Voltage Sags and Equipment Sensitivity: A Practical Investigation

Hussain Shareef, Azah Mohamed and Nazri Marzuki
Universiti Kebangsaan Malaysia
Malaysia

1. Introduction

In recent years, interruption of manufacturing processes due to power quality degradation has become a major focal point for many power utilities. The most prominent power quality issue plaguing utility customers is voltage sag or dip. It is a sudden decrease in voltage amplitude followed by a return to its initial level after a short time.

The use of automation and energy efficient equipment with electronic control would greatly improve industrial production. However, since these new devices are more sensitive to supply voltage deviations, characteristics of the power system that were previously ignored are now becoming a nuisance. To evaluate the technical aspects and economic issues related to voltage sags, the process and equipment immunity level has to be known. However, there is little available information related to equipment sensitivity due to voltage sags.

Studies assessing sensitivity of voltage sags on customer loads are divided into practical and theoretical approaches. The practical approaches investigate the effects of voltage sag by monitoring and conducting experiments on customers' sensitive loads, as well as by performing pertinent surveys (Bollen, 2000). Equipment sensitivity to voltage sag can also be considered and presented in the form of power acceptability curves. These curves are plots of bus voltage deviation versus time duration which separate the bus voltage deviation - time duration plane into two regions namely, "acceptable" and "unacceptable" regions. The lower limb of the power acceptability curve relates to voltage sags and momentary outages. The latest power acceptability standards are the SEMI F47 issued by the Semiconductor Equipment and Materials International (SEMI) in the year 2000 (Djokic et al., 2005) and ITIC curve of the Information Technology Industry Council (ITIC) (Kyei et al., 2002). The SEMI F47 specification simply states that semiconductor processing, metrology, and automated test equipment must be designed and built to confirm to the voltage sag ride-through capability as per the defined curve. Equipment must continue to operate without interruption during conditions identified in the area above the defined acceptable region (Institute of Electrical and Electronics Engineers Inc, 2005).

As an effort to understand the voltage immunity level of sensitive equipment, some works have been reported in the past. The categories of sensitive equipment commonly evaluated for voltage sags are personal computers (PCs) that control the on line and off line processes, lighting systems, and ac contactors that are usually used to control motors and other industrial machineries.

The sensitivity of PCs to voltage sags is addressed in several references in the past. Seven PCs of different ages were investigated for voltage sags (Pohjanheimo & Lehtonen, 2002). The malfunction criterion for the PCs selected was automatic reboot. The authors reported that the PCs tolerate the under voltage level up to 50-60 % of remaining voltage for 100 ms. However, there was no clear correlation between the device age and sensitivity observed. Test results on standard restart/reboot malfunction criterion for computers due to voltage sags can also be found in (Saksena et al., 2005). It was reported that if the depth of voltage sag is larger than 30% and lasts more than 8 cycles, the voltage sag may cause a computer to restart. These tests were only carried out for the 120V/ 60 Hz systems. Similar experiments were conducted by Bok et al. (2008) to identify the effect of rectangular and non-rectangular voltage sags on the same restart/reboot malfunction criteria. It was noted that rectangular sags with loading condition influence most on the susceptibility of PCs. Another comprehensive study on the behavior of PCs during voltage sags and short interruptions was presented in (Djokic et al., 2005). Laboratory experiments were performed with rectangular voltage sags as well as with non-rectangular sags to simulate the starting of the large motors. Results show that all the voltage tolerance curves for different computers have the same rectangular shape with two clearly distinctive vertical and horizontal parts, with a very sharp “knee” between them. In references (Shareef et al., 2009a; Shareef et al., 2009b), the authors conducted laboratory experiments to answer why almost all the PCs have rectangular shaped voltage immunity curves with the flat vertical and horizontal part with a sharp knee between them and developed generic voltage tolerance curves for PCs. Most of these studies also declare that the PC test results can also somewhat extend to microprocessor/ CPU based devices.

Like test findings about PCs during voltage sags, there are published information that gives details on sensitivity of light flicker for different types of lamps. Experiments conducted on most common two categories of lightning loads namely fluorescent lamps (FLs) and helium lamps can be found in (Saksena et al., 2005). For both the fluorescent and helium lamps, it was concluded that the reduction in the intensity of the lamp depends only on sag depth. However, this conclusion was made on the basis of visual inspection. It was also reported that for sag depth of 60%, and 2 cycles, the fluorescent lamps start to switch off but no tests caused helium lamps to malfunction. These tests were conducted only for 120V/60 Hz system. The effects of voltage sags on several 150-W high pressure sodium (HPS) lamps combined with two different types of electronic ballast have been studied by another team of researchers (Díaz et al., 2007). It was notified that the two electronic HPS ballasts allowed the lamp to ride through for at least one cycle of power loss unlike the lamp with electromagnetic ballast. The best immunity level was found to be 57% of nominal rms voltage. Different types of gas discharge lamp namely mercury, HPS and metal halide rated from 70 to 250 watts were exposed to voltage sags by Pohjanheimo and Lehtonen (2002). The study concluded that the mercury and HPS lamps are less sensitive to voltage sags than the metal halide ones. Extensive laboratory tests with FLs having two different types of ballasts were carried out out by Shareef et al. (2009c) to observe the light intensity variation of the FLs during voltage sags and the researchers implemented a method to improve the sensitivity of the electronically ballasted FLs to voltage sags.

Similar to the other categories of sensitive equipment, ac contactors are also susceptible to power system disturbances such as voltage sags. It can disconnect circuits and cause expensive shutdown in industrial processes. Therefore some research work has been conduced to predict the behaviour of ac contactors during voltage disturbances (Pohjanheimo & Lehtonen, 2002), (Djokic´ et al., 2004), (Hasmaini & Khalid, 2004). The experiment described in (Pohjanheimo & Lehtonen, 2002) was performed to show the impact of the point on wave, sag duration, and sag amplitude on the performance of ac contactors. It was shown that voltage sag with a specific magnitude and duration can have different effects on a contactor depending on the point on wave where it originates. Additional research was conducted by Djokic´ et al. (2004) to observe the effect of phase shift during the sag, two-stage sags and sags due to the starting of large motors. It was reported that the threshold voltage that affect tripping does not have a big impact on phase shifts and for two stage sags. Digital simulation procedure for obtaining the contactor susceptibility can be found in (Hasmaini & Khalid, 2004). It concludes that the contactor disengagement initiates for voltage sags that last for 50 ms with 47% remaining voltage. But this result does not very well agree with other aforementioned research findings.

This chapter focuses on investigating the vulnerability of sensitive loads to voltage sags in the 240V/50Hz distribution system. Extensive laboratory tests are conducted for this purpose by analyzing the operation of different equipment during various events of voltage sag. From the analysis of the test findings, it also explains some of the parameters affecting the sensitivity of the tested equipment.

2. Sensitive Equipment

It is not practical to test all sag sensitive devices available in industrial or commercial facilities. Testing an adequate number of devices representing one component category is sufficient to justify the generalization of the acquired results. For this reason, the most sensitive equipment such as PCs, FLs and ac contactors are selected for testing. Functional overviews of these devices are given in the next sub sections.

2.1 Personal computers (PCs)

Personal computers first appeared in the late 1970s. It is a complex electronic computing device designed to be powered by a switch mode power supply (SMPS) which converts incoming single phase ac line voltage into a dc voltage that feeds the electronics components (Fujita & Akagi, 1999). A SMPS can be a fairly complicated circuit with stages such as rectification, filtration, conversion, and protections, as can be seen from the block diagram shown in Fig. 1.

In the first stage, a diode bridge rectifies the incoming voltage. A large capacitor then filters the pulsating dc voltage to create a nearly constant dc voltage. However, under normal operating conditions, over a half-cycle, the capacitor voltage decays to some value. Depending upon the minimum voltage value set by the design of the SMPS, the dc-dc converter in the conversion stage will deliver rated dc output voltage until the capacitor voltage reaches the designed minimum value. The time to reach this voltage at rated load is defined as the holdup time, T_h, which is represented mathematically as (Fernandez et al., 2005):

$$T_h = \frac{C_{dc}(V_{norm}^2 - V_{min}^2)}{2P} \tag{1}$$

where
C_{dc} is the capacitance of the filter capacitor.
V_{norm} is the peak nominal voltage.
V_{min} is the peak minimum voltage set by the SMPS design.
P is the rated power of the SMPS.

