# Transmission Planning Technical Guide

# Appendix E

## Dynamic Stability Simulation

## Voltage Sag Guideline


System Planning
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# Table of Content

## VOLTAGE SAG PARAMETERS

The minimum post-fault positive sequence voltage sag must remain above 70% of nominal voltage and must not exceed 250 milliseconds below 80% of nominal voltage within 10 seconds following a fault.

These limits are supported by the typical sag tolerances shown in Figures C.5 to C.10 in IEEE Standard 1346-1998.

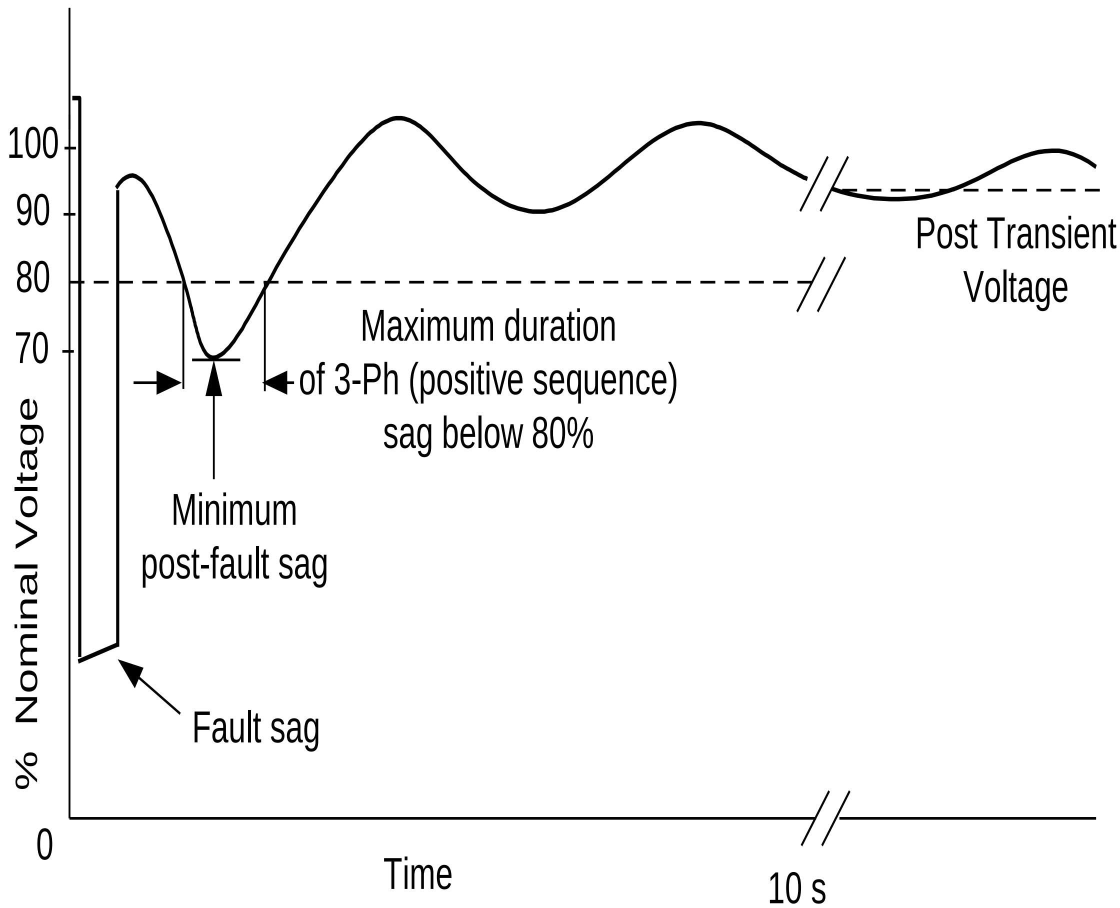


Figure 1– Transient Voltage Sag Parameters

## Voltage Sag Introduction

The intent of this guideline is to avoid uncontrolled significant load shedding that may lead to unintended system performance, such as widespread system collapse.  This guide is not intended as a standard of utility supply to individual customers, as a standard of power quality, nor used for transmission or distribution protection design.

The voltage sag resulting from a system short circuit or fault depends on the location of the fault in relation to the measured voltage, and may vary from zero to a few percent of normal. The duration of the sag is determined by the fault clearing time and ranges from as low as 3 cycles on 345kV systems to one or more seconds on 34.5 kV sub-transmission systems. Following the fault clearing, the voltage passes through a transient recovery period before settling to the post-fault value. During this oscillatory transient period, additional voltage dips typically occur immediately after the voltage attempts to return to the pre-fault level. The starting voltage, sag, and duration of these post-fault transient under-voltages are a measure of the system strength. The performance indicators for prompt restoration of voltage are the object of this guide.

