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# A New SAIFI Based Voltage Sag Index

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**Abstract – Reliability measures of SAIDI (System Average Interruption Duration Index) and SAIFI (System Average Frequency Index) are well established industry standards used world wide. While both measures have their limitations, they give a broad indication of average reliability that allows comparison within networks and across networks world wide. No such industry standard indices exist for voltage sags. The main reason being that voltage sags are multi-dimensional, involving retained sag voltage, sag duration, number of phases effected, phase angle jumps and the time between successive sags. This paper proposes a new voltage sag index that is dimensionally the same as SAIFI having units of equivalent interruptions per year, allowing a direct comparison with SAIFI. The proposed new index called "Sag SAIFI" has been designed to allow voltage sag comparisons between sites, within networks and across networks. In addition, Sag SAIFI provides a means to directly compare the customer impacts of voltage sags with reliability (interruptions) and can assist in optimising expenditures on networks to maximise customer benefits of both reliability and voltage sag performance in their aggregate.**

*Index Terms*— Index, Power Quality, Reliability, Sag SAIFI, SAIFI, Voltage, Voltage Sag, Voltage Sag Index.

## I. Introduction

The aim of this paper is to propose a new method of assessing the voltage sag performance of networks with a single number index measure that is linked to customer equipment immunity and the reliability index SAIFI (System Average Frequency Index). A brief review is made of existing voltage sag measures [6] and indices, followed by an assessment of voltage sag impacts on customers from field and laboratory measurements of customer installations and equipment. The method of calculating the new "Sag SAIFI" index is then described with examples.

## II. Voltage Sag Characteristics

Voltage sag events are considerably more complicated to characterise and describe than power interruptions. A single power interruption can be described by a duration (e.g. 5 minutes). A voltage sag is generally described by the lowest retained voltage measured during an event and the time duration that the RMS voltage is below a specified threshold. Voltage sags are further complicated by phase angle jumps, unbalance between phases and impacts of auto reclosing where voltage sags occur in rapid succession, often within 10 seconds of each other. By using phase and time aggregation and neglecting phase angle jumps, voltage sags can be reduced to two measures, namely retained voltage and duration as shown in Fig. 1.

The immunity levels of electronic equipment can vary significantly with switch mode power supply powered devices generally having an immunity curve that is rectangular in shape on the voltage sag plane[2],[8]. The impact of voltage sag events can vary greatly from customer to customer with continuous process industrial plants being particularly susceptible to disruption.

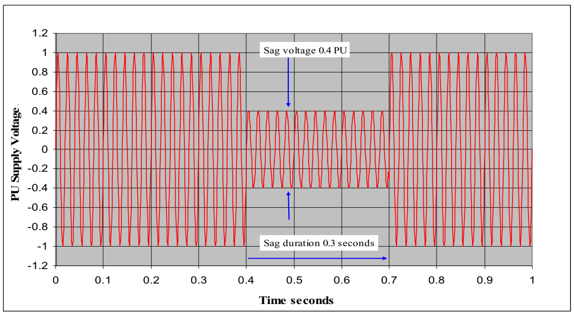


Fig. 1. Typical voltage sag waveform

## III. Existing Voltage Sag Measures and Indices

### A. 4.1 CBEMA curve approach

Under the CBEMA curve approach, voltage sag severity is assessed by comparing the sag distribution with the CBEMA curve or the ITIC curve as a reference [4,5]. The CBEMA curve is shown on the voltage sag plane in Fig. 2. This graphical approach allows a visual assessment of the number of events and their severity. The sags which cause the most customer disruption are those lying far below and to the right of the lower CBEMA curve.

