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Voltage sag susceptibility of 230 V equipment

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Abstract
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Voltage Sag Susceptibility of 230 V Equipment

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***Abstract*— The ITI Curve developed by the Information Technology Industry Council (USA) describes an AC input voltage envelope which typically can be tolerated by most Information Technology (IT) equipment supplied by nominal 120 V 60 Hz electricity networks. Although the curve ostensibly applies only to IT equipment supplied at 120 V 60 Hz it is often used throughout the electricity supply industry, including at other nominal voltages and frequencies, without modification or consideration of applicability to provide an indication of the input voltage tolerance of a wide range of equipment.**

This paper details a preliminary study aimed at developing an ITI style curve to suit 230 V 50 Hz electricity networks. A range of domestic and industrial equipment has been tested to determine voltage sag susceptibility. Overall, results for domestic appliances show that equipment connected to the Australian 230 V 50 Hz electricity network has voltage sag immunity considerably better than that defined by the ITI Curve. The same may be said for the majority of industrial equipment tested. As such, the suitability of the ITI Curve in describing a sag immunity envelope for individual pieces of equipment connected to 230 V 50 Hz electricity networks is highly questionable.

1 INTRODUCTION

The ITI (formerly CBEMA) Curve describes an AC input voltage envelope which can typically be tolerated by most information technology (IT) equipment [1]. The curve was specifically designed to be applicable to nominal 120 V 60 Hz electricity distribution systems. The original curve (the CBEMA Curve) was a continuous curve which was later modified to the piece-wise curve in use today. Figure 1 shows the ITI Curve. The y-axis relates to a nominal voltage of 120 V.

Although the curve was specifically designed for 120 V 60 Hz systems it is often directly translated to 230 V 50 Hz system with no adjustment of the y-axis. The curve is often included in many power quality software packages to indicate the impact of voltage sags on equipment. Modern IT equipment is now almost universally supplied using switch mode power supplies (SMPS) which have a nominal input range which is generally 110 V – 240 V. When connected to a 230 V system such power supplies could reasonably be expected to operate down to a voltage level of 52 % of nominal voltage (110 V). As such, when translated to a 230 V system, using 230 V as the 100 % level, the ITI curve will not define an envelope which will describe the sag immunity of the modern SMPS. Instead the curve will define an envelope which is much too large and as such does not give a valid indication of whether a particular sag should reasonably be expected to cause equipment to maloperate. A discrepancy also exists between 50 Hz and 60 Hz systems when the timeframe on the x-axis is presented in terms of cycles as opposed to seconds. Obviously, timeframes presented as a function of 60 Hz cannot be directly related to 50 Hz systems. This is another limitation of the curve for application to 230 V 50 Hz systems. Therefore it stands to reason that the curve cannot be directly translated to 230 V 50 Hz systems without adjustment to both the x and y axis.

The voltage sag susceptibility of equipment connected to the electricity distribution network is extremely important to electricity consumers, particularly those involved in manufacturing. In some cases estimates of national losses due to voltage sags are in the billions of dollars [2], [3]. Data presented in [2] and [3] provide some details of the potential costs of voltage sags to manufacturing plants. In some cases it is one vital piece of control equipment which is particularly susceptible to voltage sags, which may lead to the loss on an entire plant. As such, an argument can be made that voltage sags are the most costly of all power quality disturbances due to costs associated with lost production. Many electricity users will employ systems to mitigate voltage sags. In some cases these systems can be very expensive. It is fair to assume that many of these systems are based around the voltage sag immunity levels described by the ITI curve. As such, if the curve is not applicable to 230 V 50 Hz electricity networks these sag mitigation systems may be over engineered.

The depth and duration of voltage dips within a distribution system depend on the fault level at the fault point and network protection time settings [4]. At present, protection systems cannot operate quickly enough to clear reflected faults in order to comply with the magnitude and duration envelope defined by the ITI Curve. Instead, protection system performance is more in line with the protection curve as defined in [5]. The protection curve describes an ‘underlying boundary for voltage sags resulting from the reflection of network faults’. [5]. With respect to the CBEMA or ITI curves, the protection curve indicates that the minimum timeframe over which network protection can operate to clear a fault at the 11 kV level is in the order 0.8 s for even the deepest voltage sag. As such, if equipment is to have immunity to all voltage sags due to reflected faults, it must be able to continue to operate for at least 0.8 s with an applied voltage of 0 V. The disparity between ITI Curve specification and protection system performance results in a significant gap between equipment susceptibility and network capability based on the original ITI Curve designed for 120 V 60 Hz systems.

