Power Systems Engineering Research Center

Effects of Voltage Sags on Loads in a Distribution System

Final Project Report

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Power Systems Engineering Research Center

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Executive Summary

Voltage sags pose a serious power quality issue for the electric power industry. Much work has been done assessing the effects of voltage sags on power system operation, and on industrial and commercial loads. However, more research has been needed on the effects of voltage sags on residential loads, particularly sensitive equipment such as computers.

This project helps fill that information gap by providing new detailed information on the effects of voltage sags of varying depths and durations on selected residential equipment. In addition, to better understand how voltage sags affect the residential customer class, surveys were conducted to determine the type of equipment present in residential apartment complexes in Tempe, Arizona. With testing and survey data, it was possible to develop predictions of the overall effect of voltage sags of various depths and durations on selected apartment complexes. Finally, the testing enabled assessment of the accuracy of standard “CBEMA” curves that allow prediction of the effect of voltage sags on equipment performance.

Tests performed on selected residential equipment suggest that voltage sags tend to not damage the equipment. Equipment performance may degrade, but the duration is typically quite short for the types of voltage sags residential customers most often experience. Hence, for residential customers, the economic cost due to voltage sags alone is probably negligible. More significant costs would be incurred if a power service outage followed a voltage sag, such as if a feeder on which the sag occurred went out of service.

Tests were conducted on contactors, circuit breakers, air conditioner compressors, helium and fluorescent lamps, computers, microwave ovens, televisions, VHS/DVD players, CD players, digital clock radios, sandwich makers, and toasters. Testing was done with EPRI’s Process Ride-Through Evaluation System (PRTES) which provided a voltage sag generator and a built-in data acquisition system. Voltage sags ranged from depths of 90% to 50%, and durations of 5 cycles to 60 cycles. The current and the voltage across the load were recorded, and equipment performance was observed. Here is a summary of the test results.

1. **Contactors**. Test results for 10 and 15 ampere contactors showed that the contactors were not affected by sags to depths of 70%. Chattering occurred for sag depths of 60% and duration greater than 30 cycles. In the case of 50% and 40% sag depths, the contactors tripped without chattering for all sag durations. The contactors behaved identically under load and no-load conditions. Circuit breakers were unaffected.
2. **Air Conditioners**. The compressor motors stalled for sags greater than 50% and durations greater than 10 cycles. The point of initiation of the voltage sag in the voltage cycle did not noticeably affect motor performance. However, as expected, motor speed decreased and current increased during the sags.
3. **Lamps**. Reduced light intensity occurred for the tested helium and fluorescent lamps. The reduction depended on sag depth, but not duration.
4. **Computers**. Computers restarted for sags of depth greater than 30% and duration longer than 8 cycles.
5. **Microwave Ovens**. Microwave ovens switched off for 50% sag depth and duration of 10 cycles or more. They also switched off at 60% sag depth and duration of 30 cycles

or more. There were only visible effects (such as flickering of light inside the oven and blinking of a digital clock) for sags of depth 90%, 80%, and 70%.

6. **Televisions.** The televisions switched off for 50% sag depth and duration of 30 cycles or more. The switching off was preceded by shrinking and collapsing of the video image.
7. **Audio and Video Equipment**. Performance of DVD/ VHS players and stereo CD players was largely unaffected by sags, except for flickering of the electronic timer displays.
8. **Digital Alarm Clock Radios**. Digital alarm clock radios suffered severe audio quality loss for sags of depths 60% and 50% for a few seconds.
9. **Toasters.** Sags of 60% depth and 50 cycle duration, and 50% depth and 40 cycle duration caused a toaster that had just begun operation to turn off automatically because the coils of the toaster did not get red hot due to the sag. However, the sag had no effect on already operating toasters.

Computer Business Equipment Manufacturers Association (CBEMA) curves were created for all the appliances that switched off or stalled due to voltage sags; that is, CBEMA curves were estimated for air conditioner compressors, lighting loads, microwave ovens, televisions, and computers. CBEMA curves depict graphically the severity versus duration of voltage sags. Essentially, the curves show the sensitivity of equipment performance to voltage sags. Results showed that the CBEMA curves obtained through testing were more conservative in comparison to standard CBEMA/ ITIC curves. In other words, CBEMA curves from the test results showed greater sensitivity to sags than standard curves.

Apartment complexes in the Tempe, Arizona area were surveyed to determine the type of electric equipment used. From the equipment testing and survey data, it was possible to construct a table to estimate the effect of voltage sags on a single apartment as a function of sag depth and duration. For example, the most severe effect of sags on the apartment would be for a sag of depth 50% and duration greater than 30 cycles as air conditioner compressors stall, microwave ovens and televisions switch off, and computers restart resulting in data loss. The use of such tables by distribution utilities could enhance their power quality analyses.

The results suggest the conditions under which residential feeder loss may be caused by a voltage sag. This scenario is possible if the air conditioner compressors in an apartment complex stall for a sag of 50% depth and duration greater than 30 cycle,. and then try to restart simultaneously. This could produce an overcurrent that triggers the protection on the feeder.

Equipment testing performed in this project should be redone periodically, perhaps every two years, to keep up with the latest residential equipment technologies. The effect of sags on this equipment could well change as technology improves. It may also be useful to test the equipment of a wider range of manufacturers. Finally, these results suggest that the basis for the standard CBEMA curves should be reassessed.

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Chapter 1 Introduction: Review on Voltage Sags

Voltage sags are a common power quality problem. Despite being a short duration (10ms to 1s) event during which a reduction in the RMS voltage magnitude takes place, a small reduction in the system voltage can cause serious consequences.

1.1 Definition of Voltage Sags

The definition of voltage sags is often set based on two parameters: magnitude/depth and duration. However, these parameters are interpreted differently by various sources. Other important parameters that describe a voltage sag are (1) the point-on-wave where the voltage sag occurs, and (2) how the phase angle changes during the voltage sag. A phase angle jump during a fault is due to the change of the X/R-ratio. The phase angle jump is a problem especially for power electronics using phase or zero-crossing switching.

A sag or sag, as defined by IEEE Standard 1159, IEEE Recommended Practice for Monitoring Electric Power Quality, is "a decrease in RMS voltage or current at the power frequency for durations from 0.5 cycles to 1 minute, reported as the remaining voltage". Typical values are between 0.1 p.u. and 0.9 p.u. Typical fault clearing times range from three to thirty cycles depending on the fault current magnitude and the type of overcurrent detection and interruption.

Terminology used to describe the magnitude of a voltage sag is often confusing. Throughout the course of the project work, a usage of sag 'of' a certain value has been used and has been represented as ΔV. Thus, a sag of 20% means a voltage drop, ΔV, of 20% from its initial voltage level. In the report, sag depth refers to ΔV. Just as an unspecified voltage in a three-phase system is assumed to be mean line-to-line voltage, in the same way, sag magnitude (depth) will refer to the voltage drop, ΔV, from its initial value, throughout the report.

Another definition as given in IEEE Std. 1159, 3.1.73 is "*A variation of the RMS value of the voltage from nominal voltage for a time greater than 0.5 cycles of the power frequency but less than or equal to 1 minute. Usually further described using a modifier indicating the magnitude of a voltage variation (e.g. sag, swell, or interruption) and possibly a modifier indicating the duration of the variation (e.g., instantaneous, momentary, or temporary)*". Figure 1 shows the rectangular depiction of the voltage sag.

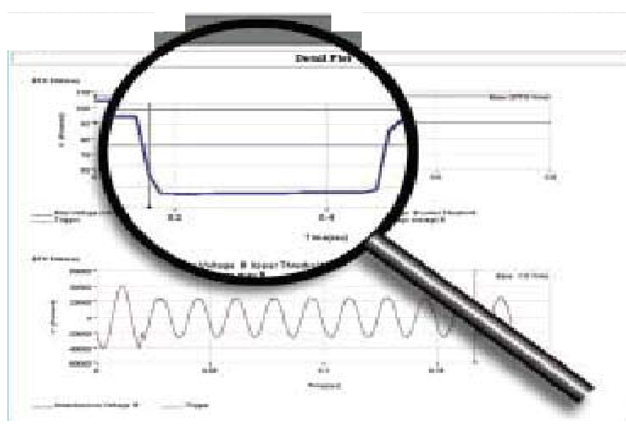


Figure 1. Depiction of voltage sag

1.2 Characterization of Voltage Sag

The voltage during a voltage sag is assumed to be a constant RMS value, usually the lowest phase voltage. However, in reality, the RMS value varies during a sag. Hence, various methods have been proposed to characterize voltage sags.

The most common approach to define a voltage level during a sag is to consider the lowest phase voltage and ignore the rest. However, this method reports only one sag per fault and does not distinguish between single-phase and multi-phase voltage sags.

Another method is to consider the voltage in each phase. A voltage sag in each phase will be counted as a separate event. With this method. a three-phase-voltage sag will be counted as three voltage sags. The third representation is to use the average voltage of all phases. This method only reports one voltage sag per fault, and usually none of the phases has the same voltage as the average.

A three-phase voltage study of voltage sags results in two main groups, balanced and unbalanced voltage sags. A balanced voltage sag has an equal magnitude in all phases and a phase shift of 120º. between the voltages, as shown in Figure 2.

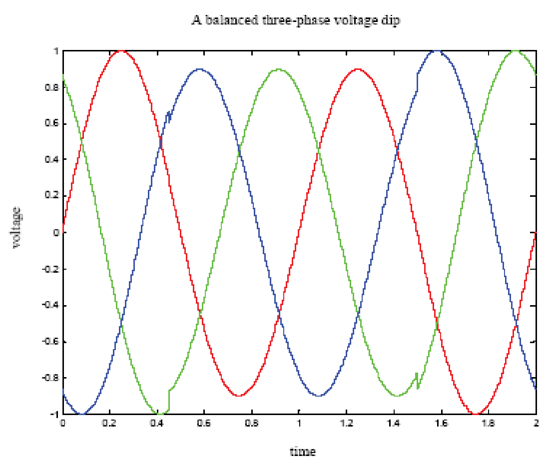


Figure 2. A Balanced 3-phase voltage sag

Unbalanced voltage sags do not have the same magnitude in all phases or a phase shift of 120° between the phases. These types are more complicated and can be further divided into 6 subgroups. An example of a two-phase voltage sag is shown in Figure 3.

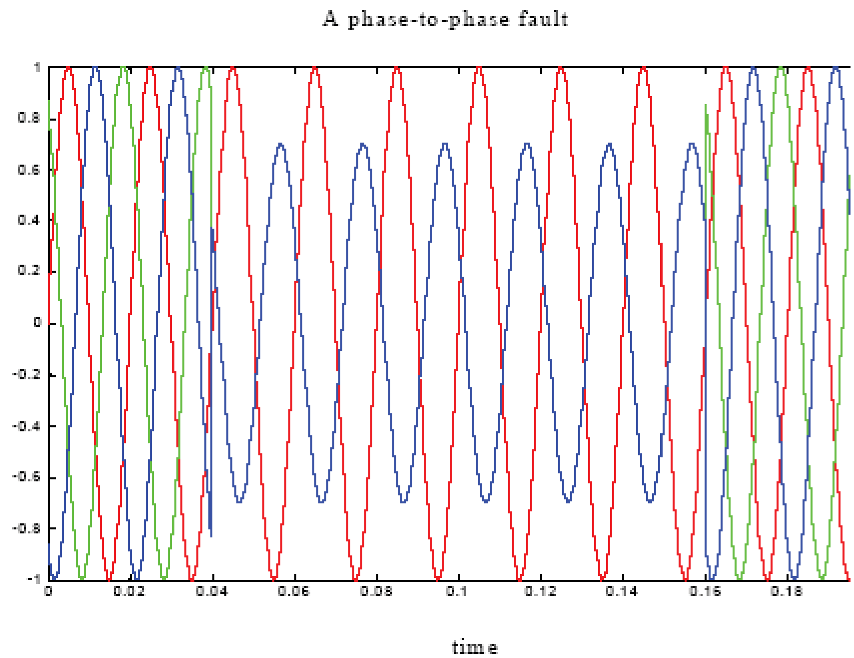


Figure 3. An unbalanced 3-phase voltage sag

1.3 Standards Associated with Voltage Sags

Standards associated with voltage sags are intended to be used as reference documents describing single components and systems in a power system. Both the manufacturers and the buyers use these standards to meet better power quality requirements. Manufactures develop products meeting the requirements of a standard, and buyers demand from the manufactures that the product comply with the standard.

The most common standards dealing with power quality are the ones issued by IEEE, IEC, CBEMA, and SEMI. Other standards worth mentioning are CISPR, UNIPED, CENELEC, and NFPA. A brief description of each of the standards is provided below.

1.3.1 IEEE

The Technical Committees of the IEEE societies and the Standards Coordinating Committees of IEEE Standards Board develop IEEE standards. The IEEE standards associated with voltage sags are given below.

IEEE 446-1995, "IEEE recommended practice for emergency and standby power systems for industrial and commercial applications range of sensibility loads"

The standard discusses the effect of voltage sags on sensitive equipment, motor starting etc. It shows principles and examples on how systems shall be designed to avoid voltage sags and other power quality problems when backup system operates.

IEEE 493-1990, "Recommended practice for the design of reliable industrial and commercial power systems"

The standard proposes different techniques to predict voltage sag characteristics, magnitude, duration and frequency. There are mainly three areas of interest for voltage sags. The different areas can be summarized as follows:

- Calculating voltage sag magnitude by calculating voltage drop at critical load with knowledge of the network impedance, fault impedance and location of fault.
- By studying protection equipment and fault clearing time it is possible to estimate the duration of the voltage sag.
- Based on reliable data for the neighborhood and knowledge of the system parameters an estimation of frequency of occurrence can be made.

IEEE 1100-1999, "IEEE recommended practice for powering and grounding electronic equipment"

This standard presents different monitoring criteria for voltage sags and has a chapter explaining the basics of voltage sags. It also explains the background and application of the CBEMA (ITI) curves. It is in some parts very similar to Std. 1159 but not as specific in defining different types of disturbances.

IEEE 1159-1995, "IEEE recommended practice for monitoring electric power quality"

The purpose of this standard is to describe how to interpret and monitor electromagnetic phenomena properly. It provides unique definitions for each type of disturbance.

IEEE 1250-1995, "IEEE guide for service to equipment sensitive to momentary voltage disturbances"

This standard describes the effect of voltage sags on computers and sensitive equipment using solid-state power conversion. The primary purpose is to help identify potential problems. It also aims to suggest methods for voltage sag sensitive devices to operate safely during disturbances. It tries to categorize the voltage-related problems that can be fixed by the utility, and those which have to be addressed by the user or equipment designer. The second goal is to help designers of equipment to better understand the environment in which their devices will operate. The standard explains different causes of sags, lists of examples of sensitive loads, and offers solutions to the problems.

1.3.2 Industry Standards - SEMI

The SEMI International Standards Program is a service offered by Semiconductor Equipment and Materials International (SEMI). Its purpose is to provide the semiconductor and flat panel display industries with standards and recommendations to improve productivity and business. SEMI standards are written documents in the form of specifications, guides, test methods, terminology, practices, etc. The standards are voluntary technical agreements between equipment manufacturer and end-user. The standards ensure compatibility and interoperability of goods and services. Considering voltage sags, two standards address the problem for the equipment.

SEMI F47-0200, "Specification for semiconductor processing equipment voltage sag immunity"

The standard addresses specifications for semiconductor processing equipment voltage sag immunity. It only specifies voltage sags with duration from 50ms up to 1s. It is also limited to phase-to-phase and phase-to-neutral voltage incidents, and presents a voltage-duration graph, shown in Figure 4.

SEMI F42-0999, "Test method for semiconductor processing equipment voltage sag immunity"

This standard defines a test methodology used to determine the susceptibility of semiconductor processing equipment and how to qualify it against the specifications. It further describes test apparatus, test set-up, test procedure to determine the susceptibility of semiconductor processing equipment, and finally how to report and interpret the results.

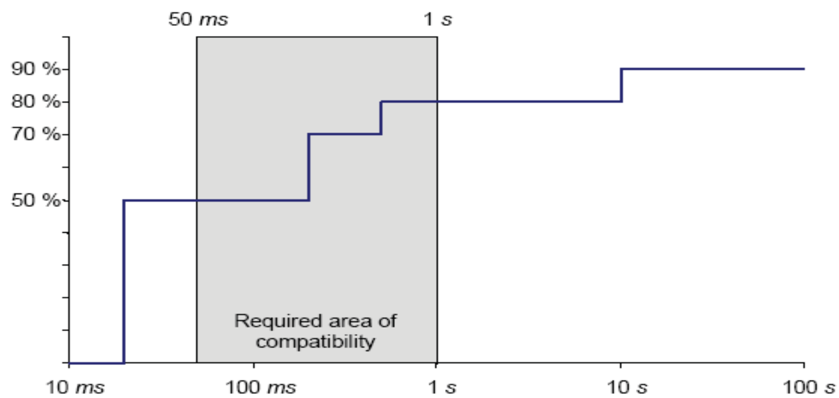


Figure 4. Immunity curve for semiconductor manufacturering equipment according to SEMI F47

1.3.3 Industry Standards - CBEMA (ITI) Curve

Information Technology Industry (ITI, formally known as the Computer & Business Equipment Manufactures Association, CBEMA) is an organization with members in the IT industry. Within the organization, the Technical Committee 3 (TC3) has published the "ITI (CBEMA) curve application note" [1]. The note describes an AC input voltage that typically can be tolerated by most information technology equipment. The note is not intended to be a design specification (although it is often used by many designers for that purpose), but a description of behavior for most IT equipment. The curve assumes a nominal voltage of 120VAC RMS and 60Hz and is intended for single-phase information technology equipment [IEEE 1100 – 1999].

The voltage-time curve in Figure 5 describes the border of an area. Above the border the equipment shall work properly and below it shall shutdown in a controlled way.

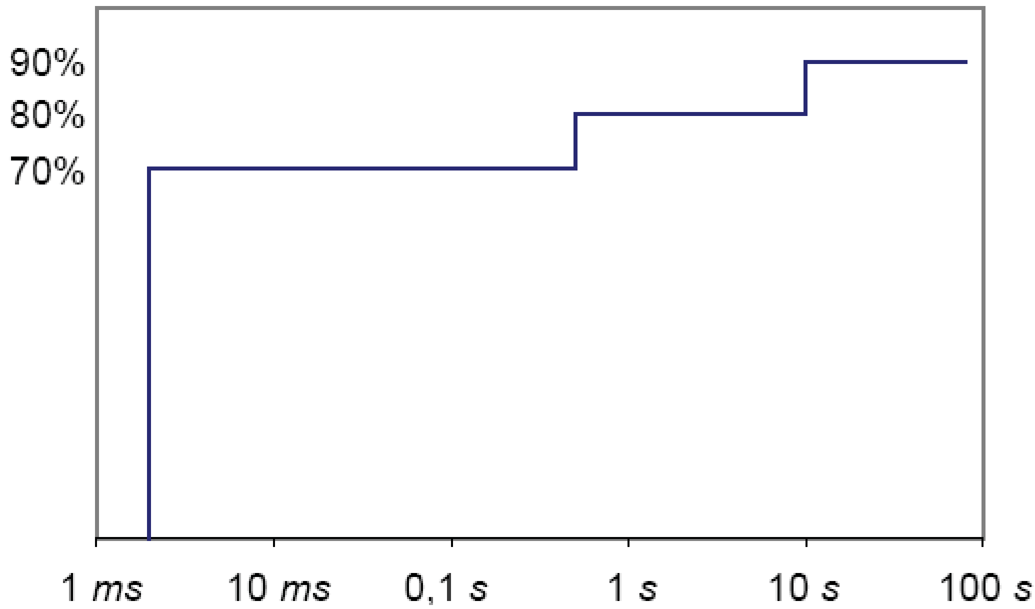


Figure 5. Revised CBEMA curve, ITIC curve, 1996 [37]

This chapter has described the term "voltage sags" and provided a foundation for the following chapters. The definitions provided by IEEE standards are the ones that are used universally. The characterization of voltage sags has also been discussed. This complies with the industry concerns related to the problem of power quality.

Chapter 2 Literature Review

2.1 Introduction

In this chapter, a detailed and thorough review of the literature in the area of effects of voltage sags on power system operation is presented. The literature includes technical papers from IEEE journals and few other sources (including websites). The literature has been divided into five sections in view of the project objective as follows:

- General overview of voltage sags in power systems
- Effect of voltage sags on induction motors
- Effect of voltage sags on synchronous machines
- Effects of voltage sags on adjustable speed drives
- Effects of voltage sags on lighting loads.

In the first section, papers pertaining to a general overview of the causes and effects of voltage sags on power systems are presented. It also presents a brief understanding of the voltage sags by providing a classification of voltage sags. Voltage sag indices for measuring the effect of sags on industrial equipment and CBEMA and ITIC power acceptability curves are also discussed. The remaining sections deal with specific categories of loads as defined in the project objective.

The second and third sections deal with the literature on motor loads, induction motor loads, and synchronous motor loads respectively. Effect of voltage sags on motor loads, classification of voltage sags on the basis of nature of sag and type of fault, application of CBEMA sensitivity curves to unbalanced sag types, motor reacceleration, reclosing and auto transfer, and saturation are discussed.

In the fourth section, a review on the effect of sags on adjustable speed drives (ASDs) is presented. It includes factors determining the performance of motor drives, both AC and DC, during voltage sags, effects of voltage sags on unbalanced sag types, methods to improve the ride through capability of the drives, and tolerance curves depicting capacitance variation.

The final section presents a review on the effect of voltage sags on lighting loads. The lighting loads mainly include incandescent lamps, fluorescent lamps, sodium and mercury vapor lamps, metal halide lamps and ballasts. Results of the experiments conducted on the lighting loads are also summarized.

2.2 General Overview of Causes and Effects of Voltage Sags on Power Systems

There are various causes of voltage sags in a power system. Bollen [2] has provided a brief review of the causes of voltage sags. They are as follows.

2.2.1 Voltage sags due to faults

Voltage sags due to faults can be critical to the operation of a power plant, and hence, are of major concern. Depending on the nature of the fault (e.g., symmetrical or unsymmetrical), the magnitudes of voltage sags can be equal in each phase or unequal respectively.

For a fault in the transmission system, customers do not experience interruption, since transmission systems are looped/networked. Figure 6 shows voltage sag on all three phases due to a cleared line-ground fault.

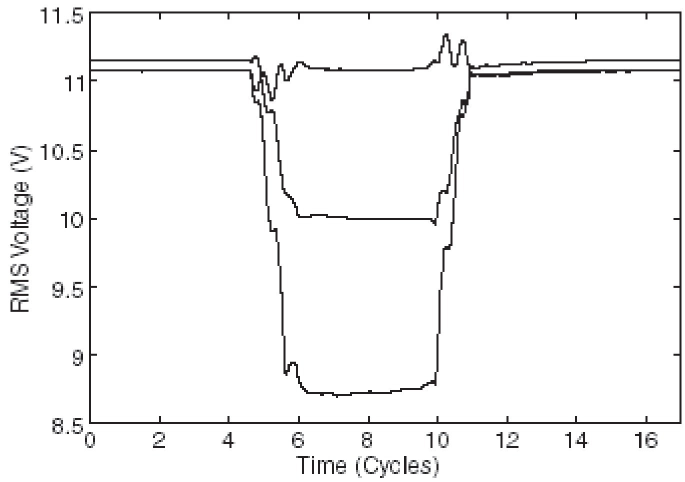


Figure 6. Voltage sag due to a cleared line-ground fault

Factors affecting the sag magnitude due to faults at a certain point in the system are:

- Distance to the fault
- Fault impedance
- Type of fault
- Pre-sag voltage level
- System configuration
    - ➢ System impedance
    - ➢ Transformer connections

The type of protective device used determines sag duration.

2.2.2 Voltage sags due to induction motor starting

Since induction motors are balanced 3ϕ loads, voltage sags due to their starting are symmetrical. Each phase draws approximately the same in-rush current. The magnitude of voltage sag depends on:

- Characteristics of the induction motor
- Strength of the system at the point where motor is connected.

Figure 7 represents the shape of the voltage sag on the three phases (A, B, and C) due to voltage sags.

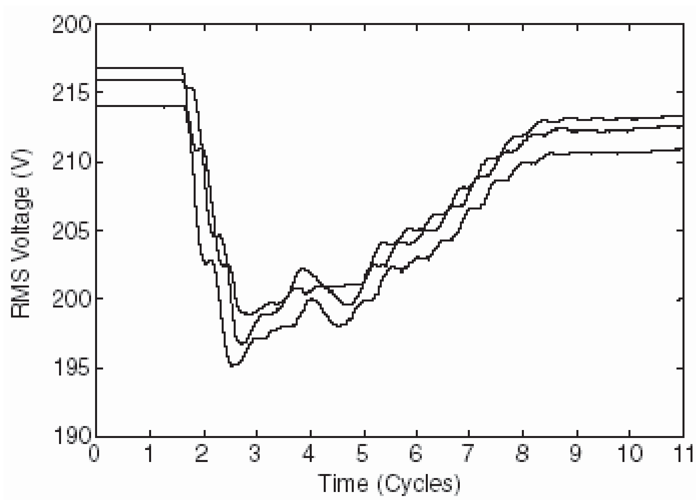


Figure 7. Voltage sag due to motor starting

2.2.3 Voltage sags due to transformer energizing

The causes for voltage sags due to transformer energizing are:

- Normal system operation, which includes manual energizing of a transformer.
- Reclosing actions

The voltage sags are unsymmetrical in nature, often depicted as a sudden drop in system voltage followed by a slow recovery. The main reason for transformer energizing is the over-fluxing of the transformer core which leads to saturation. Sometimes, for long duration voltage sags, more transformers are driven into saturation. This is called Sympathetic Interaction.

2.2.4 Multistage voltage sags due to faults

Multistage voltage sags are associated with faults related to transmission systems. They present different levels of magnitude before the voltage reaches a normal level. The main causes for such type of sags are:

- Changes in the nature of the fault
- Changes in system configuration (e.g., time delay of circuit breaker).

Bollen [2] discovered that a new type of voltage sag caused by transformer energizing has been found to be very common and efforts need to be made to minimize it. Multistage voltage sags are also increasing in number and the effect they have on the functioning of a power system plant is enormous. Hence, causes of multistage voltage sags need to be studied further.

Many short circuits are initiated by overvoltages [3]. As an example, a single-phase to ground fault can be initiated by a lightning stroke to a shielding-wire. The excessive voltage can result in a flashover between the tower and the phase conductor over the insulator string. Approximately 70% of voltage sags are caused by a single-phase to ground faults. Other fault types are two-phase fault, two-phase to ground fault, three-phase fault and three-phase to ground fault.

In high voltage systems, faults are cleared by protective devices and circuit breakers. Typical fault clearing times are between 100 and 500ms. The voltage sag duration strongly depends on the fault clearing time. Faults in low voltage systems are normally cleared by fuses with typical fault clearing times between 10ms and a few seconds.

The system grounding affects the magnitude of the current during a fault [4]. In a solidly grounded system, the fault current is not limited. This causes the faulted phase voltage to almost drop to zero at the fault location. The non-faulted phases remain unchanged. In an impedance-grounded system, the fault current is limited. As with a solidly grounded system, the faulted phase voltage drops to almost zero at the fault location, but voltages rise on the non-faulted phases.

The type of the transformer determines the propagation characteristic of the voltage sag through the different voltage levels. There are three different types of transformers with respect to voltage sag behavior.

- The individual phases are not affected (Y_ny_n).
- The zero-sequence is removed (Dd, Y_ny).
- The phase voltage is changed to phase voltage or vice versa (Dy, Yz)

Voltage sags can be classified as balanced and unbalanced depending on the type of faults [5]. In general, voltage sags can be classified into seven groups. The seven different types of voltage sags are shown in Figures 8 and 9 respectively.

A balanced three-phase voltage sag will result in a *Type A* sag. Since the voltage sag is balanced, the zero-sequence is zero, and a transformer will not affect the appearance of the voltage sag. This holds both for the phase-to-ground voltage and phase-to-phase-voltage.

A phase-to-ground fault will result in a *Type B* sag. If there is a transformer that removes the zero-sequence between the fault location and the load, the voltage sag will be of *Type D* sag. A phase-to-phase-fault results in a *Type C* sag.

The voltage sags of *Types E*, *F* and *G* are due to a two-phase-to-ground fault.

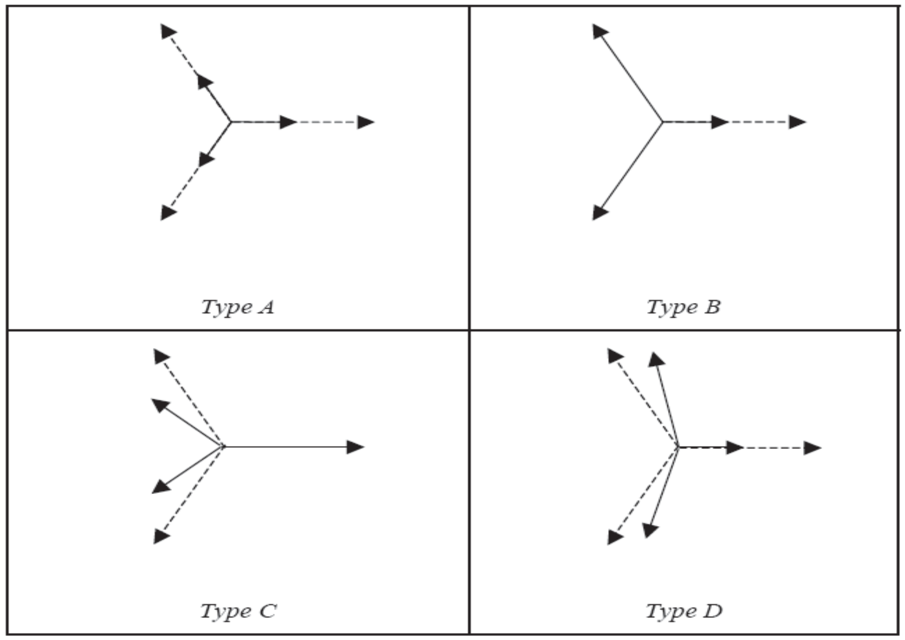


Figure 8. Voltage sag types due to one or three-phase faults

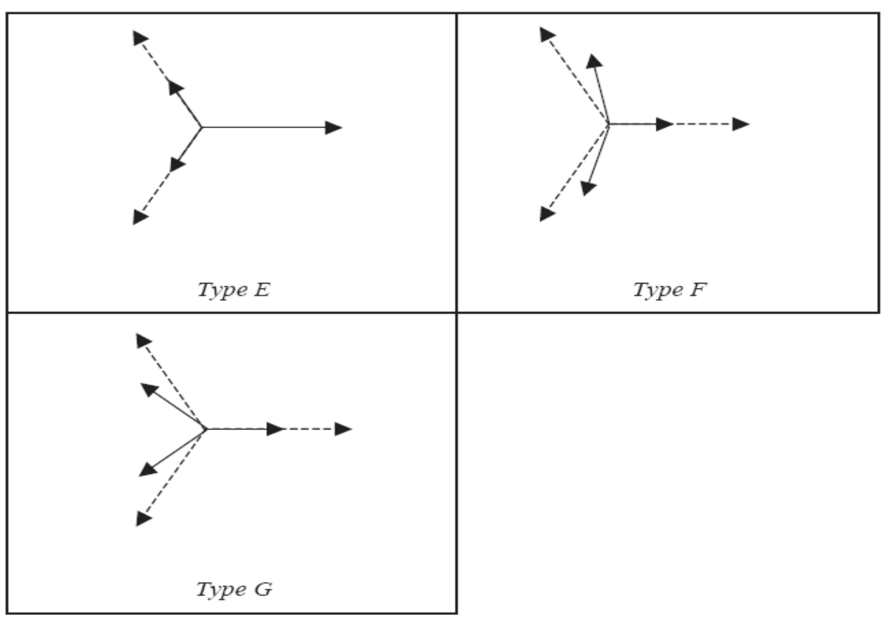


Figure 9. Voltage sag types due to two-phase faults

Table 1 gives a brief overview of the different types of voltage sags and their associated faults.

Table 1. Different sag types and their associated faults

Voltage Sag Type	Fault Type
Type A	Three-phase
Type B	Single-phase to ground
Type C	Phase-to-phase
Type D	Phase-to-phase fault (experienced by a delta connected load), single-phase to ground (zero sequence component removed)
Type E	Two-phase-to-phase fault (experienced by a Wye connected load)
Type F	Two-phase-to-phase fault (experienced by a delta connected load)
Type G	Two-phase to phase fault (experienced by a load connected via a non-grounded transformer removing the zero sequence component)

In the paper by Heydt and Thallam [6], various voltage indices have been discussed to measure the effect of line voltage sags on industrial equipment. Special emphasis has been placed on three phase cases, while considering the merit of any index. The authors have discussed the CBEMA and the ITIC power acceptability curves, noting their effectiveness in describing the tolerance of any particular equipment (data processing) towards voltage sag. All sag events with voltages between 85% and 10% have been considered for sag index calculation.

Hence, in this section, the effects and causes of voltage sags in a power system as a whole have been discussed. A major contribution of this section has been to emphasize the importance of voltage sag classification to characterize the type of faults affecting power system operations.

2.3 Effect of Voltage Sags on Induction Motors

Induction motors represent the most typical loads in power system applications. They consume about 60% of the electrical energy generated in industrialized countries. The loss of their service in a continuous process plant may result in a costly shutdown. The reasons for the tripping of essential induction motor service are many. However, research reveals that voltage sags constitute one of the prime causes for induction motor stoppage, thus disrupting the industrial production process leading to financial losses.

Irrespective of the type of sag, the basic observed effects of voltage sags on induction motors are:

- Speed loss
- Current and torque peaks.

The response of induction motors to voltage sags differ depending on the type of voltage sag. A detailed classification and comparison of the voltage sags experienced by three phase loads has been presented [7]. The classification and comparison was supplemented by the phasors and their equations. The comparisons were made on the basis of nature of the voltage sags and the type of fault. Table 2 and Figure 10 provide a summary.

Table 2. Classification of voltage sag and its effect on individual phasors [7]

Type	Nature	Type of Fault	Observations in Phasors	
			Change in Magnitude	Change in Phase
Type A	Balanced	Three Phase Short Circuit	Equal Drop in all phases	None
Type B	Unbalanced	SLGF/ Phase to phase (LL)	Drop in one phasor	None
Type C	Unbalanced	SLGF/ Phase to phase (LL)	Drop in two phasors	In both phasors
Type D	Unbalanced	SLGF/ Phase to phase (LL)	Drop in all phases	In two phasors
Type E	Unbalanced	LLG	Drop in two phasors	In two phasors
Type F	Unbalanced	LLG	Drop in all phases	In two phasors
Type G	Unbalanced	LLG	Drop in all phases	In two phasors

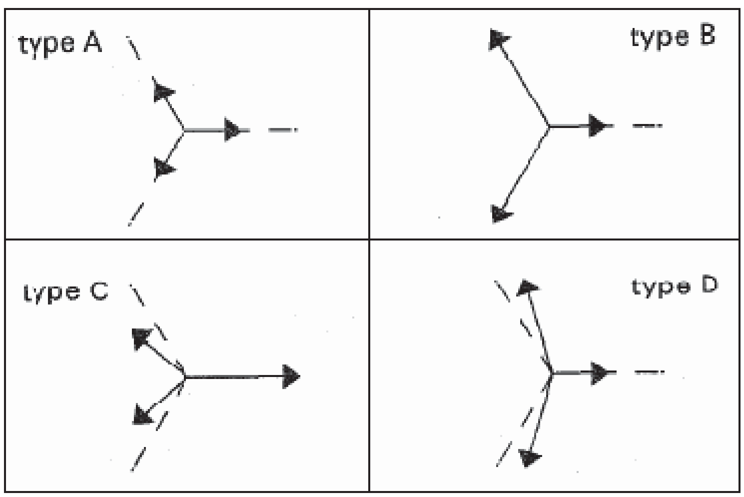


Figure 10. Classification of sags

The effects of different voltage sags on the performance and behavior of induction motors depend on factors such as:

- Magnitude of sag
- Duration of sag
- Electrical parameters of the motor
- Load and mechanical inertia.

Since the voltage at the customer bus is transient during the fault and after clearing the fault, these effects have been considered at two instants: fault and recovery voltage instants.

To analyze the behavior of induction motor for the different types of voltage sags, an induction motor was selected. For the test, a ventilator motor in a cement plant was selected with the following specifications: 610 kW, 3300 V (star), 50Hz, 7850.5 Nm, 148 A. The motor was subjected to sag of magnitude ΔV= 10% of duration 200ms.

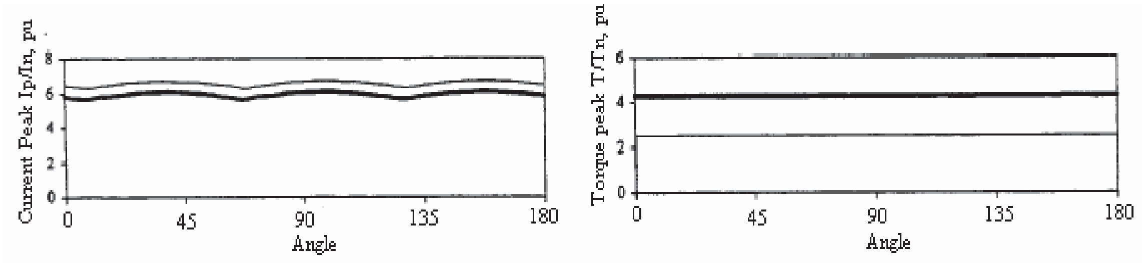
The waveforms obtained in Figure 11 show that for sag *Type E* (similar waveforms obtained for sag *Types C* and *G*), the current and the torque waveforms experienced maximum at phase angle $\phi = 0°$. However, for sag *Type F* (similar waveforms obtained for sag *Types B* and *D*), the waveforms witnessed a maximum at a $\phi = 90°$. Sag *Type A* had minimal influence on the current and torque waveforms. None of the sag types had any influence on the speed loss of the induction motor.

Table 3 summarizes the influence of various sag types on the current, torque, and speed loss of the induction motor.

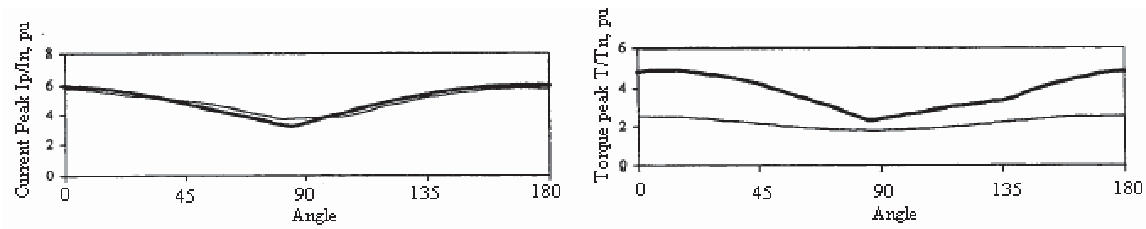
Table 3. Induction motor behavior for different sag types [7]

Voltage Sag Type	Influence on Motor Current	Influence on Motor Torque	Influence on Speed Loss
Type A	Minimal influence	No Influence	No Influence
Type B	Maximum at $\phi = 90°$	Maximum at $\phi = 90°$	No Influence
Type C	Maximum at $\phi = 0°$	Maximum at $\phi = 0°$	No Influence
Type D	Maximum at $\phi = 90°$	Maximum at $\phi = 90°$	No Influence
Type E	Maximum at $\phi = 0°$	Maximum at $\phi = 0°$	No Influence
Type F	Maximum at $\phi = 90°$	Maximum at $\phi = 90°$	No Influence
Type G	Maximum at $\phi = 0°$	Maximum at $\phi = 0°$	No Influence

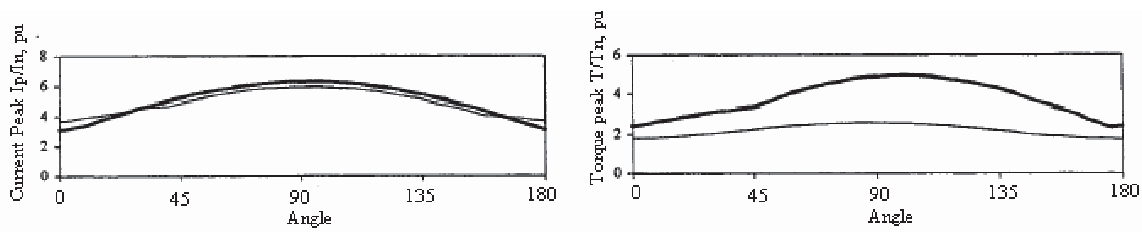
In the figures shown, the thick line represents the voltage drop, while the thin line represents the recovery.



Sag *Type A*



Sag *Type E*



Sag *Type F*

Figure 11. Different sag types during sag and post-sag period [7]

Finally, the CBEMA sensitivity curves (as noted previously recently revised and renamed "ITIC curves") have been used to graphically show the machine sensitivity to different unbalanced sag types. The following noticeable observations were made:

1. Current peaks are lower in unsymmetrical sags whereas torque peaks can be higher.
2. Sag *Types C* and *D* have similar CBEMA curves. Hence, they can be represented in the same graph.

3. Different unsymmetrical sag types produce similar effect with same positive sequence voltage.

Based on the observations of CBEMA curves, the use of positive sequence voltage to study the effects of unsymmetrical sags on the machines has been suggested. This reduces the classification of voltage sags from seven different types to two: symmetrical and unsymmetrical voltage sags.

According to Das [8], an induction motor can show two different behaviors on the occurrence of a voltage sag.

1. The induction motor stops and cannot accelerate on restoration of supply voltage to normal. This is called “stalling”.
2. The induction motor loses speed and reaccelerates on restoration of supply voltage to normal.

Voltage sag for an induction motor is defined as a reduction of voltage to 20-30% of rated value for duration less than 10 cycles. The above behaviors are a result of various interrelated factors.

1) *The Fault Voltage Sag and Voltage Recovery*: The factors affecting the fault voltage sag and voltage recovery are:

- Fault location in electrical system
- Type of fault
- Fault clearance time
- Response of exciters and voltage regulators
- Characteristics of motors and their loads.

