MV DISTRIBUTION VOLTAGE SAG LIMITS FOR NETWORK REPORTING

Chandana Herath, Vic Gosbell, Sarath Perera
Integral Energy Power Quality Centre
School of Electrical, Computer and Telecommunications Engineering
University of Wollongong
NSW 2522, Australia
msch01@uow.edu.au

Abstract
Suitable voltage sag objectives are not yet found in any standard document. One of the reasons for the lack of objectives is the difficulty of defining suitable site sag indices. In this paper present sag characterisation methods are reviewed and discussed. The University of Wollongong sag index is summarized which shows a better way of characterizing voltage sags. A new method is then given for defining MV distribution sag limits and their suitability is shown by an examination of sag data for some Australian sites.

1. INTRODUCTION

Regular Power Quality (PQ) monitoring will eventually produce a large volume of data covering the various types of PQ disturbances. The PQ disturbances can be classified into two main categories, “Continuous” and “Discrete” [1]. Continuous or variation type disturbances are present in every cycle to a greater or lesser degree and typically include voltage level, unbalance, flicker and harmonics. The discrete or event type disturbances appear as isolated and independent events and can be given as series of diary entries, where for each date and time stamped event a captured waveform (rms in the case of sags and instantaneous in the case of transients) is given. The discrete disturbances covered mainly include voltage sags, swells, and oscillatory and impulsive transients.

Many studies have been undertaken on continuous disturbance characterization and related indices. Comprehensive standards have been developed specifying objectives to be met with specific limits for all continuous disturbance types. Characterization of discrete disturbances is poorly described in the literature requires a somewhat different approach. Suitable objectives are not yet found in standard documents and no specific standard limits are defined for discrete disturbances.

Literature suggests that among discrete disturbances, voltage sags has increased focus where the sags account for the vast majority of recorded equipment trips [2]. European standard EN 50160 [3] which considered as the most comprehensive PQ standard at present, states that “under normal operating conditions the expected number of voltage sags (dips) in a year may be from up to a few tens to up to one thousand”. One of the reasons for the lack of objectives is the difficulty in defining suitable sag site indices. More specific objectives are in use in South Africa and in Chile, which will be discussed in the sections to follow. These Standards (i.e. NRS 048-2:1996 [4] and DS 327:1997 [5]) developed their network sag limits based on their long term PQ monitoring data.

The paper begins by reviewing the existing sag characterisation schemes and their limitations followed by an improved approach of characterising voltage sags which we have developed at the University of Wollongong. Then a new method of defining MV voltage sag limits for normal network operating conditions is given, based on the comparison of existing survey data of different countries and present standard limits. This has been applied to Australian conditions with an application example.

2. VOLTAGE SAG CHARACTERIZATION

2.1 Voltage Tolerance Curves

Voltage tolerance curves also known as power acceptability curves [6] are plots of bus voltage deviation versus time duration. They separate the bus voltage deviation – time duration plane into two regions: “acceptable” and “unacceptable”. Various voltage tolerance curves exist but the most widely publicised is the CBEMA curve. The CBEMA curve has been in existence since 1970’s [7]. Its primary intent is to provide a measure of vulnerability of mainframe computers to the disturbances in the electric power supply. However its use has been extended 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 [6]. The CBEMA curve was revised in 1996 and renamed for its supporting organisation Information Technology Industry Council (ITIC).

The CBEMA curve and ITIC curve differ in the way the acceptable region is represented. CBEMA represents the acceptable region by a curve, whereas
ITIC depicts the region in steps. The guiding principle is that if the supply voltage is within the acceptable region then the sensitive equipment will operate well. The ITIC curve has an expanded acceptable region compared to the CBEMA curve. Both these curves have been accepted as standards and published in the latest versions of IEEE Std. 446 [8] and IEEE Std. 1100-1999[9]. These curves have been used by various PQ studies for discrete disturbance reporting and the development of indices.

2.2 Review of Present Sag Characterization Practices

There are few methods that can be found in the literature for voltage sag reporting which are shown as a table of logged entries or by a choice of graphical formats. Some of these methods are reviewed in [10]. One of the most common is to show sag voltages and durations on a voltage-duration plot overlaid with the CBEMA or ITIC curves (Fig 1). Another, adopted by EPRI, is to show the number of sags in different sag voltage and duration windows as shown in Fig 2.

There is a need for a method based on sound arguments lead to a single meaningful indicator from a sag site report such as that shown in Figures 1 & 2. [10] 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 an 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 [10] 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 Fig 3. The UOW sag index is calculated as the sum of the CBEMA numbers, giving 12 (equal to 1+2+2+3+4) for the example shown. This has not been examined in any detail in the literature to our knowledge.

3. MV VOLTAGE SAG LIMITS

3.1 Standards of Relevance

As described above, there are only two standards available at present that describes 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.