The work presented in this paper examines the voltage sag susceptibility of a range of equipment designed for use in the Australian 230 V 50 Hz electricity distribution networks with a view to develop a voltage sag susceptibility curve applicable for equipment connected in Australia. Behaviour for swells, which are included in the ITI Curve, is beyond the scope of this study. Voltage sags are deemed to be of more importance and more costly than swells in this instance due to the fact that they occur far more frequently.

A range of equipment has been assessed including devices designed for both domestic and industrial use. While it is accepted that the ITI Curve is designed for use with IT equipment, the equipment assessed here is not limited to this. The rationale behind this is that the curve which will be developed will apply to a much broader range of equipment and as such may be useful across a wider range of industries. A special emphasis is given in this paper on the results for industrial equipment and the implication of these results for Australian electricity networks. A full description of testing and results for domestic equipment was published in [6] and as such only an overview of the results of that study are presented here.

2 DEVICES TESTED

2.1 Domestic Appliances

The domestic appliances tested were of two main types; electronic and refrigeration. The list below gives a summary of the domestic equipment assessed. A full description of the domestic equipment assessed is available in [6].

- Three television technologies: CRT, Plasma and LCD.
- A Pentium 4 personal computer (PC).
- A 43 cm LCD PC monitor.
- Two DVD players.
- Two clock radios.
- A 1100 W microwave oven.
- A laser and an inkjet all-in-one type home printer.
- A 1 TB portable hard disk drive.
- A 14W Compact Fluorescent Lamp (CFL).
- Air Conditioners; a portable type and an inverter split system type.
- A modern refrigerator.

2.2 Industrial Equipment

The industrial equipment tested was as follows:

- Contactors: Five contactors have been assessed. These contactors come from a variety of well-known manufacturers. All of the contactors had rated voltages of 220 V – 240 V.
- Fluorescent lighting: A twin 36W fluorescent light has been assessed.
- Variable Speed Drives (VSD): Two variable speed drives have been assessed. The first is an older style 10 kW BJT transistor VSD. The second is a modern IGBT 3 kW drive. The variable speed drive systems were tested while driving a three phase induction motor load. The load for the 10 kW VSD was 5.5 kW while the 3 kW VSD was loaded to its rated capacity.
- PLC Unit: One PLC unit has been assessed. The device tested was a programmable relay. This device had a rated input voltage of 100 – 240 V AC.

3 VOLTAGE SAG SUSCEPTIBILITY ASSESSMENT METHODOLOGY

3.1 Application of Sags

An arbitrary waveform generator was used to apply voltage sags of various depths and durations to the equipment under test (EUT). This device is capable of generating voltage sags with durations down to 0.1 cycles. A methodology has been developed to assess whether or not the EUT is operating normally during the applied voltage sag and to determine if the EUT is functioning as expected after the application of the voltage sag. This methodology is tailored to suit each specific EUT and is used to assess the susceptibility of the EUT to the applied voltage sag. It is not feasible to apply every potential voltage sag duration and depth to each EUT. As such, a range of sag depths and durations has been developed to assess the EUT. The voltage sag depths and durations which have been applied to each EUT are shown in Table 1. In this table, the voltage sag levels which were applied to the EUT are marked with an "X". Special emphasis is placed on deeper short duration sags as it is believed that most resolution is required in this area as opposed to shallower sags due to the fact that impact on equipment will be greatest for deeper sags.

Table 1: Voltage Sag Depths and Durations Applied to Each EUT

Retained Voltage (%)	**Duration (Cycles)**																		
	1	**3**	**5**	**7**	**9**	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**200**	**300**	**400**	**500**
80										X					X	X	X	X	X
60						X	X	X	X	X	X	X	X	X	X				
40				X	X	X	X	X	X	X									
20	X	X	X	X	X	X	X	X	X	X									
10	X	X	X	X	X	X	X	X	X	X									
0	X	X	X	X	X	X	X	X	X	X									

3.2 Equipment Susceptibility Assessment

Assessment of equipment voltage sag susceptibility was undertaken using a number of methods depending on the EUT. These methods include audio and visual observation, specialised test circuits and data monitoring. Regardless of the assessment method, monitoring of equipment behaviour was performed for all tests using a Hioki 3196 power quality analyser. This is a modern instrument compliant with IEC61000-4-30 Class A [7].