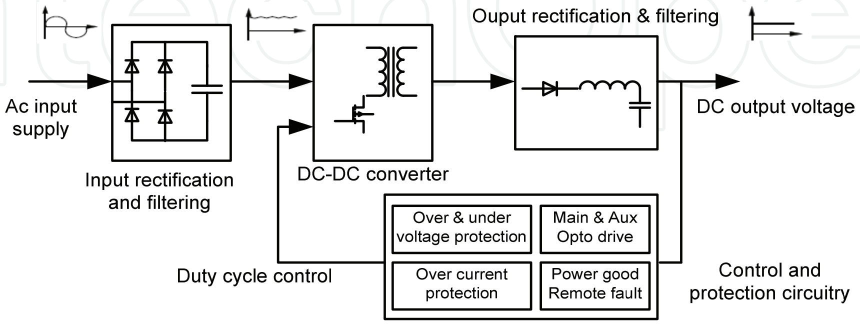


Fig. 1. Block diagram of a SMPS used in a PC

Another component related to sensitivity of PCs is the protection circuit of SMPS. These circuits monitor critical circuit conditions and report any violations of prescribed limits. Protection circuit provides over voltage and over current protection for 3.3V, ±5V and ±12V, generates power good logic output signal, programmable timing for power good signal, stable internal voltage reference and voltage reference for main and auxiliary regulation. In addition, there is a special under voltage detection input for sensing the input voltage to the power supply. This input causes the power good signal to toggle if there is insufficient voltage to run the power supply unit outputs. A high power good logic output indicates that the power from the mains is good for PC operation.

2.2 Fluorescent Lamps (FLs)

The operating principle of FLs is the same whether the form is a straight tube, circular, or convoluted as in compact fixtures. When a voltage is applied across the ends of a sealed glass tube containing mercury vapour, it causes the vapour to ionize. This vapour radiates light in the ultra violet region of the spectrum, which is converted to visible light by a fluorescent coating on the inside of the lamp. However, it requires a high voltage pulse across the tube to start the process and some form of limiter to prevent the current increasing to a level where the lamp can be destroyed. The current limiter is commonly known as ballast.

The traditional ballast contains an inductor connected in series with the lamp, and a starter (Vitanza et al., 1999). The starter triggers the tube when it is first turned on, by easing the current flow through the inductor and the filaments of the tube in the first place. When the starter bimetal strip reopens, the high circuit impedance and consequent sharp reduction in inductor current causes enough overvoltage to ionize the gas in the tube. However, this solution has significant weaknesses which include a high power loss in the inductor core, light flickering, and a very low power factor due to high inductive reactance.

Electronic ballasts replace the starting and bulk inductive elements of the conventional electromagnetic ballasts. The electronic ballast improves the performance of the lamp by operating at a higher frequency above the 50Hz determined by the mains supply. This eliminates lamp flickering because the gas in the tube does not have time to de-ionize between current cycles which also leads to lower power consumption, and longer tube life. Moreover, since the inductor required to ionize the tube is smaller, resistive loss and the system size is reduced (Vitanza et al., 1999).

Fig. 2 depicts a block diagram of an electronic ballast. The first block contains the protection, filtering, and current peak limiting components. Block 2 is the full diode bridge rectifier to convert the ac line into a dc stage. Block 3 is the smoothing capacitor. It provides the dc link voltage of the resonant inverter for the tube in Block 4. The resonant inverter normally runs at 10-40 kHz. The most commonly used resonant inverter circuits for low-wattage FLs are voltage fed half-bridge quasi-resonant circuits and current fed half-bridge resonant circuits (Vitanza et al., 1999).

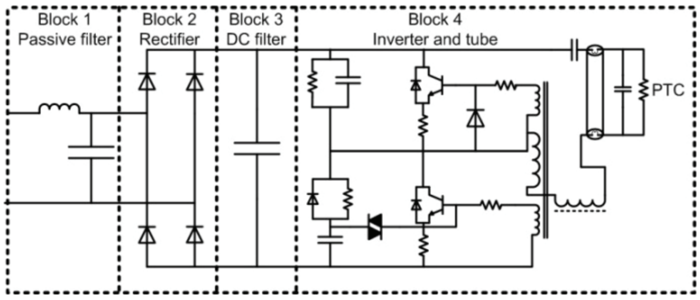


Fig. 2. Block diagram of an electronic ballast

2.3 AC contactors

An ac contactor utilizes a solenoid to cause one or more pairs of electrical contacts to engage when an appropriate voltage is applied to solenoid's coil as shown in Fig. 3. The solenoid consists of an electromagnet that attracts a moveable bar. The moveable bar is spring loaded so as to cause the bar to move away from the electromagnet when the electrical signal is not present on the coil. Electrical contacts are attached to the moveable bar and the movement causes the contacts to close or open depending on the strength of the magnetic field. The instantaneous flux, φ, and the force, F, that tends to close the air gap in the contactor can be expressed respectively as (Hasmaini & Khalid, 2004):

$$\phi = \frac{NI}{l/\mu A}\cos(\omega t) \tag{2}$$

$$F = \frac{\phi^2}{2\mu_0 A} \tag{3}$$

where
N = number of winding in the coil.
I = current flow through the coil.
l = the length of magnetic path.
μ_0 = absolute permeability.
μ = permeability of the coil substances.
A = the cross sectional area of the air gap.
ω = steady state frequency in radians.

Then, assuming the coil self inductance is constant and dominant, the minimum voltage, V_{hold}, required to keep the contactor from dropping out is given as (International Electrotechnical Commission, 2009):

$$V_{hold} = \frac{N\omega\phi}{\sqrt{2}} \tag{4}$$

According to (4) the hold in voltage, V_{hold}, depends very much on the flux which is directly proportional to the instantaneous current applied to the coil. Since the solenoid coil is assumed to be a pure inductor, the phase difference between the coil's current and voltage have a dramatic effect on the point on wave of the voltage sag event. For instance, a voltage sag initiates at the peak of the voltage waveform may leave a very small amount of current to produce enough force to hold the contacts while an event at zero crossing of voltage waveform will leave a much higher current to hold the contacts.

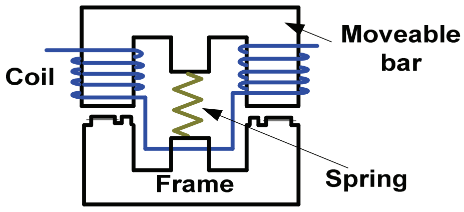


Fig. 3. Basic structure of an ac contactor

3. Methods and Materials

This section illustrates the design of the experiment for equipment testing and the procedures followed to obtain the results on the performance of the equipment during voltage sags.

3.1 PC testing

The methodology that is used in the testing is generally based on the guideline given in International Electrotechnical Commission (1994). Five PCs with different specifications are tested to study the effect of voltage sags on the performance of the computers. The specifications of the tested PCs are shown in Table 1. The specifications of the test PCs listed in Table1are assumed to cover some old and new models of PCs that are commonly in use at the time of the experiments.

The experimental set up consists of four components namely, sag generator, equipment under test (EUT), data acquisition system, and a computer to analyze the signals. In this case, an industrial power corruptor (IPC) from the Power Standards Lab is used, which is a voltage sag generator combined with built-in data acquisition system that is capable of producing and interrupting voltages up to 480V and current at 50A in single or three phase systems.

A series of test results on PCs are obtained by following the pre-defined procedure given below.

I. Using the terminal blocks available at the back of IPC, the conductors from mains panel and conductors to the PC under test are connected and the IPC is powered on.
II. The PC with all input/output (I/O) and pointing devices connected is switched on, allowing it to boot and load the operating system.
III. Allow Disk Defragmenter program to scan and defragment system discs.
IV. Starting from nominal voltage, voltage sags are initiated in steps of 2.5% down to zero volts. The sag initiation angle and the duration are kept constant. The initial sag duration and phase angle are set to 1 cycle and 0° respectively. The critical sag depth for the pre-defined malfunction criteria is determined by repeated testing for at least 3 times for a particular sag magnitude and duration. If reboot malfunction condition is observed, a quick inspection for proper operation of PC under test is conducted before initiating the next sag. For each triggered sag event, different voltage and current waveforms supplying and controlling the PC under test are recorded. Observations such as visible or audible influence on the PC are also noted.
V. The duration of sag is adjusted in steps of 1 cycle and measurements outlined in Step 4 are repeated.

