

Effects of Voltage Sags on Household Loads

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Introduction

- Voltage sags is an important part of the power quality problem
- Significant amount of research concentrated on power quality issues
- Detailed literature review was performed to study the effect of sags on power system operation, induction motors, synchronous machines, and adjustable speed drives (ASDs)
- The literature survey incorporated around 40 IEEE and other technical journal papers

Motivation

- **No significant and authentic data is available to study the effect of sags on household loads**
- **Very few journal papers are published on the effect of sags on residential loads, specially on sensitive equipment**
- **The sensitivity of household equipment is increasing because of increasing use of electronics**
- **Due to the fast changing technology, the test results performed few years ago have become obsolete**

Objectives

- To present an experimental study of the effect of voltage sags on household loads such as air conditioners, lighting loads, DVD players, televisions and other sensitive equipment
- To design Computer Business Equipment Manufacturers Association (CBEMA) curves for loads that stalled/ switched off due to sags, and compare with the standard CBEMA curves
- To create a prediction table for the effect of sags on a single apartment unit
- To discuss financial implications of sags on customers and utilities

Experiments on Household Loads

- **Contactors and Circuit Breakers**
- **Motor loads eg. Air conditioners**
- **Lighting loads eg. Fluorescent and Helium Lamps**
- **Sensitive equipment**
 - ✓ **Computers**
 - ✓ **Microwave Ovens**
 - ✓ **Televisions**
 - ✓ **DVD and VCR players, digital radio clocks**

What are voltage sags???

A sag or dip, as defined by IEEE Standard 1159, IEEE Recommended Practice for Monitoring Electric Power Quality, is

“a decrease in root mean square (rms) voltage at the power frequency for durations from 0.5 cycles to 1 minute, reported as the remaining voltage”

Typical values of sags are between 0.1 pu and 0.9 pu.

Terminology used...

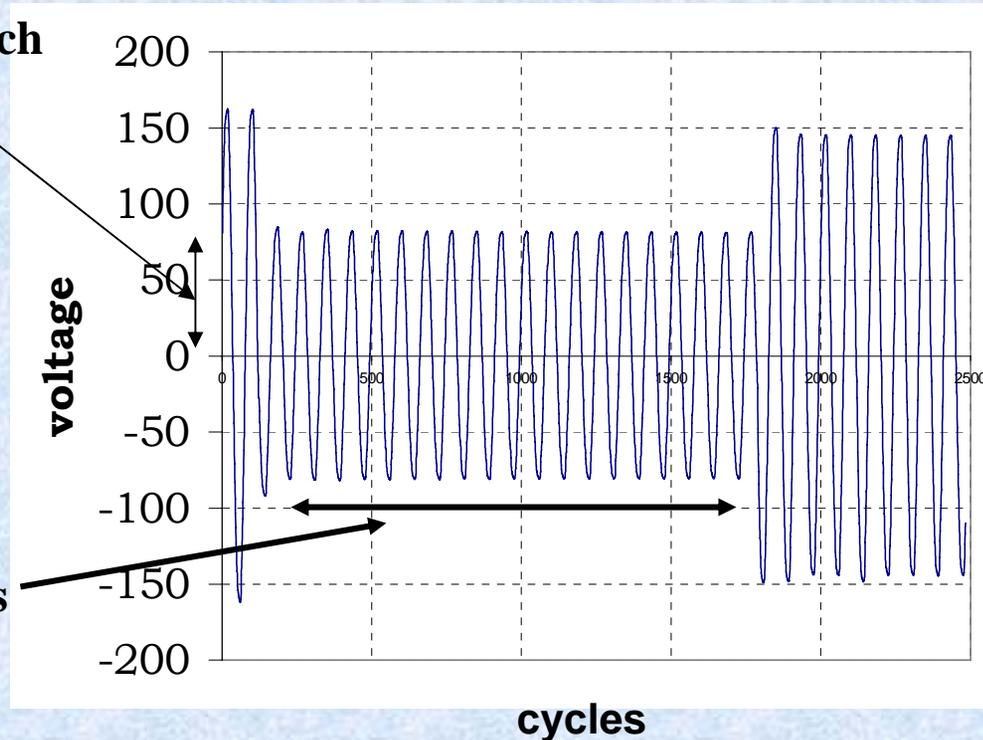
- The terminology used to describe voltage sag is confusing
- Sag “of” 20% means a voltage drop, ΔV of 20% from its initial voltage level
- 20% sag depth represents that the “remaining voltage” is 20% of the original line voltage

