

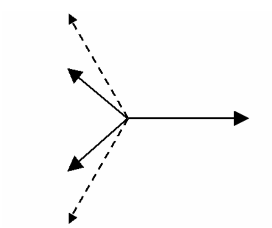
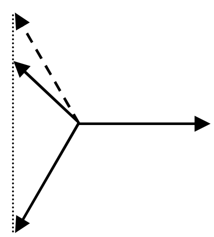
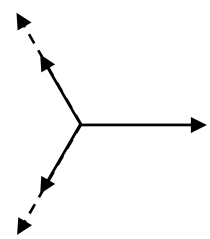
Next, the document notes that when performing voltage-sag testing, alternate voltage-sag vector forms are allowable. When conducting three-phase tests, single-phase Type I voltage sags are created on one phase at a time. Although the allowable Type I voltage sag has no phase shift with respect to the neutral, it is relatively easy to create with standard test equipment and has been used in existing standards—such as IEC 61000-4-11, IEC 61000-4-34, and SEMI F47-0706—to represent Type I events. Table 3-1 shows the recommended Type I test vector for voltage sag testing [5].

Table 3-3
Recommended Type I Test Vector



Next, phase-to-phase Type II voltage sags are discussed. Type II sag events normally occur on the secondary side of a delta-wye transformer when there is a single-phase fault on the primary side of the transformer. A Type II event can also occur when two conductors are faulted together[6] . As noted in the draft recommended practice, there are three common methods for creating Type II voltage sags. Table 3-4 shows the recommended two-phase test vector (Type II) and two allowable alternatives designated as Type II.A1 and Type II.A2 [5]. A Type II.A1 event does not occur often and induces the most phase shift. The Type II.A2 event may occur when there is a simultaneous phase-to-phase-to-ground fault. Because the choice of test vector for Type II sags has been known to change the outcome of the voltage-sag test result, consult Annex A for guidance.

Table 3-4
Recommended and Alternative Type II Test Vectors

Type II (Recommended)	**Type II.A1 (Alternative 1)**	**Type II.A2 (Alternative 2)**
 $\overline{U}_a = \overline{E}$ $\overline{U}_b = -\frac{1}{2}\overline{E} - \frac{1}{2}j\overline{V}\sqrt{3}$ $\overline{U}_c = -\frac{1}{2}\overline{E} + \frac{1}{2}j\overline{V}\sqrt{3}$	 $V_a = E$ $V_b = -\frac{1}{2}E - \frac{1}{2}jE\sqrt{3}$ $V_c = -\frac{1}{2}E + \frac{1}{2}j(2X - E)\sqrt{3}$	 $V_a = E$ $V_b = -\frac{1}{2}X - \frac{1}{2}jX\sqrt{3}$ $V_c = -\frac{1}{2}X + \frac{1}{2}jX\sqrt{3}$

For Type III voltage sags, the recommended test vectors are the same as those shown in Table 3-1.

The P1668 draft document specifically recommends voltage-sag immunity levels for the Type I, Type II, and Type II voltage sags. It is important to note that the test point with the longest duration has been increased from 1 second to 2 seconds to reflect the longer clearing times of utility breakers that are known to occur for shallow distribution-level voltage sags caused by faults in Zone 3.

[6] The Type II scenario results from a single-phase line-to-ground fault on the primary of a delta-wye transformer with a solidly grounded neutral on the secondary.

Table 3-5 and Figure 3-1 detail the recommended test points for Type I and Type II voltage sags [5].

Table 3-5
Recommended Test Points for Type I and Type II Voltage Sags

Minimum Test Point No.	Sag Depth in Percent Nominal	Duration in Seconds	Duration at 50 Hz	Duration at 60 Hz
1	50%	0.2	10 cycles	12 cycles
2	70%	0.5	25 cycles	30 cycles
3	80%	2.0	100 cycles	120 cycles

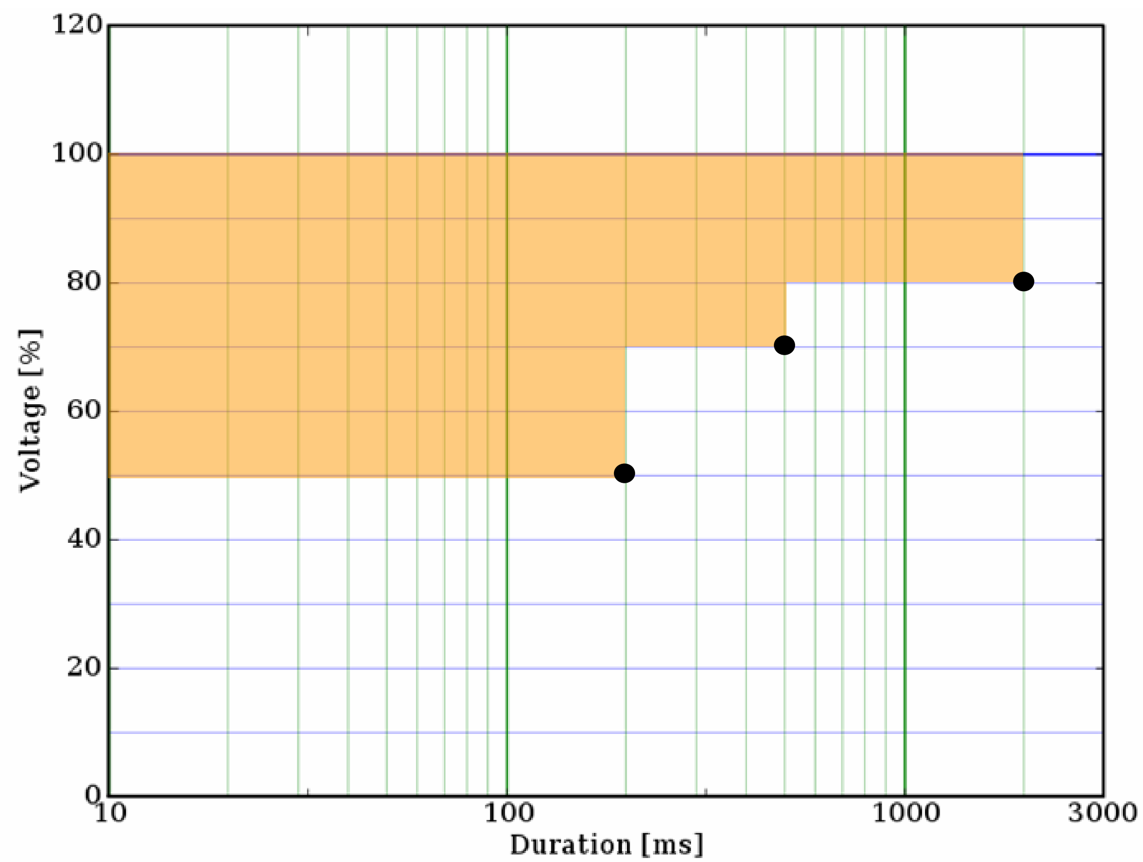


Figure 3-1
Recommended Type I and Type II Test Levels Shown in Table 3-5

Because of the variation of three separate Type II voltage-sag test vectors, the recommended practice details the expected phase-vector magnitudes for each of the three scenarios. Figure 3-2 details the expected magnitude and vector diagrams for the three main test points for Type II, Type II.A1, and Type II.A2 test vectors [5].

