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Benchmarking utilities for the impact of voltage sags on customers

H. M. Herath
University of Wollongong

V. J. Gosbell
University of Wollongong, vgosbell@uow.edu.au

S. Perera
University of Wollongong, sarath@uow.edu.au

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Abstract

Most utilities have increased their focus on voltage sags as the sags account for vast majority of recorded equipment trips. Although these events are not necessarily the most frequent, they have a tremendous economic impact on end-users. The process of benchmarking customer voltage sag levels generally requires voltage sag monitoring data for a period of minimum one year. This data can then be quantified to relate voltage sag performance with standardized limits for acceptable performance. This work suggests a methodology for benchmarking the impact of voltage sags on customers of different utilities by means of a three stage reporting procedure that covers a site, a network and a utility. This is followed by a simple method of defining a single sag index for a utility that deals with the average values across the utility which enable comparison of different utilities for their overall sag performance.

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Benchmarking Utilities for the Impact of Voltage Sags on Customers

H.M.S.C. Herath, *Student Member, IEEE,* V.J. Gosbell, *Member, IEEE,* and S. Perera, *Member, IEEE*

***Abstract*-Most utilities have increased their focus on voltage sags as the sags account for vast majority of recorded equipment trips. Although these events are not necessarily the most frequent, they have a tremendous economic impact on end-users. The process of benchmarking customer voltage sag levels generally requires voltage sag monitoring data for a period of minimum one year. This data can then be quantified to relate voltage sag performance with standardized limits for acceptable performance. This paper suggests a methodology for benchmarking the impact of voltage sags on customers of different utilities by means of a three stage reporting procedure that covers a site, a network and a utility. This is followed by a simple method of defining a single sag index for a utility that deals with the average values across the utility which enable comparison of different utilities for their overall sag performance.**

***Index Terms*-Power quality (PQ) monitoring, PQ indices, Advanced PQ data analysis.**

I. Introduction

Electric utilities throughout the world are adopting the concept of benchmarking service quality. Utilities have realized that they must understand the levels of service quality provided throughout their distribution systems and determine if the levels provided are appropriate. This is certainly becoming more prevalent as many utilities establish contracts with specific customers to provide a specified quality of service.

For most utilities and consumers, the most important power quality (PQ) variations are the voltage sags as recorded number of equipment trips [1]. Although voltage sags are not necessarily the most frequent occurring, they have a tremendous economic impact on end-users. The process of benchmarking voltage sag levels generally requires at least one years worth of sag monitoring data [2]. This data can then be quantified to relate voltage sag impact on customers with standardized sag indices that are acceptable to both utility and customers.

After an appropriate amount of data has been acquired, the service provider must determine what levels of voltage sag quality are appropriate and economically feasible. Electric utilities are aware that any level of customer voltage sag quality is achievable through the use of systems such as dynamic voltage restorers (DVR) and UPS systems. However, at some point the costs cannot be economically justified and must be balanced with the needs of end-users and the value of the service to them.

The first issue in voltage sag monitoring is that there be consistency in measurement procedure so that the impact of voltage sag levels on customers of different utilities can be compared and best practices can be established. Standards such as IEEE 1159 [3], CENELEC EN 50160 [4] and IEC 61000-4-30 [5] are important for specifying a consistent set of procedures for obtaining measurement results such as the retained voltage and duration of voltage sags.

The second issue requiring standardisation is reporting of a monitoring campaign, particularly where it involves many sites over a period (e.g. one year). Summary sag indices need to be defined which do not mask important diagnostic details.

Following [6, 7], the reporting structure for customer sag levels of each utility can be classified into three levels,

(i) Site report: The details of all sag incidents of one Site.
(ii) Network report: A single sag index for a one site for comparison of different sites in one network.
(iii) Utility report: Average sag index for a utility.

Many studies have been undertaken on characterisation and reporting sags covering some aspects of above three levels. Some different methods for obtaining single sag indices such as sag energy index, EPRI $SARFI_X$ indices are discussed in IEEE task force P1564 and in joint working group (JWG) CIGRE C4.07/CIRED (formerly WG36.07) documents [8-10]. However, none of those methods specifically addresses the issue of benchmarking utilities for their voltage sag performance.