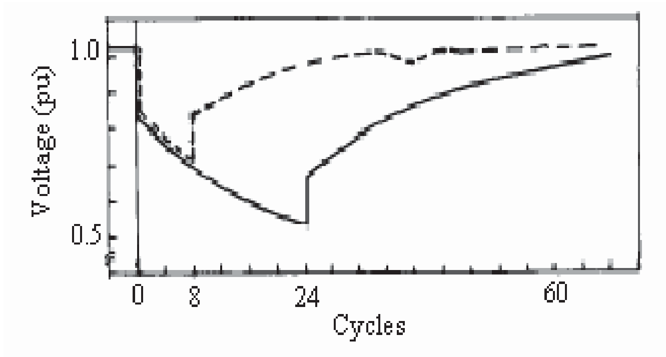


Figure 12. Fault voltage sag and recovery for fault cleared in 8 and 24 cycles [8]

The effect of various faults on the stability of the system is given in the following ascending order of decreased stability:

Phase to Ground < Phase to Phase < Two Phase to Ground < Three Phase Bolted

2) *Motor Speed Loss*: Occurrence of voltage sag reduces the motor torque since motor torque $\propto$ (motor terminal voltage). Low inertia motors rapidly decelerate and may stall whereas high inertia motors lose speed but reaccelerate on recovery. On recovery, the motor will subsequently reaccelerate, depending on the loss of speed during the sag condition as well as on the voltage after recovery.

3) *Motor Reacceleration*: Reacceleration depends on the initial speed loss and magnitude of recovery voltage after clearance. The recovery is made in stages as shown in the Figure 13.

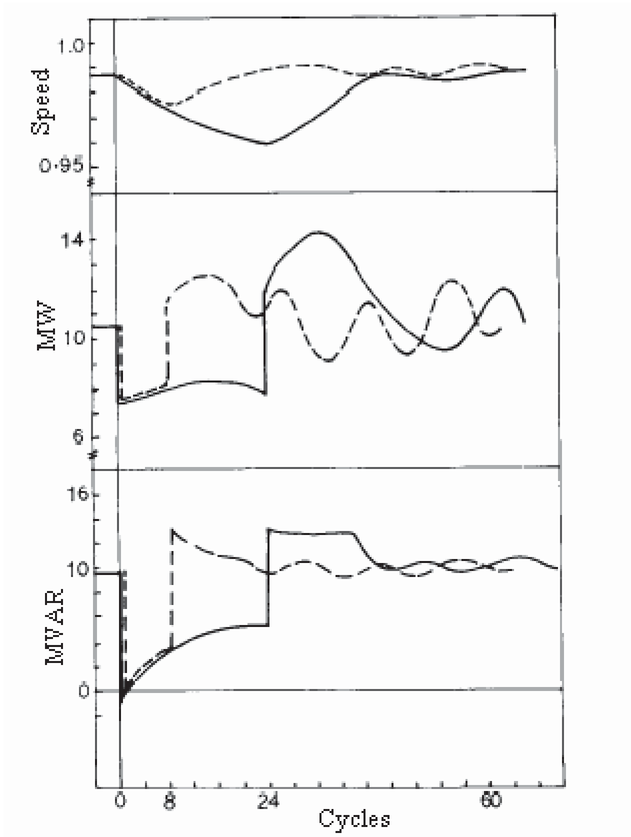


Figure 13. Speed, MW and MVAR transients of a 10.7 MW induction motor [8]

4) *Transient Characteristics:* On the basis of assumption of direct on-line starting of induction motors, it can be stated that if the motor remains connected to the supply system, the transients associated with the voltage sag and on restoration of voltage will be less severe than normal starting currents.

5) *Reclosing and Autotransfer of Power*: Autotransfer bus schemes have been employed to maintain the continuity of operations. Very fast transfer can avoid high reclosing transients. Transfer should not be performed on a wound rotor with shorted slip rings.

6) *Stability:* Motors with high breakdown torque can tolerate greater speed loss before becoming unstable. The stability of induction motors is shown in Figure 14.

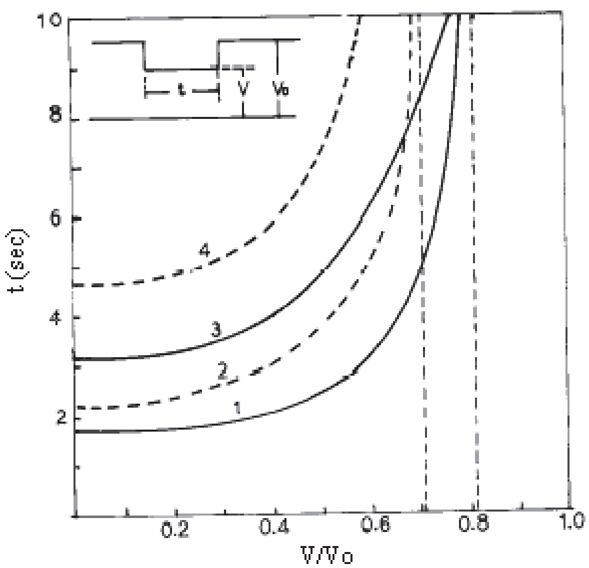


Figure 14. Stability of induction motors on voltage sags: 1 – 2000 hp, H=3.6, Tp=150%; 2 – 1000 hp, H=3.3, Tp=200%; 3 – 2000 hp, H=7.2, Tp=150%; 4 – 1000 hp, H=6.6, Tp=200% [8]

Das [8] has also presented simplified stability calculations of induction motors on voltage sags. He suggested a need for a computer-based study to analyze how to avoid a shutdown on voltage sags. In this context, analysis is suggested of the stiffness of power systems in relation to motor loads, motor protection and controls.

One of the most intriguing problems for an induction motor due to a voltage sag is that it initiates torque oscillations at the beginning and end of the voltage sag [9]. This might cause damage to the motor or disrupt the production process. This can be severe if the motor flux is out of phase with supply voltage.

Bollen [10] discussed the behavior of induction motors during voltage sags. In his paper he proved that the rectangular shape of voltage sag is rarely obtained due to the presence of large induction motor loads. This will, therefore, make it difficult to compare voltage sags with voltage withstand curves which are based on the same assumptions of the rectangular shape.

At the beginning of voltage sag, the voltage drops. Since torque is proportional to the square of the voltage, the speed also drops. The speed will drop further during the voltage sag since the magnetic field in the rotor is driven out of the air gap and the associated transient causes an additional drop in speed. This is due to the flux being unbalanced with the stator voltage, thus causing the torque to decrease. A positive effect is that when the flux starts to decay, the motor will contribute energy and act as a generator. This behavior usually mitigates the voltage sag, but it also deforms the voltage characteristics so that the voltage sag is no longer rectangular. The air gap field first has to be rebuilt, and then the motor will start to reaccelerate. After the voltage sag stage, the motor will draw a large inrush current to build up the air gap field and reaccelerate the motor.

The high current during recovery after the initial voltage sag can prolong the voltage sag long enough to trip the under-voltage protection [11]. Especially in cases with a large number of machines, or in a weak network, this problem is common. Normally, the protective equipment incorporated in the motor drive would drop out in the event of sag and reconnect when the voltage recovers. This leads to high reaccelerating currents drawn from the line. A number of motors connected together may slow down the whole plant system recovery from the sag in this manner. At the same time, a number of motors connected to the plant network will stabilize the sag magnitude by supplying energy stored inherently in the motor. The line voltage is helped by the back-EMF of the motor.

Therefore, if motors are kept running during a sag, the plant system gets significant support. In fact, keeping medium voltage motors from dropping out during a sag event can help the system to the extent that lower voltage level motors will not require any sag protection mechanism up to 40% of sag magnitude. Various methods to prevent motors from dropping out too soon during such an event are described in detail in Carrick [12]. To avoid the problem, it is suggested that industry should have a reaccelerating plan for a controlled start-up after a sudden stop.

The induction motor starting current, which is usually five to seven times the full load current, is one of the main causes of sensitive equipment dropout [13]. An immediate approach for voltage sag mitigation is the application of motor starters. Motor starters reduce the sag depth but increase the sag duration which produces a new sag separated from the first one by a few seconds.

Carrick [12] proposes a methodology which allows for transforming the starting current vs. time characteristics to voltage sag depth/time characteristics. This transformation is suggested as the data for the sensitive equipment ride through capability and is given in graphical voltage sag depth/time characteristics. The transformed characteristics are directly comparable with the sensitive equipment susceptibility curves such as CBEMA, ITIC, SEMI F47 and others.

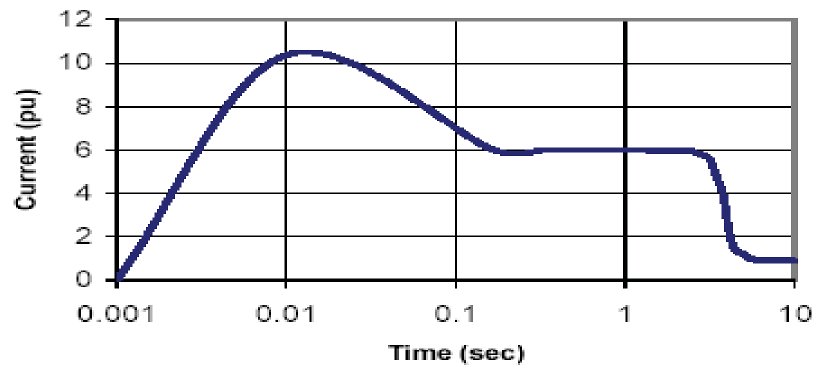


Fig. 1 Induction motor direct starting current (V = 1 pu)

⇓

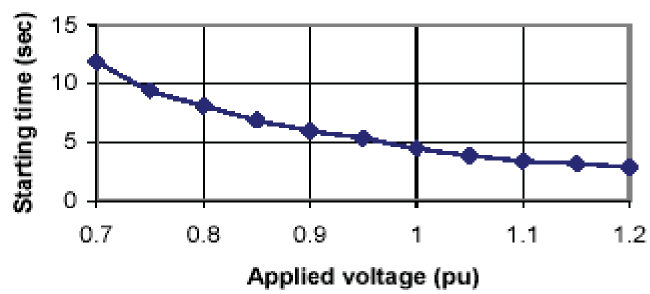


Fig. 2 Start duration as applied voltage function (V from 0.7 to 1.2 pu)

Figure 15. Transforming the starting current v/s time characteristics to voltage sag depth/time characteristics [13]

This method is based on the Specific-Energy Constant Criterion which assumes that the energy necessary for the whole starting process can be considered to be constant. That is,

$$\int V^2 dt = \text{constant}$$

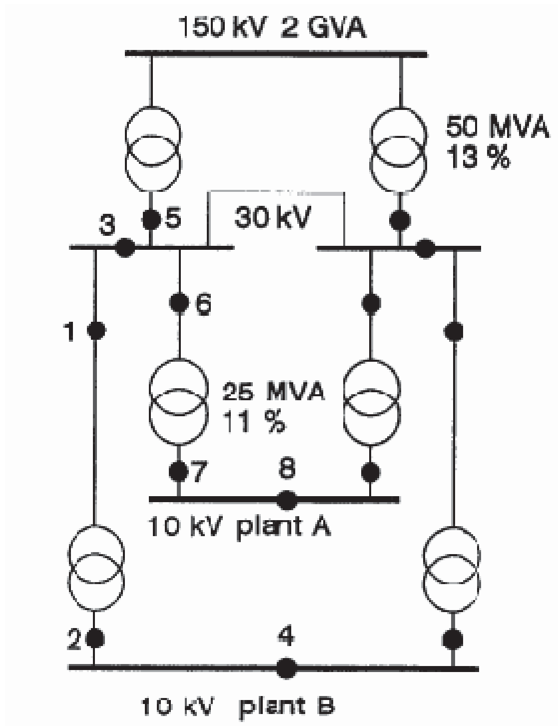


Figure 16. Circuit of sample power network [10]

Then a comparison between the energy required for the motor starting process and energy stored in the sensitive equipment is made. If the starting duration is long enough to exhaust the sensitive equipment stored energy, the device will drop out. The results of this methodology are in close agreement with the values of the different susceptibility curves such as the CBEMA curves. The results allow easy consideration of the effect of motor starting current on sensitive equipment dropout, even for complex assisted-starting processes.

Bollen [10] presented a method for the stochastic analysis of voltage sags. This method has been implemented in a computer program. The stochastic analysis is based on Monte Carlo simulation. In Figure 16, both plants A and B consist of 6 induction motors of 10 kV, 2.8 MW and 3.355 MVA rating. Four points have been shown at which faults have been simulated and resultant sag wave shapes are shown below.

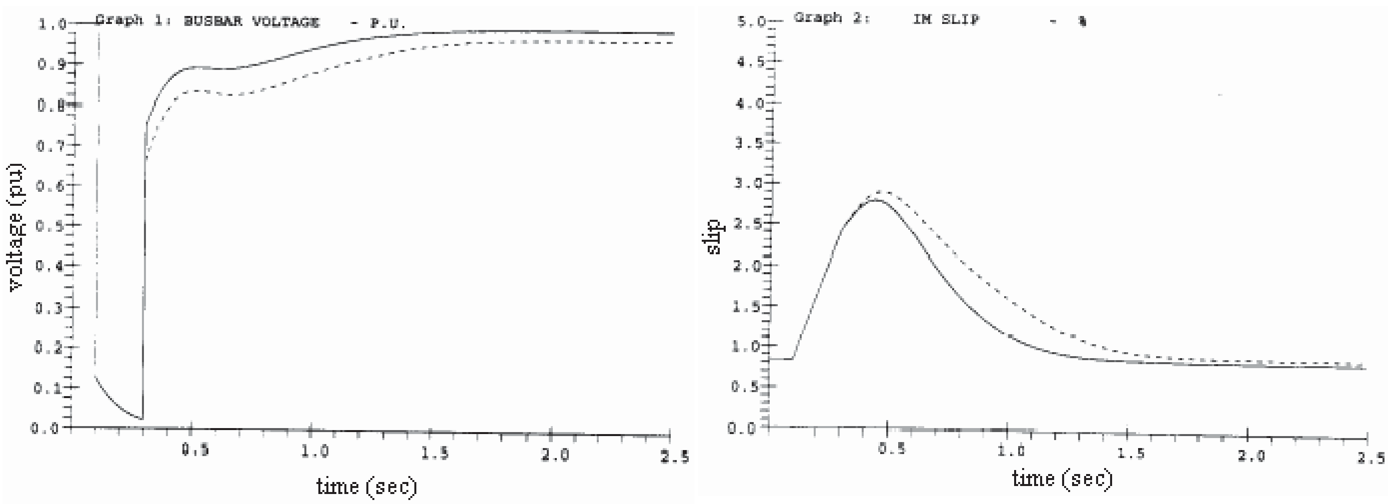


Figure 17. Voltage sag and induction machine slip (fault position 1) [10]

The induction motors temporarily act as generators during the voltage sag. Fault clearing time or duration of the sag is 200ms, and the maximum slip reached 100ms after the fault is cleared. There is a sag in the voltage approximately 200ms after the recovery from the sag. This is due to the high current drawn by the motor during re-acceleration, when its slip is at a maximum. Similar curves have given for faults at position 2, 3 and 4. See Figure 16. The fault at position 4 is cleared after 600ms. Therefore; the sag duration is effectively increased.

Plant B has a sustained interruption due to a fault at position 4. Hence, in spite of the increased sag duration for plant A, since plant B does not draw any post-sag current, plant A has more power available and there is no post-sag voltage minimum.

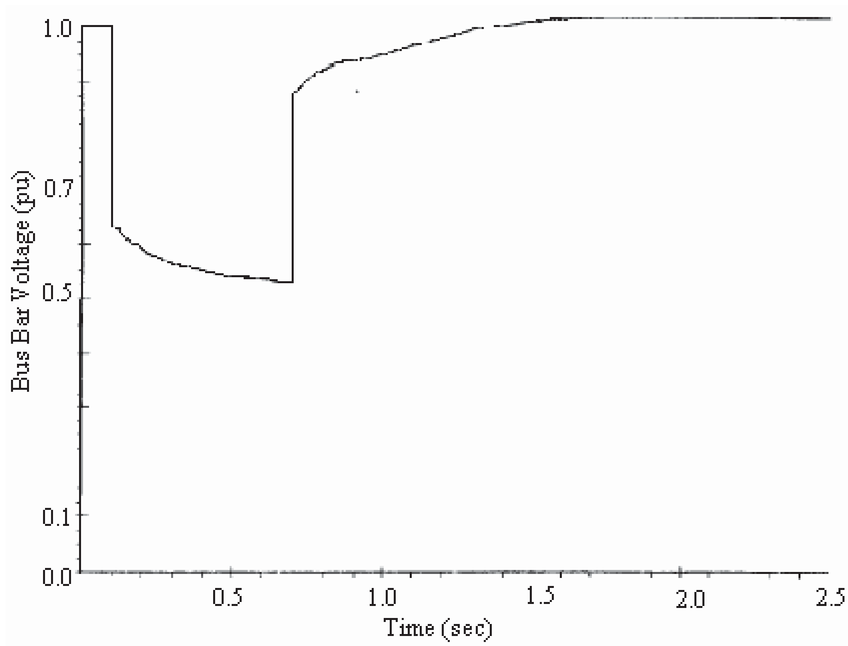


Figure 18. Voltage sag for fault at position 4 [10]

The Electromagnetic Transients Program (EMTP) has been used to simulate faults in a network that has an in-house generator for improved stability of power supply to sensitive loads [14]. The circuit diagram of the system under study is shown in Figure 19. The utility network, as well as the generator through a bus coupler, supplies the critical load. This coupler opens in the event of a fault in the utility network. The action of the coupler is crucial in preventing the effect of the fault in the network from reaching the critical load in the form of sag. A bus coupler, using a conventional circuit breaker and relay, takes 0.3 sec to detect under voltage or overcurrent conditions and disconnect the circuits.

Gate Turn-Off (GTO) type switchgear, on the other hand, would operate within 0.016 sec to isolate the critical load. A time controlled ordinary switch in the EMTP simulation simulates the conventional circuit breaker. The GTO-type switchgear is simulated by the TACS-controlled switch. When, due to fault in the network, a sag condition reaches the generator, transient electromagnetic torques generated inside the generator result in oscillations in the torque. To study the electrical torque, mechanical shaft torque and the generator terminal voltage are plotted during the time of the initiation of fault to the action of the bus coupler and beyond.

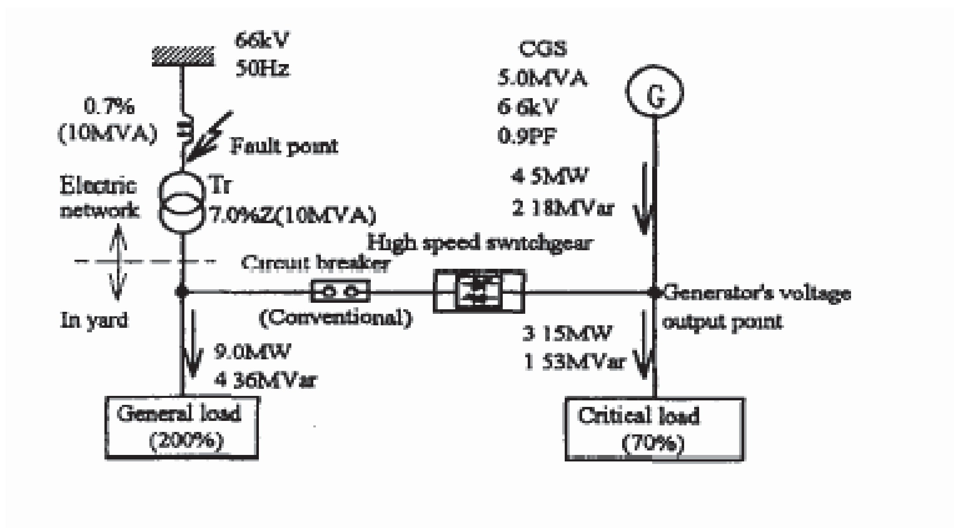
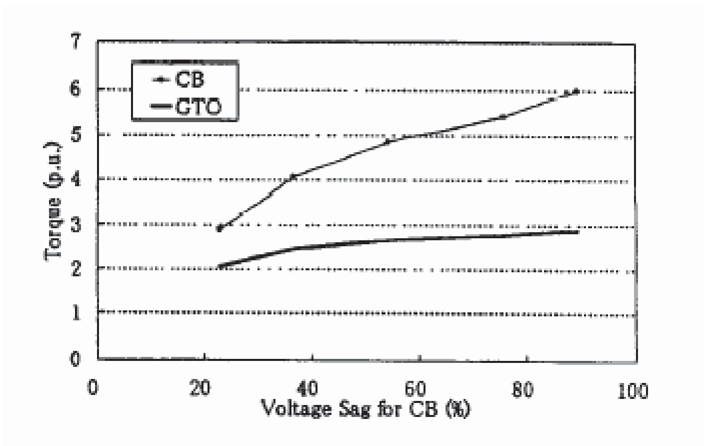


Figure 19. Circuit diagram of the system under study [14]

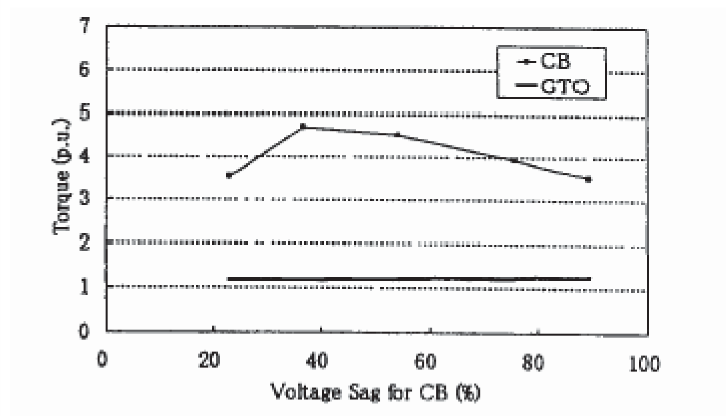
The fault occurs 0.5 seconds after observation starts. In case of a conventional circuit breaker, the time of operation is 0.3 seconds after fault. Thus, the duration of sag is 0.3 seconds. The GTO switch opens when the lowest phase-to-phase voltage falls below 85% or any line current exceeds 300% of rated value. In case of the conventional circuit breaker, voltage sag of 80% magnitude and duration of 0.3 seconds is observed. Any critical load experiencing this sag would be severely affected. The GTO restricts the sag to only 30%, while the duration is much smaller.

As shown in Figure 20, the electrical torque oscillates at a frequency of 50Hz, peaking at 6.0 p.u. in the case of a conventional circuit breaker, and 2.9 p.u. in the case of the GTO. In the GTO case, there are hardly any noticeable oscillations in the electrical torque. The mechanical shaft torque in the case of a conventional circuit breaker oscillates at a frequency of 20.2Hz, peaking at 3.5 p.u. In case of the GTO, the oscillations are much smaller although of same frequency, with the peak value being 1.3 p.u.

When the fault impedance is varied, the magnitude of the voltage sag varies. For the conventional circuit breaker, the duration remains 0.3 seconds; while for the GTO, the duration of sag is negligibly small.



Peak Electrical Torque



Peak Shaft Torque

Figure 20. Peak electrical torque and peak shaft torque [14]

As can be observed from the figures, the peak electrical torque increases in proportion to the magnitude of the sag, in the case of a conventional circuit breaker. The corresponding rise in the case of a GTO is considerably slow. The peak shaft torque in the case of a GTO shows no change when the sag magnitude is increased. In the case of a conventional circuit breaker, the peak shaft torque increases to a maximum value with increase in sag magnitude, after which it starts to decrease.

Hence, induction motors affect the behavior and propagation of voltage sags in the vicinity of their installation.

2.4 Effects of Voltage Sags on Synchronous Motors and Synchronous Generators

Synchronous machines are affected by voltage sags in a similar manner as induction motors. The main similarities between the induction and synchronous motors on the basis of the occurrence of voltage sags are drop in speed, overcurrents, and torque oscillations. However, the additional concern of synchronous machines during voltage sags is that of loss of synchronism.

A balanced voltage sag causes diminished power from the machine and, if the load power is constant, the motor will experience a negative torque. The motor will decelerate and the load angle between flux in the stator and rotor will increase. The increment of the angle will enlarge the output power according to the equation:

$$P = \frac{3.V.E_r}{X}.\sin(\delta)$$

where P is the output of active power from the synchronous machine; V is the applied phase voltage; E_r is the voltage induced in the rotor; X is the synchronous reactance between the feeding voltage and the motor; and δ is the angle between the supply voltage and the induced voltage. If the power is large enough, a new operation point will be reached and the speed will return to the nominal speed. If the voltage sag is too severe and the power cannot reach the load requirement, the load angle will increase and will enter the unstable area. This will cause a loss of synchronism and the motor will have to be restarted [15].

The above only holds if the magnetizing current is fixed and the armature current in the stator has no limit. If the synchronous machine is overexcited (i.e., overmagnetized), the motor operates with a leading power factor supplying reactive power to the feeding grid. During a voltage sag, the power factor will become more lagging. The result is that an overexcited motor is more stable (i.e., has a larger margin) than an underexcited motor.

Figure 21 shows the active power from a synchronous machine with fix E_r and different feeding voltages [16]. A voltage reduction by 30% will still keep the machine in stable operation. A voltage sag with 50% remaining voltage will cause the motor to reach the unstable area if the voltage sag duration is long enough. Analysis of the stability of the synchronous machine is done with the equal area criteria. As shown in Figure 21, A1 ≤ A2, thus, the motor has found a new stable operating point.

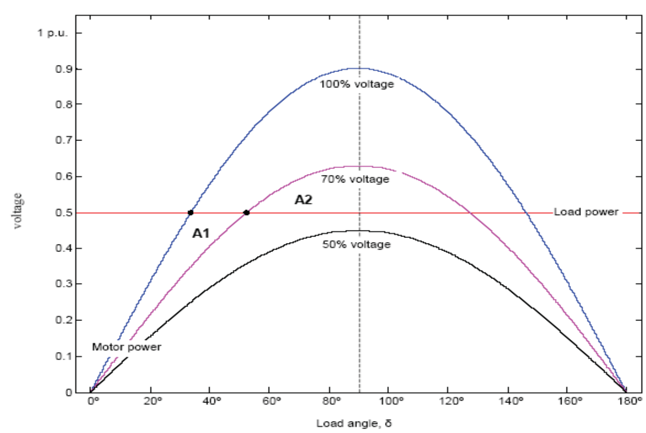


Figure 21. Active power in a synchronous motor as a function of the load angle for different voltages [17]

The subtransient and transient behavior of synchronous motors on occurrence of voltage sags is of critical importance to the stability of power systems because the rotor oscillations in synchronous motors are the determining factor in stability calculations. Das [8] presents a brief overview of the transient behavior of the synchronous motors during voltage sags, as well as other important operations such as automatic resynchronization, synchronous motor excitation, etc., as summarized below.

1. *Transient Behavior on Voltage Sags:* The transient and sub transient characteristics of synchronous motors are of prime importance during voltage sags. Voltage sags act as a stumbling block to power flow from generator to motor, accelerating the generators, and initially slowing the motors. Both machines share the impact of the sag such that the torque angles change according to the machine share of impact to attain mean retardation. Thus, motors and generators swing with respect to each other such that

   - The internal torque angle displacement narrows leading to stability.
   - The internal torque angle displacement broadens leading to instability.

   High inertia machines usually share smaller portion of impact. Hence, while striving for mean retardation, they might lose synchronism due to their torque angles being much displaced.

2. *Synchronous Motor Excitation:* Overexcited motors are more stable than under excited ones during voltage sags. This is because overexcited motors operate at leading power factor and supply reactive power into the system.

3. *Automatic Resynchronization:* During voltage sag, instead of disconnecting the motor from the supply, pullout relays are connected to remove the rotor (field) excitation. When the relay senses the current pulsations in the rotor, instead of tripping the motor from the power supply, it will only trip the field excitation. Thus, the unexcited synchronous motor behaves as induction motors and follows its way during the sag. Excitation may be reapplied at optimum slip**.**

4. *Fast Transfer of Motors:* This is not recommended because the phase angle between the motor generated voltage and supply voltage on disconnection varies between 0° and 360° per cycle.

A computer study needs to be performed to analyze ways of avoiding a shutdown on occurrence of voltage sags. Studies reveal that the use of shunt capacitors will help in reducing the effect of voltage sag on the terminal voltage, torque, field current, and excitation current of the generator [17]

The stability limit of operation for a synchronous motor is inversely proportional to the pullout torque. The stability of a 2000 hp, 6 pole, 0.8 pf, and 175% pullout torque synchronous motor is demonstrated in the Figure 22.

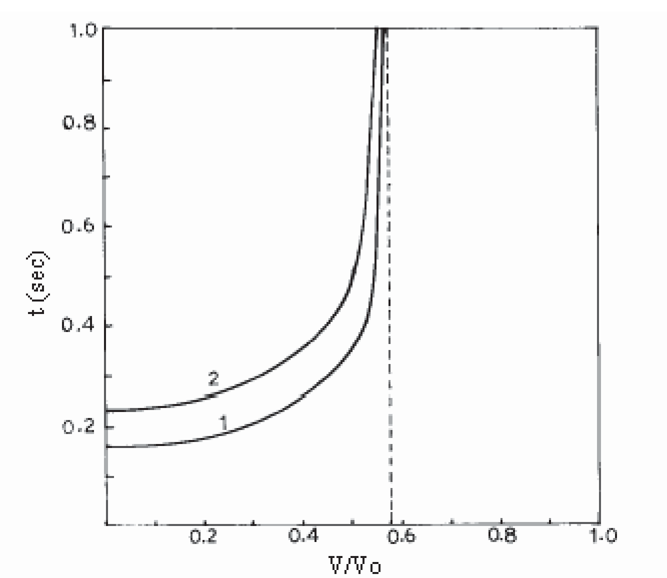


Figure 22. Stability of a 2000 hp, 175% pullout torque synchronous motor: 1-H=3.6, 2-H=7.2 [8]

Carlsson [18] illustrates the variation of stator flux in synchronous machines during three-phase symmetrical voltage sags. The variations reveal that voltage sags may cause saturation, usually after the voltage sag, not during the sag. This saturation leads to high currents and torques. However, saturation reduces the transient time after voltage sag thereby making the machine reach steady-state faster.

The author has also presented a comparative study between a synchronous machine model with and without saturation, and implemented the simulation in a MATLAB program. The results suggest that saturation has a positive effect on the machine model. The oscillations are damped faster and stator fluxes are smaller. The peak torque and peak current are higher for models having saturation.

Hence, synchronous motors and generators are not suitable for fast autoclosing or bus transfer, although these can be auto-resynchronized. Moreover, saturation caused by voltage sags enables the machine to reach the steady-state faster. In summary, voltage sags have both positive and negative effects on the operation of synchronous machines.

2.5 Effects of Voltage Sags on Adjustable Speed Drives

Adjustable speed drives (ASD) are very susceptible to slight variation in voltages. The reason for their high susceptibility is the presence of power electronics components that are sensitive to voltage variation. A trip of industrial process equipment due to sag, such as a motor drive or programmable logic controller, can prove to be extremely costly in context of the overall operation of a power plant. This section has been divided into two subsections, dealing with AC and DC adjustable speed drives independently. Each subsection includes the effects of voltage sags on their ASDs. The ride-through capability is also discussed.

2.5.1 AC adjustable speed drives

The basic configuration of an AC ASD is shown in Figure 23.

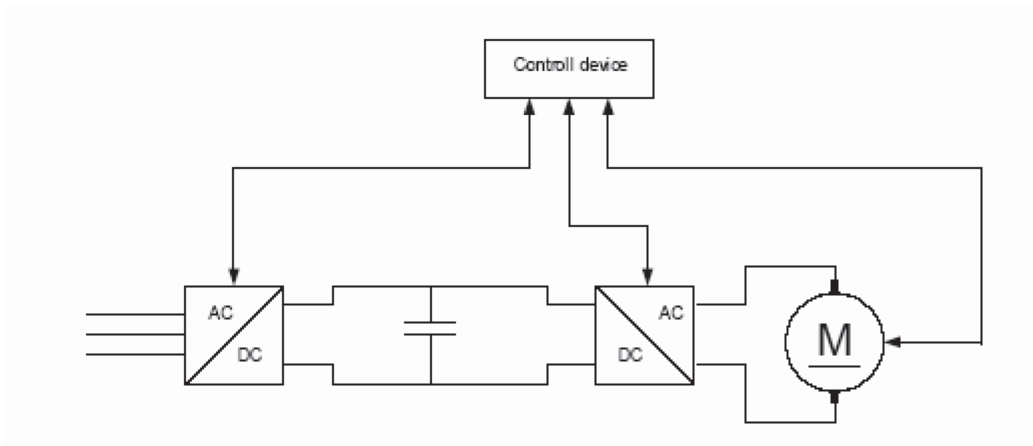


Figure 23. An AC adjustable speed drive

In Figure 24, the six diodes D_1-D_6 form the rectifier, L_S is the source impedance, L_D is the DC link inductor, and C is the DC-link capacitor. With higher values for L_S and L_D, there is a higher variation in the DC-link voltage which may result in an increase of the susceptibility of the ASD.

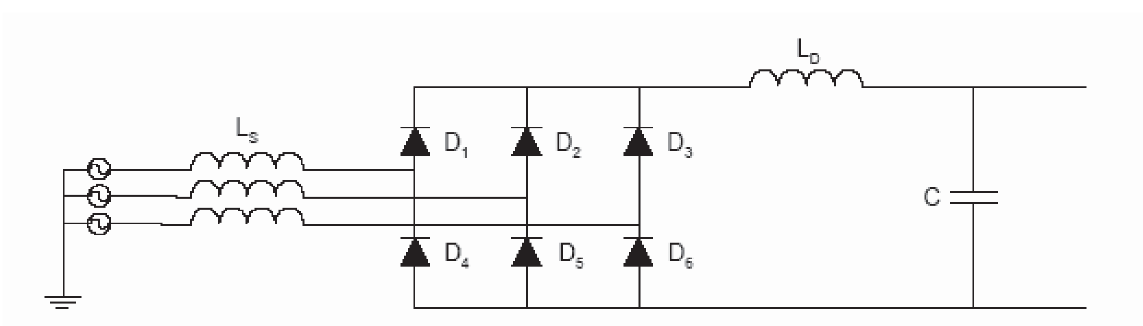


Figure 24. Six-pulse rectifier

Bollen and Zhang [19] have briefly described the operation of AC ASDs. The capacitor is charged when the instantaneous voltage on the AC-side is higher than the DC voltage. A current then flows from the AC-side to the capacitor and the DC voltage increases. When the DC voltage is equal to the voltage on the AC-side the current decreases to zero. The load is then fed from the capacitor and the DC voltage decreases until the AC-side voltage is greater than the remaining DC voltage. In steady-state there are six current pulses on the DC-side per cycle.

The various factors determining the performance of AC motor drives during voltage sags are [20]:

- Sag magnitude variation
- Sag duration
- Sag asymmetry
- Phase jump
- Non-sinusoidal wave shapes

The main reasons for AC drive tripping during voltage sag are:

1. DC link under voltage
2. Drop in speed of motor load
3. Increased AC currents during sag or post-sag over currents charging the DC capacitor.

During a voltage sag the voltage on the AC-side is reduced. Depending on type and duration of the voltage sag, the voltage on the DC-side may change. A voltage sag of *Type A* (balanced three-phase) will result in a reduction of the voltage on the DC-side that is proportional to the AC-side. This type of voltage sag is normally the most severe. The undervoltage or over current-protection on the DC-side may trip the ASD. If the voltage sag is of *Type C,* the circuit will behave as a single-phase rectifier. A 10% voltage sag will result in a single-phase operation of the three-phase diode rectifier [20]. The voltage between the two nonfaulted phases is un-affected and the DC-side voltage will not be reduced. The current pulses, however, will be changed. The same amount of energy must be transferred, but now in two pulses instead of six. The peak value of the current will be 200% larger, and may cause an overcurrent or a current unbalance. The overcurrent or unbalance protection may trip the ASD. A phase angle jump will affect the phase voltages. It will affect the DC-link voltage.

An integrated boost converter approach to improve the performance of ASDs has also been presented. A commercially available 480V, 22kVA ASD is modified with integrated boost converter approach. Apart from being low cost, this model requires no additional energy storage device such as supercapacitors. Experimental results show that the integrated boost converter approach prevents nuisance tripping and maintains DC link voltage within acceptable limits. This facilitates continuous operation of critical ASD load at rated torque.

The sensitivity of AC ASDs to voltage sags is presented in a voltage tolerance curve as shown in Figure 25 [19]. It may be seen that the ASD can withstand a sag in the line voltage to 85% of nominal value for an extended duration of time. This figure may change, depending on the sensitivity of the process controlled by the drive. For all points falling below the voltage tolerance curve, the drive will trip.

In all AC drives, the output DC voltage is smoothed by a capacitor. The tripping of the drive takes place on detection of a DC undervoltage or overcurrent situation resulting from a sag.

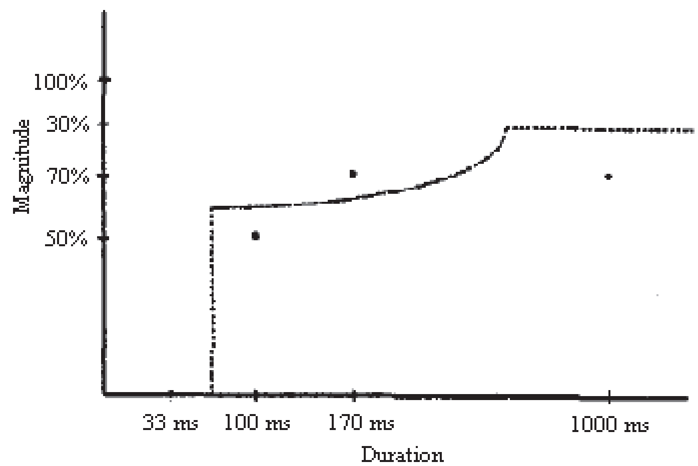


Figure 25. Average Voltage Tolerance Curve [19]

When a sag event occurs, the output voltage V at a time t is given by

$$V=\sqrt{(V_0^2 - (2P / C)\, t)}$$

where

V_0 is the voltage before the event.

P is the load connected to the output bus.

Varying the capacitance *C*, the time for the drive to trip may be varied. From Figure 26, it is clear that the immunity against voltage sags can be improved by adding more capacitance to the DC bus.

When the ASD is subjected to unbalanced sags (*Type C* and *D*), all three phases of the drive are affected differently. When the positive and negative sequence source impedances are not equal (due to the presence of a rotating load), a PN factor is defined in addition to the magnitude of the sag for unsymmetrical sags. This PN value, obtained from sequence transformations, lies from 0.9 to 1.0 (distribution systems to transmission systems).

The AC and the DC-side voltages are shown for sag *Type C* and *Type D* in Figure 26. The solid line represents the drive with a capacitance of 433μF/kW for 620V drive, while the dashed line represents operation with capacitance of 57.8μF/kW for 620V drive. The dotted line represents no capacitor operation.

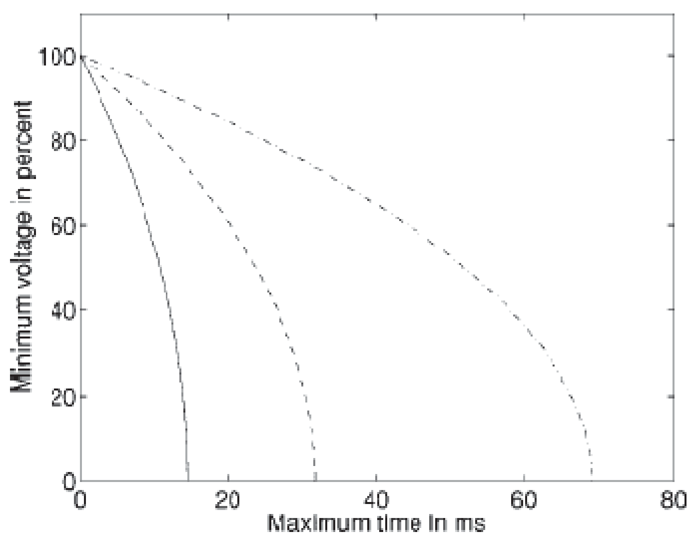


Figure 26. Voltage tolerance of ASD for different capacitor values (solid line: 75μF/kW; dashed line: 165μF/kW; dotted line: 360μF/kW) [19]

Figure 27 shows the voltage curves for sag *Types C* and *D*. For a sag *Type C* of magnitude 50%, the DC bus voltage does not drop below 70%, even for a small capacitance. This is because there is at least one phase that is still at 100% magnitude, and this phase stabilizes the DC bus voltage. In the case of sags of *Type D* of magnitude

50%, there is no such phase and, therefore, the effect is more harmful on the DC bus, although not as much as in a balanced sag case.

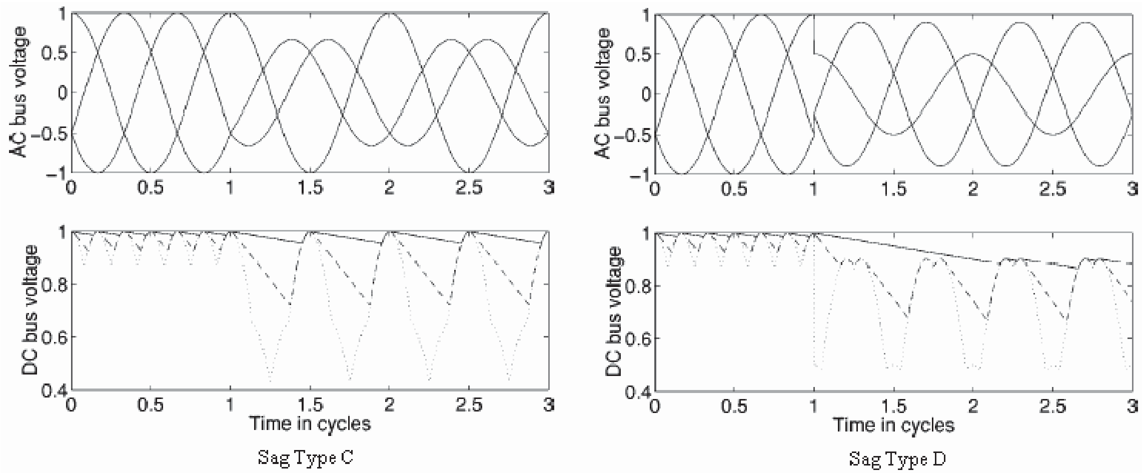


Figure 27. Voltage curves during three-phase unbalanced sag [19]

If the magnitude of sag is varied, the DC voltage does not fall below a certain value for a particular capacitance. This is demonstrated in the Figure 28 below for sag *Type C* and *D*.