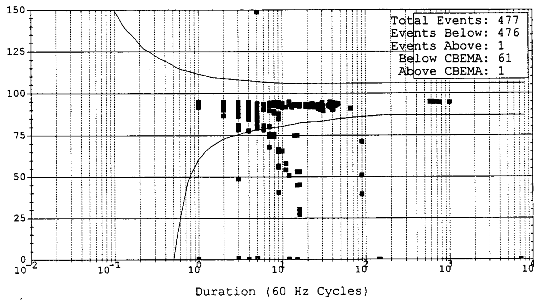


Fig. 2. Comparison of voltage sags with the CBEMA curve

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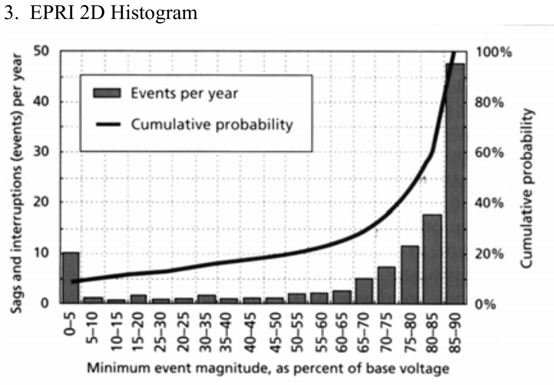
The number of sags above/below the CBEMA curve is sometimes taken as a simple type of sag index. This index can be rescaled for different monitoring periods. However, there is poor discrimination for sags lying close to the CBEMA curve. A site with one sag event lying just below the curve will be assessed as being worse than one with a hundred sags just outside the CBEMA curve. This is clearly not the case and is a result of the "all or nothing" nature of this particular method of sag assessment.

*B. 2D-3D Histogram Method*

The EPRI 2D and 3D histograms shown in Fig. 3 and Fig. 4 and are well established as a means of reporting site sag performance. They have the same limitation as for the CBEMA overlay method for comparing more than a couple of sites. These display methods are well suited to studying of the sag impact on a particular plant and for developing sag mitigation measures. While visually effective this approach does not lend itself to generating a single measure or voltage sag index for a site or network.

Fig. 3. EPRI 2D Histogram



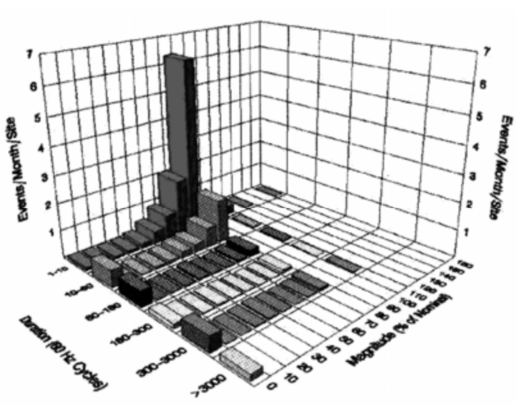




Fig. 4. EPRI 3D Histogram

*C. 4.2 ESKOM Voltage-duration windows*

The ESKOM approach is to divide up the voltage sag plane into several defined windows as shown in Fig. 5 and to give a count of the number of sag events in each [3]. This is similar to the EPRI 3D histogram method with the exception that the resolution of voltage and time is reduced from 60 windows to 5. The smaller number of windows makes it practicable to list a target number of sags for each window as shown in Table I for 6.6 - 44 kV.

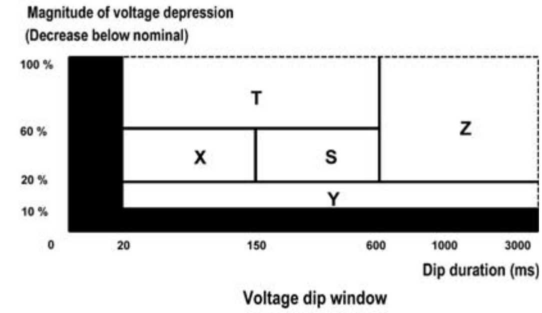



Fig. 5. ESKOM Windows

TABLE I
MAXIMUM ACCEPTABLE NUMBER OF SAGS IN EACH WINDOW FOR A 6.6-44KV SYSTEM

| Window | Z | T | S | X | Y |
|---|---|---|---|---|---|
| No. of dips per year | 20 | 30 | 30 | 100 | 150 |

*D. University of Wollongong Sag Index*

This method has been used with great success in the Australian Long Term National Power Quality Surveys [2],[10]. The graph in Fig. 6 represents estimates of constant customer complaint rate. Each contour is allocated a CBEMA number which is an estimate of the customer complaint rate. CBEMA CN=1 is the fitted CBEMA curve.