South African PQ Standard (ESKOM)

Figure 4. ESKOM Voltage Sag Windows [4]
The South African PQ Standard NRS 048-2:1996[4] primarily developed by utilities, although the process included customer forums hosted by the South African National Electricity Regulator (NER) [13]. 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 (see Fig. 4 and Table 1) superimposed on the five windows.

**Table 1. ESKOM Sag Characterisation [4]**

<table>
<thead>
<tr>
<th>Network Voltage</th>
<th>Number of voltage sags per year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sag/Dep Window Category</td>
</tr>
<tr>
<td>6.6 kV ≤ 44 kV</td>
<td>6/75/100/150</td>
</tr>
<tr>
<td>6.6 kV ≤ 44 kV (Rural)</td>
<td>40</td>
</tr>
<tr>
<td>&gt; 44 kV ≤ 132 kV</td>
<td>16</td>
</tr>
<tr>
<td>&gt; 132 kV ≤ 765 kV</td>
<td>5</td>
</tr>
</tbody>
</table>

It is worth of being recommended for each utility to maintain a customer complaints database. This will ensure the validity of all the technical information developed through the incident reporting process using recorded PQ monitoring data and how it reflects on the customers.

The other consideration given in defining voltage sag limits is the sensitivity of voltage sags less than 90% of magnitude and of short duration (less than 3 seconds as described in many standard documents). The electromagnetic contactors and control relays will drop out at voltages below approximately 70% of nominal voltage (V_n) and computer equipment and sensitive electronic equipment will tend to be susceptible to instability for voltage sags of below about 40% of V_n unless provided with short time rated UPS or battery back up to ride through sags [2]. And also VSDs are sensitive to large voltage sags and typically contend with voltage sag of 40% - 50% of V_n for 300ms. Therefore, we have segmented the sag contour distribution in Fig 6 in to voltage events as 90% -70%, 70%-40% and below 40%. All together there are twelve sag windows which are similar to the way UNIPEDE sag distribution chart [15] and named them as A1, A2…C 3, C4. This is to define a common format to present all sag survey data using UOW sag characterisation approach.

**Figure 6. Sag window distribution**

**3.3 Comparison of Different Sag Survey Results**

As explained above, some standards have been developed voltage sag limits based on their long term PQ monitoring data. However, the combined information from all the surveys would give a good comparison between different countries and regions, which may be helpful to develop universal sag limits. We have developed MV voltage sag limits comparing all the survey data available at present from different customer supply point and customer sag requirements also may varies from customer to customer. Therefore it is recommended that requirements in this context defined as a number of customer sag events for a given survey category (MV or LV) that is met by 95% of sites measured (see Fig 5).

In the case of sags, the period of observation about the number of events need to be at least one year [14]. This is because the unpredictable behaviour of voltage sag performance that highly dependent on the utility fault performance which causes environment and other various system events varies from location to location and season to season. The way this fault performance translates to sag performance at the

**Figure 5. Definition of the 95% Statistic**
Table 2. Voltage sag limits (95% percentile) of different standards translated into one A, B, C format.

<table>
<thead>
<tr>
<th>Voltage Sag Window</th>
<th>A1</th>
<th>A2</th>
<th>A3</th>
<th>A4</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>Sum</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average UOW Sag Index</td>
<td>0.683</td>
<td>1.15</td>
<td>1.341</td>
<td>1.392</td>
<td>1.527</td>
<td>2.188</td>
<td>2.95</td>
<td>3.048</td>
<td>2.688</td>
<td>4.5</td>
<td>5.15</td>
<td>5.394</td>
<td>139</td>
<td>42</td>
</tr>
<tr>
<td>IEC 61000-2-8:2002 Sag Count (U/G)</td>
<td>23</td>
<td>19</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>19</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td>81</td>
<td>139</td>
</tr>
<tr>
<td>IEC 61000-2-8:2002 Sag Count (Mixed)</td>
<td>61</td>
<td>68</td>
<td>12</td>
<td>6</td>
<td>8</td>
<td>38</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>20</td>
<td>4</td>
<td>2</td>
<td>226</td>
<td>330</td>
</tr>
<tr>
<td>Chilean Limits (DS 327:1997 Std.)</td>
<td>38</td>
<td>26</td>
<td>30</td>
<td>52</td>
<td>58</td>
<td>20</td>
<td>19</td>
<td>7</td>
<td>12</td>
<td>6</td>
<td>12</td>
<td>10</td>
<td>330</td>
<td>330</td>
</tr>
<tr>
<td>Eskom Limits (NRS 048-2:1996 Std)</td>
<td>39.67</td>
<td>29.9</td>
<td>67.03</td>
<td>72.38</td>
<td>88.57</td>
<td>43.76</td>
<td>56.05</td>
<td>21.34</td>
<td>32.26</td>
<td>27</td>
<td>61.8</td>
<td>53.94</td>
<td>594</td>
<td>89</td>
</tr>
<tr>
<td>EPRI DPQ Survey Sag Count</td>
<td>36</td>
<td>15</td>
<td>3</td>
<td>1</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>77</td>
<td>108</td>
</tr>
</tbody>
</table>