This guide:

- provides background information on the cause and effects of voltage sags associated with transmission faults
- discusses relevant IEEE Recommended Practices and Guides and technical papers which discuss voltage sags and their effect on transmission system performance or utilization equipment
  (IEEE has developed Recommended Practices to guide equipment manufacturers and customers regarding end-use equipment sensitivity to voltage transients and the application of power-conditioning equipment. Note that there are no utility transmission design or operating voltage sag standards.)
- defines guideline criteria for the post-fault sag magnitude and duration.

This Voltage Sag Guideline applies only to the transmission system and therefore cannot be assumed to represent the voltage at the points of utilization. The voltage sag during the fault is not covered by this guide.

## The Cause of Voltage Sags

During the fault period, the active power transferred from the generators to the system is reduced, causing the generators' internal angles to advance. When the fault is cleared, the generators have to supply the pre-fault active load again and their internal angle moves toward to their pre-fault value. This slowing of the local generators draws inrush decelerating power from the remote generators and, coupled with motors' demand for accelerating power (the motors have slowed down during the lower fault voltage), causes a new voltage sag on the system. This second sag is then followed by an oscillatory transition to the post-fault steady-state voltage, as the machine prime mover power is again in balance with the electric load.

## VOLTAGE SAG EFFECTS

### Power Quality

The voltage sags caused by high voltage transmission faults are classified as "Instantaneous" sags in IEEE (Institute of Electrical and Electronics Engineers) Standard 1159-1995 Table 2 (0.4 cycles to 30 cycles, 0.1 to 0.9 per-unit voltage) and the post-fault voltage swings are categorized as "Momentary" (30 cycles to 3 seconds, 0.1 to 0.9 per-unit voltage). The voltage dips affect sensitive loads such as computer, computer-based equipment, power conversion, etc. The voltage sags also contribute to the deterioration of the power quality, which the utilities strive to maintain for their customers. An IEEE T&D Working Group on Distribution Voltage Quality (WG 15.06.05) has commissioned a Task Force on Voltage Sag Indices (P1564 and CIGRE WG 36-07) to draft a document to survey and propose methods to measure, characterize and index voltage sag disturbances. Among some of the indices is a set of indices, similar to the popular SAIFI (System Average Interruption Frequency Index) defined in IEEE Standard 1366-1999. The proposed index (EPRI-Electrotek Indices, § 7.3 [Reference 10]) is $SARFI_x$ (System Average RMS (Variation) Frequency Index of magnitude less than threshold x), along with subsets:

- $SIARFI_x$ (System Instantaneous Average RMS (Variation) Frequency Index of magnitude less than threshold x),
- $SMARFI_x$ (System Momentary Average RMS (Variation) Frequency Index of magnitude less than threshold x)
- $STARFI_x$ (System Temporary Average RMS (Variation) Frequency Index of magnitude less than threshold x).

The thresholds and time durations of these indices are apparently chosen to correspond to standard reference equipment susceptibility curves such as the CBEMA curve (Computer Business Equipment Manufacturers Association) and the more recent ITIC (Information Technology Industry Council, the CBEMA replacement) Voltage-versus-Time curves, appearing in Figures 2 & 3. These curves are included in this report for convenience. It is of interest to note that the expected sag in these CBEMA and ITIC curves, during the "Momentary" period (from 30 cycles to 3 seconds) identified in IEEE Standard 1159-1995, is not lower than 80%.

### Loss of Load

Voltage sags affect all types of customers, depending on the sensitivity of their equipment and the extent of their power conditioning. IEEE Standard 493-1997 ("Gold Book") [Reference 12] reports that voltages to 85-90% of nominal as short as 16 milliseconds have triggered immediate outages of critical industrial processes.  In the same Standard 493-1997, Table 9-12 accounts for sags ranging from 90% to 70% with durations up to 1250 milliseconds to include the effect of motor starting.

Domestic and commercial electronic (computer) loads are more likely to ride through a sag if the magnitude and duration are within the ITIC curve. Central air conditioners' internal protection may operate or their motors may stall and contribute to a protracted recovery [Reference 11]. Florida Power & Light had hundreds of megawatts of load lost during transients due to this phenomenon.  Industrial loads are the most vulnerable to severe voltage sags. IEEE Standard 141-1993 ("Red Book") [Reference 7] Figure 3-9 compares probable sag magnitudes to a 80% baseline and advises designers to consider both the sag voltage magnitude and duration when specifying equipment performance capability during voltage sags. If a motor control contactor is unable to ride through a voltage sag, the motor and associated process is interrupted.