PC no.	**Specifications**
PC1	CPU: Pentium III, 450MHz Processor, 128 MB SDRAM
	OS: Windows Me
	Power Supply: 100-127V/200-240V, 5/2.5A, 60/50Hz, 145W, Model: PS-5141-2D1
PC2	CPU: Pentium 4, 2.40GHz Processor, 261 MB RAM
	OS: Windows 2000 Professional
	Power Supply: 100-120V/200-240V, 5/3A, 60/50Hz, 180W, Model: NPS-180BBA
PC3	CPU: Core 2 Duo, 2.00GHz Processor, 1 GB RAM
	OS: Windows XP Professional
	Power Supply: 100-127V/200-240V, 8/4A, 60/50Hz, 250W, Model: PS-5251-08T
PC4	CPU: Pentium III, 933 MHz Processor, 256 MB RAM
	OS: Windows 2000 Professional
	Power Supply: 100-127V/200-240V, 9/4.5A, 60/50Hz, 300W, Model: SA-320-35005
PC5	CPU: Pentium 4, CPU 1.90GHz, 504 MB RAM
	OS: Windows XP Home Edition
	Power Supply: 100-127V/200-240V, 6/3A, 60/50Hz, 250W, Model: ATX-480W

Table 1. Specifications of tested PCs

3.2 FL testing

Many FLs with different ballast types are tested to study the effect of voltage sags on the performance of the lamps. The specifications of these FLs are shown in Table 2. The selected lamps are commonly found in residential and commercial applications. Since the main objective of lamp testing is to detect and determine light output variations of the FLs during voltage sags, it is important that the design of the test system must be fast enough to capture the light intensity variation of the test lamps accurately. Therefore, in addition to the materials used for PC testing an advanced photometer which is fast enough to capture the light intensity variation of the test lamps during sag events is used.

FL no.	Ballast type	Power rating	Lamp Type
FL1	Electronic	8W	CFL, Convoluted
FL2	Electronic	8W	CFL, Convoluted
FL3	Electronic	8W	CFL, Convoluted
FL4	Electronic	8W	CFL, Convoluted
FL5	Electronic	14W	CFL, Convoluted
FL6	Electromagnetic	18 W	Straight tube
FL7	Electronic	18 W	Straight tube
FL8	Electronic	18 W	CFL, Convoluted
FL9	Electronic	32 W	CFL, Convoluted
FL10	Electromagnetic	36 W	Straight tube

Table 2. Specifications of tested FLs

The test system shown in Fig. 4 has been built to perform the voltage sag disturbances and evaluate the resultant light output levels from the lighting source. The lamp under test is enclosed in a prefabricated lighting chamber which eliminates stray light and reduces reflections by its internal matt black surface. This point source method measures the light directly produced by the lamp with a light detector at the opposite end of the chamber. The detector head photocurrent is converted to a voltage and it is more than capable of detecting flicker in the human visible range of 0-35Hz (Frater & Watson, 2007). The conversion process of light detector current into an appropriate level of voltage is performed by the processor in the photometer. However, since the photometer does not have its own built in data acquisition system, the converted voltage waveform is therefore fed to the data acquisition system channels available in the IPC for post processing and analysis.

Similar to the series of tests conducted on PCs, test results for FLs are obtained for predefined malfunction conditions known as zero illuminance condition. At transition points where zero illuminance condition is start to observe, the procedure is repeated for at least three times to avoid probable errors that may occur during the experiments.

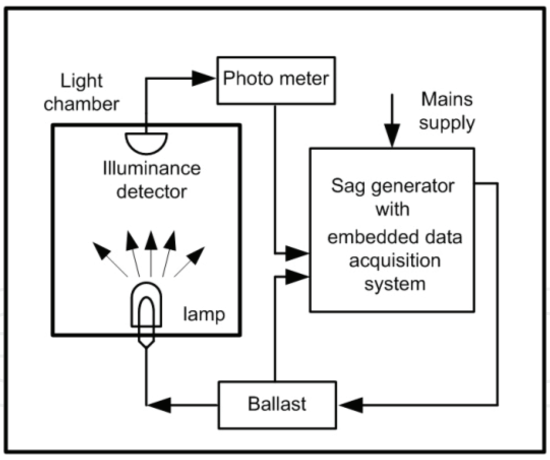


Fig. 4. FL test setup

3.3 AC contactor testing

In order to find the impact of voltage sags on ac contactors, different contactors listed in Table 3 are tested. All contactors are tested with a 2000 Watt spot light load attached to their main electrical contacts. First the contactor is warmed up to its normal operating temperature by applying nominal coil voltage for a couple of minutes before initiating the sag event. In the case of ac contactor testing, the malfunction condition was defined as the disengagement of the main contacts. The disengagement of contacts can be guaranteed with the test setup shown in Fig. 5 where one of the normally open contacts is used to energize the ac coil of the contactor.

Contactor no.	Manufacturer/ Model	Current rating
C1	LG Industrial System / GMC-18	18 A
C2	LG Industrial System / GMC-40	40 A
C2	FUJI / SC-N2 S	50 A

Table 3. Specifications of tested AC contactors

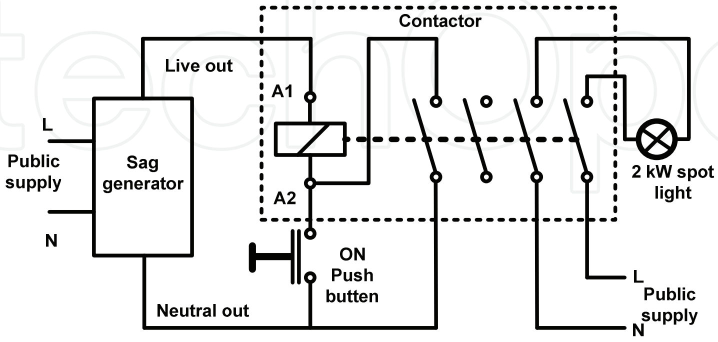


Fig. 5. AC contactor test setup

Here again, the test procedure follows the same basic steps illustrated in PC testing where the main variables are sag depth and duration. However, since point on wave of sag initiation affects contactor performance, point on wave of sag is also added as a test variable in this case. Sag initiation angle was varied in steps of 15° at a specific sag magnitude and duration.

4. Results and Analysis

The test findings of different equipment to voltage sags are initially presented as typical voltage tolerance curves. The upper region of these curves represents proper operation region while the lower region indicates unacceptable voltage conditions for equipment operation. Based on the findings, a generic voltage tolerance curve for each equipment category is then constructed.

4.1 Analysis of PCs' voltage tolerance level

Effect of voltage sag on all the tested PCs is shown in Fig. 6 along with the standard SEMI F47 and ITIC voltage acceptability curve. Like in previous research findings on sensitivity of PCs to voltage sags, the obtained curves have the same rectangular shape with two clearly distinctive vertical and horizontal parts, with a very sharp "knee" between them. From Fig. 6, it can be seen that for PC1 to PC5, the knee points are 47.5% - 14 cycles, 25% - 8 cycles, 40% - 12cycles, 50% - 11 cycles and 45% - 14 cycles, respectively. If one compares these individual voltage tolerance curves, it can be observed that PC4 is the most sensitive PC to voltage magnitude while PC2 is the least. When the sensitivity of the PCs in terms of duration is considered, PC2 starts to malfunction at 8 cycles. One final observation that can be obtained from Fig. 6 is that all tested PCs can ride through indefinitely if the magnitude of the sag is less than 50 % nominal voltage and satisfy the design goals of SEMI F47 and ITIC standard.

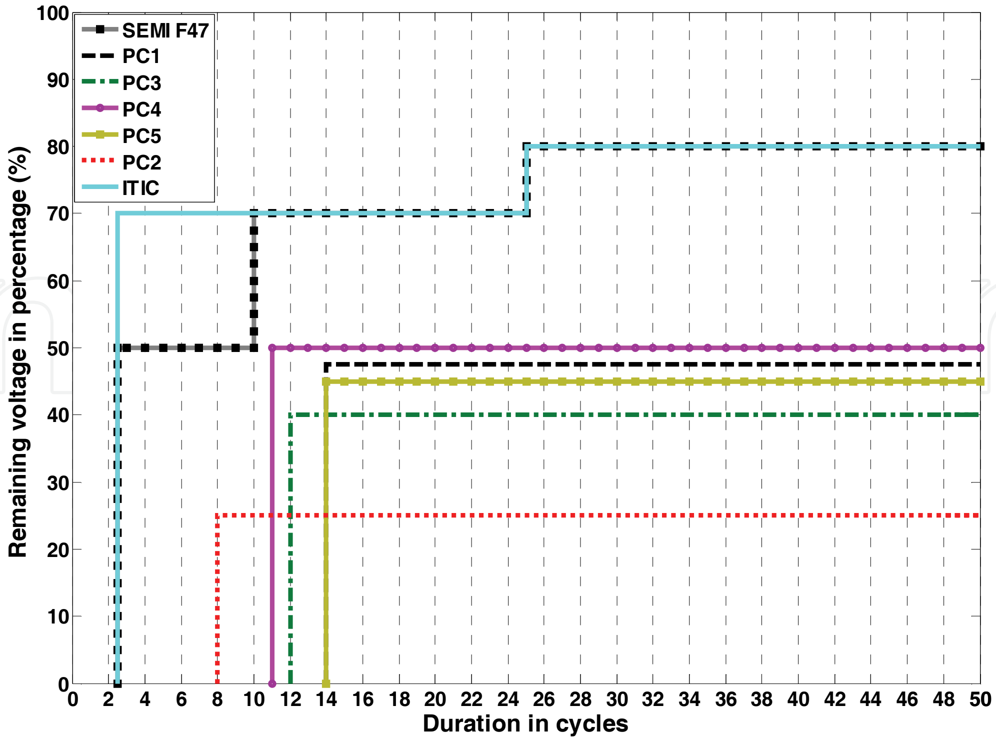


Fig. 6. Voltage tolerance curves of various PCs

As illustrated in Fig. 6, each personal computer potentially has its own standard of power acceptability. An approach to define the overall acceptability region is to apply intersection to the individual voltage tolerance curves (Kyei et al., 2002) as shown in Fig. 7.