The exact method of assessment of the susceptibility of the EUT for each voltage sag level was dependent on the specific EUT. In all cases, the EUT was considered to be susceptible to the sag if it did not continue to function in what was considered to be a normal fashion for the duration of the applied voltage sag. What was considered to be normal behaviour varied for each EUT. Details of what constituted normal behaviour for domestic appliances is detailed in [6] while what constituted normal behaviour as far as testing of industrial equipment was concerned, as well as the methods used to assess the immunity/susceptibility of each EUT for industrial equipment, is detailed below:

3.2.1Contactors

A special latching circuit was designed for testing of contactors. This circuit locked the contactor out if the voltage sag was sufficient to cause the contactor to open (disconnect the load). For all tests, a basic incandescent light globe was connected through the contactor. The contactor was assessed to be susceptible to the voltage sag if the contactor circuit locked the contactor out, i.e. contactor chatter was acceptable as long as the contactor did not fully open.

3.2.2Fluorescent Lighting

Normal operation of fluorescent lighting was considered to be light output of any intensity. Voltage sag susceptibility was assessed through visual observation and the device was considered susceptible if the tube extinguished.

3.2.3Variable Speed Drives

Variable speed drives were tested using a motor load. The drives tested included undervoltage protection. The drive was considered susceptible to the voltage sag if the drive undervoltage protection operated.

3.2.4PLC Unit

The PLC unit was tested while implementing a simple program. The PLC tested was a programmable relay. This device has electronic switches which are used to turn on and off circuits. The program used for testing involved switching of light globes. The unit was considered susceptible to the voltage sag if the program failed or if one of the switches operated incorrectly.

4 VOLTAGE SAG SUSCEPTIBILITY

This section of the paper shows voltage sag susceptibility curves for the equipment tested based on the test levels applied to each piece of equipment being tested as defined in Table 1. For all of the figures in this section of the paper, y-axis values are expressed as a percentage of 230 V.

4.1 Domestic Appliances

4.1.1IT Equipment

The ITI Curve was specifically designed for use with IT equipment. Figure 2 shows the voltage sag susceptibility envelopes for the IT equipment which have been assessed. The figure shows that the PC is the most susceptible device followed at some distance by the laser printer. Other equipment showed very high sag immunity. In all cases, it can be seen that sag immunity is considerably better than that defined by the ITI Curve.

4.1.2 Electronic Appliances

Figure 3 shows the voltage sag susceptibility envelopes of the four most susceptible electronic (excluding IT) appliances which were assessed. It can be seen that the microwave oven is by far the most susceptible device. It should be noted that the microwave oven was tested while cooking at high power level and that the failure mode used to determine the susceptibility envelope shown in Figure 3 was interruption of cooking. In all cases, although cooking was interrupted, the low power microwave oven clock continued to function normally. The next most susceptible devices are the televisions and the 14W CFL. However, these devices have voltage sag immunity levels much greater than that seen for the microwave oven. In all cases, the appliances have sag immunity levels which are significantly better than that defined by the ITI Curve.

4.1.3 Refrigeration Appliances

Figure 4 shows the voltage sag susceptibility envelopes for the refrigeration type equipment tested. The figure shows envelopes which are dominated by the performance of the two air-conditioners (the inverter air-conditioner envelope is almost the same as the portable air-conditioner envelope which is why most of it can not be seen in the figure). Performance for the air-conditioners is similar to that seen for the microwave oven.

4.1.4All Domestic Appliances

The fact that the majority of the electronic equipment has voltage sag immunity considerably better than that defined by the ITI Curve is due to the fact that most modern electronic equipment is supplied by switch mode power supplies with a large input voltage range, typically 100 – 240 V. This means that even if the input voltage falls to 50 % or 115 V for a 230 V nominal system, the voltage is still within the normal operating range of the switch mode power supply. In fact the voltage must drop to 43 % of a nominal 230 V before the input voltage is 10 % below the switch mode power supply nominal voltage rating. As such, it is clear that the retained voltage values defined by the ITI Curve do not transfer well to equipment connected to the Australian power system. Based on the results shown in Figures 2 – 4, Figure 5 shows a voltage sag susceptibility envelope which could be met by all of the domestic appliances assessed.