Table 3. Annual UOW sag index density (IEC U/G)

<table>
<thead>
<tr>
<th>V</th>
<th>t</th>
<th>0.01-0.1 s</th>
<th>0.1-0.3 s</th>
<th>0.3 - 1 s</th>
<th>1 - 3 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>70-90%</td>
<td>15.71</td>
<td>21.85</td>
<td>4.023</td>
<td>1.392</td>
<td></td>
</tr>
<tr>
<td>40-70%</td>
<td>7.635</td>
<td>41.57</td>
<td>2.95</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>0-40%</td>
<td>2.688</td>
<td>36</td>
<td>5.15</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Annual cumulative sag index (IEC U/G)

The voltage sag index coordination charts shown in Tables 3 & 4 have been developed on the basis of the same concept as in [17]. We have used voltage sag
index contour charts to define a single sag limit based on the results of Table 2. As in [16] for sag events, we have taken the resultant annual sag index limits into sag index density tables and converted into cumulative sag index density tables (Tables 3 & 4 shows the case for IEC U/G networks). A further step is needed to come to the annual sag index contour chart. The values given in the cumulative sag index tables can be interpreted as a function of values of a two-dimensional function (Fig 7) that gives the cumulative sag index as a function of magnitude and duration that corresponds to Table 4.

Figure 7. IEC under ground networks

The contour charts corresponding to all standards in Table 2 are shown Figures 8 - 11, with contours indicated for annual UOW sag index equal to 20, 50, 90, 100 & 110. These contour charts form the basis for defining a single sag limit for MV distribution systems in normal operating conditions.

Figure 8. IEC (U/G)  
Figure 9. IEC (Mixed)  
Figure 10. ESKOM  
Figure 11. EPRI

It is evident from the above contour charts that more than 90% of sites have an annual UOW sag index below 110, except for ESKOM sites. South African NRS 048 Working Group paper [13] indicates that ESKOM sag limits are on high side in relation to the customers and utilities. The ESKOM Standard was adopted on the condition that it would be reviewed in 5 years time. Taking that in to account, we could consider that the ESKOM limits would give higher values than it should. Therefore the sag limit should be based on the other three contour charts and be between 90 and 110. We prefer, 100 to be the sag limit as it lies between the sum and maximum of the annual UOW sag indices shown in the Table 2.

4. APPLICATIONS TO FIELD DATA

The analysis given below has been carried out using data of four Australian sites. The measurements took place over a one year, sufficient to give useful results for voltage sag performance. The available data was collected from two industrial and two rural sites for a one year period.

4.1 Existing Sag Characterization Approach

The field data of four Australian sites monitored over a one year period was analysed and reported to illustrate some of the discussed sag characterization schemes. Sag data from four sites is included in Figure 12(a) & 12(b), overlaid with CBEMA Number contours (CN=1 giving the fitted CBEMA curve).

Figure 12(a) Rural sags overlaid on CBEMA  
Figure 12(b) Industrial sags overlaid on CBEMA

It is evident that there is no possibility of defining a voltage sag limit using the CBEMA overlays other than the general acceptance of CBEMA limit exceedance.
4.2 UOW Index Approach with Sag Limits

It is clear from Figure 13, that the new method will give a clearer differentiation of sites of their limits of acceptability. Site 4 is well within the limit and Site 3 is marginally within the limit needs immediate attention. It is also shown that general voltage sag limits do not apply to the rural sites (i.e. Sites 1 & 2).

![Site Sag Comparison - UOW Sag Index](image)

Figure 13. UOW Sag Index and Limits

5. CONCLUSIONS

Existing sag characterization methods are summarized and a new method for defining MV voltage sag limits is given. The new voltage sag limits can be used in two ways. For utilities, it is useful for worst site identification to determine the priority for PQ improvements and for the formation of custom PQ contracts. For Regulatory bodies, it is useful for setting up new standards.

Initially the network sag limits are developed for general networks. However, a provision is given to develop limits for rural networks upon the availability of suitable sag survey data.

Further research is aimed at developing the network limits for voltage swells and transients that have not yet been addressed by any International Standard.

6. ACKNOWLEDGEMENTS

Assistance given to me by my colleagues Mr. Duane Robinson and Mr. John Braun for finding long-term voltage sag monitoring data is greatly acknowledged.

7. REFERENCES