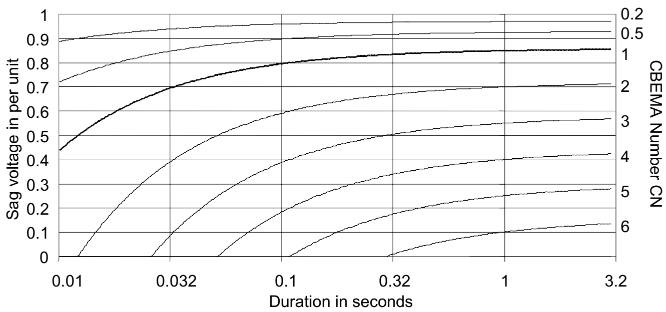



Fig. 6. CBEMA Number Contours

Each voltage sag that occurs over a survey period is allocated a CBEMA number. The CBEMA numbers are then added together through the survey period and normalised to a rate per year (The UOW Index). Australian experience has shown that sites with a UOW sag index less than 100 are considered good, 100 to 500 are considered fair and above 500 poor.

## IV. Assessing the Threshold of Voltage Sag Disturbance on Equipment

The proposed new Voltage Sag SAIFI index is based on two basic assessments. The first being an assessment of the threshold on the voltage sag plane where some sensitive electronic pieces of equipment will maloperate. The second boundary is the threshold on the voltage sag plane where almost all susceptible electronic equipment will maloperate.

Fig. 7 shows the key findings from previous published work titled "Distribution Network Voltage Disturbances and Voltage Dip/Sag Compatibility"[1]. The graph shows that the ITIC is a good indicator of the voltage sag boundary between where a sag event is likely to disrupt a manufacturing plant or leave the plant operating unaffected.

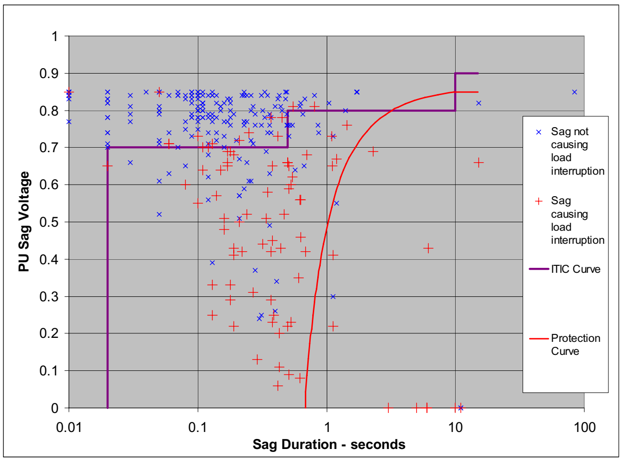



Fig. 7. ITIC Curve and voltage sags causing industrial plant interruptions

The data shown in Fig. 7 is the result of a collaborative study into the impact of distribution network voltage disturbances on the operation of manufacturing plants located in rural Australia. The results are based on seven manufacturing plants all being at least 150km from a state capital. Each plant site takes supply at 22kV, has an operating load of 5MW to 10MW and was the largest customer on each of the zone substations. Each plant contains many hundreds of variable speed drives, PLCs and other sensitive electronic equipment. These plants all contain continuous process operations with hundreds of voltage sag sensitive pieces of equipment, the maloperation of which can cause a plant shut down. These shut downs are similar in effect to a complete interruption of supply. Hence the sag characteristics measured for these plants do not represent individual pieces of equipment but fully integrated systems comprising of hundreds of components.

The protection curve [9] which is related to voltage sags associated with typical standard inverse overcurrent protection settings found in distribution networks is also shown for completeness in Fig. 7.

The conclusions drawn from Fig. 7 in the construction of the Sag SAIFI index is that the ITIC is a reasonable estimate of the threshold of voltage sag impacts on equipment. Although it is not a perfect measure of the threshold, over 90% of voltage sags causing plant load interruption are to the right of the ITIC curve and most of the remaining 10% of the voltage sags were close to the ITIC curve.

