POWER QUALITY MANAGEMENT IN A REGULATED ENVIRONMENT:  
THE SOUTH AFRICAN EXPERIENCE

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1. INTRODUCTION

A comprehensive regulatory power quality standard (NRS 048) was introduced by the South African National Electricity Regulator (NER) in 1996 [2]. Adherence to the standard has since been specified as a basic licence condition for all distribution and transmission companies by the NER. The standard was revised in 2003, based on the experience gained since its introduction, and developments in IEC 61000-4-30, EN 50160, Cigrè/CIRED JWG C4-07, and SEMI [4]. This paper discusses the impact that the standard has had on power quality management in South Africa, and in particular in the context of Eskom’s power quality management program introduced in the early 1990’s.

2. NRS 048 INDICES AND OBJECTIVES

2.1 Site Indices and Objectives

For the purpose of performance management, site indices for voltage magnitude, harmonics, unbalance, and flicker are based on 95% (weekly) 10 min r.m.s. values measured according to IEC 61000-4-30. Voltage magnitude further requires no more than two consecutive 10 min values to be exceeded. The weekly assessment has in 2003 replaced the daily assessment used since 1996. This aligns with EN 50160, and Cigrè/CIRED recommendations, and provides a more robust criterion (reporting a site as “exceeding” based on a single day exceeding the site objectives in a 12-month period was found to be problematic in system performance reporting).

The following objectives are applied at HV (mainly 88 kV and 132 kV): harmonics (IEC-61000-3-7 planning levels), unbalance (2%), flicker (site-specific), voltage magnitude (3% to 7.5%), voltage dips (site specific). The objectives for MV and LV are similar to that of EN 50160. Voltage dips have since 1996 been assessed according to X, S, T, and Z type dip categories [2].

![Figure 1. NRS 048-2:1996 dip characterisation.](image)

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The aim of this characterisation was to balance the need for a limited number of indices that still provide a good representation of both system characteristic performance and customer equipment immunity (e.g. a high number of Z-type dips is generally not considered normal or acceptable for a transmission company). The modification in NRS 048-2:2003 to these categories is discussed below.

2.2 System Indices and Objectives

The agreed levels apply to each individual site. For voltage waveform parameters, system reporting is based on the number (percentage) of monitored sites exceeding the agreed limits associated with the site indices. In the case of voltage dips, each dip type (X, S, T, and Z) is reported as a percentage of sites exceeding the limit. Annual targets are also set for system indices (i.e. the percentage of sites exceeding for a given parameters - this is generally below 5%).

3. POWER QUALITY MONITORING

Based on the NRS 048 requirements, Eskom in 1996 developed an in-house power quality database as a business tool that addresses key network operator requirements such as automatic reporting, data flagging, data integrity auditing, instrument tracking, dip-to-fault matching, and contract monitoring. The data for specific instrument locations is made available on-line to key customers via the internet. The database presently manages some 115 Transmission sites (mainly 88kV and 132kV) and some 600 Distribution sites. Voltage magnitude, voltage unbalance, voltage dips, and voltage harmonics (generally only 3rd, 5th, 7th, 11th, 13th and THD) are permanently monitored. Interruption performance monitoring, which is not instrument-based, is undertaken by separate Transmission and Distribution databases. These databases are used in setting targets and reporting power quality performance for the Eskom Operational Sustainability Index (OSI) and Transmission and Distribution Business Plans, as well as for customer complaint investigations, contract development, and regulatory performance reporting.

4. PQ PERFORMANCE REPORTING

The Eskom Operational Sustainability Index (OSI) was introduced in 1996 to monitor the long-term health and performance of the system, thereby balancing the long and short-term objectives of the business. It is based on a scoring system where progressive score-loss occurs when the objectives for various system indices (including environmental, safety, and power quality indices) have been exceeded. Where historical performance is used, the standard is generally set when the 12-month performance exceeds performance levels that statistically have a 1:20 chance of occurring, and an alarm set at levels where the performance has a 1:5 chance of occurring - based on a statistical analysis of historical data. The OSI standards and alarms for interruption performance (e.g. Distribution: SAIDI, SAIFI, CAIDI, RSLI, DSLI, and Transmission: Number of Interruptions, Average interruption restoration time SAIRI, System Minutes), voltage dip performance (X,S,T,Z types), and line faults (faults/100km) are set using historical data. The standards for voltage magnitude, harmonics, and voltage unbalance are based on 95% of sites not exceeding contracted or NRS 048-2 site objectives in a given 12-month period. The alarm level is generally set when more than 4% of sites exceed the site objectives in a given 12-month period. Shorter-term annual business performance targets are aligned with the OSI. In the case of objectives that are based on historical data, these are generally set at a 1:2 chance of occurring. For indices for which specific improvement is targeted, tighter targets are set.

