Contextualisation and reporting of Quality of Supply data

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DECLARATION

I hereby declare that all the material incorporated in this dissertation is my own original unaided work except where specific reference is made by name or in the form of a numbered reference. The work herein has not been submitted for a degree at another university.

Signed:

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SUMMARY

Quality of Supply (QoS) concerns the interaction of the loads on the electrical grid with the voltage supplied by generation, in the transmission and distribution portions of the grid. Most power quality standards and regulatory frameworks, describe power quality only in terms of voltage behaviour. This energy regulator requires, for licensing purposes, that data on voltage behaviour should be recorded and submitted for auditing purposes. A large portion of Southern African utilities therefore use power quality instruments to record only these voltage parameters. This is cost-effective and fulfils the requirements set by regulator, but valuable other information, already present in the measurement data, is often not utilised.

In this dissertation, a large power quality database is investigated, through exploratory visualisation techniques. This was done by identifying several contexts for power quality data. The information obtained through these investigations was used to create visualisations and interactive dashboards. This may aid, utilities and consumers alike, in the management of power quality in their respective businesses.

The developed model was implemented and validated using real-life data produced by more than 600 QoS recorders located all over Southern Africa. To demonstrate how the model works, and to evaluate the results, the implementation for two QoS parameters: voltage magnitude and voltage sags, will be presented. These two were selected, since practical experience with a number of South African utilities indicated that these parameters are prioritised in managing distribution networks.

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OPSOMMING

Kwaliteit van toevoer omvat die interaksie tussen verbruikers en die elektriese energie versprei deur die transmissie en distribusie netwerk. ’n Groot gedeelte van Suider Afrikaanse munisipaliteite en energie verskaffers doen metings van die spanning alleen. Dit is koste effektief en voldoen aan die vereistes gestel deur die standaarde en regulatoriese raamwerke wat kwaliteit van toevoer alleenlik beskryf in terme van spannings gedrag.

Hierdie beperkte inligting word hoofsaaklik versamel en aan die reguleerder gelewer as deel van lisensie voorwaardes. Waardevolle inloging vervat in die data word selde onthul deur ondersoeke.

Hierdie verhandeling ondersoek die data vervat in ’n omvattende kwaliteit van toevoer databasis, met behulp van data visualisering- en ontkennings metodes, deur verskeie kontekste te identifiseer waarin kwaliteit van toevoer data geplaas kan word. Die insig bekom word dan verpak in die ontwerp van verskeie, meestal interaktiewe, toepassings applikasies ten doele die verbruikers en verskaffers van elektriese energie by die staan in die bestuur van die toevoerkwaliteit as deel van hulle besigheidspraktyke.

Die bestuur van spanningsvlakke en die verskynsel van kort-spanningsval word ondersoek om die tegnieke te demonstreer, aangesien probleme ondervind daarmee deur Suider Afrikaanse energie verskaffers volop is in die beskikbare databasis.

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1 Introduction

Power quality (PQ) concerns the measurement, analysis and reporting of electrical parameters in an electrical network to qualify and quantify the quality of electrical energy. To this end, voltage parameters are mostly used. This is because voltage is delivered to the load, where current or power parameters describe the consumption of energy and the influence the load has on the delivered voltage. The operational and regulatory principles of PQ are mostly voltage based and that is why the concepts of Quality of Supply (QoS) and PQ are interchangeably used in literature.

QoS parameters describe how the actual voltage delivered to the load differs from the ideal, perfectly symmetrical, perfectly sinusoidal voltage at a fixed and repeatable period. The difference is referred to as voltage waveform or PQ disturbances. Both short term and long term disturbances (also known as steady state disturbances) are of interest. Short-term voltage waveform disturbances are events such as dips, swells and transients. The duration of a short-term disturbance may vary from a sub-cycle to several seconds.

Steady state voltage disturbances are deviations in the magnitude, phase symmetry and harmonic distortion of the waveform. Parameters are calculated on a cycle-by-cycle basis and aggregated to: 3 second, 1 minute or 10-minute values, depending on the measurement standard subscribed to. Most compliance and compatibility assessments however use 10-min interval values, because changes in the steady-state conditions in a power system normally do not happen suddenly. However, number of countries is moving towards 1 minute interval values.

PQ assessment normally requires data continuously recorded for at least 7 days. The recordings are then statistically analysed and benchmarked against the applicable PQ standard. The concept of PQ is generally treated as a measurement of compatibility between the grid-supplied voltage and the equipment operating at this voltage. PQ standards are sets of criteria that prescribe the acceptable voltage the utility should supply.

The utility has the responsibility (normally as part of a license agreement with a regulatory body) to operate the electrical network above the minimum standards. When designing production plants, equipment manufacturers and users, can use this information to ensure that equipment perform as designed when supplied by a supply conforming to minimum standards.

The Electricity Supply Industry (ESI) constitutes several role players, each with different needs requirements regarding information produced by PQ monitoring systems.

Large-scale generation of electricity by mostly coal-, nuclear- and gas generators is the least concerned with power quality, since voltage at the point of generation should be near perfect. This is however changing as a result of distributed generation sources such as renewable energy and other alternative energy sources of energy connected to the grid. These sources, when grid-connected, can be located all over the network. Distributed sources of generation have been recognised as beneficial, but it also provides a challenge in terms of QoS, due to the variation in the generation. To address this problem, smart grid solutions aim to maintain voltage stability, by on-line control of generation to match demand.

Transmission and distribution are responsible for distributing electrical energy from the point of generation to the point of consumption. Transmission is the high voltage part of this network (normally 275kV and above) while distribution makes up the medium and low voltage part of the network. Most resellers of electrical energy are in essence distributors, but will for operational reasons refer to for example a 132 kV (strictly speaking a distribution voltage) as a transmission intake point. This is because the transmission provider often delivers energy, to operators of distribution networks, at this voltage or lower.

Different levels of compatibility are defined for transmission and distribution by PQ standards. Normally, transmission will deliver to distribution who, in turn, will deliver to the consumer. However, transmission can directly deliver to consumers if they are large industrial users. These connections often have contractual power limits that differ from the power quality standard. The compatibility level decreases as voltage increase, since the downstream flow of energy (from higher voltages to lower voltages) comes with degradation in voltage quality.

In several countries generation, transmission and distribution are either state-owned or monopolised, which necessitates governmental regulation of the ESI. Electrical energy is a strategic commodity. Modern economies rely on reliable electrical energy of sufficient quality to be sustainable and support growth.

In a competitive electricity market, self-regulation in terms of quality is possible. However, non-competitive electricity markets (such as South Africa), need government intervention and participation to regulate the quality of electrical energy. The lack of government intervention and participation in most African countries is known to be a major contributor to poverty and economic insignificance.

In South Africa, all parties wishing to sell electrical energy require a licence to do that. The need for measuring PQ at transmission and distribution level then originated as a result of the governmental mandate given to the national energy regulator (NERSA). This mandate requires licensees to record PQ data and report it to NERSA. The goal of PQ monitoring is actually the integration of operational processes and not the obligatory reporting. Therefore, most licensees in South Africa (and Southern Africa) did not engage in PQ monitoring because it was required of them, but rather because PQ can affect their sustainability. Many success stories in this regard were noted in the Southern African Electrical Supply Industry (ESI). These are cases where PQ monitoring became PQ management by being an integral part of proper business management practices.

Industrial and commercial electricity consumers are the most susceptible to poor PQ. The industry and commercial sector of the economy determines growth, which is the primary goal of many governments. Since modern production processes often make use of sensitive electronics and microprocessor-based control circuits, these consumers may suffer significant losses as a result of poor PQ. Examples of PQ sensitive systems are: continuous production processes (e.g. paper making industry), multi-stage batch operations and data processing operations (e.g. stock exchange, electronic banking systems) etc.

1.1 Context and the use of PQ data visualisation

The measurement and direct evaluation of PQ parameters gives insight on *when*, *how often* and by *how much* the compatibility criteria were not met. Proper context can furthermore reveal:

- Why criteria were not met;
- How many sites were involved;
- Where it originated;
- Who is responsible; and
- What can be done to prevent or resolve a problem?

Creating a context, and then performing analysis on PQ parameters, can furthermore reveal patterns in network behaviour or deviation from expected or historical behaviours. Context in the analysis of PQ data is not determined by the PQ standard, but depends on the user requirement of the client at the site where the PQ monitoring is done.

The requirements of each user have to be recognised when tools are developed to analyse PQ data, because the result of the analysis has to find operational application. Business processes will dictate what format of information will be useful.

Additional contextualisation with external or annotated data can also be useful. Weather data can help to understand the voltage dip performance of a network. Other location or relational information such as geographical, network topology, voltage level and connectivity information can aid the creation of context of applicable PQ data.

The goal of contextualising PQ data is to extract additional information not visible by considering the recorded PQ data in isolation. Data visualisation techniques aid the exploration of the large dataset and discovery of patterns and relationships contained in such data.

1.2 Problem statement

The supply and demand role-players in the ESI have different needs to visibility on PQ. The supply-side typically has access to large numbers of instruments distributed throughout the network. Instruments will mostly be voltage-based only. The demand-side (users) mostly has limited (or no) visibility by means of a single instrument at the service entrance to the site. This PQ instrument however will regularly have the capability of recording both voltage and current parameters.

1.3 Research aim

In this dissertation, the author illustrates how standardised reporting of PQ data to the ESI can benefit from the contextualisation of complimentary data sources relevant to the network. The additional information and increased understanding of the root causes of problems and the interaction between parameters can be valuable if it is properly integrated into operational processes.

Using exploratory data analysis, recorded PQ data is examined. The data is equivalent to approximately 1000 instrument years (collected over a period of more than 10 years). It was recorded in several different networks in Southern African countries. The results are then used to develop tools to extract additional information based on the contexts in which the analysis is performed.

Energy regulators such as the National Energy Regulator of South Africa (NERSA) only require PQ monitoring and limited reporting from resellers of electrical energy. PQ Monitoring in Southern Africa, as required by NERSA, was proved to be of limited practical value to network operators, because it is not necessarily enforced. Even if statistics are submitted, NERSA does not service the ESI by publishing national benchmarking statistics, as was promised in the PQ Directive published in 2002. The result is that few licensees do *monitor* PQ and even less *manage* PQ.

A painless transition from a PQ Monitoring System to a PQ Management System is possible, if modern database and information technology is employed. The tools developed and presented in this dissertation will be shown as useful for network operators to extract the operational value of PQ data. It will also shift the focus of PQ monitoring to PQ management. This will be of practical value in operating networks and in managing the risk of users relying on electrical energy to have sustainable businesses. The success of the developed tools is the result of ensuring proper context to recorded data.

In this dissertation, data visualisation, by means of interactive brushing and linking methods to interrogate a PQ database, is enabled. It is implemented as exploratory data analysis tools, which intuitively extract useful network performance information. This solution therefore enables users to get access to information for which PQ specialist knowledge and advanced information system knowledge would be needed, if recorded data was analysed by means of traditional tools.

Application of these visualisation techniques, that are uncommon to the PQ industry, enables the intuitive communication of additional PQ information. This can help network operators to manage risk in the ESI, while reducing the need for on-site PQ specialists.

1.4 Focus and methodology

Voltage magnitude control and dip performance is internationally perceived as the biggest priority in managing PQ. The focus of the research presented in this theses is on voltage magnitude and dips. The following methodology is used:

- Firstly, opportunities for the improvement of current PQ assessment and reporting practices are identified. This is done through detail analysis of each parameter in context to other (relevant) data sources such as climate data.
- Secondly, improvements to PQ management are proposed. The aim of this process is to minimise the impact on data and instrumentation, by quantifying the existing additional information that are merely not mined in QoS data recording systems.
- Thirdly, exploratory data analysis techniques are evaluated. These include visualisation of brushing and linking techniques in the interrogation of a PQ database.
- Finally, the results are evaluated to determine the possible improvement of forensic analysis of PQ data, to better understand root cause and network behaviour of PQ performance.

The above mentioned process requires identification of what information will be useful and then translating it into SQL (structured query language) queries. Visualisations that can aid in data exploration then require coding, for example to apply interactive brushing and linking techniques.

The development of the tools is an iterative process that converges by extensive testing and verification of results and with limited opportunity for prediction of success. A sound understanding of power system operation and PQ phenomena was needed to enhance the accuracy of the SQL queries developed and to minimise the premium on time before it could be made available to network operators.

Tools developed were made available to operators of PQ management programs for operational evaluation and changes made when a deficiency in performance of a tool was reported. Once useful information has been identified, interactive visual applications are used to intuitively communicate the results to a user. These tools are presented in this document based on real-life network data. The South-African NRS 048-2: 2007 will mostly be used as reference standard for analysis and investigation.

1.5 Availability of data

Vast resources of PQ data were available for this study. CT Lab (Pty) Ltd has been manufacturing PQ instrumentation since 1990 and has managed recorded PQ data as an outsourced service for many utilities since 2006. Recorded data is concentrated into an Oracle database for more than 30 different utilities all over Southern Africa.

This database was used to test the models developed in this dissertation and some of the proposals which proved to be useful, were commercialised and implemented by means of web applications, extracting the information as proposed in this document.

It was therefore possible to extensively evaluate all methods and applications developed by the research work reported in this thesis. Application can be found at www.pq-portal.com (unfortunately not open to the public).

1.6 Overview of dissertation

The remainder of this dissertation is organised as follow:

Chapter 2 presents a literature study on relevant aspects of PQ and data visualisation. Several visualisation techniques are presented and evaluated. PQ standards, parameters and regulatory frameworks are presented and analysed to understand application in the assessment of QoS.

After which Chapter 3 will focus on the assessment and reporting of voltage magnitude. The South-African NRS 048-2 approach to this parameter is shown as ambiguous under certain conditions. A useful contribution by the author is presented as an alternative (or complimentary) to the standardised reporting of voltage magnitude. The chapter concludes with interactive dashboard applications to aid utilities in the optimisation of voltage magnitude control by understanding the root cause to voltage regulation concerns.

Voltage dips will be the theme of Chapter 4. It is the PQ parameter internationally recognised as the most problematic to the economy. The depth-duration categorisation of NRS 048-2 is analysed and other single-value indices used for voltage sag reporting investigated. Improvement on voltage dip recording practises is proposed and demonstrated to contribute to dip management in the context of the network where the dips were recorded. Aggregation of events is demonstrated and applied. Interactive visualisation tools developed are presented and shown to be useful in benchmarking of network dip performance, analysis of root cause, the location of the network fault and others.

Chapter 5 concludes the dissertation by evaluating the results obtained and proposing opportunities for improvement in best practises in PQ Management programs.

2 Literature Study

2.1 Introduction

In this chapter, the concept of Power Quality is introduced. The parameters used to quantify PQ are discussed and compared in terms of different international and national standards. Application of standards, interpretation of PQ reports and compatibility assessments are presented. Different approaches to PQ benchmarking are also evaluated for application in the Southern African context.

Data visualisation methods to aid the interpretation of assessment results are studied to identify possible application in the context of PQ reporting and benchmarking. Time-aggregation and other principles on how to identify a single network incident relating to a number of voltage events recorded all over the network are discussed.

Opportunities are identified to report PQ not only at a single site but also for a number of sites in a network of similar geographical of electrical interconnectivity (such as voltage level) on a global basis. Query tools to extract network performance information from a database requires careful consideration to further network performance information in context of the network in which that data was recorded. Exploratory data analysis techniques to extract trends and relational aspects between different data sets are finally presented.

2.2 Power Quality Standards

The IEEE 1159 standard [1] defines PQ terms and concepts. It states the objectives for monitoring, the types and instrumentation class of measurement equipment and concludes with recommended practices in interpretation of measurements. IEEE 1433 [2] is the minutes of a working group dealing only with PQ definitions.

IEC 61000 is a comprehensive set of PQ standards, with IEC 61000-4-30 [3] specifying the measuring of PQ parameters. Measurement instruments implementing the techniques and algorithms set out in this standard can be certified against the standard to be classified as PQ instruments. Measurements made by two Class A power quality instruments from different manufacturers can be directly compared.

The above standards describe unambiguously what to measure and how to measure it. It does not provide minimum standards for the measured values of each parameter as local authorities (energy regulator in South Africa for example) can adapt minimum standards to acknowledge local conditions.

Providing internationally agreed upon regulatory standards for PQ is challenging:

- Varying local conditions like weather, age of the electrical supply infrastructure, loading factor and others are unique.
- Consensus-based standards tend to converge to the lowest common denominator (or average), which counters the ideal of maximum quality.
- Holding the electricity supply industry to the standards is the responsibility of the energy regulator. The regulatory bodies (where it exists) of different countries have different mandates and measures to enforce conformance to standards. In markets where regulation is not needed, free market principles drives utilities to adhere to best practices, as described in IEEE 1159 [1] for example.

The above affected the development of several independent regional regulatory standards. From [4], the EN 50160 standard introduced in Europe in 1994, was the first regulatory standard and used as reference by several authorities, such as in the South African NRS048 document, the NVE standard in Norway, GB/T standards in China and by the Dutch energy regulator. Although based on EN50160, these standards have some significant differences in the assessment strategies and imposed minimum standards.

Most African countries south of the equator use the NRS048-2 document to set minimum standards to QoS. The Regional Electricity Regulatory Authority (RERA) coordinates the harmonisation of QoS standards on behalf of Southern African Power Pool (SAPP) members. This was needed to facilitate the trading of electrical energy between different utilities, as quality of the product (electrical energy) requires qualification and quantification in the economic model employed.

Minor differences between countries exist. Characteristic numbers in dip performance depends on geographical location, climatic conditions, type of network and others.

2.3 PQ parameters

Quality of Supply (QoS) is a concept adhered to the quality of the voltage waveform as the electrical utility supply a voltage to the terminals of a load. It is commonly found in literature that the term “PQ” is used rather than QoS. Some definitions of PQ include the quality of the current waveform. The discussion of PQ parameters in this document is based on a QoS approach.

2.3.1 Voltage magnitude

Voltage regulation is the process by which control of voltage magnitude is done to ensure that all users connected to the electrical grid receive voltage at a magnitude compatible to the design parameters of the equipment in use. Planning of supply impedance, loading, fixed or automatic tap changer transformers are all part of managing the process. Having voltages all over at near nominal is self-explanatory as the most important QoS parameter. Some difference in what the definition of voltage magnitude compatibility entails exists in different countries.

The European standard EN50160 [5] sets the acceptable voltage magnitude to be within ± 10% of the expected or nominal voltage for 95% of the time. It literally means that 95% of the 10-min voltage rms values have to be within ± 10% of the nominal value. This is in principle a compatibility statement. Performance of equipment being supplied with voltages within the range of variation and time allowed has to be as designed.

In addition, all 10-min values have to be within -15% and +10% for 100% of all samples, that is, for 100% of the time. The latter requirement is a limit statement.

The South African NRS 048-2 [6] is stricter and requires voltage to be within ± 5% for 95% of the time (95% of all 10-min values). An additional requirement is that no more than 2 consecutive 10-min V_{RMS+} values are allowed to be outside the ± 5% variation.

The 3rd 10-min V_{RMS} value that falls outside the ± 5% variation will result in non-compliance to voltage magnitude compatibility. The reason for this is to attain a statistical distribution of the 5% of 10-min V_{RMS} values all over the time period under investigation. If the 5% of the time allowed for 10-min V_{RMS} values to be outside the ± 5% variation can imply 1.5 continuous days per month, for example. This is avoided by the additional requirement of only 2 consecutive 10-min V_{RMS+} values allowed outside the ± 5% variation. A limit criterion is set to voltages in Southern Africa by a ± 10% limit for 100% of the time.

Delivery of voltage at too low a magnitude could cause constant power devices such as electrical motors to overheat due to additional current withdrawn in maintaining the mechanical torque requirement of a load [7]. Delivery of voltage at too high a magnitude can contribute to insulation breakdown in rotating loads, causing permanent damage to electrical equipment [5].

In an analysis of the costs of power quality problems [8] it was calculated that a constant 10% over- or under voltage condition could result in up to 20% losses in revenue to a utility due to extra losses in cables, transformers and induction motors. Since voltage magnitude is a long-term power quality parameter, it is mostly assessed based on an aggregation of cycle-by-cycle rms values updated every ½ cycle over a period of 10 minutes. A trend of 10-min values is shown in Figure 2-1.

Utilities manage voltage regulation by proper network design, conservative loading and tap-changing transformers. Some transformers have fixed taps, requiring manual change, while others are automated and respond to how the load affects the voltage.

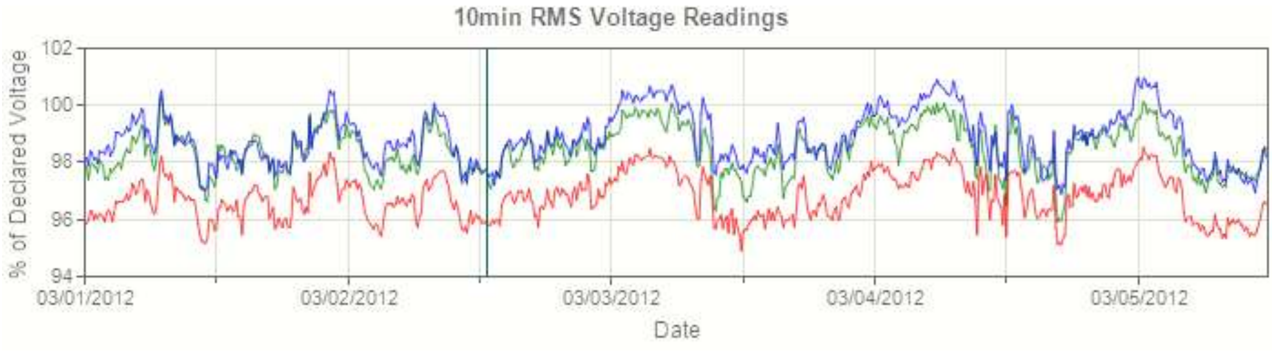


Figure 2-1 Voltage magnitude readings

2.3.2 Voltage unbalance

Phase currents can be unbalanced, but the concept of "voltage asymmetry" is generally used to refer to the unbalance in voltage, whilst load unbalance is normally described by unbalance in load currents.