## V. Assessing the Voltage Sag Disturbance Level for Likely Maloperation of Most Equipment

As part of developing the Voltage Sag SAIFI model the next part of the process was to determine the part of the voltage sag plane where maloperation of sensitive equipment was very likely (almost certain) to occur. This was estimated by taking voltage sag immunity measurements [7],[8] of a small but wide range of equipment. The results are detailed in Table II.

TABLE II
Voltage Sag Immunity for a Range of Sensitive Equipment

| Appliance Description | Mode | Sag Voltage | Sag ms | Mode % of time |
|---|---|---|---|---|
| Microwave oven 1 | Microwave on Standby | 60 | 830 | 99% |
| Microwave oven 1 | Microwave On | 75 | 330 | 1% |
| Microwave oven 2 | Microwave on Standby | 85 | 560 | 99% |
| Microwave oven 2 | Microwave On | 92 | 250 | 1% |
| Clock Radio | Clock Only | 103 | 340 | 90% |
| Clock Radio | Clock & Radio | 110 | 330 | 10% |
| CD Player/Radio | CD On | 130 | 20 | 10% |
| Computer A | On | 140 | 60 | 20% |
| Computer B | On | 160 | 40 | 40% |

These same results are shown in graphical form in Fig. 8. The device with the highest level of voltage sag immunity is the microwave oven in standby mode. Based on this sample the area marked "area of very likely maloperation" represents that area of the voltage sag plane where the vast majority of voltage sag prone electronic equipment will maloperate.

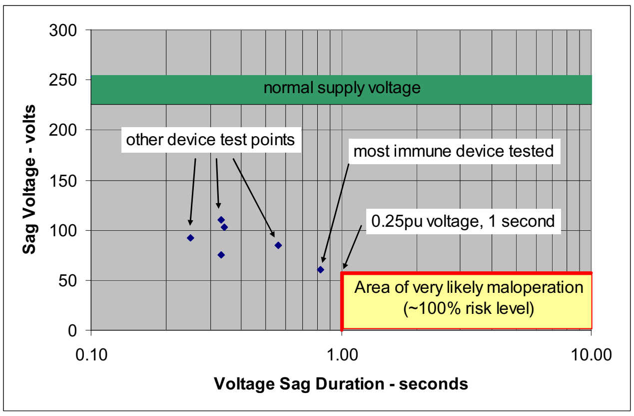



Fig. 8. Voltage Sag Immunity of a Range of Electronic Equipment

The selection of 0.25PU voltage and 1.0 second duration for the corner of the rectangle in Fig. 8 is appropriate for the small number of 230V appliances tested because all items of equipment tested would maloperate when exposed to voltage sags of this severity. This corner point could be adjusted in the Sag SAIFI model in the light of further experience, especially on 110V equipment.

## VI. Estimating the Customer Disturbance Level for an Individual voltage Sag

As part of building the Sag SAIFI model, the next part of the process was to "grade" voltage sags between the threshold of disturbance to the "very likely" maloperation of all sensitive electronic equipment. This was achieved by using the log linear interpolation of points between the ITIC curve (0% voltage sag sensitivity level) and the 100% voltage sag level curve (very likely maloperation) as shown in Fig. 9.

