INTEGRAL energy

Power Quality Centre

VOLTAGE SAG MEASUREMENT AND CHARACTERISATION

This Technical Note discusses voltage sags, their causes and effects, and how they are measured and reported. Integral Energy, your local Network Operator, or the Integral Energy Power Quality Centre can give you advice if you have particular concerns with these issues.

Summary

Voltage sags are common events on the electric power network. They are caused by network faults and the connection of large loads. They can affect a wide range of electrical equipment and are of particular concern to industry. Sags can be characterised by their depth and duration but careful consideration need to be given to sags occurring simultaneously on several phases or occurring in quick succession. Individual sites can be assessed for their sag performance using sag indices which use statistical methods to give a number which represents sag performance and which can be used to compare to other sites. The specifications for a power quality instrument to perform a voltage sag survey are given.

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University of Wollongong

1. Introduction

Voltage sags are said to be the power quality problem of most concern to industrial customers [1]. Many overseas distributors are involved with surveys to measure the voltage sags on their network and with calculating simple numbers to measure their sag performance. Some of the reasons for this are to:

1. Provide customer information so they can specify critical equipment specifications with more confidence in new installations or determine cost-effective sag mitigation techniques in old installations which are giving problems.
2. Meet regulator requirements to demonstrate an acceptable level of power quality disturbances.
3. Allow utility benchmarking so they can be judged relative to other utilities, some of whom may be their competitors.
4. Provide a firm level of normal supply quality as a basis for customer PQ contracts & premium power.
5. Allow comparisons of different parts of a network to guide for network expansion, upgrade and maintenance practices.

Sags can be caused by faults/recloser operation or by the start-up of large loads such as DOL connected induction motors. In both cases there are many factors giving a wide variety of sag envelope waveshapes, for example arc characteristic, earthing impedance, feeder R/X ratio, motor and load characteristics. This can give a corresponding variety of envelope waveshapes with differing depth, duration, unbalance, fall time etc. Initially we shall ignore this detail and assume that the voltage waveform remains sinusoidal at fundamental frequency with an envelope which is rectangular and balanced across all phases. Thus one sag event can be represented by two numbers, one for depth, usually given as a percentage of the nominal voltage, and one for duration given variously in seconds or cycles. A particular sag can be represented on a graph with duration as abscissa and depth (or sometimes the height of the remaining voltage) as ordinate.

2. Load Susceptibility

The characterisation of a single sag on a feeder or a whole network necessarily involves a great simplification of the sag process and must be guided by some definite objective. A common one is to represent the effect of the sag on customer equipment. Here, some further simplification must be made as different types of equipment or different ratings of the same type do not respond the same. We discuss here the range of sag susceptibility which can occur.

The sag susceptibility of a particular item of equipment can be determined using a sag generator [2] able to produce one or three phase waveforms with balanced rectangular sags. For a given depth, the duration is progressively increased until there is a trip or malfunction. The point of susceptibility can be then shown as a point on a duration/depth graph.

CBEMA (Computer Business Equipment Manufacturers Association) produced a graph of this type in 1977 which showed the manufacturer's aim for mainframe computers at the time. The complete graph, shown as Figure 1, also shows an overvoltage region for swells and transients.

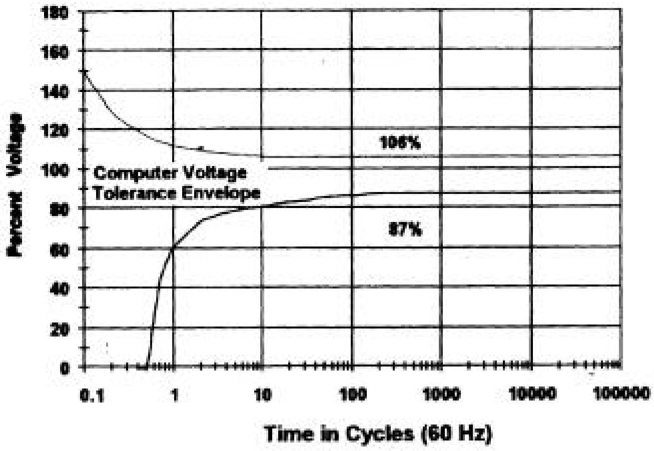


Figure 1: CBEMA Curve of 1977 [3]

This organisation has been replaced by ITIC (Information Technology Industry Council) who have recently updated the graph to represent modern practices for single phase information technology equipment (eg pc, copier, fax) as shown in Figure 2 for 120 V systems.