### Emergency and Standby Power

The Western Electricity Systems Coordinating Council's (WECC), formally the Western Systems Coordinating Council (WSCC), voltage sag criteria are based in part on a need to maintain a margin for nuclear unit auxiliary undervoltage protection and load transfer [Reference 1. A more general application is found in the setting guidelines of load-transfer devices in IEEE Standard 446-1987 ("Orange Book") [Reference 9]. In Section 4.3.6 of this Standard, typical transfer threshold settings of 75% to 95% of pickup are given, with pickup settings raging from 85% to 98% of nominal. Time delays are on the order of 1 second. This means that voltages below 80% ( the limit suggested on the ITIC curve) are likely to initiate automatic load transfers.

### Modeling Limitations

In order to determine if a voltage disturbance for a system transmission fault falls below a level and duration set in transient voltage criteria, the power system model should represent the dynamic response of load as accurately as possible. Steady state and dynamic power studies in New England have relied on static load models (constant admittance and current). An analysis done by Florida Power & Light [Reference 11] shows that the voltage recovery is worse for a simulation with a mix of static and motor models [Reference 10, Figure 4], than with the static load model only. This was confirmed in a feasibility study conducted by American Superconductor for CMP in September 2000: the post-fault voltage sag was about 0.08 per-unit lower when the industrial, commercial and residential load models were modified to include 80%, 60% and 40%, respectively, of high and low inertia motor load.

## Voltage Sag Mitigation Options

Voltage sags in power systems are unavoidable. The system can be designed and operated to minimize severe voltage sags. High speed fault clearing, special protection systems, field forcing, transmission reinforcements, and transmission interface transfer limits can be considered by generation and transmission owners as options to improve voltage sag performance. Customers can apply power-conditioning technologies such as Uninterruptible Power Supplies (UPS), and Distributed-Superconducting Magnetic Energy Storage System (D-SMES) to sensitive loads. IEEE Standard 1346-1998 [Reference 13] lists voltage sags as the greatest financial risk due to lack of compatibility of electric supply systems with electronic process equipment, and offers a method to evaluate the financial impact of incompatibility as well suggestions of financial analysis of alternatives to improve compatibility.

### APPLICABLE STANDARDS

IEEE Std 1159-1995 “IEEE Recommended Practice for Monitoring Electric Power Quality”

IEEE Std 1250-1995 “Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances”

IEEE Std 141-1993 “IEEE Recommended Practice for Electric Power Distribution for Industrial Plants” (“Red Book”)

IEEE Std 493-1997 “IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems” (“Gold Book”)

IEEE Std 1346-1998 “IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment”

P1564, Task Force on Voltage Sag Indices (proposed standard, in progress)

## RECOMMENDATION

The IEEE standards leave the sag and duration up to the specific user and application (Section 9.7 in IEEE Standard 493-1997 [Reference 12] states that “utilization equipment response to sags must be known from manufacturer specifications or from performance test data. Both supply characteristics and equipment response data sets are required…”). In this context, Planning and Operating Engineers are faced with judging between the probability of undesirable load loss and the imposition of stricter design criteria and operating limits. Based on the references, the industry has accepted 80% as a typical sag magnitude for momentary voltage sags at the point of utilization. It should be noted that the IEEE remains divided on the adoption of standard sag limits for application to utility transmission or distribution systems, and no IEEE standards for this exist today.

## APPENDIX A

## THE CBEMA and ITIC CURVES [Reference 3]

The well known CBEMA and ITIC power acceptability curves are not the direct objective of this voltage sag guideline and were not developed as a guide for utility supply. Rather, these curves were intended to be used as a guide for equipment manufacturers and utility customers in making decisions for power conditioning equipment for sensitive loads. The curves are reproduced here for reference and comparison to this voltage sag guide only.

Note that the voltage scale shows percent deviation from pre-sag operating voltage, not percent of nominal voltage.