Terminology used



Voltage Sag: A Pictorial View

Sag depth of 50% which depicts the remaining voltage in%



Sag period of 20 cycles

Voltage sag showing 50% sag depth, 20 cycle duration

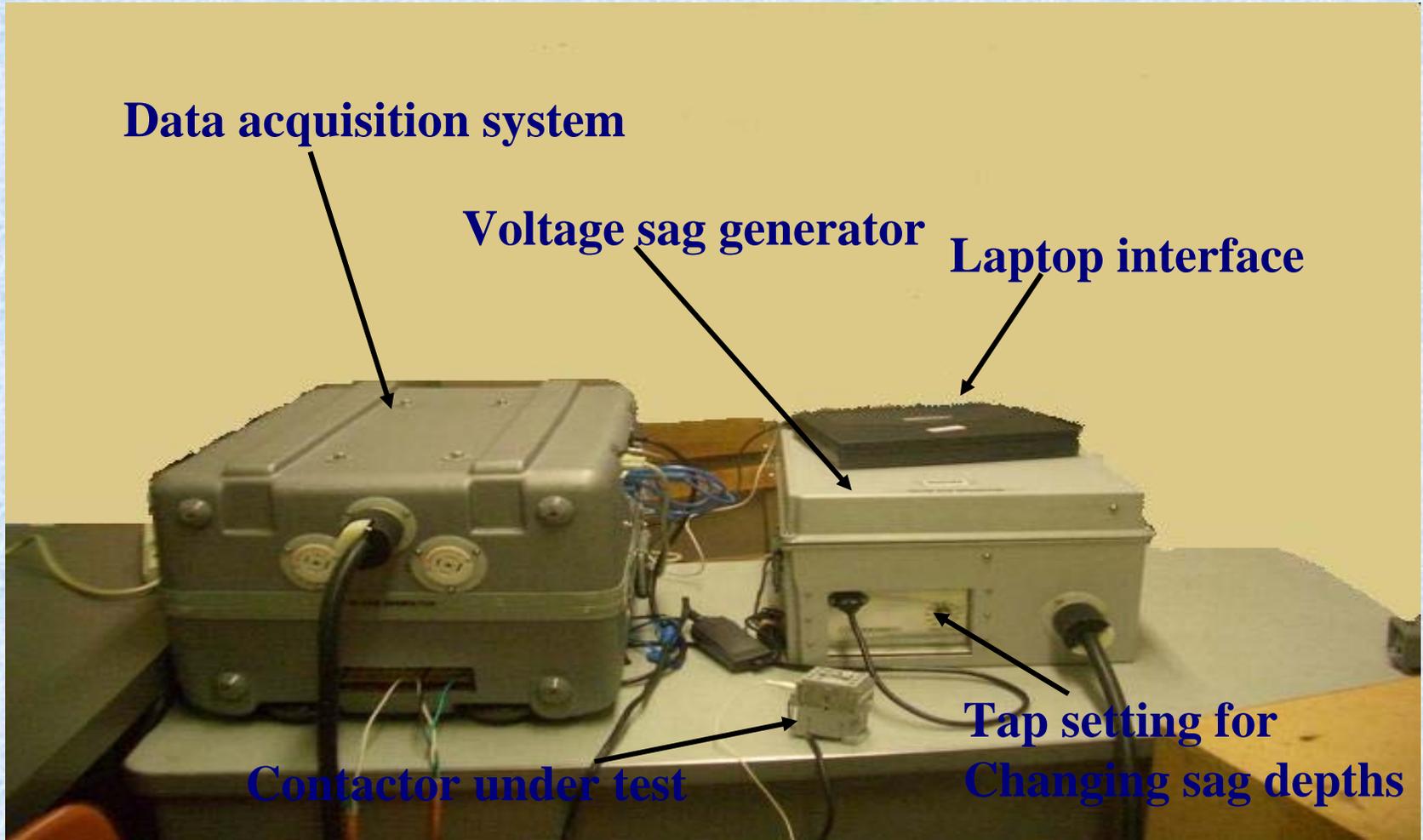


Experimental Configuration

Experimental Configuration

- The sags are created using the EPRI Process RideThrough Evaluation System (PRTES) which is a portable voltage sag generator with built in data acquisition system
- Salt River Project (SRP) lent the voltage sag generator
- **The sag generator supplied directly the test object.**
- **The current of the test object and the voltage across the terminals was measured and recorded**

Experimental Configuration



EPRI PRTES system – portable sag generator and built-in data acquisition system

Test Procedure

- The sag depths are varied in steps of 10% starting from 90% and going to 50% using the tap setting
- At each sag depth the sag duration was varied from 5, 10, 20... 60 cycles. (10 Cycle steps)
- The voltage and current wave shapes were measured and recorded in an excel file



Experiments on Air- Conditioner Compressors

Experiments on Air-Conditioner Compressors

Three window unit air conditioners were tested:

- **Air conditioner A**, 2kW, 9A full load
- **Air conditioner B**, 1kW, 7.4A full load
- **Air conditioner C**, 670W, 6.1 A full load

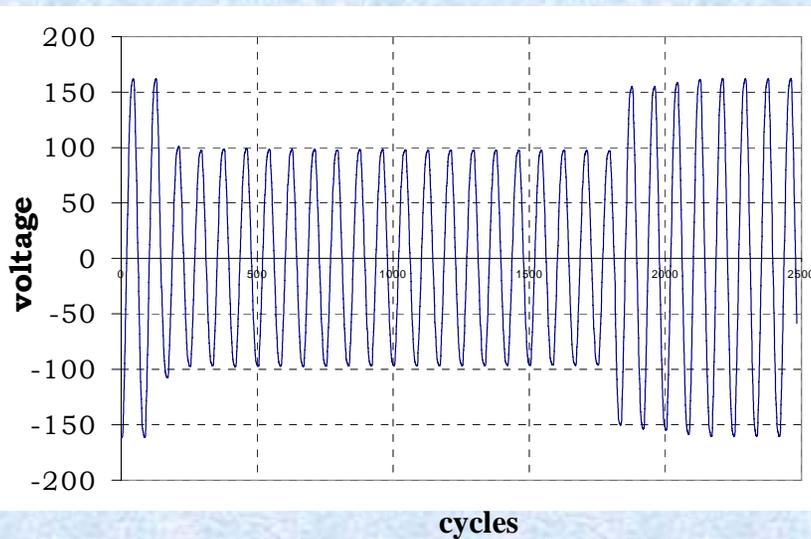
Experiments on Air-Conditioner Compressors

Specifications of air conditioner compressor A

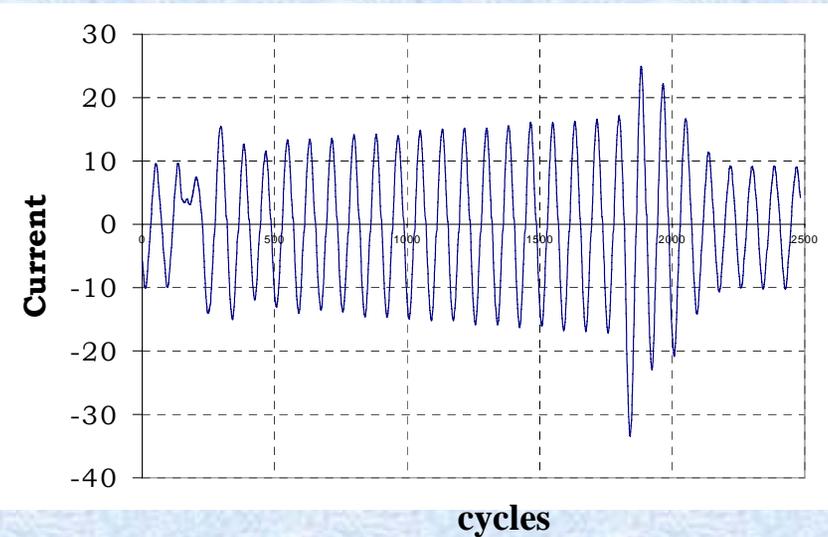
- 120 V ac single phase thermally protected
- Full load amperes: 7.4 A
- Locked rotor amperes: 35.7 A
- Measured operating current: 6.7 A
- Peak value of starting current of the compressor before subjected to sags: 48 A

Experiments on air-conditioner compressors

Non stalling condition for compressor A



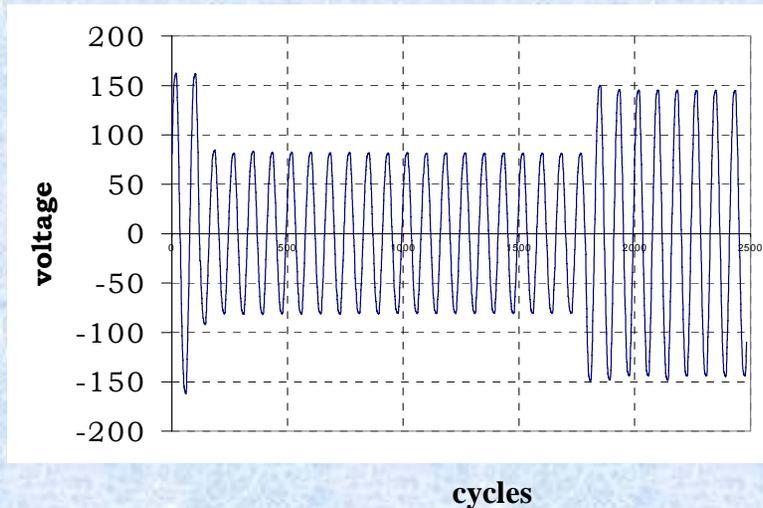
Voltage sag (60% depth, 20 cycles)