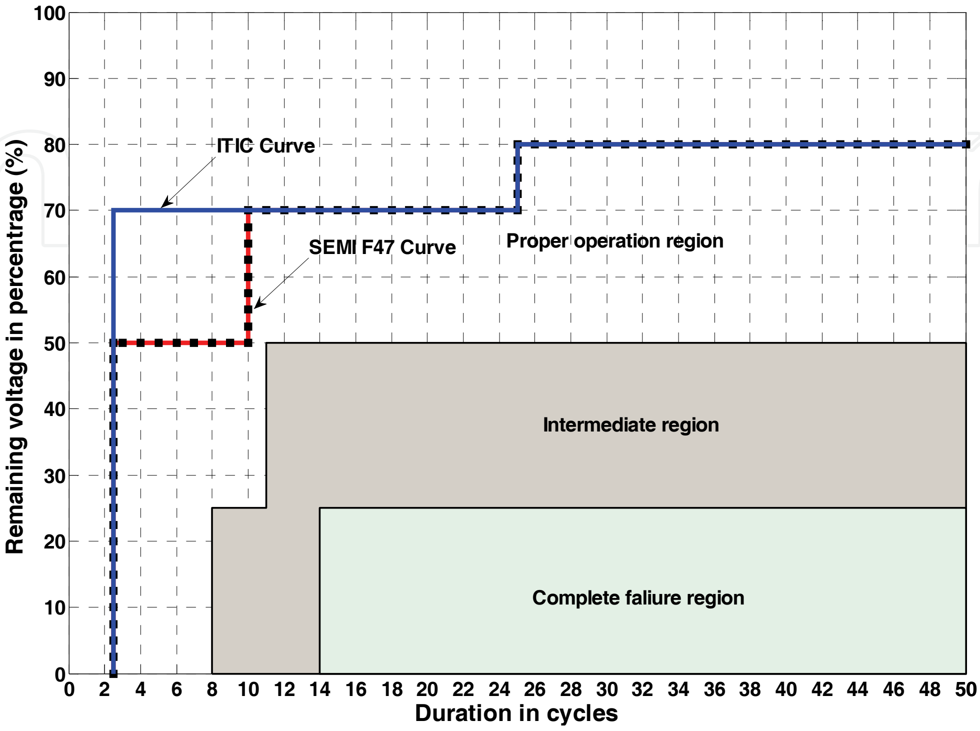


Fig. 7. Generic voltage tolerance curves of various PCs

In Fig. 7, the upper acceptable region is the region that all PC loads properly operate, the lower region indicates that all PCs fail, and the intermediate region corresponds to some PC failures and some ‘ride-throughs’.

To further understand the reason why almost all the PCs have rectangular shaped voltage sensitivity curves, signals obtained at different points of the SMPSs are analyzed. Figs. 8 and 9 illustrate the waveforms obtained at the rectifier dc output and power good logic output of the PC4 SMPS during different magnitude of voltage sags. From Fig. 8, it can be observed that by varying sag depth from 52.5% to 30 % remaining voltage for 10 cycles, the voltage decay at the rectifier dc output remains almost unchanged even for very deep sags. At 10 cycles, the energy stored in the dc link capacitor does not allow the rectifier dc output to decrease up to its minimum voltage as defined in (1). For this reason, the under voltage detection section of the housekeeping circuit does not toggle the power good signal as shown in Fig. 8. This indicates that PC4 will continue to operate normally for 10 cycles even if there is no mains supply for 200 ms.

Fig. 9 shows the variation of the rectifier dc output voltage and power good signal where PC4 starts to malfunction at 11 cycle. Since the sag duration is 20 ms longer at 11 cycles, the rectifier dc output voltage decays further. From Fig. 9, it is clear that deeper sags cause the power good signal to toggle and PC4 to reboot. This is due to the fact that the deeper sags starting from 50% remaining voltage cause the rectifier dc output to fall below the set minimum voltage of 154 Volts for PC4. Almost similar waveforms are obtained for the series of tests conducted on other PCs. In order to observe the effect of voltage sag duration, waveforms at the rectifier dc link are also observed for constant sag magnitude. It was noted that the dc link voltage decreases at a constant rate no matter what the sag duration is. So voltage sag duration does not have an effect on the time to reach the set minimum voltage of the SMPS design.