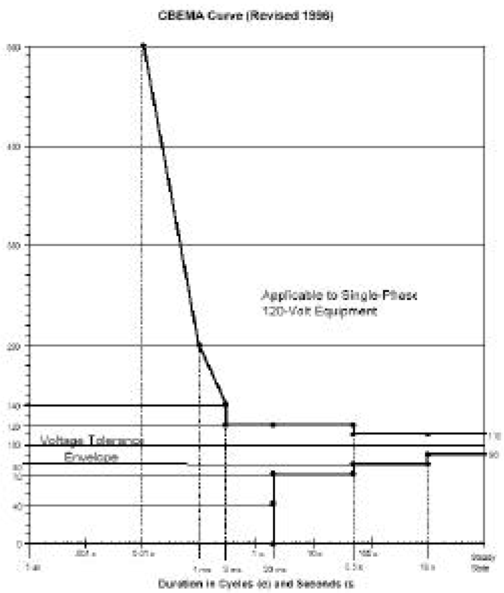


Figure 2: ITIC Curve of 1997 [4]

In the lack of any other information, the sag characteristics of equipment or whole installations are often assumed to be the same as the lower curves of the CBEMA or ITIC curves. It is also common to show the sag incidents at a site on a duration/depth graph overlaid with either of the above curves.

This would allow quick visual assessment of the number of sags likely to cause equipment problems if the CBEMA/ITIC curves were generic. However, many items of equipment have different characteristics and such graphs fail to be useful for individual installations. This method of representation of sag events at a site possibly has some value in allowing a simplified comparison of the sag performance at two sites from the number of sag events which lie outside (that is below) the lower curve.

Let us now consider individual items of equipment. Switch-mode power supplies (SMPS) are a common item at the front end of electronic equipment such as computers, TV, PLCs etc. From the point of view of sag performance, their important components are a full-wave bridge rectifier and a smoothing capacitor for the dc voltage applied to the next stage of the circuit. During a deep sag, the supply is unable to charge the capacitor whose voltage is then decreased by the current drawn by the next stage. If the sag duration is sufficiently long, the capacitor voltage will fall too low for proper operation and, depending on the design, the equipment will trip or malfunction. The maximum sag duration allowing proper operation depends on the capacitor size, the current drawn and the range of acceptable capacitor voltage, and can be 1-20 cycles for electronic equipment. In the case of digital clocks, it is longer, in the range 1-10 seconds.

An ac variable speed drive (VSD) has a very similar front end to a SMPS except that it is three phase. Their susceptibility has been given as lying in the range 85% voltage for ½ cycle to 70% voltage for 0.5 sec [5]. Modern VSDs are made with small sized smoothing capacitors to reduce volume and cost and it has been stated that they appear to be more sensitive to sags than data processing equipment. Lesser sags can allow continuous operation of the drive in a manufacturing plant but cause speed fluctuations which degrade the product. Unbalanced sags can cause a larger unbalance in the rectifier currents which can cause problems at smaller sag depths than for balanced sags.

Directly connected induction motors can trip or depart from acceptable speed for sag durations in the range 10 cycles-secs. The behaviour depends sensitively on the mechanical load characteristics. When the sag recovers, the reduced motor speed causes a large current which can slow down the voltage recovery. For this reason the sag performance of a plant can be improved by disconnecting all non-essential motors under some conditions.

AC contactors are very sensitive, tolerating 60% voltage for only a few cycles before tripping out. Their replacement by appropriately specified dc contactors is suggested as a means of improving plant sag performance.