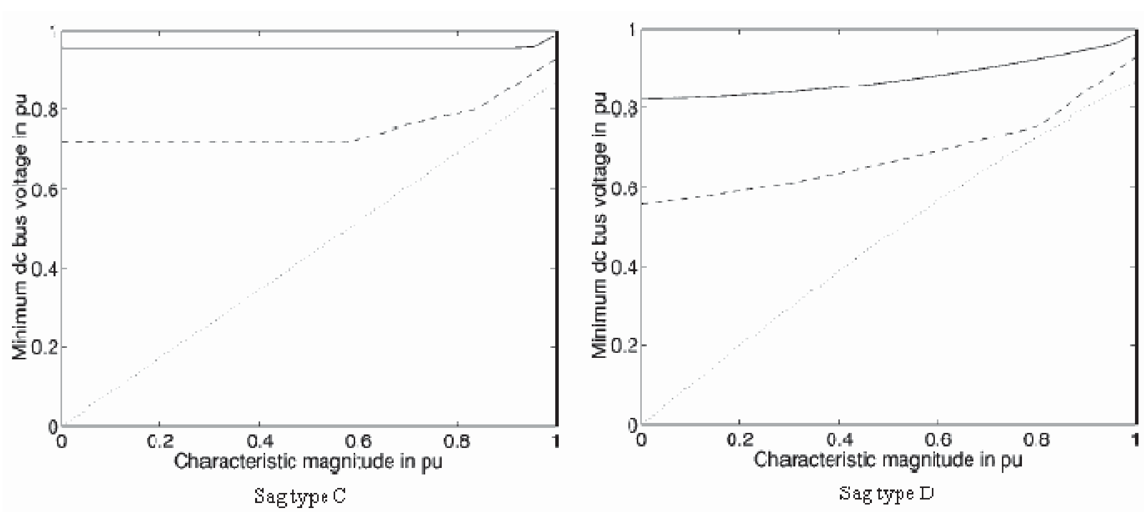


Figure 28. Minimum DC bus voltage as a function of the sag magnitude [19]

The solid line shows the effect of a large capacitance, while the dotted line is for a small capacitance. The dashed line shows the operation without any capacitance. The effect of the PN factor on the minimum DC bus voltage is also studied in a similar fashion. When there is a voltage sag on the output DC bus, as a result of the sag in the input AC-side, there is a corresponding deceleration of the motor controlled by the drive. When the increase in slip for the motor is the limiting factor for the stability of the drive, voltage tolerance curves are obtained as shown below.

Similar curves have been presented for *Type C* and *D* sags. The presence of even a small capacitance improves the voltage tolerance of the drive.

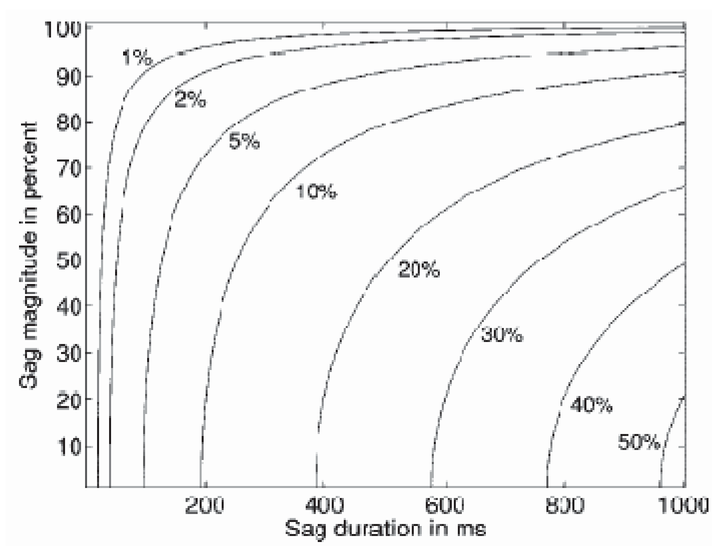


Figure 29. Voltage tolerance curves, when increase in slip is the limiting factor [19]

The current power electronic technology does not allow significant improvement in energy storage in the drive, and, hence, in sag tolerance. However, if the drive is prevented from tripping during a balanced sag event, the effect is not so much on the mechanical load. For unbalanced sag events, even a small capacitance prevents the DC bus voltage from dropping below 80% of rated voltage.

A case study was performed for an ASD with rating 380V, 15kW using voltage source inverter (VSI) PWM type [21]. The voltage of the output DC bus is measured, although the undervoltage trip condition is measured at the AC input side. As a result of this, the drives tripped before any deterioration of performance was observed. The effect of the connected load did not have much effect on the results obtained. The experiment was conducted at 25% and 75% loading with pre-sag voltage 0.95 p.u., 1.0 p.u., and 1.05 p.u. The results are shown in Figures 30, 31, and 32 respectively.

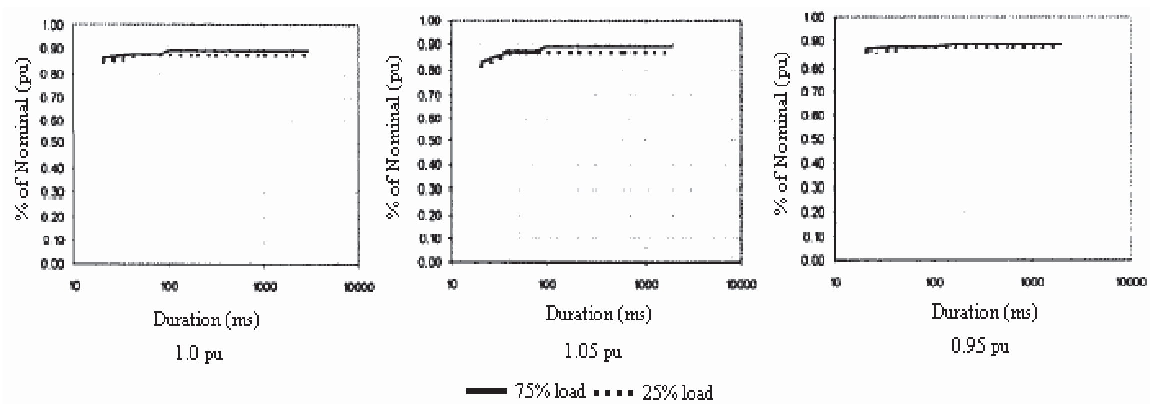


Figure 30. Three phase voltage sag for ASD ride-through performance [21]

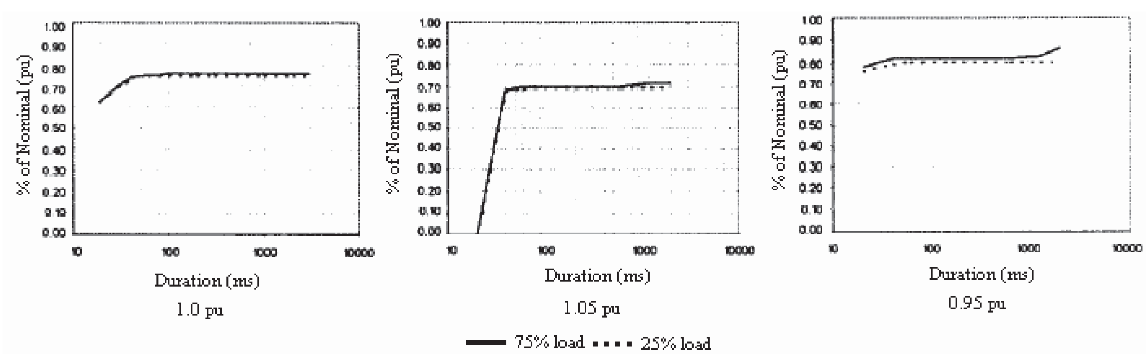


Figure 31. Single-phase voltage sag ASD ride-through performance [21]

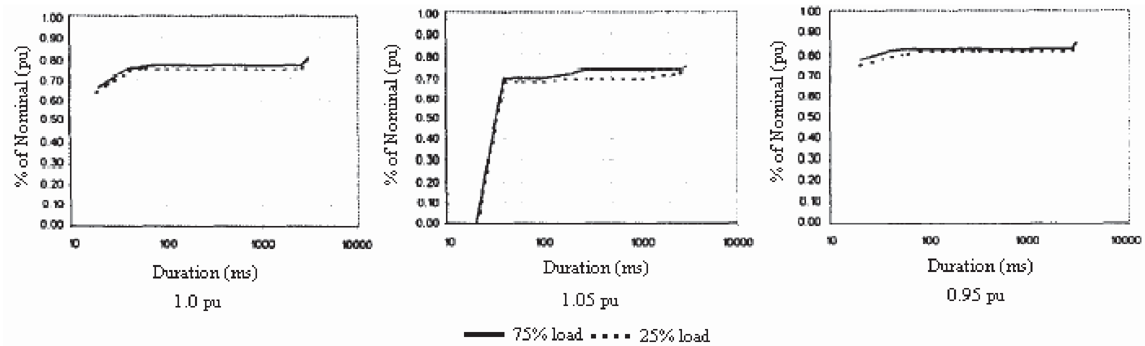


Figure 32. Two phase voltage sag ASD ride-through performance [21]

It may be noted, that when the pre-sag voltage is increased, the tolerance to low duration sags is increased.

Sarmiento and Estrada [22] proved that ASDs are more sensitive to voltage sag than data processing equipment. They collected the data about the failure of ASDs due to voltage sags from two industries for a period of 17 months. The tolerance curve for data processing equipment (ANSI/IEE Std. 446-1987) was compared with the distribution of the events that caused the ASDs to trip, as shown in Figure 33.

An asterisk shows events that caused the ASD to trip, while a square means the ASD did not trip. All disturbances falling within the envelope are not supposed to be harmful for the equipment. It is seen that events harmful for the ASD fall within this envelope, and so it can be concluded, that ASDs are more sensitive to voltage sags than data processing equipment.

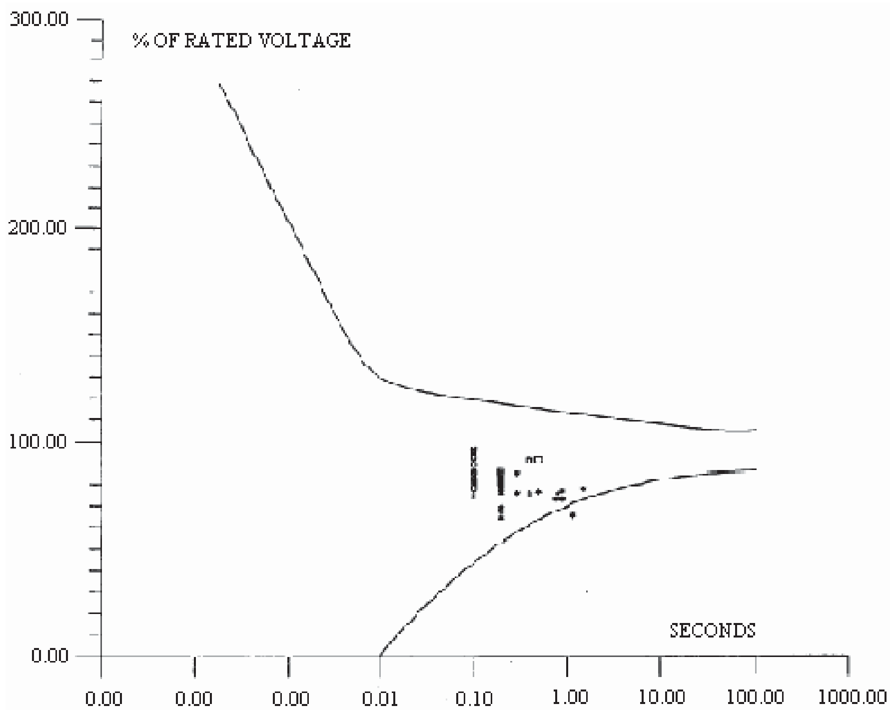


Figure 33. Tolerance Curve with sag events plotted.
(square means no trip; asterisk means trip for ASD)

The ability to ride-through a voltage sag depends also on the DC-link energy storage capacity, the speed and inertia of the load, the power consumed by the load, and the trip-point settings of the drive [22]. A motor with a larger inertia results in a slower speed change due to a voltage sag [23]. The most frequent ASD trips are due to the undervoltage protection of the DC-link. A test of the ride-through capability for an ASD shows that there is a very small difference between a 75% load and a 25% load.

2.5.2 DC adjustable speed drives

A DC ASD is commonly used in the industry due to the simplicity to regulate the speed. The DC adjustable drive requires only a variable magnitude of the DC voltage. The basic configuration of a DC ASD is shown in Figure 34.

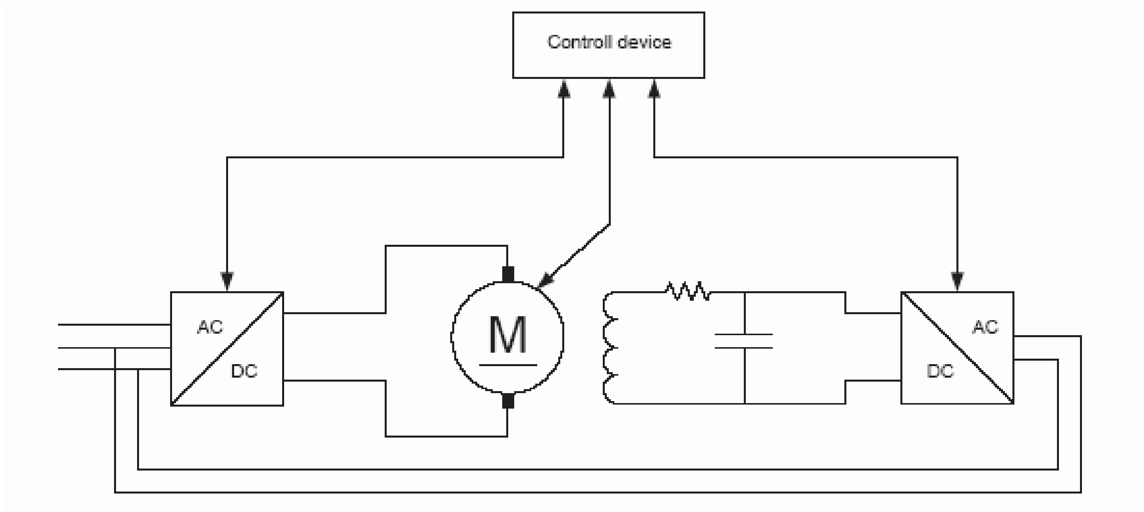


Figure 34. A DC adjustable speed drive

A brief overview of the effects of voltage sags on DC motor drives and methods to improve the ride-through capability of the equipment has been discussed [24]. According to the author, DC drives are more susceptible to voltage sags than their AC counterparts because they lack extra energy storage other than the motor's own inertia. The main reasons which prevent capacitors to be connected in parallel with DC motor are:

- Control range becomes limited.
- SCRs may get damaged due to high charging current drawn by the partially discharged capacitor.
- The field may be weakened due to voltage collapse during sag.

Finally, a number of equipment types have been suggested for the improvement of ride-through capability of the DC drives. They are:

a. Motor-Generator (MG) sets
b. Uninterruptible Power Supplies (UPS)
c. Constant Voltage Transformers (CVT)
d. Superconducting Magnetic Energy Storage Devices (SSD)

e. AC Power Conditioners.

A comparative study of various equipment suggested that all have some limitations for the improvement of ride-through ability. Therefore, it is suggested that a method be applied for desensitizing components affected by sags.

In summary, this section has provided a thorough literature survey on ASDs.

2.6 Effects of Voltage Sags on Lighting Loads

Voltage sags may cause lamps to extinguish. Light bulbs will just twinkle; that will likely not be considered to be a serious effect. High pressure lamps may extinguish; it takes several minutes for them to re-ignite.

All lamps, except incandescent lamps, require high voltage across the lamp electrodes during starting. This voltage is essential to initiate the arc. Traditionally, a choke coil is employed across the electrodes to produce high voltage pulses. The lamp starting voltage is affected to a large extent by the ambient temperature and humidity levels as well as the supply voltage. Fluorescent lamps reach their full emission level immediately after ignition. High-pressure lamps need a few minutes to reach their full light output, while low-pressure lamps take up to 15 minutes for the same.

The types of industrial lights are described below.

2.6.1 Incandescent lamps

This is the oldest and therefore, the most basic technology used in lighting systems. Current passed through a filament (typically tungsten) produces infrared radiation initially. At temperatures greater than 500˚C, emitted radiation falls in the range of visible light. Tungsten has a high melting point and is ideal for such applications. The filament is usually coiled to reduce thermal losses. It also helps in fitting the entire length of the filament within the glass bulb. The level of the nominal voltage dictates the length of filament required.

While the immediate discernible effect of a sudden sag in the line voltage is the lessening of visible light emitted by the lamp, there is no documented evidence on its effect on the overall life of the bulb. Research conducted by Phillips in 1975 found a working relationship between prolonged operation at reduced voltage and the life of the lamp. The lamp life is found to be inversely proportional to the *nth* power of the voltage. Value of *n* is 13 for vacuum lamps and 14 for general lighting service lamps. Thus, prolonged operation at 5% increased voltage would reduce the lamp life by half. The current varies proportionally with the square root of the voltage. The efficacy of the bulb is proportional to the square of the voltage while the luminous flux is proportional to the operating voltage raised to the power 3.6 [25].

2.6.2 Fluorescent lamps

Fluorescent lamps have two tungsten electrodes on either ends of a sealed glass tube filled with mercury and argon gas. When voltage is applied to the electrodes, thermionic emission takes place from the surface of the electrodes. In a cascading effect, the mercury and argon gases inside the tube emit radiation in the ultraviolet range. This radiation stimulates the phosphor coating on the inside of the glass tube to emit visible light. To start the lamp, a high voltage is required at the electrodes. This high voltage is generated using special starter circuits that are typically associated with some thermal inertia. There are also rapid starters available for fluorescent lamps.

Fluorescent lamps are more resilient to variations in line voltage. Usually, manufacturers recommend operation within 10% variation of line voltage. Unlike incandescent lamps, fluorescent lamps have proportional variation of luminous flux, current, and power with the variation in line voltage. If the voltage sag is severe, the lamp may go off, and according to its starter characteristics, take time to light up again. The starter may also have a minimum voltage below which it is unable to start the tube light. Manufacturers typically provide the minimum voltage values.

2.6.3 Sodium vapor lamps

The natural wavelength of sodium metal is corresponds to the most visually sensitive wavelength region. This makes it one of the most efficient lamps currently available. In sodium vapor lamps, the gas inside the glass tube is sodium vapor, which has a higher melting point than mercury. Therefore, it operates at a higher temperature level, thus requiring special insulating mechanisms. Sodium vapor lamps, like all discharge lamps, require special ballast circuits to enable their starting. They are slow to start, with starting time as high as 5 minutes.

Due to the inherent principle of operation, when there is a minor sag in the line voltage [26], the arc temperature falls leading to a rise in the arc resistance. This lowers the current through the lamp, and thus stabilizes the effect of the sag. This happens in the case of a low-pressure sodium vapor lamp. It must be remembered that if the sag is very severe, then the lamp may turn off. On reapplication of nominal voltage, the lamp will take time to start up (normally couple of minutes). It takes about 10-15 minutes to reach full light output condition. The high-pressure sodium vapor lamp operates at a low power factor as a result of which, it is considerably more vulnerable to voltage sags. High-pressure sodium vapor lamps require ballasts that are typically of an inductive type. If the lamp goes off due to a sag event, on voltage recovery, the ballast takes about 30s to re-ignite the lamp. The lamp is most vulnerable to a sag event during the time of run up because the light output and the power developed by the lamp are directly proportional to the line voltage.

2.6.4 Mercury vapor lamps

Mercury vapor lamps are high-pressure mercury vapor filled lamps that emit light that is a combination of blue, green, and yellow. The resultant color of the light is white and is very soothing to the eyes. The construction is similar with two electrodes separated inside a glass tube filled with mercury vapor that reaches a minimum vapor pressure of 5atm during operation.

Mercury lamps have high resistance initially, which falls as the arc establishes itself within the tube. A series choke (sometimes along with a parallel capacitor) is used to limit the current flowing into the lamp. In the event of sag, the current through the lamp will be marginally reduced, according to the ballast characteristics. If the lamp is in its normal operating region, marginal changes in current will not lead to any condensation of mercury within the tube. Hence, mercury is added to the lamp in limited amounts; otherwise, small changes in the current would lead to rapid condensation of mercury. Since the operating pressures are very high, instant reignition in the event of a sag is almost impossible. It takes 3-4 minutes before the arc can re-strike within the tube [26].

2.6.5 Metal halide lamps

Metal halide lamps consist of the halide (such as fluorine, chlorine, and bromine) salts of metals mixed with small amounts of mercury. These salts have a high vapor pressure at the arc temperature and are extremely stable compounds. Initially, the lamp light is due to the mercury vaporizing. Subsequently, when the arc temperature rises above a certain level (800°C), the metal halide salt vaporizes and its natural wavelength of emission improves the color of the lamp. Metal halide lamps require electrical (or electronic) ballasts to limit the current flowing through them as well as for starting purposes. Compared to mercury vapor lamps, these lamps require a higher voltage pulse in the range of 10kV to get started.

In general, the materials inside the metal halide lamps exceed the minimum amounts require to effectively sustain the arc. As a result, metal halide lamps are more immune to minor voltage variations than most other lamps. Typically, voltage sag of 10% for duration of 5 cycles is easily tolerated without extinction [26].

2.6.6 Ballasts

Most discharge lamps require a current limiter, as the arc has negative V-I characteristics. These current limiters, also called ballasts, are conventionally series inductor type. Sometimes the choke inductor has a capacitor connected in parallel to increase the ballast tolerance to voltage disturbances. Electronic ballasts are a great improvement on electromagnetic ballasts. For understanding purposes, discharge lamps are [26] modeled by a resistor and a non-linear inductor is series. The result of the non-linearity is that the impedance of the lamp is a function of the frequency of the supply voltage and the generation of harmonics.

Compared to incandescent lamps, discharge lamps are less sensitive to voltage sag, but this variation is due to the effect of the ballast more than anything else. The variation of the supply voltage appears across the choke primarily. The choke operating in the linear region shows minimum change in current, and consequently, the arc within the lamp is unaffected by the sag event. The power output is also held steady by this phenomenon. The stability of operation is characterized by the ability of the lamp current and light output to remain immune to sudden changes in supply voltage. Minimizing the voltage across the lamp electrodes and maximizing the voltage across the series ballast element helps achieve this stability. For instance, [26] when the ratio of the supply voltage to the voltage across the terminals of a mercury vapor lamp is 1.667, the maximum sag it can tolerate before extinguishing is 20%. However, if this ratio is 2.0, the maximum sag tolerated is 28%.

In summary, in this section, effects of voltage sags on lighting loads have been discussed. This has helped in understanding the behavior of lamps and other illumination components during sags.

2.7 Conclusions from Literature Review

The literature review has provided a deep insight into the fundamentals of the causes and effects of voltage sags. It has also helped in providing better understanding of the effect of sags on specific load categories, such as motor loads, lighting loads, and industrial processes. They have provided a benchmark for future experiments.

A new type of voltage sag caused by transformer energizing has been explained. Multiple voltage sags due to faults has also been discussed. The use of positive sequence voltages to study the effect of unsymmetrical sags on the machines has been suggested which, in turn, reduces the classification of voltage sags from seven to two (i.e., symmetrical and unsymmetrical. Fast transfer of induction motors to a healthy sag frequency on the occurrence of voltage sags has been suggested, whereas the fast transfer of synchronous motors has not been recommended.

In the case of ASDs, an integrated boost converter approach has been suggested to prevent nuisance tripping, and to maintain the DC link voltage within acceptable limits. Methods to desensitize the components have been suggested to improve the ride-through ability of the drives.

However, the literature review presented does not discuss the effect of voltage sag parameters, sag depth/magnitude and duration, on specific loads. This is the underlying aim of the project and experiments performed on specific loads will accomplish this task. The experiments will be conducted at various sag depths and durations, and sag effects on performance of the loads will be studied. This will help in predicting the performance of the loads on the occurrence of voltage sag events of specific depth and duration.

Hence, the literature review has served as a platform to fulfill the objectives of the project. The project objectives will be accomplished by theoretical investigation, supplemented by experimental results.

Chapter 3 Experimental Set-up and Test Procedure

3.1 Experimental Set-up

To study the effect of voltages sags on household equipment, a voltage sag generator was required to initiate voltage sags. Salt River Project (in Arizona) lent one of their voltage sag generators for the experimental purposes. The sags were initiated using the EPRI created Process Ride-Through Evaluation System (PRTES) which is a voltage sag generator combined with a built-in data acquisition system. With the PRTES, the user can induce voltage sags of controlled depth and duration while monitoring voltages, currents, or other signals. Figure 35 shows the experimental set-up that was arranged to conduct experiments.

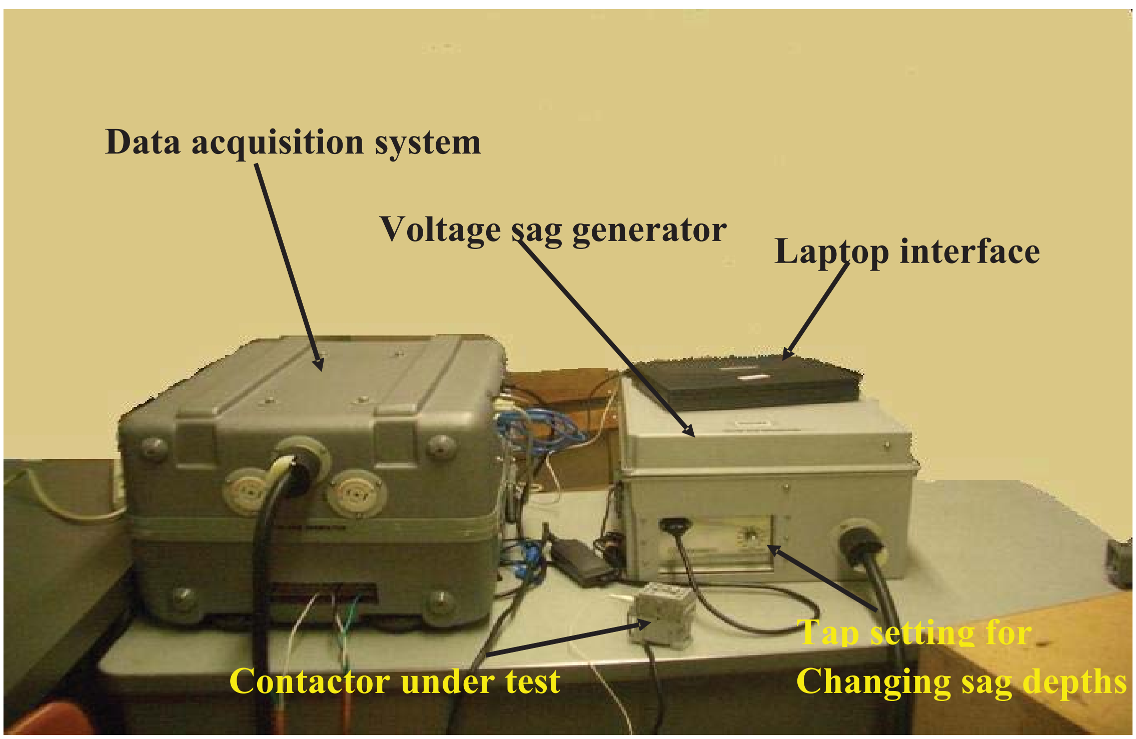


Figure 35. EPRI PRTES system – portable sag generator and built-in data acquisition system (testing a contactor)

The PRTES creates voltage sag by switching rapidly between nominal supply voltage and reduced voltage. This reduced voltage is termed as “sag depth”. The sag depth is obtained by a multi-tapped autotransformer which has been adjusted to the desired sag depths. As can be seen in Figure 35, the tap setting is provided for changing the sag depths.

The system is controllable from a laptop computer using graphical software that is based on a Windows operating system, and is user-friendly. The key functions of the software that were used during experiments are:

1. Control the sag duration
2. Control the phase angle at which the sag is applied
3. Trigger a sag event
4. Display data that was acquired on selected channels during the sag event
5. Save/recall the data for further analysis.

3.2 Test Procedure

The following test procedure was adopted to perform experiments on various household loads to study the effect of voltage sags:

1. Connect the load (household appliance) to the PRTES system.
2. Vary the sag depths in steps of 10% starting from 90% and going to 50% using the tap setting.
3. At each sag depth, vary the sag duration from 5 cycles to 60 cycles in the following way 5, 10, 20, 30, 40, 50 and 60 cycles using the software.
4. For each sag depth and at every sag duration, a sag event is triggered

5. For each sag depth and at every sag duration for which the sag event is triggered, voltage and current waveforms are recorded and the data is transferred in the form of an Excel sheet.
6. A table is created to note the observations such as any visible or audible effect on the load due to the initiation of the sag event. A sample table is shown below.

Sample table format for noting observations

Depth	Duration (in cycles)						
↓	→	5 ~	10 ~	20~	30 ~	40 ~	60 ~
90%							
80%							

The recorded waveforms are analyzed and conclusions are derived using both waveforms and observations noted.

Chapter 4 Effects of Voltage Sags on Contactors

4.1 Market Survey on Contactors

A market survey was done to ascertain what various manufacturers of contactors are doing to control the tolerance level of their range of contactors towards voltage sags. This information is not readily available from manufacturers because of fears that it may be used in a competitive manner against them. Manufacturing firms contacted include Allen Bradley (brand of Rockwell Automation), Automatic Switch Corporation, ABB Control Inc., Moeller Electric Corporation, Siemens Energy & Automation Inc., and Eaton Corporation (Cutler-Hammer Group).

Typically manufacturers provide the pickup and dropout voltage of the contactor coil in the contactor specifications. This data is provided for both hot as well as cold coil conditions. Pickup voltage of the coil refers to the coil voltage at which the contactor is able to close its power contacts. The dropout voltage refers to the voltage at which the contactor separates its contacts. For most NEMA type contactors, the coil picks up at 80-85% of the nominal line voltage. Once the contactor is energized, it only takes about 40% of the voltage to keep the contacts closed. This figure may vary widely for different manufacturers and contactor ratings.

The pickup time for the coil is defined as the average time elapsed from the closing of the coil circuit to the touching of the main contacts. Similarly, the dropout time for the coil is defined as the average time taken from the opening/interruption of the coil circuit to the separation of its power contacts. The pickup and dropout times of a contactor are dependent on several mechanical aspects of the contactor design. These aspects include the mass of the contact moving assembly, the spring tension, and the total air gap to be covered. The manufacturer, in its specifications sheet, provides these values of pickup and dropout times. The dropout time may be indirectly related to the sag performance of the contactor.

For a standard coil, if there is an absence of voltage, or if the voltage sags to less than the dropout voltage, for durations longer than its dropout time, the contactor will dropout. For instance, a CN15A NEMA size 00 contactor with dropout voltage 55.2V can withstand voltage sag to this value for a maximum duration of 12ms, which is its dropout time. Some manufacturers, therefore, directly relate the contactor sag ride-through capability to its dropout time. It must be noted that the nature of the load may have an effect on the dropout time. An inductive load supplied by the contactor will make the opening period of the contactor prolonged due to the formation of an arc. Table 4 presents typical contactor pickup and dropout voltage values.

One of the recent standards developed in the field of power quality is the SEMI F47 standard developed by the Semiconductor Equipment and Materials International. This organization investigated the reasons for plant and equipment shutdown in semiconductor industry. Electromechanical contactors were identified as the primary reasons for shutdown during momentary line voltage sags, in 47% of the cases. After reviewing the available data, including the ITI (CBEMA) curves, the SEMI F47 standard were developed to specify the voltage sag immunity levels for semiconductor processing equipment.

Table 4. Typical contactor pickup and dropout voltage values

Contactor type	Contactor current (A)	Coil operating voltage (V)	Coil pickup voltage (V)	Coil dropout voltage (V)	Pickup time (ms)	Dropout time (ms)
Cutler Hammer (CN15A NEMA 00) (600 VAC)	9	120	88.8 (cold) 93.6 (hot)	54 (cold) 55.2 (hot)	12	12
Cutler Hammer (CN15B NEMA 0) (600 VAC)	18	120	88.8 (cold) 93.6 (hot)	54 (cold) 55.2 (hot)	12	12
Cutler Hammer (CN15K NEMA 3) (600 VAC)	90	120	86.4 (cold) 91.2 (hot)	60 (cold) 62.4 (hot)	14	11
Cutler Hammer (CN15S NEMA 5) (600 VAC)	135	120	87 (cold) 91.2 (hot)	64.8 (cold) 67.2 (hot)	28	14
Cutler Hammer (CN15T NEMA 6) (600 VAC)	540	120	90 (cold) 90 (hot)	24–36 (cold) 24–36 (hot)	105	200
Cutler Hammer (CN15V NEMA 8) (600 VAC)	1215	120	90 (cold) 90 (hot)	24–36 (cold) 24–36 (hot)	70	50

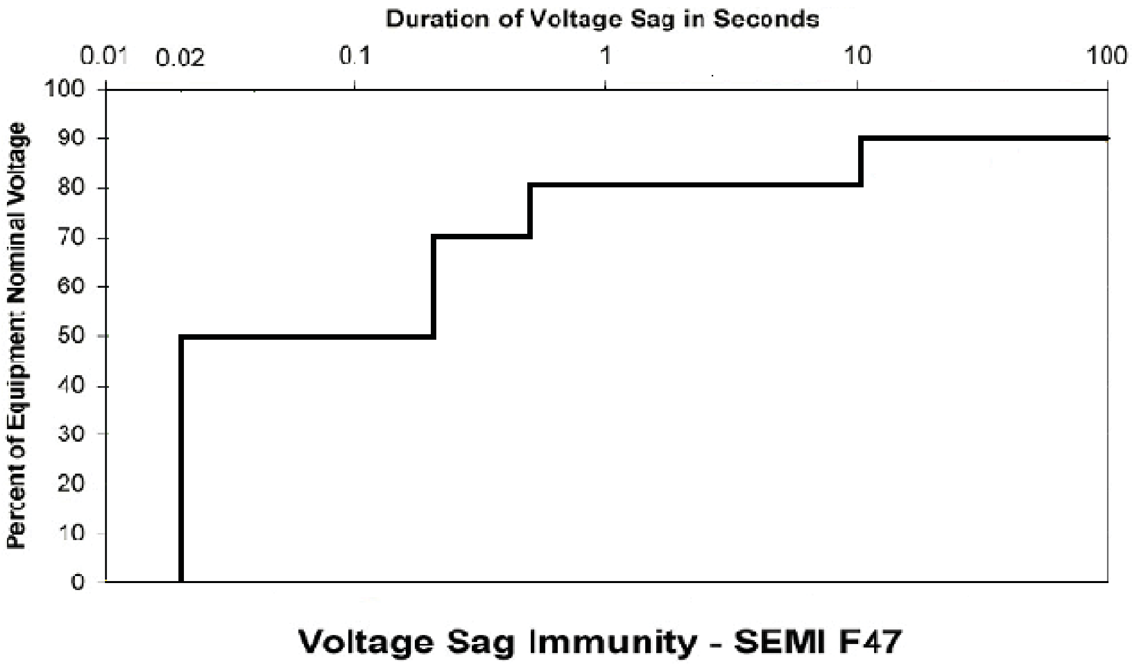


Figure 36. The SEMI curve for voltage sags

The SEMI F42 standard defines the method to test the sag ride-through capability of all semiconductor equipment. Essentially, SEMI F47 sets the minimum AC power line voltage sag ride-through requirements for semiconductor processing, metrology, and automated test equipment. According to this standard, the equipment must be able to tolerate a voltage sag to 50% of nominal for up to 200ms, 70% of nominal for up to 500ms and 80% of nominal for up to one second. Additionally, it recommends that the equipment be able to withstand 0% of nominal voltage for one cycle, 80% of nominal for 10 seconds and a continuous voltage of 90% of nominal indefinitely.

There are various methods to improve sag ride-through capability of contactors, prevalent in the market. Contactors supplying lighting loads are frequently provided with a mechanical latch, so that the contactor does not automatically open, when the system voltage collapses or sags. Once energized, the contactor does not require the line voltage to keep its contacts together. Instead, a reliable source of control power is required for tripping purpose. Frequently, a DC auxiliary source is used, which is especially useful if the mass of the contact assembly is large, as in high amperage contactors. Sometimes, if the DC source is unavailable, an AC capacitor trip device is used while deriving control power from the primary voltage line.

Many manufacturers also incorporate a time delay in low rating contactors to improve their sag ride-through capability. Schneider Electric has developed a Low Voltage Ride-Through Module specifically to comply and even exceed the SEMI F47 set standards. This module may be used with their range of AC powered TELEMECANIQUE contactors and relays inside the front end semiconductor-manufacturing equipment. These 8-bit microcontroller modules are compatible with contactors ranging from 9A to 80A. They provide over voltage protection during coil energization and protection from transient surges and 20ms outages. These can be programmed to ride through a voltage sag to 45% of nominal voltage for indefinite duration.

4.2 Market Survey Conclusion

From the market survey it has been found that there is no specific information available on the voltage sag characteristics of contactors of different rating. Manufacturers consider the dropout time and the value of the dropout and the pickup voltage as yardsticks for measuring the sag characteristics. This does not give a complete picture of the dynamic behavior of the contactors during momentary sag conditions in the line. It is proposed to conduct experimentation to measure the dynamic characteristics of contactors of different ratings.

4.3 Experiments on Contactors

Contactors are used extensively as a source of protection in residential apartments. When a relay is used to switch a large amount of electrical power through its contacts, it is designated by a special name: contactor. Contactors typically have multiple contacts, and those contacts are usually (but not always) normally open, so that power to the load is shut off when the coil is de-energized. The most common industrial use for contactors is the control of electric motors. Figure 37 shows the connection of a 3-phase electric motor with the contactor.

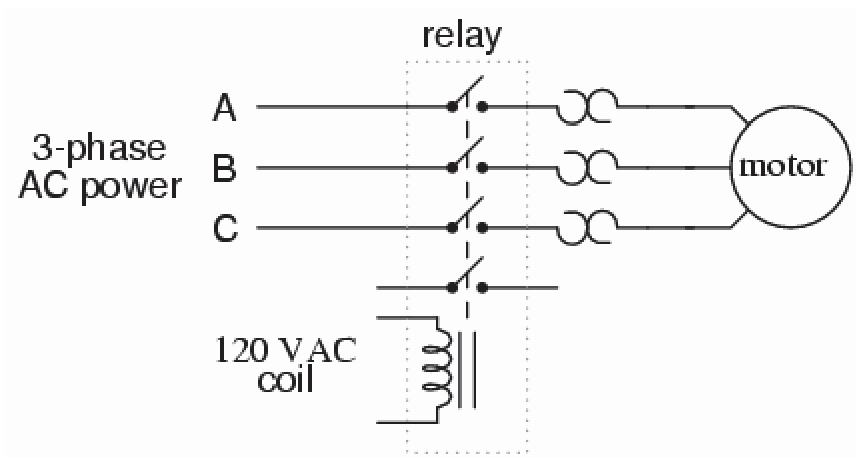


Figure 37. Connection diagram of contactor with electric motor [27]

To study the effect of voltage sags on contactors, the contactors were subjected to sags of depths varying from 90% to 40% and sag durations varying from 5 cycles to 60 cycles. It was also of significance to observe the behavior of contactors on being subjected to voltage sags in two cases:

- Operation of contactors with load
- Operation of contactors without load.

Both the cases have been considered to study the performance of contactors on voltage sags.

4.3.1 Definitions

The terms which are of interest in the experiments are being defined as follows:

Dropout voltage: The dropout voltage for a contactor is defined as the voltage below the coil nominal voltage at which the contactor opens or drops out.

Chattering: Chattering is a phenomenon that is observed when the voltage supplied to the contactor coil falls below a certain value. It refers to the distinct impact sound caused due to the repeated making and breaking of the armature circuit inside the contactor. There is a continuous mechanical separation and union of the contactors without complete sustained electrical separation.

4.3.2 Contactors tested

Two contactors of different manufacturers were tested to study the effect of voltage sags on them. Their ratings are as follows:

1. **Contactor A**
    - 120VAC, 60Hz, 15A
    - Normally open
    - Dropout voltage: 50V
2. **Contactor B**
    - 115VAC, 60Hz, 10A
    - Normally open
    - Dropout Voltage: 45V

To measure the dropout voltage, the voltage supplied to the AC coil of the contactor was lowered very slowly from nominal value until the contactor tripped. This is the drop out voltage for the contactor. Subsequently, the voltage was increased from zero until the contactor closed. This process was repeated five times, and the mean of the readings calculated. The respective values for the 15A contactor were measured to be 45V and 55V. For the 10A contactor with a 115V, 60Hz coil, these values were measured and found to be 40V and 50V respectively. It is important to change the voltage gradually to rule out any transient effects on the measurements.

4.3.3 Voltage sag tests on Contactor A

The tests on contactor A were conducted both with and without load. A resistive load was used. The value of the load current was purposefully maintained close to the current rating of the contactor to simulate nearly worst case scenario, the worst case scenario being the overloaded condition. Thus, for a current rating of 15A for contactor A, the load was maintained at a current value of 14.4A.

There was no effect on the performance of the contactors for sags of depths 90%, 80%, and 70%, for all sag durations. However, for the sag depth of 60%, for sag durations greater than 20 cycles, a very small duration beep sound is heard which cannot be captured in the waveforms. The sound did not produce any change in the separation of the contacts and the contactor continued to operate in the normal condition. The sound heard is constant for all sag durations, indicating that the sag duration has no effect on the sound produced.

In the case of 50% sag depth, sound similar to the one heard in the case of 60% sag depth was noticed. However, the sound produced was for a longer duration, around 1-

2 cycles. Once again, as in the 60% sag depth, the sound did not produce any change in the separation of the contacts and the contactor continued to operate in the normal condition. The sound heard is constant for all sag durations, indicating that the sag duration has no effect on the sound produced.

The performance of contactors when subjected to 40% sag depth has a significant effect of sags on them. For 5-cycle duration, the contactor tripped and returned back to its normal position almost immediately (4-5 cycles). For 10-cycle duration, the contactor tripped once again. However, it took about 9-10 cycles for the contactors to return to its normal operating condition. It can be seen that the contactors return to their normal operation once the sag is over. Figures 38 and 39 show the current waveforms for sag durations of 5 and 10 cycles.