A difficulty experienced is in the application of historical data to setting site objectives for dips. Statistical studies on measured data from 1998 has shown that sites with a low number of dip events have a higher variance. Thus for sites with a limited set of history data (e.g. less than 3 years) limit setting is extremely difficult. Studies show site dip performance for each of the dip categories to be best described by a Poisson distribution. Limits have since set using this statistical model and experience with this will be gained over time.
5. **SYSTEM PERFORMANCE**

5.1 Voltage Magnitude

In 2000 Eskom Transmission integrated power quality recorder data with its SCADA system, providing alarms directly to the national control room. This allows operators to take action to avoid an exceedance of the voltage magnitude levels contracted annually in the Transmission / Distribution supply agreement. The significant improvement in the performance due to this action and the optimisation of automatic tap changer settings is shown below (the percentage of sites where the daily 95% of the 10min values exceeds the limit in a 12-month period). The standard for the OSI of 5% of sites has been maintained since 2000.

![Figure 2. Voltage quality improvement.](image)

Eskom Distribution has developed a comprehensive voltage drop apportioning standard for its networks. This ensures optimal planning and tap coordination from its HV systems down to its LV connection points.

5.2 Voltage Dips

The initial dip limits set in NRS 048-2:1996 were found to be very conservative. Because these are also highly site-specific, annually negotiated site-specific limits have been used in internal supply agreements.

In the past, Eskom Transmission has used a single figure in the calculation of dip costs (about €8k per event). A more detailed procedure has been developed recently for economic justification purposes. The procedure applies to a specific network area and includes the cost to customers, the cost of transmission equipment life reduction, and the cost of energy not supplied. The procedure has been applied in the economic justification of new transmission expansion projects, and may similarly be applied to interventions such as bird guards on transmission lines.

Various projects have been implemented by Eskom specifically to improve dip performance. These include Operation Firebreak (an ongoing project to pre-emptively switch out transmission lines under which farmers burn sugar cane in the eastern region of the network), and the installation of bird guards on identified transmission lines.

5.3 Harmonics

The number of sites exceeding the site objectives over a 12 month period is generally well below 5% for the system. Common causes of exceeding these site objectives are capacitor resonances due to gradual changes in system configuration (fault level) and loading, and system contingencies associated with traction supplies. Particularly the 5th harmonic limit is often problematic. The planning levels are therefore generally appropriate as a management tool, but JWG C4-07 proposals to consider higher objectives at HV levels may be appropriate (particularly for the 5th harmonic) with the increasing number of shunt capacitors used on the transmission system.
5.4 Unbalance

The number of sites exceeding the site limits over a 12 month period is generally well below 5% for the system. Common causes of exceeding the site objectives (limits) at HV sites are generally single-phase traction supplies in remote areas, and line transpositions under specific loading or contingency scenarios. The 2% level is generally conservative, and lower HV and EHV planning levels and objectives may be appropriate for non-traction sites (particularly given the need for HV-MV-LV co-ordination purposes). Most MV network unbalance problems occur where single-phase systems are used to supply remote areas, and ongoing phase balancing is required as load changes occur on these single-phase supplies.

5.5 Flicker

Significantly and continuously higher flicker levels than the IEC 61000-3-7 recommended planning levels (1.5 Pst to 1.8 Pst) have been measured at HV T&D interfaces without corresponding customer complaints. Although the HV/LV flicker attenuation ratios play a role, corresponding LV levels exceed the 1 Pst compatibility level with no complaints for all sites measured up to at least 1.25 Pst. Eskom experience therefore is that, because flicker only really affects LV customers, site indices must be defined on a site-by-site basis, taking local factors into consideration. From a system performance point of view, flicker is therefore managed according to substantive and sustained customer complaints.