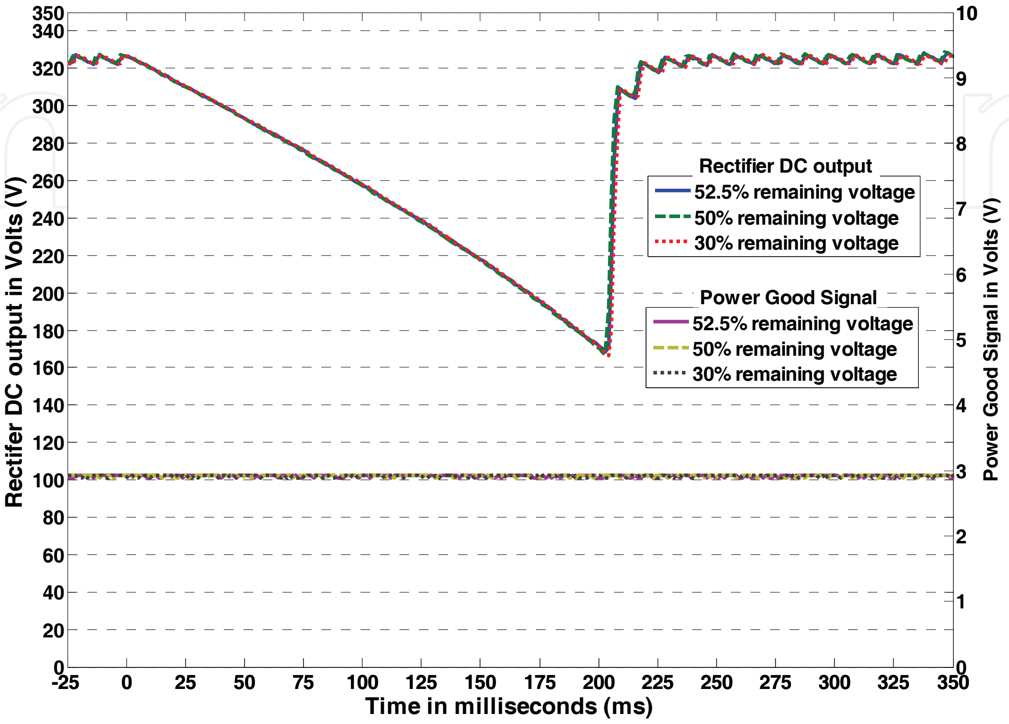


Fig. 8. Effect of sag depth on the rectifier dc output at 10 cycles for PC4

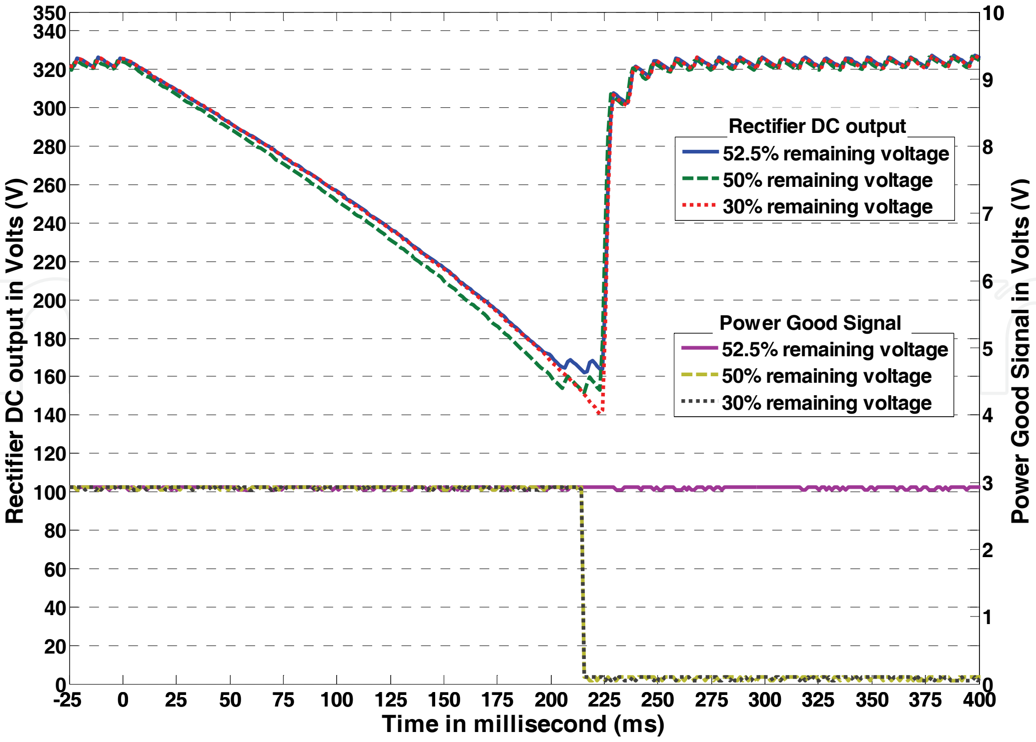


Fig. 9. Effect of sag depth on the rectifier dc output at 11 cycles for PC4

From the extensive tests and analysis, it can be concluded that the standard reboot/restart malfunction in the event of a voltage sag depends upon the energy stored in the dc link capacitor and the minimum voltage for which PC is designed to trigger the under voltage protection circuit embedded in the SMPS of the PC. Moreover, studies conducted to analyze the effect of sag depths and duration help to understand the rectangular nature of voltage tolerance curves of PCs.

4.2 Analysis of FLs' voltage tolerance level

Numerous test results of FLs are analyzed in this section. It is done by investigating the signals obtained from the photo sensor, lamp current, supply voltage and current. In the case of FLs with electronic ballast, the voltage variation at the dc bus which feeds the resonant inverter circuit shown in Fig. 2 is also investigated.

The overall immunity level of all 10 FLs to voltage sags are presented in Fig. 10 as typical voltage tolerance curves along with the SEMI F47 and ITIC standard. The upper region of these curves represents proper operation region while the lower region indicates zero illuminance conditions for FLs' operation. From Fig. 10, the FLs with electromagnetic ballasts are found to be the most sensitive lamps for short duration sag events. The lamp turn off condition for FLs with electromagnetic ballast generally initiated for voltage sags as short as 1 cycle. CFLs and conventional FLs with electronic ballasts are also sensitive to voltage sag. The main difference in the case of electronically ballasted FLs is that it is a little more immune to sags in terms of duration. However they are generally more sensitive of voltage sag magnitude as shown in Fig 10. FL7 with electronic ballast happened to be the most immune lamp to voltage sags. It is found to malfunction for sag magnitude beginning from 5% and for all durations greater than 5 cycles as shown in Fig. 10.

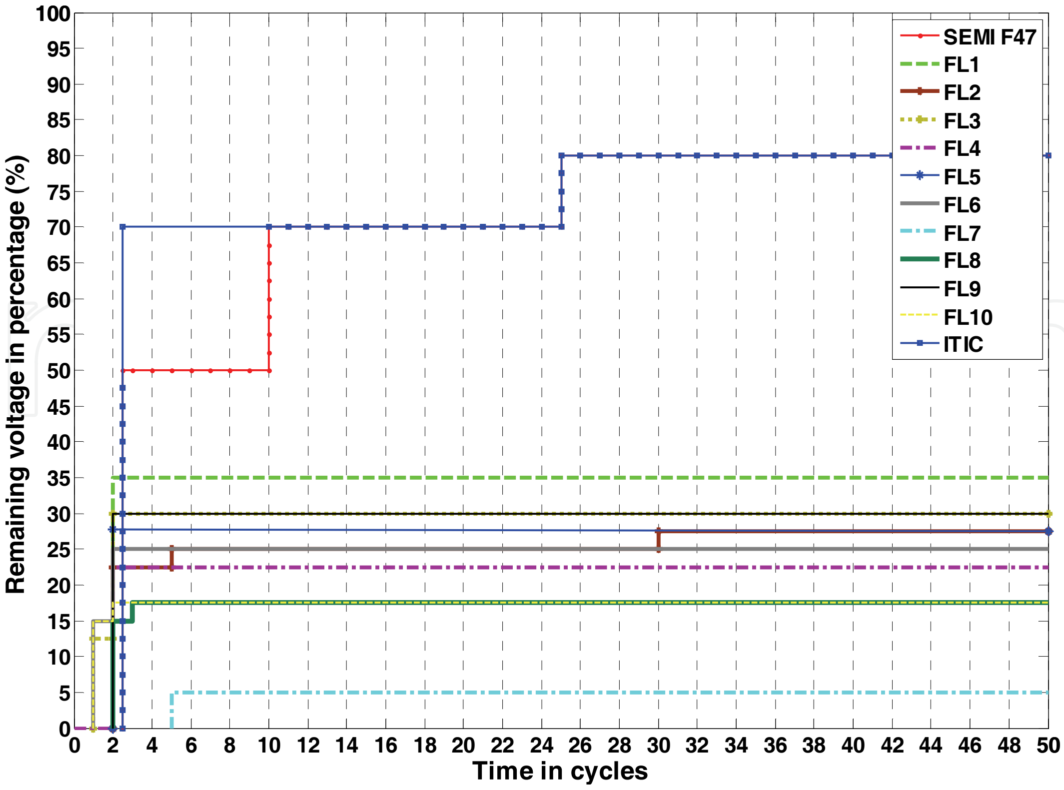


Fig. 10. Voltage tolerance curves of various FLs

Fig. 11 shows the generic voltage tolerance curve generated for FLs using intersection method. By comparing immunity curve of FLs shown in Fig. 11 it can be said that many FLs do not satisfy the design goals of SEMI F47 and ITIC standard as most of the FLs fail to deliver light for voltage sags lasting more than 2 cycles.

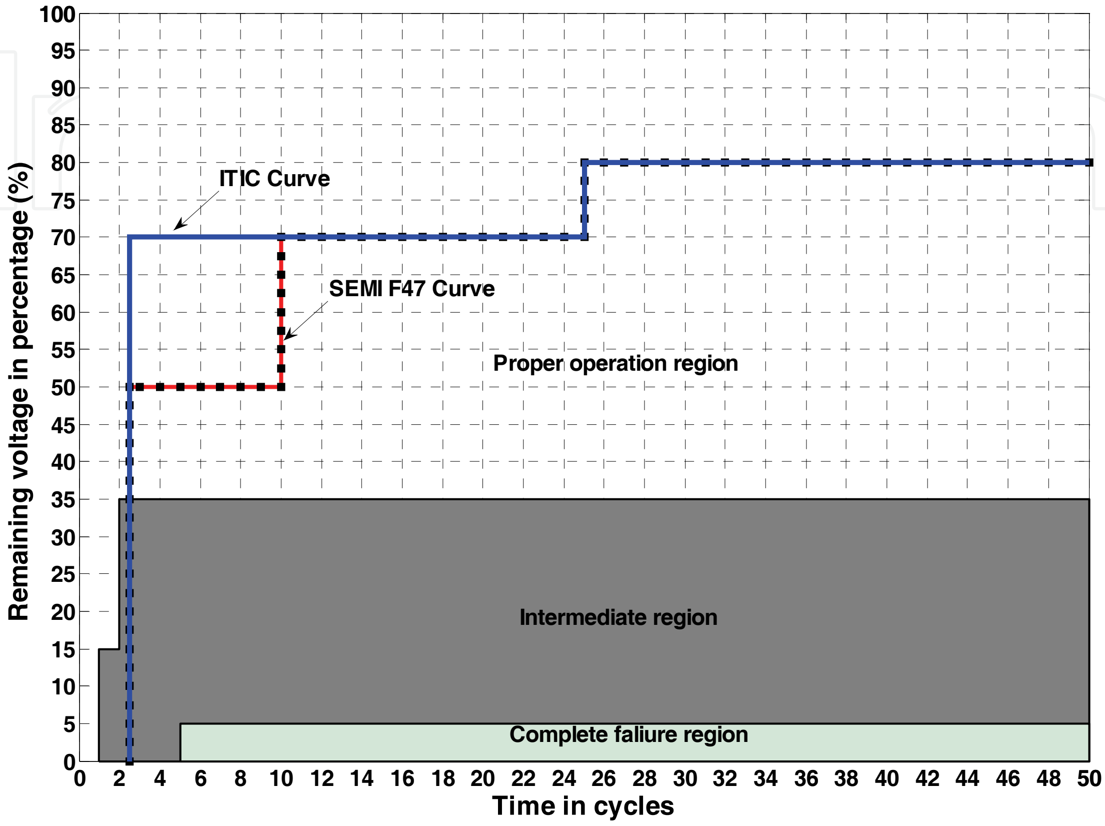


Fig. 11. Generic voltage tolerance curves of various FLs

Since the above voltage tolerances do not show how the lamp current, voltage and light output variation changes during voltage sag events, some observations obtained for FL6 and FL7 are illustrated below.