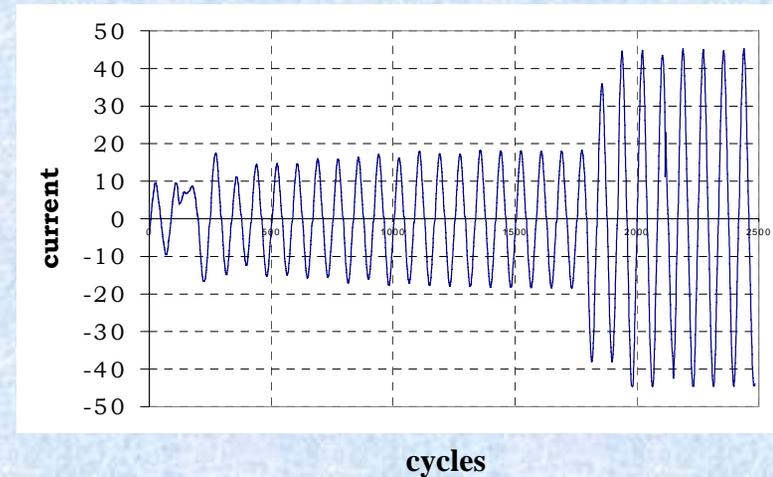
Responding motor current

Experiments on air-conditioner compressors

Stalling condition for compressor A



Voltage sag (50% depth, 20 cycles)



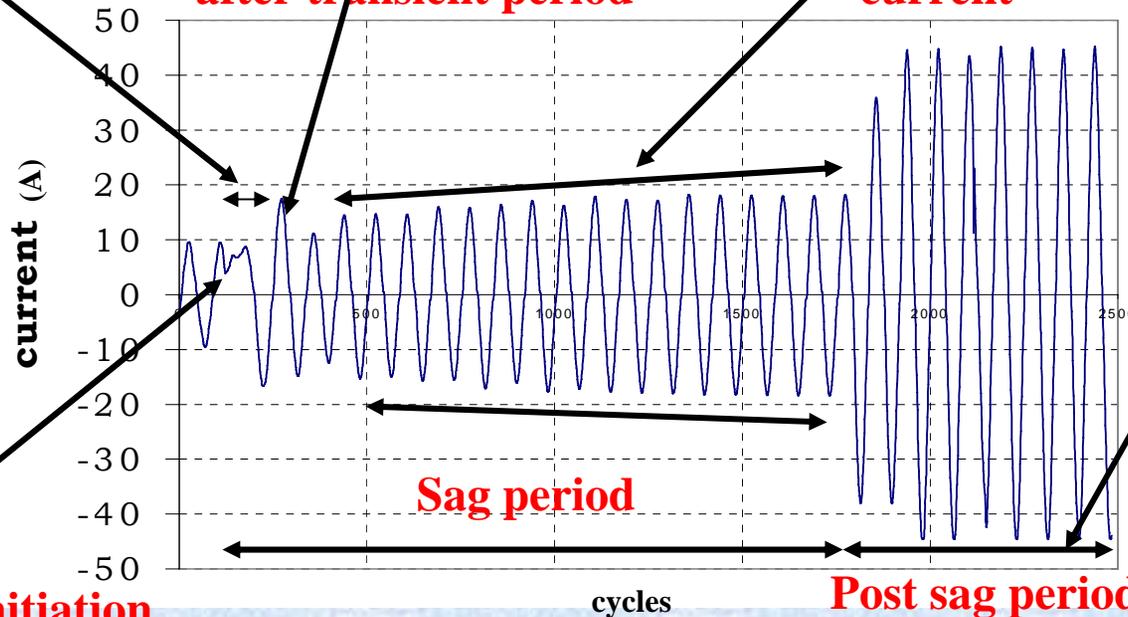
Responding motor current

Experiments on Air-Conditioners

Momentary transient period

1.5 times normal current after transient period

Gradual increase in current



High current greater than locked rotor current signifying stalling condition

Responding motor current for stalling condition for compressor A

Experiments on air-conditioner compressors

Results of stalling conditions for different sag depths and durations for compressor A

	60%	50%	40%	30%	20%	10%
5Cycle	N	N	N	N	N	N
10Cycles	N	N	N	N	N	N
12Cycles	Y	N	N	N	N	N
15Cycle	Y	Y	N	N	N	N
20Cycles	Y	Y	N	N	N	N
30Cycle	Y	Y	N	N	N	N
40cycle	Y	Y	Y	N	N	N
45Cycle	Y	Y	Y	N	N	N
60cyle	Y	Y	Y	N	N	N
90cycle	Y	Y	Y	N	N	N
120cycle	Y	Y	Y	N	N	N
150cycle	Y	Y	Y	N		

N: Non- stalling condition Y: Stalling condition

For a sag of 50% depth and duration 60 cycles, compressor A stalls

Experiments on Air-Conditioners

Three window unit air conditioners were tested

Results of stalling conditions for air-conditioners

Sag Depth (%)	Sag Duration (cycles)					
	5	10	20	30	40	60
90	N	N	N	N	N	N
80	SR	SR	SR	SR	SR	SR
70	SR	SR	SR	SR	SR	SR
60	SR	SR	SR	SR	S	S
50	SR	SR	S	S	S	S

N – no effect on speed of compressor

SR – speed reduction due to sag

S – air-conditioner stalls

Experiments on Air-Conditioners

Conclusions

- Air conditioners stall for sags of 60% depth and 40 - cycle and 60 - cycle duration, and sags of 50% depth and duration greater than 10 cycles; thermal protection causes the compressor to stall
- The motor current can rise to as high as 4.7 pu during sag
- Initiation phase of the sag has no obvious effect on the performance of the motor