A three-phase power system is balanced when the fundamental frequency phasors are perfectly symmetrical in phase displacement and equal in magnitude [1]:

- The magnitudes of the voltage phasors are equal.
- The phase shift between voltage phasors is 120 degrees.

Should any of the above conditions not be met, the three-phase voltages are qualified as asymmetrical or unbalanced.

Voltage unbalance is quantified by means of the fundamental frequency sequence components:

$$\%V_{unb} = \frac{V_{neg}}{V_{pos}} \times 100 \qquad (2\text{-}1)$$

V_{neg} is the magnitude of the 50 Hz[1] negative sequence component and V_{pos} the magnitude of the 50 Hz positive sequence component. Positive and negative sequence fundamental frequency components are obtained by means of the Fortesque transform applied to the fundamental frequency phasors. It is a synthetic concept useful for analysis of 3-phase power system phenomena.

[1] The fundamental frequency in South Africa (and Africa) is 50 Hz.

A cause of voltage asymmetry is uneven single-phase loading, especially large industrial single-phase loads such as arc-furnaces and electrical trains. Network faults such as blown capacitor bank fuses or faulty single-phase line regulators [1] can also contribute to voltage unbalance.

Incomplete transposition of transmission lines can cause significant enough asymmetrical phase impedances to result in different voltage drops per phase. Asymmetrical voltages at the receiving end of the line will then result even when the loading between phases is perfectly equal. Unbalanced load currents are then unavoidable.

Voltage asymmetry causes an increase in apparent power loading. It degrades the ability of the power system to transfer useful (active) power. The installed capacity can be optimised if the power factor remains high by avoiding the contribution to useless (reactive) power by asymmetrical voltages and unbalanced loading.

Observe that power factor correction by capacitive reactive power injection compensates for reactive power consumption by a local load. Capacitors are normally designed to be equal per phase and as such will not mitigate the reactive power resulting from unbalanced loading and asymmetrical voltages. Special mitigation is needed to compensate for practical cases where voltage asymmetry is noted as a concern.

Rotating loads operate at higher temperatures when supplied by asymmetrical voltages. Due to the difference in sequence impedances of rotating loads, the negative sequence current will be a factor of at least 6 times the negative sequence voltage [11]. The higher temperatures degrade the insulation strength faster than at normal operating temperatures.

The negative sequence voltage is only zero when the voltages are perfectly symmetrical. A voltage unbalance factor (equation 2-1) of 2% can cause a negative sequence current being 12% of the positive sequence current. The additional heat relates to the square of the negative sequence current ($P = I_{neg}^2 R$).

Motor manufacturers, in an attempt to both optimise performance and energy efficiency, will rather use the NEMA guideline of 1.5% in voltage unbalance to achieve the nameplate ratings of the motor. The thermal path is under constraints to dissipate heat sufficiently for temperatures to not rise above values degrading insulation strength.

The exponential relationship between voltage unbalance and temperature rise in motors is shown in Figure 2-2.

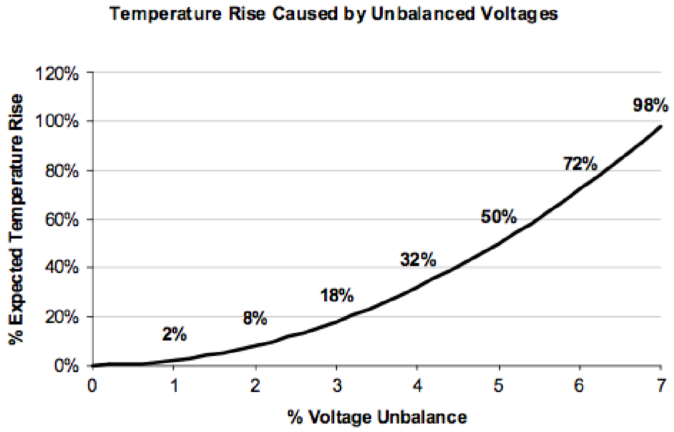


Figure 2-2 Relationship between voltage unbalance and temperature rise [11]

Voltage unbalance can be shown as a trend of 10-minute values over time as shown in Figure 2-3.

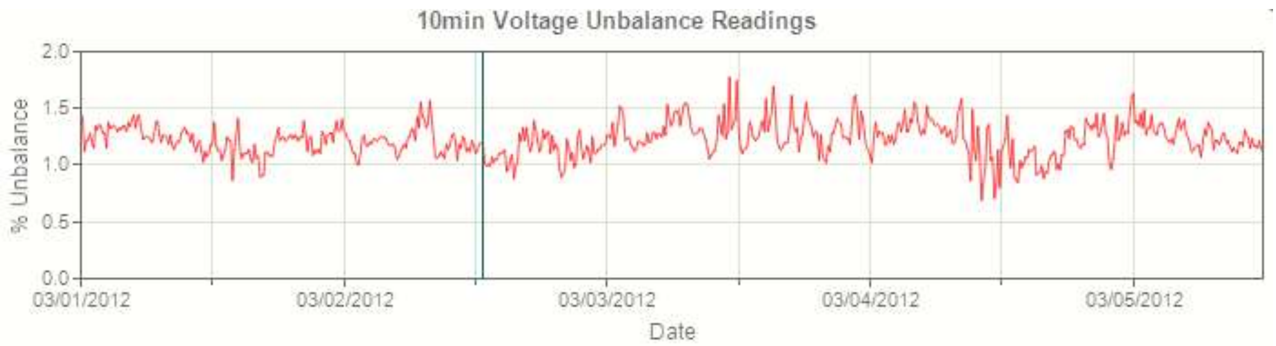


Figure 2-3 Voltage unbalance 10-minute values

2.3.3 Voltage harmonics and total harmonic distortion

Power stations generate perfectly sinusoidal voltages (50/60 Hz). Non-linear loads withdraw harmonic load currents, distorting the voltages at points of common coupling as a result of non-linear voltage drops over the system impedance.

Voltage harmonics are integer multiples of the system frequency (e.g. 100 Hz and 150 Hz are the 2^{nd} and 3^{rd} harmonics of a 50 Hz system) [6]. Uneven harmonics are characteristic in a power system with the spectrum dictated by the type of non-linear load. For example, a 6-pulse rectifier withdraws harmonic current at harmonic numbers $6n\pm1$ (n an integer starting at 1).

Voltage interharmonics are non-integer multiples of the system frequency [6] caused by non-linear loads such as static frequency converters and induction furnaces whose control is not synchronised to the network frequency.

Some long-term effects of harmonics are:

- Overheating and consequential de-rating of transformers

- Premature ageing of equipment
- Energy losses in conductors
- Increase in apparent power loading

The impact of voltage harmonics is qualified by the concept of Total Harmonic Distortion (THD) in voltage and quantified as:

$$THD = \sqrt{\sum_{h=2}^{N} V_h^2} \quad (2\text{-}2)$$

N is the highest harmonic considered and V_h^2 the rms value of the h^{th} harmonic expressed as a percentage of the nominal voltage. THD factors are normally calculated for integer harmonics and indicated as such when calculated for interharmonics.

Voltage THD can be displayed as a trend of 10-minute values over time shown in Figure 2-4.

Individual harmonics can also be displayed either as a trend over time or as a harmonic spectrum for a specific 10-minute period shown in Figure 2-5.

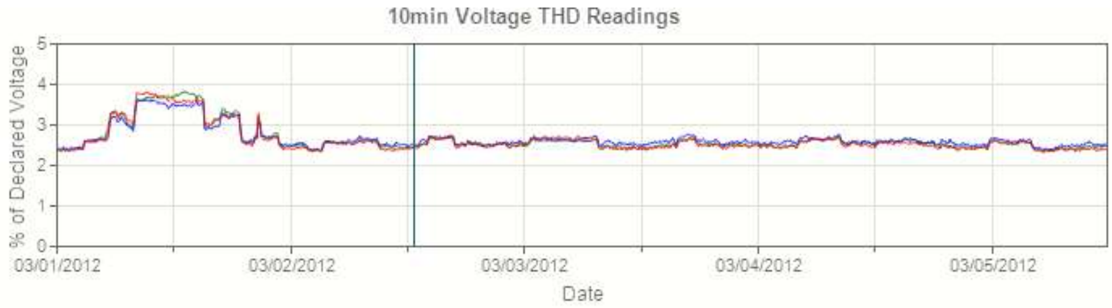


Figure 2-4 Voltage THD readings

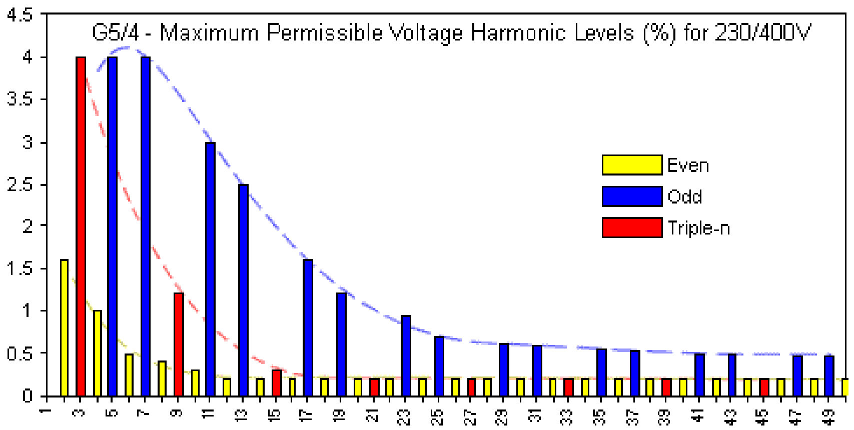


Figure 2-5 Voltage Harmonic spectrum [12]

2.3.4 Voltage flicker

Equipment that draws large amounts of current in a repetitively varying rate causes changes in voltage at the same rate due to voltage drops over the supply impedance. It manifests as an amplitude modulation in voltage.

At certain frequencies (8 – 11 Hz) and magnitudes of change, it becomes perceptible to the human eye due to the change in lumen output of some lighting armatures. The eye will attempt to compensate. It can cause migraine and even epileptic seizures in severe cases [5]. The sensitivity curves of the eye to varying voltages are displayed in Figure 2-7.

The sources of flicker are electric welding machines, arc furnaces, motors at lifts and hoists, equipment with varying torque such as saw and rolling mills and large photocopy machines.

To measure flicker, the human eye-brain response to a 60 W incandescent light bulb with fluctuating voltage was modelled in a software flicker meter, described in standard EN60868 and shown in Figure 2-6 [13].

Demodulation of the waveform is done to remove the fundamental frequency component. Two simulation filters are then used. The first models the eye's response to the light bulb and the second filter models the averaging of this response by the brain.

The annoyance factor depends on the level and rate of occurrence of these voltage variations and the extent determined by statistical analysis. P_{st} is the short-term flicker severity index and based on 10-minutes of data accumulation.

Since less often, but more severe fluctuations also irritate the eye, a longer value – the long-term flicker severity(Plt) is also calculated from 2 hours of (Pst) readings by the formula:

$$P_{lt} = \sqrt[3]{\sum_{1}^{12} \frac{{P_{st}}^3}{12}} \quad (2\text{-}3)$$

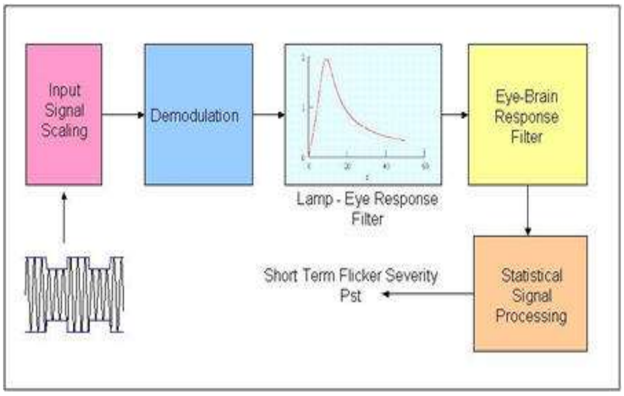


Figure 2-6 Block diagram of flicker meter [13]

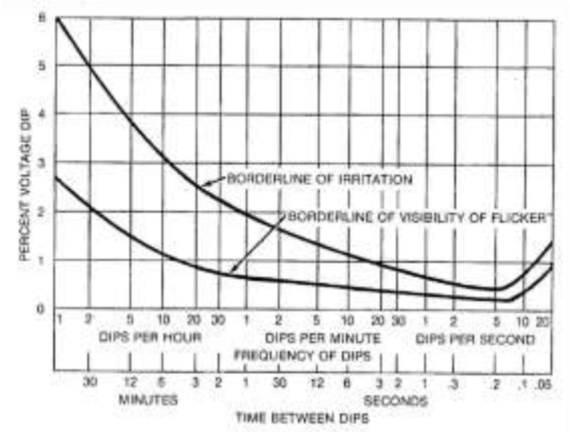


Figure 2-7 Sensitivity of the eye to voltage flicker [15]

2.3.5 Voltage waveform disturbances

Short-term voltage disturbances discussed below are included in most PQ standards. These are waveform-distorting events caused by faults and by switching events during network operation.

The duration and change in magnitude of the voltage rms value during an event is used to classify a disturbance. Different classification categories are used in the Southern African PQ standard and in other international standards.

2.3.6 Voltage transients and surges

Voltages transients are caused by normal network operations like switching, while surges are mainly caused by lightning. Both have durations of a few milliseconds or less.

Ferro-resonance is the result of the loss of a single phase (impulse response) in a lightly loaded three phase system. The transformer acts as the inductive element, while several network elements act as the capacitive element required for Ferro-resonance to occur [14]. An example is shown in Figure 2-11.

A voltage transient is sometimes referred to as a “spike”. It is a non-technical attempt to describe a steep rise in voltage, transient in nature and relatively “short” compared to the 20 ms (50 Hz) of the fundamental frequency.

Durations of a few milliseconds or less are normal for voltage transients. Some examples are shown in Figure 2-8 to Figure 2-11. Although transients, surges and ‘spikes” are noted as PQ concerns, limited opportunity for accurate analysis is possible due to the limited bandwidth of voltage and current measurement transducers used in power systems. It is only possible to accurately record these parameters if special voltage and current transducers are used.

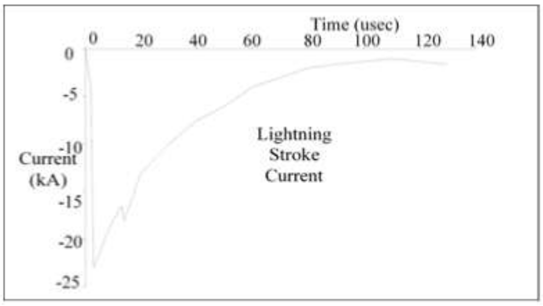


Figure 2-8 Current from lightning strike that could cause a transient [1]

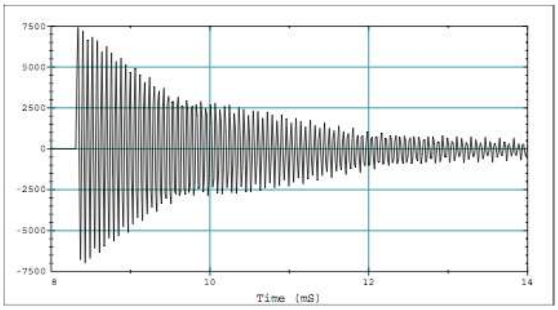


Figure 2-9 Transient caused by back to back capacitor switching [1]

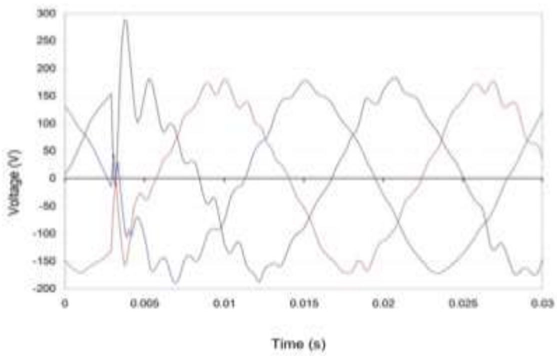


Figure 2-10 Transient caused by capacitor bank energisation [1]

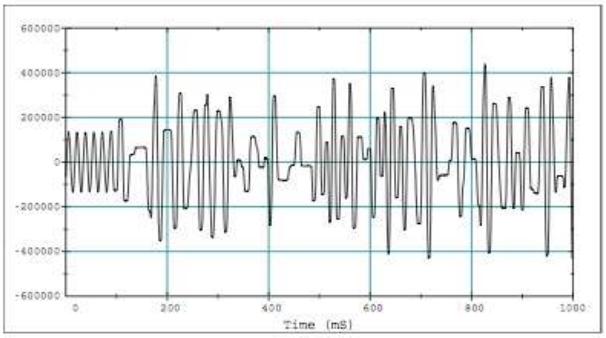


Figure 2-11 Transient caused by ferroresonance of unloaded transformer [1]

2.3.7 Voltages dips and swells

Voltage dips (sometimes referred to in literature and technical standards as voltage sag conditions) and swells are deviations from nominal voltage larger than 10% for the duration of one cycle (20 ms) up to 3 seconds [6] as per NRS 048:2-2007 definition.

The characteristic cause of voltage dips is network faults. A short-circuit in the transmission or distribution network will cause a high level of current withdrawal resulting in a “sag” of the voltage at a point in the network due to the voltage drop over the supply impedance. The duration of the sag is determined by the time-setting of protection equipment.

The depth of a voltage dip is set by the distance to the fault [16]. Physical distance normally correlates well to “electrical distance”. A nearby fault condition will cause the dip to be deeper, as the fault voltage will be very small with little impedance towards that fault.

As distance between the point of measurement and the fault increase, the depth of the dip will decrease. Due to the interconnection of the electrical network, dips are a global problem. Far-away dips can cause process interruptions event at remote sites.

Most dips are the result of single line to ground faults. Line-line faults and double line to ground faults occurs much less. Normal network operations such as load shedding and the switching of large loads or capacitor banks can cause three-phase dips. Three-phase faults are rare and can be contained, as information on the root cause should be available.

Voltage sag conditions are mostly depicted by the change in voltage rms values based on a ½-cycle sliding principle. An example is shown in Figure 2-13 based on the transient condition in the waveform depicted in Figure 2-12.

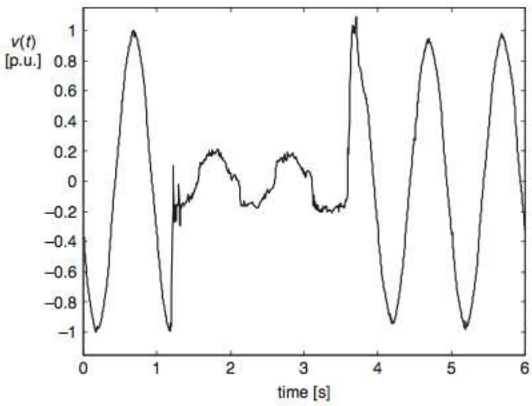


Figure 2-12 Voltage dip - voltage waveform [1]

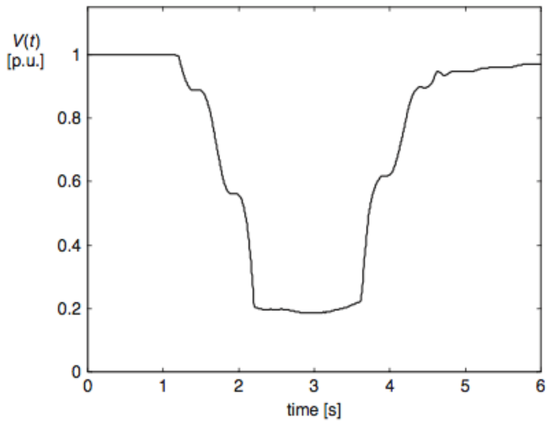


Figure 2-13 Voltage dip – RMS values [1]

Voltage dips are responsible for the biggest portion of financial losses due to PQ related problems. Figure 2-14 summarizes typical losses as published by Leonardo Energy [8], a research and educational institute funded by the European Copper Institute.

Industry	Typical financial loss per event	
Semiconductor production	€ 3 800 000	
Financial trading	€ 6 000 000	per hour
Computer centre	€ 750 000	
Telecommunications	€ 30 000	per minute
Steel works	€ 350 000	
Glass industry	€ 250 000	

Figure 2-14 Typical costs of voltage dip events [8]

It was also found that the losses in the European Union during 2006 due to poor PQ, which was mostly due to voltage dips, is 150 billion Euros [9].

2.3.8 Voltage interruptions

Voltage interruptions, or blackouts, are a complete loss of supply for duration of 3 seconds or more [1]. Proper network protection planning and good practises in operation can contain interruptions well and will normally be significantly less than the number of voltage dips.

Reliability indices such as the System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) can be used to benchmark interruption performance.

2.4 Power Quality Parameter Assessment

The procedures set out in EN 51060 [5] and other related regulatory standards specify the assessment of PQ at a single point of measurement. This assessment is then compared to a set of minimum standards to determine whether the measurement point complies with the minimum levels of the PQ standard.

Assessment of long-term voltage parameters is based on a compatibility approach. The principle of limit is only used for voltage magnitude. All other parameters are assessed on a compatibility approach. Compatibility approach means compliance for 95% of the time; limit approach means compliance for 100% of the time.

The procedure prescribed for all long-term parameters (voltage regulation, voltage unbalance, voltage THD, individual voltage harmonics, voltage flicker and frequency) is as follows:

- Continuously monitor a parameter for at least 7 full days.
- Each measurement is aggregated into 10-min values as specified in IEC 61000-4-30 [3]. The result is 1008 records (144 10-min values per day for 7 days).
- In the case of per phase measurements (voltage regulation, VTHD, etc.), the 95th percentile of each phase is compared and the worst of the 3 phases retained as the assessed value.
- In the case of a measurement not pertaining to a specific phase (frequency, unbalance), the 95th percentile of the measurement is retained as the assessed value.
- The assessed value is compared to compatibility criteria to determine compliance with the minimum standard.
- For longer-term assessments, such as at permanently monitored installations, the assessment window of 7 days is slid over the monitoring period, resulting in an assessed value every day, each acknowledging conditions over 7 days. These values are commonly referred to as 7- day sliding assessments.