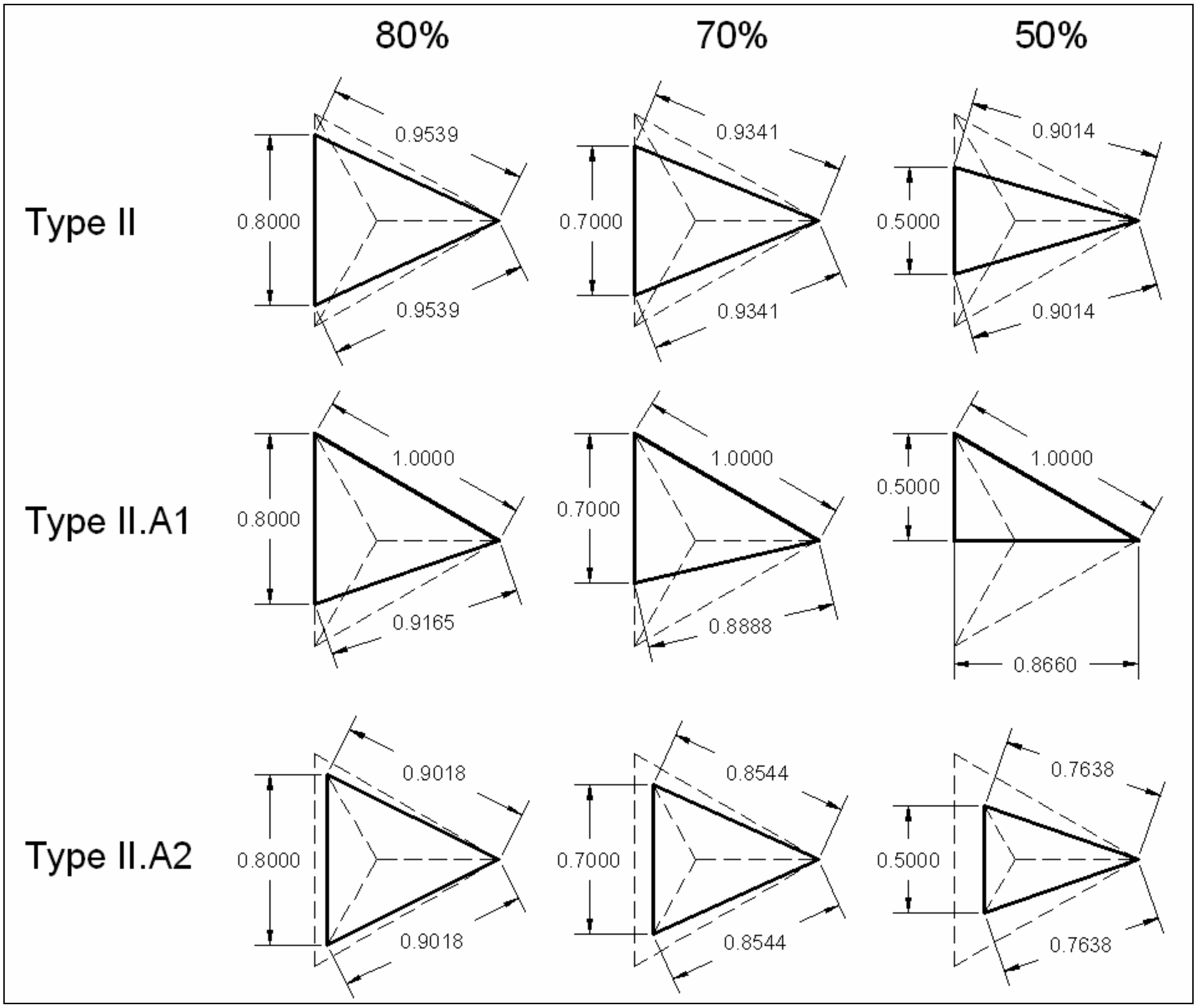


Figure 3-2
Vector Details for Type II, Type II.A1, and Type II.A2 Voltage-Sag Compliance Test Points

The working group considered typical industrial equipment voltage sag test data and the C4.110 study when considering what levels would be reasonable for three-phase systems. For variable-frequency AC drives, many units have built-in ride-through capability and thus have the ability to ride through even three-phase voltage sags to 80 percent of nominal and continue operation, albeit with some drop in speed. However, DC drives are known to be one of the most sensitive load types to voltage sags. Therefore, three-phase test results from these units were examined from EPRI research to understand their capabilities as representative of one of the worst types of three-phase loads [6]. The recommended voltage-sag test levels for Type II sags are shown in Table 3-6 and Figure 3-3 [5].

Table 3-6
Recommended Test Points for Type III Voltage Sags

Minimum Test Point No.	Sag Depth in Percent Nominal	Duration in Seconds	Duration at 50 Hz	Duration at 60 Hz
1	50%	0.05	2.5 cycles	3 cycles
2	70%	0.1	5 cycles	6 cycles
3	80%	2.0	100 cycles	120 cycles

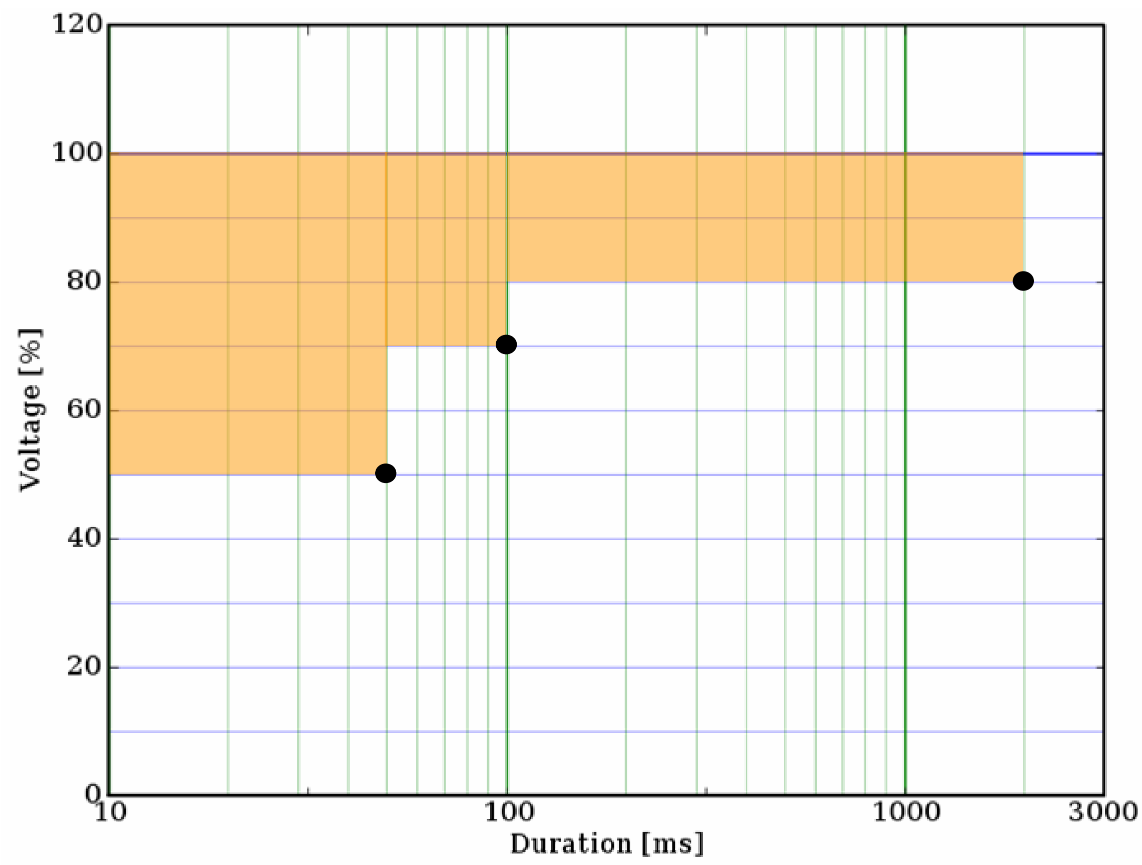


Figure 3-3
Recommended Type III Test Levels Shown in Table 3-6

The document now addresses the test conditions in which the equipment should be subjected to voltage sags in order to best understand its immunity to power quality events. To that end, the P1668 recommended practice is designed to allow reasonable efforts at determining the immunity of process equipment, subsystems, and components to typical voltage sags. The document recommends that the EUT be tested for voltage-sag immunity under conditions that will, according to the reasonable engineering judgment of the equipment manufacturer, approximate expected factory operating conditions. Engineering judgment shall take into account the following considerations:

- The EUT shall be tested in its most sensitive process states, as determined by the EUT manufacturer. For example, this may include robot movement, maximum power processing, and most sensitive measurement.
- Components and subsystems when tested independently shall be tested under load (for example, DC power supplies and AC drives.)

Specific pass/fail criteria are now defined in the document as well. A clear identification of equipment behavior during and after voltage sags is crucial for the assessment of equipment immunity. Accordingly, equipment immunity to various types/severities of voltage sags can be quantified only if a clear distinction is made between the two following equipment-performance criteria: “normal equipment operation” and “equipment tripping/malfunction.” Generally, a process or equipment (including all components and subsystems) will respond to a voltage sag in one of the following ways:

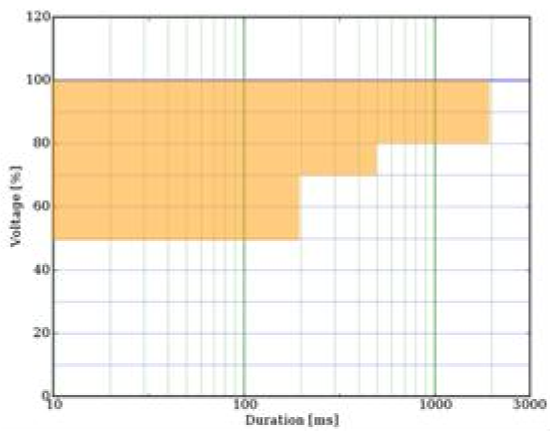
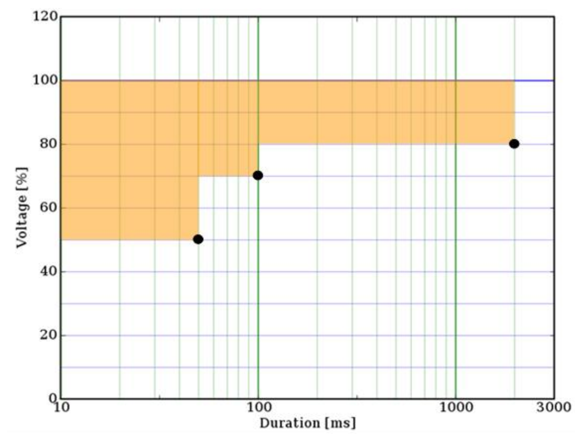
- Full (normal) operation: Equipment performs as expected or as intended and all of its relevant parameters are within technical specification or within allowed tolerance limits. Equipment performance should be expressed and measured against the set of relevant/critical “equipment outputs” (such as speed, torque, and voltage level), which have to be defined according to the process requirements.
- Self-recovery: Equipment does not perform its intended functions, or its outputs vary outside the technical specification/limits, but equipment is able to automatically recover after the end of a voltage sag without any intervention from the user.
- Assisted-recovery: Equipment does not perform its intended functions, or its outputs vary outside the technical specification/limits, and equipment is not able to automatically recover after the end of a voltage sag. Assisted-recovery criteria should be applied only when there are dedicated and/or trained personnel/staff, who either operate the equipment or are responsible for supervising the equipment at all times when equipment is in use. If some external control circuit is applied for automatic restarting of equipment, it should be treated as a self-recovery criterion [5].