6. Power Quality Contracting

Since 1995, detailed power quality contracts have been introduced at individual customer interfaces, and at bulk supply points. These contracts include both utility commitments and customer (emission) commitments. Voltage magnitude, harmonics, unbalance, flicker, rapid voltage changes, frequency, voltage dips, and interruptions are addressed. In order to meet the requirements of these contracts, Eskom has implemented internal power quality agreements at T&D interfaces. Some formal T&D contracts already exist in the form of bulk supply agreements to large metropolitan distributors. Experience with these will form the basis of future contracts when the supply industry is restructured in the next years.

Customer power quality contracts are based on the general provisions of NRS 048-2 [2,4], but may be individually tailored based on historical data. Internal Eskom T&D interface PQ agreements are individually negotiated, based on NRS 048-2 and on historical experience. The latter agreements are renegotiated on an annual basis. The external contracts allow for re-negotiation in the case of significant system changes.

A limited number of Premium Power contracts have been entered into, where equipment is installed and maintained by Eskom Enterprises and paid for on a monthly basis by the customer. Although installations at a wafer fabrication plant (120kW), a paper machine (1 MW), and a telecommunications installation (250kW) were operationally and successful, the number of customers interested in premium contracts has not been significant over the past 5 years.

7. NRS-048-2:2003

The 2003 edition of NRS 048-2 was developed by a working group comprising the National Electricity Regulator (NER), utilities and end-customers.

7.1 Waveform Requirements

The revised assessment methods in NRS-048-2 generally align with those presently proposed in the JWG C4-07. One of the main changes for voltage quality criteria is a change from a daily assessment to a weekly 95% assessment criterion. This criterion is expected to form a basis for system and regulatory reporting. However, from an individual customer point of view, the 95% weekly criterion alone was felt to be inappropriate because of the potentially long durations of exceedances. Shorter-time have therefore been addressed by introducing characteristic limits (maximum exceedances that are typically not exceeded for the system). These may be used by individual customers when addressing the performance of the supplier in
terms of the new regulator framework (see below). The reason for this differentiation is that a utility will not realistically put in place corrective measures at all sites where two 10-minute values have been exceeded once or twice in a year.

7.2 Dip Requirements

The actual dip performance requirements in NRS-048 2:1996 were based at the time on limited statistical information (18 to 24 months) obtained from about 100 Eskom power quality instruments. The availability of these initial instruments was poor, typically failing in the lightning season when many of the dips would have occurred. At the time, the dip figures tabled were considered to be too high by customers, and as realistic by utilities. Voltage dip and interruption requirements are in this context defined as the number of events for a given category that is met by 95% of the sites measured.

![Figure 3. Definition of the 95% dip statistic.](image)

In order to define dip performance in a manner that allows typical utility performance and customer plant immunity to be taken into consideration, dips of various depth and duration were categorised as in figure 1. These dip categories were based on typical protection operation times (e.g. < 150ms dip duration for transmission unit protection schemes), and on equipment sensitivity (e.g. dip magnitudes greater than 20% affecting many variable speed drives, and dip magnitudes of greater than 60% affecting plant motor contactors).

### Table 1. NRS-048-2 dip limits - 95% of sites [2]

<table>
<thead>
<tr>
<th>Network voltage</th>
<th>Number of voltage dips per year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dip window category</td>
</tr>
<tr>
<td></td>
<td>Z</td>
</tr>
<tr>
<td>&gt;44kV..≤132kV</td>
<td>16</td>
</tr>
<tr>
<td>220kV..≤765kV</td>
<td>5</td>
</tr>
</tbody>
</table>

Actual measured utility dip performance has consistently resulted in higher numbers of dip events than the limits in NRS-048. The figure below shows an example of the actual 95% statistic for X-type events on a month-on-month basis in relation to the NRS-048 over-all system compatibility level of 80 events. (Also shown in the figure is the number of instruments and the average dip statistic).