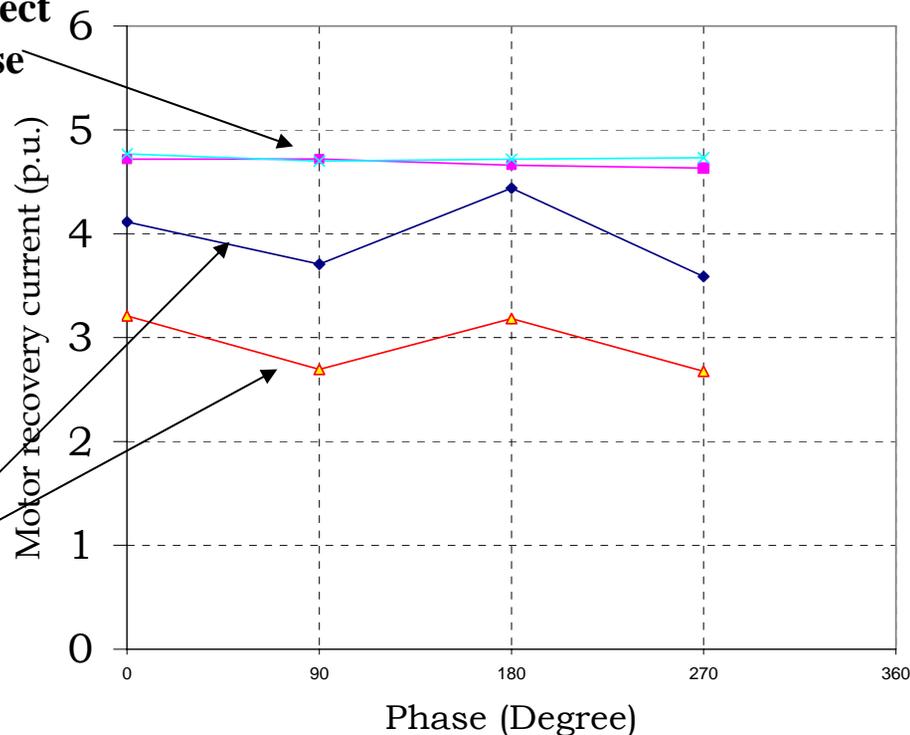
Experiments on Air-Conditioner Compressors

Impact of sag initiation phase on motor recovery current

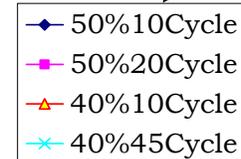
Stalling cases; no effect of sag initiation phase on recovery current

Motor recovery current in per unit

Non-stalling cases; recovery current for sags initiated at 0 and 180 deg. Is greater than that for 90 and 270 deg.



Sags represent voltage drop in this case



Experiments on Air-Conditioner Compressors

Conclusions

- **Compressor A stalls for sags of depths 60% and more and duration greater than 40 cycles**
- **Compressor B stalls for sags of depths 60% and more and duration greater than 20 cycles**

Experiments on Air-Conditioner Compressors

Conclusions (Generalized)

- Test results of 2 motors show that motor stalls for sags deeper than 60% and longer than 20 cycles
- The motor current can rise to as high as 4.7 pu during sag
- Initiation phase of the sag has no obvious effect on the performance of the motor.

Experiments on Air-Conditioner Compressors

- The gradual increase of sag and sag duration leads to the stalling of the motor
- The motor stops and current increases to the starting current
- The large current activates the thermal protection in the winding
- The motor is re-started manually



Experiments on Lighting Loads

Experiments on Lighting Loads

- **Experiments were conducted on**
 - **fluorescent lamps and**
 - **helium lamps**
- **Lamps were subjected to sags of different depths, durations and initiation phases**

Experiments on Lighting Loads

Fluorescent lamps

Specifications of Fluorescent Lamp Tested

- **GE/Philips SP35 32W Canada**
 - 110VAC/32Watt
- **Regular size (4 feet) fluorescent lamp**
 - 120V, RMS value of operation current is 0.33 A.

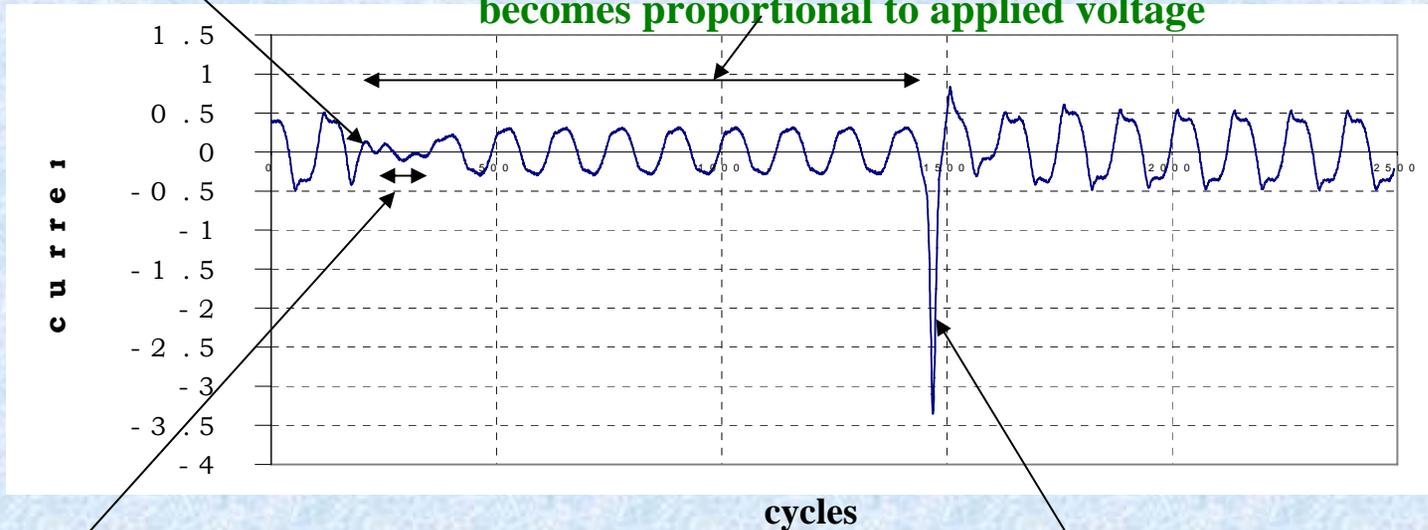
Experiments on Lighting Loads

- **The sag produces a sudden reduction of light intensity**
- **The current becomes zero at the beginning of sag for two cycles**
- **Subsequently, current increases to a value, which is proportional to the sag voltage**
- **When sag ends, a current spike occurs and then current returns to its normal**
- **During the current spike the light intensity increases sharply**

Experiments on Lighting Loads

Point of sag initiation

Sag period where current becomes proportional to applied voltage



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

Zero current indicating beginning of sag

Current spike indicating end of sag

Experiments on Lighting Loads

Helium Lamps

Specifications of Helium Lamp Tested

- **GE Helium Lamp**
 - **120V AC/ 750 Watts**
 - **Measured operating current: 6.19 A**

Experiments on Lighting Loads

Conclusions

- Light dims during sags in helium lamps
- Lamp current is proportional to sag depth
- Dimness of light is dependent on sag depth and is independent of sag duration
- At the end of the sag, a current surge occurs resulting in a sharp increase in the intensity of light.
- This may reduce the life of the lamps