This paper gives a detailed analysis of the above three level structure covering site, network and utility for the impact of voltage sag performance based on statistical distribution of sag indices and compliance levels defined using actual measurement data. The site reporting procedure is related to all sag data of one site whereas the complete network covering many sites is handled by the network reporting procedure. Finally, the reporting procedure that deals with the average values across the entire utility will lead to benchmarking utilities for voltage sags. This is followed by an application example comparing the impact of voltage sags on customers

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H.M.S.C. Herath, V.J. Gosbell and S. Perera are with the School of Electrical Computer & Telecommunications Engineering, University of Wollongong, NSW2522, Australia (Corresponding E-mails of author's: chandana@elec.uow.edu.au, v.gosbell@uow.edu.au & sarath@uow.edu.au).

of three Australian utilities employing voltage sag monitoring data for a period of one year.

II. Voltage Sag Reporting Styles

A. *Flowchart of Voltage Sag Reporting Styles*

Many approaches have been given in the literature on how voltage sag measurements should be processed [8-10]. In this section we discuss a flowchart that describes in general terms the voltage sag data processing stages involved in utility surveying, starting with the waveform of the sag event, and then sag event recognition, classification and single sag index determination to characterise the monitored site and the aggregation of site indices to give a utility index.

Following [9, 11], the raw data available is the sampled points of voltage waveforms at a particular site (Figure 1). The first step involves the separation of sag data from other disturbances followed by classification and parameterisation (Blocks 1 & 2). Voltage sag event characterisation is the process of describing a single sag event (output of Block 3). For a three-phase balanced, rectangular sag, it might consist of obtaining the sag voltage and duration. Once the sag events are characterized, a utility needs to prepare information on sag performance levels for several different types of parties, each of which requires a different reporting style. The network planner needs summary information on the worst sites having poor sag performance and the more detailed information on the worst sites to assess what the problem might be. The regulator is not interested in the details of individual sites but requires some type of overall indication of the voltage sag performance of a utility.

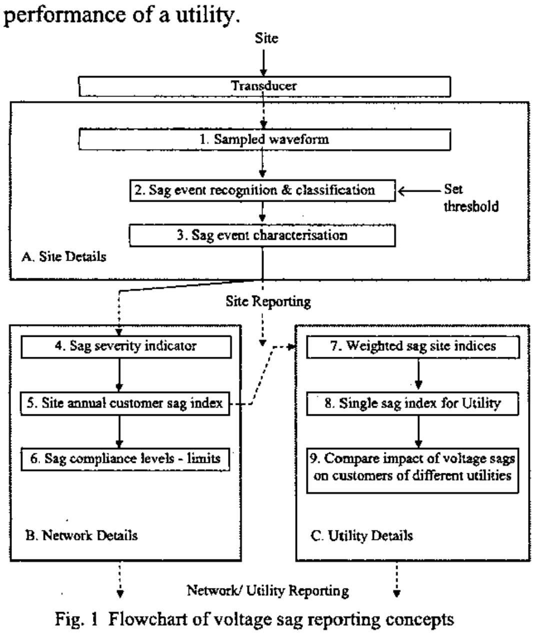

Fig. 1 Flowchart of voltage sag reporting concepts

Blocks 4, 5 and 6 consist of details which show summary data for each site so that the compliance levels can be simply checked and problem sites identified. This is achieved by the sag severity indicator (SSI), a single number to characterise the severity of each sag (output of Block 4). All sags with the same sag severity indicator are considered to affect the same fraction of customer equipment at monitored site. Site annual sag index (Block 5) is a single number to summarise the sag activity at a site over a year obtained by combining together the SSIs of each sag event. Block 6 is the level at which the above sag indices for all sites are compared against the set standards limits to see the severity of the site sag levels.

At the input to Block 7 site indices are combined by a simple weighting in proportion to the customer kVA or the customer numbers to give a sag index for the impact of voltage sags on customers (i.e. customer sag index) of a utility (Block 8). The customer sag index for a utility represents an "average site" sag performance to allow overall voltage sag planning effectiveness to be assessed. The customer sag index for a utility will be compared with other utilities (output of Block 9) for benchmarking the impact of voltage sag performance on customers of distribution utilities.

B. *Reporting Structures*

The above proposal results in each sag reporting style being derived from the data in the previous style in which follows the similar procedure proposed in [11]. The same style can be formed for all other PQ disturbance types which lead to the ultimate goal of benchmarking overall PQ performance given to their customers in different utilities.

III. Site Reporting

A. *General Introduction*

The aim of site reporting is to give sufficient detail about voltage sags at a site so that post-mortem investigation and remedial decisions can be made. A scatter graph with a voltage tolerance curve overlay shows the duration/retained voltage characterisation of each individual event occurring in the sag monitoring period. There are also many other reporting styles that have been used by utilities around the world [8]. Descriptions of the methods are described in the sections to follow.