![Figure 4. Dip performance v.s. NRS-048 limits.](image)
Licensee perspective: The inability to meet the limits and the impact of seasonal changes, lead to the conclusion that these dip limits were unrealistic and unachievable without significant investment in the network. At the same time, experience has shown that many of the less severe X-type dips (typically less than 30% in depth) do not affect customers, making such investment questionable (figure 4). Customer perspective: At the time of implementing NRS 048 in 1996, customers were unhappy about the large gap between actual performance at some sites in the country, and the limits in the standard. An expectation was present at the time that a revision of the numbers in 5 years would result in improved numbers. As shown above, actual experience has not supported this. A survey of customer power quality costs (undertaken in 1995) also revealed that a large percentage of customers are not willing to pay for more for improved power quality [1].

From a benchmarking perspective, international comparisons of dip performance are also difficult. Studies apply different dip characterisation methods and criteria for locating instruments.

Figure 5. Dip density plot: networks >132kV.

Figure 6. Dip density plot: networks >44kV and ≤132kV.

7.3 New Dip Requirements

The original NRS-048 dip characterisation method was based on theoretical considerations. Figures 5 and 6 show actual dip density plots based on national Eskom dip measurements over 5 years [4]. From this data it is clear that as far as large industrial customers are concerned, voltage dips of less than 30% to 40% in magnitude, and a duration shorter than 150ms, have a high probability of occurring in South African HV networks. Many customers are not affected by these events. This has resulted in the development of a revised dip categorisation method, published in the December 2003 revision of NRS 048-2.

Some customers report other dip parameters besides dip magnitude and duration (e.g. phase jump and negative sequence) as having a significant impact on their plant. These issues are addressed through a revised framework for power quality management.
Table 2. NRS 048-2:2003 dip categorisation method.

<table>
<thead>
<tr>
<th>Remaining Voltage $u %$ of $U_d$</th>
<th>Duration $t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$20 \leq t &lt; 150$ (ms)</td>
<td>$0.6 \leq t &lt; 3$ (s)</td>
</tr>
<tr>
<td>$150 \leq t &lt; 600$ (ms)</td>
<td></td>
</tr>
<tr>
<td>$0.6 \leq t &lt; 3$ (s)</td>
<td></td>
</tr>
<tr>
<td>$90 &gt; u \geq 85$</td>
<td></td>
</tr>
<tr>
<td>$85 &gt; u \geq 80$</td>
<td></td>
</tr>
<tr>
<td>$80 &gt; u \geq 70$</td>
<td></td>
</tr>
<tr>
<td>$70 &gt; u \geq 60$</td>
<td>$X_1$</td>
</tr>
<tr>
<td>$60 &gt; u \geq 40$</td>
<td>$X_2$</td>
</tr>
<tr>
<td>$40 &gt; u \geq 0$</td>
<td>$T_1$</td>
</tr>
</tbody>
</table>

Table 3. Indicative dip numbers - 95% of sites [4].

<table>
<thead>
<tr>
<th>Network Voltage</th>
<th>Number of Dips per Year</th>
<th>New Dip Window Category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X_1</td>
</tr>
<tr>
<td>&gt;44 &lt;=132kV</td>
<td>35 35 25 40 40 10</td>
<td></td>
</tr>
<tr>
<td>&gt;132kV</td>
<td>30 30 20 20 10  5</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Indicative dip numbers - 50% of sites [4].

<table>
<thead>
<tr>
<th>Network Voltage</th>
<th>Number of Dips per Year</th>
<th>New Dip Window Category</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X_1</td>
</tr>
<tr>
<td>&gt;44 &lt;=132kV</td>
<td>13 10 5 7 4 2</td>
<td></td>
</tr>
<tr>
<td>&gt;132kV</td>
<td>8 9 3 2 1 1</td>
<td></td>
</tr>
</tbody>
</table>

8. **A NEW REGULATORY PQ FRAMEWORK**

One of the concerns around the original power quality management framework was the lack of direct participation by customers in the NRS 048 working group (although public stakeholder consultation meetings were held). In response, the NER instituted a PQ Advisory Committee in 2001, comprising a balanced representation of customers, licensees, equipment suppliers, standards bodies, and the service industry (academics, consultants). The NER further solicited detailed comments from all interested stakeholders on the manner in which power quality is managed in South Africa. The table below summarises the opinions of these stakeholders of the manner in which other stakeholders address power quality concerns. An important conclusion is that more needed to be done to address the manner in which end-use equipment is specified (equipment suppliers feel that customers do not sufficiently specify the power quality requirements, and customers feel that equipment suppliers do not design for, or communicate power quality limitations).