Experiments on Computers

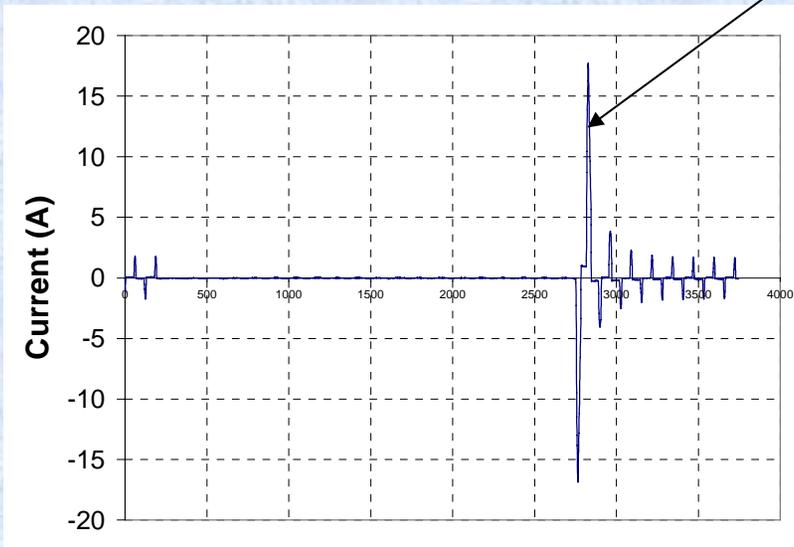
Experiments on Computers

Specifications of the tested computers

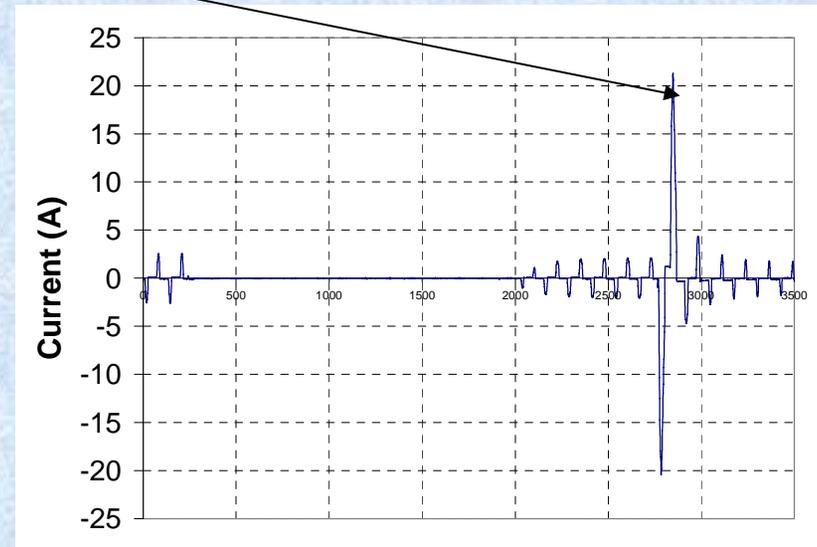
	Computer A	Computer B
	<i>Dell Optiplex</i>	<i>Genuine Intel</i>
CPU	Pentium3	Pentium2
RAM	328M	32M
Hard Disk	15G	3G
Monitor	Dell 17'	Optiquess 17'
CD-R	CD-R	CD-R
Operating system	Windows 2000	Windows 98

Experiments on Computers

High current surges of the order of 7-10 times the normal current indicating end of sag



Current for 60%/ 20 ~ No loading/ Restart



Current for 50%/ 30 ~ loading/ Restart

Loading refers to the case when the hard disk is loading data

Experiments on Computers

Effect of voltage sag on computer A's restarting and data loading

Experiments were conducted considering two cases: when the hard disk is loading data and one when it is functioning normally without loading data

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

For a sag of depth 40%, duration of 15 cycles or less and when hard disk is not loading data, there is no effect on computer A

For a sag of depth 50%, duration of 8 cycles or more and when hard disk is loading data, computer A restarts

Experiments on Computers

- If the sag duration is shorter than 7 cycles, sags do not cause the restart of a computer and the loss of data
- 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
- 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

Experiments on Computers

- **Voltage sag is normally not a huge problem to single computers unless they are used as servers or mainframe computers.**
- **The sag typically restarts the computer, which results in loss of data**
- **This may cause financial losses to trading and telecommunication offices**

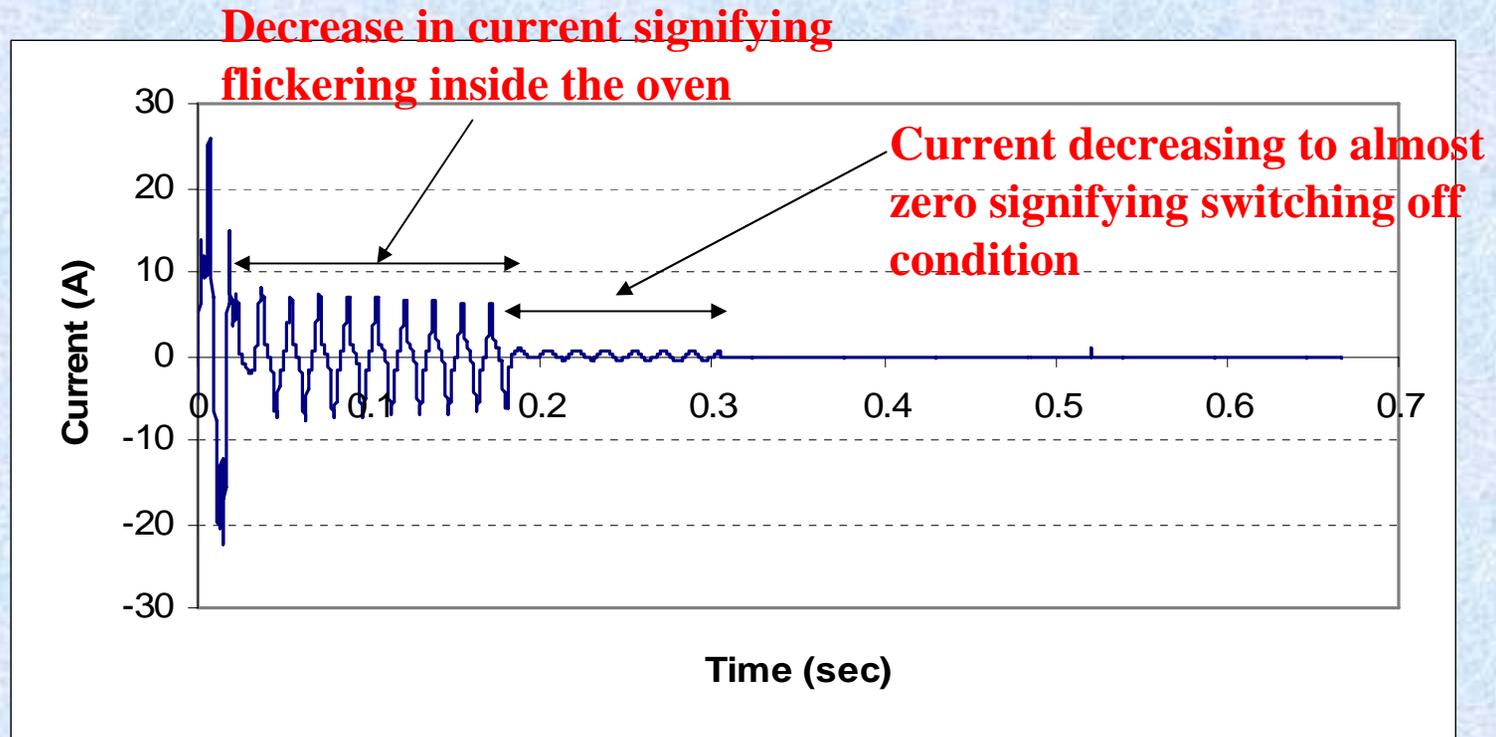
Experiments on Computers

- The obtained numbers (which represent sag depths and sag duration) were put in the CBEMA curve and were seen to comply with the experimental values.