- Ignoring the worst 5% of values is because it is not economically viable for the electrical utility to have all parameters in compliance 100% of the time. Compatibility statements for long-term parameters are based on compliance to the minimum standard for 95% of the time.

The results of these assessments, in the South African context, have to be reported to the regulator (NERSA) on an annual basis by each electrical utility as part of the license agreement. In theory, NERSA uses the data to ensure utilities conform to licensing agreements in terms of PQ. Evidence of this happening is lacking. Few utilities reports to NERSA, as it seem not to be enforced in practise.

PQ data can be used to compile characteristic values. NERSA has committed in the PQ Directive [17] to use the reported data to perform and publish benchmarking between utilities, as well as update characteristic values, as more and more data becomes available. This information has not materialised as of yet.

Several of the independent, national standards have improved on the 95% compliance criteria set by EN50160, to protect the consumers. Norway and China have compliance criteria for 100% of the time. South Africa kept the 95% compatibility criteria, but has limit on voltage magnitude that applies for 100% of the time. In addition, no more than 2 consecutive 10-minute voltage magnitude values are allowed outside of the 95% compatibility criteria.

2.4.1 Alternative PQ assessment methods

2.4.1.1 Cobben: The STAV method

Cobben [18] has suggested an alternative, the STAV method to overcome the shortcomings of percentile method of assessment. An example of a deficiency in the percentile approach is presented below.

Two statistically different distributions of power quality measurements can have the same 95th percentile, as illustrated in Figure 2-15. The 95th percentile alone does not provide information on the distribution of the values.

Cobben calculates the 95th percentile of a flicker distribution and creates a normalised classification scheme to express the flicker as very high quality, high quality, normal quality, poor quality, very poor quality and extremely poor quality, each with an associated classification identifier of A, B, C to F as shown in Figure 2-16. Note the counter-intuitive usage of green as bad and red as good in the visualisation. It is corrected in Figure 2-17.

Figure 2-15 Different distributions of flicker with the same 95th percentile [18]

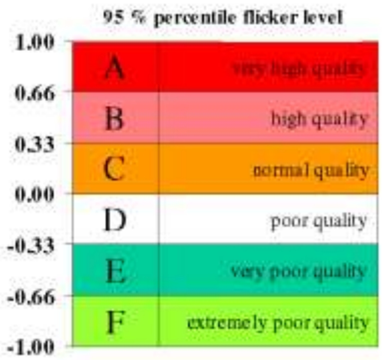


Figure 2-16 Percentile ABCDEF Classification scheme [18]

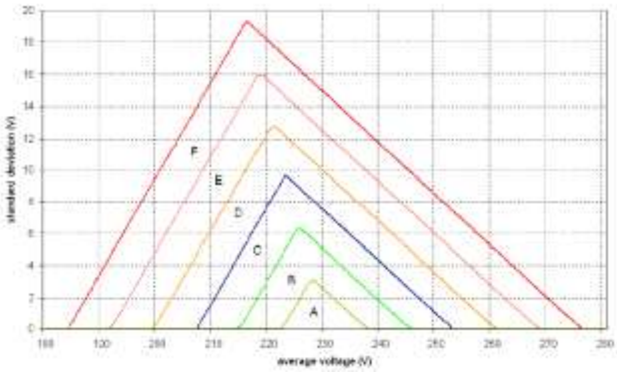


Figure 2-17 Improved ABCDEF classification scheme, Cobben [18]

This classification method of Cobben is similar to the ABC energy efficiency classification of household appliances.

The STAV method makes use of the average (AV) and standard deviation (ST) of the measured values as an assessment. For each 7-day period, the mean and standard deviation are calculated and retained as a two-parameter assessment. Cobben then relates the upper and lower compatibility criteria for voltage magnitude to the two-parameter assessment. The plot resulting is a triangle relating the standard deviation and average voltage parameters with the area within the triangle representing the range of values assigned to each classification (ABCDEF) as seen in Figure 2-17.

The normalised ABCDEF values allows for a simple classification with the added benefit of information on the distribution of the recorded values. It has advantages as the STAV method over use of 2 parameters which can be visualised in a two dimensional plane against the percentile approach using one value.

A similar approach has been used in a reporting methodology developed by the author [21] of this dissertation. It is presented in chapter 3. The 50th and 95th percentile, or alternatively the average and the 95th percentile are used.

Cobben states that the percentile method requires larger amounts of data to be processed, whereas the STAV method requires less as it is based on only average and standard deviation data. This is not correct:

- Assume that both methods are applied to the same 1008 weekly data samples.
- The STAV method retains 2 values for each assessment.
- The percentile method retains only one.
- Less data is used for the percentile method.

The alternative percentile method developed by the author [21] produces similar volumes of data as the STAV method but result in enhanced visualisation of voltage magnitude regulation. In contrast to the STAV method, the alternative method can be used directly to assess compliance to those standards that measure compliance with percentile values, such as EN50160.

The ABCDEF classification and related categories (very high, high etc.) is derived by Cobben by taking the arbitrary range of assessed values from *no disturbance* to a level of *twice the minimum standard*, normalising it and then linearly dividing it into six areas. This normalised, linear view of quality is useful in communicating PQ to consumers with limited knowledge on power quality. Quality in electrical energy is not a linear commodity though.

A modern definition of quality, derived from Juran's "fitness for intended use" [22] concept, is that "quality is meeting or exceeding customer expectations". Defining the minimum standards of e.g. EN50160 as the customer expectations, there should then only be two classifications – comply and don't comply. The assessed value of a specific PQ parameter in itself is a quantitative indication on compliance. Defining the minimum standard as the customer's expectation however is in many cases far removed from reality – especially where a client is accustomed to excellent quality. Degradation in quality to the minimum standards will definitely not meet this client's expectations.

2.4.1.2 The Jan Meyer PQ Classification method

Another view on quality is conformance quality [22], which measures the degree to which a product/service was produced correctly. Quality is then defined as conformance to requirements and not as "goodness". Meyer's approach [20] to a classification scheme for PQ parameters follows a similar normalisation approach to Cobben's, but the classification descriptors align with the concept of conformance quality instead of goodness, as is the case with Cobben's.

Meyer divides the range of assessments between no disturbance and the compatibility limit into three areas, with descriptors of *large* reserve to the limit, *medium* reserve to the limit and *small* reserve to the limit.

A fourth area consists of all values that are over the limit, termed *no* reserve to the limit (limit exceeded). This concept is illustrated in Figure 2-18.

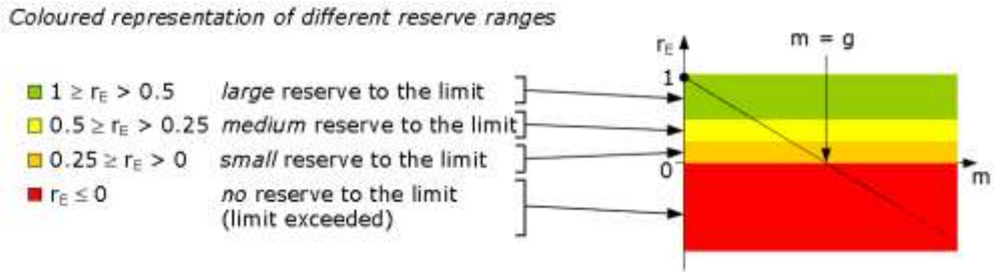


Figure 2-18 Normalised classification scheme as suggested by Meyer [20]

The respective chosen sizes of the areas seem to be more considered than Cobben's, with it not merely being a linear allocation of the range. Half the range between no disturbance and the limit is allotted to *large* reserve. The remaining half is then halved again and allotted to *medium* and *small* reserve. All values over the limit are lumped together as *no* reserve.

Both classification schemes (Cobben and Meyer) add more value than a simple conform/does not conform outcome of an assessment. The visualisation communicates PQ information without the need for a detail understanding of the concept of PQ and the technical standard pertaining. The normalised values also allow for time and other aggregation methods to be applied to PQ data recorded at a single point.

The possibility of a classification or visualisation scheme that additionally communicates more practical information, either about the possible causes of the disturbance or even possible solutions for it, would add immense value for the electricity user or provider in aiding with the management thereof, and will be investigated for each parameter in this dissertation. .

2.4.2 Minimum standards in short-term voltage disturbances

Determining minimum standards for short-term voltage disturbances (voltage dips, swells and surges) is difficult. Utilities do not have control over for example, lightning, which is a major contributor to the voltage sag performance of some networks. No regulatory standard contains compatibility limits for short-term voltage disturbances.

The South African standard (NRS 048-2 [6]) provides characteristic voltage dip values for networks operated at different voltage values. Overhead and cable networks at the same voltage level will experience different dip numbers due to the exposure to climatic conditions.

The NRS 048-2 values were obtained from the Eskom transmission network, based on data recorded up to the year 2000. Network loading and operating conditions in 2013 are very different.

The intention of characteristic dip numbers is to benchmark the dip performance of a single site in a similar network against the characteristic performance of 50% or 95% of the sites.

Voltage dips are the most well-known PQ concern as interruption in production processes can occur without the utility recording an interruption in the supply voltage. The effect to the user is however similar.

It is expected that equipment should operate as designed if the duration and depth of the dip is contained within certain levels. This concept is discussed next.

2.4.2.1The CBEMA/ITIC and SEMI-F47 voltage dip standards

The Computer Business Equipment Manufacturers Association (CBEMA) developed the CBEMA curve in the 1970's by studying the immunity of mainframe computers to voltage magnitude variations [31]. It was originally developed as a guideline for the design of power supplies for computer equipment, to increase system reliability.

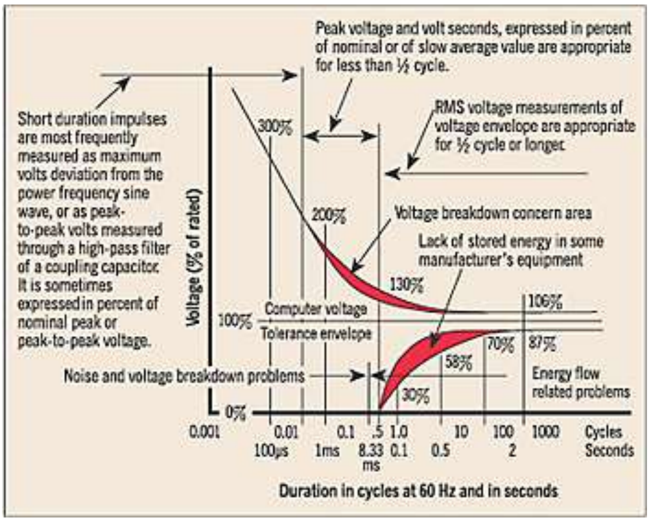


Figure 2-19 CBEMA Voltage dips withstand curve [31]

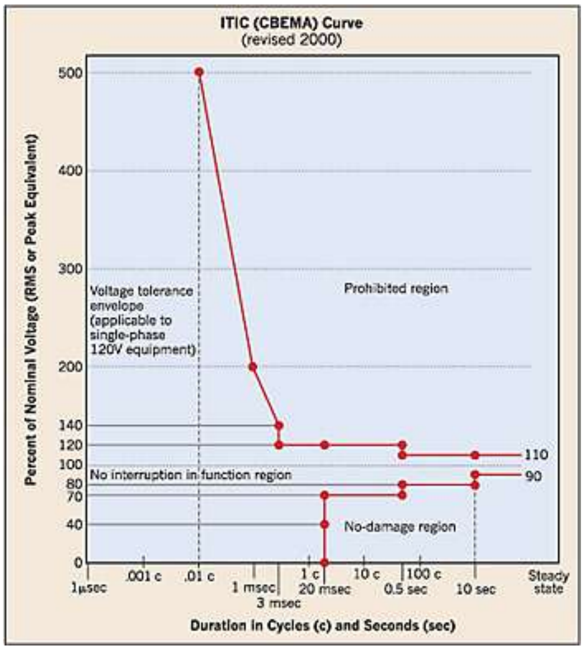


Figure 2-20 ITIC voltage dip withstand curve [32]

Figure 2-19 depicts voltage events by the duration on the x-axis against the magnitude on the y-axis. Magnitude is expressed as a percentage of the rated voltage.

Three regions are defined in Figure 2-19. The centre region, around 100% of the rated voltage, is the acceptable area for voltage deviation. Equipment will perform as designed during voltage events in this region. Events in the region above the top curve could result in overvoltage trips and insulation failure, while events in the lower region represent a high probability of equipment malfunction due to a lack of energy served.

CBEMA was reorganised in 1994 and renamed the Information Technology Industry Council or ITIC [32]. By this date IT equipment such as personal computers, fax machines, copiers and point-of-sales equipment were widely in use.

EPRI's (Electric Power Research Institute) PEAC (Power Electronics Application Centre) revised the CBEMA curve to reflect the performance of a comprehensive collection of computer and peripheral equipment and published it as the ITIC curve.

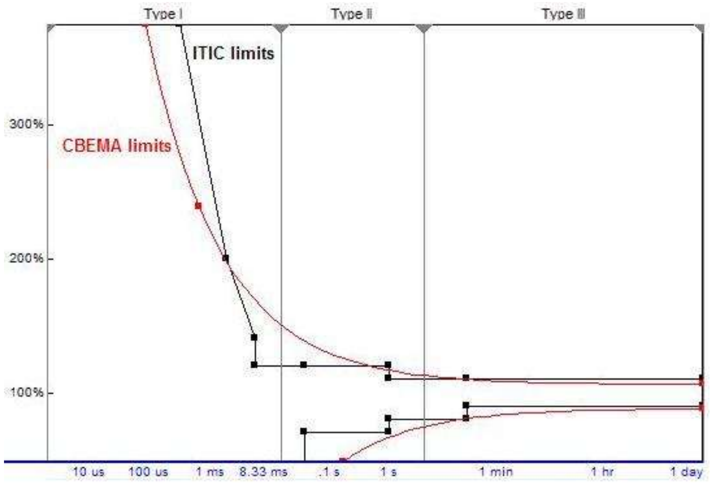


Figure 2-21 Comparative overlay of CBEMA and ITIC curve [32]

The step-changes in the ITIC curve compared to the filter-like curve of the older CBEMA curve allows for easier conformance testing.

SEMI F47 is an industry specific voltage dip and swell standard. It is the result of research conducted by EPRI [33] on behalf of members. It included manufacturers such as Intel, Texas Instruments, Motorola, AMD, National Semiconductor as well as several large American utilities.

More than 30 instrument years' worth of disturbance data were analysed by EPRI. It was found that 15.4% of events were below the ITIC curve [33]. The average number of events per site per year below the curve was 5.4. The ITIC curve was found to be insufficient as a standard for tool manufacturers in this specific industry and a more restrictive standard deemed necessary.

Figure 2-22 shows the results of the events analysis. Observe the contour curves for the number of events per site per year.

The first edition of the SEMI F47 standard followed. It is based on the contour depicting 0 to 1 events per year. The current version of this standard is SEMI F47-0706 and shown in Figure 2-23.

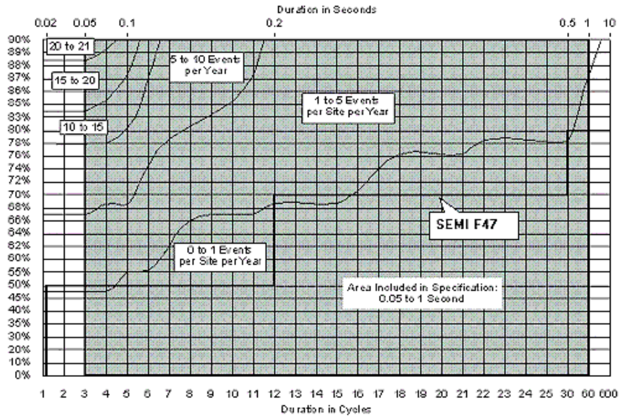


Figure 2-22 Events per site per year contour map basis for SEMI F47 [33]

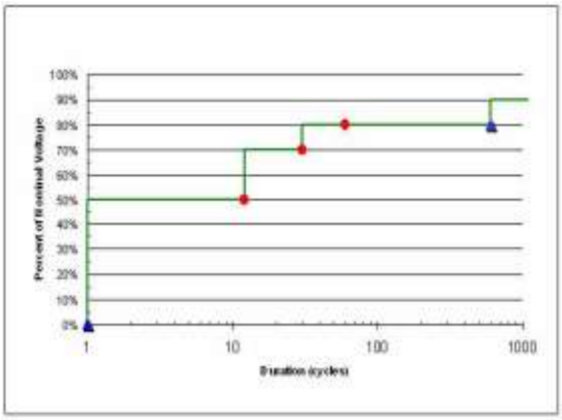


Figure 2-23 SEMI F47 Voltage dip withstand curve [33]

2.4.2.2The NRS 048 dip classification

The South-African dip classification standard (NRS 048-2 [6]) defines specific regions according to probable causes of the events, shown in Table 1 and Table 2. This approach is useful from a network management perspective as it relates to typical protection settings.

Table 1: NRS048 voltage dips classification scheme [6]

<table>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td rowspan="2">Range of dip depth
ΔU
(expressed as a % of U_d)</td><td rowspan="2">Range of residual voltage
U_r
(expressed as a % of U_d)</td><td colspan="3">Duration
T</td></tr>
<tr><td>20 < t ≤ 150 ms</td><td>150 < t ≤ 600 ms</td><td>0,6 < t ≤ 3 S</td></tr>
<tr><td>$10 < \Delta U \leq 15$</td><td>$90 > U_r \geq 85$</td><td rowspan="3"></td><td rowspan="2">Y</td><td></td></tr>
<tr><td>$15 < \Delta U \leq 20$</td><td>$85 > U_r \geq 80$</td><td rowspan="2">Z1</td></tr>
<tr><td>$20 < \Delta U \leq 30$</td><td>$80 > U_r \geq 70$</td><td rowspan="3">S</td></tr>
<tr><td>$30 < \Delta U \leq 40$</td><td>$70 > U_r \geq 60$</td><td>X1[a]</td><td rowspan="3">Z2</td></tr>
<tr><td>$40 < \Delta U \leq 60$</td><td>$60 > U_r \geq 40$</td><td>X2</td></tr>
<tr><td>$60 < \Delta U \leq 100$</td><td>$40 > U_r \geq 0$</td><td colspan="2">T</td></tr>
<tr><td colspan="5">NOTE In the case of measurements on LV systems it is acceptable to set the dip threshold at 0,85 pu.</td></tr>
<tr><td colspan="5">[a] A relatively large number of events fall into the X1 category. However, it is recognized that dips with complex characteristics (such as phase jump, UB, and multiple phases) might have a significant effect on customers' plant, even though these might be small in magnitude. Customers might not have the means to mitigate against the effects of such dips on their plant.</td></tr>
</table>

Table 2: Technical basis for the NRS048 voltage dip classes [6]

1	2	3	4
Dip category	**Values of duration and depth**		**Basis for definition**
Y	Duration	> 20 ms to 3 s	Dip definition (20 ms to 3 s)
	Depth	30 %, 20 %, 15 %	Minimum plant compatibility requirement (this covers a significant number of short duration dips)
X1	Duration	> 20 ms to 150 ms	Typical zone 1 clearance (no pilot wire)
	Depth	30 % to 40 %	Desired plant immunity – as this spans many dips caused by remote faults on the licensee network
X2	Duration	> 20 ms to 150 ms	Typical zone 1 clearance (no pilot wire)
	Depth	40 % to 60 %	Dips potentially causing drives to trip, caused by remote faults on the licensee network
S	Duration	> 150 ms to 600 ms	Typical zone 2 and accelerated clearance Also some distribution faults
	Depth	20 % to 60 %	Plant compatibility (drives trip > 20 %) caused by remote faults on the licensee network
T	Duration	> 20 ms to 600 ms	Zone 1 and zone 2 clearance times
	Depth	60 % to 100 %	Plant compatibility (contactors trip > 60 %) caused by close-up faults on the licensee network
Z1	Duration	> 600 ms to 3 s	Back-up and thermal protection clearance or long recovery times (transient voltage stability) or both
	Depth	15 % to 30 %	Remote faults Post-dip motor recovery without stalling
Z2	Duration	> 600 ms to 3 s	Back-up and thermal protection clearance
	Depth	30 % to 100 %	Closer faults Potential motor stalling

2.5 Power Quality Indice Aggregation, Benchmarking and Reporting

For utilities and regulators, with data collected from hundreds of measurement points, the need exists to aggregate the individual daily site indices into meaningful and easy comprehendible and communicable system indices. Such a compact set of indices can be easily compared and tracked over time, to monitor whether power quality delivered by the utility complies with standards and whether it trends positively or negatively.

When reporting on PQ data, it needs to be distilled sufficiently to provide a succinct overview of PQ performance whilst retaining enough detail to provide forensic information to resolve specific concerns. A multi-level hierarchy of power quality indices is proposed in [34] and [35] to fulfil both requirements.

From [34], reporting should be able to answer questions like:

1) Which sites need immediate attention?

2) What could be the cause for a high disturbance level?
3) How does utility *X* compare to utility *Y* with regards to *Z*?
4) What would be suitable limit criteria for parameter *X*, in a national context?

In order to answer such questions, a proposed reporting hierarchy follows to be:

1) **Detailed site reporting**, where diagnostic data about each event and power quality disturbance should be available.
2) **Network reporting**, where aggregated site indices from a utility are benchmarked against each other to determine the worst performers.
3) **Utility reporting**, where aggregated network indices from several utilities are benchmarked for performance between utilities, or to investigate compatibility criteria for industry regulation..