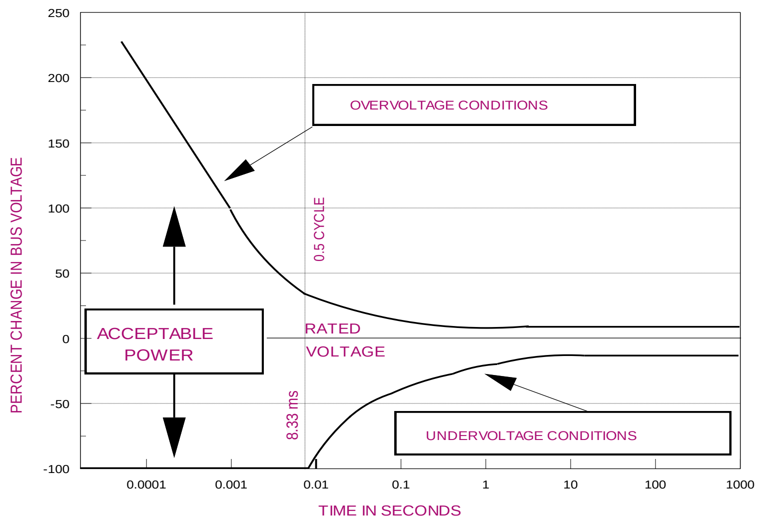


**Figure 2 – CBEMA Curve**

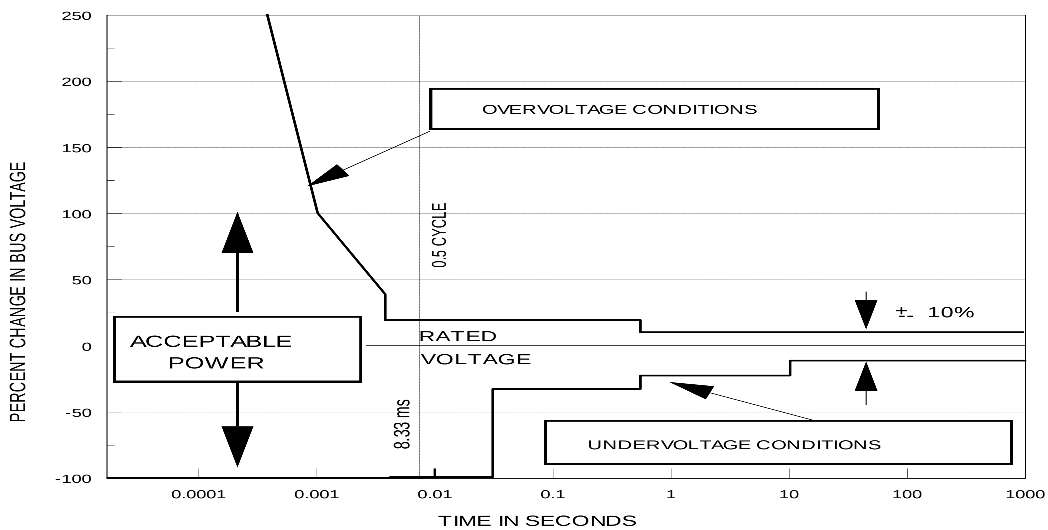


**Figure 3 – ITIC Curve**

## Composite Curve [Reference 10] (IEEE P1564_99_01.doc)

This curve was reproduced from a draft document posted on the IEEE P1564 Working Group site, and may be adopted into the proposed Standard for classifying voltage sags.

This curve applies to equipment at the point of utilization.