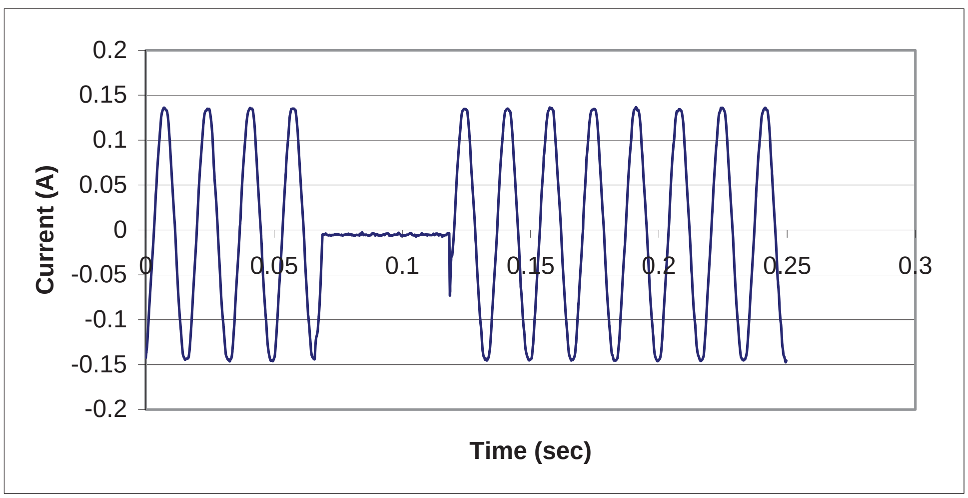


Figure 38. Current waveform for 40%, 5-cycle sag (contactor tripped)

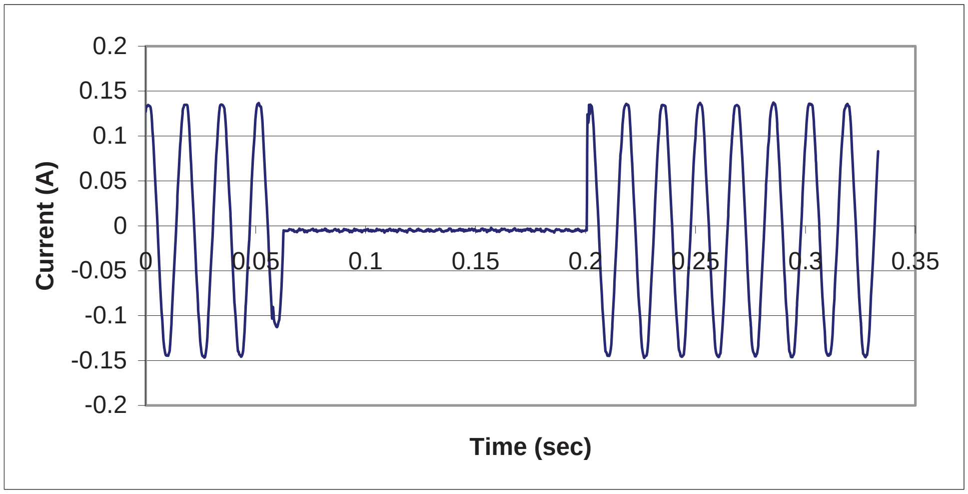


Figure 39. Current waveform for 40%, 10-cycle sag (contactor tripped)

As can be seen from the figures, in both the cases, the contactor tripped for duration equal to the sag duration for which the sag was initiated. Once the sag is over, the contactors return to their normal operation.

In the case of 20-cycle duration, chattering phenomenon is observed. Figure 40 shows this phenomenon for the 20-cycle sag duration.

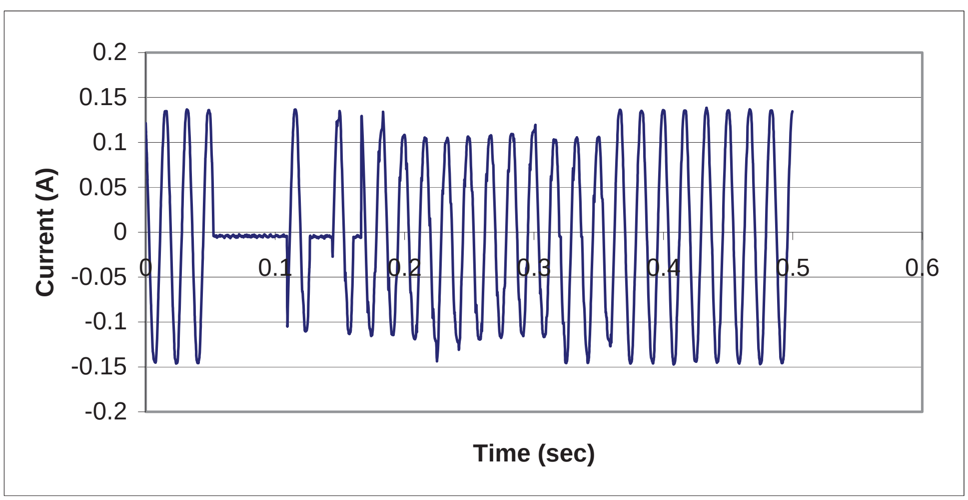


Figure 40. Current waveform for 40%, 20-cycle sag (chattering observed)

As can be seen from the figure, once the sag occurs, the mechanical contacts of the contactor open for few cycles. The contacts then close again for a cycle and then reopen again. There is a distinct impact sound caused due to the repeated making and breaking of the armature circuit inside the contactor. Thus, it is observed that there is a continuous mechanical separation and union of the contactors without complete sustained electrical separation.

Similar observations were found for sags of duration 30, 40 and 60 cycles. The chattering increases with the sag duration. Figure 41 shows the same chattering phenomenon for 60-cycle duration.

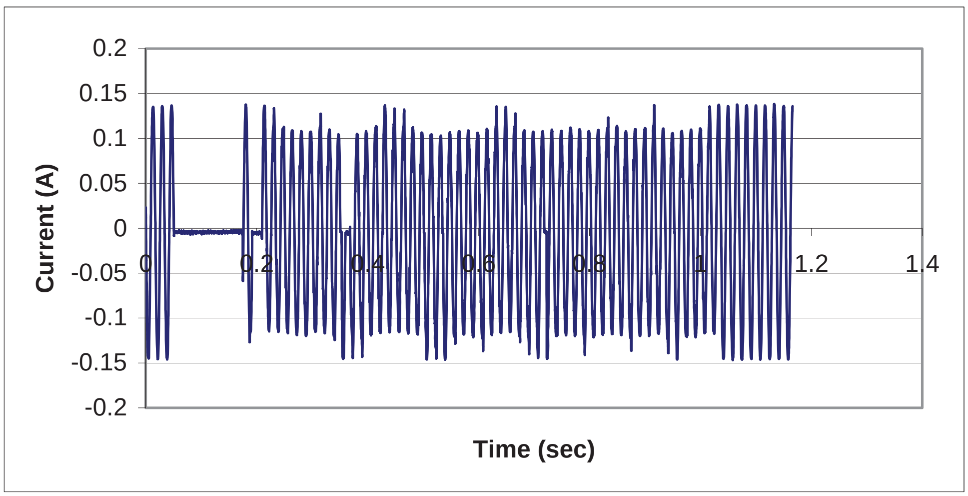


Figure 41. Current waveform for 40%, 60-cycle sag (chattering observed)

There is a significant difference in the behavior of the contactor depending on the exact point on wave of initiation of the sag. The contactor is more vulnerable to sag if it is initiated at the zero crossing rather than if it is initiated at the peak of the voltage wave.

Similar tests were conducted on contactor A, but without load. However, no notable difference in the performance of the contactors was observed. Figures 42 and 43 show the current waveforms for sag depth of 50% and duration of 30 cycles for both with load and without load, respectively. As can be seen, there is no difference in the performance of the contactors under different conditions.

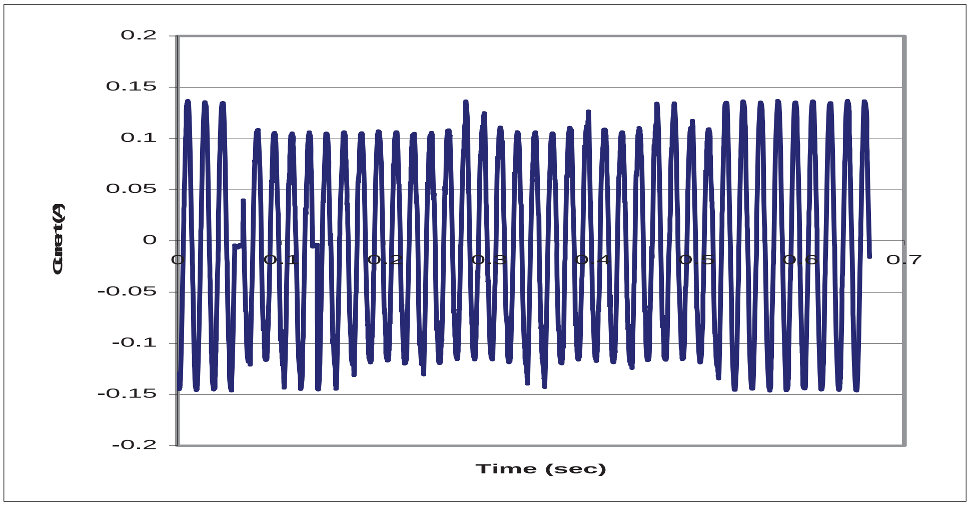


Figure 42. Current waveform for 50%, 30-cycle sag (with load)

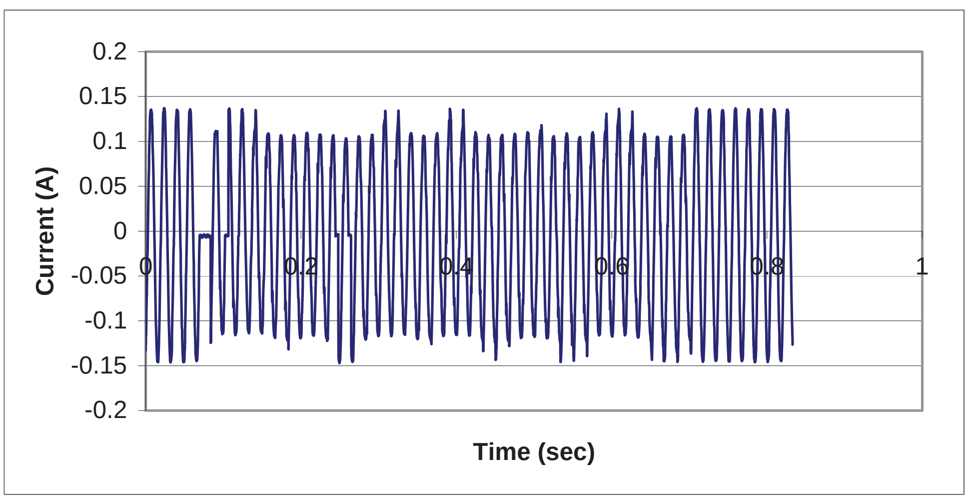


Figure 43. Current waveform for 50%, 30-cycle sag (without load)

4.3.4 Conclusions from Contactor A tests

The most significant conclusion that can be drawn by observing the behavior of contactor A under both load and no load condition is that there is no difference in the contactor performance under both conditions. The contactor is not affected by sags of depths 90%, 80% and 70%. For 60% and 50% sag depths, it produces noise; however, it does not affect the normal operation of the contactor. For sag depth of 40%, for smaller durations of 5 cycles and 10 cycles, there is clear tripping of the contactor. As the sag duration increases, chattering phenomenon is observed. The chattering increases with the sag duration. There is a significant difference in the behavior of the contactor depending on the exact point on wave of initiation of the sag. The contactor is more vulnerable to sag if it is initiated at the zero crossing rather than if it is initiated at the peak of the voltage wave.

4.3.5 Voltage sag tests on Contactor B

The tests on Contactor B were also conducted both with and without load. A resistive load was used. The value of the load current was purposefully maintained close to the current rating of the contactor to simulate nearly worst case scenario, the worst case scenario being the overloaded condition. Thus, for a current rating of 10A for Contactor A, the load was maintained at a current value of 9.43A.

There is no effect of voltage sags on the performance of the contactor for sags of depths 90%, 80% and 70%. In the case of 60% sag depth, contactors experience chattering for sag durations greater than 30 cycles. Figure 44 shows the chattering phenomenon for 60% depth and 40-cycle duration sag. It is clear from the figure, that the contacts experience the repeated making and breaking of the armature circuit inside the contactor.

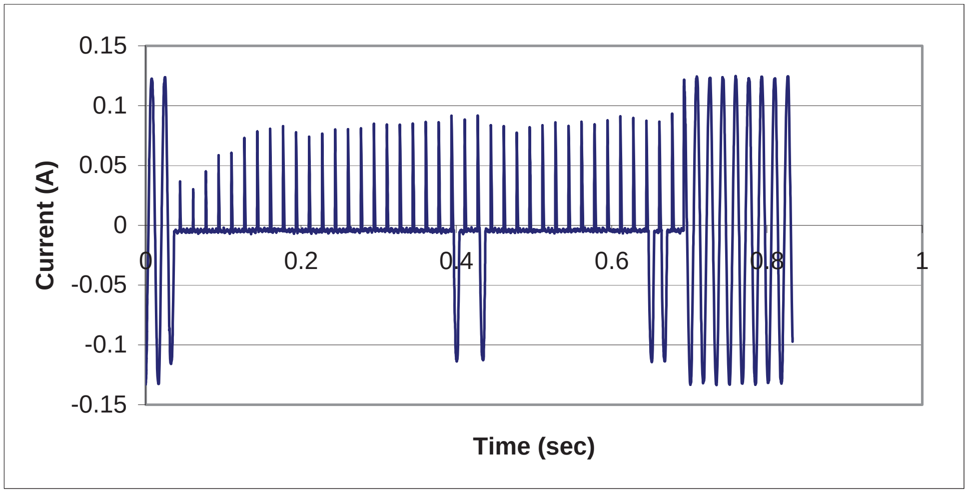


Figure 44. Current waveform for 60%, 40-cycle sag (chattering observed)

In the case of 50% sag depth, it is noticed that there is no chattering for all sag durations. However, for all sag durations varying from 5 cycles to 60 cycles, there is clear tripping of the contactor. Figure 45 shows the waveform for 50% depth and 40 cycles, indicating tripping of the contactors.

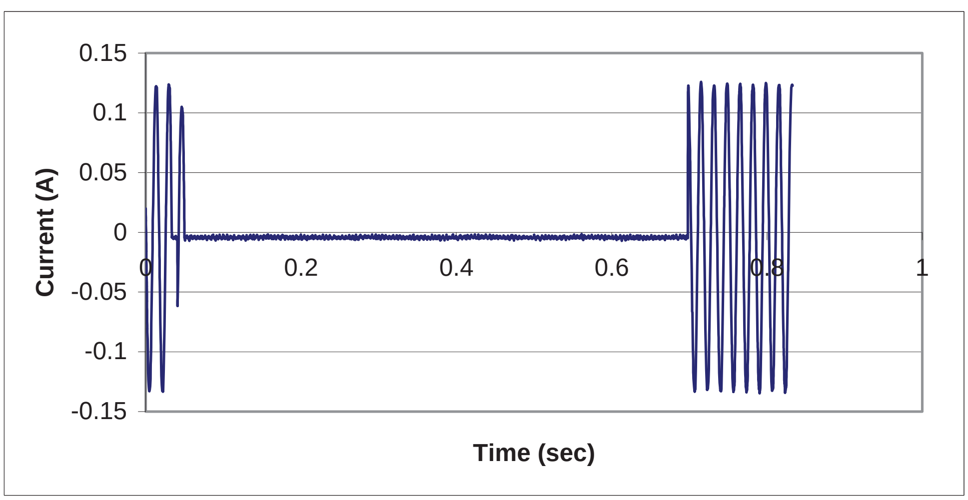


Figure 45. Current waveform for 50%, 40-cycle sag (contactor trip)

Similar observations were found for sag depth of 40%. For all sag durations the contactors tripped. No chattering phenomenon was observed for any of the sag durations. However, arcing between the contacts was noticed for sag durations greater than 30 cycles. Figures 46, 47, 48, 49 and 50 show the current waveforms indicating tripping of the contactor for 40% sag depth and various durations.

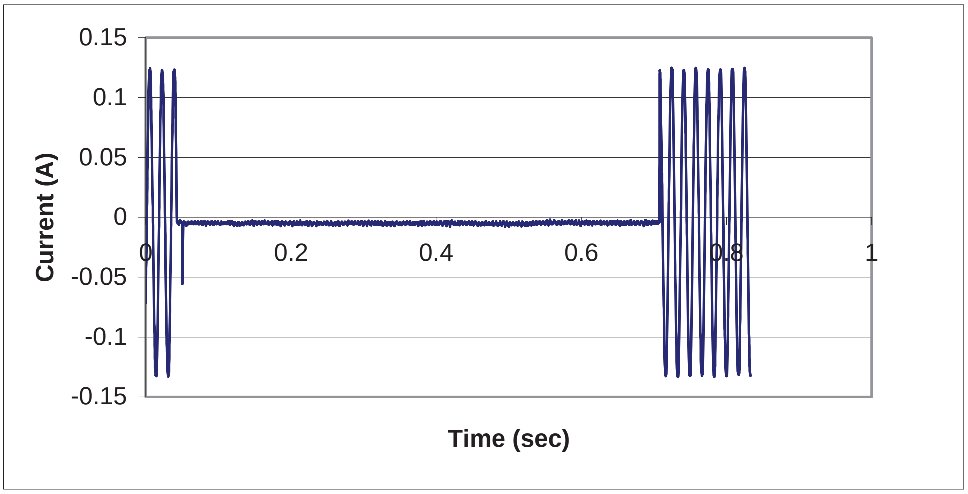


Figure 46. Current waveform for 40%, 40-cycle sag (contactor trip)

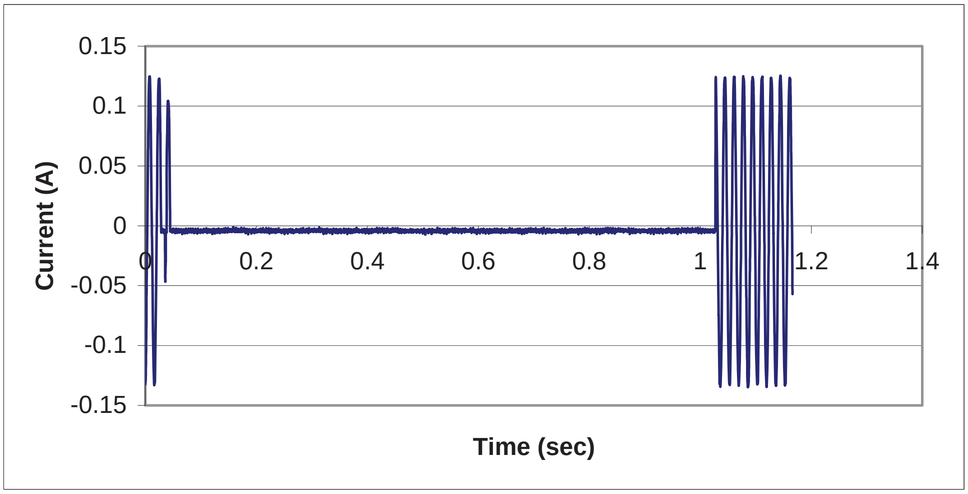


Figure 47. Current waveform for 40%, 60-cycle sag (contactor trip)

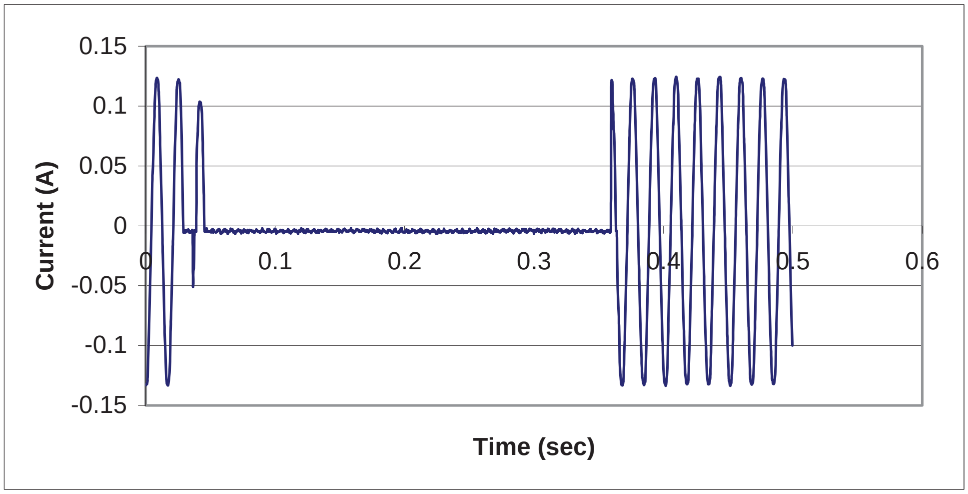


Figure 48. Current waveform for 40%, 20-cycle sag (contactor trip)

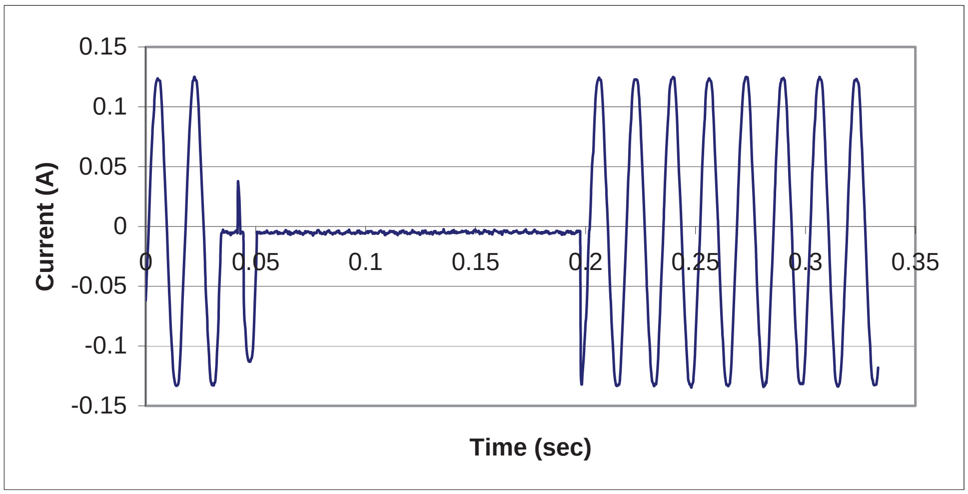


Figure 49. Current waveform for 40%, 10-cycle sag (contactor trip)

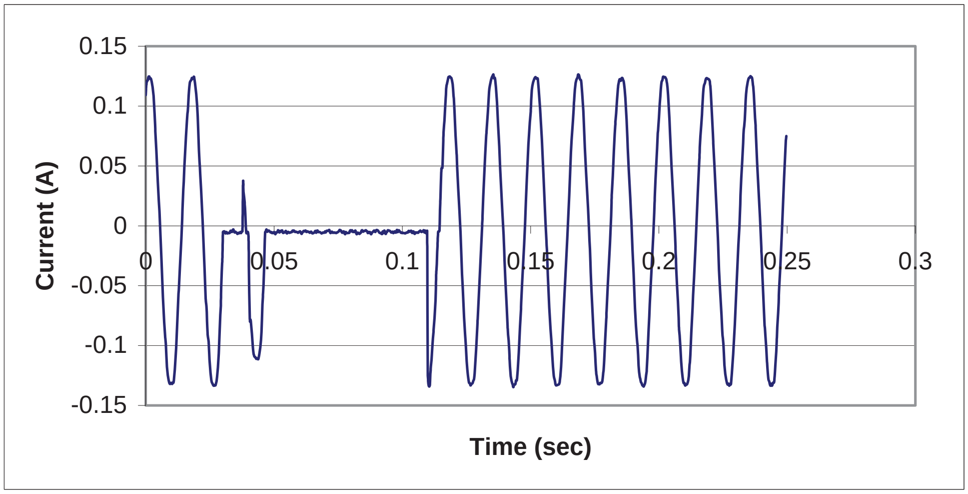


Figure 50. Current waveform for 40%, 5-cycle sag (contactor trip)

Similar tests were conducted without load. However, like contactor A results, no notable difference was observed.

4.3.6 Conclusions from Contactor B tests

Similar to the result obtained for Contactor A, the most significant conclusion that can be drawn by observing the behavior of Contactor B under both load and no load condition is that there is no difference in the contactor performance under both conditions. The contactor is not affected by sags of depths 90%, 80% and 70%. For sag depth of 60%, there is chattering observed for sag duration greater than 30 cycles. In the case of 50% and 40% sag depths, the contactors trip for all sag durations. There is no chattering phenomenon observed in these sag depths.

4.3.7 Conclusions from Contactor tests

The results of both the contactors can be summarized in a tabular form as shown in Table 5.

Table 5. Tabulated summary of the performance of contactors due to voltage sags

Depth	Duration (in cycles)							
↓	→	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	No effect
80%		N	N	N	N	N	N	No effect
70%		N	N	N	N	N	N	No effect
60%		N	N	N	N	Y	Y	In the case of contactor A, a beep is heard. For contactor B, chattering is observed for sag durations greater than 30 cycles.
50%		Y	Y	Y	Y	Y	Y	In the case of contactor A, only chattering occurs. However for contactor B, there is clear tripping without chattering
40%		Y	Y	Y	Y	Y	Y	Tripping occurs contactor B for all sag durations. However, for contactor A, for 5-cycle and 10-cycle duration, chattering occurs. For sag durations greater than 10 cycles, tripping occurs

Y: Contactor trips/ chattering occurs

N: Contactor does not trip/ no chattering

4.4 Experiments on Circuit Breakers

Low voltage circuit breakers are the primary protection devices for electrical circuits. A circuit breaker provides protection for each of the electrical circuits by stopping the flow of current if an overload or fault occurs. When an electrical fault occurs or the load on the current increases, the breaker on that circuit trips and interrupts the flow of current to that circuit. They are used extensively as protection devices in residential complexes. The performance of circuit breakers on being subjected to voltage sags is of great significance to sag studies. Hence, two low voltage circuit breakers were tested to study the effect of voltage sags on them.

To study the effect of voltage sags on circuit breakers, the circuit breakers were subjected to sags of depths varying from 90% to 40% and sag durations varying from 5 cycles to 60 cycles. It was also of significance to observe the behavior of circuit breakers on being subjected to voltage sags in two cases:

- Operation of circuit breakers with load
- Operation of circuit breakers without load.

4.4.1 Circuit breakers tested

Two circuit breakers were tested. Their rating are:

Circuit Breaker A

- 120VAC, 60Hz
- Current rating: 15A, single pole

Circuit Breaker B

- 120VAC, 60Hz
- Current rating: 20A, single pole

4.4.2 Conclusions from circuit breaker tests

Both the circuit breakers tested had no effect of voltage sags of varying depths and durations on their performance. Similar to the observations made for contactors, there is no difference of load and no load on the circuit breaker performance. Table 6 summarizes the performance of circuit breakers on being subjected to sags.

Table 6. Tabulated summary of the performance of circuit breakers due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20 ~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	No effect
80%		N	N	N	N	N	N	No effect
70%		N	N	N	N	N	N	No effect
60%		N	N	N	N	N	N	No effect
50%		N	N	N	N	N	N	No effect
40%		N	N	N	N	N	N	No effect

N: No effect

Chapter 5 Experiments on Motor Loads, Lighting Loads and Sensitive Equipment

5.1 Introduction

The main purpose of conducting experiments on various household loads is to determine and study the effects of voltage sags on their operation. For experimentation purposes, the loads are divided into the following categories:

- Motor loads: air conditioners
- Lightning loads: florescent lamps and helium lamps
- Sensitive loads: computers, microwave ovens, televisions, VHSs and DVDs, compact discs, radio alarm clocks, sandwich makers and toasters.

The impact of voltage sag amplitude/depth, duration and phase shift on each of the above loads will be investigated. As mentioned in the previous chapter, the sags were initiated using the EPRI created Process Ride-Through Evaluation System (PRTES). The sag depths are varied from 90% to 50%. At each sag depth, the sag duration is varied from 5 cycles to 60 cycles.

5.2 Definitions

The terms which are of interest in the experiments are being defined as follows:

Sag depth: It is the remaining voltage in percentage.

Sag duration: It represents the number of cycles during voltage sag.

Maximum responding current, I_{max} (p.u.): It is the maximum motor current during sag period.

Recovering current (p.u.): It is the magnitude of the overcurrent at the instant when voltage sag ends and applied voltage recovers.

Instant overcurrent, I_o (A, p.u.): It is the maximum current at the instant when voltage sag starts.

Voltage Drop, V_d (V, p.u.): It is the voltage drop caused by the starting motor current after normal applied voltage returns in the post-sag period.

Flickering: An inconstant or wavering light associated with dimness in light.

5.3 Experiments on Motor Loads (Air Conditioner Compressors)

To study the impact of voltage sags, two air conditioning systems, categorized as Air Conditioner A and Air Conditioner B, were tested. The air conditioners are subjected to sags of depths varying from 90% to 50% and duration ranging from 5 cycles to 60 cycles. To study the effect of phase shift, the starting point of the sag has also been varied.

5.3.1 Air conditioners tested

The specifications of the air conditioners tested are given below.

Air Conditioner A

- 120VAC single phase/thermally protected cooler
- Full load amps: 7.4A
- Locked rotor amps: 35.7A
- Measured operation current: 6.7A

Air Conditioner B

- 230VAC single phase/thermally protected air conditioner
- Full load amps: 8.2A
- Locked rotor amps: 49.0A
- Measured operation current: 8.6A

Air Conditioner C

- 120VAC single phase
- Full load amps: 9.4A
- Locked rotor amps: 55.4A
- Measured operation current: 9.7A

All the air conditioners have thermal protection relays. There are two types of effects of voltage sags on the air conditioner compressors depending on the sag depths and durations:

1. Decrease in speed accompanied by a sound without stalling the compressor
2. Stalling of the compressor.

5.3.2 Air Conditioner A tests

The starting current of the cooler is measured before subjected to voltage sag experiments. The starting current waveform is shown in Figure 51. The peak value of starting current is 48A.

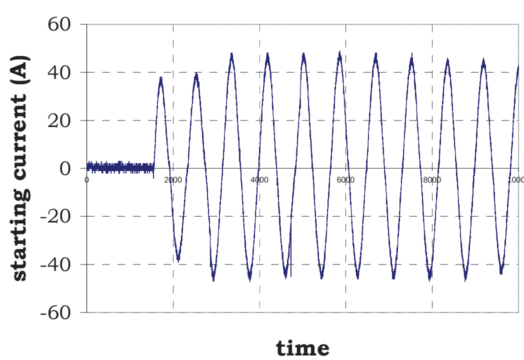


Figure 51. Starting current waveform for Air Conditioner A

In the case of 90% sag depth, there is no decrease in the speed of the air conditioner compressor for all the sag durations. As a result of this, there is no decrease in the compressor current.

For 80% sag depth, there is no decrease in the speed of the compressor for sag durations of 5 and 10 cycles. However, for sag duration of 20 cycles, there is a slight decrease in speed. The reduction in speed increases with the sag duration. For sag durations greater than 40 cycles, the reduction in speed is accompanied by a noticeable noise.

Similar observations are obtained for 70% sag depth. However, there is speed reduction in the compressor from sag duration of 5 cycles onwards. The decrease in speed increases as the sag duration increases. For sag durations greater than 30 cycles, the reduction in speed is accompanied by significant noise. The compressor stalls at sag duration of 60 cycles.

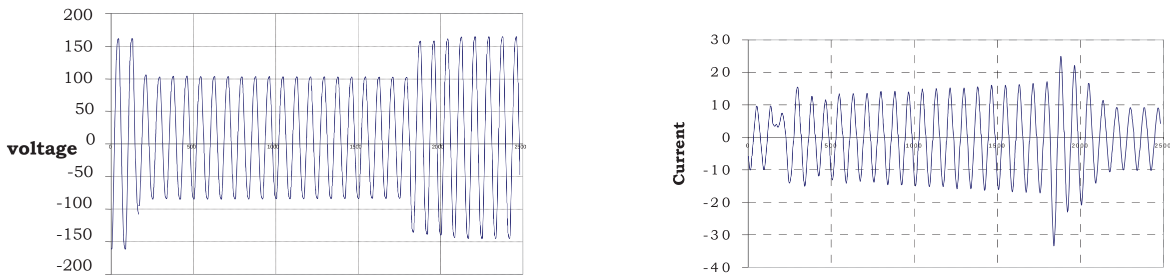
In the case of 60% sag depth, the speed decreases significantly accompanied by significant noise for sag durations of 5, 10, 20 and 30 cycles. The reduction in speed is drastic for sag durations of 40 cycles and more. As a result, the compressor stalls for sag durations of 40 and 60 cycles. For sag depth of 50%, the compressor stalls for sag durations greater than 10 cycles.

The readings for motor responding current, recovery current and voltage drop were taken for various sag depths and sag durations. They are given in Table 7.

Table 7. Test results for different sag depths and duration

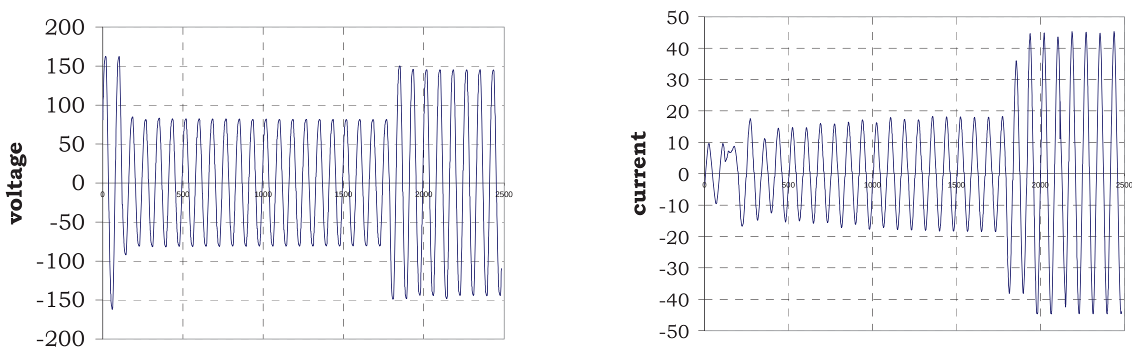
Depth (%)	Cycles	Motor responding current (A)		Recovering current (A)	Voltage after sag event (V)	Voltage Drop after sag, $(V_o - V)/V_o$ (V_d, %)
		I_0	I_{max}	6.7 (RMS)	V_o 162.45	
50	5	17.15	14.69	35.67	148.39	8.7
	10	17.64	16.71	39.41	138.72	14.6
	20	17.35	18.10	45.19	144.29	11.2
	60	17.40	18.20	45.20	144.50	11.0
60	10	15.64	14.42	30.74		
	20	15.42	17.15	33.43	153.81	5.3
	30	15.20	20.01	36.50	143.38	11.7
	40	15.10	21.82	45.07	144.00	11.4
	45	15.00	22.25	45.68	144.87	10.8
	60	15.15	22.05	45.73	144.00	11.4
	90	15.01	22.06	45.12	145.12	10.7
70	10	12.78	10.66	22.29		
	30	12.92	10.63	22.49		
	60	12.46	10.51	22.29		
80	10	10.17	9.33	16.37		
	20	10.16	9.19	16.06		
	30	10.08	9.20	16.10		

Figure 52(b) and Figure 53(b) show the compressor current waveforms when subjected to sag depths of 60% and 50% as shown in Figure 52(a) and Figure 53(a) respectively, with the sag duration being constant at 20 cycles.



a) Voltage sag (50% depth, 20 cycle duration)　　　　b) Responding motor current

Figure 52. Voltage sag on Air Conditioner A and its responding current (non-stall condition)



a) Voltage sag (60% depth/20 cycle duration)　　　　b) Responding motor current

Figure 53. Voltage sag on Air Conditioner A and its responding current (stall condition)

Figure 52(b) represents the non-stalling condition of the compressor and Figure 53(b) represents the stalling condition of the compressor. When the voltage sag occurs, the compressor speed decreases. When the sag ends and the voltage returns to normal, the compressor accelerates and returns to nominal speed drawing higher than normal rated current. From Figure 52(b) and Figure 53(b), during the sag period, both current waveforms show similar patterns. At the start of sag, the compressor current becomes higher than normal, about 1.5 times the normal current and then drops to a certain value within one cycle. Subsequently, the current gradually increases during the sag period. For higher sag depths and longer sag durations, the compressor current usually reaches its locked rotor current value. This represents the stalling condition for the compressor, as shown in Figure 53(b). For sag depths greater than 50% and duration greater than 10 cycles, the compressor under experimentation, stalls.

During the post-sag recovery period, different sag depths show different patterns. For sag depths of 50% and more, the compressor drives about three times the normal operating current and sustains for 2-5 cycles. The voltage may drop at this moment substantially, and the motor is switched off by thermal protection.

1) Effect of sag depth and duration on motor recovery current

Figure 54 shows a graph between motor recovery current (p.u.) and sag duration with sag depth being constant. Five different sag depths are considered.

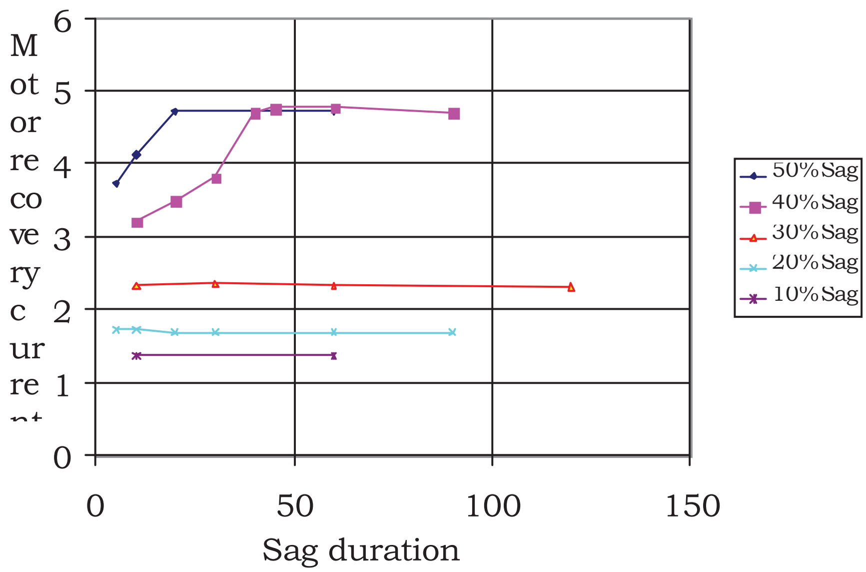


Figure 54. Effects of voltage sag depth and duration on motor recovery current

In the figure the legend represents voltage drop. When sag depth is less than 30%, the motor does not stall. If the motor does not stall, the motor recovery current is influenced by sag depth, not sag duration. The deeper the sag depth, the larger the recovery current. From the figure, the recovery current is 2.4 p.u. for sags of 30% depth. When sag depth is more than 40%, the motor may stall. If the motor stalls, the motor recovery current will be affected by neither the sag depth nor duration. The overcurrent is 4.7 p.u. Under the condition when the motor does not stall, the recovery current will increase when the sag depth or sag duration increases.

2) Effect of sag initiation phase on motor recovery current

Figure 55 shows the impact of sag initiation phase on the compressor recovery current.

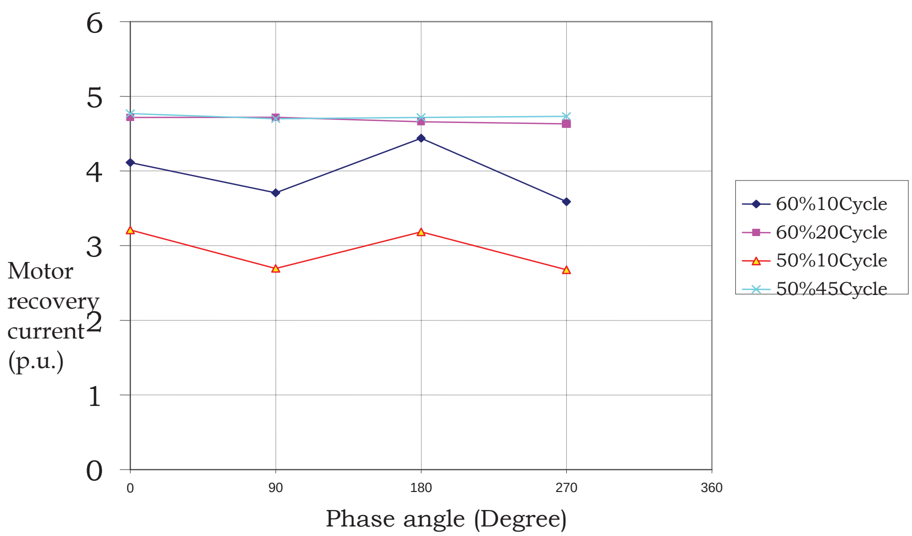


Figure 55. Impact of sag initiation phase on the motor recovery current

Motor recovery current is not affected by sag initiation phase under the situation that the motor stalls. If the motor does not stall, its recovery current resulted from the sags of 0 and 180 degree initiation phase is larger than that of 90 and 270-degree initiation phase. Table 8 summarizes the various possibilities of stalling and non-stalling under different sag depths and duration for air conditioner A.

Table 8. Results of stalling conditions for different sag depths and duration for Compressor A

	50%	60%	70%	80%	90%
5Cycle	N	N	N	N	N
10Cycles	N	N	N	N	N
20Cycles	Y	N	N	N	N
30Cycle	Y	N	N	N	N
40cycle	Y	Y	N	N	N
60cyle	Y	Y	N	N	N

5.3.3 Air Conditioner B tests

The starting current of the cooler is measured before subjected to voltage sag experiments. The starting current waveform is shown in Figure 56.