4.2 Industrial Equipment

4.2.1 Contactors

Figure 6 shows the voltage sag susceptibility envelopes for the contactors which were tested. Overall, all contactors had very similar performance. They were found to be slightly more susceptible to voltage sags than most domestic appliances but had a performance much better than that defined by the ITI Curve. Some of the contactors also showed some unusual behaviour when voltage sags to 0 volts were applied. In some cases, contactors held in longer at 0 volts than was observed for higher voltages such as 10 % or 20 % of nominal voltage. These results are not shown on the graphs as they unnecessarily complicate the results and the difference was of the order of a cycle or two. This apparent abnormality is a function of the contactor operation. Literature such as [8] explains the mechanism by which a contactor may hold in longer for a deeper voltage sag than a shallow one. The same source also illustrates the importance of the point on the wave at which the voltage sag begins (i.e. the phase angle) on contactor performance. This variable has not been considered here as it is beyond the scope of this basic study.

4.2.2 Variable Speed Drives

Two variable speed drives were assessed. Both drives have almost identical performance and are highly susceptible even to shallow voltage sags. The mechanism by which the drives are susceptible to the sags is observed by the operation of the drive undervoltage protection. In both cases, this undervoltage protection operated for any voltage sags below 80% of nominal voltage (in one case, the threshold was 83% while in the other it was 80%). This undervoltage protection is set by the equipment manufacturer and the user does not appear to be able to change the undervoltage protection settings. Given this operation, the drives are by far the most susceptible of the equipment tested in this study.

This drive behaviour means that it may be the most susceptible device in a manufacturing plant due to the way in which undervoltage protection settings are configured. For the drives assessed it was not apparent if the undervoltage protection settings could be altered. It is beyond the scope of this study to determine if drive undervoltage protection systems could be configured differently to allow greater voltage sag immunity, however, this might be a consideration for plants where voltage sags have the potential to cause significant economic losses.

4.2.3 Other industrial Equipment

The other industrial equipment assessed was a twin-tube fluorescent light and a PLC unit. The voltage sag susceptibility envelopes for these devices are shown in Figure 7. It can be seen that the fluorescent lamp has quite high sag susceptibility while the PLC unit has high sag immunity.

4.2.4All Industrial Equipment

Based on the data for all of the industrial equipment tested, with the exception of the variable speed drives (VSDs), Figure 8 shows a single voltage sag immunity curve which could be met by all of the assessed industrial equipment except for the variable speed drives. Figure 8 shows that the performance of the industrial equipment tested is superior to the envelope defined by the ITI Curve.

4.3 All tested equipment

By combining the data shown in Figure 5 and Figure 8, a new curve can be generated for all tested equipment (except for VSDs). This curve is shown in Figure 9.

5 230 V ITI CURVE AND LV NETWORK VOLTAGE SAG PERFORMANCE

Based on the appliances assessed in this paper it is clear that 230 V equipment has voltage sag immunity which is considerably better than that described by the ITI curve. Consequently, it can be expected that 230 V equipment can continue normal operation during voltage sag levels which fall below the ITI curve.

This section of the paper uses voltage sag data monitored in the field to compare the impact of voltage sags on equipment using both the traditional ITI Curve and the 230 V voltage sag susceptibility curve developed in this paper. If the curve which has been developed in this paper using a limited range of test appliances is found to be relevant to most equipment, it will define the operating tolerance of equipment connected to the 230 V 50 Hz electricity distribution network. In combination with network performance data, this information can be used by customers to evaluate the likely voltage sag performance of their facility and to take voltage sag mitigation action as required.