The recommended practice states that in the absence of other instructions or requirements, the default pass/fail criteria for voltage-sag immunity testing of equipment shall be full (normal) operation. Furthermore, in the absence of other instructions or requirements, the default pass/fail criteria for voltage-sag immunity testing of components shall be full (normal) operation. Each system integrator/OEM, when constructing equipment that will comply with this specification, must select components and subsystems that respond appropriately to voltage sags.

The recommended practice details how to use the specification for procurement purposes. The format in which this is presented is based on the format proposed by the C4.110 Working Group in its final report. Equipment-immunity specification sheets, shown in Table 3-7 and Table 3-8, are given in the draft standard for use by equipment buyers when purchasing three-phase or single-phase equipment [5].

Table 3-7
IEEE P1668 Equipment-Immunity Specification Sheet (For Use with Three-Phase Equipment)

Equipment-Immunity Specification
IEEE P1668 Voltage-Sag Immunity Requirement for Three-Phase Equipment

Immunity Curve for Type I & Type II Sags	Immunity Curve for Type III Sags
	

Type I and II voltage sag test points:	**Testing for Type III voltage sag required :**
80% for 2 seconds 70% for 500 milliseconds 50% for 200 milliseconds Repeat for test points for each phase-neutral and phase-to-phase combination.	80% for 2 seconds 70% for 100 milliseconds 50% for 50 milliseconds

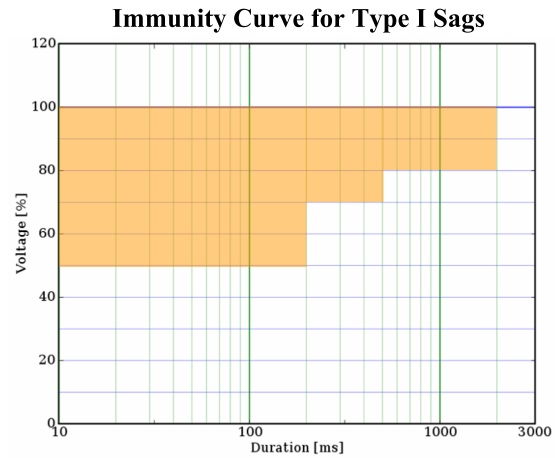
Desired Type II Test Vector

Type II	**Type II.A1**	**Type II.A2**
☐	☐	☐

Pass/Fail Criteria			**Pass/Fail Criteria**		
Full Operation	**Self-Recovery**	**Assisted-Recovery**	**Full Operation**	**Self-Recovery**	**Assisted-Recovery**
☐	☐	☐	☐	☐	☐

Testing Procedure Requirements: IEEE P1668

Table 3-8
IEEE P1668 Equipment-Immunity Single Specification Sheet (For Use with Single-Phase Equipment)

<table>
<tr><th colspan="3">Equipment-Immunity Specification
IEEE P1668 Voltage-Sag Immunity Requirement for Single-Phase Equipment</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><td colspan="3">Type I voltage sag test points:

80% for 2 seconds
70% for 500 milliseconds
50% for 200 milliseconds</td></tr>
<tr><td colspan="3">Pass/Fail Criteria</td></tr>
<tr><td>Full Operation</td><td>Self-Recovery</td><td>Assisted- Recovery</td></tr>
<tr><td>☐</td><td>☐</td><td>☐</td></tr>
<tr><td colspan="3">Testing Procedure Requirements : IEEE P1668</td></tr>
</table>

Forward Path

After four years of effort, the P1668 recommended practice is nearing completion. It is expected that the document will be completed in late 2010 and will be circulated for internal review and comment by participants of the working group. With comments incorporated by late early February 2011, the document will be sent to the IEEE editorial committee and it will go to ballot afterward. The next expected face-to-face meeting to discuss the document and possibly review the ballot responses will be at the 2011 I&CPS (Industrial & Commercial Power Systems) Technical Conference. This conference will be held May 1 through May 5, 2011, in the Los Angeles area.

4
SAE J2894 STANDARD

Background

When GM introduced the EV-1 in the 1996, it was realized that power quality must be addressed in the charging systems to make sure that the vehicles were compatible with the power system and were robust to common power quality disturbances. From a utility standpoint, the plug-in electric vehicle[7] (PEV) should not cause harm to the electric grid. Increased load from a multitude of charging stations should not cause increased transformer failures or grid stability issues. From a consumer standpoint, the PEV should be ready to drive first thing in the morning to take us to work. If the car's charging system is upset or damaged by normal power quality events, adoption of this new form of transportation could be hampered. Because of these reasons, it was realized that there needed to be a recommended practice for EV charging systems as related to power quality issues. In 1997, EPRI's Infrastructure Working Council (IWC) published a set of power quality guidelines for PEV charging of electric vehicles in its report [1]. Although the EV-1 program was only a trial run of the electric transportation, the EPRI report that was produced was generally perceived as the initial guidelines for any future electricity-powered vehicles [7].

[7] The industry has recently adopted the terminology of "plug-in electric vehicle" (PEV) rather than the former terminology of EV. This is due in part to the fact that today's electric vehicles may be plug-in electric hybrids, electric extended-range vehicles, or purely electric vehicles.

EPRI Customer Systems Search Home

Electric Transportation

EV Charging Equipment Operational Recommendations for Power Quality

TR-109023
Final Report, October 1997
EPRI Project Manager Layla Sandell

Abstract

Designers of EV battery charging equipment must understand the characteristics of the AC service to which the equipment will be connected if they are to develop products that are sufficiently robust, reliable and cost effective to satisfy the needs of the EV owner. The engineer must also understand that the battery charger can have a significant impact on the quality of the AC service to which it is connected. Since the charger is the conduit through which energy moves from the AC line to the vehicle battery, it is the battery charger that controls the rate at which energy is transferred and the manner in which energy is transferred to the battery. In other words, it is the battery charger that controls power quality.

The information presented in this paper may be useful to power supply designers, managers of charger development programs, and electric utility staff responsible for certifying or approving chargers that will be allowed on the utility system. The purposes of this paper, then, are threefold:

1. To identify those characteristics of the AC service that may significantly impact the performance of the charging equipment.
2. To identify those parameters of EV battery chargers that must be controlled in order to preserve the quality of the AC service.
3. To recommend target values for power quality, susceptibility, and power control parameters which are based on and consistent with applicable U.S. and international standards, and which should be technically feasible and cost effective to implement in EV battery charging equipment.

Finally, a set of control parameters is presented that the utility industry feels are necessary to minimize the impact EV battery chargers will have on the power distribution infrastructure. A brief discussion of the different types of EV battery chargers is provided as background information.

I. Types of EV Battery Chargers

Electric vehicle battery chargers can be identified as belonging to one of two basic categories - those which provide galvanic (DC) isolation between the AC line and the charger output terminals, and those which provide no isolation whatsoever. Isolated chargers use some form of magnetic coupling to effect the DC isolation between the AC line and the charger output.

By definition, inductively coupled chargers are isolated chargers. Galvanic isolation is provided by the charge coupling which is composed of two components; the vehicle inlet and the coupler. The charge coupling is actually a take-apart transformer, the coupler comprising the transformer primary and the vehicle inlet housing the transformer secondary.

Conductively coupled chargers may or may not provide galvanic isolation. Galvanically isolated, conductively coupled chargers use power transformers to achieve isolation between the AC line and the charger output. The power transformer is generally a large, heavy and expensive component. On the other hand, a non-isolated charger does not require an isolation transformer. It is, therefore, smaller, lighter and less expensive than its isolated counterpart.

EV battery chargers are further classified by power level as being capable of either Level 1, Level 2 or

Figure 4-1
1997 EPRI Report Laid the Initial Groundwork for PEV Charger PQ Requirements

The initial recommendations given by EPRI in the 1997 document are summarized in Table 4-1 [7]. This document summarized power quality emissions, susceptibility, and restart control after a power outage. These are the basic parameters that formed the starting point for the J2894 working group.