Site-specific indices and how to aggregate it into meaningful network and utility indices is a subject of much research. One specific set of indices cannot be identified and standardised on as reporting indices needs to be chosen to support specific needs.

A challenge during aggregation is whether to use weighted indices and how to choose the weighting factors. The data captured at a busbar feeding a single large industrial customer should probably not have the same weight as a busbar feeding an industrial park, or a residential area with hundreds of thousands of residents. How to choose the weights should be determined by the goal intended for the indices.

The bulk of research and publications on system PQ indices mostly considers the aggregation of voltage dip indices. Long-term voltage waveform parameters should also be benchmarked to understand global performance and the development of trends. Methods for aggregating long-term voltage waveform disturbances do exist and are discussed next.

2.5.1 Aggregation of long-term voltage parameters

Meyer [36] suggests a normalised index with aggregation over all parameters for a site to arrive at a single indice enumerating the overall PQ of a site. This allows a ranking of sites to set priority for mitigation if applicable.

A concern is noted in this approach. Improving PQ requires knowledge of the source and root cause of the disturbance. Unless a singular source of disturbances affects several PQ parameters simultaneously, aggregation across parameters does not contribute to the identification of the source of the problem.

Normalised indices of the same numerical value could mean something very different, if not normalised according to the same PQ standards. This is not a problem if all indices are calculated for a single standard, but it means normalised indices cannot be taken at face value, but needs to be annotated with the standard used to normalise to.

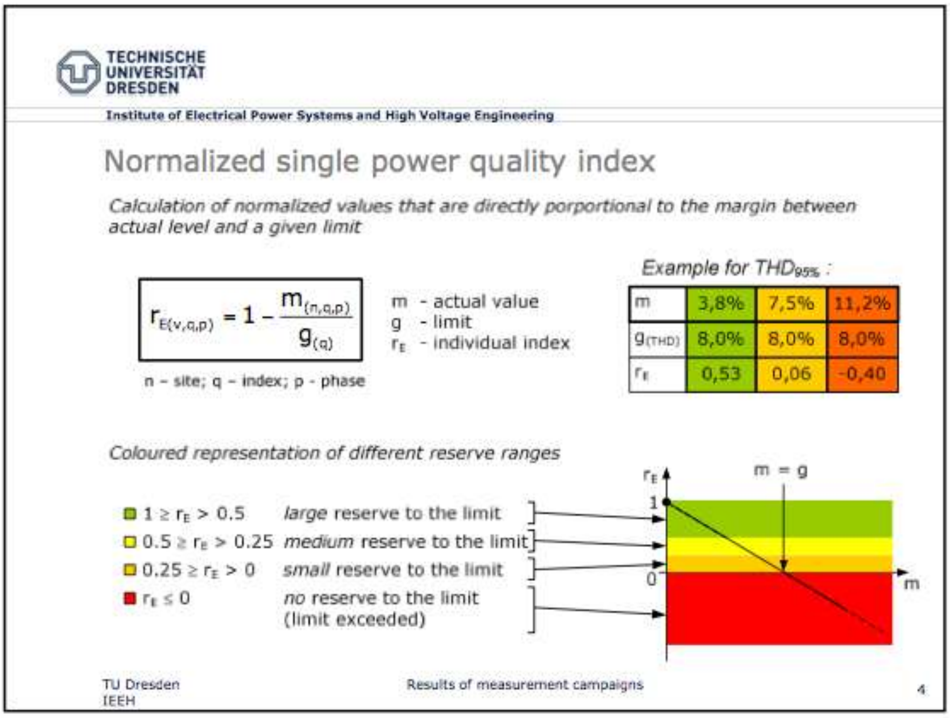


Figure 2-24 Meyer's normalised power quality index [36]

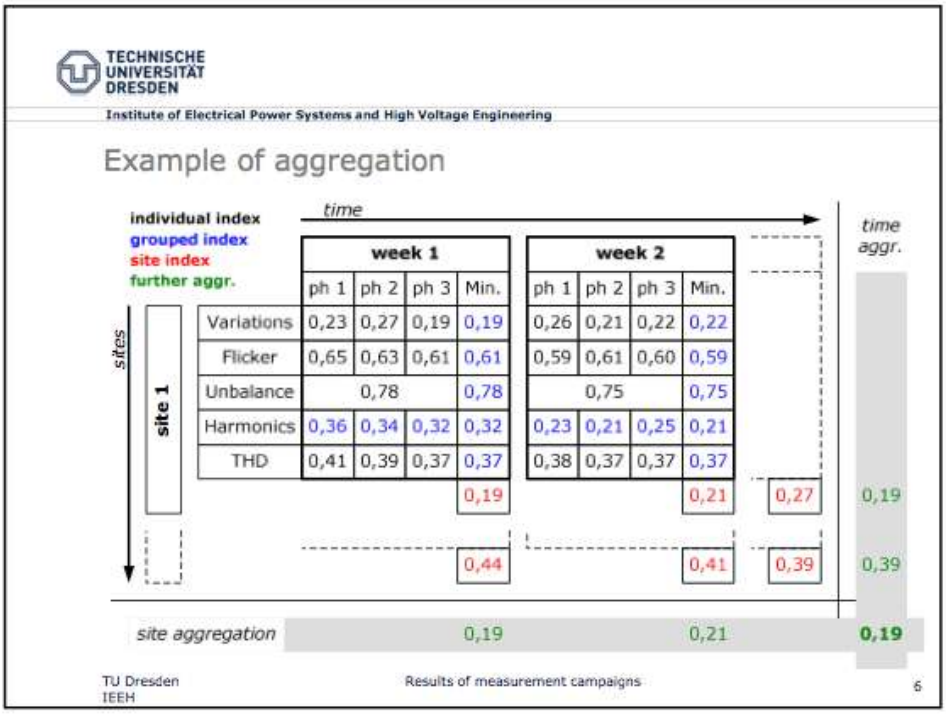


Figure 2-25 Aggregation method for Meyer's indices [36]

An Australian study [40] suggested using a Global Utility Average (average over all the measurement points, for all sites and all utilities involved in the measurement campaign) as a measure to normalise to.

This method works well to compare sites against each other, but the utility score cannot be assessed to a regulatory standard for compliance or how much of a reserve margin remains. The tabular method of reporting shown in Table 3 use both actual and normalised values, which alleviates some of this concern. The proposed method of reporting on the ranking for each individual parameter and the overall performance in Figure 2-26 and Figure 2-27 demonstrates the reason for the concern.

A possible improvement on the method could be to express the compatibility criteria of the standard in terms of the Global Utility Average, and then indicate this level on the graphs. However, since the compatibility criteria in most standards are stipulated for the 95th or 99th percentile and not the average value, as used in this method, adding the normalised compatibility levels to the charts cannot aid in verifying compatibility.

The concern with using the average is that it contains no information about compliance to a standard. Considering that for normally distributed values the average and the 50th percentile should be close to each other, using the average is a comparison of how utilities perform during the best half of the time. Regulation of PQ is concerned about the worst performance for 1% to 5% of the time.

An adaptation of this method by normalising to the Global Utility PC95 or PC99 (95th or 99th percentile) value will enable a normalised reference to the graphs indicating compatibility to a specific standard in addition.

Table 3: Normalising by the Global Utility Average

Indices	Utility Average		Global Utility Average		Normalised Utility Average	
	LV	MV	LV	MV	LV	MV
Voltage Deviation	5.30%	2.12%	5.10%	2.50%	1.04	0.85
Unbalance	1.40%	6.30%	1.29%	1.02%	1.09	6.18
Harmonics	5.80%	3.98%	5.90%	2.70%	0.98	1.47
Sags	342	98.7	394.5	165.2	0.87	0.60

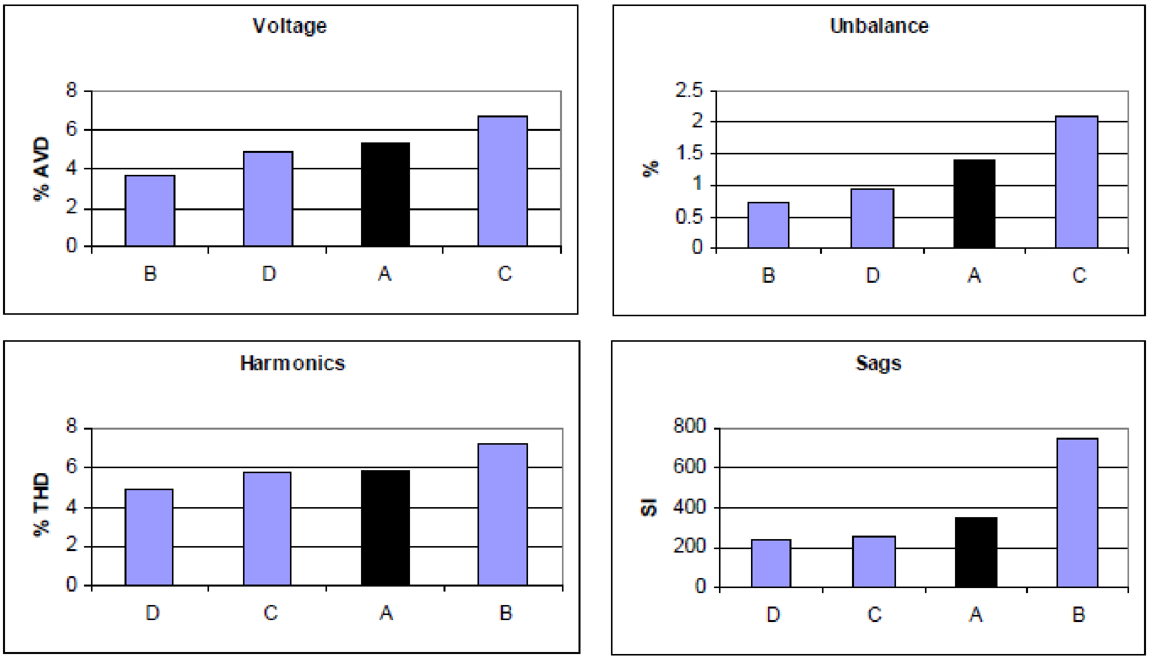


Figure 2-26 Ranking of utilities on their normalised utility averages [40]

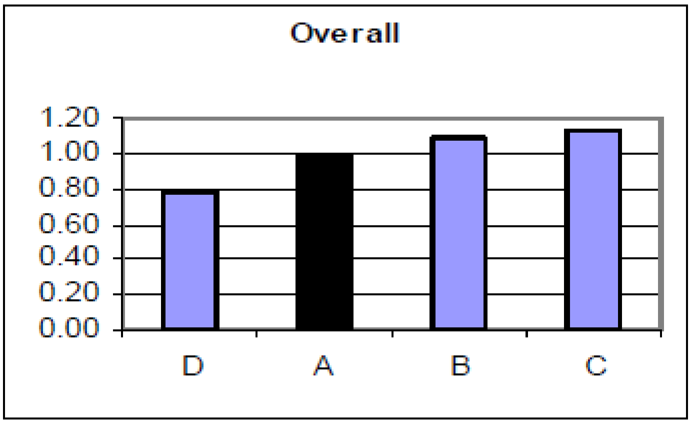


Figure 2-27 Overall ranking of utilities using the Global Utility Average method [40]

Indices in the yet to be finalised standard P1564 on Voltage Sag Indices [41] falls into three categories:

- The standard magnitude-duration indices are used and then aggregated in a tabular format, similar to the NRS 048 dip diagram.
- New single parameter voltage dip indices are calculated, such as Voltage Sag Energy and Voltage Sag Severity. These can be easily aggregated into site and system indices.

- Different System Average RMS Variation Frequencies Indices (SARFI) can be calculated. For example, SARFI-X counts the number of events with residual voltage less than X %. SARFI-CURVE counts the number of events beneath the acceptable regions on several voltage withstand curves (ITIC, SEMI F47).

Aggregation into site and system indices can be done based on an average, a percentile (CP50, CP95 or CP99) or a weighted average of the individual sag indices.

The calculation for the mentioned indices is discussed next.

2.5.2 Magnitude-Duration

Site indices are determined by simply recording a count of events in a table as shown in Table 4. System indices are determined by taking the average, a CP value, or weighted average of each cell over all sites and reported in the same table.

Table 4: Voltage dip reporting table [41]

	<0.1s	0.1-0.25s	0.25-0.5s	0.5-1s	1-3s	3-20s	2-60s	1-5 min
80-90%								
70-80%								
60-70%								
50-60%								
40-50%								
30-40%								
20-30%								
10-20%								
<=10%								

2.5.3 Voltage Sag Energy

This indice is an indication of the energy loss (E_{vs}) during the event:

$$E_{vs} = \int^{T} [1 - v(t)]^2 \, dt \tag{2-4}$$

$v(t)$: the rms voltage in per unit

Two site indices are calculated, the Voltage Sag Energy Index ($VSEI$) and the Average Voltage Sag Energy Index ($AVSEI$).

1. The Voltage Sag Energy Index ($VSEI$) is the sum of all voltage sag energies for a site over a period of time:

$$VSEI = \sum E_{vs} \tag{2-5}$$

2. The Average Voltage Sag Energy Index ($AVSEI$) is calculated as the average voltage sag energy per event:

$$AVSEI = \frac{1}{N}\sum_{i=1}^{N} E_{vs\_i} \tag{2-6}$$

System indices are determined by taking the average, a CPF (cumulative provability function) value, or a weighted average of either $VSEI$ or $AVSEI$.

2.5.4 Voltage Sag Severity

The individual event indices are determined by comparing the retained voltage and duration to the SEMI F47 voltage withstand curve:

$$S_e = \frac{1 - V}{1 - V_{curve}(d)} \tag{2-7}$$

V is the rms voltage in per unit. The algorithm for calculating the voltage sag severity is:

- d ≤1 cycle: S_e=1−V
- 1 cycle <d≤ 200 ms: S_e =2(1−V)
- 200 ms <d≤ 500 ms: S_e =3.3(1−V)
- 500 ms <d≤ 10 s: S_e =5(1−V)
- d >10 s: S_e =10(1−V)

Two site indices can be calculated from the voltage sag severity.

1. The Total Voltage Sag Severity is the sum over all voltage sags for the site during the period:

$$S_{site} = \sum S_e \tag{2-8}$$

2. The Average Voltage Sag Severity is the average voltage sag severity per event:

$$S_{average} = \frac{S_{site}}{N} \tag{2-9}$$

System indices are determined by taking the average, a CPF value, or weighted average of either S_{site} or $S_{average}$.

2.5.5 SARFI-X

The System Average rms Variation Frequency Index for a site is calculated as the number of events with a residual voltage under *X%* in the case of voltage dips, or over *X%* in the case of voltage swells:

- SARFI-90 is the count of events with residual voltage less than 90%.
- SARFI-70 is the count of events with residual voltage less than 70%.
- SARFI-110 is the count of events with residual voltage over 110%.

System indices are calculated by taking a weighted count of all events over all sites, with the weighting factor being the number of customers affected by the event, divided by the total number of customer:

$$SARFI_x = \frac{\sum N_i}{N_T} \tag{2-10}$$

N_i is the number of customers experiencing a specific event and N_T the total number of customers supplied by the system.

2.5.6 SARFI-Curve

SARFI-ITIC and SARFI-SEMI are the counts of events falling below the lower portions of the ITIC and SEMI F47 curves. It can be aggregated in the same manner as SARFI-X.

2.6 Data Visualisation

"Why should we be interested in visualization? Because the human visual system is a pattern seeker of enormous power and subtlety. The eye and the visual cortex of the brain form a massively parallel processor that provides the highest-bandwidth channel into human cognitive centers. At higher levels of processing, perception and cognition are closely interrelated, which is the reason why the words "understanding" and "seeing" are synonymous. However, the visual system has its own rules. We can easily see patterns presented in certain ways, but if they are presented in other ways, they become invisible.... If we can understand how perception works, our knowledge can be translated into rules for displaying information. Following perception-based rules, we can present our data in such a way that the important and informative patterns stand out. If we disobey the rules, our data will be incomprehensible or misleading." – Colin Ware [23].

2.6.1 Visual perception

The largest percentage, up to 70%, of our sensory receptors resides in our eyes. When we look at an image, billions of neurons in the eye simultaneously extracts features from the image and passes it directly to the primary visual cortex of the brain – instantaneously and without conscious thought. This is the first stage of visual perception [23].

The features extracted are called pre-attentive attributes and include colour, size, shape, location, orientation and texture. These are the attributes humans use to encode data graphically and to make use of “free” processing to aid in communicating the meaning of data.

As an example of pre-attentive processing and the varying effectiveness of different attributes to visually encode data, identify the number of times the letter “s” is used in this paragraph. The only attribute available here is the shape of the letters, which are too complex to be used pre-attentively. However, when one uses color or hue, the answer is easy to obtain pre-attentively, as shown in a copy of this paragraph following.

As an example of pre-attentive processing and the varying effectiveness of different attributes to visually encode data, identify the number of times the letter "s" is used in this paragraph. The only attribute available here is the shape of the letters, which are too complex to be used pre-attentively. However, when one uses color or hue, the answer is easy to obtain pre-attentively, as shown in a copy of this paragraph following.

During the second stage of visual perception, the image is broken down into regions and simple groupings and patterns, as the grouping by proximity and identification of a line with a slope illustrated in Figure 2-28.

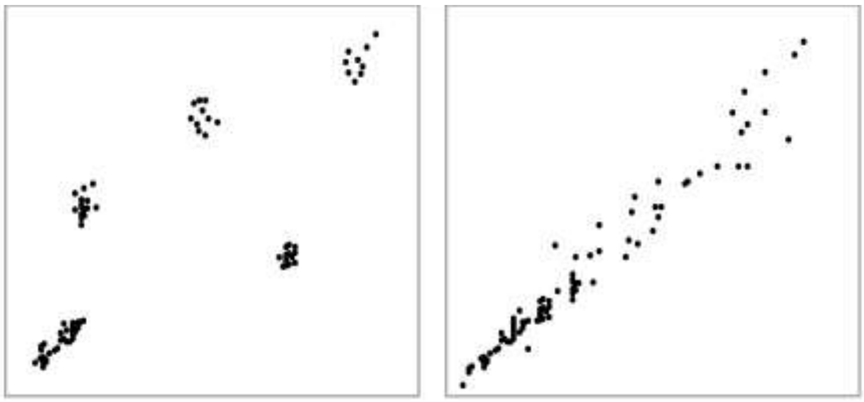


Figure 2-28 Stage 2 of visual perception - grouping and patterns [23]

During the third and final stage of visual perception humans attempt to make sense of the information in an iterative process of swapping patterns of interest in and out of short-term memory, making it available to consciousness.

As an example of the power of visual perception, consider the following table with data regarding voltage dips. The performance of a single site is compared to the performance of the utility as a whole (total of all sites).

Table 5: Table comparing site to utility dip performance (hypothetical data)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Utility Total	132	143	132	143	176	187	198	176	154	143	132	121
Site A	10	11	10	9	11	8	9	10	25	11	12	10

Instinctively discerning trends from this table is not easy. The graphical display of data simplifies identification as seen in Figure 2-29

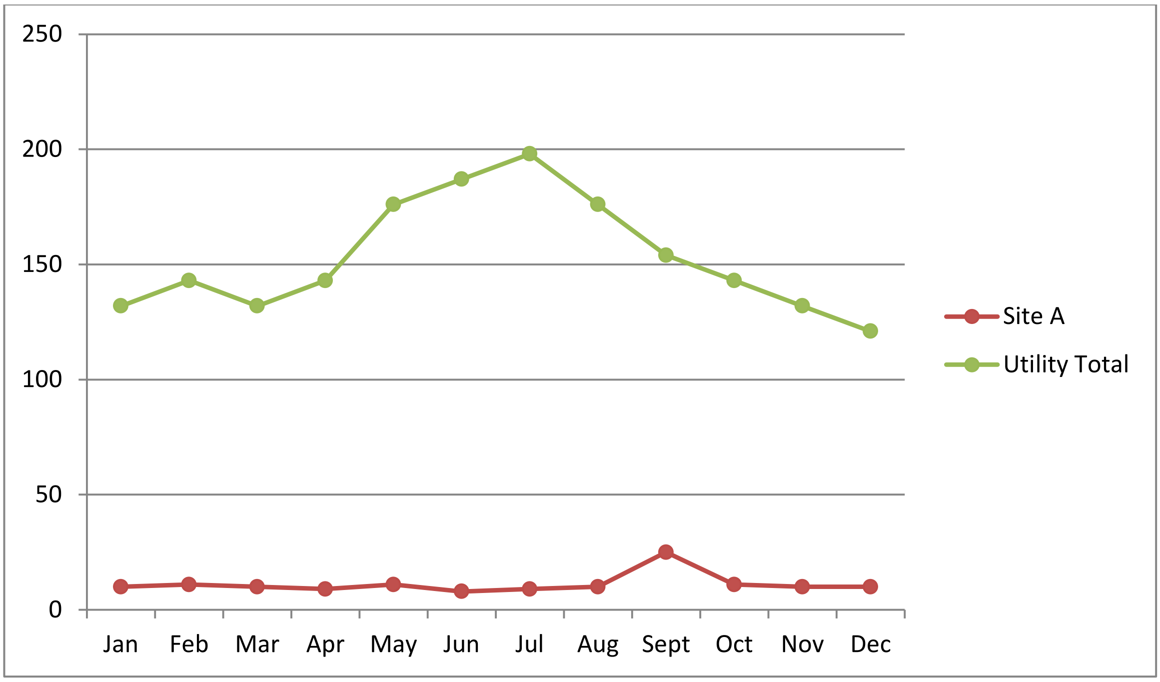


Figure 2-29 Comparing a single site to the dip performance of all sites in a utility

The following conclusions are now possible:

- There is an increase in total utility dip events during the winter months.
- Site A does not experience a similar dip increase during the winter months.
- Site A has a relatively constant number of monthly dips, except for the month of September.