Experiments on Microwave Ovens

Experiments on Microwave Ovens



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

Experiments on Microwave Ovens

Two microwave ovens were tested

Summary of performance of microwave oven A due to sags

Sag Depth (%)	Sag Duration (cycles)					
	5	10	20	30	40	60
90	V	V	V	V	V	D
80	V	V	V	V	V	D
70	V	V	V	V	V	D
60	V	V	V	S	S	S
50	V	S	S	S	S	S

V: oven does not switch off, only visible effects such as flickering

D: oven does not switch off, visible effects such as flickering and momentary stopping of digital clock

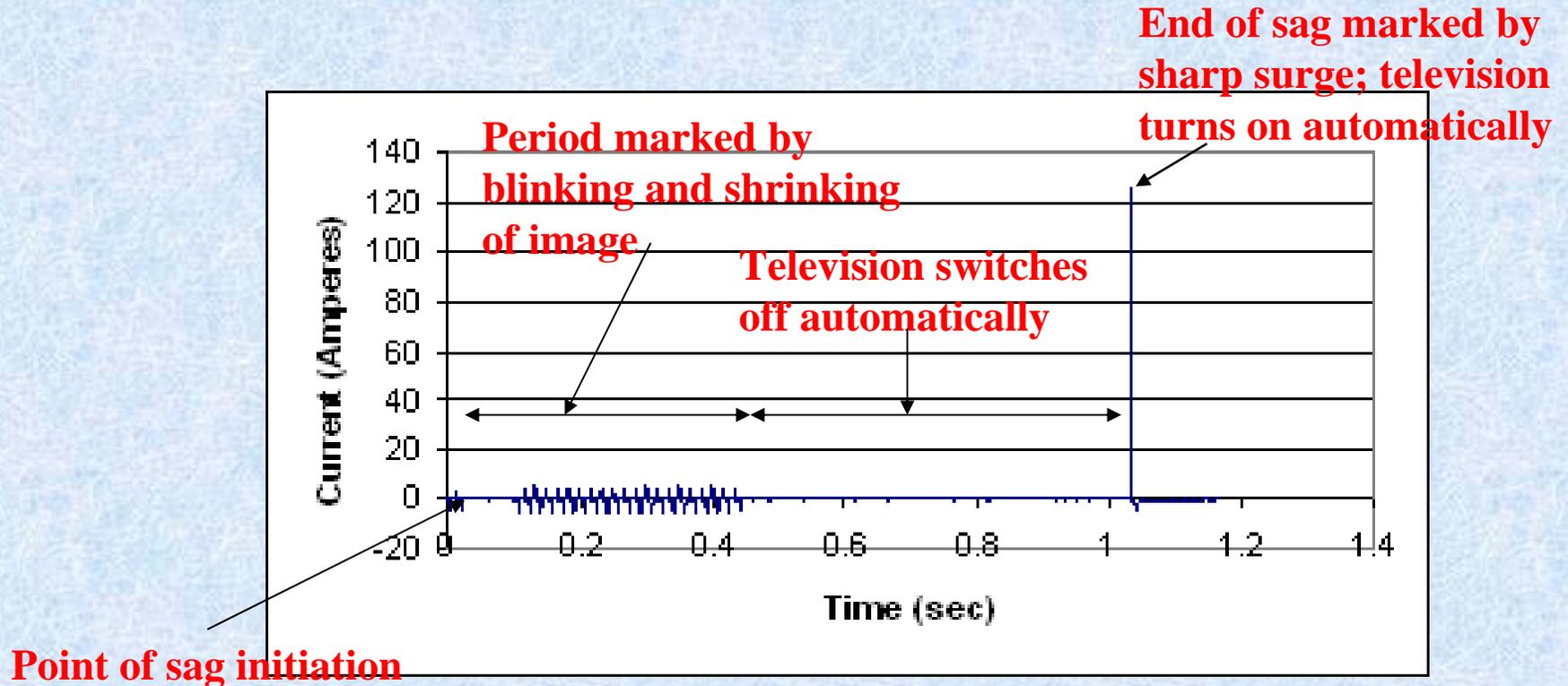
S: oven switches off without getting damaged

Experiments on Microwave Ovens

Conclusions

- No microwave oven was damaged due to sags of varying depths and duration
- Microwave oven A switched off for 60% depth/ 30 cycle duration and 50% depth/ 10 cycle duration
- Microwave oven B showed only visible effects of sags such as flickering

Experiments on Televisions



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

Experiments on Televisions

Two televisions were tested

Summary of performance of televisions due to sags

Sag Depth (%)	Sag Duration (cycles)					
	5	10	20	30	40	60
90	N	N	N	N	V	V
80	N	N	V	V	V	V
70	V	V	V	V	V	V
60	V	V	V	V	V	V
50	V	V	V	S	S	S

- **N:** television has no effect of sag
- **V:** television does not switch off; only visible effect such as blinking and shrinking of image
- **S:** television switches off without getting damaged

Experiments on Televisions

Conclusions

- No television was damaged due to sags of varying depths and duration because of internal protection circuitry
- The televisions switched off for 50% depth and duration greater than 20 cycles
- The end of sag was marked by a surge; at this instant the television switches on automatically
- The cause of the surge is Switch Mode Power Supply (SMPS) inside the television