Table 4-1
Electric Vehicle Charging Equipment Power Quality Parameters - EPRI 1997 Report

Item	Parameter	Level 1 Charging (120 V_{AC})	Level 2 Charging (240 V_{AC})
1	Total Power Factor (minimum)	95%	95%
2	Power Conversion Efficiency (Minimum)	85%	85%
3	Total Harmonic Current Distortion	20% Maximum	20% Maximum
4	Current Distortion at Each Harmonic Frequency	IEC 555-2 IEC 1000-3-2 3/95	IEC 1000-3-4 (Draft)
5	Inrush Current	28 A	56 A
6	Voltage Range	90% to 110% of Nominal	90% to 110% of Nominal
7	Voltage Swell	180% of Nominal for 2 Cycles	180% of Nominal for 2 Cycles
8	Voltage Surge	6 kV Minimum ANSI C62.41 & C62.45	6 kV Minimum ANSI C62.41 & C62.45
9	Voltage Sag	Down to 80% of Nominal for 2 Seconds	Down to 80% of Nominal for 2 Seconds
10	Momentary Outage	0 Volts for 12 Cycles	0 Volts for 12 Cycles
11	Frequency Variations	+/- 2% of Nominal	+/- 2% of Nominal
12	Power Control Parameters – Staggered Restart after Power Loss	Delay Restart 2 Minutes + 10-Minute Random Start or Ramp Up	Delay Restart 2 Minutes + 10-Minute Random Start or Ramp Up

Updating the Requirements

Based on the recommendation of many electric utilities, the 1997 EPRI report became the cornerstone of many PEV charger designs. In December of 2008, the IWC decided to update the document and integrate it into the SAE vehicle standards. In April of 2009, the SAE Hybrid Committee accepted a proposal to integrate EPRI PQ Vehicle Requirements into the standards group. With that move, the SAE J2894 Task Force Committee was formed with a goal of writing a two-part recommended practice. The requirements in part 1 are written in the form of a recommended practice for surface vehicles titled J2894/1 *Power Quality Requirements for Plug-In Electric Vehicle Chargers.* This document is currently being balloted. The second part will involve writing the test methods in which the PEV chargers are to be evaluated. This portion of the work has not yet officially begun at this time.

The scope of the J2894/1 document is to develop a recommended practice based on EPRI's TR-109023 report, *EV Charging Equipment Operational Recommendations for Power Quality,* which will enable vehicle manufacturers, charging-equipment manufacturers, electric utilities, and others to make reasonable design decisions regarding power quality. As stated in the document, the three main purposes of this work are:

1. To identify those characteristics of the AC service that may significantly impact the performance of the charging equipment.

2. To identify those parameters of PEV battery charging that must be controlled in order to preserve the quality of the AC service.
3. To recommend target values for power quality, susceptibility, and power-control parameters that are based on current U.S. and international standards [8].

The recommended practice has set the goal that the recommended values within the document should be technically feasible and cost-effective to implement into PEV battery-charging equipment.

As a rationale for this, the document notes three main reasons for the need of the recommended practice. First, sensitive microprocessor-based devices are more susceptible to power variances. Therefore, the charger and onboard electronics need to be robust in order to handle these variances. Secondly, increasing numbers of nonlinear devices have resulted in the rise of harmonics in the power system, leading to reduced system reliability. Should there be widespread deployment of these chargers, they must be designed for minimal harmonic contributions to the electrical grid. Finally, the vast networkability of devices has led to larger consequences from failure. If a charger circuit fails to properly interface with the electric vehicle supply equipment (EVSE) or the EV's onboard electronics, the consequences could upset the charging operation and possibly the vehicle operation. Although the EVSE may be referred to as a *charger,* it is technically supplying AC power to the on-board charger of the PEV.

It is important to understand the configuration and terminology surrounding a PEV and its charging configuration. A simple diagram of a PEV connected to the EVSE, a residential circuit and panel, and the utility meter is shown in Figure 4-2.

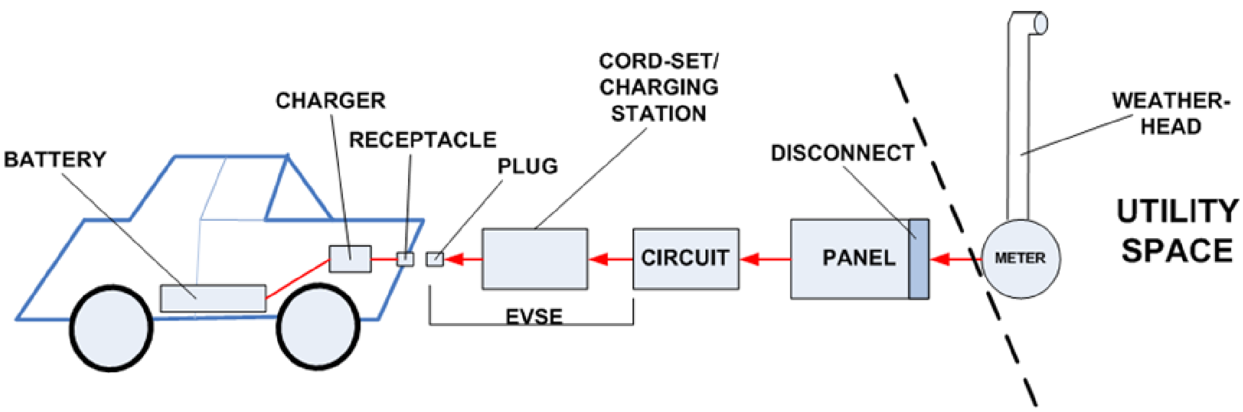


Figure 4-2
Plug-in Electric Vehicle Charging System Diagram

The home "service" is the main AC feed that supplies the power for the residence. The "panel" contains circuit breakers and distributes AC power circuits throughout the residence. The "circuit" consists of the wires and interconnects from one breaker at the home to the EVSE. The EVSE supplies power to the vehicle. Finally, the onboard charger converts AC to DC for use in charging the batteries in the PEV.

There are two main classes of AC charge voltages that will be used. AC Level 1 refers to 120 V_{AC} single-phase charging. These circuits may have charging currents up to 16 amps and 1.92 kW. AC Level 2 charging circuits may be 208 or 240 V_{AC}. Level 2 circuits can draw up to 80 A and are rated up to 19.2 kW.

Basic Requirements of Draft J2894 Part 1

The basic requirements of the draft recommended practice regarding power quality and the AC service characteristics are shown in Table 4-2 [7, 8]. In each case, the new draft J2894 requirement is shown in contrast to the 1997 EPRI report guidelines.

Table 4-2
J2894 Part 1 Charger PQ Requirements vs. EPRI's 1997 Recommended Practice

Parameter	**SAE J2894**	**EPRI 1997 Document**
Power Factor	95%	95%
Power Transfer Efficiency	90%	85%
$\%I_{THD}$	10%	20%
Inrush Current	120% Nominal Max.	Specific Value

As shown in Table 4-2, the new document increases the efficiency requirement for the charger circuit from 85 percent to 90 percent. This is significant and is a testament to the improvements in power electronic circuit design. Furthermore, EPRI's 80 PLUS power supply testing work has demonstrated that it is feasible for power supply circuits to reach higher efficiencies. The J2894 Part 1 document also cuts the current limit for total harmonic distortion from 20 percent down to 10 percent. As was demonstrated through these efforts, newer power electronic topologies can achieve lower harmonic distortion through the use of power-factor-corrected designs.

Another key element in the recommended practice is the definition of service limits in which the equipment should operate. Table 4-3 compares the requirements of the J2894 Part 1 document against the original EPRI report [7, 8]. The J2894 Task Force has adopted nearly all of the original requirements of the EPRI 1997 document with one notable exception. The requirement for voltage swell has been reduced from 180 percent of nominal down to 175 percent, and the duration has been reduced from 2 cycles down to ½ cycles in duration.

Table 4-3
J2894 Part 1 AC Service Limit Requirements versus EPRI's 1997 Recommended Practice

Parameter	AC Level 1 & 2	EPRI 1997 Document (TR 109023)
Voltage Range	90% to 110% of Nominal	90% to 110% of Nominal
Voltage Swell	175% of Nominal for Min. ½ Cycle (8 ms)	180% of Nominal for 2 Cycles
Voltage Surge	6 kV Minimum ANSI C62.41 & C62.45	6 kV Minimum ANSI C62.41 & C62.45
Voltage Sag	Down to 80% of Nominal for 2 Seconds	Down to 80% of Nominal for 2 Seconds
Voltage Distortion	5%	5%
Momentary Outage	0 volts for 12 cycles	0 volts for 12 cycles
Frequency Variations	2% of Nominal	2% of Nominal

In reading the requirements, one may also note that the voltage-sag requirement is that the charger should ride through an event down to 80 percent of nominal for 2 seconds. There is no requirement for the charger to ride through deep voltage sags. Instead, if the voltage drops below the service limit range of 80 percent of nominal, the charger is to perform the same as if there were an interruption of power. In other words, it is to perform a "cold load pickup." A graphical depiction of cold-load pick up is shown in Figure 4-3 [8].