2.6.2 Exploratory data analysis

Exploratory data analysis is an approach to statistical data analysis coined by scientist and mathematician, John Wilder Tukey and published in 1977 in his book, “Exploratory Data Analysis” [24]. It is described more as an attitude towards statistical analysis of data rather than a collection of techniques. Tukey recognised two types of data analysis, exploratory (EDA) and confirmatory (CDA). In EDA the data is sacred, while in CDA the data model is sacred.

EDA is used to investigate what the data has to say, without prejudicing the investigation with pre-formed models of the data. It is useful to identify errors and unexpected patterns in data.

CDA is used to decide whether data supports the hypotheses a study is based on.

2.6.3 Data visualisation techniques

The bulk of the information provided in this section has been gained from studying blogs, articles and guest articles from a leading visualisation expert, author and consultant, Stephen Few. It is disseminated by a professional website www.perceptualedge.com. Information obtained from other sources will be separately referenced.

Several graph types and techniques specifically suited for exploratory data analysis are briefly discussed.

2.6.3.1 Line graphs and cycle plots

The most successful graph for investigating and communicating change over time is the simple line graph. Comparing magnitudes can be done on the same graph, or separate graphs with the same scale.

Comparing rates of change over time can be accomplished by using a logarithmic scale for the axis containing the independent variable (i.e. not the time axis). Figure 2-30 and Figure 2-31 illustrates the difference between linear and log scales. In the first figure it seems like the rate of change for utility 1 is significantly larger than utility 2. The log scale of the second figure however shows the rates of change to be very similar.

Comparing patterns of change are best done by employing separate graphs, independently scaled and organised to share a common time axis. Similarly, stacking charts for each parameter with a shared time axis can investigate the change of several different parameters over time.

Figure 2-35 shows how the same data, plotted on separate auto scaling graphs for several utilities, illustrates the differing pattern for average dips per quarter of utility 5, compared to others. The similarities point out the influence of seasonal patterns in dip numbers.

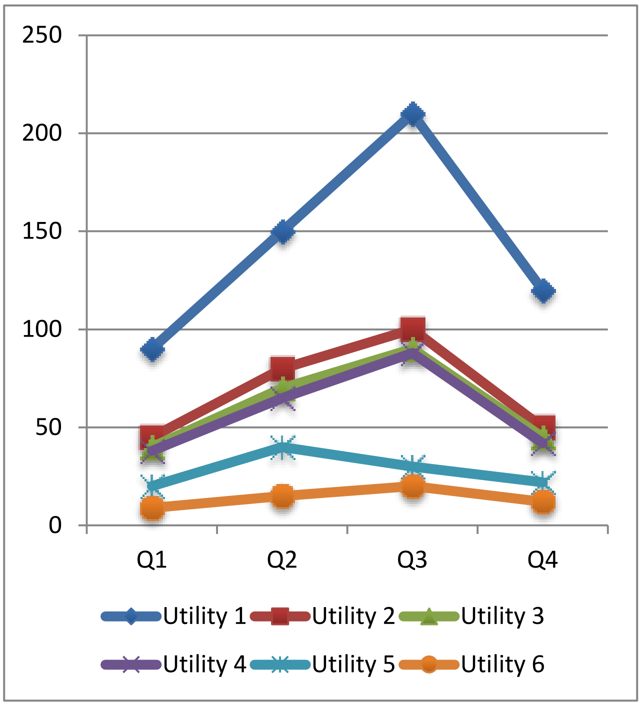


Figure 2-30 Average number of dips per utility per quarter - linear scale

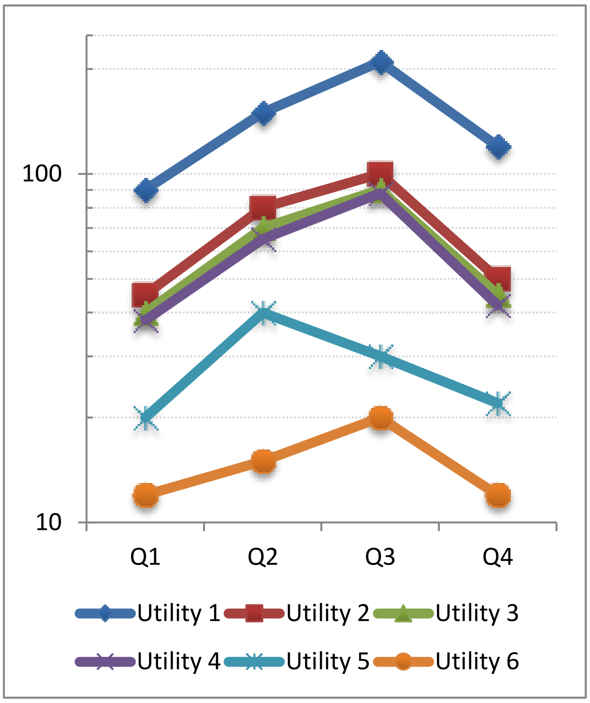


Figure 2-31 Average number of dips per utility per quarter - logarithmic scale

To investigate cyclical properties in data, [43] describes a special arrangement of the data in so-called cycle plots. Investigating day-of-the-week or month-of-the-year cycles in data with line graphs are cumbersome.

Plotting all the data end-to-end (Figure 2-32) shows the presence of a cyclic pattern, but comparing the values at a specific point in the cycle over several cycles is difficult. Plotting each cycle as a separate line series (Figure 2-33) simplifies this, but still lacks the ability to show trends over the entire period.

The cycle plot (Figure 2-34) satisfies both needs. Points corresponding to the same point-on-cycle are clustered together, with each cluster representing a successive point in the cycle. Within each cluster one can compare cycles to each other. Reviewing the relationship between the clusters is helpful to investigate the general behaviour.

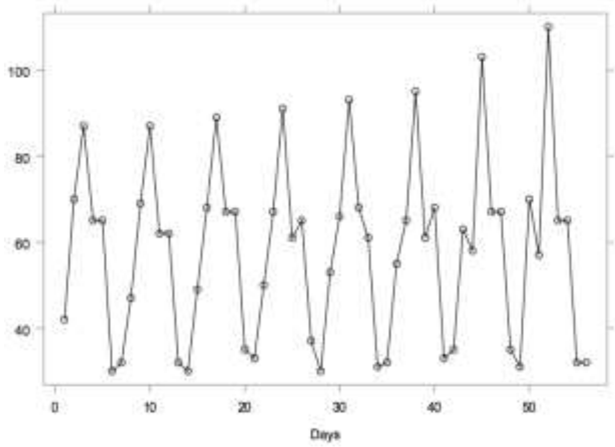


Figure 2-32 End-to-end plot of several cycles [42]

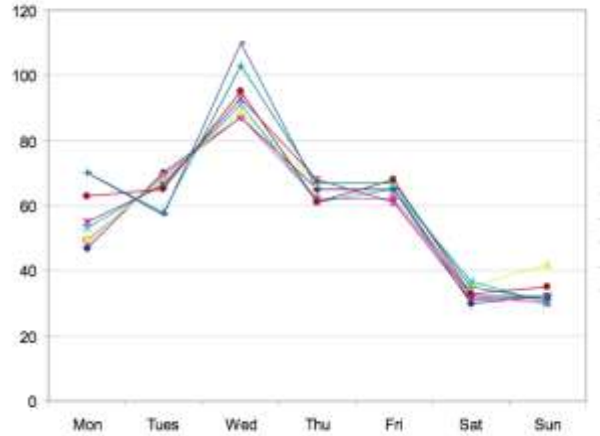


Figure 2-33 Overlay plot of several cycles [42]

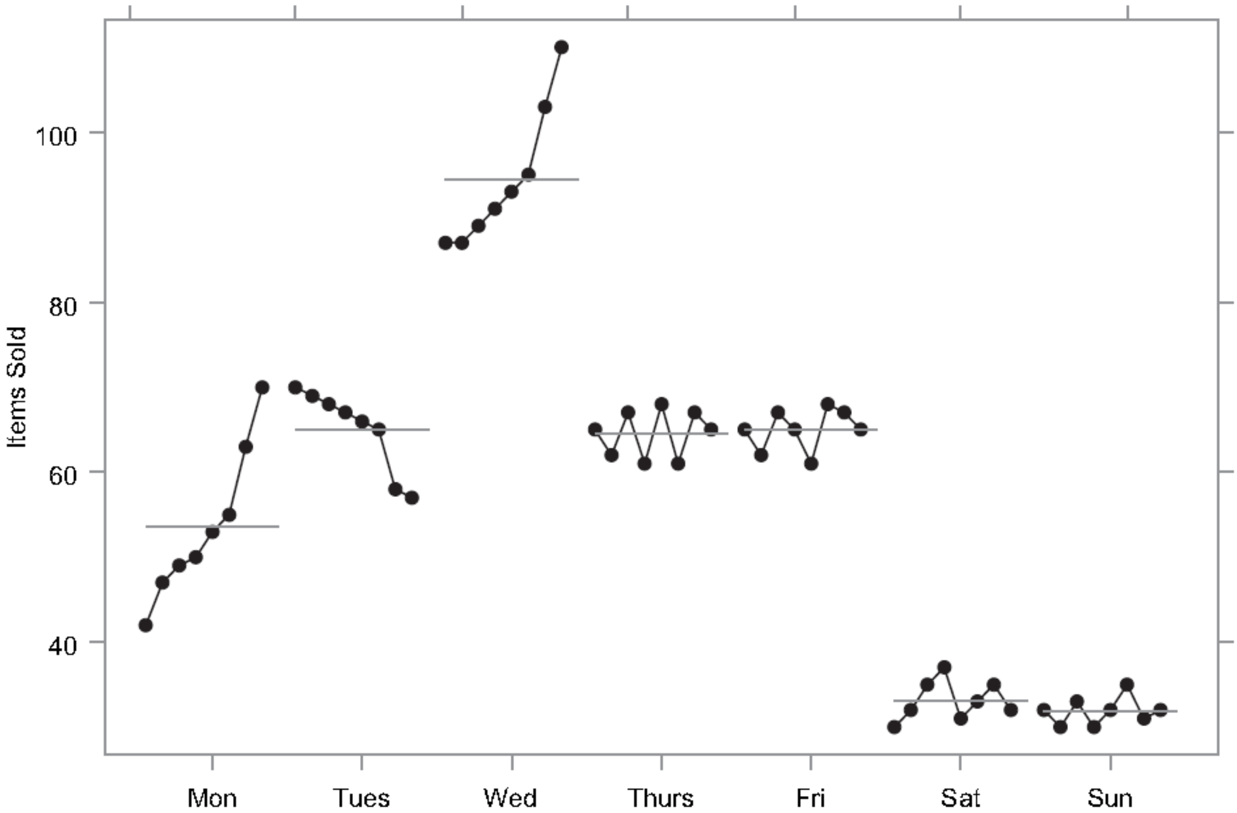


Figure 2-34 Cycle Plot [42]

Proper investigation of change over time requires that data be evaluated over several different time intervals (i.e. per year, per quarter, per month etc.). Several years' of data is required to ensure an out-of-the-norm year is not used to characterise the subject under investigation.

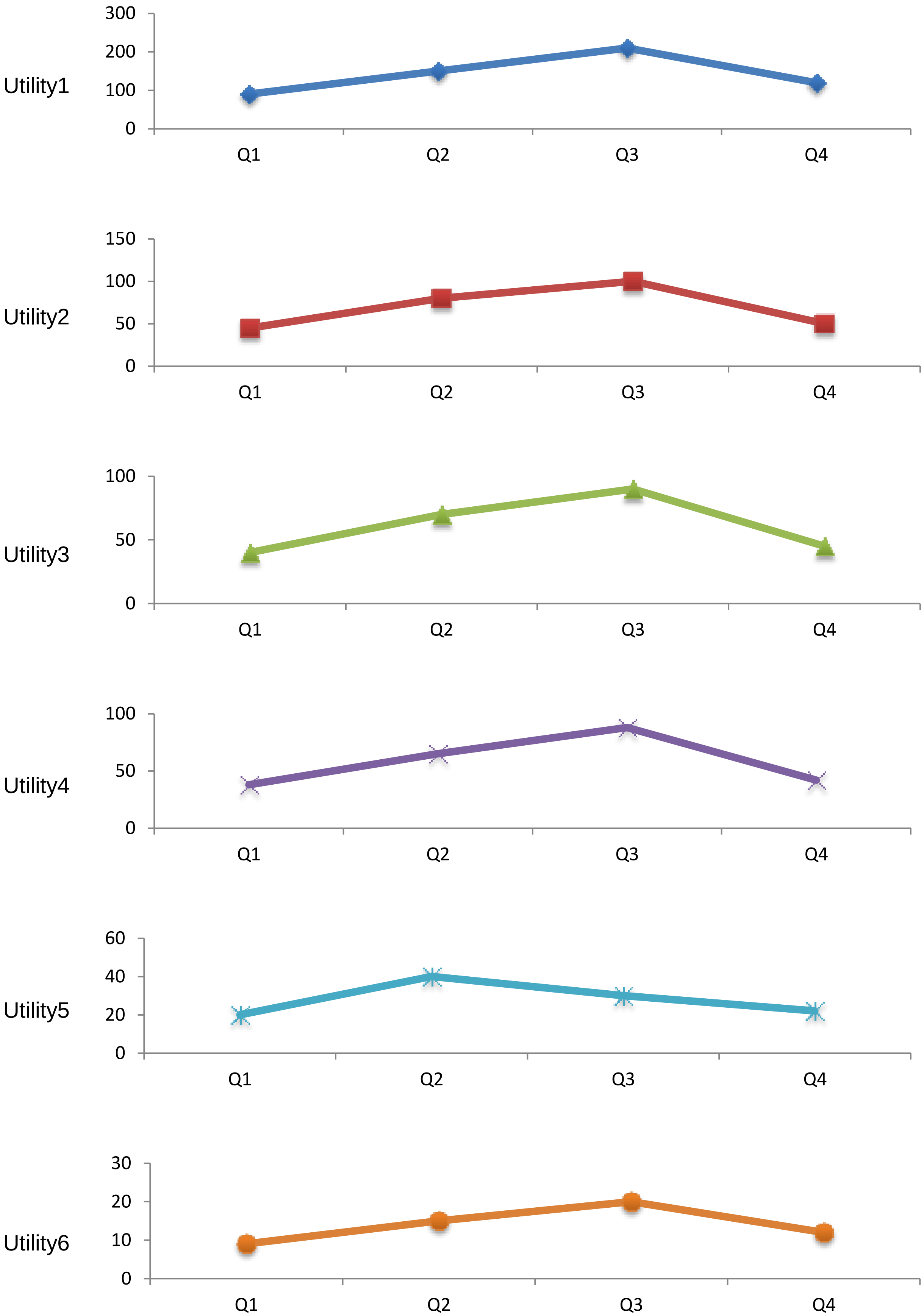


Figure 2-35 Comparing patterns of change

2.6.3.2Histograms, box plots and bean plots

These chart types are used to investigate and communicate the distribution of values.

Subdividing a quantitative range into discrete intervals (alternatively called bins) and plotting the number or percentage of items in each bin as a bar graph, results in a histogram. An example is the number of people falling into age ranges (bins) of 10 years each, shown in Figure 2-36.

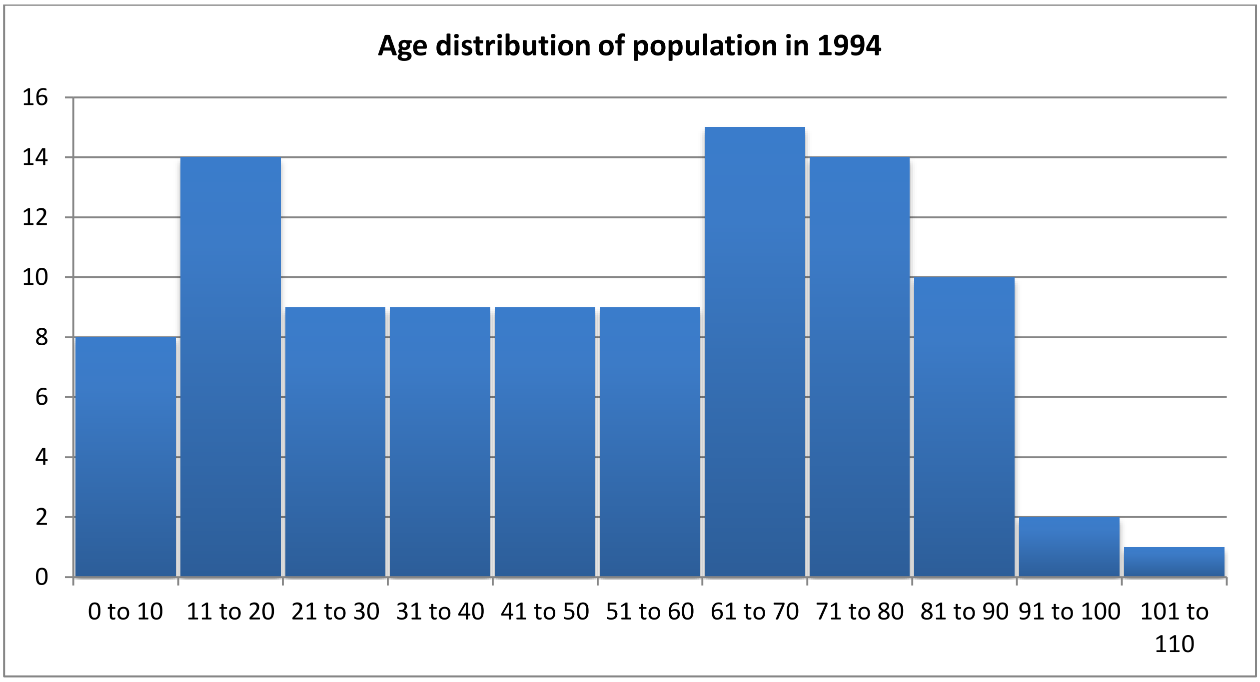


Figure 2-36 Histogram of age distribution (improvised data)

The box plot was introduced in the 1970's by Tukey [24] and displays the statistical distribution of values in a compact manner shown in Figure 2-37. It concisely visualises the following parameters for a distribution of values:

- The extremes (minimum and maximum values)
- The median (50th percentile)
- A boxed area representing 50% of the values (from the 25th to the 75th percentile)

Adapting the standard box plot to show an area representing 95% (or 99%) of the area enables displaying the statistical assessments prescribed by EN50160 [5] with box plots.

A bean plot (and close relative, the violin plot) [25], is shown in Figure 2-38 as a modern extension of the box plot. It replaces the boxed area with the actual distribution of the values.

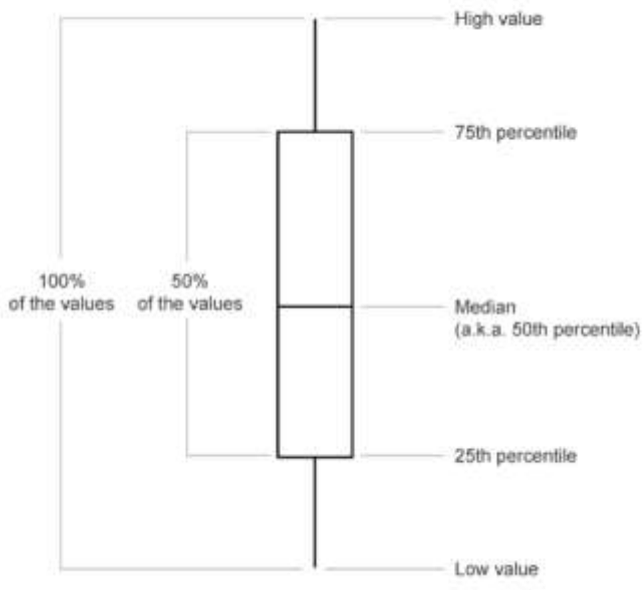


Figure 2-37 Box plot symbol explanation

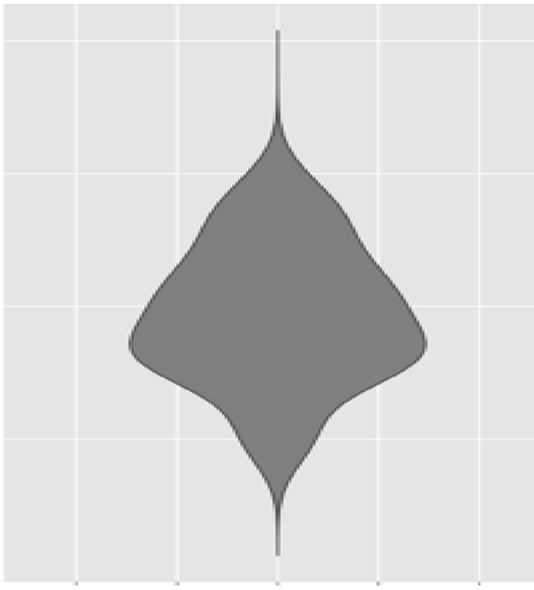


Figure 2-38 Example bean /violin plot

2.6.3.3 Stratification

Stratification is the process of grouping data values according to several categorical properties when examining the distribution of the values. Without investigating several groupings, exploratory data analysis can miss some important patterns in the data.

For example, when examining the distribution of voltage unbalance values in a large dataset, an obvious grouping would be the sites involved in the measurement. Other groupings however can be voltage level, rural/industrial or even month of the year to investigate seasonal differences in the distribution.

2.6.3.4 Bar charts, Dot plots and Bullet graphs

The human brain is very successful at automatically decoding comparative length from a common baseline. The simple bar chart is the prime candidate to use when comparisons of values need to be made. It is widely used to communicate the ranking of several entities over a specific parameter.

Figure 2-39 demonstrates the ranking of 3 sites for number of voltage dips over a period of time. Without reading the values on the Y-axis, it is clear that site A had double the number of dips relative to site B, and site B double the number of dips to site C.

This holds true only for zero-based charts, i.e. where the bar represents the full range from zero to the measured value.