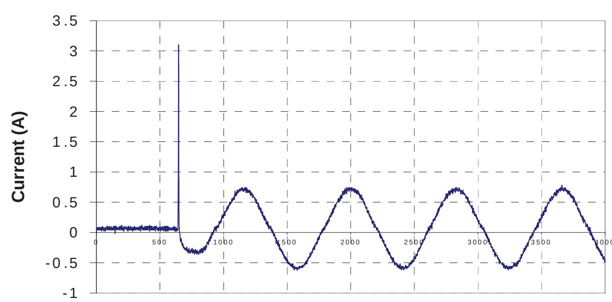


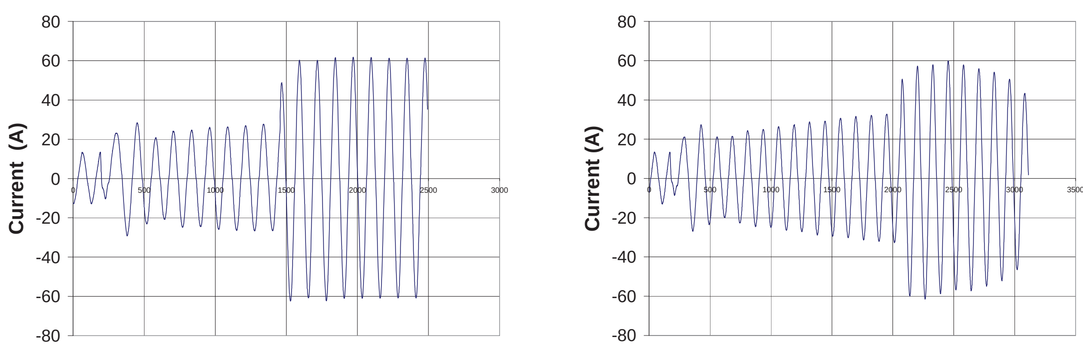
Figure 56. Starting current waveform for air conditioner B

The compressor of Air Conditioner B has similar observations as the compressor of Air Conditioner B. For 90% sag depth, there is no decrease in the speed of the air conditioner compressor for all the sag durations. For 80% sag depth, there is no decrease in the speed of the compressor for sag durations of 5, 10 and 20 cycles. However, for sag duration of 30 cycles, there is a slight decrease in speed. The reduction in speed increases with the sag duration. For sag durations greater than 40 cycles, the reduction in speed is accompanied by a noticeable noise.

In the case of 70% sag depth there is speed reduction in the compressor from sag duration of 5 cycles onwards. The decrease in speed increases as the sag duration increases. For sag durations greater than 20 cycles, the reduction in speed is accompanied by significant noise. The compressor stalls at sag duration of 60 cycles.

In the case of 60% sag depth, the speed decreases significantly accompanied by significant noise for sag durations of 5, 10, 20, 30 and 40 cycles. The reduction in speed is drastic for sag durations of 60 cycles. As a result, the compressor stalls for sag durations of 60 cycles. For sag depth of 50%, the compressor stalls for sag durations greater than 10 cycles.

The waveforms for 60% sag depth and 20-cycle duration, and of 50% sag depth and 10-cycle duration for Air Conditioner B are shown in Figure 57. The waveforms are plotted between motor recovery current and sag duration for different sag depths.



a) 50%/10-cycle, Stall   b) 60%/20-cycle, No Stall

Figure 57. Test results for Air Conditioner B for different voltage sag depths and durations

Figure 57(a) represents the stalling condition of Compressor B for sag depth of 50% and sag duration of 10 cycles. As explained for Compressor A, in this case the current reaches its locked rotor current value at the beginning of the post-sag period and hence the motor is switched off by thermal protection. In the case of 60% sag depth and 20-cycle duration, the current returns to its normal value during the post-sag period and hence, it does not stall.

Table 9 summarizes the various possibilities of stalling and non-stalling under different sag depths and duration for air conditioner B.

Table 9. Results of stalling conditions for different sag depths and duration for Compressor B

	50%	60%	70%	80%	90%
5cycles	N	N	N	N	N
10cycles	Y	N	N	N	N
20cycles	Y	N	N	N	N
30cycle	Y	N	N	N	N
40cycle	Y	Y	N	N	N
60cyles	Y	Y	N	N	N

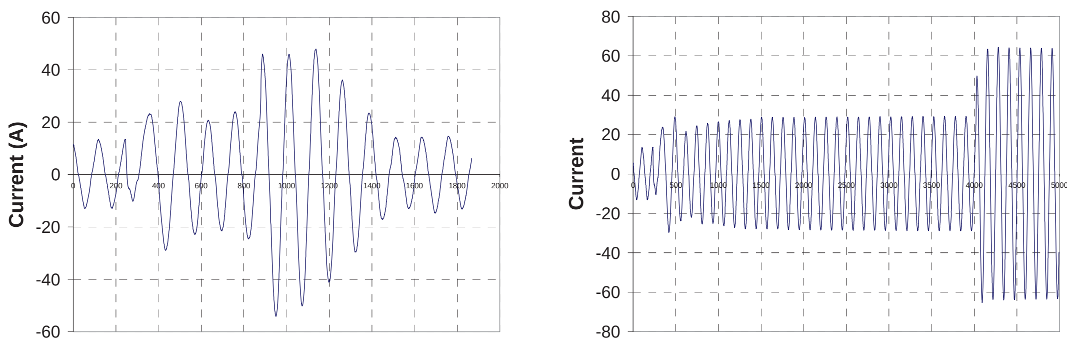
5.3.4 Air Conditioner C tests

For 90% sag depth, there is no decrease in the speed of the air conditioner compressor for all the sag durations. For 80% sag depth, there is a slight decrease in the speed of the compressor for sag durations of 5, 10 and 20 cycles. However, from sag duration of 30 cycles onwards, the reduction in speed is accompanied by a noticeable noise. The reduction in speed increases with the sag duration.

In the case of 70% sag depth there is speed reduction in the compressor from sag duration of 5 cycles onwards. The decrease in speed increases as the sag duration increases. For sag durations greater than 20 cycles, the reduction in speed is accompanied by significant noise. There is a drastic decrease in the speed of the compressor at 60-cycle sag duration. However, the compressor does not stall and rides through the sag.

In the case of 60% sag depth, the speed decreases significantly accompanied by significant noise for sag durations of 5, 10, 20, 30 and 40 cycles. The reduction in speed is drastic for sag durations of 60 cycles. As a result, the compressor stalls for sag durations of 60 cycles. For sag depth of 50%, the compressor stalls for sag durations greater than 10 cycles.

The waveforms for 50% sag depth and 5-cycle duration and 50% sag depth and 30-cycle duration for Air Conditioner C are shown in Figure 58, representing the non-stalling and stalling condition of the compressor respectively.



a) 50%/5-cycle, No Stall

b) 50%/30-cycle, Stall

Figure 58. Test results for Air Conditioner B for different voltage sag depths and durations

Table 10 summarizes the various possibilities of stalling and non-stalling under different sag depths and duration for Air Conditioner C.

Table 10. Results of stalling conditions for different sag depths and duration for compressor C

	50%	60%	70%	80%	90%
5Cycle	N	N	N	N	N
10Cycles	Y	N	N	N	N
20Cycles	Y	N	N	N	N
30Cycle	Y	N	N	N	N
40cycle	Y	N	N	N	N
60cyle	Y	Y	N	N	N

5.3.5 Conclusions from air conditioner tests

Experimental results reveal that the air conditioner compressors are affected by sags. However, the compressors do not get damaged and once the sag is over, the air conditioners can be switched on manually.

During the period of voltage sag, the speed of air conditioning motors decreases and consequently causes an increase of motor current. The motor current can rise to as high as 2.3 p.u. at the beginning of the post-sag period. If motors stall, they will draw more current when restarting after applied voltage recovers. Because of sustained large restarting current (as high as 4.5 p.u., more than 10 cycles), the motor may be switched off by thermal protection.

For Air Conditioners A and B, the motor stalls for sag depth 60% and durations 40 and 60 cycles, and for sag depth of 50% and durations of 10 cycles or more. For Air Conditioner C, the motor stalls for sag depth of 60% and duration.

The results also show that the initiation phase of the voltage sag does not have an obvious effect on the performance of the motor. Combining the results of the three air conditioner compressors, a tabulated summary of the performance of air conditioner compressors on being subjected to sags of various depths and durations is presented in Table 11.

Table 11. Tabulated summary of the performance of air conditioner compressors due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	**Observations**
90%		N	N	N	N	N	N	No noticeable decrease in speed, compressor current
80%		N	N	N	N	N	N	Slight decrease in speed & compressor current
70%		N	N	N	N	N	Y	Slight decrease in speed & compressor current. Stalls at 60 ~
60%		N	N	N	N	Y	Y	Motor stalls for duration above 30 cycles.
50%		N	N	Y	Y	Y	Y	Drastic reduction in speed, stalls above 10 cycles

5.4 Experiments on Lighting Loads

Experiments were done on two of the most common categories of lightning loads: fluorescent lamps and helium lamps. The lamps are subjected to sags of depths varying from 90% to 50% and duration ranging from 5 cycles to 60 cycles. To study the effect of phase shift, the starting point of the sag has also been varied.

5.4.1 Lamps tested

The specifications of the lamps tested are:

Fluorescent Lamp A

- Manufacturer A SP35 32W Canada
- 110VAC/32Watt
- Regular size (4 feet) fluorescent lamp
- RMS value of operation current is 0.33A. (see Figure 59)

Fluorescent Lamp B

- Manufacturer B F32T8 USA
- 110VAC/32Watt
- Regular size (4 feet) fluorescent lamp

Helium Lamp:

- 120VAC, 750 Watts
- Measured operation current: 6.19A

5.4.2 Fluorescent Lamp A tests

Figure 59 shows the current signal of the fluorescent lamp under test. The RMS value of the operation current can be seen to 0.33A from the figure.

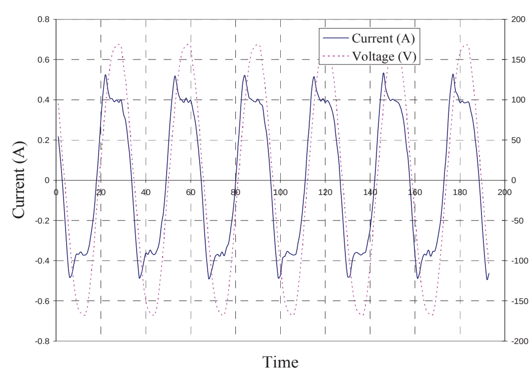


Figure 59. Current signal of the tested fluorescent lamp

In the case of 90% sag depth, there is no perceptible dimness in the light for all sag durations. The fluctuation in the lamp's light is noticeable for 80% sag depth. The reduction in the light of the lamp is significant as the sag duration increases. Once the sag is over, the lamp current recovers and returns to its normal value. Similar observations are made for sag depths of 70% and 60%. In the case of 50%, lamps switch off for sag durations of 30 cycles or more. Figure 60 shows the response of the lamp current for 50% sag depth and 10-cycle duration.

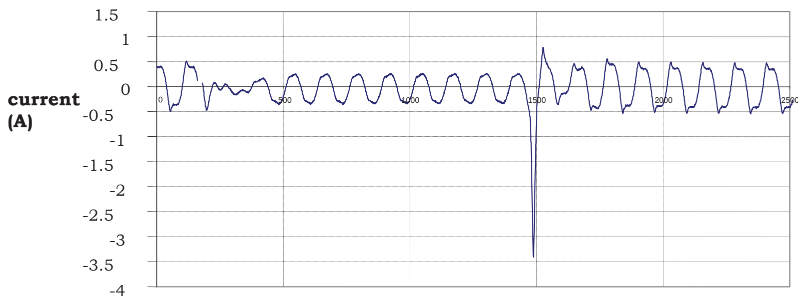
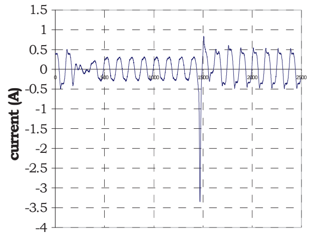


Figure 60. Typical responding current signal for florescent lamp (40% depth, 10 cycles)

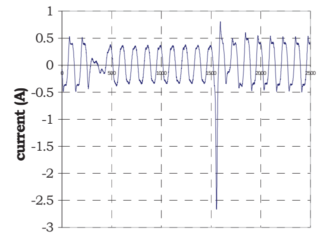
It is observed there is a short period of zero current at the start of voltage sag (about 2 cycles). Subsequently, current increases and becomes proportional to the magnitude of applied voltage. When applied voltage recovers, a current spike occurs and then current returns to normal operation current. During the current spike the light intensity increases sharply.

Effect of sag depth on lamp current:

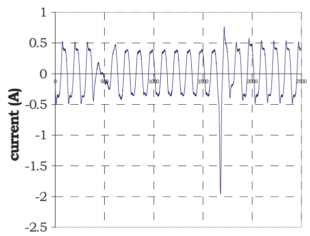
Figure 61 shows the response of lamp currents for different sag depths and fixed sag duration of 10 cycles.



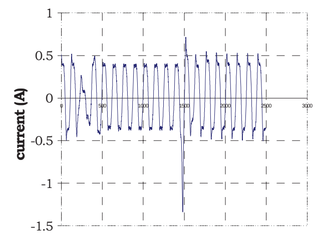
a) 40% sag depth



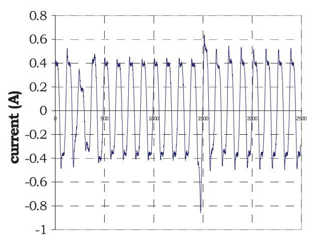
b) 50% sag depth



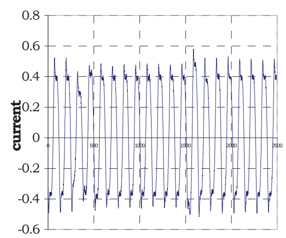
c) 60% sag depth



d) 70% sag depth



e) 80% sag depth



f) 90% sag depth

Figure 61. Current responses to different sags depths for sag duration 10 cycles

As can be seen in the figure above, the value of the current spike increases with the increase in sag depth. In the case of 90% depth, there is no current spike. However, with the increase in sag depth, the value of the current spike becomes significant. Table 12 provides the values of current spikes for different sag depths.

Table 12. Values of current spikes for different sag depths for Fluorescent Lamp A

Sag Depth (%)	Current Spike value (in Amperes)
90	Nil
80	0.85A in negative cycle
70	1.4A in negative cycle
60	1.95A in negative cycle
50	2.6A in negative cycle

Figure 62 shows the relationship between lamp current for different sag depths and fixed sag duration of 10 cycles. It shows that the sag depth is proportional to lamp current.

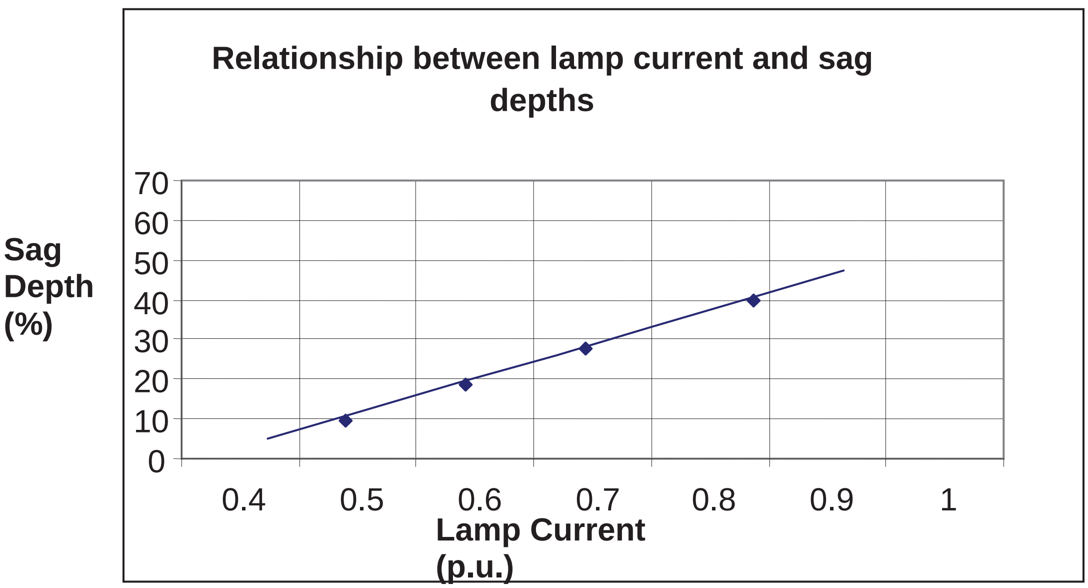
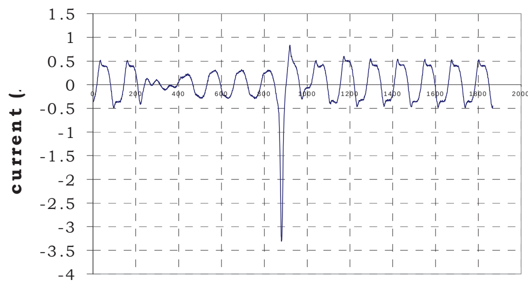


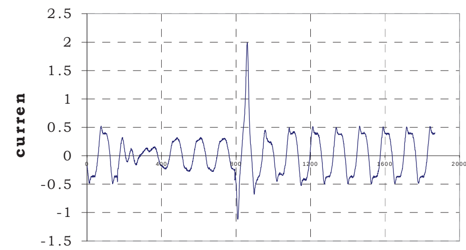
Figure 62. Relationship between lamp current and sag depths (duration: 10 cycles)

Effects of sag initiation phase on lamp current

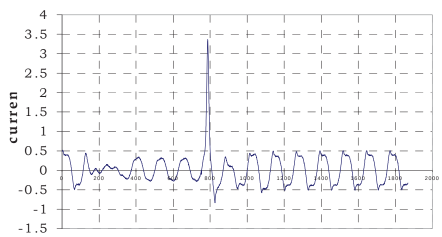
Figure 63 shows waveforms of lamp currents for different sag initiation phases for a fixed sag depth of 40% and duration of 5 cycles.



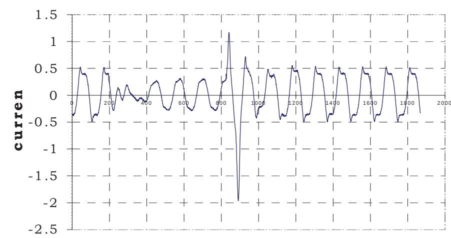
a) 0 ˚



b) 90˚



c) 180˚



d) 270˚

Figure 63. Effect of sag initiation phase on lamp current (40%, 5 cycle duration)

It can be concluded from the figure that for phase angles of 0˚ and 270˚, a negative current overshoot occurs at the end of voltage sag. However, for phase angles of 90˚ and 180˚, a positive current overshoot occurs at the end of the voltage sag.

5.4.3 Florescent Lamp B tests

For 90% sag depth, there is no perceptible dimness in the light for all sag durations. The fluctuation of the lamp output is noticeable for 80% sag depth. The dimness of the light of the lamp increases as the sag duration increases. During the post-sag period, the lamp current recovers and returns to its normal value. Similar observations are made for sag depths of 70%. For sag depth of 60%, there is drastic reduction in the intensity of light. As a result for sag durations of 20 cycles or more, the lamps switch off. In the case of 50%, lamps switch off for sag durations of 10 cycles or more. The lamps need to be switched on manually, once the sag is over.

Figure 64 shows the current response of the lamp for manufacturer B. The waveform is similar to the one obtained for manufacturer A. As explained previously for Lamp A, there is a short period of zero current at the start of voltage sag for about 2 cycles. Subsequently, current increases and becomes proportional to the magnitude of applied voltage. When applied voltage recovers, a current spike occurs due to which the light intensity increases sharply. Finally the current returns to its normal operation value.

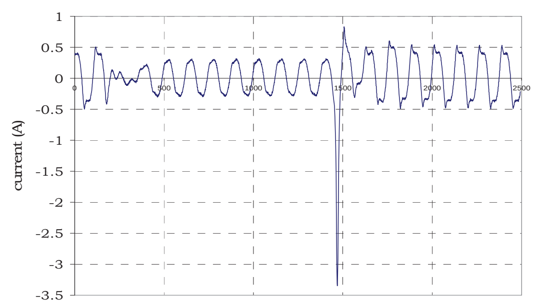


Figure 64. Lamp current response for the fluorescent lamp

5.4.4 Conclusions from fluorescent lamp tests

The fluorescent lamps have been tested for voltage sags varying from 90% to 50% and sag duration of 5-60 cycles. During the sag period, there is reduction in the intensity of light. The duration of voltage sag does not affect fluorescent lamp's light output. The output is dependent on sag depth. The responding current of the fluorescent lamps is inversely proportional to sag depth. The end of the sag is marked by a current spike. The spike is assumed to be caused by the inductance of the ballast. This may reduce the life of the lamp. For the same sag depth and duration, sag initiation phase does not affect the brightness of the lamp. The results show that there is no obvious effect on the performance of lamps from different manufactures of on being subjected to voltage sags.

5.4.5 Helium lamp tests

The operation current waveform for the helium lamp is shown in Figure 65.

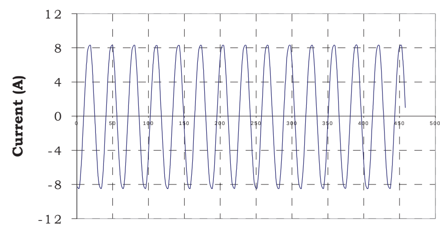


Figure 65. Helium lamp operation current waveform

The performance of helium lamps on being subjected to voltage sags is similar to the performance of fluorescent lamps. In the case of 90% sag depth, unlike fluorescent lamps, there is flickering in the lamp for all sag durations. The dimness in the light of the lamp is significant as the sag duration increases. Once the sag is over, the lamp current recovers and returns to its normal value. Similar observations are made for sag depths of 80% and 70%.

For 60% sag depth, for sag durations until 20 cycles, there is little dimness in the intensity of the lamp. However, for 30-cycle duration and onwards, the dimness increases significantly. Moreover, once the sag is over, the recovery is marked by a sharp increase in the intensity of the light. However, the helium lamps do not blow off. Similar observations are found in the case of 50%.

Figure 66 shows the current response of the lamp being tested. The test was done for 50% sag depth and 10 cycle duration. As can be seen from the figure, during the sag period the current is proportional to the sag voltage as the load is resistive. Once the sag is over, the current returns to its normal value without a current spike.

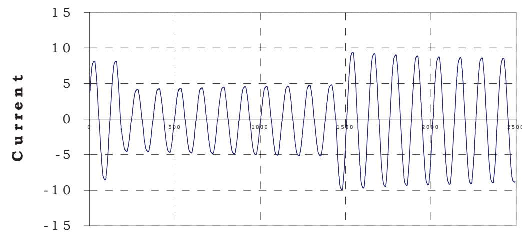


Figure 66. Typical responding current signal for helium lamp (50% depth, 10 cycles)

5.4.6 Conclusions from helium lamp tests

A helium lamp was tested under voltage sags of 50-90% depth and 5-60 cycle duration. The result shows that voltage sags do not cause helium lamp to go out. The intensity of light reduces during the sag period. Sag duration does not affect the performance of helium lamp. The reduction in the intensity caused by voltage sag is due to the sag depth. For the same the sag depth and duration, sag initiation phase does not affect the brightness of the lamp.

Combining the fluorescent and helium lighting loads, a tabulated summary of the performance of lighting loads on being subjected to voltage sags is being presented in Table 13.

Table 13. Tabulated summary of the performance of lighting loads due to voltage sags

Depth	Duration						
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	↓ Increase in dimness as depth increases. Recovers with sharp increase in intensity. For greater sag depths (~50%), the lamps are blown off while recovering in the case of fluorescent lamps. Helium lamps do not get blown off.
80%		N	N	N	N	N	N	
70%		N	N	N	N	N	N	
60%		N	N	Y	Y	Y	Y	
50%		N	Y	Y	Y	Y	Y	
40%		N	Y	Y	Y	Y	Y	

5.5 Experiments on Sensitive Equipment

Sensitive equipment have gained prominence in sag studies as they involve complex circuitry. Hence, experiments on sensitive equipment form the core of the experiments performed to study the effect of voltage sags. The sensitive equipment that have been tested are computers, microwave ovens, televisions, VHSs and DVDs, compact discs, radio alarm clocks, sandwich makers and toasters. The subsequent sections explain in detail the performance of these equipment on being subjected to voltage sags.

5.5.1 Experiments on computers

Voltage sag is normally not a significant problem to single computers unless they are used as servers or mainframe computers. In such cases it is relatively easy to protect them, for a minor cost, by using backup power supply. The problem is not very significant to ordinary single PCs since the lost work not often exceeds 1-2 hours work and often there is a backup or automatic restore of the file. However, there are some PC-based offices where a disruption will cost greatly. Financial trading and telecommunication offices are typical examples.

Two different computers are tested to study the effect of voltage sag on the performance of computers. The specifications of them are shown in Table 14. The experiment results show that the impact of voltage sag is similar with different computers.

Table 14. Specification of the tested computers

	Computer A	Computer B
	Dell Optiplex	*Genuine Intel*
CPU	Pentium3	Pentium2
RAM	328M	32M
Hard Disk	15G	3G
Monitor	Dell 17'	Optiquest 17'
CD-R	CD-R	CD-R
Operating system	Windows 2000	Windows 98

Figure 67 shows the current signal when the computer is running. Its RMS value is 58mA. The current of the monitor is not included. Except for specific clarification, all the results shown in the following are from Computer A unless it is noted specifically.

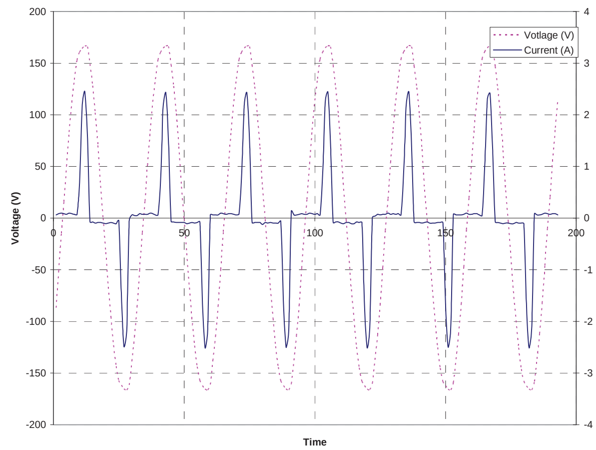


Figure 67. Current signal of power supply when the computer is running

It is discovered that under a certain voltage sag with given depth and duration, the restarting of the computer has an impact on data loading from hard disk. Hence, the impact of voltage sag is investigated under both situations:

1. When the hard disk is loading data
2. When the hard disk is not loading data.

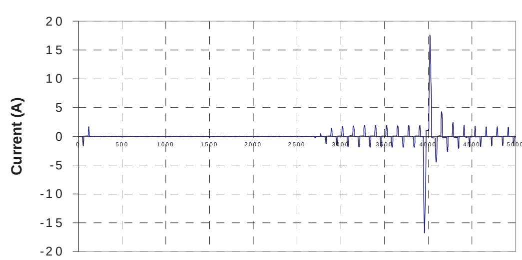


Figure 68. Responding current of computer power supply during voltage sag period for 50% depth and 30-cycle duration, computer restarts

Figure 68 shows the current of computer power supply for a sag depth of 50% and 30-cycle sag duration. This is the case when the computer is loading data from the hard disk. The restart of the computer is marked by high current surges of the order of 7-10 times the normal current, which also indicates the end of sag. Tables 15 and 16 show the impact of voltage sag on the performance of Computer A and Computer B.

Table 15. Effect of voltage sag on the restarting of Computer A

Depth (%)	Cycles	Normal/Loading	Ok/Restart
40	<=15	Normal	ok
	>=16	Normal	restart
	<=7	Loading	ok
	>=8	Loading	restart
50	<15	Normal	ok
	>=16	Normal	restart
	<7	Loading	ok
	>=8	Loading	restart
60	<120	Normal	ok
	<=15	Loading	ok
	>=18	Loading	restart
70	<120	Normal	ok

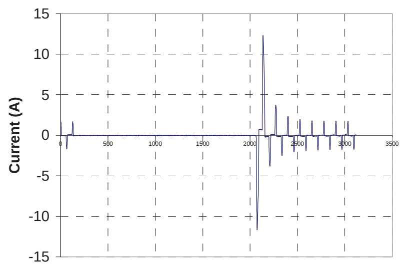
Table 16. Effect of voltage sag on the restarting of Computer B

Depth(%)	Cycles	Normal/Loading	Ok/Restart
40	<18	Normal	ok
	>=18	Normal	restart
	<10	Loading	ok
	>=10	Loading	restart
50	<18	Normal	ok
	>=18	Normal	restart
	<10	Loading	ok
	>=10	Loading	restart
60	<120	Normal	ok
		Loading	ok
70	<120	Normal	ok
		Loading	ok
80	<120	Normal	ok
		Loading	ok

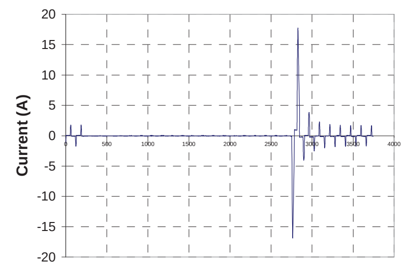
From table 14, for sag of depth 40% and duration of 15 cycles or less, and when hard disk is not loading data, there is no effect on Computer A. However, for sag of depth 50%, duration of 8 cycles or more and when hard disk is loading data, Computer A restarts.

5.5.1.1 Effect of sag depth and duration on computers

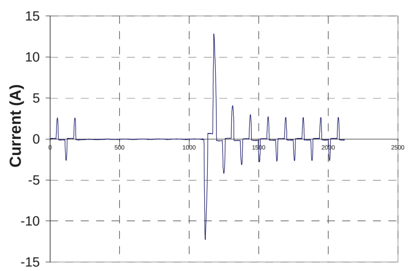
The waveforms for different sag depth/duration for Computer A are shown in Figure 69.



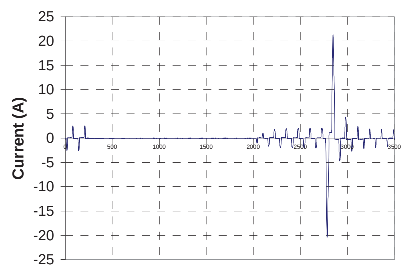
a) 60%/15Cycle/0˚, (No load/OK)



b) 60%/20Cycle/0˚ (No load/Restart)



c) 60%/7Cycle/0˚ (load/OK)



d) 60%/20Cycle/0˚, (load/Restart)

Figure 69. Current waveforms for 60% sag depth

The figures show all four possible combinations of current waveforms such as :

1. Hard disk is not loading data, no effect of sag on computer restarting, Figure 69(a).
2. Hard disk is not loading data, computer restarts, Figure 69(b).
3. Hard disk is loading data, no effect of sag on computer restarting, Figure 69(c).
4. Hard disk is loading data, computer restarts, Figure 69(d).

In the case of hard disk not loading data, it is observed that the value of current spike signifying the end of the sag is greater for cases in which the computer restarts. The value of spike is 17A when the computer restarts as against 13A when there is no effect of sag on the computer. Similar observations hold true for the case when the hard disk is loading data. In this case, the value of spike is 21A when the computer restarts as against 13A when there is no effect of sag on the computer.

5.5.1.2 Effect of sag initiation phase

The effect of sag initiation phase on the computers is also investigated. The results show that sag starting point affects the overcurrent. However, for the same depth and duration, sag phase causes no difference on the performance of the computer.

5.5.1.3 Conclusions from Computer tests

- Voltage sags can cause computers to restart and lose data. Voltage sags have more severe effect on computer's restarting if the computer power supply is driving more devices such as hard disk, CD-R, etc.
- If the depth of voltage sag is larger than 30% and duration is longer than 8 cycles, voltage sag may cause a computer to start.
- If the sag duration is shorter than 7 cycles, voltage sags do not cause the restart of a computer and the loss of data.
- Sag initiation phase does not affect the restarting of computers.
- The performance (specification) of the switching power unit and the power consumption of a computer plays very important role on the sag effect.

5.5.2 Experiments on microwave ovens

Microwave ovens are a common sight in every household in United States. They are regarded as sensitive equipment as they involve complex electronic circuitry. To study the effect of voltage sags on microwave ovens, two microwave ovens of different manufacturers were tested. These ovens are subjected to sags of depths varying from 90% to 50% and duration ranging from 5 cycles to 60 cycles.

5.5.2.1 Microwaves tested

The specifications of the microwave ovens tested are

1. Microwave Oven A (Manufacturer A)
    - Supply Voltage - 120VAC
    - Frequency – 2450MHz
    - Rated Current – 0.8A
2. Microwave Oven B (Manufacturer B)
    - Supply Voltage - 120VAC
    - Frequency – 2450MHz
    - Rated Current – 0.8A

In microwave ovens, the visible effect of sags is on the light inside the oven and the digital clock of the oven. Voltage sags may cause the flickering of light inside the oven and cause the digital clock to stop momentarily, depending on the sag depth and duration. The intensity of the flickering increases with the increase in sag depth and duration. Apart from the visible effect of sags on microwave ovens, sags can cause the ovens to stop functioning with or without damaging the ovens.

5.5.2.2 Microwave Oven A tests

For 90% sag depth, there are only visible effects of sags on the oven. In the case of 5 cycles and 10 cycles sag duration, the light inside the oven flickers and restores back immediately. The digital clock has no effect of sag for these durations. From 20 cycles onwards, the light inside the oven takes time to return back to its normal intensity after flickering. For 50 cycles and 60 cycles, the flickering occurs for at least 2-3 seconds before it recovers. The digital clock also stops for 2-3 seconds during 50 cycles and 60 cycles respectively.

Similar observations are made in the case of 80% and 70% sag depths. However, the intensity of the flickering inside the oven is more as compared to that at 90% sag depth. For sag duration of 50 cycles and 60 cycles, there is almost total darkness inside the oven for 2-3 seconds after which it returns to normal. The digital clock also stops for that period.

In the case of 60% sag depth, the flickering occurs for around 2-3 seconds for sag duration of 10 cycles and 20 cycles. This type of flickering of 2-3 seconds occurred for sags of depth 90%, 80% and 70%, and durations of 50 and 60 cycles. This suggests that the effect of 60% sag depth is relatively severe since for less sag duration, it is showing flickering for 2-3 seconds. As the duration is increased to 30 cycles, the microwave oven automatically switches off without damaging the oven. On further increasing the duration to 120 cycles, the same observation is made; that is, the microwave oven switches off without damaging the appliance.

In the case of 50% sag depth, almost similar observations are noticed. However, the microwave oven switches off for sag durations greater than 10 cycles without getting damaged. This can be seen in Figures 70 and 71 respectively.

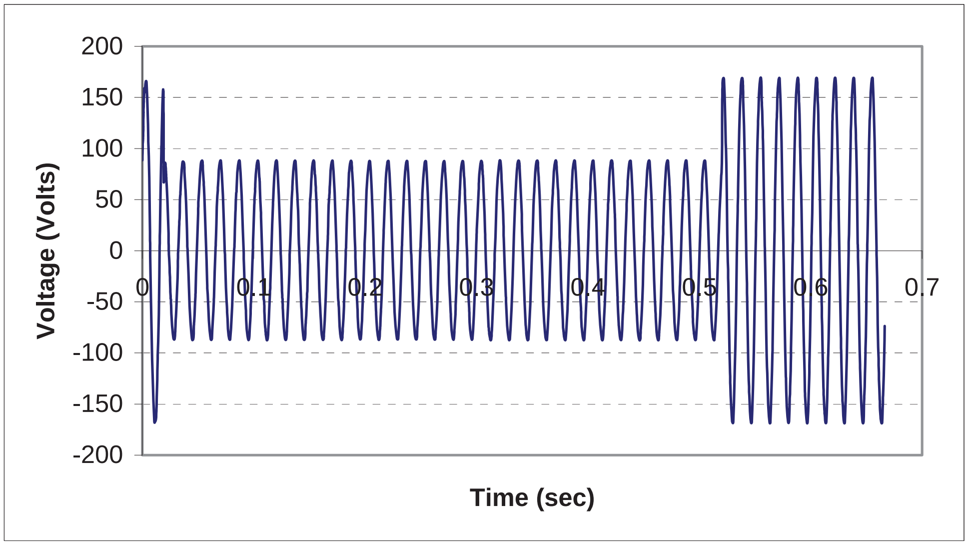


Figure 70. Waveform representing voltage sag of 50% depth and 30 cycles duration

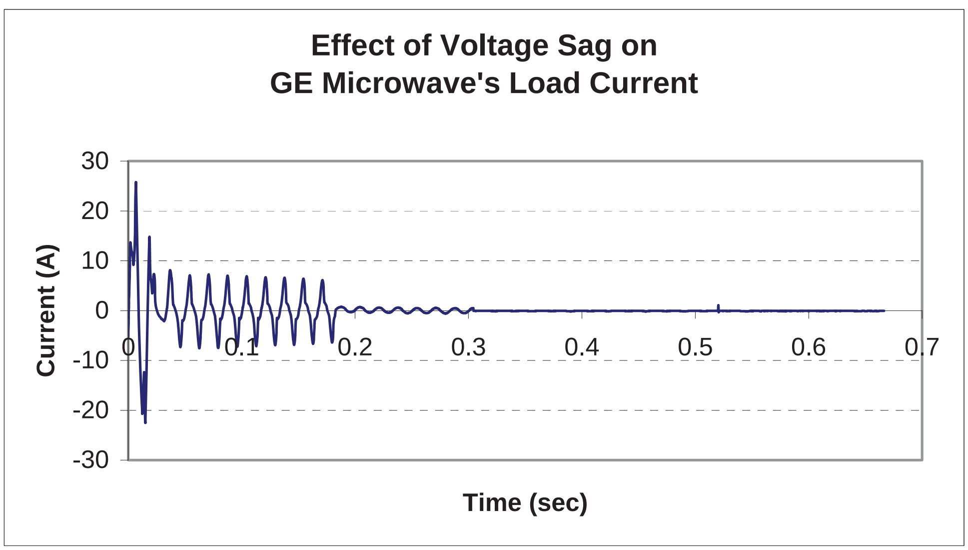


Figure 71. Load current for 50% sag depth and 30-cycle sag duration

Figure 70 shows the voltage waveform for sag of depth 50% and duration 30 cycles. Figure 71 shows the corresponding phase current for the microwave oven. When the sag occurs, the current decreases, representing the flickering inside the oven. After few cycles, the current goes to zero signifying that the microwave oven has switched off without getting damaged.

5.5.2.3 Conclusions of Microwave A tests

It is seen that for sags of depth 90%, 80% and 70%, there are only visible effects of sags. As the sag duration is increased to 50 cycles and more, the effects become more pronounced such as almost complete darkness inside the oven for 2-3 seconds and stopping of the digital clock during that period. The microwave oven switches off for sag depths of 60% and sag duration of 30 cycles and more, and for sag depth of 50% and sag duration of 10 cycles and more.

5.5.2.4 Microwave Oven B tests

Similar to the observations for Microwave Oven A, the Microwave Oven B also shows visible effects on subjected to sags of depths 90%, 80% and 70% respectively.

In the case of 90% sag depth, there is no noticeable flicker inside the oven for sag duration of 5 cycles. For sag duration of 10 cycles and 20 cycles, the flicker occurs and recovers immediately. For 30-cycle and 40-cycle sag durations, the flicker occurs for a second before returning to normal intensity. The digital clock also flickers for that period although it does not stop. For sag durations of 50 cycles and 60 cycles, the flicker increases to about 2-3 seconds and the digital clock also stops during that period.

Similar observations are made in the case of 80% and 70% sag depths. However, the intensity of the flickering inside the oven is more as compared to that at 90% sag depth. For sag duration of 50 cycles and 60 cycles, there is almost total darkness inside the oven for 2-3 seconds after which it returns to normal. The digital clock also stops for that period.

For 60% and 50% sag depths, the visible effects become more pronounced. The flickering inside the oven occurs for 1-2 seconds for sags of duration 10 cycles, 20 cycles, and 30 cycles. For sag duration of 50 cycles and more, there is darkness inside the oven for 5-6 seconds suggesting that the oven will switch off automatically; however, it does not happen and the oven rides through the sag easily. The digital clock also stops during that period and recovers once the sag is over. This can be seen in Figure 72. During the sag period, the current decreases signifying the flickering occurring inside the oven. The end of the sag period is marked by a surge current. The current returns to its normal during the post-sag period indicating that the oven rode through the sag.

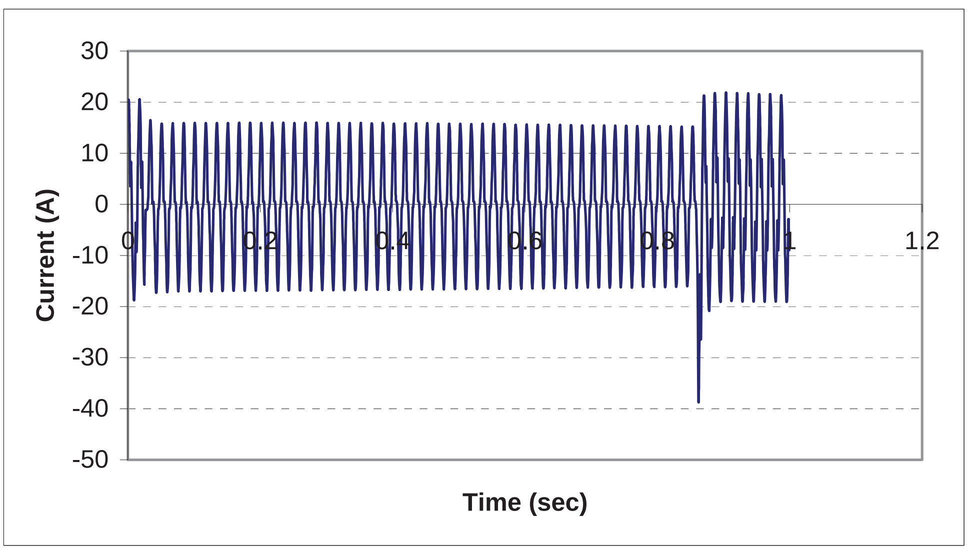


Figure 72. Current waveform for 50% and 50-cycle sag

5.5.2.5 Conclusions from Microwave B tests

For sag depths of 60% and 50% and duration greater than 50 cycles and 30 cycles respectively, the effect of sag is severe and the oven manages to ride through the sag. However, intuitively, if the oven is subjected to repeated sags of same 60% depth and duration greater than 50 cycles, the oven might switch off automatically. For sag depths of 90%, 80%, and 70%, there are only visible effect of sags and the oven functions well.

5.5.2.6 Conclusions from Microwave tests

In general, the microwaves can get switched off for sags of depth 60% and 30-cycle duration and 50% and 10-cycles as seen in the experiments. The results will vary depending on the manufacturers and the electrical protection used inside the oven. However, no microwave oven was damaged due to sags of varying depths and durations.

Combining the results of the two microwave ovens, a tabulated summary of the performance of microwave ovens on being subjected to sags of various depths and durations is presented in Table 17.