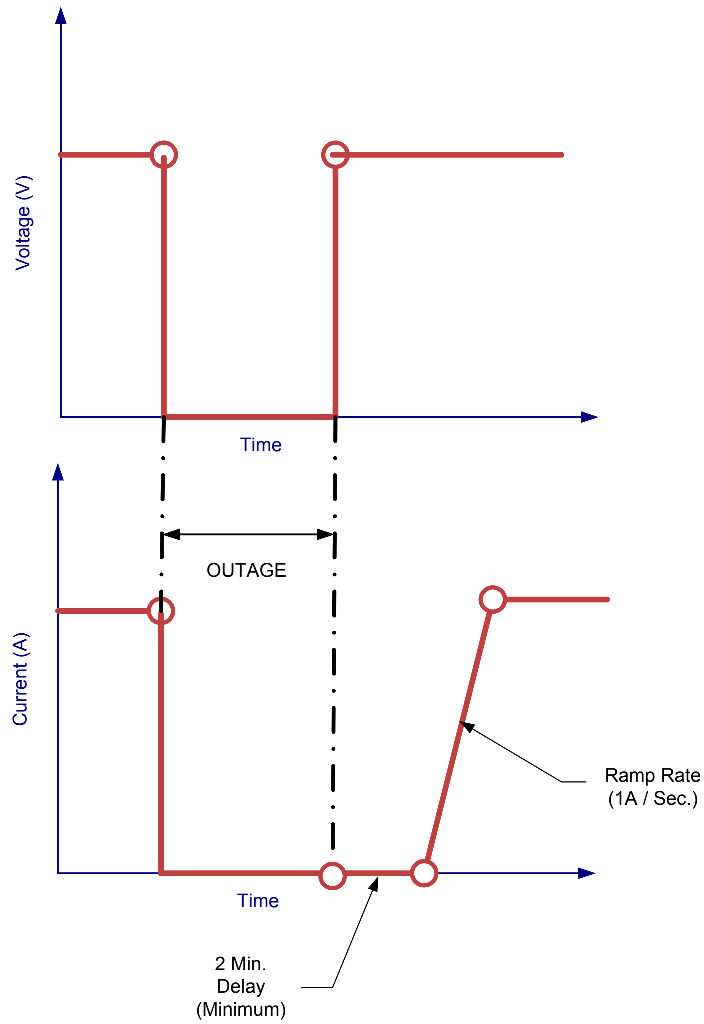


Figure 4-3
Cold-Load Pickup after an Interruption of Power

The draft document states that following a complete loss of AC service, cold-load pickup should occur. This is necessary because up to five times the normal load current can be drawn for a short period of time, depending on the duration of the outage, time of year, and general load mix on a feeder. Because this condition can cause a temporary overload of a utility's facilities and possible nuisance trips of protective equipment, a graduated restart of battery chargers after a specified time delay is desirable to help reduce this condition.

Regarding when a cold load pickup should occur, the draft J2894 document states it should occur:

1. For a voltage sag longer or deeper than 80 percent of nominal and 2 seconds in duration.[8]

---

[8] It should be noted that the requirement for voltage sags is somewhat of a recovery based approach. Rather than trying to fight through the event and ride-through, the charger is instructed to yield and perform a cold-load pick-up operation instead.

2. When there is a momentary outage longer than 200 milliseconds.
3. After a sustained loss of utility AC power.

In any of these cases, it is recommended that restart for PEV supply equipment (EVSE) be delayed for a minimum of two minutes after the power returns to normal. Two caveats are presented as well. First, it is recommended that, in case of owner/operator manual intervention, the EVSE restarts immediately without any time delay. Furthermore, during the delay period, it is recommended that an indication be provided to clearly show that the EVSE is on and operational.

EPRI PEV Testing Support of J2894 Efforts

One of the major items that the J2894 task force needed to understand in order to set the power quality requirements involved the goal of lowering the total harmonic distortion from 20 percent as advocated in the EPRI 1997 document down to 10 percent as written in the draft J2894 document. In order to supply the J2894 Task Force with decision-making data, EPRI conducted additional charger system tests and data collection with the purpose of determining the effects on the grid.

Of the eleven PEVs for which data was collected, the units demonstrated a wide range of current harmonic distortion. The lowest level was found to be in the neighborhood of 2 percent, while the highest level was nearly 30 percent. Closer analysis contained in the report shows that, overall, distortion is highest for the 120-V charger systems. The average distortion for 120-V chargers amounts to 11 percent, with the 240-V chargers at 4 percent.

Figure 4-4 and Figure 4-5 show the results obtained from PEV testing for total harmonic distortion in the current for Level 1 120-V_{AC} and Level 2 240-V_{AC} charging. As can be seen by the results, five of the seven Level 1 chargers met the 10 percent I_{THD} objective. Furthermore, all of the 240-V_{AC} chargers tested met the objective. This finding validates that lowering of the total harmonic distortion levels in the current to 10 percent is a reasonable requirement given today’s power electronic designs.

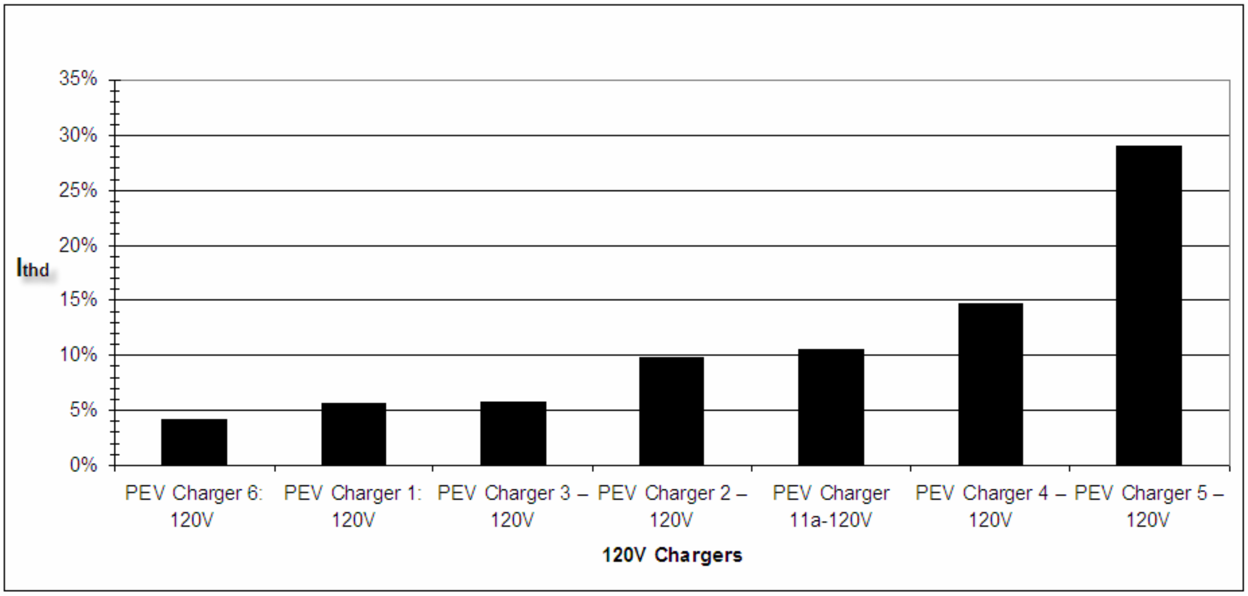


Figure 4-4
Current Total Harmonic Distortion (I_{THD}) for Seven 120-V PEV Chargers

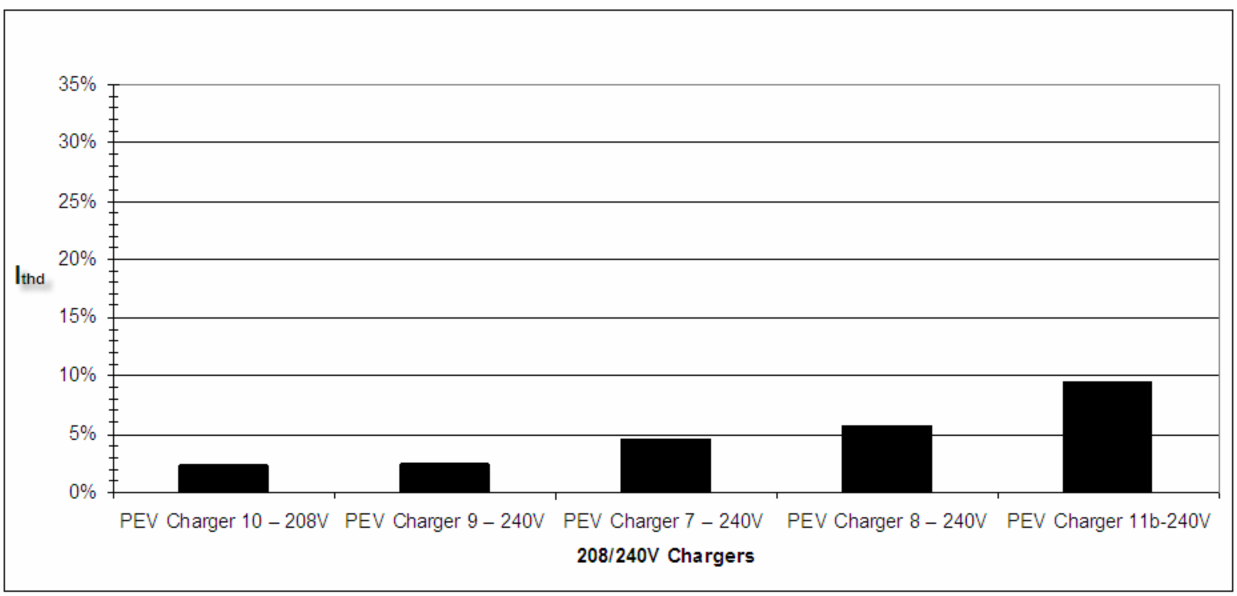


Figure 4-5
Current Total Harmonic Distortion (I_{THD}) for five 240V PEV Chargers

Another area of observation was the power factor. In nearly all cases, the power factor was above 0.95, with the average of both the 120-V and 240-V chargers approximately 0.98.