B. *Voltage Tolerance Curves*

Voltage tolerance curves also known as power acceptability curves [12] are plots of voltage deviation versus time duration. They separate the voltage deviation – time duration plane into two regions: "acceptable" and "unacceptable". Various voltage tolerance curves exist but the most widely publicised is the ITIC curve (formerly the CBEMA curve). The CBEMA curve has been in existence since 1970s [13]. Its primary intent is to provide a measure of vulnerability of mainframe computers to the disturbances in the electric power supply. However, in practice it has been used to give a measure of power quality for electric drives and solid state loads as well as a host of wide-ranging residential, commercial, and industrial loads [12].

C. *Other Characterisation Schemes*

One of the most common is to show sag voltages and durations on a voltage-duration plot overlaid with the

CBEMA or ITIC curves [15]. Another set of methods adopted by EPRI, known as EPRI 2D or 3D histograms [15, 16] and $SARFI_X$ indices [8, 9]. There are many other characterisation methods that are reviewed in [8].

IV. Network Reporting

A. General Introduction

Network reporting aims to give simple voltage sag indices for all measurement points in the network so that sites can be prioritised for further investigation. Different methods for obtaining single site indices for voltage sags are discussed in [8-10, 14]. One approach to achieving this is described below.

B. Single Sag Index for a Site

There is a need for a method based on sound arguments leading to a single meaningful indicator from a site sag report. [14] Discusses this issue and recommends that each sag be given a sag severity indicator (SSI) proportional to the number of customer complaints. A sag index can then be made up from the sum of the individual SSIs. A simple approach is to give a sag has SSI of 0 if it lies above the CBEMA curve and 1 if it lies below it. The sag index then becomes the number of sags lying below the CBEMA curve.

The University of Wollongong (UOW) approach [14] proposes a method giving a better discrimination between sags lying near and far from the CBEMA curve. A series of contour lines is produced by scaling the CBEMA curve and allocating a CBEMA Number (CN) to each one. Sag events can be shown on a voltage – duration plane overlaid with constant CBEMA curve contours as shown in Figure 2. The UOW sag index is calculated as the sum of the CBEMA numbers, giving 12 (equal to 1+2+2+3+4) in this case.

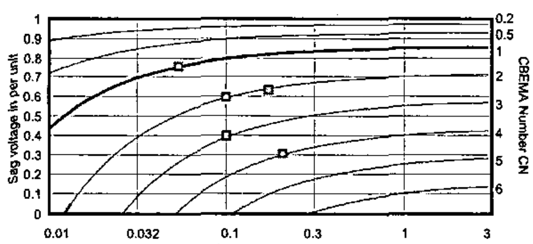

Fig.2 Hypothetical sag events overlaid with constant CBEMA Number contours (CN=1 corresponds to fitted CBEMA curve) [14].

C. Sag Limiting Standards

There are only two standards available at present that describe specific voltage sag directives i.e. South African Std and Chilean Std. South African Std covers voltage sag limits whereas Chilean Std has extension to voltage swell limits.

1) South African Standard: The South African (ESKOM) PQ Standard NRS 048-2:1996[17] primarily developed by utilities, although the process included customer forums hosted by the South African National Electricity Regulator (NER) [18]. In addition to the voltage quality requirements, the standard has prescribed utility voltage sag performance limits. In this aspect South Africa uses a two-dimensional scatter plot of the magnitude of voltage depression versus sag duration to present voltage sag data superimposed on five windows termed ESKOM sag windows.

2) Chilean PQ Standard: The Chilean Standard DS 327:1997 [19] gives limit values for the number of voltage sags and swells per year in different magnitude and duration ranges in connection with the different standard voltages than ESKOM standards. However the event count is the same as the ESKOM limits for sags.

D. Single Sag Limiting Values and Network Summary

There is a need for a single sag limiting value for sites of a network that can be compared with single site indices giving sag impact on customers of the network. This may be the sag compliance level for voltage sag impact on customers for the sites of a network or a utility that need to be consistent with long term PQ survey measurements of the overall system i.e. a large PQ survey participated by whole utilities. Large surveys of this kind has been completed in US, Canada, Europe and several other countries.