Figs. 12 and 13 illustrate the waveforms obtained from the photo sensor and the lamp current for the 18 Watt conventional FL (FL6) with electromagnetic ballast listed in Table 2, respectively. The effect of varying the sag depth starting from 25% to 15% remaining voltage for 1 cycle, on light output variation of the lamp is shown in Fig. 12. It shows very important information about the behavior of light output in conventional FL with electromagnetic ballast during voltage sag. The first information that can be derived from Fig. 12 is that the lamp turn off condition starts to occur for sag having 15% remaining voltage. At this point the lamp cannot reignite itself and requires the starter circuit to initiate ionization again. Furthermore, for different depths of voltage sags, the decay time of light output variation remains almost constant between 0 ms and 20 ms which represent the starting and end point of the sag respectively. Although FL6 starts to malfunction at 15% remaining voltage for voltage sag that last for 1 cycle, it is different for longer duration sags. For 2 cycle sags, the lamp becomes more sensitive to the depth of the sag. It starts to extinguish for all sags that is deeper than 25% remaining voltage.

Fig. 13 shows the variation of lamp current for different depths of voltage sag that last for 1 cycle. Observe that the lamp current, during all compared events of sag depth, reduce to a very low value. However, except in case of sag event that leaves 15% remaining voltage for 1 cycle, the lamp currents returns to normal as soon as the supply voltage recovers from the sag event.

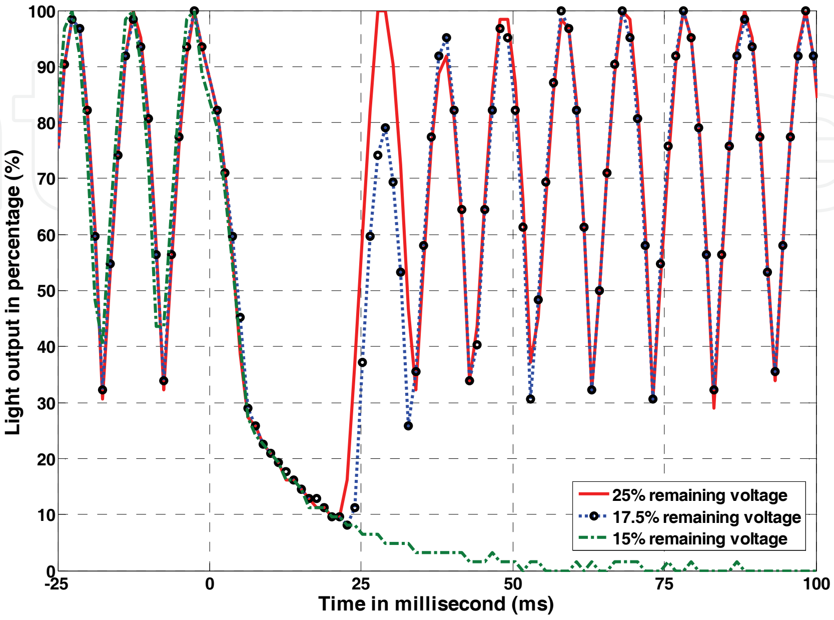


Fig. 12. Effect of sag depth on the light output at 1 cycle for FL with electromagnetic ballast

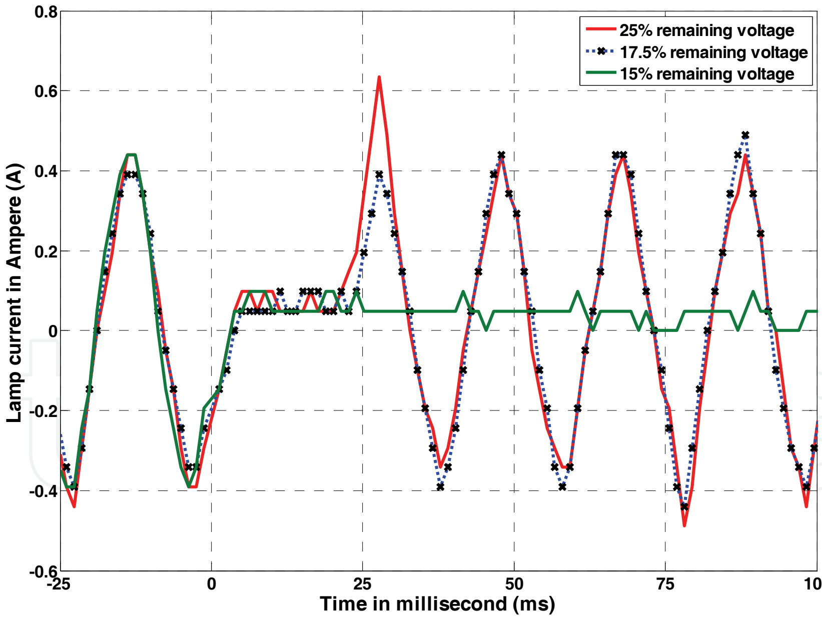


Fig. 13. Effect of sag depth on the lamp current at 1 cycle for FL with electromagnetic ballast

Similar to the FLs with electromagnetic ballasts, FLs with electronic ballasts also experienced zero illuminace condition due to voltage sag disturbances. Fig. 14 shows the variation in light output where FL7 with electronic ballast first starts to malfunction for voltage sag lasting for 5 cycles. From Fig. 14, it can be clearly seen that the FL7 is much more immune to voltage sag when compared to FL6 with electromagnetic ballast. Note from Fig.

14 that FL7 just reaches zero illuminance malfunction condition at a sag depth of 5% remaining voltage just at the end of the 5 cycles. Moreover, observe that the light output fluctuation in the steady state operation varies at a higher frequency within a narrow band of 90% to 100% of the nominal light output. This reduces the flicker effect that is obvious in the case of FL6 as seen in Fig. 12.

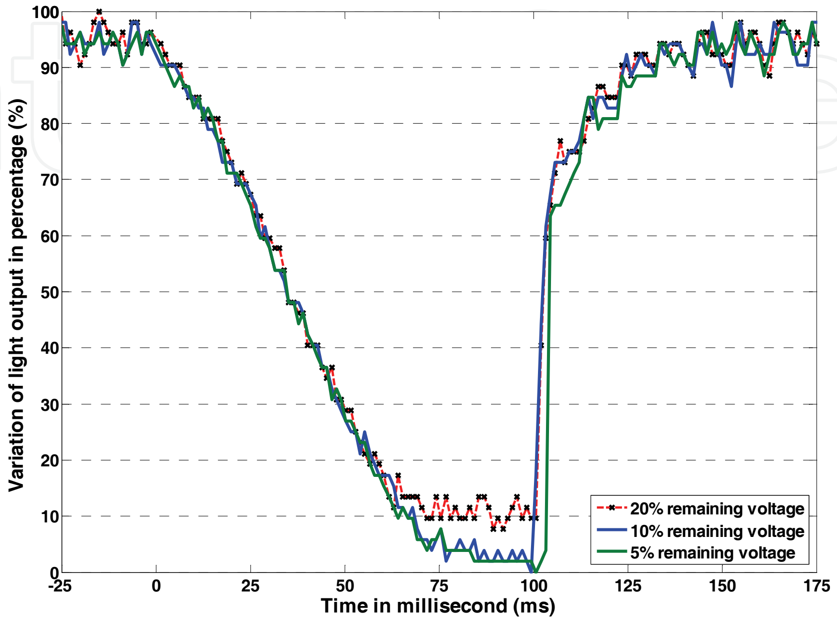


Fig. 14. Effect of sag depth on the light output at 5 cycles for FL with electronic ballast