J2894 Task Force Membership

The task force working on this standard includes standards experts, government entities, consultants, automobile manufacturers, charger original equipment manufacturers (OEMs), electric utilities, electrical contractors, research organizations, and laboratories such as EPRI. The 47-member task force participants are listed in the Table 4-4.

Table 4-4
J2894 Task Force Membership

No.	Name	Title	Company	Company Type
1	Ellwanger, Simon	Senior Engineer	BMW	Auto Manufacturer
2	Williams, W David	Product Development Engineer	Chrysler LLC	Auto Manufacturer
3	Scholer, Richard A	HEV E/E Systems Engineer	Ford Advanced Vehicle Technology	Auto Manufacturer
4	Dedona, Matt	Electrical Engineer	Ford Motor Co	Auto Manufacturer
5	Furey, Warren W	Staff Eng	General Motors LLC	Auto Manufacturer
6	Harkenrider, Linda	Design Release Engineer	GM	Auto Manufacturer
7	Kissel, Gery	Engineer	GM	Auto Manufacturer
8	Kido, Akihiko	Group Manager	Toyota Motor Corporation	Auto Manufacturer
9	Olsen, John M	Consultant	Consultant	Consultant
10	Roy, Serge	Consultant - EV Charging Infrastructure	Consultant	Consultant
11	Compton, Jason Curtis	Manager	Electric Man Products	Electrical Contractor
12	Jung, Zoltan	Engineer	EPA Office of Mobile Sources	Government
13	Paulina, Carl	Senior Project Engineer	EPA Office of Mobile Sources	Government
14	Bohn, Theodore	Power Electronics Engineer	Argonne National Laboratory	Laboratory
15	Lambert, Frank C	Principal Research Engineer	Georgia Tech /NEETRAC	Laboratory
16	Bablo, Joseph	Primary Designated Engineer	Underwriters Laboratories Inc	Laboratory
17	Hayes, Chris	Engineer	Not listed	Not Listed
18	Francis, David Oscar	Director of Engineering	AeroVironment, Inc	OEM
19	Aker, John F	President	Aker Wade Power Tech	OEM
20	Showers, Aaron	Not listed	Bosch Corp	OEM

Table 4-5 (continued)
J2894 Task Force Membership

No.	Name	Title	Company	Company Type
21	France, Jason	Principle	ClipperCreek, Inc	OEM
22	Baxter, David	VP Engineering	Coulomb Technologies	OEM
23	Hui, Conway	Sales Applications Engineer	Delta-Q Technologies	OEM
24	Dixon, Michael	Product Line Manager	Eaton Corp	OEM
25	Nitzberg, Jason	R&D Engineer	Eaton Corp	OEM
26	Morrow, Kevin	Executive Vice President	Electric Transportation Engineering Corp	OEM
27	Hochard, Dimitri	Senior Applications Engineer	ETEC Inc	OEM
28	Putnam, Melanie	Manager	Evoc	OEM
29	Rivers, Cecil	Lead System Engineer	GE Consumer and Industrial	OEM
30	Hatch, Peter	Advanced Engineering	Magna Electronics	OEM
31	Patterson, Jeff	Product Manager	Magna Electronics	OEM
32	Supinsky, Joseph	Field Application Engineer	Microchip Technology Inc	OEM
33	Stelts, Michael	Director	Panasonic	OEM
34	Sun, Qiong	Chief Engineer	Ricardo Inc	OEM
35	Periyaswamy, Parthiban	Marketing Specialist	Schneider Electric	OEM
36	Yurko, Garold	Engineering Standards Mgr.	Tyco Electronics Corp	OEM
37	Zolot, Matthew	Hardware Engineer	UQM Technologies Inc	OEM
38	Shoshiev, Alexander	Principal Engineer	Yazaki North America Inc	OEM
39	Halliwell, John	Project Manager	EPRI	R&D
40	Maitra, Arindam	Senior Project Manager	EPRI	R&D
41	Stephens, Mark	Senior Project Manager	EPRI	R&D
42	Ebejer, Pat	Standard Specialist	SAE International	Standards
43	Giumento, Angelo	Engineer	Hydro Québec	Utility
44	Ornelas, Efrain	Sr. Program Manager	Pacific Gas & Electric Co	Utility
45	Chen, Chris	Enterprise Architect	Sempra Energy	Utility
46	Salazar, Jose	Technical Specialist	Southern California Edison	Utility
47	Boroughs, Ralph	Electrical Engineer	Tennessee Valley Authority	Utility

5
AC RELAYS APPLIED FOR IMPROVED POWER QUALITY

Numerous Electric Power Research Institute (EPRI) studies have found that the common general-purpose AC relay contributes to many of shutdowns of electrical equipment that occur in industrial control systems. Typically referred to as an “ice cube” relay due its clear plastic cover that resembles a square ice cube, these AC-powered relays may be susceptible to many voltage sags that do not affect other elements of a control system. A bin-full of these relays is shown in Figure 5-1. These simple components present an “Achilles heel” that may cause an entire machine, processing line, or entire factory to shut down during minor voltage sags [9]. For this reason, EPRI wrote a white paper to bring attention to this issue and to call for industry to build an improved relay. This section contains excerpts from the white paper as well as the outcomes that have occurred since this issue was raised.

Figure 5-1
Typical AC *Ice Cube* Style Relays

Typical voltage-sag ride-through curves for a sample of these kinds of relays are shown in Figure 5-2. Tolerance curves range from trip points as high as the 84 percent of nominal to as low as 62 percent. All of the relays trip for voltage sag durations of 1 cycle or more at the given trip magnitude.