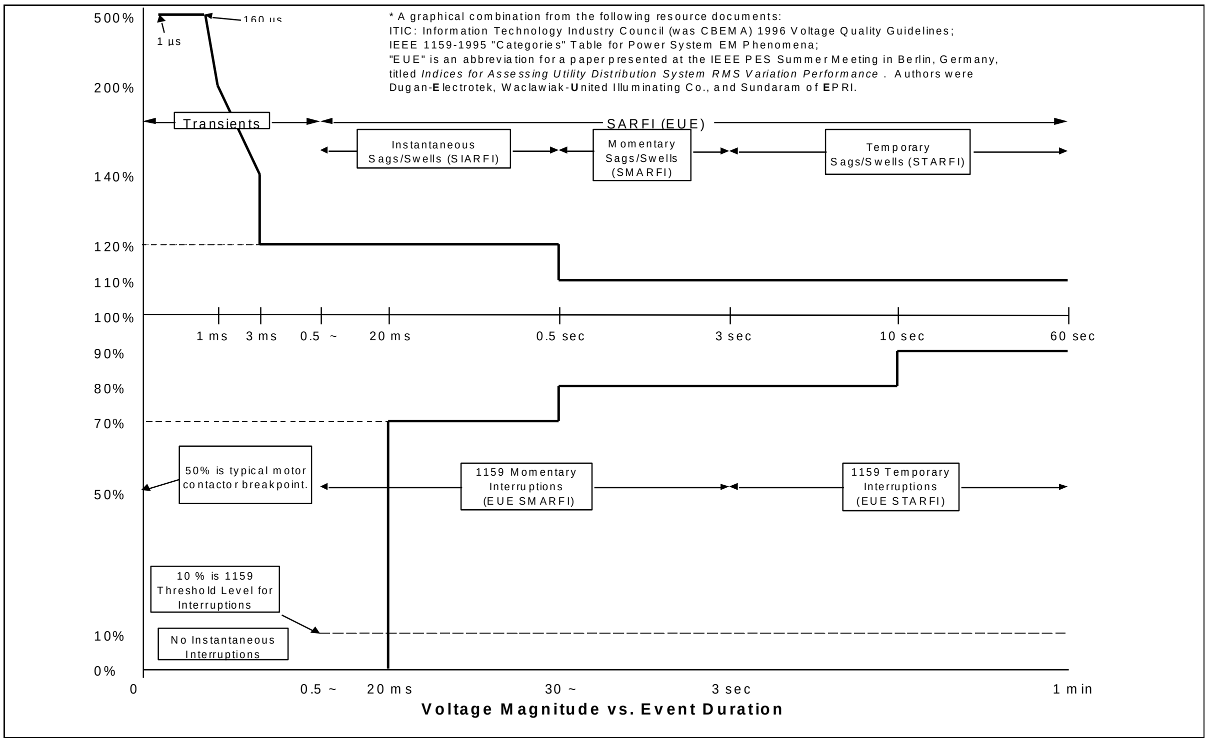


**Figure 4 – Composite Curve From IEEE P1564**

## Evolution of Power Acceptability Curves

The following table lists the chronology of significant power acceptability curves. According to [Reference 3] the CBEMA curve was redesigned in 1996 and renamed for its supporting organization.

| *Curve* | *Year* | *Application* | *Source* |
|---|---|---|---|
| FIPS Power Acceptability Curve | 1978 | Automatic Data Processing Equipment | U.S. Federal Government |
| CBEMA Curve | 1978 | Computer Business Equipment | Computer Business Equipment Manufacturers Association |
| ITIC Curve | 1996 | Information Technology Equipment | Information Technology Industry Council |
| Failure Rate Curves for Industrial Loads | 1972 | Industrial Loads | IEEE Standard 493 |
| AC Line Voltage Tolerences | 1974 | Mainframe Computers | IEEE Standard 446 |
| IEEE Emerald Book | 1992 | Sensitive Electronic Equipment | IEEE Standard 1100 |

**Table 1 – Listing of Alternative Power Acceptability Curves from [3]**

## SYSTEM VOLTAGE SAG SIMULATIONS

The following plots were generated from a G.E. PSLF simulation for the loss of Section 392 (similar to the fault which occurred on June 1, 2001 at Maine Yankee Substation). The two traces on each plot show the difference between a slow (0.6 second) and fast (0.2 second) operation of the overcurrent Special Protection Systems at Maxcy's and Bucksport.