Figure 2-40 demonstrates the discrepancy between perception and fact when the bar length does not represent the full value. Although site A only recorded 5% more events than site B, the graph suggests double the number of site B.

For non-zero based charts, the dot plot is more appropriate. Since the relative position of the dots is what encodes the data in a dot plot, rather than the line lengths as with a bar chart, the same discrepancy between perception and fact does not occur in Figure 2-41.

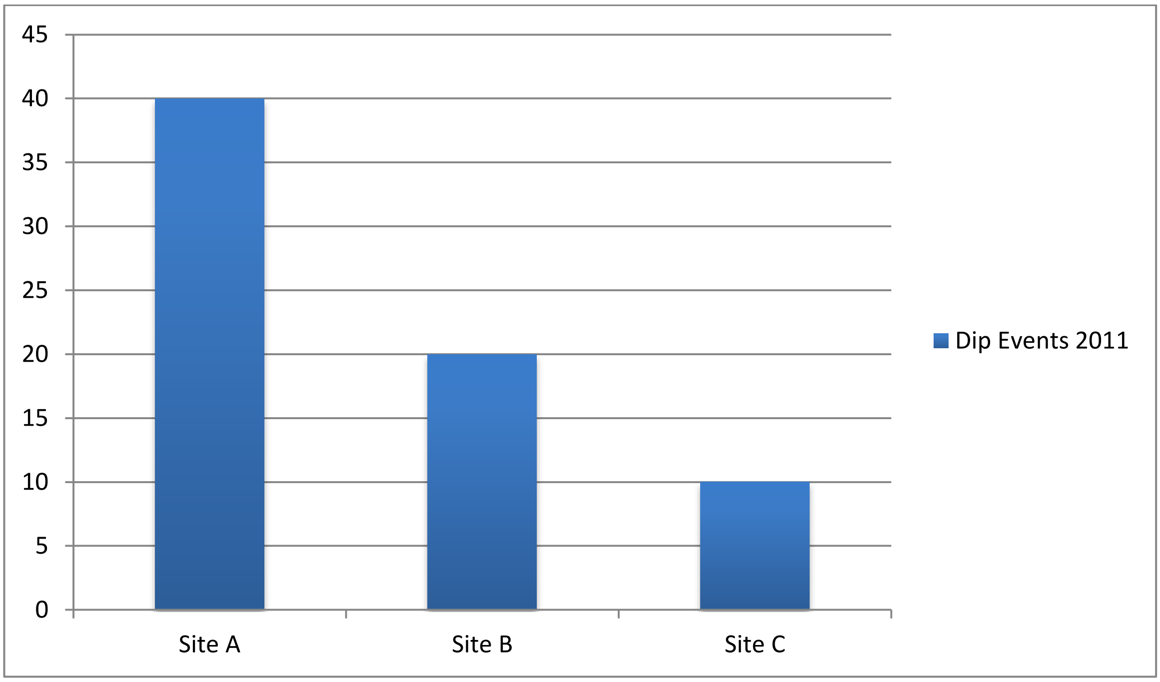


Figure 2-39 Bar graph for ranking dip performance

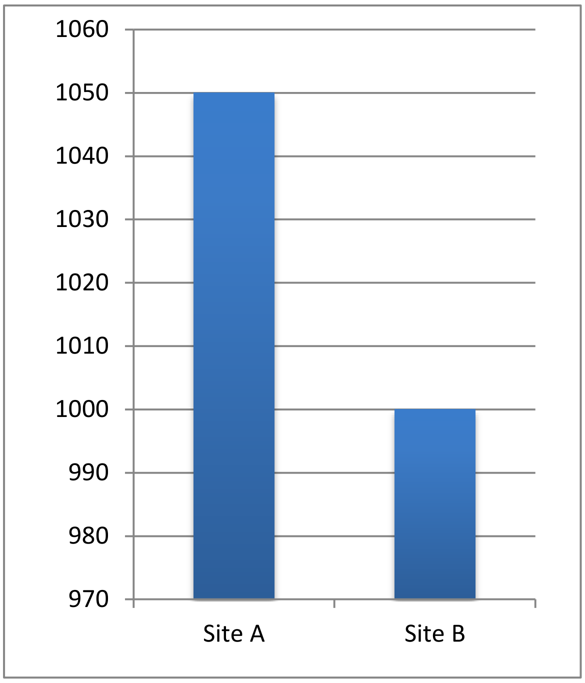


Figure 2-40 Misleading bar chart with non-zero reference

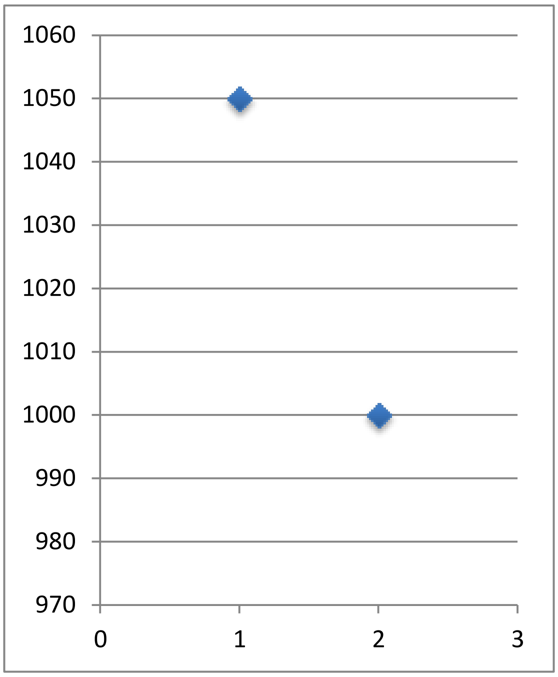


Figure 2-41 Dot plot with non-zero reference

The bullet graph is an extension of the bar graph. It is useful in information dashboards when a lot of information needs to be presented in a limited space.

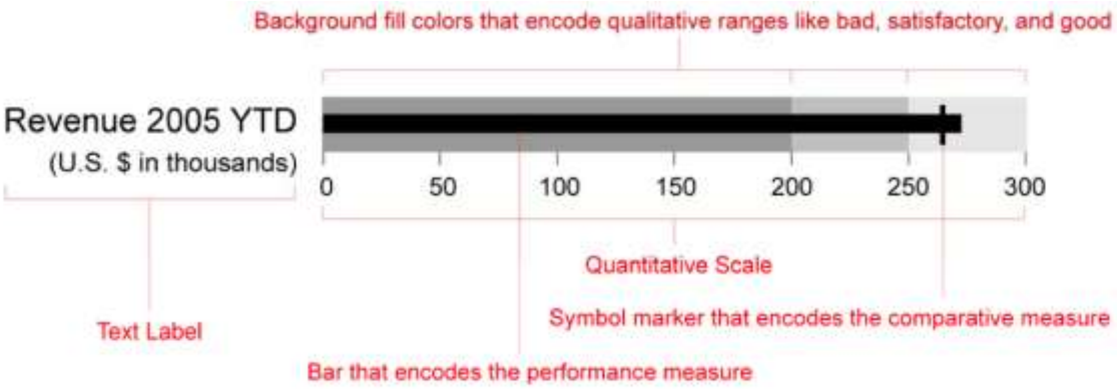


Figure 2-42 Example of a bullet graph [26]

Figure 2-42 shows the components of the bullet graph:

- A text label - to identify the measure
- A single linear axis with a quantitative scale
- A bar representing the featured measure
- Optional comparative measures, indicated as markers on the measure bar. This is used to compare the measure against e.g. a reference or historical measure.
- Several colour-coded ranges along the quantitative scale, to indicate state or classification of the measure, i.e. bad, satisfactory and good.

2.6.3.5 Scatter diagrams

To investigate and communicate correlation between two parameters, a scatter diagram is useful. Scatter diagrams are often used to test cause-and-effect relationships as shown below.

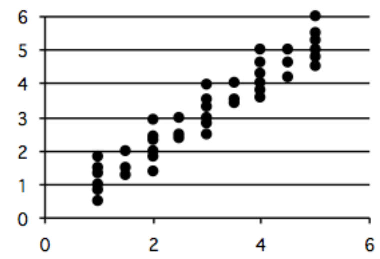


Figure 2-43 Strong positive correlation

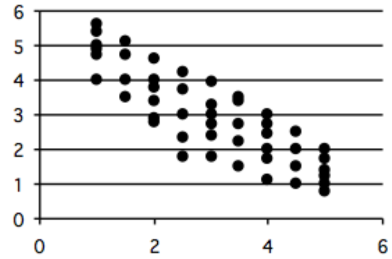


Figure 2-44 Strong negative correlation

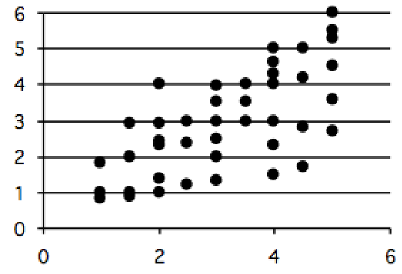


Figure 2-45 Weak positive correlation

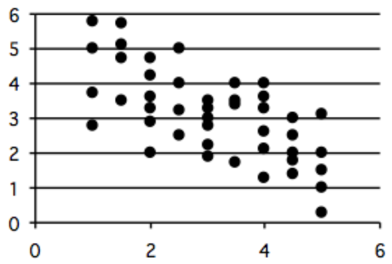


Figure 2-46 Weak negative correlation

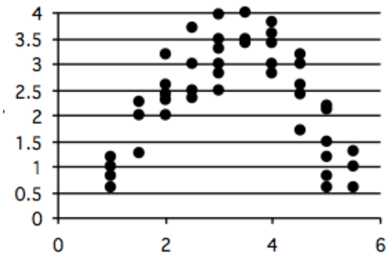


Figure 2-47 Complex correlation

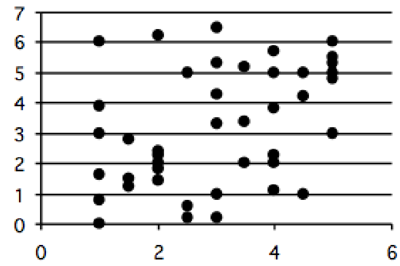


Figure 2-48 No correlation

One variable is plotted on the horizontal axis and the other on the vertical axis. The clustering of the data points can be used to determine the relationship:

- Closely clustered points that indicate a line with a positive gradient indicates a strong (high) positive relationship between the parameters (Figure 2-43)
- Closely clustered point that indicate a trend line with a negative gradient indicates a strong (high) negative correlation between the parameters (Figure 2-44)
- Loosely clustered points that indicate a trend line with a positive gradient indicates a weak (low) positive relationship between the parameters (Figure 2-45)
- Loosely clustered points that indicate a trend line with a negative gradient indicates a weak (low) negative relationship between the parameters (Figure 2-46)
- Clustered values that indicate a definite pattern, but not a straight line indicates a complex relationship between the values (Figure 2-47)
- No visible pattern indicates an uncorrelated set of parameters (Figure 2-48)

2.6.3.6 Brushing and linking

Being able to interact with the display of visual data enhances interpretation. Brushing and linking is an interactive technique to investigate interconnections between variables or parameters [28].

Application of this principle was developed in this research, an example is shown in Figure 2-49. It requires a real-life demonstration by means of the on-line PQ reporting system hosted at www.pq-portal.com to appreciate the functionality.

Several histograms or bar charts are shown simultaneously. Clicking on a single bar in one of the charts (brushing) highlights that bar in the graph. Concurrently, each bar in each other graph shows a shaded portion corresponding to the records associated with the selected bar in the first chart (linking).

In Figure 2-49, the voltage events for a specific utility over a period of 18 months are depicted. The graph on the left ranks the worst performing sites. The graph on the top right ranks the event types (classified according to NRS 048-2: 2007).

The predominant event is dip type Y. It is normal as dip Y can be contributed by network faults far away. Impedance between the point of measurement and the network fault increases with distance, resulting in the decrease of the dip depth. Remote faults can be recorded locally as dip type Y, but with most of type Y, the concern is less. Equipment should operate as normal when subjected to a voltage variation of category Y.

An additional 4 graphs in Figure 2-49 present the distribution of events over several different aggregation periods, per year, month-of-the-year, day-of-the-week and hour-of-the-day. These can be used to investigate seasonal patterns, weekly and daily cycles.

Observe the application of brushing: in Figure 2-49, the interruption event class in the top right graph has been brushed (selected). The bar is now red, indicating that interruption events have been selected. The red portions of the bars on all the other graphs represent this same set of events in each graph.

Brushing has now revealed he following:

- Interruption events make out a small percentage of the total number of events for most of the worst performing sites based on the ranking chart.
- Node H is different. Interruptions represent most of the events occurring at this site.
- Node H experienced about 50% of all the interruptions recorded for this utility over the 18-month period.

- The distribution of the interruptions as function of time indicate that most interruptions occurred in 2012, probably more that 80-90%.
- Most interruptions occurred during the month of February (more than 50-60%).
- Most events occurred on a Thursday (more than 50-60%).
- Most events occurred during a specific hour of the day (once again it looks like more than 50-60%).

From these observations one can deduce some hypotheses and confirm or disprove them by closer inspection of the specific event data.

One could deduce that, since a large percentage of interruptions occurs at a single site, during a single year, a single month, a single day – even a single hour, that those interruptions occurred on the *same* day, in close succession, because of either a measurement transducer fault or a network cable or other device failing. Should this be a measurement error, this data should be either discarded or marked/flagged, as it skews the real interruption performance of the utility.

If the data represents a network device failure, it would also serve as an argument for the use of temporal aggregation of interruption events. Should an appropriate temporal aggregation period be employed on this dataset, the number of interruptions would be drastically reduced, since the interruptions in close succession of each other will be counted as a single interruption.

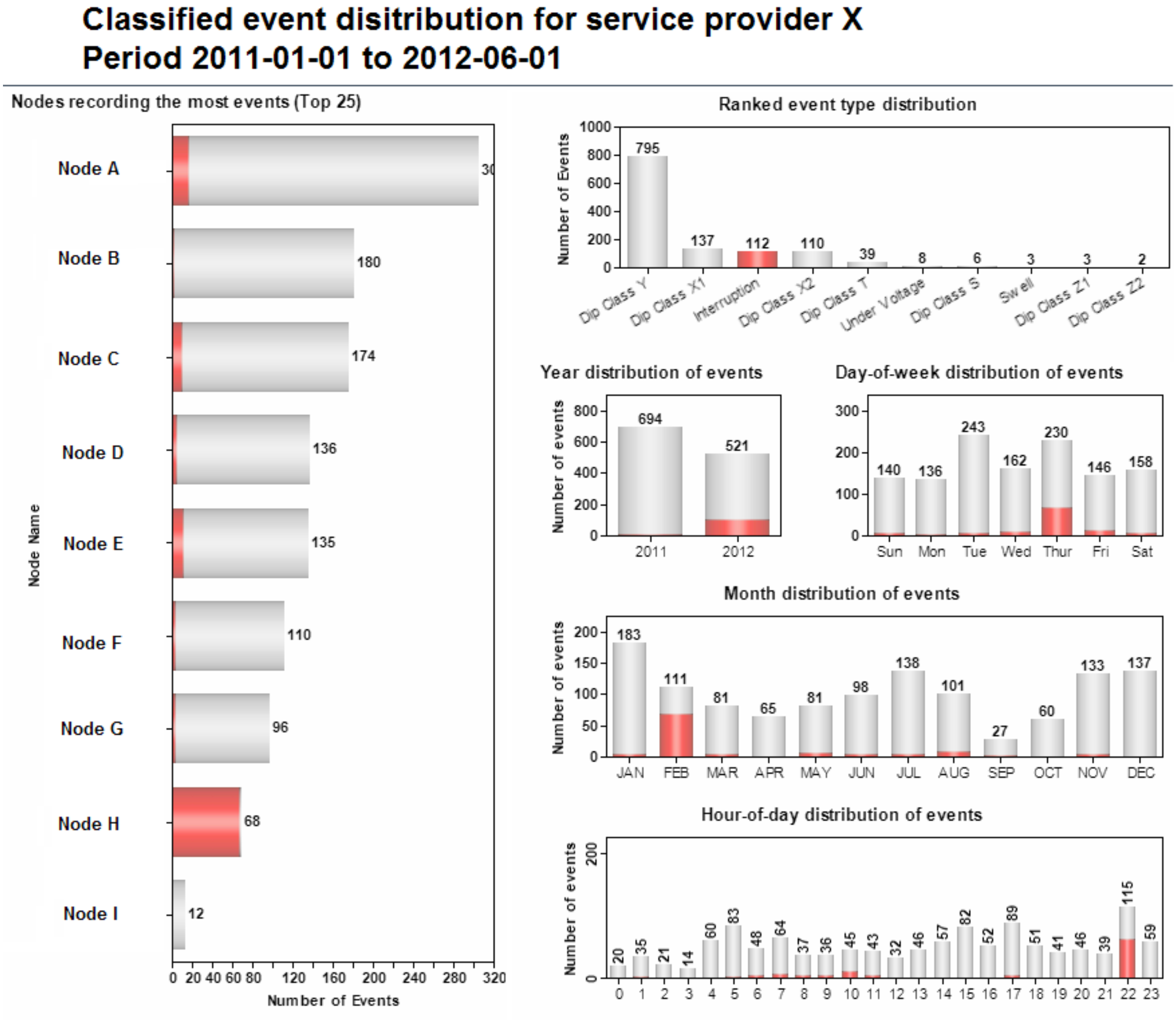


Figure 2-49 Example of brushing and linking

Figure 2-50 shows the same dataset, without the brushing and linking principle employed. Although valuable information can be attained from this visualisation, the extent of the information deduced in Figure 2-49 would not be possible.

Interactive visual queries made possible by brushing and linking enables a much deeper understanding of the dataset and the relation between different variables.

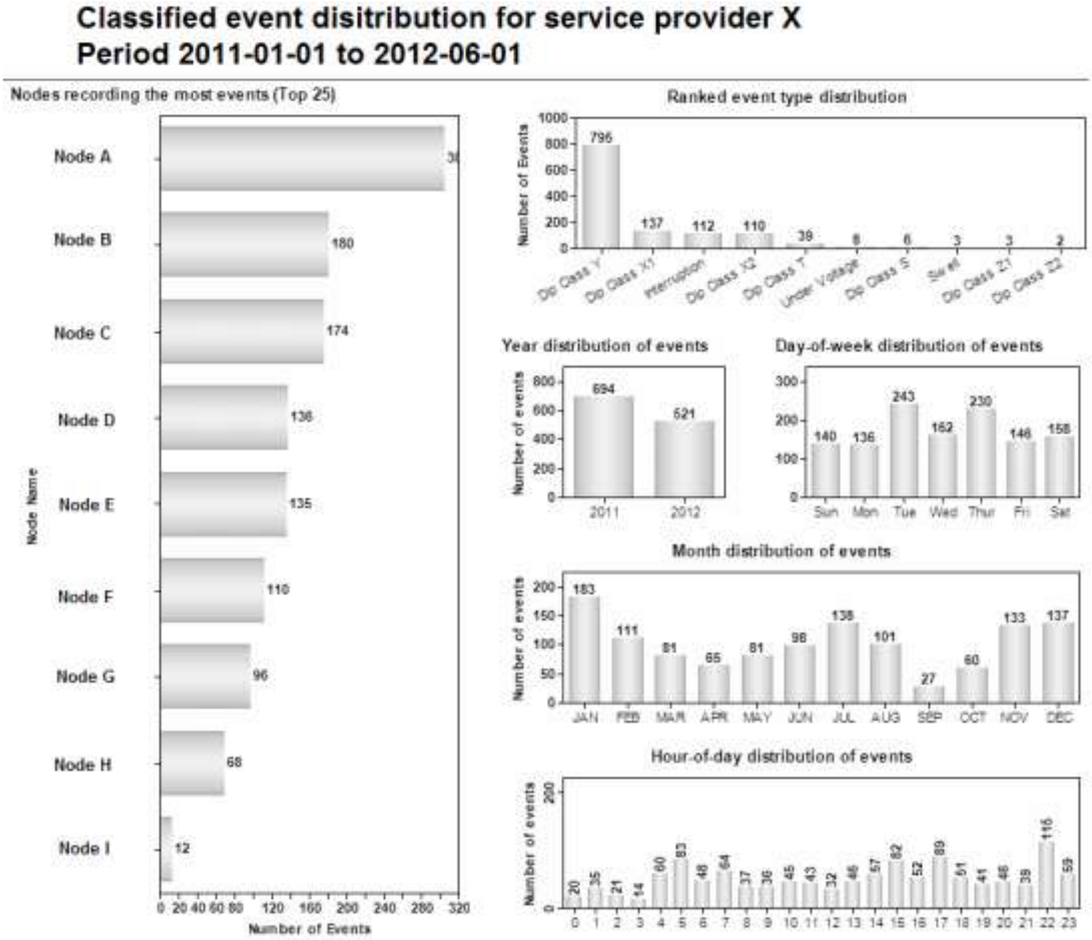


Figure 2-50 Event distribution - no brushing and linking

2.6.3.7 Data Dashboards

The human working memory is constrained to a limited number of items (4 to 6) at once [28]. Investigating a dataset by the sequential analysis of different views is not optimal. Our memory system is adept at swapping items in and out of memory in quick succession to be investigated consciously.

Dashboards are mechanisms to make optimal use of our memory and reasoning, by placing several different views of a dataset together in close proximity, allowing it to be swopped in and out of working memory in a quick succession of visual queries. The examples used in the previous section on brushing and linking are some examples of dashboards. Data shown are focused on the ranking and distribution of values over several categories.

Well-designed data dashboards make use of several different types of views on the dataset, to optimise the ability to extract information. Other types of views include parts of whole, correlations between variables, changes over time and geographically mapped locations.

2.7 Summary

A common vocabulary and measurement standard for power quality do exist. However, there is neither unequivocal agreement on what is considered good enough (minimum standards) in terms of power quality parameters, nor how to assess it.