Table 17. Tabulated summary of the performance of microwave ovens due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	Digital output disappears but recovers almost immediately for 5, 10, 20 cycles. For 50 cycles and 60 cycles, the flickering occurs for at least 2-3 seconds before it recovers. The digital clock also stops for 2-3 seconds during 50 cycles and 60 cycles respectively
80%		N	N	N	N	N	N	Similar observations as above. Intensity of flickering increases. For 50-cycle and 60-cycle duration, there is almost total darkness inside the oven for 2-3 seconds after which it returns to normal. The digital clock also stops for that period
70%		N	N	N	N	N	N	Similar observations as above
60%		N	N	N	Y	Y	Y	Microwave oven switches off automatically for duration of 30 cycles or more
50%		N	Y	Y	Y	Y	Y	Microwave oven switches off automatically for duration of 10 cycles or more

N: Oven does not switch off Y: Oven switches off

5.5.3 Experiments on televisions

Televisions are a common household appliance in every residence in United States. They are susceptible to lightning strikes, and hence, are always surge protected. Voltage sags may cause disturbances in the picture quality of the televisions and, in the worst case scenario, damage the equipment. Hence, to determine the effect of voltage sags on televisions, two televisions of different manufacturers and ratings were tested. These televisions are subjected to sags of depths varying from 90% to 50%, and duration ranging from 5 cycles to 60 cycles.

5.5.3.1 Televisions tested

The specifications of the televisions tested are:

1. Television A (Manufacturer A)
    - Supply Voltage – 120VAC, 60Hz
    - Power – 74 Watts
    - Screen Size – 27 inch
2. Television B (Manufacturer B)
    - Supply Voltage – 120VAC, 60Hz
    - Power – 82 Watts
    - Screen Size – 27 inch

5.5.3.2 27 inch Television A tests

For sag depth of 90% and durations varying from 5 cycles to 60 cycles, there is no effect of sag on the television. No disturbance is seen on the picture during the sag. However, the beginning of the post-sag period is marked by a surge which is almost five times the normal current. This can be seen in Figure 73.

In the case of 80% sag depth, there is no effect on the picture for 5-cycle and 10-cycle duration. However, from 20-cycle duration onwards, a white line appears on the screen due to voltage sag. The width of the line increases with sag duration and covers part of the image on the television. As the duration increases, the image of the television shrinks. Once the sag is over, the original image is restored. There is no other effect on the television.

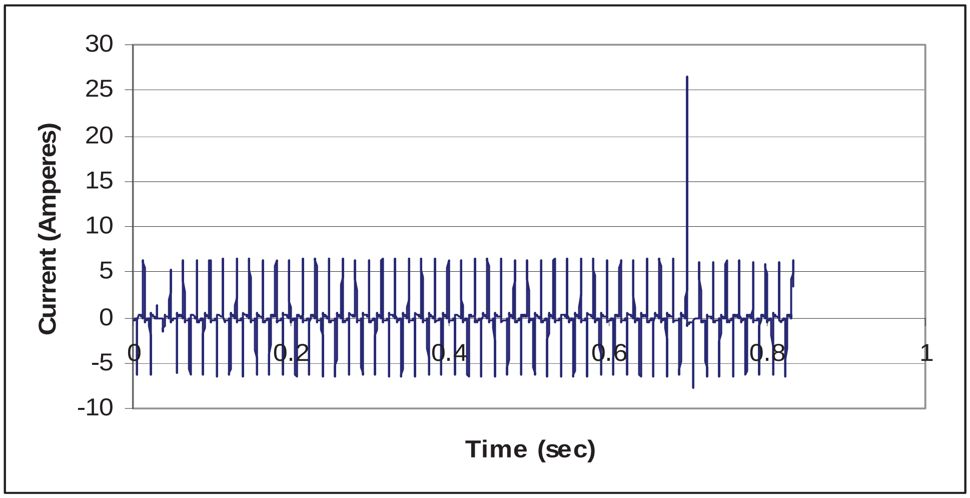


Figure 73. Current waveform for 90%, 40-cycle sag (spike observed at the beginning of post-sag period)

Similar observations are noted for sag depths of 70% and 60%. In all these sag depths, spike is noted at the beginning of the post-sag period. A notable feature of all these current waveforms is that the current momentarily goes to zero at the beginning of the sag. However, there is no effect of this on the performance of the television.

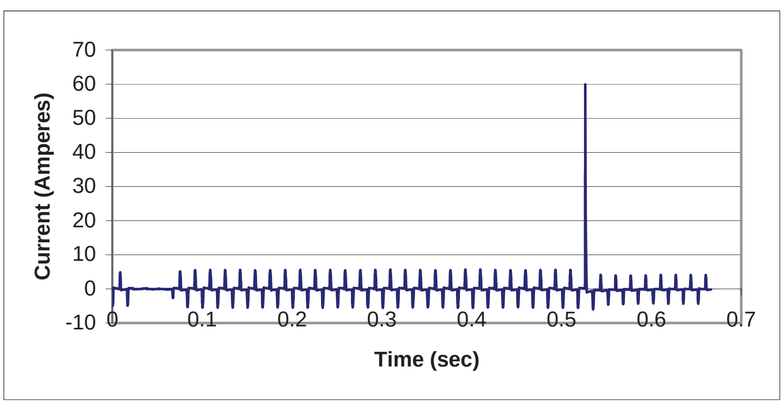


Figure 74. Current waveform for 70%, 30-cycle sag

The observations in the case of 50% sag depth are interesting. For sags of duration 5, 10 and 20 cycles, the only visible effect on the television screen is the occurrence of a white line. The width of the line increases as the sag duration increases until 20 cycles and covers part of the image. In the case of 30 cycles and more, the sag causes the television to turn off. However, once the sag is over the television turns on automatically after few cycles. Figure 75 shows the current waveform for 50% sag depth and 50-cycle duration.

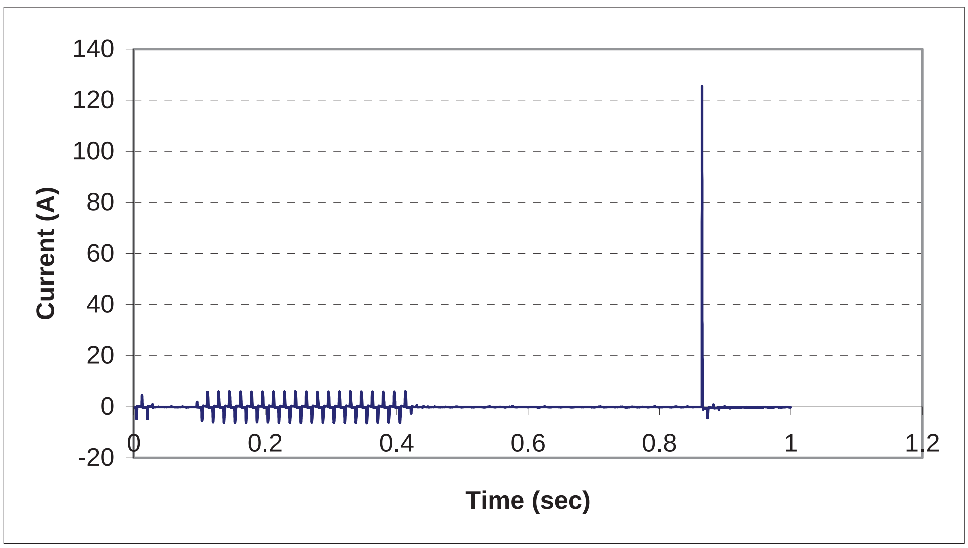


Figure 75. Current waveform for 50%, 50-cycle sag (television turns off)

In the figure, the beginning of sag is marked by the momentary decrease in current to almost zero value for 2-3 cycles. After that the current returns to the normal value. However, after few cycles the current becomes zero and continues like that until the sag is over. This represents the period during which the television switches off. The beginning of the post-sag period is marked by a sharp increase in current. Few cycles after the post-sag period, the television automatically switches on.

5.5.3.3 Conclusions from 27 inch Television A tests

There is only visible effect of sags on the television image for depths of 90%, 80%, 70% and 60%. In all these cases, a white line appears on the image whose width increases with the sag duration. This results in the shrinking of the image on the television screen. The notable conclusion is that the television switches off for sags of depth 50% and duration of 30 cycles and more.

5.5.3.4 27 inch Television B tests

The effect of sag on the 27 inch Television B is similar to that on the Television A. In the case of 90% sag, there is no effect of sag on the operation of the television. No disturbance of the image is observed. However, the beginning of the post-sag period is marked by a sharp increase in current which is of the order of 5-6 times the normal current. Figure 76 shows the current waveform for a 90% depth and 60-cycle duration.

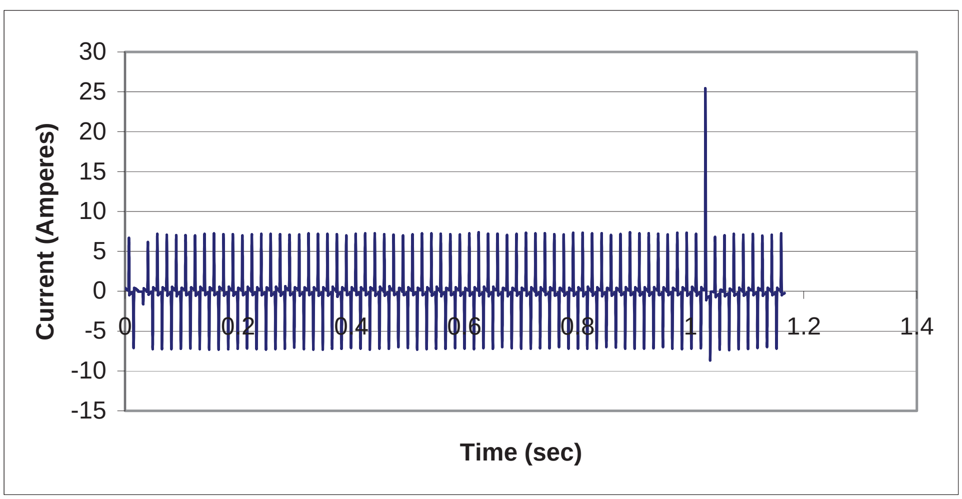


Figure 76. Current waveform for 90%, 60-cycle sag (spike observed at the beginning of post-sag period)

For 80%, 70% and 60% sag depths, there is only visible effect of sag on the television image. In the case of 80% and 70% sag depths, there is no effect of sag for sag durations of 5 cycles and 10 cycles. However, from 20 cycles onwards, a white line appears on the image representing disturbance caused due to voltage sag. The width of the white line increases with sag duration and covers part of the image. In the case of 60% depth, 5-cycle sag duration has no effect on the equipment. The white line appears on the screen from 10-cycle duration onwards.

In the case of 50% sag depth, the white line appears for sag durations of 5 cycles, 10 cycles and 20 cycles. In the 20-cycle sag duration, the width of the white line is pronounced and it almost covers the image on the screen. Simultaneously, the image on the television screen also shrinks. This observation indicates a serious visible effect. From 30 cycles onwards, the television screen switches off and once the sag is over, it turns on automatically. Figure 77 shows the phenomenon of the switching off the television for 50% sag depth and 60-cycle duration. The explanation is similar to the one for television A for 50% sag depth and 50-cycles duration.

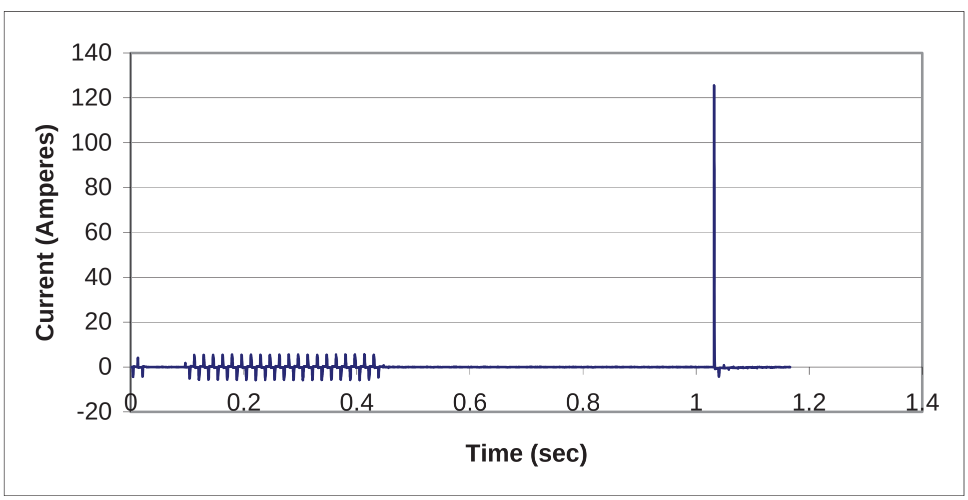


Figure 77. Current waveform for 50%, 60-cycle sag (television turns off)

5.5.3.5 Conclusions from 27 inch Television B tests

The 27 inch television B witnesses only visible sags for sags of depth 80%, 70% and 60%. There is no effect of sag on the equipment for 90% sag depth. In the case of 50% sag depth and duration of 30 cycles or more, the television switches off without being getting damaged.

5.5.3.6 Conclusions from television tests

In general, the televisions can get switched off for sags of depth 50% and 20-cycle duration or more as seen in the experiments. The results will vary depending on the manufacturers and the electrical protection used inside the television. No television was damaged due to sags of varying depths and durations. However, if the frequency of sags is high, the picture tube of the television may have an adverse effect on its performance and might damage the television in the future. Table 18 presents the tabulated results of the effect of voltage sags on the performance of the televisions.

Table 18. Tabulated summary of the performance of televisions due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**	**Observations**
90%		N	N	N	N	N	N	No effect of sag
80%		N	N	N	N	N	N	No effect of sag for 5-cycle and 10-cycle durations. White line appears on the image indicating disturbance. Width of white line increases with duration. Image shrinks but recovers almost immediately once the sag is over
70%		N	N	N	N	N	N	Similar observation as above. Image shrinks much more. Spike is observed at the starting of post-sag period indicating that normal image is restored
60%		N	N	N	N	N	N	Similar observation as above Image shrinks almost completely, darkening the screen and takes time to recover
50%		N	N	N	Y	Y	Y	White line becomes prominent for 5, 10, and 20 cycles indicating severe disturbance. Image shrinks completely and TV switches off automatically, turns on automatically after few cycles of post-sag period

N: Television does not switch off   Y: Television switches off

5.5.4 Experiments on VHS and DVD equipment

The use of VHSs and DVDs is on an increase in household loads, though it is not very common. They are used in tandem with the televisions. They involve complex circuitry and fall in the category of sensitive equipment. The effect of voltage sags on this equipment has not been studied in the past. Hence, to study the effect of sags on DVDs and VHSs, three different VHS/DVD of different manufacturers were tested. These

VHS/DVDs are subjected to sag of depths varying from 90% to 50% and duration ranging from 5 cycles to 120 cycles.

5.5.4.1 VHS/DVDs tested

Their specifications are:

1. VHS DA – 4 Head, (Manufacturer A)
   - 120VAC, 60Hz
   - Power output – 14W
2. VHS/DVD combo B (Manufacturer B)
   - 120VAC, 60Hz
   - Power output – 21W
3. DVD (CH-DVD 300) (Manufacturer C)
   - 100-230VAC, 60Hz
   - Power Output – 27W

The sags can cause two types of effects on the VHS and DVD. The visible effect on the equipment will be the flickering of the electronic timer or, in the worst case scenario, stopping of the timer. The other effect can be the switching off the equipment automatically and returning back to normal operation either manually or automatically. However, the worst effect of sag can be that of damaging the equipment.

5.5.4.2 VHS A (Manufacturer A) tests

Sag of different depths and durations are subjected on the VHS. In the case of 90% sag, there is no effect of sag on the equipment for all durations varying from 5 cycles - 60 cycles. For 80% sag depth, there is no effect of sag for durations of 5, 10 and 20 cycles. However, for sag duration greater than 20 cycles, the sag produces a flicker in the electronic timer. This can be identified as a momentary zero current at the beginning of the sag as shown in Figure 78.

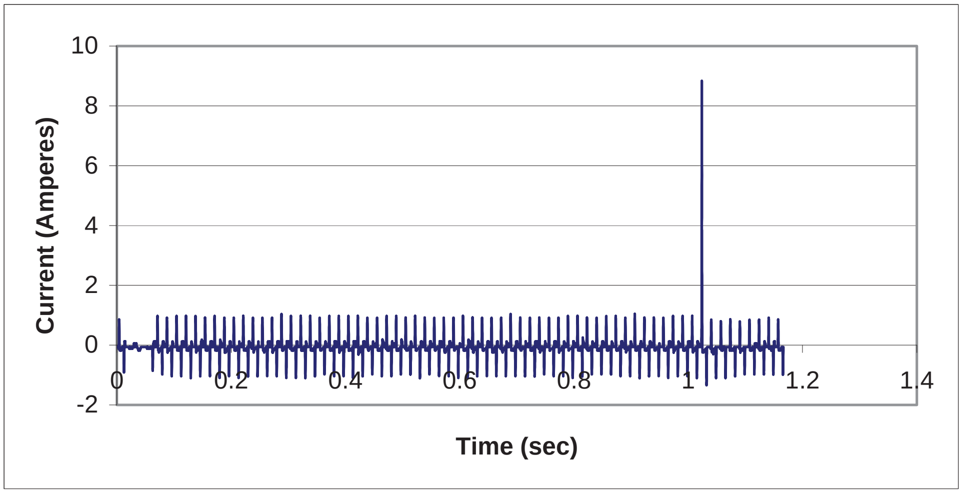


Figure 78. Current waveform for 80%, 60-cycle sag

The same observations are obtained for 70% and 60% sag depths. In the case of 70% sag depth, the flickering is obtained for sag durations greater than 20 cycles. For 60% sag depth, the flickering in the electronic timer is obtained for sag durations greater than 10 cycles. In all these cases, flickering occurs only at the beginning of the sag for few cycles and then for the rest of the sag period there is no flickering.

In the case of 50% sag depth, for sag durations of 5, 10 and 20 cycles, there is flickering in the electronic timer. For durations greater than 20 cycles, it is noticed that the timer clock stops for 2-3 cycles and then resets itself once the sag is over. However, in the current waveforms, there is no representation of the event of stopping of the timer for few cycles. It is also represented as momentary zero current at the beginning of sag similar to that of the flickering event.

In all the current waveforms for various sag depths, there is a current spike signifying the end of the sag period. No visible effect was observed when the spike occurred. However, the magnitude of the current spike is directly proportional to the sag depth. Table 19 gives the approximate current values of the spike for different sag depths.

Table 19. Values for current spikes for different sag depths for VHS A

Sag Depth	Approximate Current Magnitude (Amp)
80%	8-10 times the normal current
70%	12-14 times the normal current
60%	16-18 times the normal current
50%	19-20 times the normal current

As can be seen in Figures 79, 80 and 81, for sag depth of 80%, the current spike is approximately 9 times the normal current value; for sag depth of 60%, the current spike is around 17 times the normal operating current; and in the case of 50% sag, the current spike is approximately 19 times the normal current value.

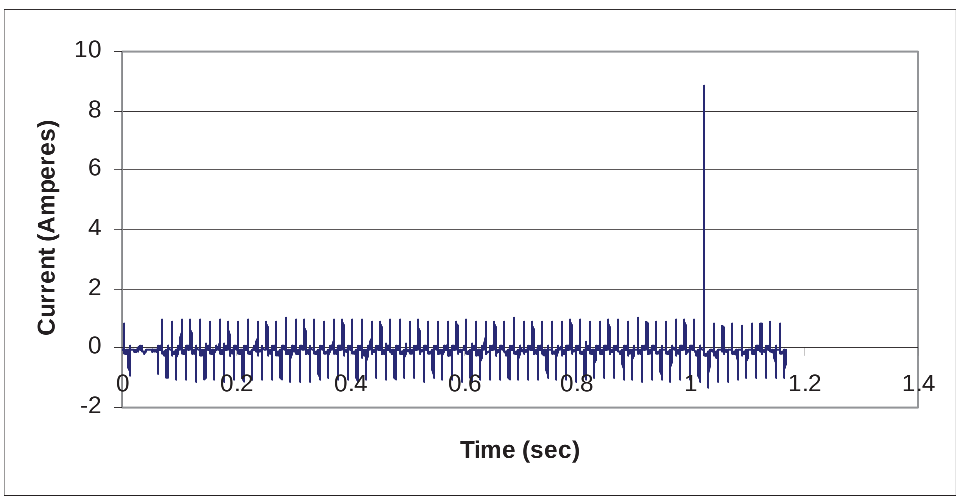


Figure 79. Current waveform for 80%, 60-cycle sag (current spike 9 times the normal)

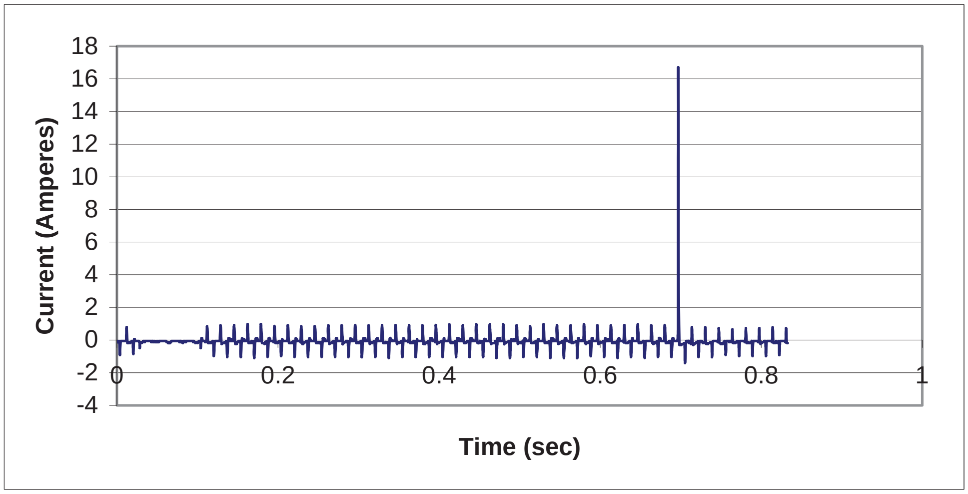


Figure 80 Current waveform for 60%, 40-cycle sag (current spike 17 times the normal)

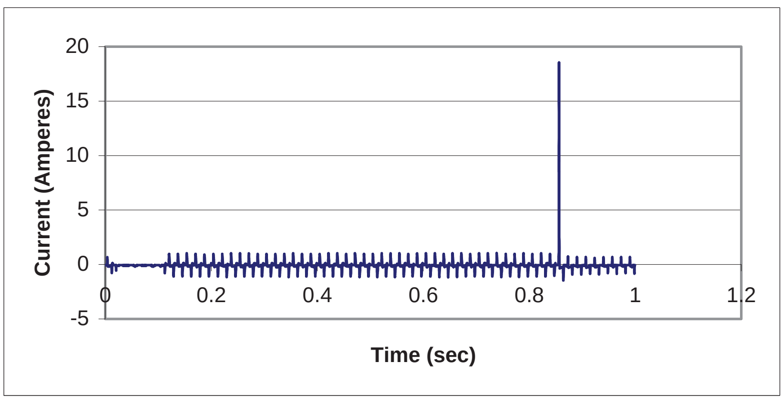


Figure 81. Current waveform for 50%, 50-cycle sag (current spike 19 times the normal)

5.5.4.3 Conclusions from VHS A tests

The VHS A rides through the sags of different depths easily. Except for the visible effects of flickering and stopping of electronic timer, none of the sag depths cause the equipment to switch off. There is no effect of 90% sag depth on the functioning of the VHS. For other sag depths, there is flickering which is shown in the current waveforms as momentary zero current.

5.5.4.4 VHS/DVD combo B tests

The VHS/DVD combo B is similar to that of the VHS A with the additional feature of a DVD system. It also falls in the category of sensitive equipment as it involves complex electronic circuitry. For 90% sag depth, there is a flicker in the electronic timer for duration greater than 40 cycles. Though this flicker is not perceptible to human eye, the current waveform in Figure 82 shows a momentary zero current which indicates flickering.

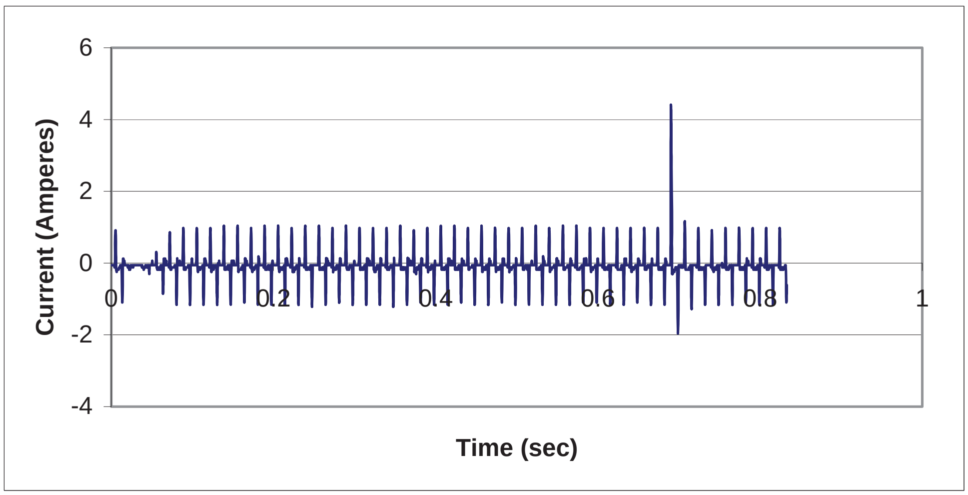


Figure 82. Current waveform for 90%, 40-cycle sag

For 80% sag depth, the flickering in the electronic timer occurs for sag duration greater than 20 cycles. The flickering occurs for 3-4 cycles. Similar observations are obtained for sags of depth 70% and 60% respectively. In the case of both 70% and 60% sag depths, the flickering occurs for sag duration greater than 10 cycles. For 50% sag depth, the flickering starts from 5-cycle duration onwards. For all the sag depths, the equipment rides through the sags easily showing only visible effects. There is no "switching off" of the equipment. However, as it was noticed in the VHS A response to sags, VHS/DVD combo's current response also shows current spikes signifying the end of sag period. No visible effect was observed when the spike occurred. However, the magnitude of the current spike is directly proportional to the sag depth. Table 20 gives the approximate current values of the spike for different sag depths.

Table 20. Values for current spikes for different sag depths for VHS/DVD Combo B

Sag Depth	Approx. Current Magnitude (Amp)
90%	4-5 times the normal current
80%	8-10 times the normal current
70%	11-12 times the normal current
60%	16 times the normal current
50%	19 times the normal current

As can be seen in Figures 83, 84, and 85, for sag depth of 90%, the current spike is approximately 4 times the normal current value; for sag depth of 70%, the current spike is around 11 times the normal operating current; and in the case of 60% sag, the current spike is approximately 16 times the normal current value.

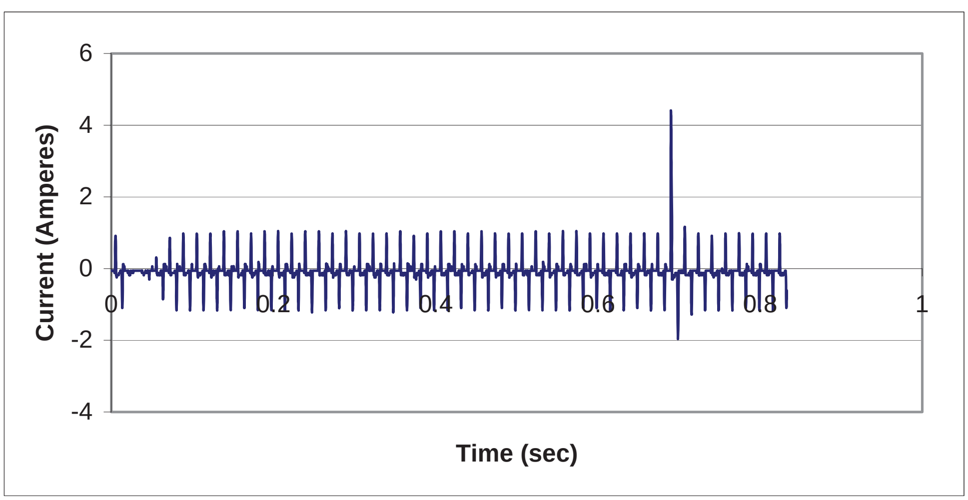


Figure 83. Current waveform for 90%, 40-cycle sag (current spike 4 times the normal)

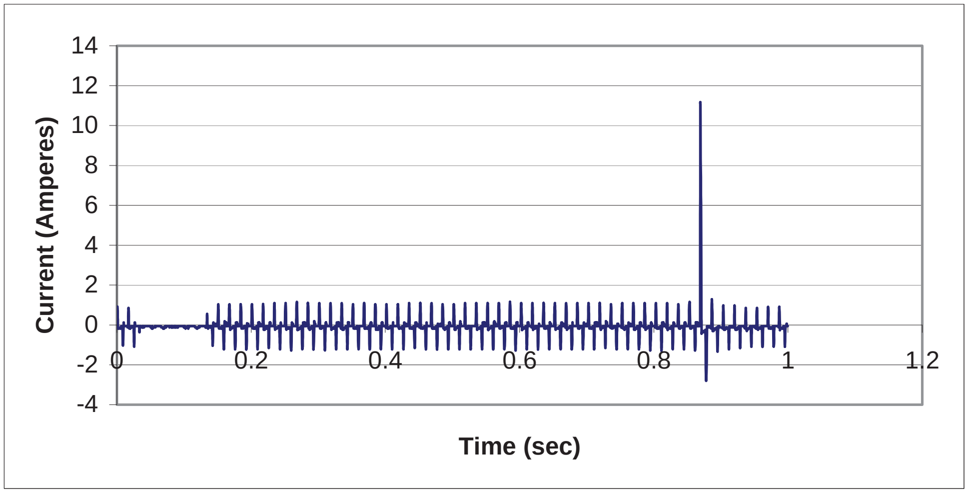


Figure 84. Current waveform for 70%, 50-cycle sag (current spike 11 times the normal)

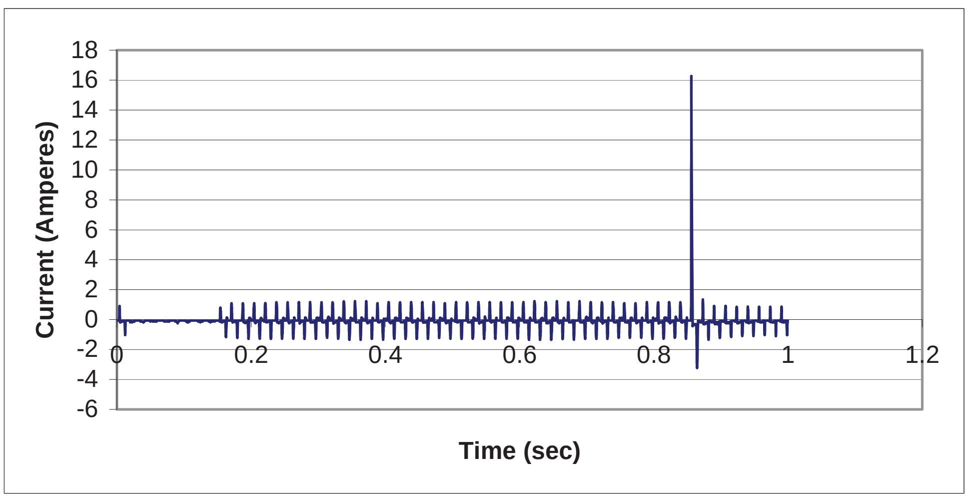


Figure 85. Current waveform for 60%, 50-cycle sag (current spike 16 times the normal)

5.5.4.5 Conclusions from VHS/DVD combo B tests

Sags of different depths also have no detrimental effect on the equipment. The VHS/DVD combo rides through the sags easily. No damage to the equipment occurred. The only visible effect is the flickering of the electronic timer which occurs for all sag depths.

5.5.4.6 DVD C tests

DVD C also falls in the category of sensitive equipment. In the case of 90% and 80% sag, there is no effect on the equipment. For sags of 70% and 60% depths, there is a slight flicker for sags greater than 20 cycles. The duration of the flicker is for only 1-2 cycles. For the rest of the sag period, the equipment behaves normally. There is no current spike for these sag depths.

In the case of 50% sag depth, the effect is more pronounced. The electronic timer stops for 8-10 cycles before recovering for sag durations of 20 cycles or more. The recovery is marked by a sharp increase in current as shown in Figure 86.

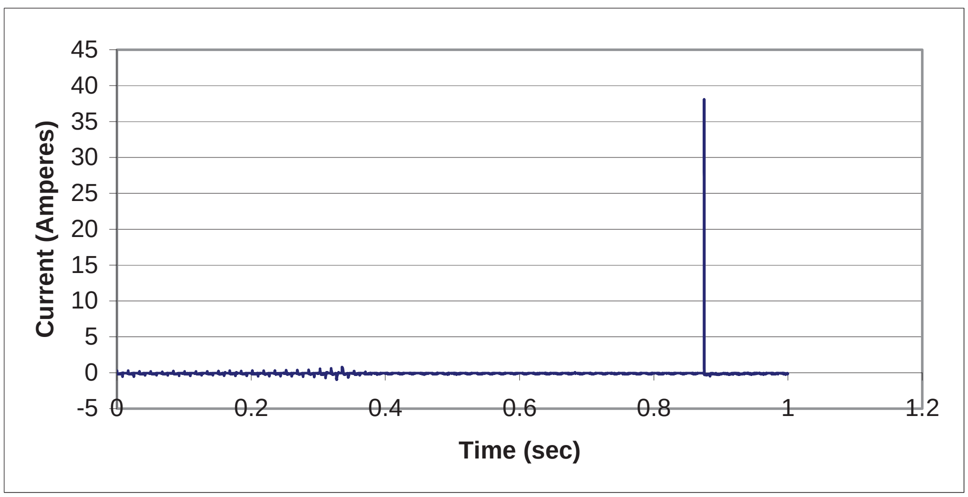


Figure 86. Current waveform for 50%, 50-cycle sag (electronic timer stopped)

5.5.4.7 Conclusions from DVD C tests

The DVD C rides through the voltage sags of different depths easily. The only worst effect is the stopping of the electronic timer for the sag depth of 50% and duration greater than 50 cycles.

5.5.4.8 Conclusions from VHS and DVD equipment tests

The DVD/VHS units are sensitive equipment. Sensitive loads are more robust to voltage sags and they ride through the sags of different depths easily. The only effect that they have on being subjected to sag is the visible effect – the flickering of the electronic timer. There is no damage to any of the equipment and they function normally once the sag is over. Combining the experimental results of VHS A, DVD/VHS Combo B and DVD C, Table 21 presents the tabulated summary of the effect of sags on the performance of the DVD/VHS equipment.

Table 21. Tabulated summary of the performance of VHSs/DVDs due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	No effect of sag for sag durations of 5, 10, 20, and 30 cycles. Flickering in electronic timer occurs for duration greater than 40 cycles.
80%		N	N	N	N	N	N	No effect of sag for 5-cycle, 10-cycle, 20-cycle durations. Flickering in electronic timer for few cycles in the beginning of sag for durations greater than 20 cycles.
70%		N	N	N	N	N	N	No effect of sag for 5-cycle and 10-cycle durations. Flickering in electronic timer for few cycles in the beginning of sag for durations 20 cycles or more.
60%		N	N	N	N	N	N	Similar observation as above
50%		N	N	N	N	N	N	Flickering in electronic timer for few cycles in the beginning of sag for durations 5, 10 and 20 cycles. For 30-cycle duration and greater, the timer stops for 2-3 seconds and resets itself once the sag is over

N: The equipment does not switch off or get damaged due to voltage sag

5.4.5 Experiments on Digital Clock Radios

Radios were the first to gain popularity, much before televisions in United States. The additional feature of making a radio compatible with alarm clocks has made it a common household appliance in most residences. To test the effect of sags on digital alarm clock radios, two such radios were tested. The sag depths were varied from 90% -50% and duration varied from 5 cycles – 120 cycles.

5.5.4.9 Alarm clock radios tested

The specifications of the alarm clock radios tested are:

1. AM/FM Digital Clock Radio A – Modern CR-500 (Manufacturer A)

   - 120VAC, 60Hz
   - Power Output – 5W
   - FM: 88-108 MHz
   - AM: 530-1700 kHz

2. FM/AM Clock Radio B – ICF – C212 (Manufacturer B)

   - 120VAC, 60Hz
   - Power Output – 5W
   - FM: 88-108 MHz
   - AM: 530-1700kHz

In both the digital clock radios, the effects of sags can be

1. Visible effects due to flickering of electronic timers
2. Audible effects due to disturbance in sound produced by radio
3. Switching off the radio and stopping of the alarm clock.

5.5.4.10 AM/FM Digital Clock Radio A tests

In the case of 90% sag depth, there is no effect of sag on the equipment for all sag durations. For 80% sag depth and durations greater than 40 cycles, the flicker in the electronic timer occurs for 2-3 cycles and then it recovers. Similar observations are obtained for 70% sag depth. However, the flickering occurs for a comparatively longer period, that is, 5-6 cycles.

Until 70% sag depth, there are only visible effects of sags due to the flickering of the electronic timers. These flickerings are easily captured in the current waveform which is indicated by momentary zero current value. Figure 87 shows the flickering occurring for a 70% sag depth and duration of 50 cycles.

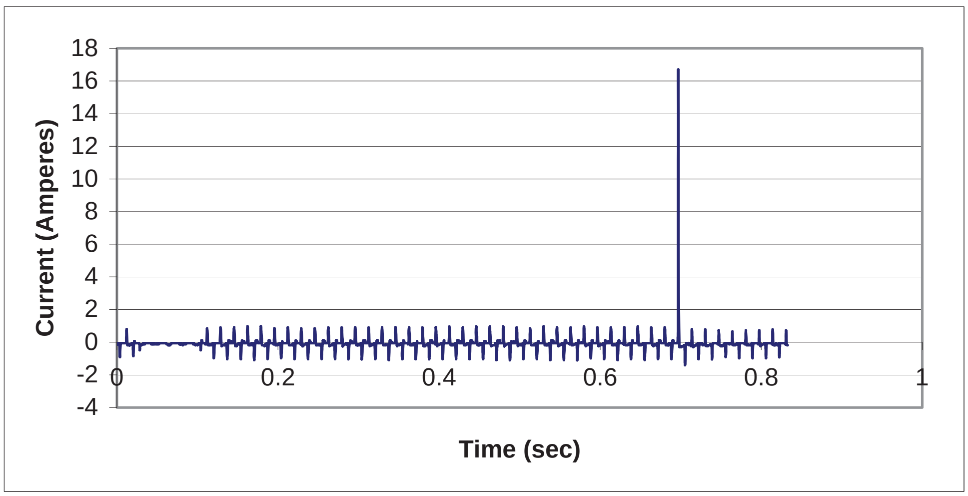


Figure 87. Current waveform for 70%, 50-cycle sag (flickering in alarm clock)

In the case of 60% sag depth, there are both visible and audible effects. For sag durations varying from 5 cycles to 30 cycles, there is only flickering of timer. However, for sag duration greater than 30 cycles, there is both flickering of electronic timer and disturbance in the audio quality. As the sag duration increases, the disturbance becomes more pronounced. For sag duration of 60 cycles, the audio is inaudible and is replaced by a “hissing” sound. Even after the sag is over, it takes few cycles for the audio to return to its original quality.

The visible and the audible effects are more pronounced in the case of 50% sag depth. The flickering of the timer occurs for all sag durations. For sag durations greater than 40 cycles, there is a momentary stop of the alarm clock The alarm clock stops for approximately 10-12 cycles during the sag period and then recovers within the sag period itself. Figure 88 shows this phenomenon.

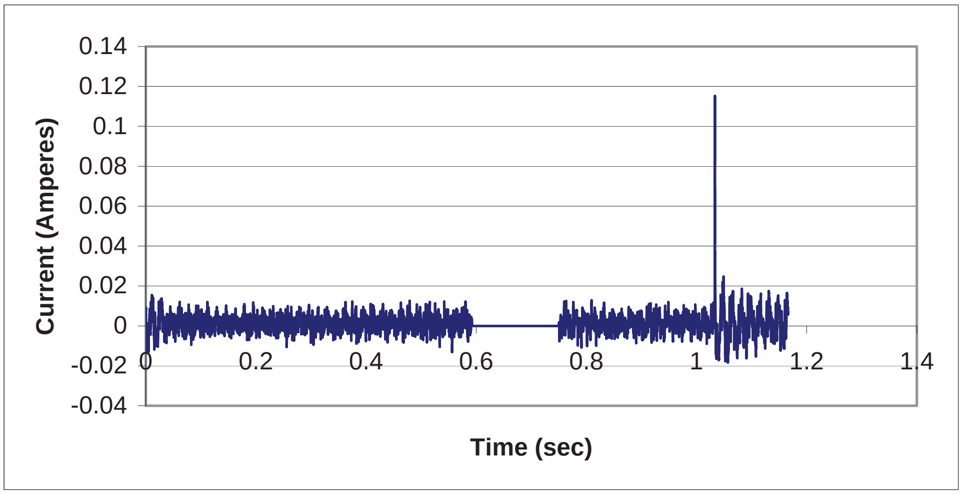


Figure 88. Current waveform for 50%, 60-cycle sag (momentary stopping of alarm clock)

The audible effects for 50% sag depth are more pronounced. However, unlike, flickering which can be captured in the current waveform, the audible effects were observed and noted in the lab book. For sag durations greater than 30 cycles, the disturbance in the sound quality occurs. This disturbance becomes pronounced and the sound is lost for 2-3 seconds for sag duration of 60 cycles. The disturbance continues even after the sag is over and takes few seconds to recover to the original sound quality.

Another important observation made was that the AM radio sound was more susceptible to sags than the FM audio. For sags of depths greater than 70%, audio from the AM radio produced disturbance always for sag durations greater than 30 cycles. However, in the case of FM radio, the disturbance might or might not occur.

5.5.4.11 Conclusions from AM/FM Digital Clock Radio A tests

There are only visible effects on the equipment for sags until 70% sag depth. For sags greater than 70%, there are both visible and audible effects. The audible effect is more pronounced if the duration increases. Moreover, if the audio is from the AM radio, there is a greater possibility of disturbance in sound as compared to the audio from the FM radio. For sag of 50% and duration of 50 cycles, the alarm clock stopped momentarily for few cycles. The audio from AM radio was also lost for few seconds during the sag. It took few cycles after the sag was over to recover the original quality of sound. No damage or switching off of the equipment occurred for different sag depths.