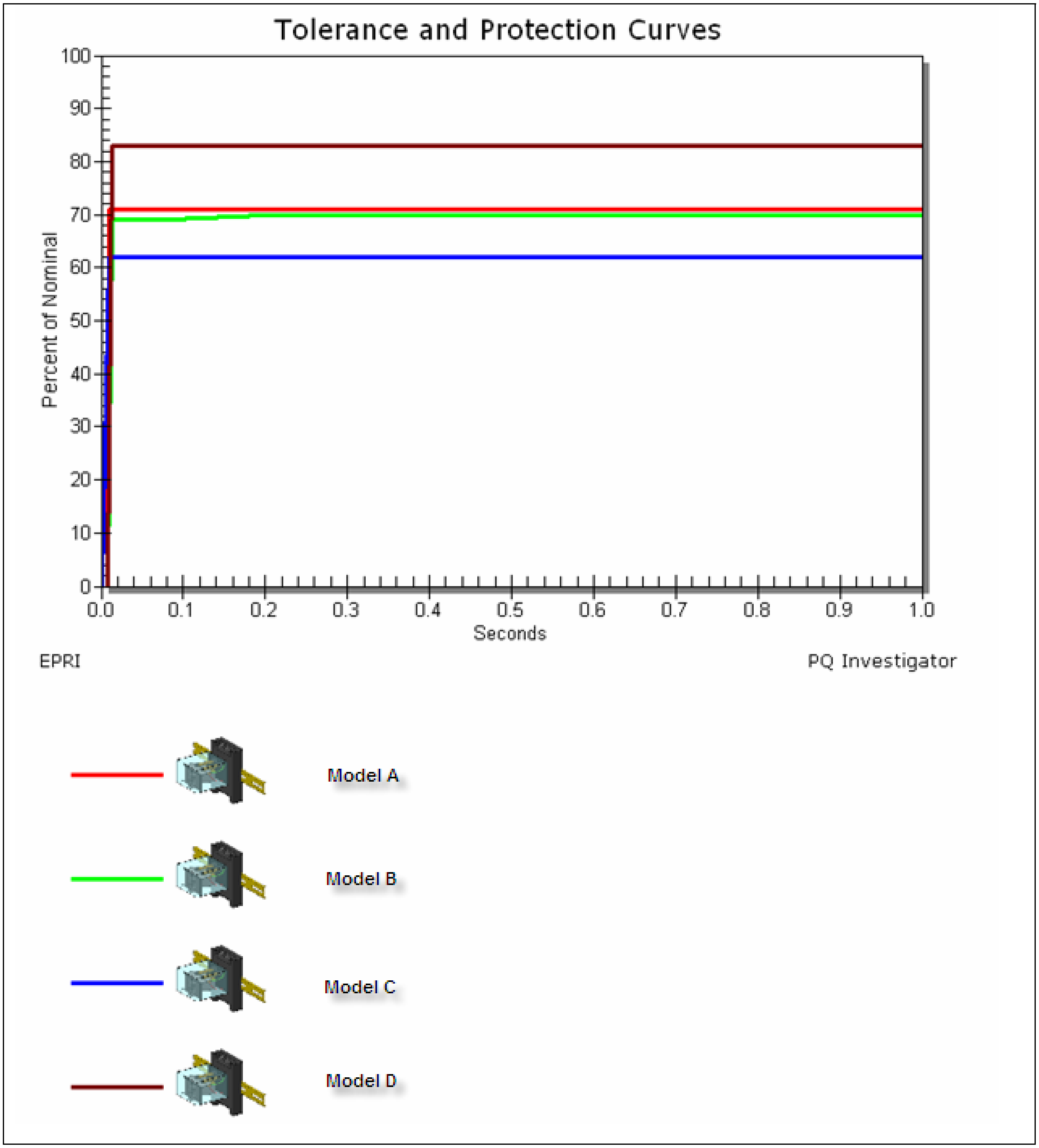


Figure 5-2
Voltage Sag Ride-Through Curves for Various AC "Ice Cube" Relays

Criteria for a Better AC Ice Cube Relay

The white paper presented seven specific criteria for the improved relay design. Ideally, the market cost of the improved relay should not be such that it would inhibit widespread adoption by industry. In general, the improved designs should meet the following criteria:

1. The units should be compliant with the SEMI F47-0706 voltage-sag standard, which requires hold-in capabilities down to 50 percent of nominal for the worst-case test point. The units can drop out for voltages less than 50 percent of nominal.
    a. Units that can meet the more rigorous requirement of 40 percent of nominal hold-in (IEC 61000-4-11 and IEC 61000-4-34 standards) would exceed the base requirements.
    b. Manufacturers who would like to take on this additional challenge are encouraged to strive for the hold-in voltage of 40% of nominal.
2. The units should not exceed the physical footprint of existing AC ice cube relay designs with the same number of contacts.
3. The units must require AC power to operate.
4. The units should provide standard contact forms such as double-pole double-throw (DPDT), three-pole double-throw, and four-pole double-throw.
5. The units should utilize standard socket and pin formats such that the new units can easily retrofit and replace relays in existing applications.
6. The pull-in and drop-out operation time of the units should be similar to those of common AC ice cube relays in order to match existing applications. Typical specifications range from 9 to 25 milliseconds.
7. The dropout voltages should be consistent with typical specifications. Typical specifications range from 10 to 30 percent of nominal.

EPRI's Specific Role in the Effort

The EPRI role in this effort is threefold:

1. Provide a test bed for demonstration of the voltage-sag ride-through performance of the new relay designs. Perform testing and document the test performance, providing feedback to participating vendors.
2. Develop a demonstration effort for actual field application for prototype units where they would be used as replacements for existing ice cube relays in control-system applications, documenting performance of the improved designs.
3. Coordinate through electric utility funders to provide appropriate information for customers (white papers, brochures, summary test results, case studies, and so on) for the improved performance that is possible with the new technology [9].

Update on the Call to Action

In order to get the word out on this important issue and the need for improvements, EPRI began with a press release about the white paper. This was followed up with an interview from *Green Tech* magazine, as well as publication of the white paper at *Smart Grid News* (www.smartgridews.com) and on *Electric Energy Online* (www.electricenergyonline.com). EPRI then held four conference calls with OEMs, including ABB, Schneider Electric, Rockwell Automation, and Tyco Electronics. The project generated interest and raised awareness of the issue in industry.

Tyco Electronics Responds

Up until the late 1990s, Potter and Brumfield produced an AC "ice cube" relay that would ride through voltage sags down to the 20 to 30 percent of nominal. This relay was promoted at the time by the EPRI Power Electronics Applications Center as a potential solution for replacing susceptible relays in actual field installations. After Potter and Brumfield changed ownership, that particular model of relay was dropped. Since that time, a robust AC "ice cube" relay has not been available.

Tyco Electronics now handles the Potter and Brumfield relay and has responded to EPRI's white paper by bringing back the relay. Tyco has added the relay back into its marketing material and shipped a batch of these units to EPRI for testing (see the R10-T model, part number R10-T1P2-115V, shown in Figure 5-3). This is an outstanding accomplishment because it represents EPRI's ability to inform and challenge industry in a way that can effect change.

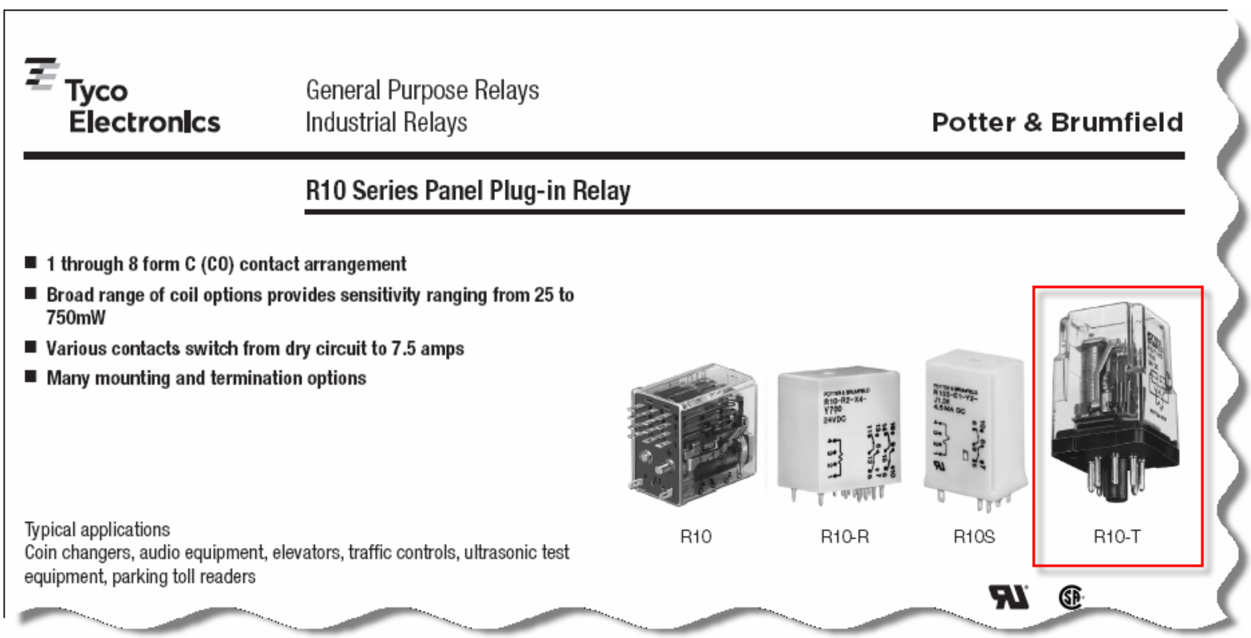


Figure 5-3
Tyco 115-V_{AC} Version of the R10-T Relay

Preliminary tests of the R10-T relay show that it holds in for voltage sags down to the 20 percent of nominal. The relay accomplishes the voltage-sag ride-through by employing two diodes on a split coil, as shown in Figure 5-4. EPRI plans to conduct SEMI F47 certification on the relay in late 2010 and supply this information to Tyco.

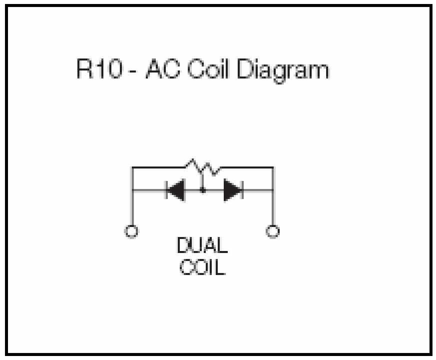


Figure 5-4
Split-Coil Design of the R10-T Relay

EPRI Demonstrates a Solution

In an effort to find a viable solution to the susceptibility of ice cube relays, EPRI engineers decided to retrofit an existing DC ice cube relay such that it could receive AC and convert it to DC. A Potter and Brumfield 110-V_{DC} off-the-shelf relay was chosen for the experiment. The relay was fitted with a full-wave rectifier and a free-wheeling diode at the terminals of the octal base. When 120 V_{AC} is rectified with a full-wave bridge, the average DC voltage is 108 V. This allows for operation of the 110-V_{DC} relay. The total cost of the full-wave rectifier and the diode was only 36 cents. The initial test setup is shown in Figure 5-5.