1) Single MV/LV Sag Limit: A method is given in [20] discussing the issue of achieving single annual sag limit based on the single sag index described in the section IV.B and given a single sag limit of 200 for the mixed networks, where a mixed network defined with varying proportions of overhead lines and underground cables of a typical network, while a single sag limit of 100 is given for the underground networks. This has been achieved by analyzing the UNIPEDE DIS DIP survey statistics [21] that was based on a measurement campaign of nine countries in Europe carried out over a period of three years. The limits defined in [20] applicable to the customer sag events for a given survey category (MV/LV mixed or underground) that is met by 95% of sites measured.

2) Network Summary: Single site sag indices are obtained by adding sag severity indicators for all events that occurred at the site during the monitoring period. The resulting indices are proportional to the average number of sag-related problems experienced by each customer. The result needs to be scaled up to an agreed survey period, typically a year, to allow comparison with other sites. Then the Network compliance report could be used to identify worst sites for PQ improvements.

V. Utility Reporting

A. General Introduction

The basic indicator for a utility should be a single parameter for sags, aggregated in some way over all the surveyed sites. This parameter would aim to compare one utility with other, for their overall sag performance.

Utilities can be compared as regards voltage sag performance in two ways, both of which are useful for different benchmarking purposes.

(i) Benchmarking utilities for the impact of voltage sags on customers
(ii) Benchmarking overall sag performance of a utility

The first approach is that a utility can determine how it performs its impact of voltage sags on customers relative to the other utility, assuming that both have similar types of power systems in terms of load density, external impacts, customers and other related utility practices.

The second approach gives a single sag indicator to compare a utility's performance under similar conditions. This task may not be possible until we understand more about which factors contribute to poor or good sag performance and will not be detailed in this paper.

B. Aggregation of Site Sag Indices

Aggregation of site sag indices is the process of combining voltage sag indices across monitored sites of a utility to get an overall indicator of customer sag levels of that utility. In particular, it can be applied to all sites in a utility to produce a utility index. As we are focusing on customer sag performance index for a utility, our index is weighted by customer load.

Utility Average Customer Sag Index (UACSI) for assessing the impact of voltage sags on customers: Our proposed customer focus sag index for a utility is given as follows,

$$UACSI = \frac{\sum_{s=1}^{n} L_s \cdot (SI_{Site})_s}{L_T}$$

Where,

s – *Site Number*

n – *Total number of sites in the system or utility being assessed*

L_s - *Connected kVA served from site s*

L_T - *Total connected kVA for the system being monitored* ($\sum_{s=1}^{n} L_s$)

$(SI_{Site})_s$ - *Annual sag index for site s*

VI. Application Example

The analysis given below has been carried out using data of nine sites of three Australian distributors. The measurements took place over a one year, sufficient to give useful results for the impact of voltage sags on customers of three utilities. The available data was collected from having similar mix of sites such as industrial, residential and commercial for a one year.

A. Site Report

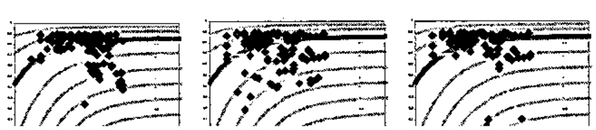

Fig.3(a) Distributor 1 (D1) sags overlaid on CBEMA curve

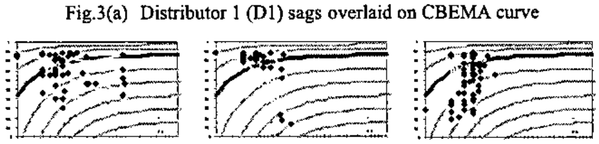

Fig.3(b) Distributor 2 (D2) sags overlaid on CBEMA curve

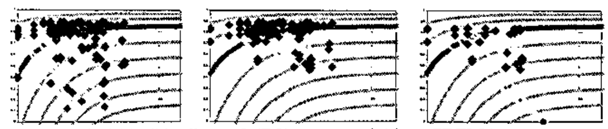

Fig.3(c) Distributor 3 (D3) sags overlaid on CBEMA curve

The field data of nine sites of three Australian distributors monitored over a one year period were analyzed and reported to illustrate one of the discussed sag characterization schemes.

Figure 3(a), 3(b) & 3(c), overlaid with CBEMA Contour Numbers (Bold line or CN=1 giving fitted CBEMA curve). It is evident that there is no possibility of differentiating sites from site sag report and no clear compliance levels can be determined.

B. Network Report

It is clear from Figure 4, that the network report gives a clearer differentiation of sites with network compliance levels and ease for ranking sites for appropriate remedial action. However, there is no possibility of ranking utilities for customer sag performance.