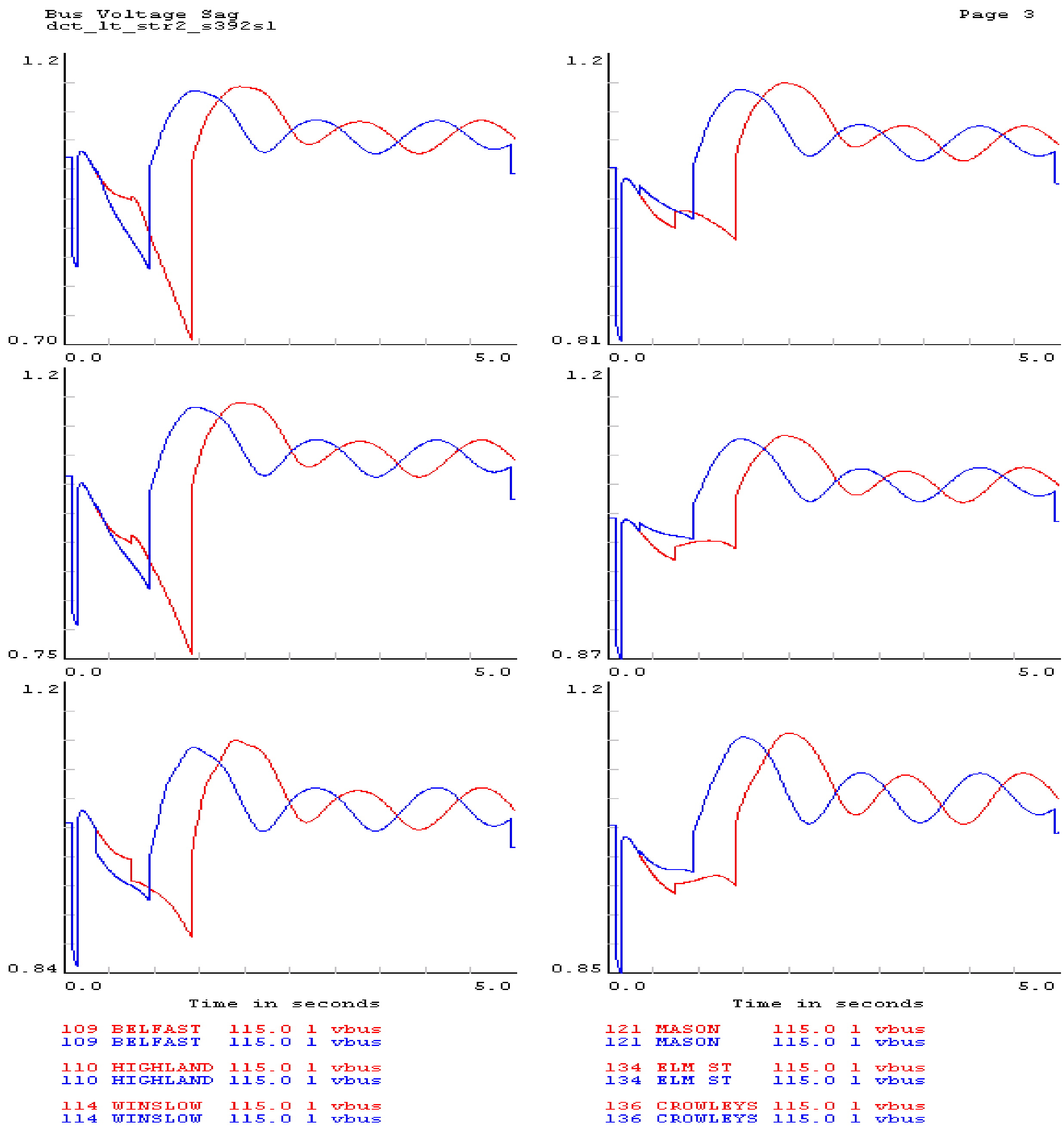


**Figure 5 – Simulated 115 kV Voltage Sag of Section 392**

## REFERENCES

1-Western Systems Coordinating Council "Supporting Document For Reliability Criteria For Transmission System Planning" – August 1994.

2- Daniel Sabin, Electrotek "Indices Used to Assess RMS Voltage Variations"- July 2000.

3-R.S.Thallam & G.T.Heydt "Power Acceptability and Voltage Sag Indices in the Three Phase Sense".

4- Daniel Sabin, T.E Grebe & A.Sundaram "RMS Voltage Variation Statistical Analysis for a Survey of Distribution System Power Quality Performance".

5-IEEE Std 1159-1995 "IEEE Recommended Practice for Monitoring Electric Power Quality".

6-IEEE Std 1250-1995 "IEEE Guide for Service to Equipment Sensitive to Momentary Voltage Disturbances".

7-IEEE Std 141-1993 "IEEE Recommended Practice for Electric Power Distribution for Industrial Plants" (IEEE Red Book).

8-IEEE Std 242-1986 "IEEE Recommended Practice for Protection and Coordination of Industrial and Commercial Power Systems" (IEEE Buff Book).

9-IEEE Std 446-1987 "IEEE Recommended Practice for Emergency and Standby Power Systems for Industrial and Commercial Applications" (IEEE Orange Book).

10-IEEE P1564 Task Force on Voltage Sag Indices (Working Group on Distribution Voltage Quality) "Voltage Sag Indices-Draft 1.2" – December 2000.

11- John W. Shaffer "Air Conditioner Response to Transmission Faults" – IEEE Transactions on Power Systems – May 1997.

12-IEEE Std 493-1997 "IEEE Recommended Practice for the Design of Reliable Industrial and Commercial Power Systems" (IEEE Gold Book).

13-IEEE Std 1346-1998 "IEEE Recommended Practice for Evaluating Electric Power System Compatibility with Electronic Process Equipment".