5.1 Characteristics of Voltage Sags in Australia

Collection of voltage sag data has been occurring in Australia for over nine years as part of the Long Term National Power Quality Survey (LTNPQS) project as described in [9] and [10]. Data has been collected from across the Australian continent from a range of voltage levels between LV and 132 kV. The data analysed in this section of the paper has been collected during the 2010/2011 financial year (July 2010 – June 2011) from 1285 low voltage sites. Overall 1089 monitor-years of data was available for analysis. The data analysed is limited to voltage sags with retained voltage greater than 0 % (i.e. interruptions were excluded) and less than 90 %. For duration, values included in the analysis are between ½ cycle and 3000 cycles (60 s).

Figure 10 shows a histogram of voltage sag depths. It can be seen that the vast majority of the measured voltage sags have retained voltages above 80% of nominal. This distribution of voltage sag depths is similar to the data shown in [11] and [12].

In Figure 9 it can be seen that voltage sags of magnitude greater than 60 % retained voltage will not impact 230 V equipment. Examination of the data shown in Figure 10 shows that approximately 67 % of voltage sags have retained voltage greater than 60 % and as such would not be expected to impact on 230 V equipment (other than variable speed drives).

Figure 11 shows a diagram of the measured voltage sags plotted on a voltage sag depth-duration plane overlaid by the ITI Curve and the 230 V curve developed in this paper. Approximately 37 % of the voltage sags fall below the ITI Curve while approximately 14 % of voltage sags fall below the 230 V voltage sag susceptibility curve. This means that, with the exception of variable speed drives, 230 V equipment can reasonably be expected to be immune to 86 % of the voltage sags seen on LV electricity distribution networks.

6 CONCLUSION

The purpose of this study was to begin development of an ITI or CBEMA type curve(s) applicable to equipment connected to the Australian 230 V 50 Hz system. In this first instance, curves have been developed to describe AC input voltage tolerances for a range of the most common domestic and industrial equipment (not limited to IT equipment).

Results for domestic appliances show that individual pieces of equipment connected to the Australian 230 V network have sag immunity considerably better than that defined by the ITI Curve. The domestic equipment tested can be roughly divided into 2 categories; electronic equipment and equipment with compressors. The sag susceptibility of the electronic appliances is dominated by the susceptibility of the microwave oven. However, even the performance of the microwave oven is considerably better than that defined by the ITI Curve. If the microwave oven is excluded, the electronic equipment tested was found to have high sag immunity. The domestic equipment with compressors was found to have significantly worse voltage sag immunity than the electronic equipment tested.

For industrial equipment, variable speed drives were found to be by far the most sensitive devices to voltage sags. The protection systems on these units tripped the device almost instantaneously for voltage sags of approximately 80% retained voltage. As such these devices have performance which is significantly worse than that defined by the ITI Curve. This drive behaviour means that the drive may be the most susceptible device in a manufacturing plant due to the way in which undervoltage protection settings are configured. For the drives tested it was not apparent if the undervoltage protection settings could be altered. It is beyond the scope of this study to determine if drive undervoltage protection systems could be configured differently to allow greater sag susceptibility, however, this might be a consideration for plants where sags have the potential to cause significant economic losses.

Contactors are another device which has been identified as being susceptible to voltage sags. Five contactors have been tested in this study. All of the contactors had rated coil voltages of 230 – 250 V AC. Results for the contactors indicated that they have sag immunity which is comparable to that seen for many of the domestic electronic appliances.

The other two items of industrial equipment tested were a fluorescent lamp and a PLC. Both devices showed performance superior to the ITI Curve, with the PLC having particularly high voltage sag immunity.

Overall, the results of testing have indicated that the vast majority of domestic and industrial equipment tested had sag immunity performance which was considerably better than that defined by the ITI Curve. The results of the testing performed in this study seriously question the suitability of the ITI Curve for use in Australia with its 230 V 50 Hz LV electricity distribution. These results are significant if sag mitigation strategies are to be applied at customer installations. Use of the present ITI curve may lead to over engineering of such systems and in turn over expenditure on such strategies.

An analysis has been undertaken which compares the voltage sag performance of Australian LV networks with the ITI and the 230 V voltage sag susceptibility curves. Based on analysis of data collected from 1285 sites over 1 year, 36 % of voltage sags will be below the ITI Curve while only 14 % of voltage sags fall below the 230 V voltage sag susceptibility curve developed in this study.

Further work is required to develop the 230 V voltage sag susceptibility curve. This work will include testing of more equipment along with continued study of the voltage sag characteristics of the LV network.