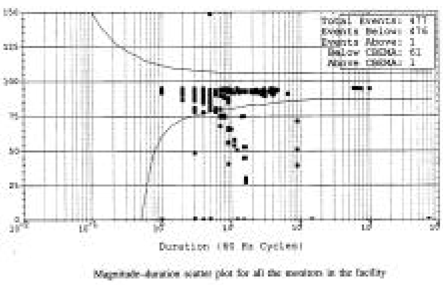
3. Event Reporting

A power quality monitor typically measures 128 points per cycle of the supply voltage. At each sampling moment, an rms value is calculated for the last half cycle of readings (in this case the last 64) giving a ½ cycle sliding window. In a single phase circuit, a sag is defined as starting when this value falls sufficiently below the normal reading and is defined as ending when the value rises sufficiently close to the normal reading. The "sufficiently below" value is typically about 90% voltage and is the sag threshold setting. On many instruments it can be adjusted to suit the monitoring site to ensure that a suitable number of sags is captured. The duration is the time which the sag is below the threshold values. The depth is the maximum depth recorded during the sag.

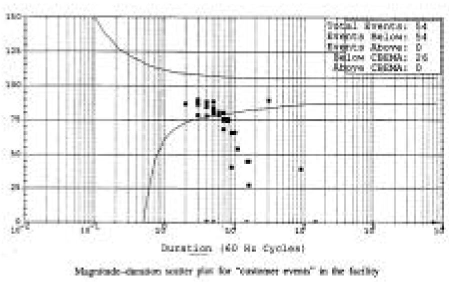
The sag characterisation process becomes more complicated when there are three phases and/or there are several sag events in close succession. Should these be considered several sag events or one complex multiphase sag event? The answer depends on whether the sequence would cause one or several incidents of equipment failure and customer complaints.

In the case of a medium voltage supply, it is assumed that most customers are three phase and a sag on three phases is no more severe than a sag on one. When there are simultaneous events on several phases, the sag with the greatest depth is taken as the one used for characterisation – a process called "phase aggregation".

When sags occur in quick succession, typically as a result of recloser operation, it is unlikely that each one will cause the same equipment to fail since time is needed to restart. One suggestion is that, when events occur less than a minute apart, only the event with the greatest voltage depth is recorded. Figures 3(a) and (b) show how the distribution of sags at a site can be affected when phase aggregation is used.



(a)



(b)

Figure 3: Comparison of site reporting with overlaid CBEMA curve (a) without and (b) with time aggregation [6]

It is obvious that more shallow sags have to have longer duration to be as disruptive to equipment. Nasrullah [7] has suggested that the parameter Depth×Duration, called "Voltage Sag Aggressiveness" (VSA) might be an effective measure of sag disruption. Figure 4, taken from this reference, shows that groups of similar equipment failing for different sag conditions share similar values of VSA.

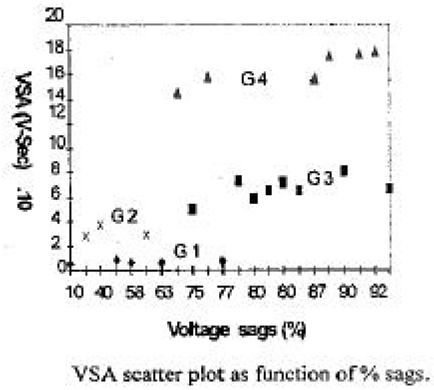


Figure 4: VSA for groups of similar equipment (G1-G4) under different sag depths [7]

4. Site Reporting

The sag characterisation of a site is a measure of all the sags recorded over an agreed period, usually a year. It has already been stated that one method of doing this is to show each sag as a point overlaid on a CBEMA or ITIC curve as shown in Figure 3. A variation on this idea is used by the South African utility ESKOM. They define rectangular regions in the duration/magnitude plane and give the number of sag incidents falling into each region.

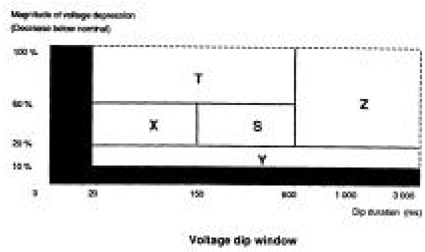


Figure 5: ESKOM voltage dip window [8]

EPRI gives a statistical approach using histograms and cumulative probability curves. Figure 6 shows approaches with 2D and 3D representations.