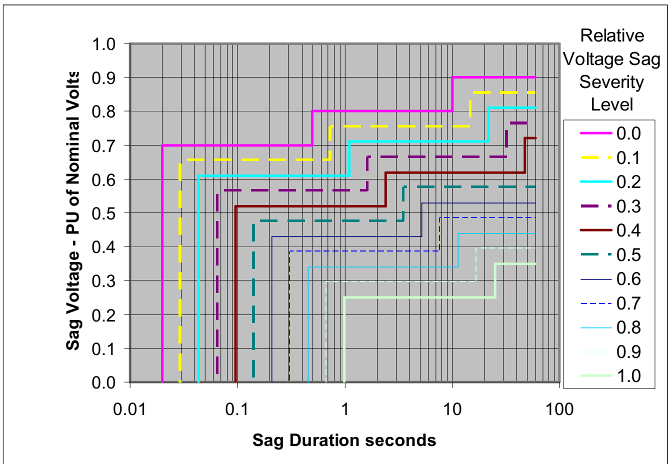



Fig. 9. Sag SAIFI Model – Voltage Sag Severity Levels

The Sag SAIFI model requires determination of the relative severity of a voltage sag to be calculated using the model shown in Fig. 9. Any sag to the left or above the ITIC curve has a relative sag sensitivity of zero. Any sag to the right or below the 100% curve has a relative sag sensitivity of unity. A relative voltage sag severity of unity is considered equivalent in customer disturbance terms to a complete single interruption of supply. A 50% sag severity is considered equivalent in customer disturbance terms to ½ an interruption to supply. This approach allows the calculation of relative sag severity for any voltage sag. The log linear nature of the model allows easy calculation of the relative sag severity index by computer. The equations to calculate the sag severity level of a particular sag event can easily be derived from the key corner points that make up the ITIC curve, the 1 second 0.25 PU voltage corner point of the 100% sag severity level and the general arrangement shown in Fig. 9.

## VII. Calculating of Interruption Equivalents For a Site over a Year

Just as SAIFI represents the average number of customer interruptions over a year (e.g. 4 interruptions per year), Sag SAIFI is also aggregated over a year to generate a value on an annual basis. Table III shows the calculation of the Sag SAFI contribution from an individual site over a year.

TABLE III
AGGREGATION OF SAG SEVERITY AT A SITE TO BUILD THE SAG SAIFI INDEX

| Voltage Sag Date & Time | Sag Voltage PU | Dur-ation seconds | Sag Severity |
|---|---|---|---|
| 5/04/2004 0:11:00 | 0.30 | 0.17 | 0.55 |
| 6/04/2004 4:51:00 | 0.62 | 0.17 | 0.18 |
| 15/05/2004 2:07:00 | 0.09 | 0.50 | 0.83 |
| 19/05/2004 5:11:00 | 0.74 | 0.17 | 0.00 |
| 31/05/2004 1:59:00 | 0.87 | 0.67 | 0.00 |
| 31/05/2004 2:44:00 | 0.87 | 0.67 | 0.00 |
| 14/06/2004 15:48:00 | 0.86 | 0.08 | 0.00 |
| 19/06/2004 9:51:00 | 0.86 | 0.08 | 0.00 |
| 27/06/2004 12:38:00 | 0.87 | 0.67 | 0.00 |
| 29/06/2004 3:18:00 | 0.43 | 0.84 | 0.60 |
| 1/07/2004 11:01:00 | 0.83 | 0.08 | 0.00 |
| 4/07/2004 3:50:00 | 0.82 | 0.08 | 0.00 |
| 3/08/2004 12:44:00 | 0.55 | 0.17 | 0.34 |
| 4/08/2004 16:24:00 | 0.46 | 0.67 | 0.53 |
| 6/08/2004 15:21:00 | 0.31 | 0.59 | 0.87 |
| 19/08/2004 6:49:00 | 0.80 | 1.09 | 0.00 |
| 25/08/2004 9:40:00 | 0.86 | 0.17 | 0.00 |
| 26/08/2004 1:30:00 | 0.80 | 0.08 | 0.00 |
| 6/09/2004 12:29:00 | 0.83 | 0.84 | 0.00 |
| 12/09/2004 2:52:00 | 0.30 | 0.25 | 0.65 |
| 25/09/2004 0:30:00 | 0.48 | 0.17 | 0.55 |
| 9/10/2004 6:18:00 | 0.70 | 0.17 | 0.01 |
| 17/10/2004 18:59:00 | 0.78 | 0.17 | 0.00 |
| 17/10/2004 19:16:00 | 0.66 | 0.08 | 0.10 |
| 22/10/2004 8:55:00 | 0.86 | 0.08 | 0.00 |
| 26/10/2004 23:42:00 | 0.33 | 0.50 | 0.83 |
| 26/10/2004 23:49:00 | 0.47 | 0.17 | 0.54 |
| 27/10/2004 21:09:00 | 0.65 | 0.25 | 0.12 |
| 27/10/2004 21:18:00 | 0.60 | 0.25 | 0.23 |
| 10/01/2005 16:54:00 | 0.83 | 0.08 | 0.00 |
| 13/03/2005 15:27:00 | 0.87 | 0.08 | 0.00 |
| | | | |
| Site contribution to Sag SAIFI Total equivalent interruptions/year | | | 6.36 |

## VIII. Calculating Sag SAIFI for a Whole Network

Fig. 10 shows a typical distribution of annual site sag severity indices for a range of 224 sites. Note that on the right hand side there is a small number of poor performing sites. This is a characteristic of many Power Quality disturbance types.