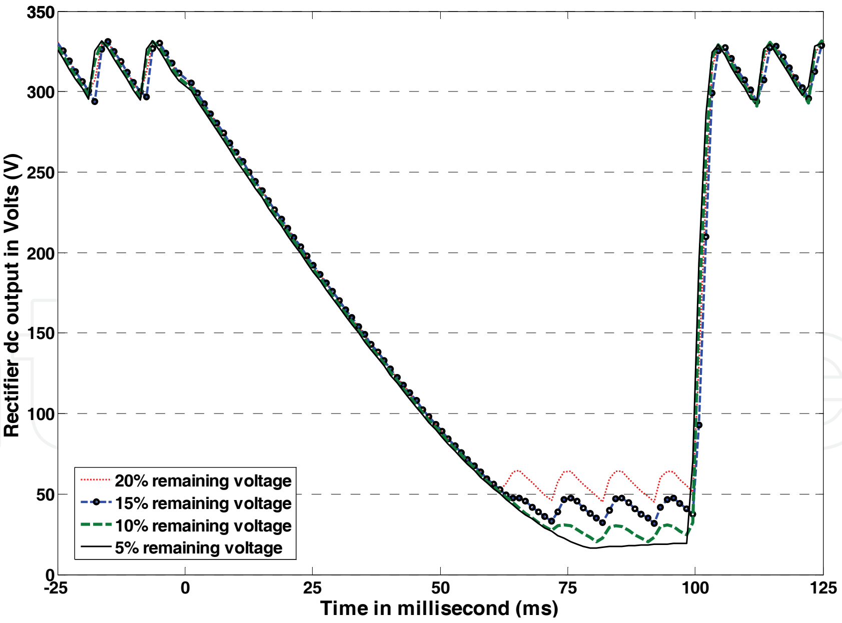


Fig. 15. Effect of sag depth on the light output at 5 cycles for FL with electronic ballast

Another way to confirm the malfunction condition of FLs that uses electronic ballast is to analyze the variations in the rectifier dc output or dc bus voltage and lamp current. These waveforms for FL7 are shown in Fig. 15 for different depths of voltage sag lasting for 5 cycles. Observe that for sag depth of 5% remaining voltage, the dc bus voltage maintains

almost at a constant voltage level just after 80 ms unlike for voltage sags that are shallower. This indicates that the lamp does not draw sufficient current for its proper operation.
To analyze the effect of variation of sag duration on the performance of FL7 at sag depth of 10% remaining voltage, Fig.16 is plotted. From Fig. 16 it can be noted that the light output variation does not drop down to zero completely even if the sag duration is varied between 3 to 6 cycles and therefore the lamp is considered to operate properly. Here again it can be observed that the decay rate of light output variation during the sag, remains almost the same. For example, all sag events cause the light output of this FL to drop up to 18% of full brightness at 60 ms as shown in Fig. 16.

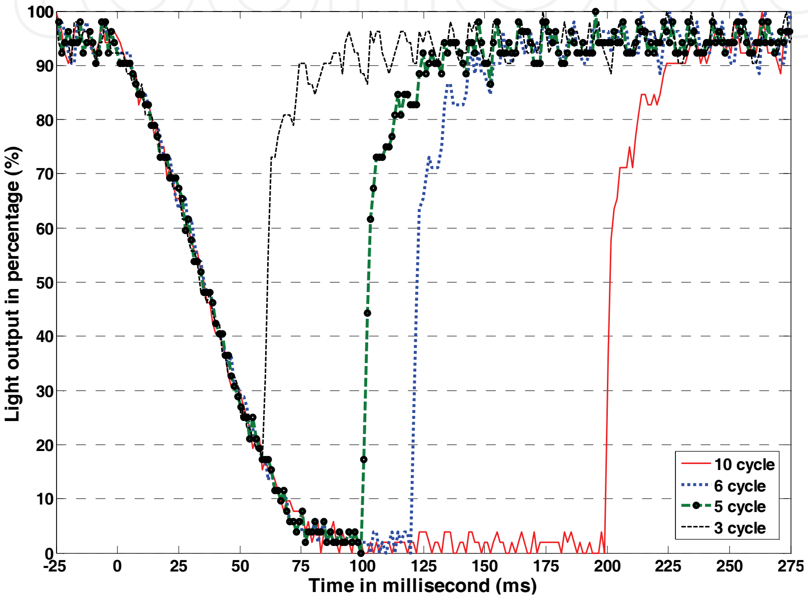


Fig. 16. Effect of sag duration on the light output at 10% remaining voltage for FL with electronic ballast

From the extensive tests and analysis, it can be concluded that the malfunction of FLs with electronic ballast, in the event of voltage sag, depends upon the energy stored in the dc link capacitor and the minimum voltage for which the ballast is designed to function properly unlike the conventional electromagnetic blasted lamps. However, this conclusion is not true for FLs with electromagnetic ballast.
Although it has not been highlighted in the FL test procedure, it is found that 0° sag initiation angle influence most on the sensitivity of electromagnetically ballasted FL compared to tests conducted to observe the effect on initial point on wave of the sag.

4.3 Analysis of AC contactors' voltage tolerance level

Test results of testing of the contactor with rectangular voltage sag do not produce a single voltage tolerance curve, but the families of curves corresponding to different point on wave initiation. Typical effect of point on wave for the contactor C1 listed in Table 1 is shown in Fig. 17. The contactor C1 tolerates for very deep sags and interruptions up to 4 cycles in cases where the sag initiation occurs at 0° or 45° on the point of voltage waveform. However, when the initiation angle is 90°, the contactor disengages for sags that last only for 1 cycle. This result also agrees with the theory highlighted in Section 2.3. For other tested contactors, the effect on point of wave shows similar behavior. Fig. 18 shows the generic voltage tolerance curve obtained from individual immunity curves of the contactors. From this generic curve it can be seen that SEMI F47 and ITIC curves are not a suitable standards to compare the tolerance levels of ac contactors. A more suitable standard to compare the performance of contactors could be IEC standard 60947-4-1 (International Electrotechnical Commission, 2009). According to this standard the limits between which the contactors should drop out and open fully are 75% to 20% of their rated control supply voltage for ac contactors. If one compares the tolerance levels of tested contactors with IEC standard 60947-4-1, all falls within the specified limits.

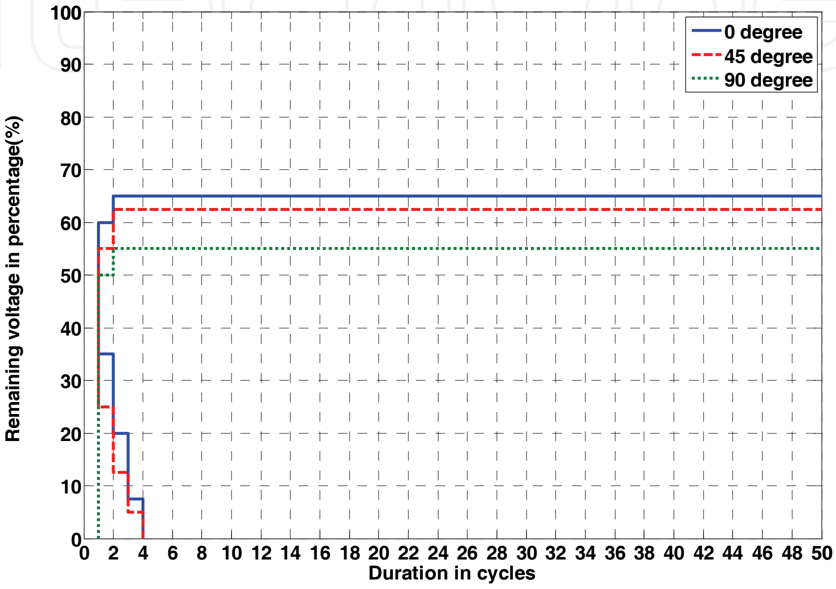


Fig. 17. Voltage tolerance curves for contactor C1

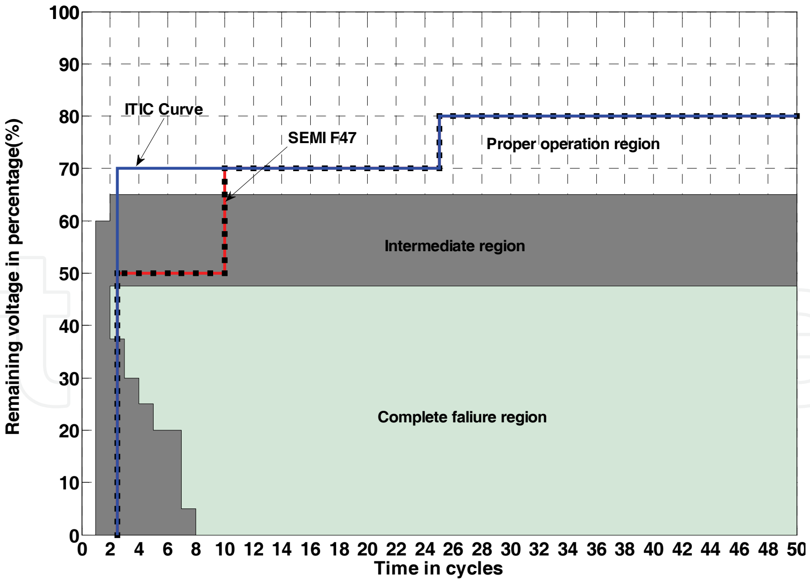


Fig. 18. Generic voltage tolerance curves for contactors

5. Conclusions

An extensive experimental study has been performed to determine the effect of voltage sag on sensitive loads such as PCs, FLs and ac contactors. Based on the experimental results it is possible to construct a generic voltage tolerance curve for sensitive equipment which can clearly show acceptable and unacceptable regions for different voltage sag disturbances. The curve provides a quick overview about the immunity level of these devices in a particular power distribution network.