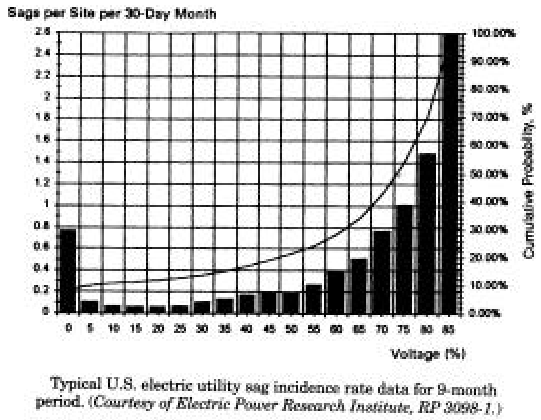


Figure 6(a): 2D statistical approach based on magnitude alone [3]

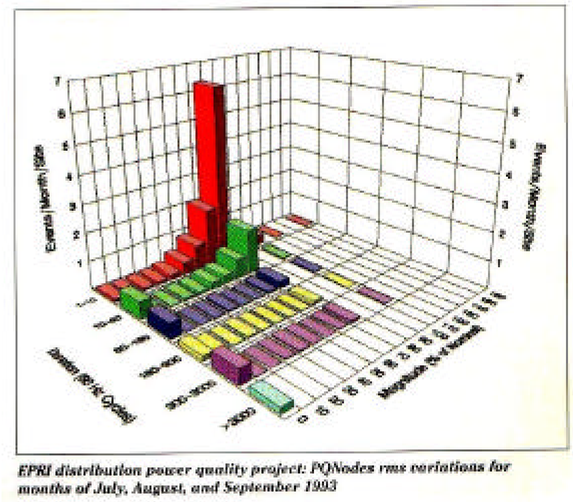


Figure 6(b): 3D statistical approach based on magnitude and duration [9]

5. Site Indices

Site indices are devised to give a simple measure of the sag performance of a site so that sites can be simply compared, for example to prioritise for upgrading. The representations discussed in the previous section involve too much information and do not allow any convenient comparison means.

One suggestion is the number of points below the bottom curve of a CBEMA graph such as Figure 3 as a measure of the number of disruptive events. Other suggestions have been based on average sag depth, duration and area.

The approach being developed by EPRI is an extension of the SARFI and similar indices used as a measure of interruptions. The System Average RMS Frequency Index with threshold V is defined as

$$SARFI_{\%V} = \frac{\text{No of customer sags to voltage V}}{\text{No of customers}}$$

Suggested values for V are 90%, 80%, 70%, 50% and 10% of nominal voltage. Duration is considered by breaking $SARFI_{\%V}$ into components corresponding to instantaneous (I), momentary (M) and temporary (T). These durations are defined in IEEE 1159 [10] as 0.5 cycles-0.5 seconds, 0.5 seconds-3 seconds, 3 seconds-1 minute respectively.

Hence $SARFI_{\%V} = SIARFI_{\%V} + SMARFI_{\%V} + STARFI_{\%V}$

6. Sag Survey

A PQ monitor to be used for sag surveys has the following requirements

- Need to record 3 voltages
- RMS sampling at preferably ½ but at least every cycle
- Adjustable thresholds
- Capture depth and duration
- Adequate memory
- Able to operate through sags/interruptions
- Good reporting software & able to export to general data analysis packages such as spreadsheets
- Time and date stamping
- Ambient temperature recording

The survey duration must be sufficient to include the full range of all the factors that affect sag incidence. The most important is the seasonal variation of atmospheric conditions. The survey period must also be sufficiently long to account for all reasonable combinations of line outages and capacitor bank connections. It is accepted that a minimum period for acceptable results is one year.

7. List of References

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7. Integral Energy Power Quality Centre

In July 1996, Integral Energy set up Australia's first Power Quality Centre at the University of Wollongong. The Centre's objective is to work with Industry to improve the quality and reliability of the electricity supply to industrial, commercial and domestic users. The Centre specialises in research into the control of distortion of the supply voltage, training in power quality issues at all levels, and specialised consultancy services for solution of power quality problems. You are invited to contact the Centre if you would like further advice on quality of supply.

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