The assessment methods of some standards that do exist are unclearly documented. The vastly varied suggestions in literature regarding assessment methods show how far the relatively young science of PQ still has to go before consensus can be reached. The different approaches indicate that there are multiple possible uses for the same underlying data.

Methods for aggregation of assessments over time and/or over multiple sites in a network in literature vary similarly. All the approaches investigated in this study, are theoretically viable and correct. However, the practical application of the aggregation over all power quality parameters to obtain a single Power Quality Indice (PQI) seems limited. This is because the resulting indice is too far removed from a specific cause or effect of an underlying problem. Further investigation, returning to the separate power quality parameters, will always be needed to resolve the problem.

Effective communication of the results of an assessment, is a topic not sufficiently covered in literature. The human visual system has the potential to ingest and analyse vast amounts of data, even inattentively, should we provide it with properly designed and formatted visualisations.

Data visualisation is a well-developed science. Modern interactive techniques allow visual querying of data, which aids in rapid investigation and understanding. Hidden information can be uncovered by properly employing these techniques.

3 Voltage Magnitude

3.1 Introduction

This chapter will focus on voltage magnitude assessment. The NRS 048-2 [6] assessment of voltage magnitude is first analysed. Deficiencies in the reporting procedure described in the NRS 048 document, are then demonstrated and discussed. An alternative methodology of reporting voltage magnitude assessment is also proposed. Contextualisation of voltage magnitude performance is then investigated, after which time and loading as context parameters are investigated and demonstrated. Finally, a set of data dashboards is suggested, which could help industrial consumers and utilities to manage voltage magnitude.

3.2 NRS 048-2 Voltage Magnitude Assessment

The South-African NRS 048-2 PQ standard prescribes the assessment method illustrated in Figure 3-1.

3.2.1 Assessment period

A minimum of 7 consecutive days, 00:00 to 00:00 shall be used to make an assessment. Data more than 7 days will be assessed on a 7-day sliding principle. A 2-week dataset for example, results in 8 week-values. The 7-day period is selected such that each assessment includes a working week and a weekend to mask the cyclic behaviour of industrial and residential loads. This allows any two assessments to be comparable, since each is then based on a full cycle.

3.2.2 Assessment principle

Voltage magnitude requires assessment of compliance to limit (never to be exceeded) values and compatibility values (voltage contained for 95% of the time within specific variation). All 10-min V_{rms} values for a full week recorded in all 3 phases are used to find the highest and lowest 10-min RMS value. The highest and lowest value over the assessment period is used to assess compliance to the limit criteria.

Voltage magnitude compatibility assessment requires that for each set of weekly values, all 10-min V_{rms} values for all phases are combined and the CP05 and CP95 values (5^{th} and 95^{th} percentile values) identified. The highest and lowest values over the assessment period are used to assess the compliance to compatibility.

3.2.2.1 Exclusion of flagged and missing data

Any 10-min V_{rms} value that coincides with a voltage dip, swell or interruption event is to be flagged and excluded from the assessment. The flagging concept is introduced to prevent a single event impacting multiple power quality assessments.

For example, without flagging, a voltage dip will be counted under the dip statistics, but could also impact the flicker assessment of the same period, resulting in an additional PQ concern, which does not really exist.

For long-term assessments, the combination of missing and flagged data is not allowed to be more than 10% of the data. For short-term (investigational) assessments, this requirement tightens to 2%.

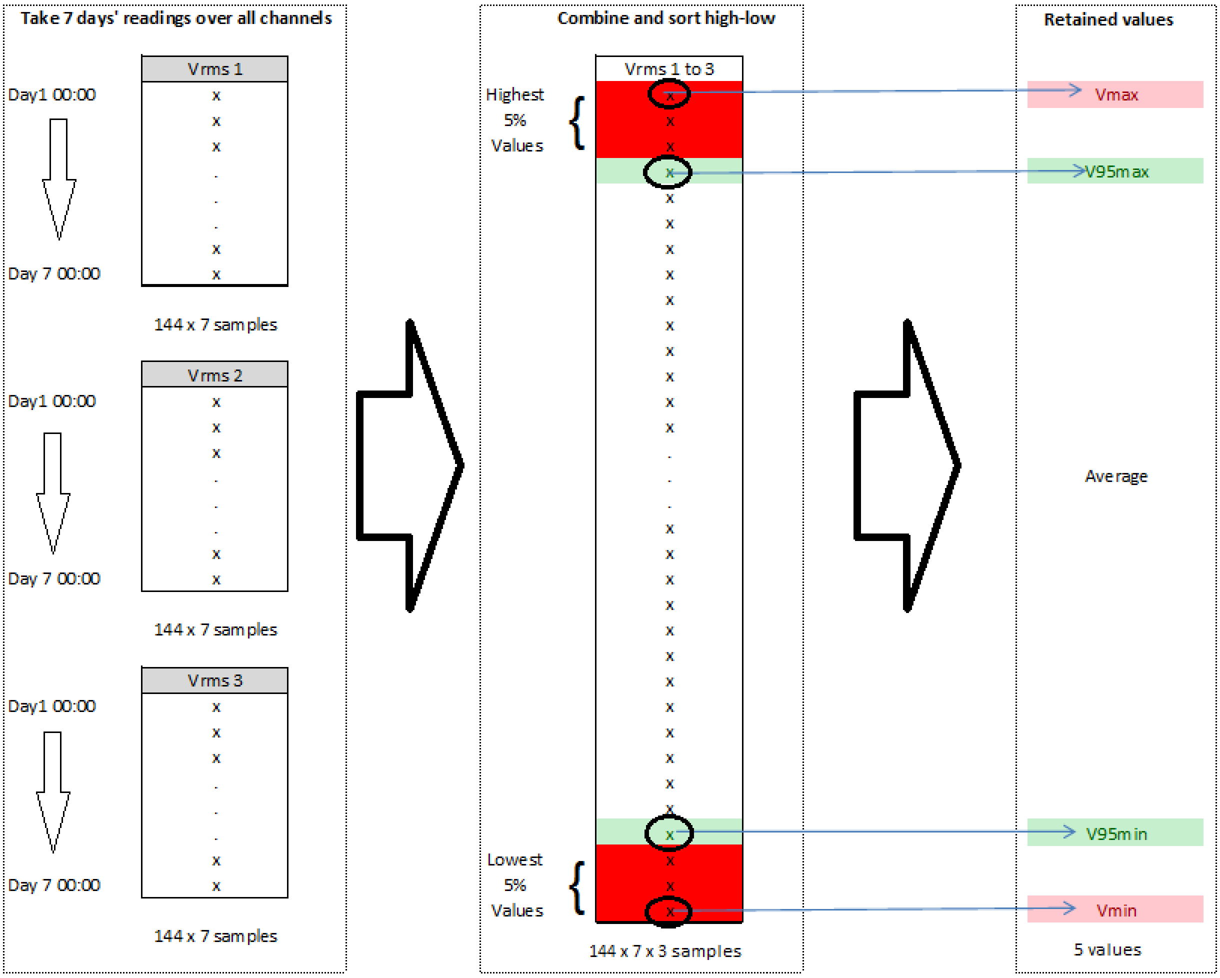


Figure 3-1 NRS 048-2 voltage magnitude assessment

3.2.3 Concerns regarding the NRS 048-2 assessment of voltage magnitude

The prescribed assessment method succeeds in producing a small dataset to be retained every day that is comparable, as each dataset represents a complete weekly cycle of industrial and residential electrical consumption (resulting from the 7-day sliding principle). This dataset can then be used to establish compliance to compatibility and limit criteria.

Some deficiencies exist in this approach and is analysed below.

3.2.3.1 Over representation of non-compliance to voltage magnitude

The NRS 048 assessment method does not take into account how or if users at the point under investigation experience the variation in voltage magnitude. This makes it impossible to assess the impact of non-compliance on users.

This can be illustrated by the following hypothetical example. A three-phase, 10 MVA distribution transformer supplies a diverse load of 5 three-phase, 1 MVA industrial clients and 150 single-phase clients, evenly distributed over the three phases (50 per phase). The industrial clients have predominantly three-phase equipment, with lighting and office equipment representing the single-phase loads.

Over a period of 7 days, phase A runs very high, while phases B and C run slightly lower than optimal. The NRS 048-2: 2007 assessment shows non-compliance with the compatibility criteria for voltage magnitude for this week.

This is reported in the annual report to the regulator. The regulator (or even the utility itself, for its own managerial usage) uses this information, together with the recorded information on client loads supplied by this measurement point, in a benchmarking effort. During the benchmarking exercise, the regulator (or the utility) decides that it is prudent to weight the non-compliances with the size of the loads supplied by each measurement point. The total load connected to the measurement point is used to weight the assessment. ***Is this the truth…what was the true extent of the non-compliance?***

Only 1/3 (those on phase A) of the domestic load experienced the non-compliance. What about the industrial clients? Only a small percentage of their total load was exposed to non-compliant phase A.

The bulk of their loads are three-phase loads, which were exposed to the effective three-phase voltage of the system, not the individual single-phase voltages. The assessments are made on the single-phase voltages instead of the effective three-phase voltage – thus does not properly represent the bulk of the industrial load.

3.2.3.2 Misinterpretation of voltage regulation

Utilities often use the voltage magnitude assessments to gauge the effectiveness of voltage regulation at a point of measurement. There is a difference in voltage magnitude compliance to NRS 048-2 and the efficacy of voltage regulation due to the combination of data from 3 separate phases into one dataset.

Figure 3-2 (a) and (b) shows graphs of NRS 048-2 voltage magnitude assessments (weekly retained values) over time of 2 different measurement points. Comparison can lead to the conclusion that the voltage regulation at Node A is significantly worse than Node B, since the spread of minimum and maximum values for 95 % of the time, is wider for site A than site B.

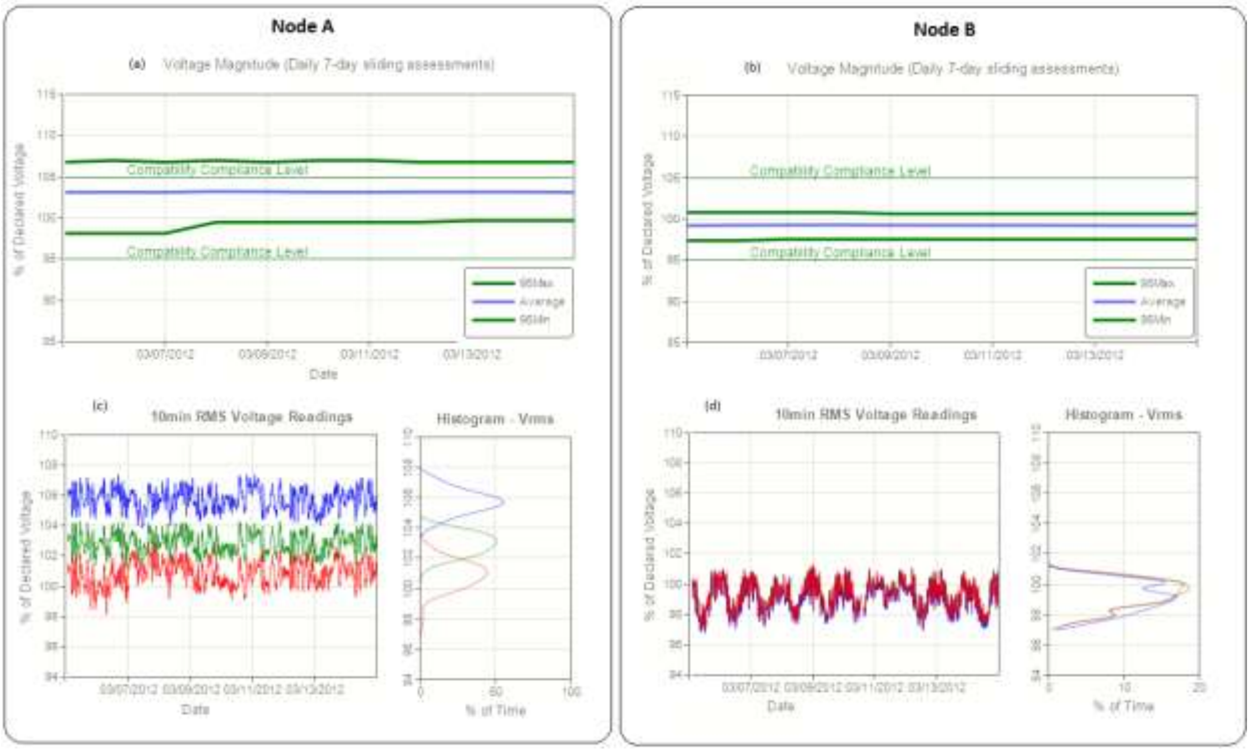


Figure 3-2 How voltage unbalance manifests in voltage magnitude assessment

This could be attributed to insufficient supply impedance at site A as the voltage is high when loading is low and voltage is low when loading is high. Such conclusion is superficial as shown in the analysis presented below.

Inspection of the 10-min V_{rms} values and a histogram thereof reveal a difference between the 2 sites to better understand the voltage regulation. Although the variance of the per-phase voltages at Node A is similar to Node B, the histogram indicates that voltage unbalance at site A is the cause to the reason why the voltage regulation is reported as seen in Figure 3-2. The highest and lowest voltage is used for the assessment, irrespective of which phase it occurs on.

The presence of voltage unbalance therefore appears as bad voltage regulation.

This is not a problem with the standard per se. The NRS 048 standard assesses the absolute voltage magnitude for compliance over, in essence, 4 *separate* criteria. Displaying it on the same graph over time and interpreting the spread of values, as “voltage regulation” is the problem. The susceptibility of the method to misinterpretation due to the presence of a different power quality problem (voltage unbalance) is clear.

3.2.3.3 Masking bad voltage magnitude performance

The flagging of certain event types can mask poor voltage regulation at some sites. Annual reporting on PQ to NERSA requires a list of short-term voltage disturbances. Voltage dips of type Y and voltage swells are excluded.

Voltage dips are measured from a moving nominal at transmission voltage levels as no end-user directly connects to the transmission network. The recording of a dip in this case requires that voltage deviate with at least - 10% from the value it is at.

At distribution voltage levels, a fixed nominal value is used for dip triggering and classification. This means that when the voltage exceeds a fixed level of nominal +- 10%, a voltage event is recorded regardless of the operating voltage before the event. The depth of the dip is deemed as the difference between the nominal value and the lowest (or highest in the case of swell) value measured during the event.

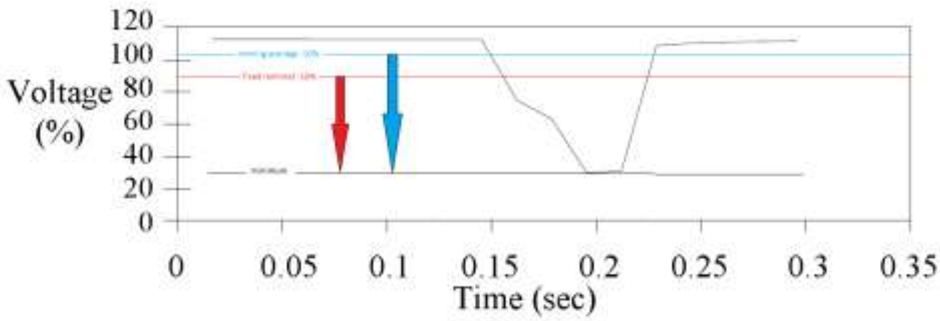


Figure 3-3 Difference between moving and fixed nominal

When the average voltage (working point) of a distribution site significantly differs from the nominal value (bad voltage regulation), a high number of dips (in the case of the working point low) or swells (in the case of the working point high) can be recorded.

These events are usually barely over the threshold and are not real network events. They are artefacts of bad voltage regulation, made visible by the application of the criteria of a fixed voltage event threshold. The dips are by nature always of type Y.

According to the NRS 048-2 standard, electricity consumers' equipment is expected to withstand Y dip types, since they are very shallow. This would then also be the reason for not having to report on them.

These events, that are not reported, however are still used to flag the 10minute values they occurred in, under the reasoning that the utility cannot be penalised twice. This has the effect that, during assessment, the utility gets to hide up to 10% of the worst performing V_{rms} values, since up to 10% of values are allowed to be lost to missing or flagged data.

Temporal aggregation of these short, shallow events could cause it to be classified as over and under voltages. These events however are also not reported to the regulator, the net effect of flagging remains the masking of bad performance.

3.2.4 Alternative voltage magnitude assessments

3.2.4.1 Meyer [20], [45]

Meyer attempts a single assessment for a site, aggregated over all power quality parameters, not only voltage magnitude. This assessment can be aggregated over time and/or sites to attain a single site or a global network assessment on PQ.

This approach requires individual assessments to be normalised in order be comparable and to be aggregated. Meyer applies the EN50160 assessments and then normalise each to the specific compliance level of that parameter. The normalised value is subtracted from 1, to express the assessment as a reserve margin (distance from non-compliance).

$$r_{E(v,q,p)} = 1 - \frac{m_{(n,q,p)}}{g_{(q)}}$$

n – site; q – index; p - phase

m - actual value
g - limit
r_E - individual index

Example for $THD_{95\%}$:

m	3,8%	7,5%	11,2%
$g_{(THD)}$	8,0%	8,0%	8,0%
r_E	0,53	0,06	-0,40

Figure 3-4 Normalisation of power quality parameter with example for THD [20]

As an example, in Figure 3-5, Meyer shows the normalised assessments for voltage magnitude (white), harmonics (light grey), flicker (dark grey) and unbalance (black) grouped per site. A separate graph per utility is used.

Meyer's method of site aggregation of the separate parameter assessments is to select the smallest reserve margin over all parameters. The mean and maximum over all parameters per site is the calculated and the resulting site assessment visualised in Figure 3-6.

The visualisation method in use is not intuitive. At first glance it looks like a combination of a boxplot and a bar graph. A variation of the box plot, termed the box-and-whisker plot, adds two "whiskers" to the vertical line. The meaning of these whiskers is not standardised and the meaning is usually declared when used. It seems that it represents the minimum and maximum of a distribution of data in this case.

Extension of the vertical line beyond the whiskers does not make sense as it indicates values beyond the minimum and maximum. The bar and the bottom whisker are used to represent the exact same thing - the minimum reserve margin over all the parameters.

No additional explanation could be found. It seems that the reason for the dual indication is that the minimum is the actual result of the assessment, while the other plot is additional information to communicate the spread of the values. Accentuating the bottom whisker in another manner (perhaps a different colour or hue) would have been more intuitive, although the reserve margin being represented by the length of the bar does make sense.

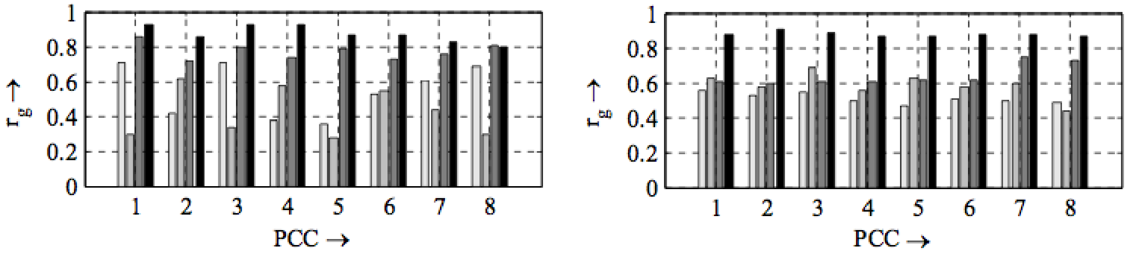


Figure 3-5 Meyer's assessments of multiple parameters for multiple sites (PCC's) of two utilities [45]

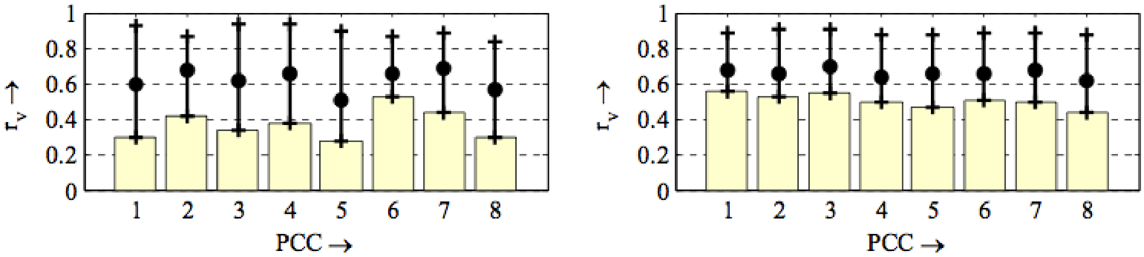


Figure 3-6 Meyer's aggregated assessment for multiple sites (PCC's) of two utilities [45]

3.2.4.2 Cobben [18], [19]

Cobben attempts to measure and analyse long-term QoS data in a non-expensive, effective and simple way with the results communicated in a well-known manner. The reduction of data for analysis is another priority.

A similar normalisation used by Meyer of EN50160 percentile values is done. The resultant values of this normalisation are such that a value of 1 represents perfect quality (no disturbance) and a value of 0 represents the compatibility level. A value of -1 represents double the level of compatibility.

Six equal regions are used in-between the value of 1 and -1. A represents “very high quality” and F represents “extremely poor quality” as shown in Figure 3-7. This ABCDEF classification is similar to the energy efficiency rating of household appliances shown in Figure 3-8.