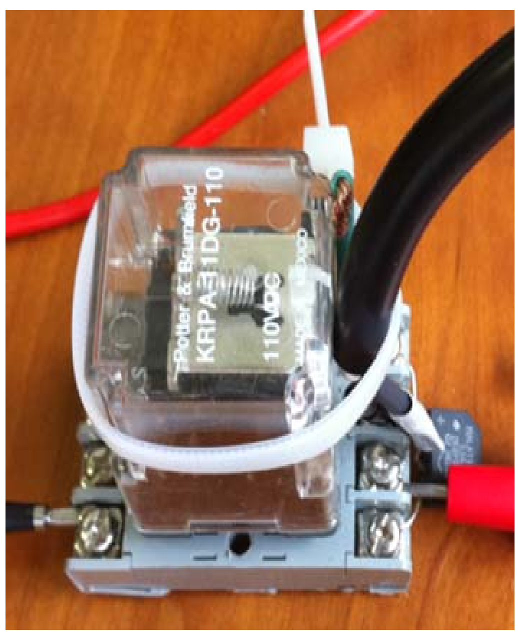


Figure 5-5
EPRI Prototype Testing with a Full-Wave Rectifier (FWR) Placed in Front of a 110-V_{DC} Relay

Voltage-sag tests were conducted on the modified model (KRPA-11DG-110). As shown in Figure 5-6, the relay exhibited marked improvement over a typical AC ice cube relay and met the SEMI F47 standard.

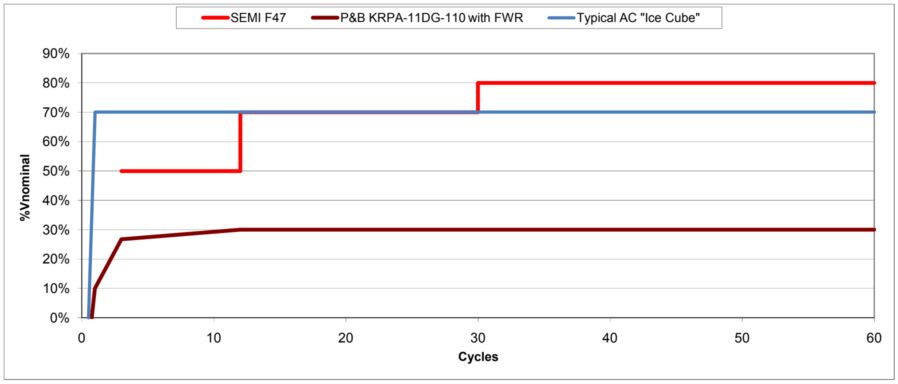


Figure 5-6
Voltage-Sag Ride-through of Modified Prototype Relay versus SEMI F47

The relay itself was next modified to fit the diode bridge and free wheeling diodes inside the package. The modified relay, dubbed the *Nice Cube* relay, is shown in Figure 5-7.

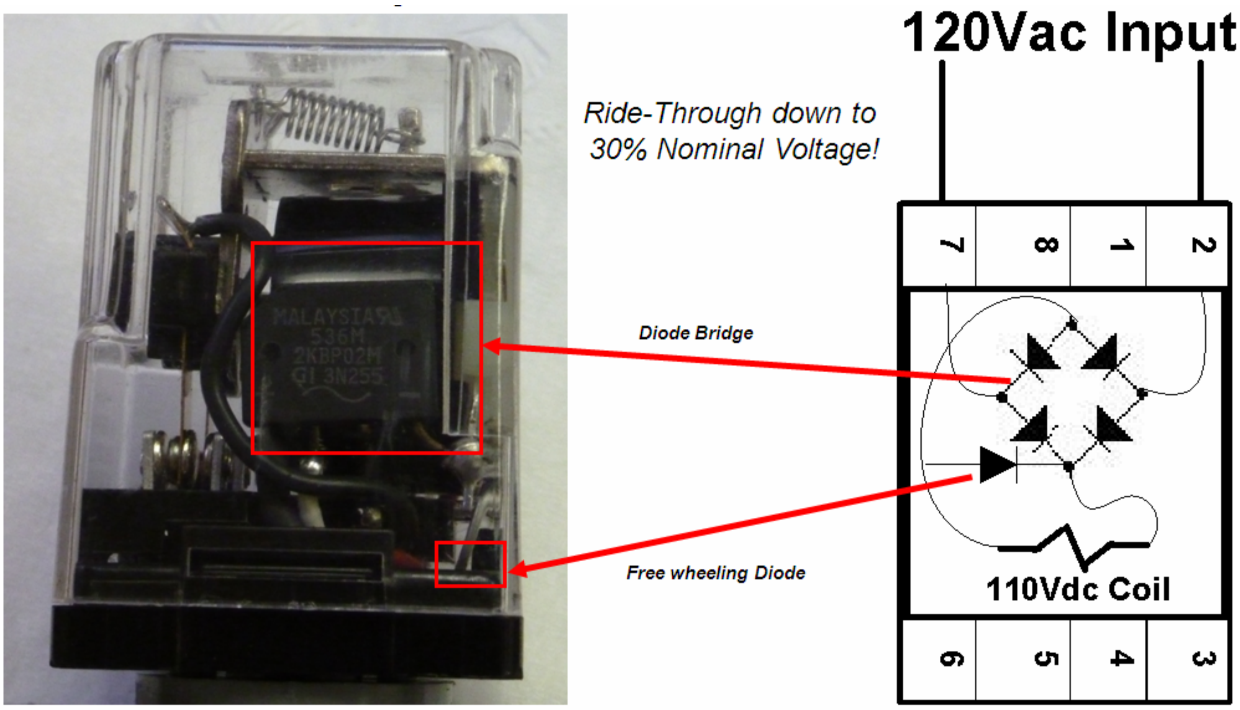


Figure 5-7
Packaging of Modified Relay Dubbed the *Nice Cube* Relay

These results suggest that a simple diode bridge integrated into the manufacturer's 110-V_{DC} relay design can enable an ice cube relay to meet EPRI's design requirements. Because almost all relay manufacturers have a 110-V_{DC} relay design, this may be a simple way for them to produce units that achieve the desired functionality.

In 2011, EPRI plans to construct multiple modified units and subject them to a series of tests. Tests will include relay operation tests. Each modified unit will be subjected to thousands of iterations of switching at various hold times to prove that the modification does not degrade relay life/performance. During the tests, rated current will be passed through the contacts to verify proper operation. Furthermore, standard 120-V_{AC} units will be used as a control group. The thermal properties of both the control group and the modified units will be recorded throughout the testing. Results of the tests will be communicated via a white paper to industry in hopes that the design or similar designs will be utilized.

6
FUTURE WORK

In 2010, EPRI participated in communicating the findings of the CIGRE C4.110 group, contributed to the development of the IEEE P1668 recommended practice, provided information for drafting of SAE J2894, and issued an industry challenge to build a better AC ice cube relay.

Because the CIGRE C4.110 work is now finalized, there is an opportunity to build on this work and to incorporate much of the findings and recommendations into future standards. Because the end goal of EPRI's work is to promote system compatibility, the output of the IEEE P1668 and C4.110 groups will ultimately lead to the creation of an IEEE recommended practice that will be in line with the recommended changes in the IEC 61000-4-34 and SEMI F47 standards. The inclusion of three-phase sags and realistic test vectors will promote further compatibility with the electrical environment. EPRI and member utilities should continue to strive towards the development of the IEEE P1668 in 2011 and issue a draft recommended practice for balloting. It is hoped that the development of a strong IEEE standard is likely to have far-reaching effects throughout all manufacturing industries because this standard would be generic in focus rather than industry-specific.

Regarding the recommended practice SAE J2894/1, *Power Quality Requirements for Plug-In Electric Vehicle Chargers,* EPRI plans to continue the evaluation of PEV chargers in 2011, subjecting the units to a full spectrum of power quality tests. Furthermore, EPRI's input to the test-plan document will be crucial as the SAE J2894 working group begins to draft the measurements and verification document that will ultimately accompany the power quality requirements.

Regarding the industry challenge to build a better AC ice cube relay, EPRI plans to continue further testing on the EPRI prototype relay and write another white paper that will highlight the results from the project thus far. Furthermore, EPRI will continue to encourage industry to expand the offering of units that meet or exceed current voltage-sag standards.

7
REFERENCES

1. CIGRE Working Group C4.110 Final Report, *Voltage Dip Immunity of Equipment and Installations,* April 2010.
2. IEC 61000-4-11, Ed.2, *Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests,* March 2004.
3. IEC 61000-4-34, *Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests for Equipment with Input Current More than 16A per Phase,* October 2005.
4. SEMI F-47-0706, *Specification for Semiconductor Processing Equipment Voltage Sag Immunity,* Semiconductor Equipment and Materials International, July 2006.
5. IEEE P1668/1P, *Draft Recommended Practice for Voltage Sag and Interruption Ride-Through Testing for End Use Electrical Equipment Less than 1,000 Volts,* interim working group draft, November 2010.
6. PQ Brief Number 51, "Ride-Through Performance of DC Drives," EPRI, Palo Alto, CA: 2007. 1017066.
7. *EV Charging Equipment Operational Recommendations for Power Quality.* EPRI, Palo Alto, CA: 1997. 109023.
8. SAE J2894, *Draft Power Quality Requirements for Plug-In Electric Vehicle Chargers,* interim working group draft, August 2010.
9. Mark Stephens and Alden Wright, "AC Ice Cube Relays Applied for Improved Power Quality," industry white paper, EPRI, Palo Alto, CA: September 1st, 2009.

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