From the experimental results, it can be concluded that the voltage tolerance level of the PCs used in the tests vary over a wide range. All the voltage immunity curves obtained appear to have similar shape with distinctive vertical and horizontal parts. When the voltage immunity levels of the tested PCs are compared with the SEMI F47 and ITIC standards, all the tested PCs satisfy their design goal. By observing different waveforms at the SMPS of PCs, the reason behind the rectangular nature of PCs voltage tolerance curves is revealed. Moreover, investigation on the rectifier dc output and power good signal of SMPS shows that malfunction of a PC occurs at a specific time for a predefined minimum voltage defined by the design of the PC SMPS. Therefore, deeper and longer duration sags do not have any correlation with the initiation of PC restart malfunction condition. It only appears to rely on the hold-up time and the set minimum voltage of the SMPS.

From the results of the tested FLs, the voltage immunity level of the lamps with electromagnetic ballasts is more sensitive to voltage sags than the FLs equipped with electronic ballasts. By observing variations in the light output of the lamps, it is possible to conclude that the light intensity of the lamp not only depends on the voltage sag depth but also on the duration of the sag event depending upon the design of the ballast used in the lamp. Moreover, investigations of rectifier dc output and lamp current of FLs with electronic ballasts show the exact timing where the ballast stops functioning properly.

The test results on ac contactors clearly show that the magnitude and the duration of voltage sag are not the only parameters that influence the sensitivity of a contactor to voltage disturbances. The point on wave initiation has significant influence on the behaviour of ac coil contactors.

6. References

Bollen, M.H.J. (2000). Understanding Power Quality Problems: Voltage Sags and Interruptions, IEEE Press, ISBN 0-7803-4713-7, New York

Bok, J.; Drápela, J. & Toman, P. (2008). Personal computers immunity to short voltage dips and interruptions, Proceeding of 13th international conference on harmonics and quality of power, pp. 1-6, ISBN 978-1-4244-1771-1, Australia, September-October 2008, IEEE, Wollongong

Djokic, S.Z.; Milanovic, J.V. & Kirschen, D.S. (2004). Sensitivity of AC coil contactors to voltage sags, short interruptions, and undervoltage transients, IEEE Transaction on Power Delivery, Vol.19, No. 3, July 2004, pp1299-1307, ISSN 0885-8977

Djokic, S.Z.; Desmet, J. Vanalme, G. Milanovic, J.V. & Stockman, K. (2005). Sensitivity of personal computers to voltage sags and short interruptions, IEEE Transaction on Power Delivery, Vol.20, No.1, January 2005, pp. 375-383, ISSN 0885-8977

Díaz, F.J.; Azcondo, F.J. Ortiz, F. Ortiz, A. Mañana, M. & Renedo, C. (2007). Effects of voltage sags on different types of ballasts for 150-W HPS lamps, Proceeding of 9th international conference on power quality and utilization, pp. 1-6, ISBN 978-84-690-9441-9, Spain, October 2007, Barcelona

Fujita, H. & Akagi, H. (1999). Control and performance of a pulse-density-modulated series-resonant inverter for corona discharge processes, IEEE Transaction on Industrial Application, Vol. 35, No.3, May-June 1999, pp 621-627, ISSN 0093-9994

Fernandez, J.; Sebastian, M. Hernando, M. Villegas, P. & Garcia, J. (2005). Helpful hints to select a power-factor-correction solution for low- and medium-power single-phase power supplies, IEEE Transaction on Industrial Electronics, Vol. 52, No.1, February 2005, pp 46-55, ISSN 0278-0046

Frater, L.P. & Watson, N.R. (2007). Light flicker sensitivity of high efficiency compact fluorescent lamps, Proceedings of australasian universities power engineering conference, pp. 1-6, ISBN 978-0-646-49488-3, Australia, December 2007, IEEE, Perth

Hasmaini, M. & Khalid, M.N. (2004). Evaluation on Sensitivity of AC Contactor During Voltage Sag, Proceeding of IEEE TENCON 2004 region 10 conference, pp. 295-298, ISBN 0-7695-2378-1, Thailand, November 2004, IEEE, Chiang Mai

International Electrotechnical Commission. (1994). Electromagnetic Compatibility (EMC), Part 4: Testing and Measurement Techniques, Section 11: Voltage Dips, Short Interruptions and Voltage Variations Immunity Tests, Std. IEC 61000-4-11

International Electrotechnical Commission. (2009). Low-Voltage Switchgear and Controlgear – Part 4-1: Contactors and Motor-Starters – Electromechanical Contactors and Motor-starters, IEC 60947-4-1.

Institute of Electrical and Electronics Engineers Inc. (2005). Recommended Practice for Powering and Grounding Electronic Equipment, IEEE Press, ISBN 0-7381-4979-9 SH9551, New York

Kyei, J. Ayyanar, R. Heydt, G.T. Thallam, R. & Blevins, J. (2002). The design of power acceptability curves, IEEE Transaction on Power Delivery, Vol.17, No.3, July 2002, pp.828–833, ISSN 0885-8977

Pohjanheimo, P. & Lehtonen, M. (2002). Equipment sensitivity to voltage sags – test results for contactors, PCs and gas discharge lamps, Proceeding 10th international conference on harmonics and quality of power, pp. 559- 564, ISBN 0-7803-7671-4, Brazil, October 2002, IEEE, Rio de Janeiro

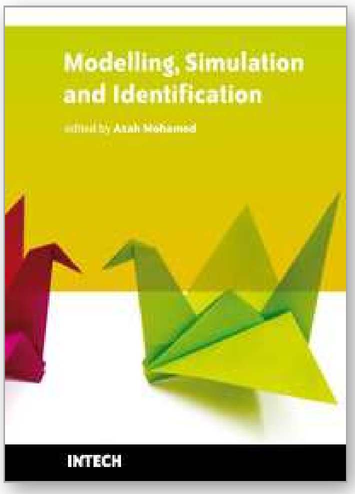
Saksena, S.; Shi, B. & Karady, G. (2005). Effects of voltage sags on household loads, Proceeding of power and energy society general meeting - conversion and delivery of electrical energy in the 21st century, pp. 2456- 2461, ISBN 0-7803-9157-8, USA, June 2005, IEEE, USA

Shareef, H.; Mohamed, A. & Marzuki, M. (2009a). Immunity level of personal computers to voltage sags in the 240 v/50 Hz distribution systems, Journal of Applied Sciences, Vol.9, No.5, January 2009, pp. 931-937, ISSN 1812-5654

Shareef, H.; Mohamed, A. & Marzuki, M. (2009b). Analysis of personal computers ride through capability during voltage sags, Electric Power Systems Research, Vol.79, No.1, December 2009, pp. 1615-1624, ISSN 0378-7796

Shareef, H.; Mohamed, A. & Marzuki, M. (2009c). Analysis of ride through capability of low-wattage fluorescent lamps during voltage sags, International Review of Electrical Engineering, Vol.4, No.5, September- October 2009, pp. 1093-1101, ISSN 1827-6660

Vitanza, A.; Scollo, R. & Hayes, A. (1999). Electronic fluorescent lamp ballast, STMicroelectronics Application Note AN527/1294



Modelling, Simulation and Identification

Edited by Azah Mohamed

ISBN 978-953-307-136-7
Hard cover, 354 pages
Publisher Sciyo

Published in print edition August, 2010

Modeling, simulation and identification has been actively researched in solving practical engineering problems. This book presents the wide applications of modeling, simulation and identification in the fields of electrical engineering, mechanical engineering, civil engineering, computer science and information technology. The book consists of 17 chapters arranged in an order reflecting multidimensionality of applications related to power system, wireless communication, image and video processing, control systems, robotics, soil mechanics, road engineering, mechanical structures and workforce capacity planning. New techniques in signal processing, adaptive control, non-linear system identification, multi-agent simulation, eigenvalue analysis, risk assessment, modeling of dynamic systems, finite difference time domain modeling and visual feedback are also presented. We hope that readers will find the book useful and inspiring by examining the recent developments in the applications of modeling, simulation and identification.

Hussain Shareef, Azah Mohamed and Nazri Marzuki (2010). Voltage Sags and Equipment Sensitivity: a Practical Investigation, Modelling, Simulation and Identification, Azah Mohamed (Ed.), ISBN: 978-953-307-136-7, InTech, Available from: http://www.intechopen.com/books/modelling--simulation-and-identification/voltage-sags-and-equipment-sensitivity-a-practical-investigation

INTECH
open science | open minds

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821