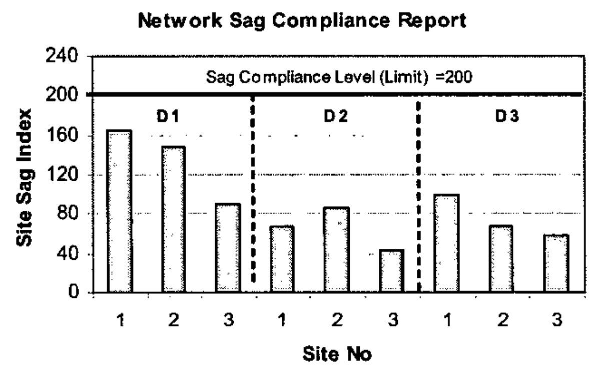

Fig.4 Network sag reporting

TABLE I
SITE SAG DATA OF THREE UTILITIES

Utility Name	Site No.	Sag Index	Connected kVA
D1	1	165.93	200
	2	148.17	200
	3	89.44	300
D2	1	68.30	500
	2	86.65	500
	3	43.08	200
D3	1	98.86	200
	2	68.36	500
	3	58.04	500

C. Utility Report

Figure 5 shows that the proposed new method gives a comparison of utilities for customer sags. Distributor #1 is considered to be the worst utility for customer sags in both network and utility reporting. However, the Distributor #2 is better performing than Distributor #3 in Network report, whereas Distributor # 2 outperformed Distributor #3 in Utility report for overall ranking for the impact of voltage sag performance on customers.

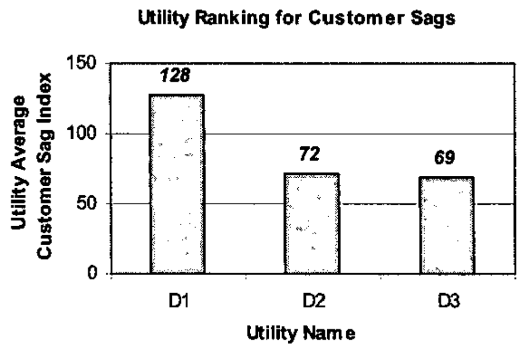

Fig.5 Utility ranking for the impact of sags on customers

VII. CONCLUSIONS

Existing voltage sag reporting methods are summarized and discussed. The voltage sag reporting has been classified into site, network and utility styles. Several sag data analysis procedures have been introduced to make the calculation of sag indices consistent and insightful for benchmarking for the voltage sags impact on customers.

For network reporting, it is proposed that a single sag index be determined for each site where the sags can be represented by the sum of individual sag severity indicators, scaled to an annual period, which can be useful for worst site identification for future PQ improvements and sag compliance reporting for regulatory bodies.

For utility reporting, benchmark comparisons can be made in two ways, (i) benchmarking utilities for voltage sag impact on customers (ii) benchmark overall sag performance of utilities. The paper gives a simple method for benchmarking utilities for sag impact on customers with an application example from sag data of sites of three Australian distributors.

Further research is aimed at developing a method for benchmarking overall sag performance of utilities by means of factor analysis of PQ survey data.

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BIOGRAPHIES

Chandana Herath (M'2000): Mr. Herath obtained his BSc. Eng. and MSc degrees from Moscow Power Engineering Institute (Technical University), Russia in 1992 & 1993. His employment experience included the Engineering Consultants Limited, Sri Lanka, the Shin Nippon Air Technologies Co., Ltd. (Incorporated in Japan), Sri Lanka, Singapore and Zimbabwe offices and the Mitsubishi Corporation, Singapore. He joined the University of Wollongong in 2001 and studying towards his PhD in power quality.

Vic Gosbell (M'1972): Dr Gosbell obtained his BE degree in 1966 and his PhD in 1971 from the University of Sydney. In 1973 he commenced lecturing at the University of Sydney and in 1990 took up the position of Associate Professor at the University of Wollongong where now he is a Professor of power engineering and working on power electronic simulation, harmonics and power quality. He is a Fellow of the Institution of Engineers, Australia and a former past-Chairperson of the Australasian Committee for Power Engineering (ACPE).

Sarath Perera (M'1988): Dr Perera graduated from the University of Moratuwa, Sri Lanka with a BSc (Eng) degree (1974) specialising in Electrical Power. He obtained his MEng.Sc degree (1978) from the University of New South Wales and the PhD degree (1988) from the University of Wollongong. He was an academic at the University of Moratuwa, Sri Lanka for nearly 12 years and is now a Senior Lecturer at the University of Wollongong. His research interests are in electrical machines and power quality.