Experiments on DVD/VHS Players

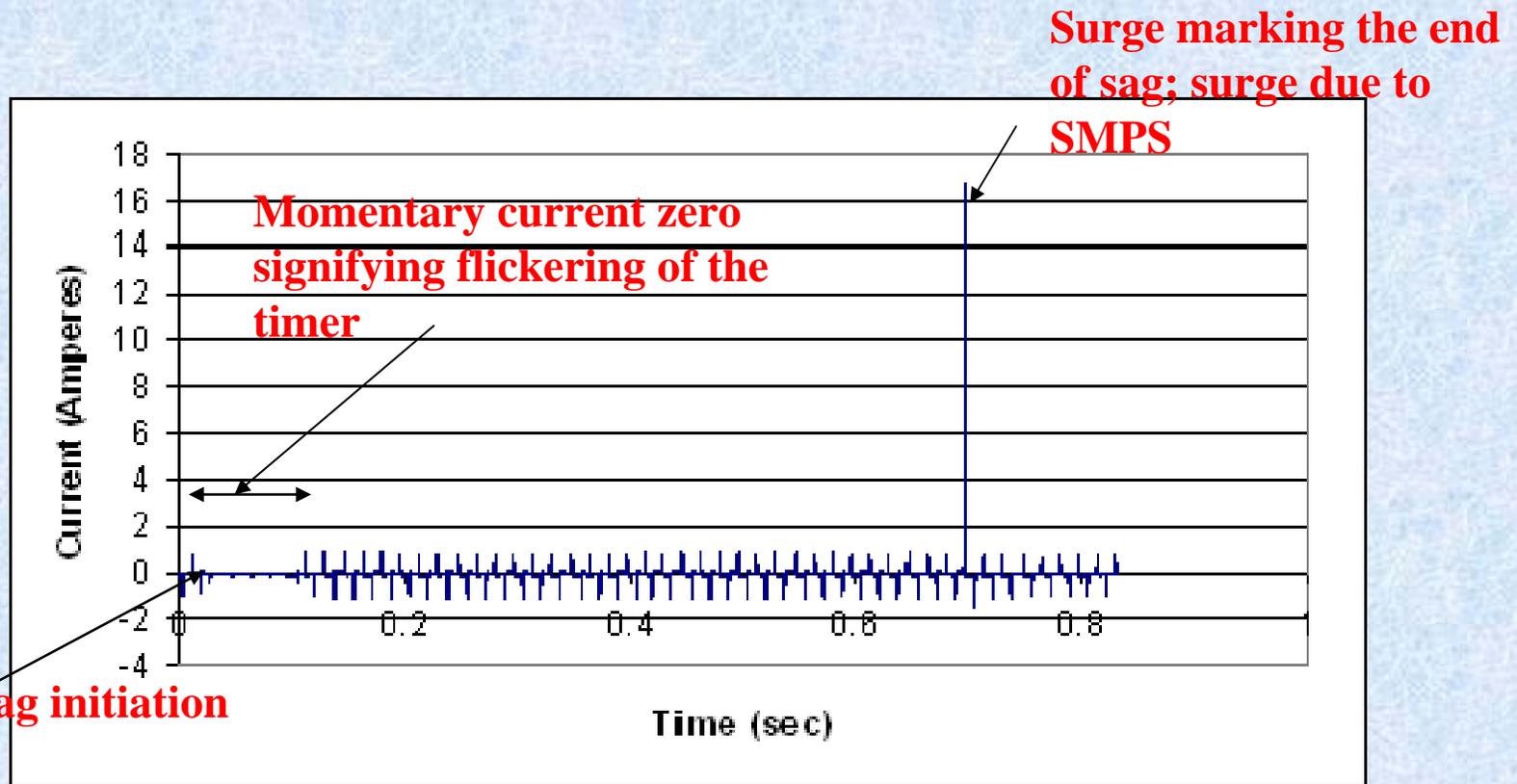
Three VHS/DVD players were tested

Summary of performance of DVD/ VHS players due to sags

Sag Depth (%)	Sag Duration (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	V	V	V
60	N	N	N	V	V	V
50	V	V	D	D	D	D

- **N:** VHS/DVD has no effect of sag
- **V:** VHS/DVD does not switch off; only visible effect such as blinking of electronic timer
- **D:** VHS/DVD does not switch off; electronic timer stops momentarily

Experiments on DVD/VHS Players



Current waveform for 70%, 50-cycle sag (flickering in timer)

Experiments on VHS/DVD Players

Conclusions

- No VHS/DVD player was damaged due to sags of varying depths and duration
- The only effect of sags is the visible effect termed as flickering of the electronic timer
- The end of sag was marked by a surge
- The cause of the surge is Switch Mode Power Supply (SMPS) inside the players

Experiments on Digital Clock Radios

Two FM/AM digital clock radios were tested

Summary of performance of digital clock radios due to sags

Sag Depth (%)	Sag Duration (cycles)					
	5	10	20	30	40	60
90	N	N	N	N	N	N
80	N	N	N	N	V	V
70	V	V	V	V	V	V
60	V	V	V	V	A	A
50	V	V	V	A	A	A

- N: digital clock radio has no effect of sag
- V: only visible effect such as flickering of the electronic timer
- A: loss of audio for few cycles

Experiments on Toasters

Two toasters were tested

Summary of performance of toasters due to sags

Sag Depth (%)	Sag Duration (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	V	V	V	V	V	S/V
50	V	V	V	V	S/V	S/V

- **N:** toaster has no effect of sag
- **V:** only visible effect such as blinking of the coils
- **S:** toaster switches off; to be restarted manually

Experiments on Toasters

Conclusions

- No toaster was damaged due to sags of varying depths and duration
- For the case when toaster has just begun operation, toaster switches off automatically for 60% depth/60 cycle and 50% depth/40 cycle, 60 cycle duration; it is restarted manually
- For the case when toaster is already operational, there is no effect of sag except blinking of red hot coils



CBEMA Curve Analysis

CBEMA Curve Analysis

- **CBEMA curve defines the envelope within which the equipment should continue to function without interruption**
- **It plots the depth of voltage sags in percentage on the vertical axis against the duration of voltage sags on the horizontal axis**
- **Curves have been created for all the appliances that were switched off or stalled due to voltage sags – air conditioners, computers, microwave ovens, and televisions**

CBEMA Curve Analysis - Methodology

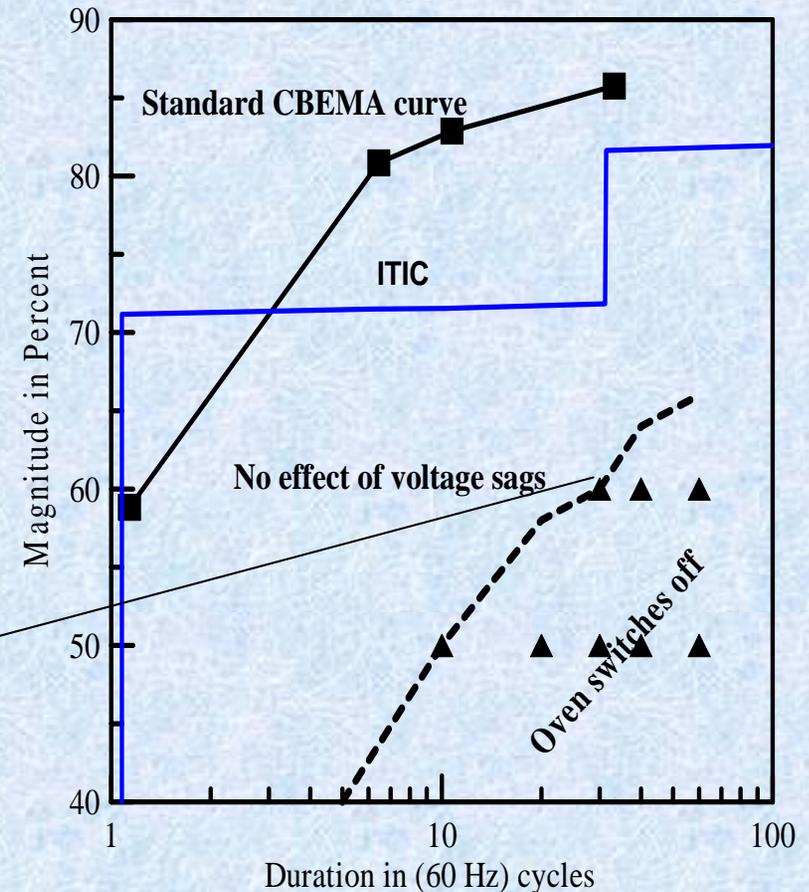
- The CBEMA curves are plotted using the results of the experiments performed on the various appliances
- The CBEMA curve for the appliance is created by looking at the voltage sag depth and duration for which the appliance is affected by the sag
- For a particular sag depth, if the appliance is affected by several sag durations, then the minimum sag duration for which the equipment stalled is taken as the boundary point