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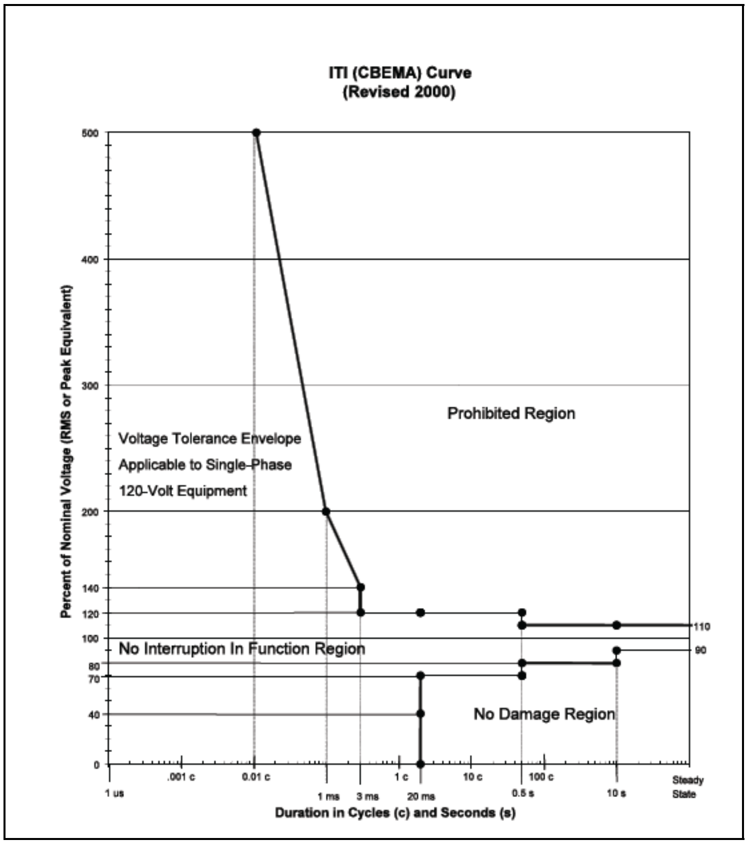

Figure 1: ITI Curve [1]

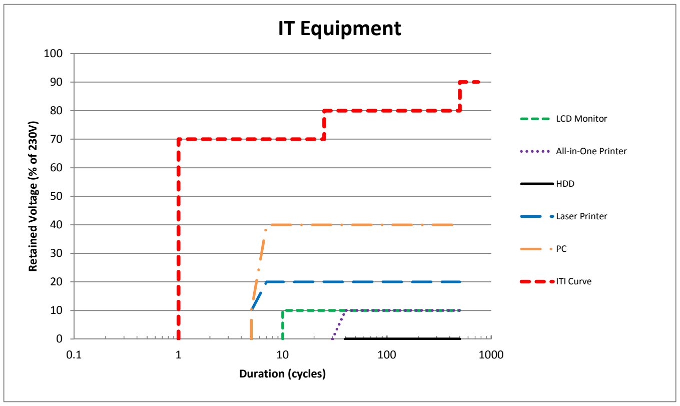

Figure 2: Voltage Sag Susceptibility Envelopes for IT Equipment

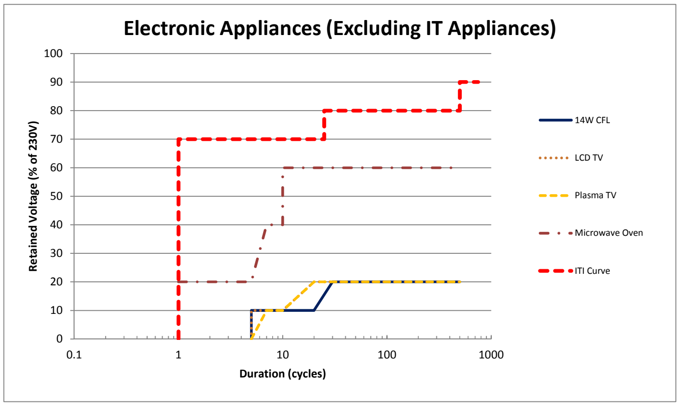

Figure 3: Voltage Sag Susceptibility Envelopes for Electronic Appliances (excluding IT appliances)