5.5.4.12 FM/AM Clock Radio B tests

FM/AM Clock Radio B has features similar to the AM/FM Digital Clock Radio A. In the case of 90% and 80% sag depths, there is no effect, visible or audible, on the equipment. In the case of 70% sag depth, there is no effect of sag until sag duration of 20 cycles. However, for sag duration greater than 20 cycles, the flickering of the timer occurs. For 30-cycle sag duration, there is very slight flickering of the timer. As the duration increases, the intensity of the flickering increases. The audible effect of the 70% sag is observed for sag duration greater than 40 cycles. There is only a slight disturbance in the audio from AM radio and no disturbance for audio from FM radio.

In the case of 60% and 50% sag depths, flickering occurs for all sag durations. As the sag duration increases, the intensity of flickering increases. However, unlike in the clock radio A, where the clock was momentarily stopped, there is no such event. Figure 89 shows the current waveform for the 50%/60-cycle sag.

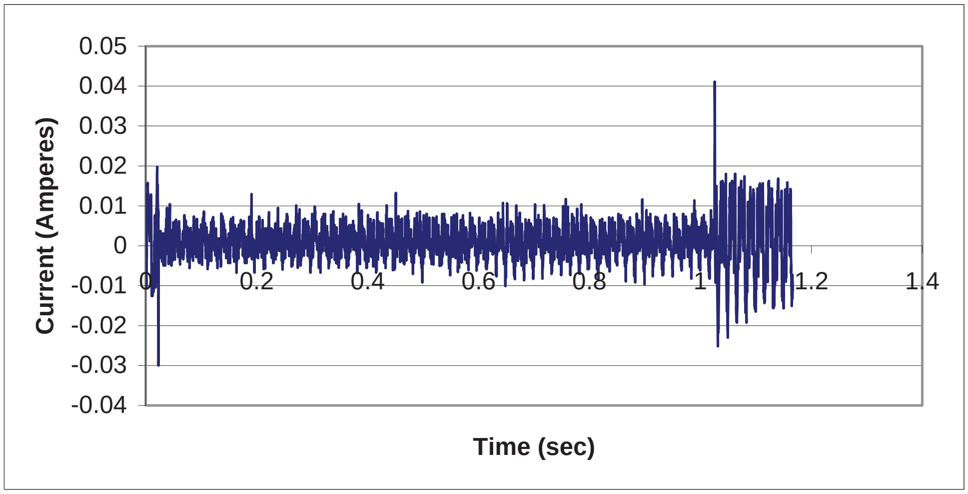


Figure 89. Current waveform for 50%, 60-cycle sag (no momentary stopping of clock)

There was severe audible effect on the radio for sag depth of 60% and 50% respectively. The effect was pronounced in the case of AM radio. In the case of FM radio, there is only slight disturbance in the audio for different sag durations. In the case of 60% sag depth and 60-cycle duration and 50% sag depth and 50-cycle and 60-cycle durations, the disturbance was severe and the audio was lost for few cycles. However, the audio was restored after the sag ended.

5.5.4.13 Conclusions from FM/AM Clock Radio B tests

The FM/AM Radio B has severe audio effects when subjected to sag of depth 60% and 50% respectively. The disturbance was more severe for audio from AM radio than FM radio. For sag durations of 50 cycles and 60 cycles, the audio was lost for few seconds before being restored. The flickering of the timer occurred for sags of depths 70% and more. However, unlike radio A, there was no stopping of the alarm clock due to sag.

5.5.4.14 Conclusions from Digital Clock Radio tests

The digital alarm clock radios have significant effect of sags on their audio quality. The audio is lost for sags of depths 60% and 50% for few seconds. The audio is replaced by large sound disturbance. Once the sag is over, it takes few cycles for the original sound quality to be restored. The flickering of the timers takes place for sag depths greater than 80%. The intensity of the flickering increases as the sag duration increases. However, there is no damage to the radio alarm clocks on being subjected to sags of varying depths and durations. Table 22 presents a tabulated summary of the experimental results of the effect of sags on the performance of the digital clock radios.

5.5.5 Experiments on a stereo compact disc player

Stereo compact discs (CD) have a substantial market for residential customers. To study the effect of sags on such appliances, one stereo CD player was tested. The player was subjected to sags of depths varying from 90%-50% and durations varying from 5 cycles to 60 cycles. The specifications of the Stereo CD Player to be tested are:

Compact Disc Portable Player A

- 120VAC, 60Hz
- Power Output – 14W
- FM: 88-108MHz; AM: 530-1700kHz

Table 22. Tabulated summary of the performance of digital radio clocks due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	No effect of sag for all sag durations.
80%		N	N	N	N	N	N	No effect of sag for 5-cycle, 10-cycle, 20-cycle, and 30-cycle durations. Flickering in electronic timer for 2-3 cycles in the beginning of sag for durations of 40 cycles or more.
70%		N	N	N	N	N	N	No effect of sag for 5-cycle and 10-cycle durations. Flickering in electronic timer for durations 20 cycles or more. Slight disturbance in audio for durations of 40 cycles or more.
60%		N	N	N	N	N	N	Similar observation as above. Disturbance in audio quality for sag durations of 30 cycles or more. Audio is lost for duration of 60 cycles and takes few cycles after the sag is over to recover
50%		N	N	N	N	N	N	Flickering in electronic timer for few cycles for all sag durations Audio is lost for duration of 50 and 60 cycles and takes few cycles after the sag is over to recover

N: The alarm clock radio does not switch off or get damaged due to sag

5.5.5.1 Stereo Compact Disc Player tests

The experiments were conducted with the CD being played in the player. In the case of 90% sag, the power LED flickers for all durations ranging from 5 cycles to 60 cycles. Initially the flickering is almost imperceptible. However, as the duration increases, the intensity of flickering and the duration of flickering increase. Similar observations are obtained for sags of 80% and 70% depths.

In the case of 60% sag depth, flickering of the power LED occurs for sag duration until 30 cycles. Beyond 30 cycles, the LED goes off for few cycles. As a result of this, the song being played in the CD produces a scratching sound before it stops momentarily. Once the sag is over, the CD takes time to restart. This is because it takes time to search the point on CD where it stopped.

Figure 90 shows the current waveform for sag of 60% depth and 50-cycle duration. As can be seen from the figure that in the beginning of the sag there is almost zero current for few cycles. This indicates the event when the power LED goes off for few cycles. The audible effect of sag on the CD player is not indicated in the current waveforms. The audible effects were observed and noted. The current spike indicates the end of the sag.

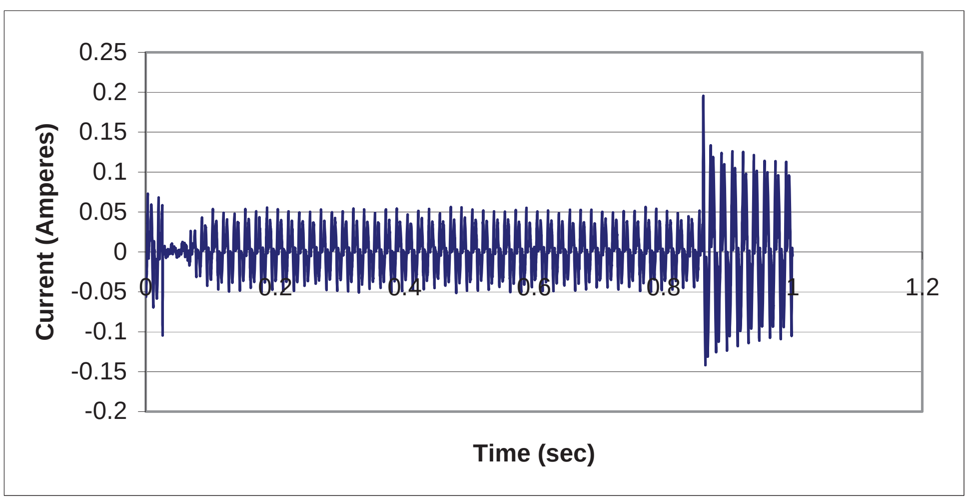


Figure 90. Current waveform for 60%, 50-cycle sag

In the case of 50% sag depth, similar observations are obtained. The flickering occurs for durations of 5 and 10 cycles. For sag duration of 20 cycles and more, the power LED goes off for few cycles ranging from 8-10 cycles. As previously mentioned, this triggers the audible effect. The song being played produces a scratching noise before it stops momentarily. Once the sag is over, the CD takes time to restart. This is because it takes time to search the point on CD where it stopped.

5.5.5.2 Conclusions from Stereo Compact Disc Player tests

There is no damage to the CD player on being subjected to sags. For sags of depths 90%, 80%, and 70%, flickering of the power LED is the only visible effect for all durations. In the case of 60% and 50% sag depths, the LED goes off for few cycles. There is no audible effect for sags of depths until 70%. For 60% and 50% sag depths, the song stops for few cycles and restarts after the sag is over. Table 23 presents a tabulated summary of the experimental results of the effect of sags on the performance of compact discs.

5.5.6 Experiments on sandwich maker/toaster

Toasters and sandwich makers have now become common in residential apartments. As with other appliances previously mentioned, the effect of sags on these appliances have never been determined. Hence, to study the effect of sags a sandwich maker and a toaster have been tested.

1. Sandwich Maker A

- 120VAC, 60Hz
- Power Output – 5 W

2. 2-Slice Toaster B

- 120VAC, 60Hz
- Power Output – 7 W

Table 23. Tabulated summary of the performance of stereo compact discs due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	Flickering of power LED for all sag durations. The intensity increases with duration.
80%		N	N	N	N	N	N	Similar observations as above
70%		N	N	N	N	N	N	Similar observations as above
60%		N	N	N	N	N	N	Flickering occurs for sag durations of 5, 10 and 20 cycles. For 30 cycles or more, the power LED goes off for few cycles. As a result, song being played is stopped accompanied by a scratching noise. Song restarts few cycles after the sag is over
50%		N	N	N	N	N	N	Flickering occurs for sag durations of 5 and 10 cycles. For 30 cycles or more, the power LED goes off for few cycles. As a result, song being played is stopped accompanied by a scratching noise. Song restarts few cycles after the sag is over

N: The equipment does not switch off or get damaged due to voltage sags

5.5.6.1 Sandwich Maker A tests

The visible effect of sags on the sandwich maker can be determined by looking at the power LED of the appliance. For all the sag depths, there is no perceptible flicker of the LED. As can be seen in Figures 91 and 92, the current waveform for sag of 70% depth and 50-cycle duration and current waveform for sag of 50% and 60-cycle duration gives no indication of a flicker.

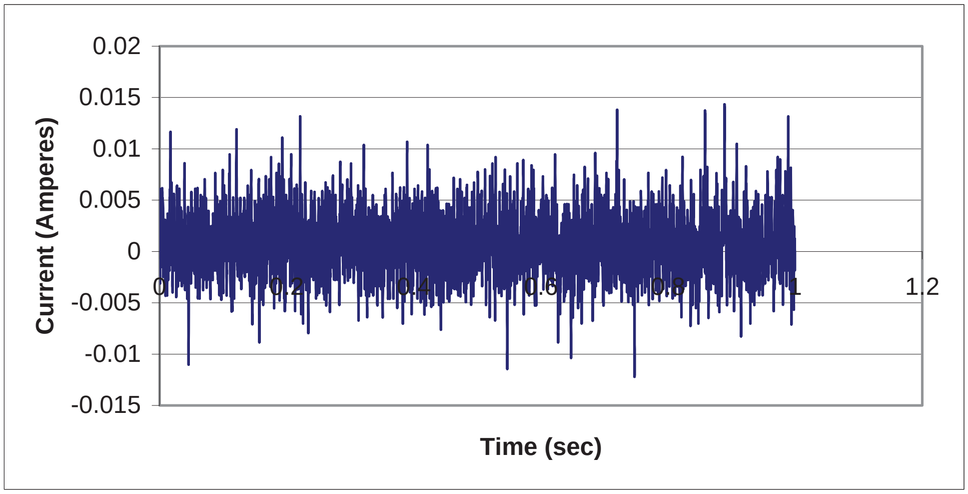


Figure 91. Current waveform for 70%, 50-cycle sag (no indication of flickering)

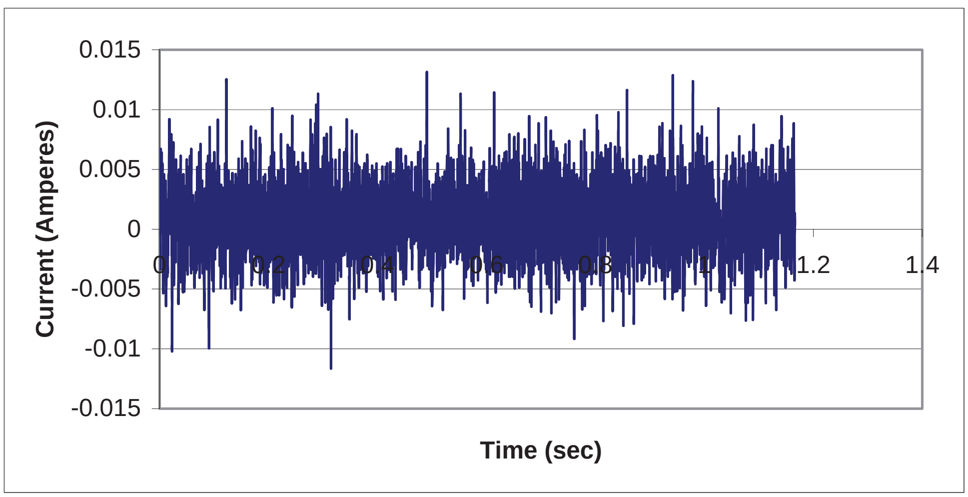


Figure 92. Current waveform for 50%, 60-cycle sag

5.5.6.2 Conclusions from sandwich maker tests

There is no effect of sag on the sandwich maker. For all the sag depths, there is no visible effect of sag which suggests that the appliance rides through the sag easily. Table 24 provides a tabulated summary of the performance of sandwich maker on being subjected to voltage sags.

Table 24. Tabulated summary of the performance of sandwich maker due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	No effect of sag
80%		N	N	N	N	N	N	No effect of sag
70%		N	N	N	N	N	N	No effect of sag
60%		N	N	N	N	N	N	No effect of sag
50%		N	N	N	N	N	N	No effect of sag

N: No effect of sag

5.5.6.3 2-Slice Toaster B tests

The 2-slice toaster works on the principle of a heater. It has coils which get red hot and in turn act as a toaster. The visible effect of sags can be noted by the blinking of the red hot coils. The major effect of sag is the "switching off" of the toaster. Two cases were considered to study the effect of sags on the toaster:

1. Initiating the sag just when the toaster is switched on. This is done because the coils do not get red hot in the beginning.
2. Initiating the sag when the coils are red hot.

Considering case 1 first, it is noted that for sags of depths 90%, 80% and 70% there is no effect of sag on the toaster. However, the toaster turns off automatically for sag depth of 60% and duration of 50 cycles. In the case of 50% sag depth and duration of 40 cycles, the toaster switches off automatically. Once the sag is over, the toaster does not restart automatically. It has to be restarted manually. The phenomenon can be explained by referring to Figures 93 and 94 respectively.

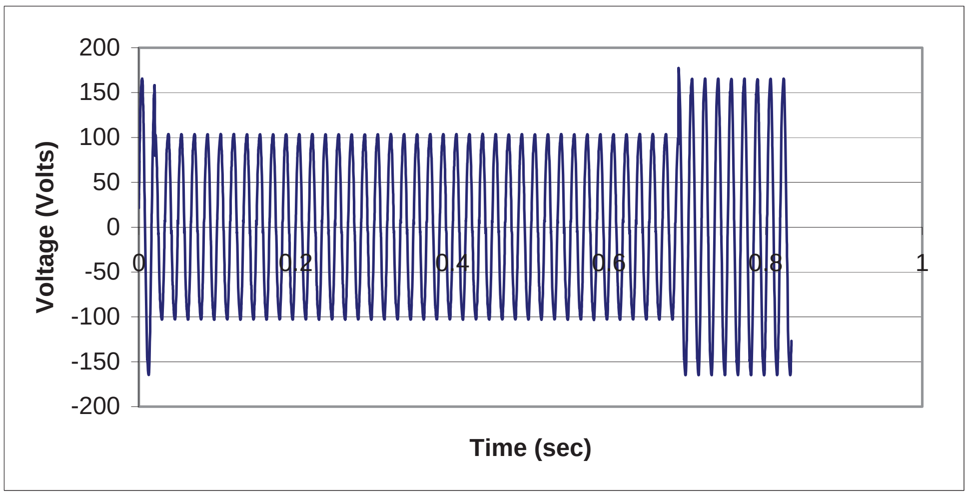


Figure 93. Voltage waveform for 60%, 40-cycle sag

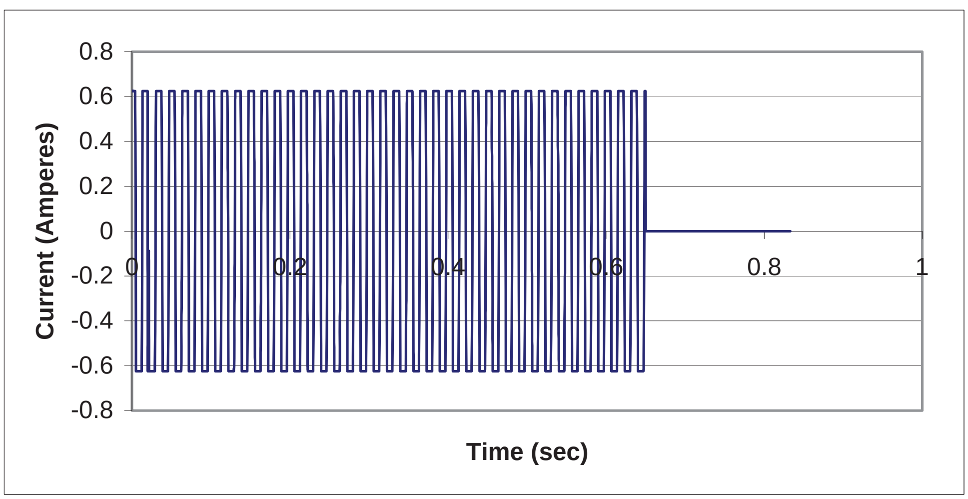


Figure 94. Current waveform for 60%, 40-cycle sag (toaster turns off automatically due to sag)

Figure 93 shows the voltage waveform for a sag of 60% and 40-cycle sag. The corresponding load current waveform is shown in Figure 94. The sag causes the toaster to turn off automatically. This is represented in Figure 94 as zero current at around 0.65 sec. The current remains to be zero even after the sag is over as the toaster does not start automatically.

Considering the second case when the coils get red hot, the toaster does not turn off for all sag depths. The only effect is the blinking of the red hot coils for various sag durations. As the sag duration increases, the intensity of blinking of the red hot coils increases.

5.5.7 Conclusions from sensitive equipment tests

The toaster behaves differently to sags depending on the time of application the sag. If the sag is applied few seconds after the toaster is switched on, the toaster turns off automatically for sags of 60% depth and 50-cycle duration, and 50% depth and 40-cycle duration. The reason for the automatic turn off of the toaster is that the coils of the toaster did not get red hot when the sag was applied. If the sag is applied when the coils are red hot, there is no effect of sags on the toaster. Table 25 presents a tabulated summary of the effect of sags on the performance of toaster.

Table 25. Tabulated summary of the performance of toasters due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**	**Observations**
90%		N	N	N	N	N	N	No effect of sag
80%		N	N	N	N	N	N	No effect of sag
70%		N	N	N	N	N	N	No effect of sag
60%		N	N	N	N	N	N	Toaster switches off for duration of 50 cycles or more
50%		N	N	N	N	N	N	Toaster switches off for duration of 40 cycles or more

N: Toaster does not switch off   Y: Toaster switches off

Chapter 6 CBEMA Curve Analysis of Voltage Sags

6.1 Introduction

Computer Business Equipment Manufacturers Association (CBEMA) produced a power acceptability curve which graphically depicts the severity of the voltage sags plotted versus the duration of the events. The curve came to be known as CBEMA curve. It plots the depth of voltage sags on the vertical axis against the duration of voltage sags on the horizontal axis. The curve has been taken up in an IEEE standard and has become a reference for severity of voltage sags as well as voltage tolerance. However, recently a "revised CBEMA curve" has been adopted by the Information technology Information Council (ITIC) and is considered as the successor of CBEMA. This new curve is referred to as ITIC curve [4].

Figure 95 shows the standard CBEMA curve and its revised version, the ITIC curve. In the figure, only voltage-tolerance part for undervoltages has been shown. This is because voltage sags come under the category of undervoltages. The CBEMA curve also contains a voltage-tolerance part for overvoltages which has not been reproduced in the figure.

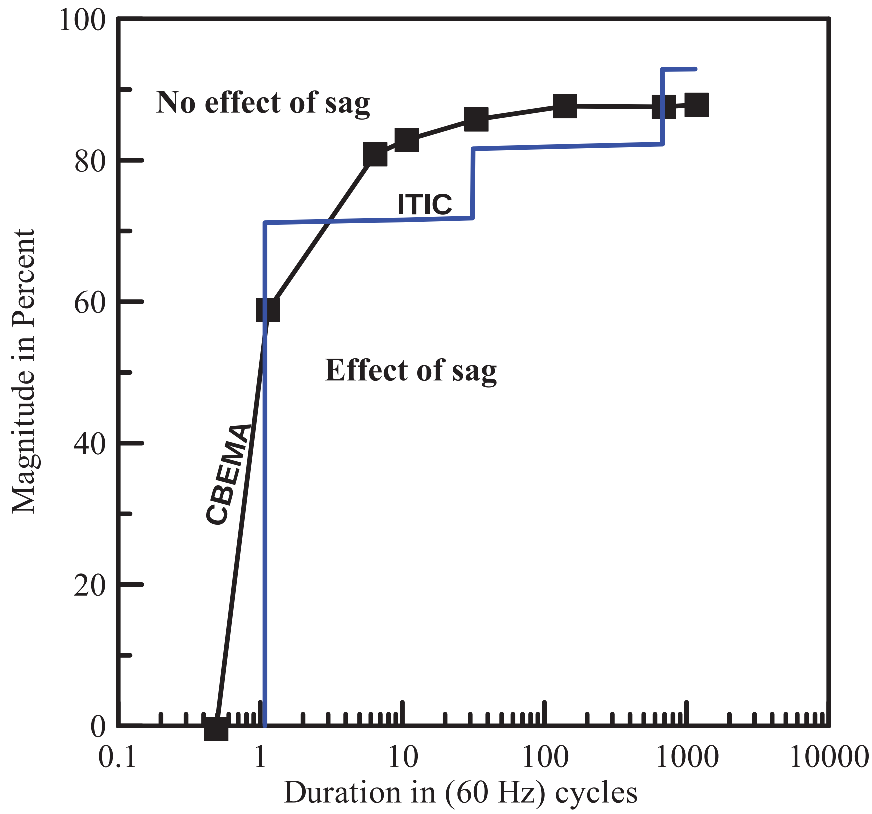


Figure 95. Standard CBEMA and ITIC curve

In the present chapter, CBEMA curves have been plotted for all household appliances on which sag tests were performed. The loads that were affected due to voltage sags can be divided into three categories:

1. Air conditioner compressors
2. Lighting loads
3. Sensitive equipment
    - Computers
    - Televisions
    - Microwave Ovens

The respective CBEMA curves are plotted using the tabulated summary of the performance of the appliances due to voltage sags. The CBEMA curve for the appliance is created by looking at the voltage sag depth and duration for which the appliance is affected by the sag.

For a particular sag depth, if the appliance is affected by more than one sag durations, then the minimum sag duration is taken as the boundary point. For example, if the computer switches off for sag depth of 50% and sag durations of 10, 20, 30, 40 and 60 cycles, the coordinates of CBEMA curve boundary point will be 10 cycles on the x-axis and 50% depth on the y-axis. Since the sag depth can be varied from 90% to 50%, and the vertical axis starts with 40%, the corresponding sag duration for 40% sag depth is chosen as any duration which is less than the minimum sag duration for the 50% sag depth for which the appliance is affected by the sag. Hence, from the previous example, for 40% sag depth, sag duration of 5 cycles will be chosen.

6.2 CBEMA Curve for Air Conditioner Compressors

The table for the performance of the air conditioner compressors due to voltage sags is shown in Table 26. The corresponding CBEMA curve is shown in Figure 96.

Table 26. Tabulated summary of the performance of air conditioner compressors due to sags

Depth	Duration (in cycles)						
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~
90%		N	N	N	N	N	N
80%		N	N	N	N	N	N
70%		N	N	N	N	N	Y
60%		N	N	N	Y	Y	Y
50%		N	N	Y	Y	Y	Y

N: No stalling Y: Air Conditioner stalls

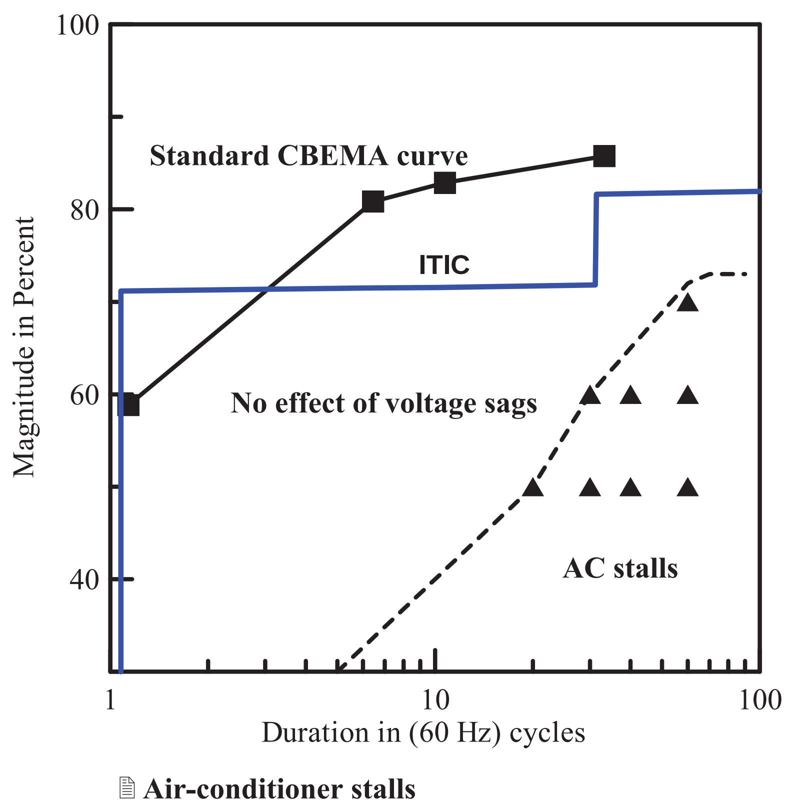


Figure 96. CBEMA curve for air conditioner compressors

As can be seen from Figure 96, the CBEMA curve for the air conditioner compressors is much lower than the standard CBEMA and ITIC curves. The part above the dotted CBEMA curve denotes that the appliance has minimal effect of sags and the compressor does not stall. However, the part below the curve represents that the air conditioner stalls.

Another important observation that can be made from the curve is that the standard CBEMA and ITIC curves are conservative in nature. In other words, the top half of the standard CBEMA curve will always be a part of the top half of the CBEMA curve for air conditioner compressors. However, it may or may not be true for the lower half of the standard CBEMA/ITIC curves as can be seen from Figure 95. The triangles denote the coordinates (sag duration and depth) at which the compressor stalls. It is clear from the curve, that the AC compressor stalls for 50% sag depth and sag durations of 20, 30, 40 and 60 cycles, 60% sag depth and sag durations of 30, 40 and 60 cycles, and for 70% sag depth and sag duration of 60 cycles.

6.3 CBEMA Curve for Lighting Loads

The table for the performance of the lighting loads due to voltage sags is shown in Table 27. The corresponding CBEMA curve is shown in Figure 97.

As can be seen from Figure 97, the CBEMA curve for the lighting loads is much lower than the standard CBEMA and ITIC curves. Above the dotted curve, the lamps do not switch off due to voltage sags. There may be visible effects such as flickering. However, below the dotted curve the lamps switch off. It is clear from Figure 97 that the lamps switch off for sags of depth 50% and durations of 10 cycles or more, and 60% and durations of 20 cycles or more. The standard CBEMA/ITIC curve is conservative in comparison to the CBEMA curve for the lighting loads.

Table 27. Tabulated summary of the performance of lighting loads due to voltage sags

Depth	Duration						
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~
90%		N	N	N	N	N	N
80%		N	N	N	N	N	N
70%		N	N	N	N	N	N
60%		N	N	Y	Y	Y	Y
50%		N	Y	Y	Y	Y	Y

N: Lamps do not switch off Y: Lamps switch off

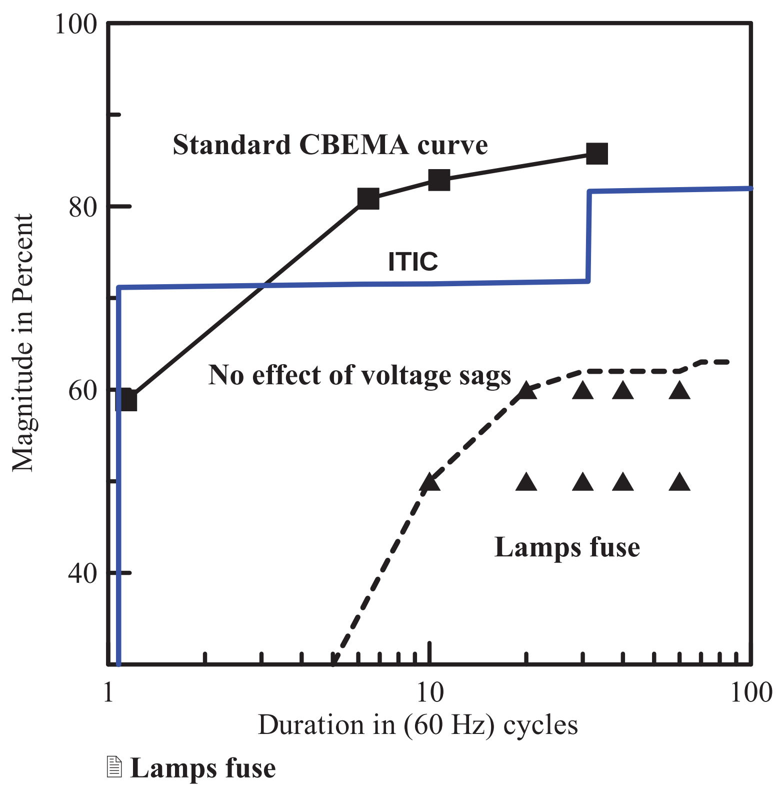


Figure 97. CBEMA curve for lighting loads

6.4 CBEMA Curve for Sensitive Equipment

Various sensitive equipment were tested to study the effect of voltage sags on them. These include computers, microwave ovens, televisions, toasters, digital clock radios, sandwich makers, DVD/VHS players, compact stereo players. Of these appliances, computers, microwave ovens and televisions are affected by sags such that the appliances get switched off. In the case of other equipment, there are only visible effects of sags such as flickering and audible effects as in the case of digital clock radios and stereo players. Hence, CBEMA curves have been plotted for computers, microwave ovens, and televisions.

6.4.1 CBEMA curve for computers

The table for the performance of the computers due to voltage sags is shown in Table 28. The corresponding CBEMA curve is shown in Figure 98.

Table 28. Tabulated summary of the performance of computers due to voltage sags

Depth	**Duration (in cycles)**						
↓	⟶	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**
90%		N	N	N	N	N	N
80%		N	N	N	N	N	N
70%		N	N	N	N	N	N
60%		N	N	N	N	N	N
50%		N	Y	Y	Y	Y	Y

N: Computers do not restart Y: Computers restart

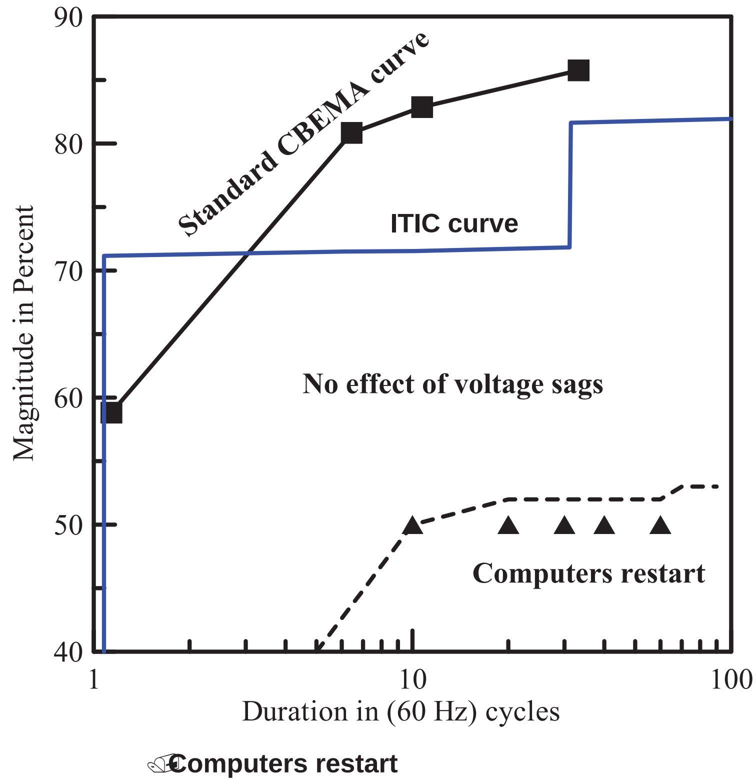


Figure 98. CBEMA curves for computers

As can be seen, above the dotted curve, the computers do not restart due to voltage sags. There are visible effects of sags in this region such as the blinking of the monitor screen. However, the region below the dotted line indicates that the computers restart on the occurrence of sags. It is clear from the triangles that for 50% sag depth and duration of 10 cycles or more, the computers restart. The standard CBEMA/ITIC curve is conservative in comparison to the CBEMA curve for the computers for the reason explained above. However, due to the ever-changing computer technology, it is important to retest the computers frequently.

6.4.2 CBEMA curve for microwave ovens

The table for the performance of the computers due to voltage sags is shown in Table 29. The corresponding CBEMA curve is shown in Figure 99.

Table 29. Tabulated summary of the performance of microwave ovens due to voltage sags

Depth	Duration (in cycles)						
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~
90%		N	N	N	N	N	N
80%		N	N	N	N	N	N
70%		N	N	N	N	N	N
60%		N	N	N	Y	Y	Y
50%		N	Y	Y	Y	Y	Y

N: Ovens do not switch off   Y: Ovens switch off

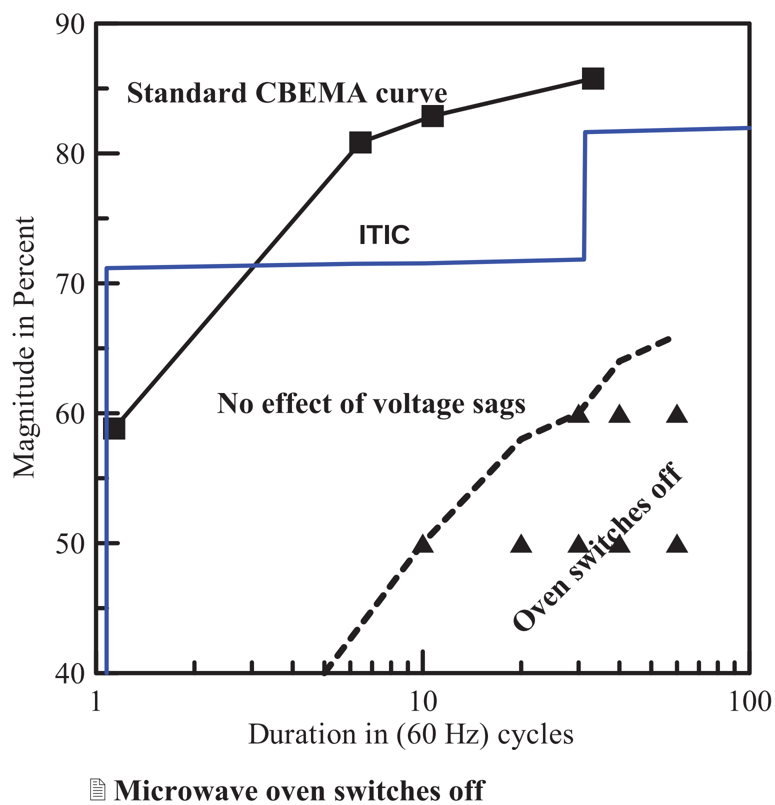


Figure 99. CBEMA curve for microwave ovens

As can be seen, above the dotted curve, the microwave ovens do not switch off due to voltage sags. There are visible effects of sags in this region such as the flickering of light inside the oven. However, the region below the dotted line indicates that the ovens switch off on the occurrence of sags. It is also clear from the triangles in the figure that for 50% sag depth and duration of 10 cycles or more and 60% sag depth and duration of 30 cycles or more, the microwave ovens switch off. Similar to other appliances, the standard CBEMA/ITIC curve is conservative in comparison to the CBEMA curve for the microwave ovens for the reason explained above.

6.4.3 CBEMA curve for televisions

The table for the performance of the televisions due to voltage sags is shown in Table 30. The corresponding CBEMA curve is shown in Figure 100.

Table 30. Tabulated summary of the performance of televisions due to voltage sags

Depth	**Duration (in cycles)**						
↓	⟶	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**
90%		N	N	N	N	N	N
80%		N	N	N	N	N	N
70%		N	N	N	N	N	N
60%		N	N	N	N	N	N
50%		N	N	N	Y	Y	Y

N: Televisions do not switch off   Y: Televisions switch off

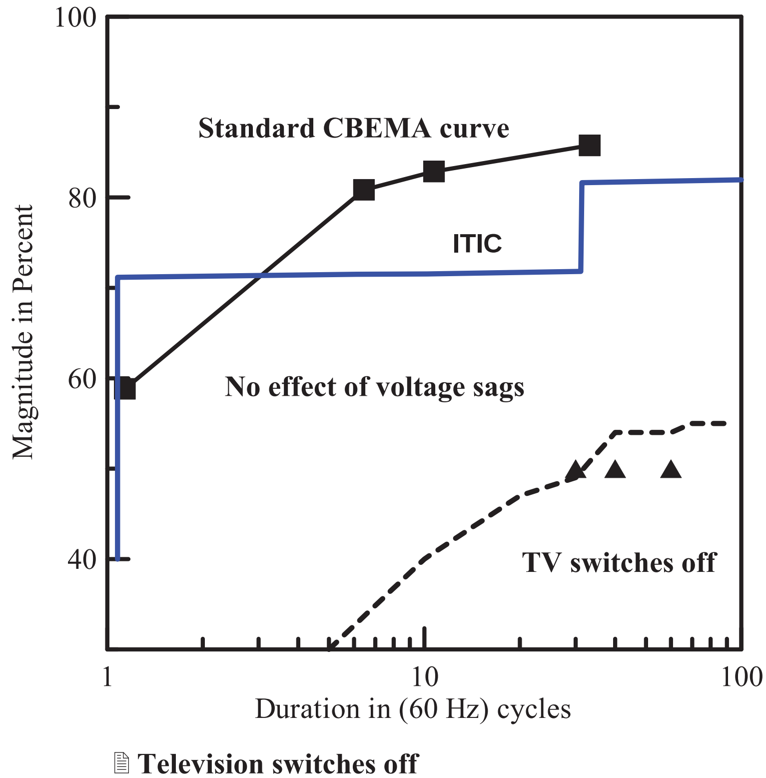


Figure 100. CBEMA curve for televisions

As can be seen, above the dotted curve, the televisions do not switch off due to voltage sags. There are visible effects of sags in this region such as the shrinking of the image. However, the region below the dotted line indicates that the televisions switch off on the occurrence of sags. It is also clear from the triangles in the figure that for 50% sag depth and duration of 30 cycles or more, the televisions switch off. However, once the sag is over they automatically turn on. Similar to other appliances, the standard CBEMA/ITIC curve is conservative in comparison to the CBEMA curve for the televisions for the reason explained above. Combining the three graphs for the sensitive equipment as shown in Figure 101, it is clear that the standard CBEMA/ITIC curves are conservative.

CBEMA curve plot for Sensitive Equipments

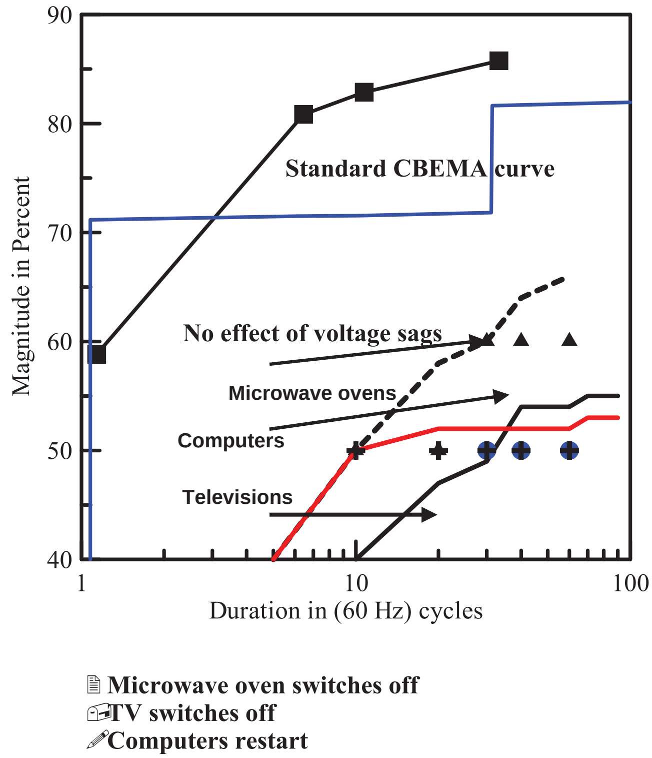


Figure 101. Combined CBEMA curve for sensitive equipment

Summarizing the entire chapter, it is noticed that the CBEMA curves provide a great graphical tool to predict the performance of various appliances on being subjected to voltage sags. The tabulated summary and the CBEMA curves for respective appliances together will provide much information on the performance of the appliances due to voltage sags. Figure 102 shows the CBEMA curves of all the appliances affected by sags in one figure.