CBEMA Curve Analysis-Methodology

- A percentage level of 40% is used to provide zero level for the CBEMA curve
- The corresponding sag duration for 40% sag depth is chosen as duration which is less than the x coordinate of the boundary point

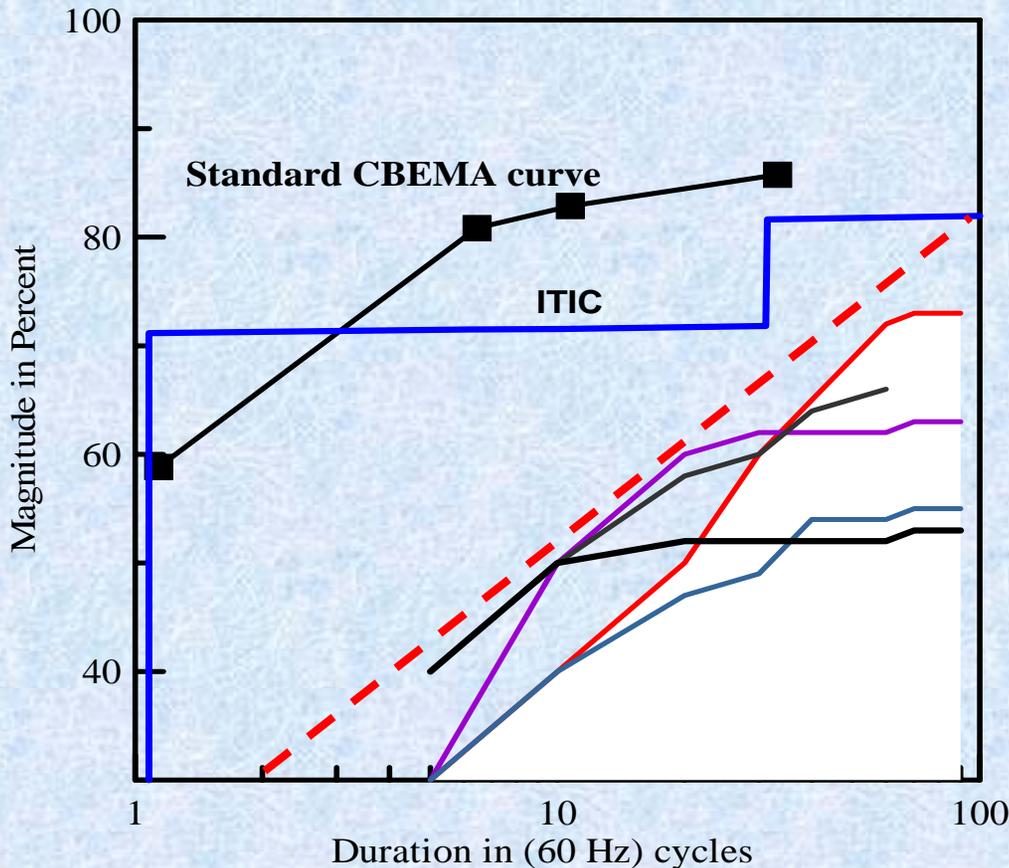
CBEMA Curve Analysis-Methodology

Sag Depth (%)	Sag Duration (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



☰ Microwave oven switches off

CBEMA Curve Analysis



Air-conditioner compressors
Lighting Loads
Microwave Ovens
Televisions
Computers

- The obtained CBEMA curves are conservative in comparison to standard CBEMA/ITIC curves
- These curves provide the utilities and the manufacturers with the information about the sensitivity of the equipment to voltage sags



Survey of Residential Complexes

Survey of Residential Complexes

- **The survey of electric loads is performed for an apartment complex to identify the most common electric loads present in each unit**
- **Two apartment complexes were surveyed – Tempe Terrace and University Crossroads**
- **The common loads are the air-conditioning motors, fan motors, refrigerators, microwave ovens, bulbs, crushers, and televisions**

Creation of Prediction Table for a Single Apartment Unit

- The identification of the common loads through surveys resulted in the creation of prediction table for a single apartment
- It predicts the effect of voltage sags on a single apartment as a function of sag depth and duration
- 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

Sample Prediction Table

		5~	10~	20~	30~		40~	60~
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 and turns on automatically after the sag		AC motor stalls, Microwave ovens switches off automatically, television switches off automatically and turns on 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



Financial Implication of Voltage Sags

Financial Implication of Voltage Sags

- **Voltage sags do not damage any household equipment. Hence, residential customers have minimal or no cost of voltage sags incurred on them**
- **Electric utilities might incur financial losses if voltage sags cause feeders to go out of operation.**
- **This scenario is possible if all the air-conditioner compressors in an apartment complex are stalled for sag of 50% depth and duration greater than 30 cycles and restarted simultaneously**



Overall Conclusions

Overall Conclusions

- **The most severely effected is the computer as sag can cause loss of data**
- **No damage occurred on any of the loads**
- **The sag may stop the air conditioners in the residential areas due to sags**
- **The restart can produce over load if all air-conditioners are started simultaneously and further sags can occur.**
- **In residential areas, the sag has minimal financial consequences to the owners**

Contribution of the Project

- **Has provided the utilities and the customers with the information that voltage sags are not a serious cause of concern in residential areas**
- **Has provided the utilities and the manufacturers of sensitive equipment with CBEMA curves which will inform them about the sensitivity of the equipment**
- **Has provided the utilities with a prediction table of a single apartment which will help in predicting the performance of loads on being subjected to voltage sags**

Publications

- **S. Saksena, B. Shi, G. Karady, “Effects of voltage sags on household loads,” IEEE Power Engineering Society, San Francisco, June 2005**
- **S. Saksena, G. Karady, “Effects of voltage sags on sensitive equipment in residential complexes,” IEEE Transaction on Power Delivery, to be submitted**
- **S. Saksena, G. Karady, “Designing CBEMA curves for household appliances affected by voltage sags,” IEEE Transaction Letter, to be submitted**

Acknowledgements

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- **Special thanks to Dr. Baj Agrawal, Arizona Public Service for key inputs**
- **Special thanks to Salt River Project for lending us the Voltage Sag Generator**