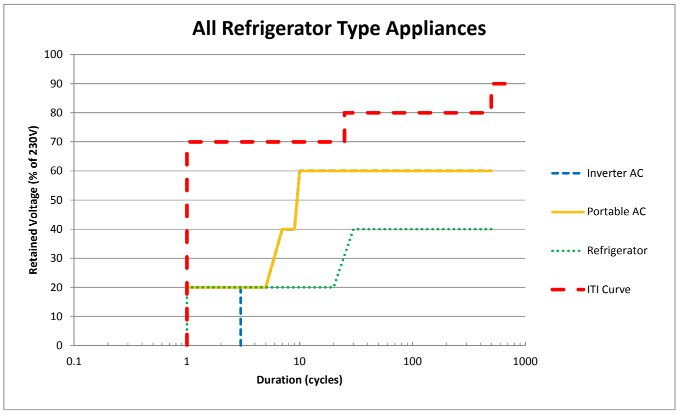

Figure 4: Voltage Sag Susceptibility Envelopes for Refrigerator Type Appliances

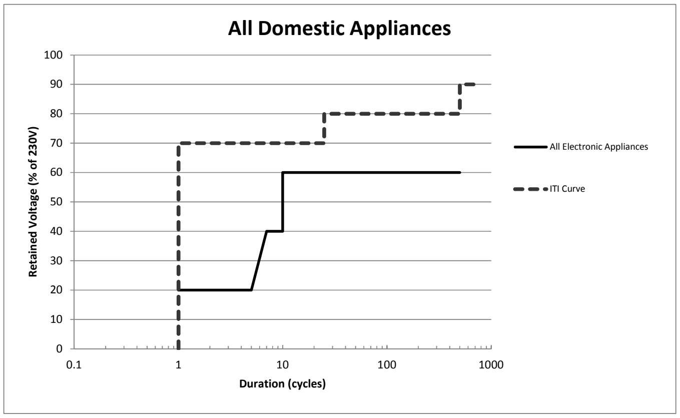

Figure 5: Voltage Sag Susceptibility Envelope for all Domestic Appliances

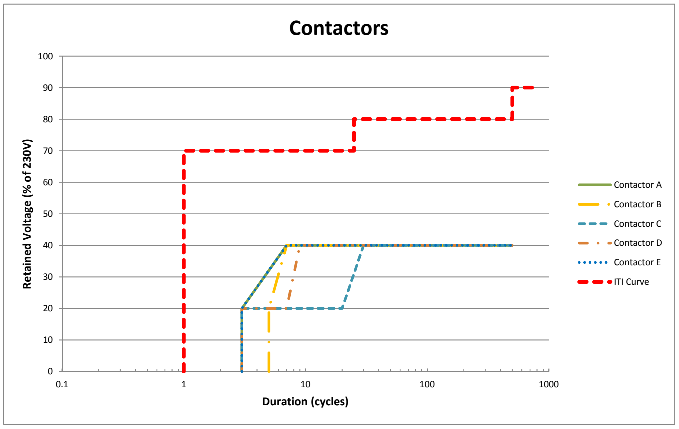

Figure 6: Voltage Sag Susceptibility Envelopes for Contactors

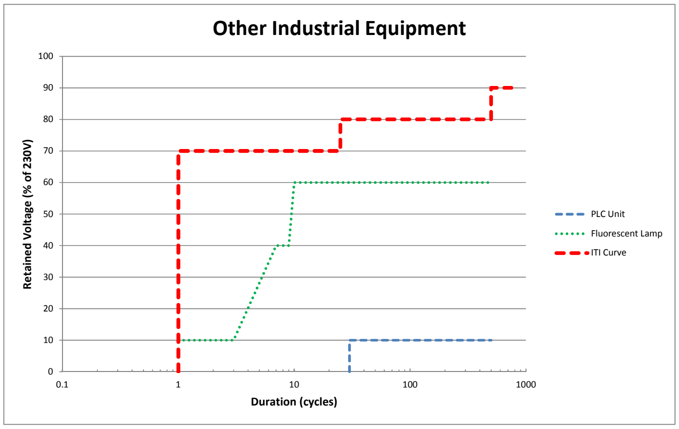

Figure 7: Voltage Sag Susceptibility Envelopes for Industrial Equipment (excluding contactors)