Table 5. Summary of stakeholder opinions.

<table>
<thead>
<tr>
<th>Opinion of</th>
<th>Attention given to power quality by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Licensee</td>
<td>Licensee: Some, Customer: Some, Supplier: Don’t know</td>
</tr>
<tr>
<td>Customer</td>
<td>Licensee: Some, Customer: Significant, Supplier: Insufficient</td>
</tr>
<tr>
<td>Supplier</td>
<td>Licensee: Some, Customer: Insufficient, Supplier: Insufficient</td>
</tr>
</tbody>
</table>

The main problems sited being voltage dips and interruptions.

A new regulatory power quality framework was developed to address the concerns identified through the submission process, as well as the difficulty of managing dip performance using national minimum standards. The new framework, defined in the NER Directive on Power Quality [1], recognises the need for each of the parties (transmission and distribution companies, customers, and equipment suppliers) to
appropriately address power quality issues in the design and operation of their plant / equipment. A practical problem is that the NER only has direct influence over licensee behaviour through its various licence requirements. The definition of a power quality management framework addresses this problem by defining the conditions under which the NER can meaningfully intervene where power quality problems are experienced by any of the stakeholders (thereby indirectly influencing the relationship between the customer and the equipment supplier). The new framework acknowledges that dip and interruption performance varies from location to location, and that customer power quality requirements vary. This is achieved by defining licensee requirements for quality management based on ISO-9001 philosophies as opposed to the application of standards alone. This management system includes non-technical aspects such as communication requirements and a formal complaints management process.

The manner by which voltage waveform quality and disturbance events (dips and interruptions) are managed differ in terms of the directive.

8.1 Voltage Waveform Quality

Voltage quality parameters have a direct impact on the rating and design of end-use equipment. For this reason, performance objectives based on international standards are applied. There is little justification from a regulatory point of view for a licensee to provide better levels of voltage quality than those specified by international standards. Clearly it is also not possible to monitor all site or to guarantee that these levels will be met at all times by a licensee. Where it is demonstrated that a licensee does not meet these levels, corrective measures must be implemented by the licensee. Licensees are expected to contract with customers for maximum disturbance emission levels that each customer is permitted to generate on the network. NRS 048-4 provides for three methods of apportioning emission.

8.2 Voltage Disturbances (Dips and Interruptions)

The new framework defines a method of managing voltage dip performance on site-specific basis. This is described below with reference to figure 7. When connecting a customer, the quality management system requires utilities to inform customers of:

1) The level of quality to be received (the detail of the information is differentiated by a range of customer categories).
2) Their responsibilities (emission levels and equipment immunity considerations).
3) The regulatory complaints protocol outlined below.
A licensee is further required to implement a system whereby a sensitive customer can notify the utility of an incident affecting its plant (called an Incident Report). The utility is required to provide the customer with an explanation of the cause of the event or group of events (where this is known) and remedial measures to be taken (if any). Should the customer not be satisfied with the response of the utility over a period of time, a Non-Conformance Report (NCR) can be issued by the customer. The aim of this is to escalate the complaint to the licensee senior management. Should a NCR not be resolved between the parties, a Dispute may be declared, escalating the complaint to the NER. The NER (usually in consultation with its PQ Advisory Committee) will review the merits of the dispute based on:

1) How the quality management system was implemented by the licensee (e.g. was the customer informed of the poor dip performance of the network).
2) Actions by the licensee to improve performance.
3) Actions by the customer to reduce dip sensitivity.
4) Technical standards (e.g. licensee vegetation management, equipment dip immunity standards).
5) Precedents of similar cases dealt with in the past.