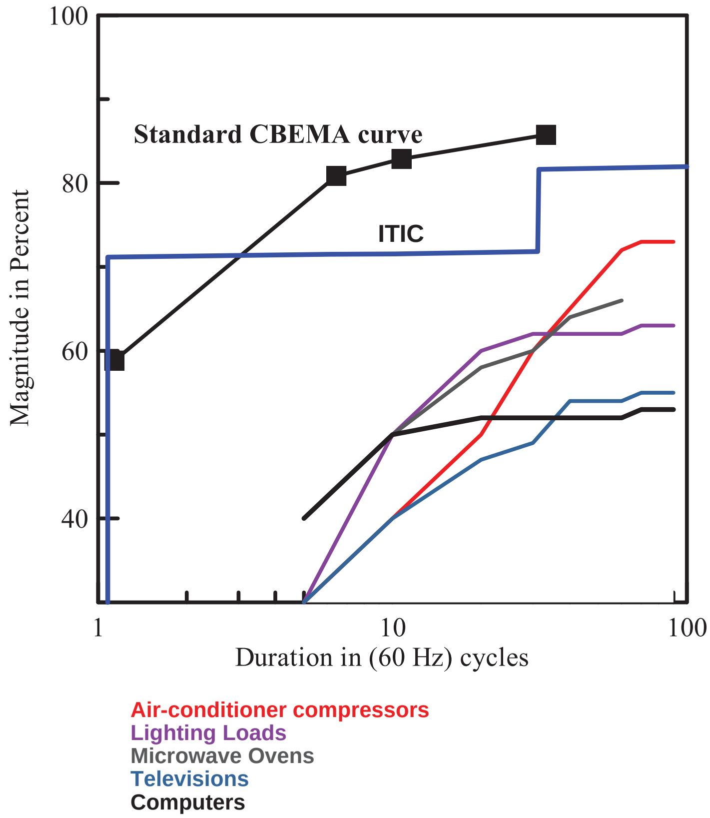


Figure 102. Combined CBEMA curves for all appliances

Chapter 7 Effect of Sags on Electric Loads in Residential Complexes

7.1 Introduction

Voltage sags experienced in residential complexes are of a greater concern to the residential customers than the electric utilities. The advent and the increase of sensitive equipment in the households have increased the awareness of the customers and the utilities towards voltage sags. In the previous chapter, results were provided for the experiments done on various electric loads present in a residential unit. This chapter provides a detailed analysis of the effect of voltage sags on household electric loads in an apartment complex. This detailed analysis can be divided into following major sections:

- Survey of various electric loads for an apartment complex
- Effect of specific sag depths and durations on individual loads in an apartment
- Effect of specific sag depths and durations on combined loads in an apartment
- Financial effect of sags on residential customers and electric utilities.

The survey of electric loads was done for an apartment complex to identify the most common electric loads present in each unit. In this chapter, after the electric loads have been identified, effect of voltage sags on those loads is discussed based on the experimental results obtained from the previous chapter. As a result, prediction tables for each individual load due to sag depths and durations are created. Finally, all the individual electric loads are combined and the effect of sags on an apartment unit is discussed.

7.2 Survey of Various Electric Loads for an Apartment Complex

The main aim in conducting the survey of apartment complexes is to identify the common loads in a residential complex and, then to create prediction tables for those loads on the basis of their performance during sags. To accomplish this task, two apartment complexes, Apartment Complex 1 and Apartment Complex 2, in Tempe, Arizona, were chosen. The survey of the electric loads in the entire apartment complex were accomplished by considering one-bedroom units, two-bedroom units, laundry room, and swimming pool separately. Each load is provided with the general specification, wattage (watts) and full load amperage, FLA (amperes). The loads for which either wattage or full load amperage (FLA) was not provided in the specifications, a power factor of 0.8 was used to calculate them. The formula used for calculations is:

$$P = V*I*\cos\varphi$$

where P is the wattage in watts, V is the single phase voltage (120V), I is the full load amperage in amperes and $\cos\varphi$ is the power factor chosen to be 0.8.

The loads mentioned in the survey for one-bedroom and two-bedroom units are the minimum necessary loads that present in each apartment. Other loads (such as computers, DVD players, and music systems) vary from apartment to apartment and have not been accounted for in taking the survey. However, these loads, collectively termed as sensitive loads, are taken into account in studying the effects of sags on household loads.

7.2.1 Survey of electric loads in Apartment Complex 1

The Apartment Complex 1 is supplied by a distribution transformer and branches out into eight feeders. Each feeder is protected by a circuit breaker of rating 200A. The apartment complex has 150 units which includes 82 one-bedroom units and 68 two-bedroom units, recreation center, swimming pool and laundry room. Each apartment is protected by three circuit breakers of 20A rating and two circuit breakers of 15 A rating. The swimming pool motor is protected by a separate 20A circuit breaker. The recreation center and the laundry room also have circuit breaker and fuse protection.

Table 31 and 32 show the various individual loads in a one-bedroom and two-bedroom units of Complex 1. The common loads are the air conditioning motors, fan motors, refrigerators, microwave ovens, bulbs, crushers and televisions. The wattage and the full load amperage for the loads have also been provided in the table.

Table 31. Survey of electric loads in single one-bedroom unit

S.No	Type of Load	Qty.	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Air conditioning motor	1	Shaded pole, 120V, 1Φ, 60Hz, 1550 rpm, 3 speed, H.P. 1/10, 1/15, 1/25, FLA: 3.5-2.4-1.8A	500	5
2	Fan Motors	2	120V, 1Φ, 60Hz	60*	$0.65\times2=1.3$
3	Refrigerators	1	115V, 1Φ, 60Hz	600*	6.5
4	Microwave Owens	1	120V, 1Φ, 60Hz, 2450MHz	800	9.3
5	Bulbs	10	120V, 1Φ, 60Hz	$60\times10=600$	$.625\times10=6.25$*
6	Crushers	1	120V, 1Φ, 60Hz	250	6.7
7	Televisions (27” regular)	1	120V, 1Φ, 60Hz	113	1.8
8	Fluorescent Tube Light	1	120V, 1Φ, 60Hz	40	.4*

Table 32. Survey of electric loads in single two-bedroom unit

S.No	Type of Load	Qty.	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Air conditioning motor	1	Shaded pole, 120V, 1Φ, 60Hz, 1550 rpm, 3 speed, H.P. 1/6, 1/10, 1/12, 1/15, FLA: 5.4-3.2-2.5-2.1A	500*	5.4
2	Fan Motors	3	120V, 1Φ, 60Hz	60*	0.65×3=1.95
3	Refrigerators	1	115V, 1Φ, 60Hz	600*	6.5
4	Microwave Owens	1	120V, 1Φ, 60Hz, 2450MHz	800	9.3
5	Bulbs	13	120V, 1Φ, 60Hz	$60\times13=780$	$.625\times13$ = 8.125*
6	Crushers	1	120V, 1Φ, 60Hz	250	6.7
7	Televisions	1	120V, 1Φ, 60Hz	200	1.8
8	Fluorescent Tube Light	1	120V, 1Φ, 60Hz	40	.4*

* Wattage/ Full Load Amperage calculated using power factor = 0.8

Tables 31 and 32 have same electric loads with similar specifications. The common electric loads in both these units comprise of air conditioning motor, refrigerator compressor, microwave ovens, televisions, crushers, bulbs and fluorescent tube lights. The only difference is the increase in the quantity of fan motors and bulbs for the two-bedroom units. The values with an asterisk sign are obtained from calculations using the power factor of 0.8.

Table 33 provides the survey of electric loads for the recreation center which consists of a treadmill, stair master and internet link. The specifications for the washers and dryers in the laundry room are provided in Table 34.

Table 33. Survey of electric loads in recreation center

S.No	Type of Load	Qty.	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Treadmill	1	120V, 1Φ, 60Hz	1550*	16
2	Stair Master	1	120V, 1Φ, 60Hz	200*	2
3	Internet Link	1	115V, 1Φ, 60Hz	1400*	15

Table 34. Survey of electric loads in laundry room

S.No	Type of Load	Qty.	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Washer Motor	12	120V, 1Φ, 60Hz	500x12= 6000	5.5x12= 66
2	Dryer Motor	12	120V, 1Φ, 60Hz	7300x12= 87600	7x12= 84

The swimming pool motor is a three-phase motor, the specifications of which are presented in Table 35.

Table 35. Swimming pool motor for university crossroads

S. No.	Type of Load	Qty.	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Motor	1	230V, 3Φ, 60Hz, 3450 rpm	2000	11.2

7.2.2 Survey of electric loads in Apartment Complex 2

The Tempe Terrace complex branches out into two feeders. Each feeder is protected by a circuit breaker of rating 200A and has approximately 20 apartments on it. The apartment complex has 39 units which includes 15 one-bedroom units and 24 two-bedroom units, swimming pool and laundry room. Each apartment is protected by three circuit breakers of 20A rating and two circuit breakers of 15A rating. The swimming pool motor is protected by a separate 20A circuit breaker. The laundry room also has circuit breaker and fuse protection.

Table 36 shows the various individual loads in a one-bedroom unit of Tempe Terrace. The common loads are the air conditioning motors, fan motors, refrigerators, microwave ovens, bulbs, crushers, and televisions. The wattage and the full load amperage for the loads have also been provided in the table.

Table 36. Survey of electric loads in single one-bedroom unit

S.No	Type of Load	Qty.	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Air conditioning motor	1	Shaded pole, 120V, 1Φ, 60Hz, 1550 rpm, 3 speed, H.P. 1/10, 1/15, 1/25, FLA: 3.5-2.4-1.8 A	74.6	3.5
2	Fan Motors	3	120V, 1Φ, 60Hz	187*	0.65×3=1.95
3	Refrigerators	1	120V, 1Φ, 60Hz	630*	6.5
4	Microwave Owens	1	120V, 1Φ, 60Hz, 2450MHz	7000	9.3
5	Bulbs	10	120V, 1Φ, 60Hz	$60\times10 = 600$	$.625\times10$=6.3*
6	Crushers	1	120V, 1Φ, 60Hz	250	6.7
7	Televisions	1	120V, 1Φ, 60Hz	200	1.8

Table 36 provides the survey of various individual loads in the two-bedroom units of Tempe Terrace apartment complex. Tables 36 and 37 have same electric loads with similar specifications. The only difference is the increase in the quantity of fan motors and bulbs for the two-bedroom units.

Table 37. Survey of electric loads in single two-bedroom units

S.No.	Type of Load	Qty	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Air conditioning motor	1	Shaded pole, 120V, 1Φ, 60Hz, 1550 rpm, 3 speed, H.P. 1/6, 1/10, 1/12, 1/15, FLA: 5.4-3.2-2.5-2.1 A	500*	5.4
2	Fan Motors	4	120V, 1Φ, 60Hz	240*	$0.65 \times 4 = 2.60$
3	Refrigerator	1	120V, 1Φ, 60Hz	630*	6.5
4	Microwave Owens	1	120V, 1Φ, 60Hz, 2450 MHz	7000	9.3
5	Bulbs	12	120V, 1Φ, 60Hz	$60 \times 12 = 720$	$.625 \times 12 =$ 7.5*
6	Crushers	1	120V, 1Φ, 60Hz	250	6.7
7	Televisions	1	120V, 1Φ, 60Hz	200	1.8
8	Fluorescent Tube Light	1	120V, 1Φ, 60Hz	40	.4*

From calculations, the total wattage and amperage for 15 one-bedroom units is 132.4kW and 500A, respectively. For the 24 two-bedroom units, the total wattage and amperage is 225.8kW and 965A.

The specifications for the washers and dryers in the laundry room are provided in Table 38. The Tempe Terrace complex has 4 washers and dryers in a single room.

Table 38. Survey of electric loads in laundry room

S.No.	Type of Load	Qty.	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Washer Motor	4	120V, 1Φ, 60Hz	1000	9.8
2	Dryer Motor	4	120V, 1Φ, 60Hz	7300	7

The swimming pool motor for Tempe Terrace is a three-phase motor, the specifications of which are presented below in Table 39.

Table 39. Swimming pool motor for Tempe Terrace

S.No.	Type of Load	Qty.	General Specifications	Wattage (in Watts)	Amperage (FLA) in Amps
1	Motor	1	230V, 3Φ, 60Hz, 3450 rpm	2000	11.2

This survey has provided an insight into the types of loads in the residential complexes. A glance at the electric loads from the survey broadly classifies the loads into motor loads such as air conditioner compressors, fan motors, refrigerator compressors, crushers, washer and dryer motors, lighting loads such as bulbs and fluorescent tubes, and sensitive loads such as microwave ovens, televisions, DVDs, VHSs, stereo compact discs, digital clock radios, etc. The next section deals with the performance of individual loads on voltage sags.

7.3 Performance of Individual Loads in an Apartment on Specific Sag Depths and Sag Durations

The previous section categorized the loads into motor loads, lighting loads, and sensitive loads. Most of the individual electric loads mentioned in the survey were subjected to sag of specific depths and durations during the experiments as explained in the previous chapter. The tabulated summaries of the performance of individual loads due to voltage sags have been presented in the previous chapter. The tables have been reproduced in this chapter for convenience sake. These tables provide the basis for predicting the performance of a single apartment unit consisting of the mentioned individual loads.

The predictions have been made for sag depths varying from 90% to 50% and duration ranges from 5 cycles to 60 cycles. For convenience, the loads have been broadly classified into three major categories

1. Motor loads – These include air conditioner compressors, and refrigerator compressors.
2. Lighting loads – These include bulbs and fluorescent tubes.
3. Sensitive loads – These include loads involving complex electronic circuitry such as computers, televisions, microwave ovens, DVDs and VHSs, sandwich makers and toasters, stereo compact discs, and digital clock radios.

Table 40. Performance of air conditioner compressors due to voltage sags

Depth	**Duration (in cycles)**							
↓	⟶	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**	**Observations**
90%		N	N	N	N	N	N	No noticeable decrease in speed, compressor current
80%		N	N	N	N	N	N	Slight decrease in speed & compressor current
70%		N	N	N	N	N	Y	Slight decrease in speed & compressor current. Stalls at 60 ~
60%		N	N	N	N	Y	Y	Motor stalls for duration above 30 cycles.
50%		N	N	Y	Y	Y	Y	Drastic reduction in speed, stalls above 10 cycles

Table 41. Performance of microwave ovens due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	Digital output disappears but recovers almost immediately for 5, 10, 20 cycles. For 50 cycles and 60 cycles, the flickering occurs for at least 2-3 seconds before it recovers. The digital clock also stops for 2-3 seconds during 50 cycles and 60 cycles respectively
80%		N	N	N	N	N	N	Similar observations as above. Intensity of flickering increases. For 50-cycle and 60-cycle duration, there is almost total darkness inside the oven for 2-3 seconds after which it returns to normal. The digital clock also stops for that period
70%		N	N	N	N	N	N	Similar observations as above
60%		N	N	N	Y	Y	Y	Microwave oven switches off automatically for duration of 30 cycles or more
50%		N	Y	Y	Y	Y	Y	Microwave oven switches off automatically for duration of 10 cycles or more

Table 42. Performance of televisions due to voltage sag

Depth	Duration (in cycles)							
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	No effect of sag
80%		N	N	N	N	N	N	No effect of sag for 5-cycle and 10-cycle durations. White line appears on the image indicating disturbance. Width of white line increases with duration. Image shrinks but recovers almost immediately once the sag is over
70%		N	N	N	N	N	N	Similar observation as above. Image shrinks much more. Spike is observed at the starting of post-sag period indicating that normal image is restored
60%		N	N	N	N	N	N	Similar observation as above Image shrinks almost completely, darkening the screen and takes time to recover
50%		N	N	N	Y	Y	Y	White line becomes prominent for 5, 10, and 20 cycles indicating severe disturbance. Image shrinks completely and TV switches off automatically, turns on automatically after few cycles of post-sag period

Table 43. Performance of VHS/DVD players due to voltage sags

Depth	Duration (in cycles)							
↓	→	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**	**Observations**
90%		N	N	N	N	N	N	No effect of sag for sag durations of 5, 10, 20, and 30 cycles. Flickering in electronic timer occurs for duration greater than 40 cycles.
80%		N	N	N	N	N	N	No effect of sag for 5-cycle, 10-cycle, 20-cycle durations. Flickering in electronic timer for few cycles in the beginning of sag for durations greater than 20 cycles.
70%		N	N	N	N	N	N	No effect of sag for 5-cycle and 10-cycle durations. Flickering in electronic timer for few cycles in the beginning of sag for durations 20 cycles or more.
60%		N	N	N	N	N	N	Similar observation as above
50%		N	N	N	N	N	N	Flickering in electronic timer for few cycles in the beginning of sag for durations 5, 10 and 20 cycles. For 30-cycle duration and greater, the timer stops for 2-3 seconds and resets itself once the sag is over

Table 44. Performance of digital radio clocks due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**	**Observations**
90%		N	N	N	N	N	N	No effect of sag for all sag durations.
80%		N	N	N	N	N	N	No effect of sag for 5-cycle, 10-cycle, 20-cycle, and 30-cycle durations. Flickering in electronic timer for 2-3 cycles in the beginning of sag for durations of 40 cycles or more.
70%		N	N	N	N	N	N	No effect of sag for 5-cycle and 10-cycle durations. Flickering in electronic timer for durations 20 cycles or more. Slight disturbance in audio for durations of 40 cycles or more.
60%		N	N	N	N	N	N	Similar observation as above. Disturbance in audio quality for sag durations of 30 cycles or more. Audio is lost for duration of 60 cycles and takes few cycles after the sag is over to recover
50%		N	N	N	N	N	N	Flickering in electronic timer for few cycles for all sag durations Audio is lost for duration of 50 and 60 cycles and takes few cycles after the sag is over to recover

Table 45. Performance of stereo compact discs due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**	**Observations**
90%		N	N	N	N	N	N	Flickering of power LED for all sag durations. The intensity increases with duration.
80%		N	N	N	N	N	N	Similar observations as above
70%		N	N	N	N	N	N	Similar observations as above
60%		N	N	N	N	N	N	Flickering occurs for sag durations of 5, 10 and 20 cycles. For 30 cycles or more, the power LED goes off for few cycles. As a result, song being played is stopped accompanied by a scratching noise. Song restarts few cycles after the sag is over
50%		N	N	N	N	N	N	Flickering occurs for sag durations of 5 and 10 cycles. For 30 cycles or more, the power LED goes off for few cycles. As a result, song being played is stopped accompanied by a scratching noise. Song restarts few cycles after the sag is over

Table 46. Performance of sandwich maker due to voltage sags

Depth	Duration (in cycles)							
↓	→	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	No effect of sag
80%		N	N	N	N	N	N	No effect of sag
70%		N	N	N	N	N	N	No effect of sag
60%		N	N	N	N	N	N	No effect of sag
50%		N	N	N	N	N	N	No effect of sag

Table 47. Performance of toasters due to voltage sags

Depth	Duration (in cycles)							
↓	⟶	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**	**Observations**
90%		N	N	N	N	N	N	No effect of sag
80%		N	N	N	N	N	N	No effect of sag
70%		N	N	N	N	N	N	No effect of sag
60%		N	N	N	N	N	N	Toaster switches off for duration of 50 cycles or more
50%		N	N	N	N	N	N	Toaster switches off for duration of 40 cycles or more

Table 48. Performance of lighting loads due to voltage sags

Depth	Duration						
↓	⟶	5 ~	10 ~	20~	30 ~	40 ~	60 ~	Observations
90%		N	N	N	N	N	N	Increase in dimness as depth increases. Recovers with sharp increase in intensity. For greater sag depths (~50%), the lamps may be blown off while recovering.
80%		N	N	N	N	N	N	
70%		N	N	N	N	N	N	
60%		N	N	Y	Y	Y	Y	
50%		N	Y	Y	Y	Y	Y	
40%		N	Y	Y	Y	Y	Y	

7.4 Effect of Specific Sag Depths and Durations on an Apartment Combining Individual Loads

In the previous section, the effect of voltage sags on individual loads was discussed and tables from the previous chapters were reproduced to summarize the performance of individual loads on being subjected to sags of specific depth and duration. In this section, all individual loads have been combined to represent the total electric load of a single apartment. The individual loads have been combined and the predictions for a single apartment are presented. The assumption made is that all the individual loads are running simultaneously at the time of the occurrence of voltage sags. Table 49 on the next page provides the summary of events that would take place for sags of specific depths and durations. This table helps to identify the electric loads that would stall or malfunction during a sag of specific depth and duration. For the tabulated summary, the sag depths vary from 90%-50% and durations from 5 cycles to 60 cycles.

Each apartment in the complex has five circuit breakers. Three circuit breakers have the current rating of 20A and two have the rating of 15A. The air conditioner is connected to a 20A breaker exclusively. The kitchen loads which comprises of the microwave ovens, electric ovens, crushers and other loads are connected to the 20A breaker too. The lighting loads are connected to the 15A breaker.

Table 49. Performance predictions of a single apartment comprising individual loads on voltage sags

Depth ↓	**Duration** →	**5 ~**	**10 ~**	**20~**	**30 ~**	**40 ~**	**60 ~**	**Observations**
90%		Non- Stalling	Non- Stalling	Non- Stalling	Non- Stalling	Non- Stalling	Non- Stalling	A flicker in the lighting loads, no noticeable decrease in speed in the motors, no effect on television image, digital output of microwave oven disappears and recovers instantly for duration less than 30 cycles, flickering in the timer of VHS/DVD and stereo players occurs for duration greater than 40 cycles, no effect on sandwich makers, toasters, digital clock radios.
80%		Non- Stalling	Non- Stalling	Non- Stalling	Non- Stalling	Non- Stalling	Non- Stalling	Increase in dimness in the lighting loads, slight decrease in speed in the motors, television image shrinks a bit and recovers instantly, in microwave ovens for 50-cycle and 60-cycle duration, there is almost total darkness inside the oven for 2-3 seconds after which it returns to normal and the digital clock also stops for that period, flickering occurs in electronic timer for VHS/DVD and stereo players for duration greater than 20 cycles, flickering in digital clock radios for duration greater than 40 cycles, no effect on sandwich makers and toasters.

70%		Non- Stalling	Non- Stalling	Non- Stalling	Non- Stalling	Non- Stalling	Air Conditioner motor stall	Increase in dimness in the lighting loads and recovers with sharp intensity, noticeable decrease in speed in the motors (refrigerator compressors, fan motors, washers, dryers and crushers) accompanied by a sound, air conditioner compressor stalls for duration greater than 60 cycles, television image shrinks more, similar observations for microwave ovens as obtained for 80% sag depth flickering occurs in electronic timer for VHS/DVD and stereo players for duration greater than 20 cycles, flickering in digital clock radios for duration greater than 40 cycles and slight disturbance in audio for durations of 40 cycles or more, no effect on sandwich makers and toasters
60%		Non- Stalling	Non- Stalling	Non- Stalling	AC motor stalls, microwave oven switches off automatically	AC motor stalls, microwave oven switches off automatical ly	AC motor stalls, microwave oven switches off automatically toaster switches off for duration greater than 50 cycles.	Air Conditioner motor stalls for sag duration greater than 20 cycles. Television image shrinks almost completely darkening the screen and takes time to recover, Microwave oven switches off automatically for duration of 30 cycles or more, sharp increase in the dimness of lighting loads, Flickering intensity increases in the case of DVD/VHS and stereo players, disturbance in audio quality for sag durations of 30 cycles or more for digital clock radios. Audio is lost for duration of 60 cycles and takes few cycles after the sag is over to recover, toaster switches off for duration of 50 cycles or more

50%		Non- Stalling	AC motor stalls, Microwave ovens switches off automatically	AC motor stalls, Microwave ovens switches off automatically	AC motor stalls, Microwave ovens switches off automatically, television switches off automatically and turns on automatically after the sag		AC motor stalls, Microwave ovens switches off automatically, television switches off automatically and turns on automatically after the sag, toaster switches off	In the case of DVD/VHS players, for 30-cycle duration and greater, the timer stops for 2-3 seconds and resets itself once the sag is over, in the case of digital clock radios audio is lost for duration of 50 and 60 cycles and takes few cycles after the sag is over to recover, in the case of stereo players song being played is stopped accompanied by a scratching noise, song restarts few cycles after the sag is over, Toaster switches off for duration of 40 cycles or more

Table 49 shows the behavior of various individual loads in an apartment as a whole. It helps to identify the electric loads which will stall for a particular sag depth and duration. For sag depths of 90% and 80%, there is no perceptible effect of voltage sags on the apartment. The lamps blink a little bit, so little that it is hard to perceive with the naked eye. Likewise, the digital output on the microwave ovens. The image of the televisions also shrinks but recover instantaneously. In the case of 70% sag depth, for duration equal or greater than 60 cycles, the air conditioner compressor stalls. For the other motor loads, there is a noticeable speed reduction which is accompanied by a noise. The lighting loads experience large decrease in the intensity of light and recover with sharp intensity. The digital output on microwave ovens, washers and dryers disappear and recover in some time. The television image shrinks considerable and takes time to recover.

For 60% sag depth, microwave ovens switch off automatically for sag durations greater than 30 cycles. The air conditioner compressor stalls for durations greater than 50 cycles. The television image shrinks almost completely and recovers after a long time. The lighting loads show significant sag in the intensity of light and recover with sharp intensity. In the case of 50% sag depth, all motor loads stall for sag duration greater than 40 cycles. The television image disappears and the set switches off automatically. It automatically switches on after the sag is over. The lighting loads sag significantly but recover with sharp intensity.

In totality, the maximum effects of voltage sags to the residential customers occur during a sag depth of 50% and duration greater than 10 cycles. Most of the single phase electric motors stall, the microwave switches off, lamps get blown off and the television switches off.

The table provides information about the performance of various loads in an apartment on the occurrence of voltage sags, assuming all loads operating at the same time. It helps in making conclusions regarding the stalling of individual loads and the extent of damage it makes to a single apartment. Consequently, this table will help the residential customers to understand the severity of sags for specific loads and take necessary protective measures to protect them from getting damaged.

7.5 Financial Implication of Voltage Sags on Residential Customers and Electric Utilities

The cost of power interruptions in U.S. is of serious concern. Power interruptions can be categorized into momentary (short-duration, lasts 5 minutes or less) interruptions and sustained (long-duration, lasts 5 minutes or more) interruptions. Voltage sags fall in the category of momentary interruptions. Recent studies reveal that momentary interruptions have a stronger impact on total cost of power interruptions than sustained interruptions [37]. This is because momentary interruptions are more frequent than sustained interruptions. Figure 103 shows the contribution of the momentary interruptions to the total power interruptions.

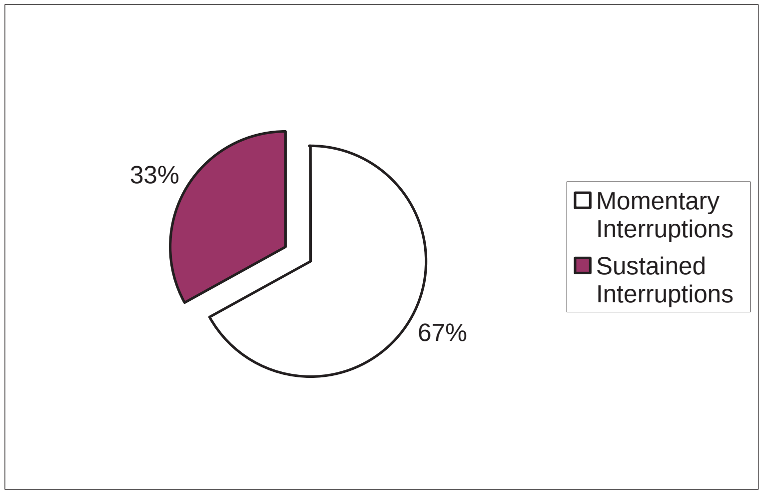


Figure 103. Break-up of types of power interruptions

As can be seen from the figure, momentary interruptions contribute 67% to the total power interruptions. Voltage sags are the most frequent events among the momentary interruptions and contribute 60% to the momentary interruptions. Hence, voltage sags contribute approximately 40% to the total power interruptions.

Majority of power outage costs are borne by the commercial and industrial sectors. Residential sector only incur 2% of the total power interruption costs. Figure 104 shows the pie diagram for the break up of total cost of power interruptions distributed among different sectors.

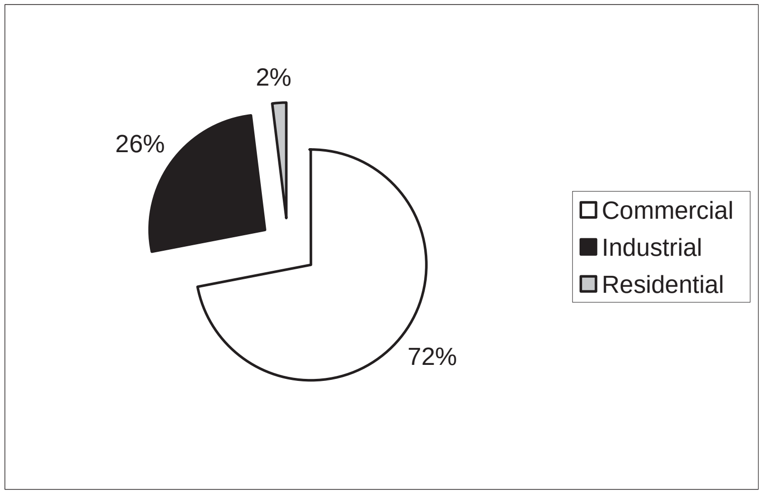


Figure 104. Break-up of cost of power interruptions by customer class

Experiments performed on various equipment types to study the effect of voltage sags suggest that voltage sags do not damage the equipment. Hence, for residential customers, the financial loss incurred by voltage sags is minimal or almost negligible. The occurrence of voltage sags may cause inconvenience to the residential customers in cases when one of the feeders on which the sag occurs is out of service or the parallel feeder faces momentary interruptions due to the sag.

Electric utilities incur significant financial losses due to voltage sags occurring in residential complexes. This is because a feeder can go out of service in the case if all air conditioners are started simultaneously due to heavy inrush currents of the order of 5-6 times the normal current. This will require corrective measures by the utilities to bring the feeder back in operation. Loss of power indirectly is loss of dollars for the utilities.

Chapter 8 Overall Conclusion

This report has presented the experimental study performed to determine the voltage sag effects on different loads such as motor loads (air conditioning), lighting loads, contactors, and computers. The study has been supported by theoretical concepts gained in the literature review.

The thorough and detailed literature review provided a strong platform to conduct experiments on motor loads, contactors, lamps and computers. The experimental results comply with the theory of the literature review. The effect of voltage sag parameters on motor loads, lighting loads, contactors, and computers have been studied and their results have been discussed.

1) The experiments on contactors provided important results. The most significant conclusion that can be drawn by observing the behavior of contactors under both load and no load condition is that there is no difference in the contactor performance under both conditions. The contactor is not affected by sags of depths 90%, 80% and 70%. For sag depth of 60%, there is chattering observed for sag duration greater than 30 cycles. In the case of 50% and 40% sag depths, the contactors trip for all sag durations. There is no chattering phenomenon observed in these sag depths. For sag depth of 40%, for smaller durations of 5 cycles and 10 cycles, there is clear tripping of the contactor. As the sag duration increases, chattering phenomenon is observed.
2) In the case of motor loads (air conditioners and coolers), the results of the experiments show that the point-on-wave of initiation of the voltage sag does not have an obvious effect on the performance of the motor. It also proves that the stalling of the motor depends on the sag depth and duration. As seen in the

experiments conducted on air conditioners, for Air Conditioner A, the motor stalls when at a depth/duration of 60%/12cycle and 40%/40cycle. For Air Conditioner B, the motor stalls when at a depth/duration of 50%/8cycle and 40%/15cycle. Moreover, the motor current can rise to as high as 2.3 p.u. during sag period.

3) The results of the experiments conducted on the lighting loads can be summarized by considering the fluorescent and helium lamps together. This is because both the lamps show similar behavior on the occurrence of voltage sags. In both cases, light dims during sag. However, the dimness in light is independent of sag duration and depends only on sag depth. The results show that there is no obvious effect of difference of voltage sags on the performance of lamps from different manufactures. The recovery of the dim light is marked by a sharp increase in the intensity of light and thereafter, it returns back to normal operation.

4) In the case of computers, the results of the experiments suggest that voltage sags have more severe effect on computer's restarting if the computer power supply is driving more devices such as hard disk, CD-R, etc. Sag duration less than 7 cycles does not cause the computer to lose data and restart. It also suggests that the performance (specification) of the switching power unit and the power consumption of a computer play a very important role on the sag effect. The power consumption of a computer is directly proportional to the severity of sag effect on the computer. Increased power consumption has a severe effect of sag on the performance of the computer.

5) Microwave ovens and televisions are also affected by voltage sags. Microwave ovens switch off for 50% sag depth and duration of 10 cycles or more and 60% sag depth and duration of 30 cycles or more. The televisions switch off for 50% sag depth and

duration of 30 cycles or more. There is only visible effect of sags on the performance of DVD/VHS players, stereo compact players, digital audio clocks, and sandwich makers. In the case of VHS/DVD players and stereo players visible effect of sags is the flickering of the electronic timers. The digital alarm clock radios have significant effect of sags on their audio quality. The audio is lost for sags of depths 60% and 50% for few seconds. The audio is replaced by large sound disturbance. The toaster behaves differently to sag depending on the time of application the sag. If the sag is applied few seconds after the toaster is switched on, the toaster turns off automatically for sags of 60% depth and 50-cycle duration, and 50% depth and 40-cycle duration. The reason for the automatic turn off of the toaster is that the coils of the toaster did not get red hot when the sag was applied. If the sag is applied when the coils are red hot, there is no effect of sags on the toaster.

6) The successful completion of the second phase included the survey of apartment complexes to classify the electric loads and creation of a prediction table to study the effect of voltage sags on a single apartment by combining individual loads. The prediction table is created by incorporating the experimental results obtained for the performance of individual loads on being subjected to voltage sags.
7) The financial implication of voltage sags on the electric utilities and residential customers has been considered. Residential customers have minimal or no cost of voltage sags incurred on them. Electric utilities, however, incur significant financial losses in case voltage sags cause an entire feeder to go out of operation.

This project has served in the better understanding of the importance of voltage sag. It has provided experimental proof that household appliances do not get damaged by voltage sags which is an important conclusion in context to the rising concern of the effect of voltage sags on sensitive equipment, which are increasing in various residential apartments. However, it is important to repeat the performed experiments almost every two years to keep up with the latest technology. This is recommended because the effect of sags on the appliance may vary with the ever-changing technology.

REFERENCES

1. "ITI (CBEMA) curve application note," Available at http://www.itic.org.
2. Bollen, M.H.J., Styvaktakis, E., Gu, I.Y.H., **"**Analysis of voltage sags for event Identification**,"** Power Quality: Monitoring and Solutions (Ref. No. 2000/136).
3. P.K. Lim, D.S. Dorr, "Understanding and resolving voltage sag related problems for sensitive industrial customers," Power Engineering Society Winter Meeting, IEEE, 2000, pp. 2886-2890.
4. M.H.J, Bollen, "Understanding power quality problems," P.M. Anderson, 2000, New York, IEEE Press, ISBN 0-7803-4713-7.
5. G. Yaleinkaya, M.H.J. Bollen, P.A. Crossley," Characterization of voltage sags in industrial distribution systems," IEEE Transactions on Industry Applications, v. 34, Issue: 4, July/August 1998, pp. 682-688.
6. R.S. Thallam, G.T. Heydt, "Power acceptability and voltage sag indices in the three phase sense," Power Engineering Society Summer Meeting, 2000. IEEE, Volume: 2, pp. 905-910.
7. Guasch, L., Corcoles, F., Pedra, J., **"**Effects of unsymmetrical voltage sag types E, F and G on induction motors," Harmonics and Quality of Power, Proceedings. Ninth International Conference, v. 3, 1 - 4 Oct. 2000, pp. 796 – 803.
8. J.C. Das, "Effects of momentary voltage sags on the operation of induction and synchronous motors," IEEE Trans. Ind. Application, v. 26, 1990, pp. 711 - 718.
9. Gomez, J.C., Morcos, M.M., Reineri, C., Campetelli, G., "Induction motor behavior under short interruptions and voltage sags," Power Engineering Review, IEEE, v.21 Issue: 2, Feb. 2001, pp. 11 –15.

10. M.H.J. Bollen, "The influence of motor reacceleration on voltage sags," IEEE Trans. Ind. Application, v. 31, 1995, pp. 667 - 674.

11. Bollen, M.H.J., **"**Characterization of voltage sags experienced by three-phase adjustable-speed drives**,"** Power Delivery, IEEE Transactions on, v. 12, Issue: 4, 1997, pp. 1666 –1671.

12. Carrick, K. W., "Minimizing the Effects of Voltage Disturbances on Continuous Industrial Processes",

13. Gomez, J.C., Morcos, M.M., "A simple methodology for estimating the effect of voltage sags produced by induction motor starting cycles on sensitive equipment," Industry Applications Conference, Thirty-Sixth IAS Annual Meeting. Conference Record of the 2001 IEEE, v. 2, 2001, pp. 1196 – 1199.

14. Funabashi, T.; Otoguro, H.; Fujita, G.; Koyanagi, K.; Yokoyama, R., "An Influence of Voltage Sag Duration on Non-utility Generator's Shaft Torque

15. W. D. Stevenson, "Elements of Power System Analysis," McGraw Hill Series, 2000, New York.

16. Pumar, J. Amantegui, J.R. Torrealday, C. Ugarte,"A comparison between d.c. and a.c. drives as regards their behavior in the presence of voltage sags: new techniques for reducing the susceptibility of a.c. drives," Electricity Distribution. Part 1: Contributions. CIRED. 14th International Conference and Exhibition on (IEE Conf. Publ. No. 438), 1997, pp 2.9.1-2.9.5.

17. Yanikoglu, E., Yilmaz, A.S., **"**Behavior of synchronous generators, during the short duration voltage sags," Electrotechnical Conference, 9th Mediterranean, v. 2, 1998, pp. 1148 –1151.

18. Carlsson, F., "Saturation in synchronous machines due to voltage sags," Electric Machines and Drives Conference, IEEE International, v. 3, 1-4 June 2003, pp. 1571 – 1575.

19. Bollen, M.H.J., Zhang, L.D., "Analysis of voltage tolerance of AC adjustable-speed drives for three-phase balanced and unbalanced sags," Industry Applications, IEEE Transactions on, v. 36 Issue: 3, May-June 2000, pp. 904 – 910.

20. Duran-Gomez, J.L., Enjeti, P.N., Byeong Ok Woo, "Effect of voltage sags on adjustable-speed drives: a critical evaluation and an approach to improve performance," Industry Applications, IEEE Transactions, v. 35, Issue: 6, Nov.-Dec. 1999, pp. 1440 – 1449.

21. Keus, A.K., Abrahams, R., Van Coller, J.M., Koch, R.G., "Analysis of voltage sag (sag) testing results of a 15 kW PWM adjustable speed drive (ASD)," Electric Machines and Drives, 1999. International Conference IEMD '99, 9-12 May 1999, pp. 213 – 215.

22. Sarmiento, H.G., Estrada, E., "A voltage sag study in an industry with adjustable speed drives," Industry Applications Magazine, IEEE, v. 2 Issue: 1, 1996, pp. 16 – 19.

23. Langley R., Mansoor A., Collins E.R., Jr., Morgan R.L.,"Voltage sag ride-through testing of adjustable speed drives using a controllable dynamic dynamometer ", Harmonics and Quality of Power Proceedings, 1998. Proceedings. 8th International Conference On, v. 1, pp. 566 –571.

24. Tunaboylu, N.S., Collins, E.R., Jr., Middlekauff, S.W., Morgan, R.L., **“**Ride-through issues for DC motor drives during voltage sags**,”** Southeastcon '95. 'Visualize the Future’, IEEE, 26-29 March 1995, pp. 52 – 58.

25. Philips, Research on incandescent lamps, Philips Technical Review, 1975.

26. Cayless, M. A., Marsden, A. M., “Lamps and Lighting,” Manual of THORN EMI Lighting Ltd, III Edition, Edward Arnold Publishers (Great Britain), 1982.

27. T.S. Key, “Predicting behavior of induction motors during service faults and interruptions,” IEEE Trans. Ind. Application, January/February 1995, pp. 6-11.

28. Ching-Yin Lee, Bin-Kwie Chen, Wei-Jen Lee, Yen-Feng Hsu, “Effects of various unbalanced voltages on the operation performance of an induction motor under the same voltage unbalance factor condition,” Industrial and Commercial Power Systems Technical Conference, IEEE 1997, 11-16 May 1997, pp. 51 – 59.

29. Richards, G.G., Laughton, M.A., **“**Limiting induction motor transient shaft torques following source discontinuities**,”** Energy Conversion, IEEE Transactions, v. 13 Issue: 3, Sept. 1998, pp. 250 – 256.

30. Tamura, J., Takeda, I., **“**A new model of saturated synchronous machines for power system transient stability simulations**,”** Energy Conversion, IEEE Transactions, v. 10, Issue: 2, June 1995, pp. 218 – 224.

31. Alexandrovitz, A., Ayal, M., **“**Dynamical behavior of synchronous generator under various transient conditions**,”** Electrical and Electronic Engineers in Israel, IEEE, 2000, pp. 213 – 217.

32. E.R. Collins, Jr., A. Mansoor, “Effects of voltage sags on AC motor drives,”IEEE Annual Textile, Fiber, and Film Industry Technical Conference, 1997, pp. 7.

33. Becker, C., Braun, W., Jr., Carrick, K., Diliberti, T., Grigg, C., Groesch, J., Hazen, B., Imel, T., Koval, D., Mueller, D., St. John, T., Conrad, L.E., "Proposed chapter 9 for predicting voltage sags (sags) in revision to IEEE Std 493, the Gold Book," Industrial and Commercial Power Systems Technical Conference, 1993. Conference Record, Papers Presented at the 1993 Annual Meeting, 2-6 May 1993, pp. 43 – 51.
34. Lidong Zhang, Bollen, M.H.J., "Characteristic of voltage sags (sags) in power systems," Harmonics And Quality of Power, 1998. Proceedings. 8th International Conference on, v. 1, 14-16 Oct. 1998, pp. 555 – 560.
35. Styvaktakis, E., Bollen, M.H.J., Gu, I.Y.H., "Classification of power system events: voltage sags," Harmonics and Quality of Power, 2000. Proceedings. Ninth International Conference on, v. 2, 1-4 Oct. 2000, pp. 745 – 750.
36. Radhakrishna, C., Eshwardas, M., Chebiyam, G., "Impact of voltage sags in practical power system networks," Transmission and Distribution Conference and Exposition, 2001 IEEE/PES, v. 1, 28 Oct.-2 Nov. 2001, pp. 567 –572.
37. "Understanding the Cost of Power Interruptions to US Electricity Consumers," September, 2004.