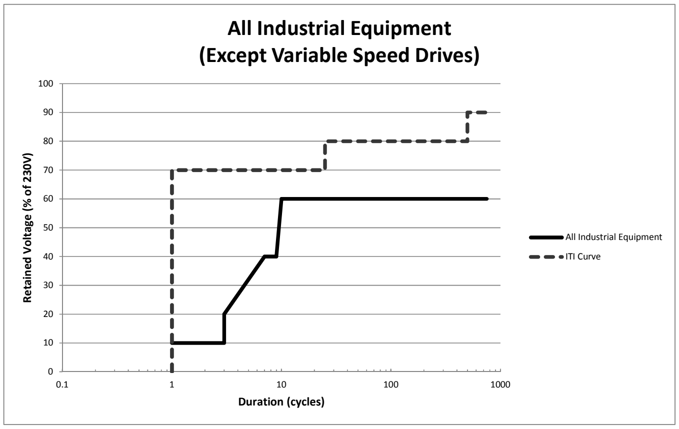

Figure 8: Voltage Sag Susceptibility for all Industrial Equipment
(excluding variable speed drives)

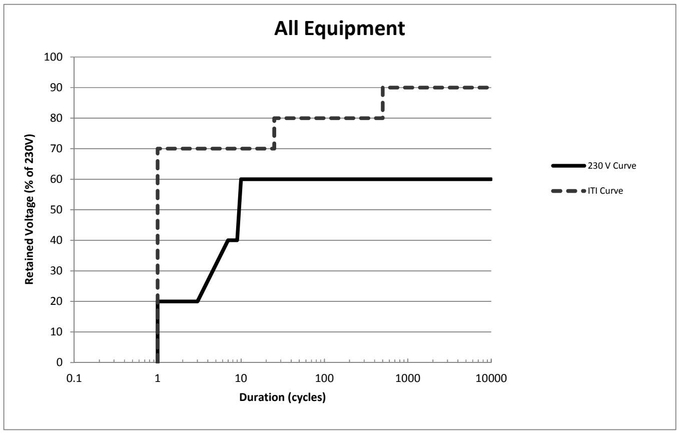

Figure 9: Voltage Sag Susceptibility Curve for all Tested Equipment (excluding VSDs)

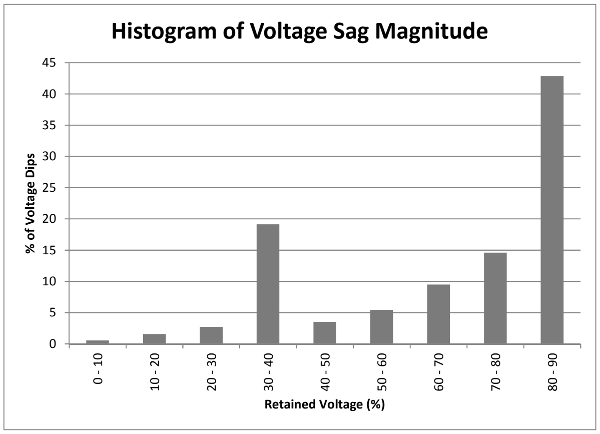

Figure 10: Histogram of Voltage Sag Magnitude

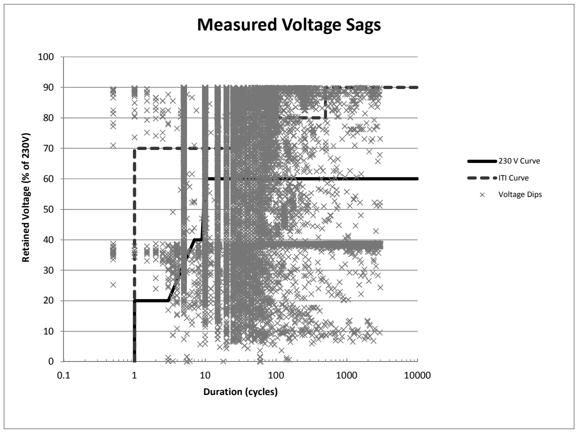

Figure 11: Measured Voltage Sags Plotted on Depth-Duration Plane