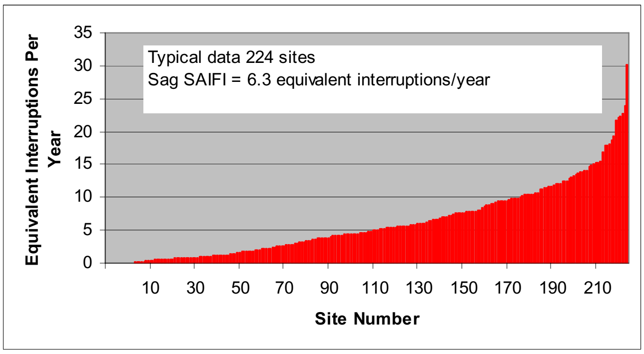



Fig. 10. Typical Sag SAIFI Distribution for a Large Number of Sites

The Sag SAIFI for a set of sites is found by averaging the equivalent interruptions per year across all the sites. The Sag SAIFI for this set of sites is 6.3 equivalent interruptions/year.

## IX. Comparison of SAIFI with Sag SAIFI

Because SAIFI and Sag SAIFI are dimensionally alike it is possible to make comparisons between the two measures. For example if a network had a reliability SAIFI of 1.5 interruptions per year and a Sag SAIFI of 6 equivalent interruptions per year, the combined SAIFI would become 7.5 equivalent interruptions per year. This is a particularly useful feature because it allows a direct comparison of customer disturbance from both interruptions and voltage sags. It also provides an indication to distributors of the relative merits of targeting improvements in reliability or voltage sags.

Initial indications from measured data is that the ratio of Sag SAIFI /SAIFI across and entire network is typically in the order of 3 to 8. This indicates that voltage sags may be more problematic for customers than interruptions. More research is required in this area.

## X. Conclusions

A new voltage sag index has been proposed, described and tested on Power Quality survey data. The Sag SAIFI measure developed allows a comparison of voltage sag performance with the well known reliability SAIFI index. The main feature of the Sag SAIFI concept is that it provides a single number measurement of the voltage sag performance at a site or across a network.

Sag severity levels are calculated by log/linear interpolation between the well know ITIC curve (0 severity) and a point on the voltage sag plane that is known to cause disruption to most items of sensitive equipment. These points relate to the sag immunity of equipment and may change over time as new generations of equipment are developed.

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## XII. Biographies

**Robert Barr** is a consulting engineer and director of his company Electric Power Consulting Pty Ltd. Robert holds an Honours degree in Electrical Engineering from Sydney University, a Master of Engineering degree from the University of NSW and a PhD in electrical engineering from the University of Wollongong. Robert has over 32 years experience in the field of electricity distribution and is a fellow of the Institution of Engineers Australia and a member of the Association of Consulting Engineers Australia. He is currently the National President of the Electric Energy Society of Australia.

**Vic Gosbell** obtained his BE degree in 1966 and his PhD in 1971 from the University of Sydney. He has held academic positions at the University of Sydney and the University of Wollongong where he was the foundation Professor of Power Engineering and Technical Director of the Integral Energy Power Quality Centre. He is now an Honorary Professorial Fellow and Technical Advisor to Integral Energy Power Quality and Reliability Centre. He is a fellow of the Institution of Engineers, Australia and is currently working on harmonic management and power quality monitoring methodologies.

**Ian McMichael** is a consulting engineer and director of his company Power Quality Solutions. Ian obtained his BE degree in Electrical Engineering from the University of Melbourne in 1967. Ian has extensive experience in manufacturing plants, power quality investigations and is a Fellow of the Institution of Engineers, Australia.