It is a requirement of the licensee to keep a record of incident reports and non-conformance reports. This ensures that all the technical information developed through the incident reporting process is available to the NER in the case of a dispute. This approach to quality management recognises both that dip performance can in some cases be improved, and that dip performance may in some cases get worse (e.g. in cases where new utility lines are constructed). The approach encourages customers to take reasonable actions to reduce their plant dip sensitivity, thus reducing the network zone (area) in which utility faults affect the customer plant. This is particularly important with the restructuring of the supply industry, where customers may be affected by faults originating in neighbouring distribution companies – making it more difficult to address such problems.

8.3 Implications of the New Framework

*Transmissions and distributions companies* are not required to meet national dip limits, but to implement a quality management process. The focus of dip performance is not on dip statistics alone, but also on how the utility interacts with its customers, and addresses the causes of the specific events that affect sensitive customers. The latter increases the focus on power quality issues in network planning, operation, and maintenance practices. Licensees have submitted to the NER a program of timeframes and actions to be taken to implement the relevant
communication and record-keeping systems. To assist smaller distribution companies a recommended format was developed by the PQ Advisory Committee. This includes standard NCR forms, examples of power quality communication material to smaller customers, and technical investigation formats. Customers may require licensees to focus on managing dip performance even in areas where this is relatively good. Customers are specifically required to focus on how power quality considerations are taken into account in the design and operation of their plant. Equipment suppliers will increasingly be required by their customers to provide the dip performance characteristics (and mitigation options) of their equipment. The NER will mediate/arbitrate on disputes that are already technically well defined by the time they reach the NER. The NER will ensure that utility quality management systems are in place, and that utilities report on power quality trends on an annual basis.

8.4 Example

With a significant expansion of the transmission system in one of the Eskom regions, a study using statistical dip prediction simulations was undertaken. The increase from 1807 km of line to 2585 km of line in the zone of sensitivity, is expected to significantly increase the number of dips (38/yr to 50/yr). Using the new NRS 048 dip characterisation method, the actual impact on customers was communicated at a power quality forum for key customers in the region. As shown the actual impact on customers is expected to improve from 37 to 28 events, given comparable fault performance for the new lines and the general area of customer responsibility for dip immunity (black). The performance is also more comparable with that for 50% of 132 kV sites in the country, based on the characteristic dip performance data in Table 4. Particularly the number of T-type dips is significantly improved.

<table>
<thead>
<tr>
<th>Voltage u % of Ud</th>
<th>Duration t</th>
<th>Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>90&gt; u ≥ 85</td>
<td>20 ≤ t &lt; 150 ms</td>
<td>1 (22)</td>
</tr>
<tr>
<td>85&gt; u ≥ 80</td>
<td>150 ≤ t &lt; 600 ms</td>
<td>0 (0)</td>
</tr>
<tr>
<td>80&gt; u ≥ 70</td>
<td>0.6 ≤ t &lt; 3 s</td>
<td>0 (0)</td>
</tr>
<tr>
<td>70&gt; u ≥ 60</td>
<td>8 (12)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>60&gt; u ≥ 40</td>
<td>7 (6)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>40&gt; u ≥ 0</td>
<td>21 (9)</td>
<td>0 (0)</td>
</tr>
</tbody>
</table>

Customers, having been informed in terms of the Quality Management System, are using this information to evaluate the actual economic impact and possible mitigation, based on their plant immunity.

9. CONCLUSIONS

1) The new Cigré/CIRED recommendations on indices and objectives for HV and MV networks are considered appropriate in the context of South African experience.

2) The X,S,T,Z dip characterisation method is used in South Africa as it provides a good description of general system performance and plant immunity characteristics, and requires only 4 indices for general site and system reporting.

3) Within Eskom, power quality monitoring and reporting has contributed positively to technical performance management. It has also formed a basis for developing and implementing an improved regulatory framework which requires dip performance data to be provided to customers.

4) Technical standards alone are not a suitable basis for managing dips and interruptions, as these cannot be appropriately defined in a national standard to the satisfaction of all stakeholders.

5) A formal quality management system that clearly defines the roles all stakeholders (the regulator, the utility, the customer, and the equipment supplier), provides an improved management framework from the point of view of all stakeholders.
6) A significant technical requirement for this framework, is need for development of improved equipment dip immunity standards and methods of characterising equipment dip performance.

REFERENCES