Figure 3-7 ABCDEF classification scheme for PQ [18]

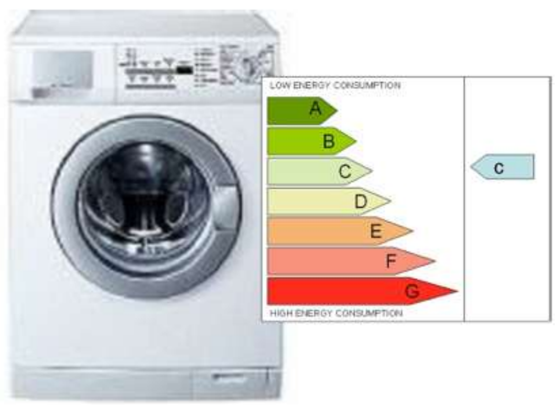


Figure 3-8 ABCDEFG Household appliance energy efficiency rating

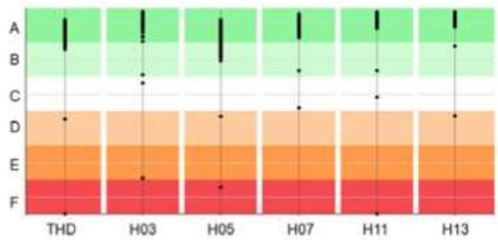


Figure 3-9 Utility assessment of multiple parameters [18]

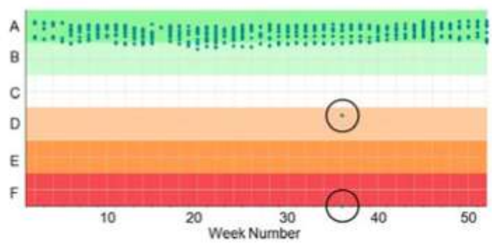


Figure 3-10 THD assessment change over time for utility [18]

A novel combination of dot plots and bullet graphs are used by Cobben to visualise and compare multi-parameter performance of a whole network (or utility) shown in Figure 3-9. The spread of assessments for each parameter over all sites is intuitive with outliers easily identified.

For example, this utility does not have a harmonics problem although one or two sites are out of compliance. The 5th harmonic can be seen to be the dominant contributor to voltage THD.

Figure 3-10 visualises the performance over time of a single parameter, voltage magnitude in this case, for multiple sites.

A limitation of the assessment qualifiers (high, very high etc.) and the visualisation method is that it is not intuitive from the qualifiers and visualisation to determine the non-compliance boundary. Prior knowledge is needed to understand that the value of 0, the boundary between the C and D regions, is the compliance level and parameters rated below C is out of compliance.

Cobben uses an additional assessment, the STAV method as discussed in section 2.4.1.1, to extract information on the spread of values under assessment. An application on voltage regulation with a nominal value of 230 V is shown in Figure 3-11.

As each assessment is represented by a pair of values (the standard deviation and the average), it is more difficult to compare two assessments and probably not possible to effectively aggregate the assessments

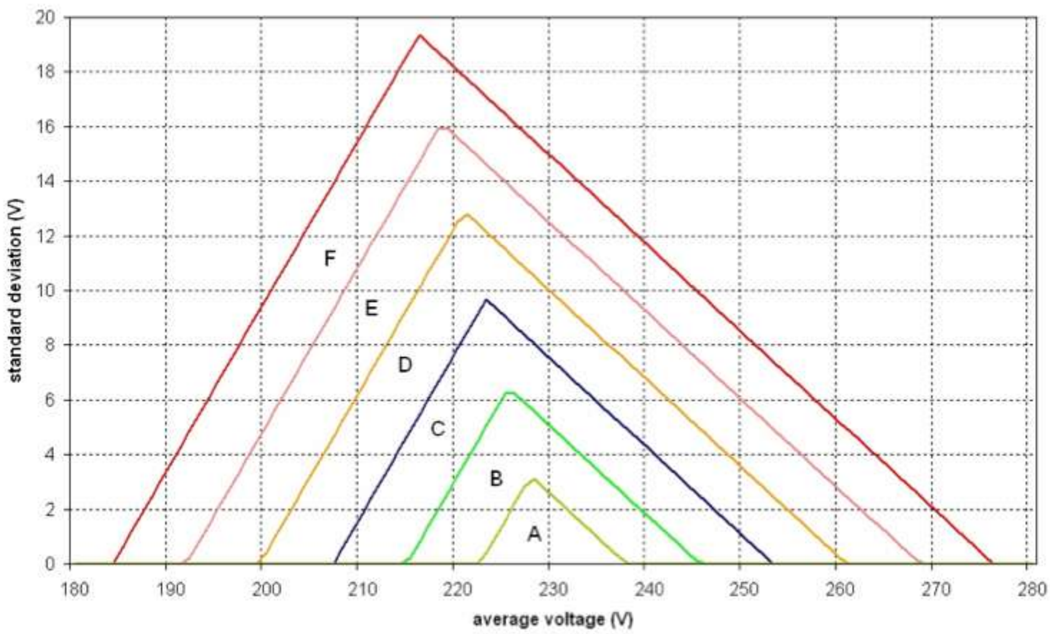


Figure 3-11 STAV assessment for LV voltage magnitude [18]

3.2.4.3 Comparison of EN 50160, Meyer [20] and Cobben [18]

The EN50160 assessment for voltage magnitude is based on 4 separate assessments:

- At least 99% of the 10-min V_{rms} values shall be below the +10% upper voltage limit.
- At least 99% of the 10-min V_{rms} values shall be above the -10% lower voltage limit.
- No 10minute Vrms value shall be above the +15% voltage limit.
- No 10minute Vrms values shall be below the -15% voltage limit.

[1]

It does not specify how multiple phases should be handled. It could be separate assessments, or it could be combined as the NRS 048-2 assessment requires, or it could be aggregated as Meyer and Cobben does. It is not clear.

Neither Meyer [20] nor Cobben [18] explain how to aggregate the 4 separate assessments over the 3 phases to find the single normalised assessment value for voltage magnitude. The following approach is deduced from the methodology used by Meyer:

An assessment is made for each of the 4 criteria and for each phase, resulting in 12 assessment values. Meyer's aggregation method is flexible enough to, depending on the need, combine these 12 assessments in multiple ways. To arrive at an assessment per phase (called a grouped assessment by Meyer), the minimum reserve over the four separate criteria is taken for each phase. To arrive at a singular assessment for voltage magnitude, the minimum reserve over all 12 separate assessments is taken.

He denotes the assessment results as follows:

- $r_{E(v,q,p)}$ is the normalised single performance index for site *v*, parameter *q* and phase *p*.
- $r_{V(v)}$ is the site performance index for site *v*, aggregated over all parameters and phases.
- r_G is a grouped site performance index, where grouping can be done over arbitrary elements (subset of parameters, sites and/or phases)

Cobben does not present an example of the percentile assessment method and deals with voltage magnitude by means of the STAV method.

3.2.4.4 Elphick, Gosbell and Barr [40]

Elphick, Gosbell and Barr [40] define a utility scorecard that can be used to benchmark utilities. It is recognized that voltage magnitude is the only PQ parameter where the value of 0 does not indicate the optimal level of disturbance (no disturbance). A new parameter, Absolute Voltage Deviation (AVD) as the absolute value of the difference between the measured value and the nominal value for a site is defined, to result in a parameter where 0 equals no disturbance. The 95^{th} percentile of the AVD is used in the voltage magnitude assessment. This represents the spread of values around the nominal for 95% of the time. It is done for each phase and the worst of the 3 phases retained as the assessment value.

This method [40] does not compare assessments to a PQ standard, it only benchmark utilities. The result is a ranking of utilities with no indication of an acceptable level of performance.

3.2.4.5 Stander, Rens [21]

In [21], the author developed and implemented an alternative reporting method for voltage magnitude. This method is a combination of the STAV and AVD methods but boasts significantly different features.

The goals were:

- Develop an alternative visualisation for NRS 048-2 voltage magnitude assessments that makes use of scatterplots instead of line graphs. Scatterplots are the prime visualisation tool for displaying or finding patterns in statistical data, while line graphs are especially good at displaying change over time.
- Identify the parameters the utility can control and define the assessment in terms of those parameters, as it will empower the utility to change performance.
- Relate the derived parameters to the NRS 048-2 assessment.
- Visualise the result in an intuitive manner with a focus on the success of voltage regulation and not only on compliance to voltage magnitude compatibility criteria.

Voltage magnitude assessment in South Africa when based on the NRS 048 part 2 produces the following daily values based on a 7-day sliding principle:

- V_{max} – the absolute maximum 10-min value in any phase.
- V_{95max} – the highest 10-min value not exceeded for 95% of the time (the 95th percentile), in any phase.
- Average – the average 10-min value, in any phase (this is not required by the standard, but it can be useful)
- V_{95min} – the lowest 10-min value not exceeded for 95% of the time (the 5th percentile), in any phase.
- V_{min} – the absolute minimum 10-min value, in any phase.

The 5 parameters obtained by this assessment are depicted in Figure 3-12.

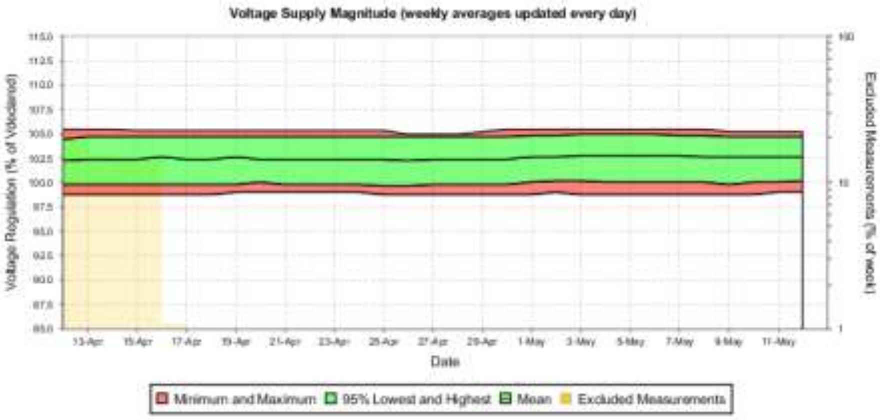


Figure 3-12 Voltage magnitude assessment: NRS 048-2

A scatterplot is a two-dimensional display of variables.

An alternative visualisation of voltage regulation was devised based on 2 parameters, which the utility can control. The 5 values resulting from the assessment above was used as input data.

The utility can control voltage magnitude at end users by proper sizing of transformers (sufficient supply impedance) and setting a nominal operating voltage for the specific network serviced. Tap changers can control voltage but not all transformers are equipped with automated on-load tap changers.

Based on the 5 vales resulting from the NRS 048 voltage magnitude assessment, 3 new parameters were derived.

- The difference between the nominal voltage (set-point) and the average voltage ($V_{\Delta nom}$) is an indication of the tap setting (at a fixed tap or for automated tap-changer). The utility has control over this setting. This is equivalent to the Average Voltage Deviation (AVD) of Elphick, Gosbell and Barr [40].
- The difference between V_{min} and V_{max} is an indication of the "stiffness" of the supply point. Fault level at the supply point will dictate how much the voltage change when loading is low and when loading is high. Tap changers, even if automated on-load types, cannot immediately adjust the voltage. The resulting parameter is termed $V_{spread100}$.
- The difference between V_{95min} and V_{95max} is an additional indication of the supply impedance ("stiffness"). It represents voltage magnitude performance for 90% of the time, as the highest 5% and lowest 5% of 10-min values are not represented by these two parameters. The resulting parameter is termed $V_{spread90}$.

The 3 new values were related to the NRS 048-2 compatibility and limit criteria. Cobben has shown [18] that voltage magnitude values are distributed normally. A normal distribution is symmetrical around the mean, which also means that the 5th and 95th percentile are equal distances from the average. Compliance to the NRS048 standard results in:

- When the average is larger than the nominal value, the average plus the distance between the average and the 95th percentile needs to be less than the upper compatibility level.
- When the average is less than nominal, the average minus the distance between the average and the 5th percentile needs to be more than the lower compatibility level.

Expressed mathematically:

$$V_{average} + \left(V_{95max} - V_{average}\right) < V_{upper\ limit} \tag{3-1}$$

And

$$V_{average} - \left(V_{average} - V_{95min}\right) > V_{lower\ limit} \tag{3-2}$$

Because of symmetry

$$\left(V_{95max} - V_{average}\right) = \left(V_{average} - V_{95min}\right) = \frac{1}{2} \left(V_{95max} - V_{95min}\right) \tag{3-3}$$

$(V_{95max} - V_{95min})$: The new parameter derived as $V_{spread\ 90}$

The equations now become:

$$V_{average} + \frac{V_{spread\ 90}}{2} < V_{upper\ limit} \tag{3-4}$$

and

$$V_{average} - \frac{V_{spread\ 90}}{2} > V_{lower\ limit} \tag{3-5}$$

Since the assessment values are expressed in % of the nominal value, a new parameter can be found:

$$V_{\Delta nom} = V_{average} - 100 \tag{3-6}$$

Substituting $V_{average}$ and the actual compatibility criteria from the NRS048 assessment for $V_{upper\ limit}$ and for $V_{lower\ limit}$ results in:

$$V_{\Delta nom} + \frac{V_{spread\ 90}}{2} < 5, \qquad where\ V_{\Delta nom} > 0 \tag{3-7}$$

and

$$V_{\Delta nom} - \frac{V_{spread\ 90}}{2} > -5, \qquad where\ V_{\Delta nom} < 0 \tag{3-8}$$

The above 2 equations (3-7 and 3-8) can be plotted as two straight lines on the $V_{\Delta nom} - V_{spread\ 90}$ plain resulting in a triangular area. Assessment values inside the triangle are in compliance with the standard.

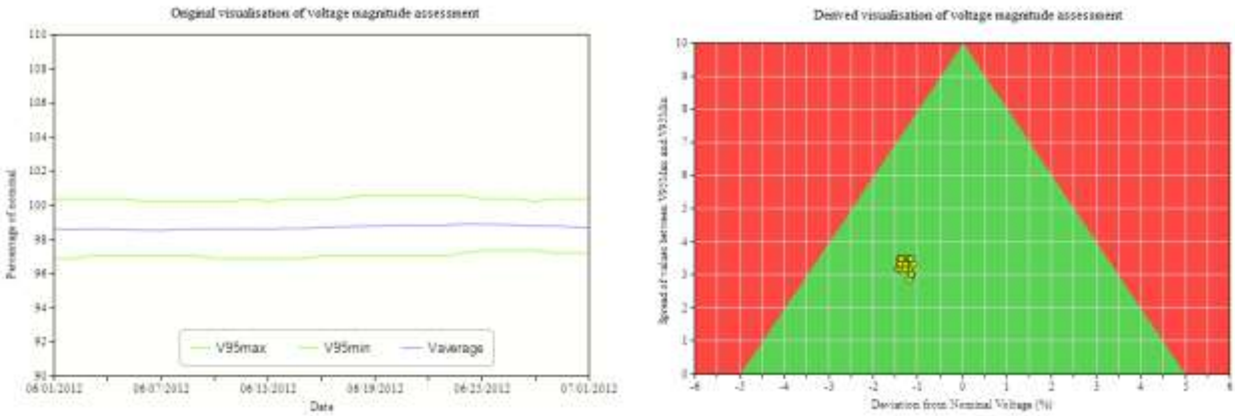


Figure 3-13 Example visualisation - very good voltage regulation

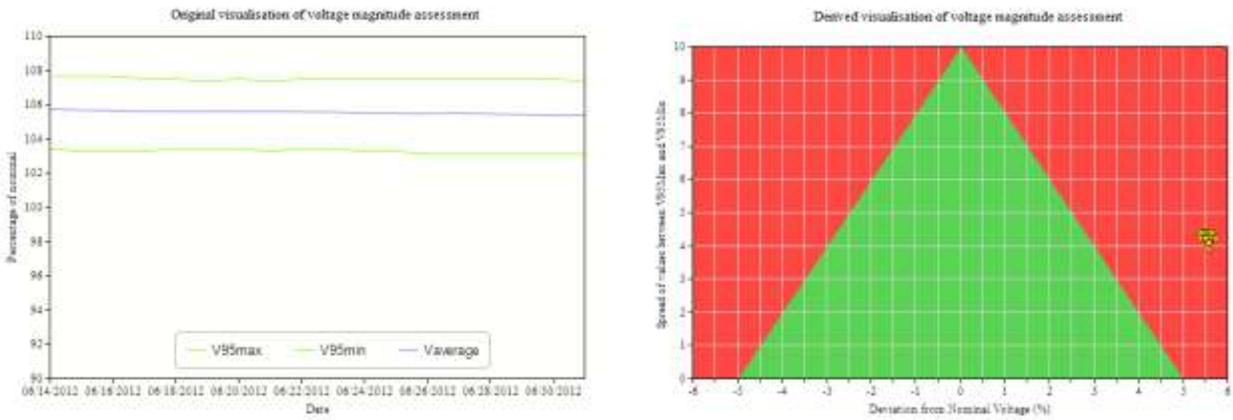


Figure 3-14 Example visualisation - incorrect operating point

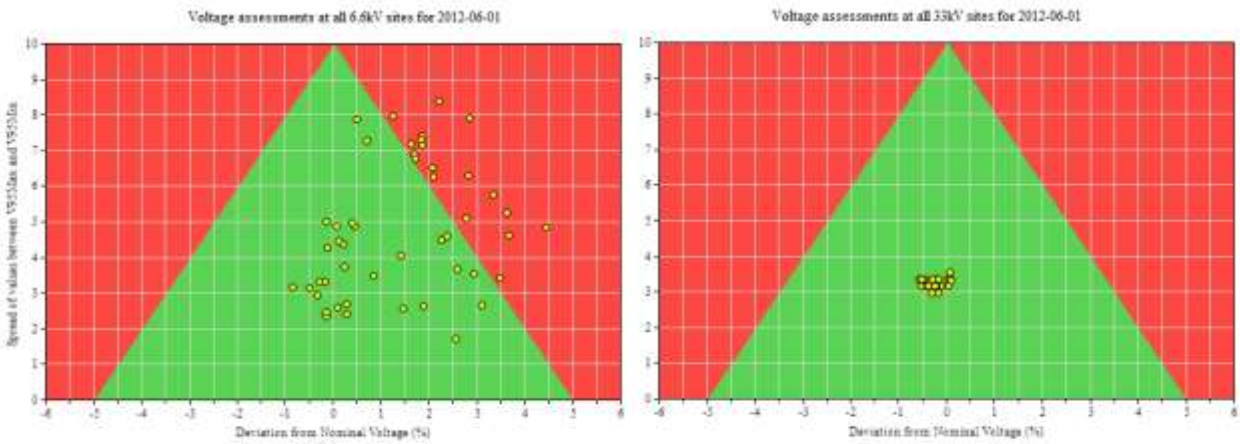


Figure 3-15 Example visualisation - comparison between networks

Figure 3-13 present the new visualisation method for a site with good voltage regulation.

- All values remained in the green area.
- Operating point is about 1% below nominal, with the spread of values on the x-axis around 0.5%. This point of supply maintained voltages near nominal.
- The average for $V_{spread\ 90}$ is just below 3.5%, with about 1% spread of the values on the y-axis over time. Sufficient supply impedance exists, resulting in limited change of voltage as load change.

Figure 3-14 presents an example of a site where the regulation of the voltage is good, but too high and therefore not in compliance.

- Voltage is on average 5.5% above nominal but the spread of values in both the *x*- and *y*-direction is well contained.
- The average on y-axis is about 4% with a spread in values of about 1%.
- The operating point can be changed by a change in the tap setting, or if the nominal voltage should be high due to for example a long radial line, simply re-declared.

Figure 3-15 illustrates a feature of the alternative visualisation not possible with the standard NRS 048-2 visualisation of voltage magnitude assessment. It presents voltage magnitude assessments for a number of 33 kV and 6.6 kV sites in a network over a 7-day period (i.e. one assessment per site).

- The 33 kV sites are a combination of intake points for this network and for industrial users directly connected to 33 kV.
- Voltage magnitude is well regulated at the 33 kV sites with sufficient supply impedance to sustain the change in loading.
- The 6.6 kV sites are not all in compliance and not well regulated in voltage magnitude.

- The non-compliances are all on the right-hand side of the graph, indicating that the V_{95max} (high voltage) compatibility criteria was exceeded.
- The spread of values to the upper half of the y-axis indicate insufficient supply impedance for the loading.
- Some sites can result in values to be relocated to the green area (compliance) by changing operating point.
- Some sites have high $V_{spread\,90}$ values due to constraints on the supply impedance causing an inherent voltage regulation problem insurmountable by changing the operational point.

The visualisation method developed above can still be affected by voltage unbalance. Application of the method on a per-phase basis will be needed to resolve such concern. Different symbols or colours can be used to indicate different phases.

3.2.5 Revised NRS 048-2 voltage magnitude assessment: proposal

The concerns with the NRS 048-2 voltage magnitude assessment (2007) can be alleviated by some minor changes. Both the concern about over-representation of non-compliance and the concern about misinterpretation are due to the *use of the retained values*, rather than the assessment method itself.

The critique against the flagging of dip events for voltage magnitude assessments is validated in the latest (2010) version of the EN50160 standard, where it is confirmed that only voltage unbalance, -harmonic distortion and -flicker levels are influenced significantly enough by voltage dips to warrant the exclusion of those 10minute values during assessment. For voltage magnitude assessment, the EN50160 standard only allows for the exclusion of 10minute values flagged by voltage interruptions, not those flagged by voltage dips.

A revision to the NRS 048-2 (2007) voltage magnitude assessment is proposed below – changes are bold and comments in italic and prepended with an asterisk.

3.2.5.1 Assessment Period

No changes to the standard sliding 7-day assessment are proposed.

3.2.5.2 Retained values for voltage magnitude assessment

For each set of weekly values, **and for each phase**, record the single highest and lowest 10-min V_{RMS} values. **This translates to 6 retained values instead of 2.*

From the above 6 values, the highest and lowest values over the assessment period are used to compare to the limit criteria. **Note that this does not change the outcome of the existing assessment method.*

For each set of weekly values **and for each phase** record the CP05, CP95 **and average** values. **This translates to 9 retained values instead of 2.*

From the above 9 values, the highest and lowest values over the assessment period are used to compare to the compatibility criteria. **Again – this does not change the assessment result.*

3.2.5.3 Exclusion of flagged and missing data

Any 10-min V_{rms} value that coincides with an **interruption** event is to be flagged and excluded from the assessment.

For long-term assessments, the combination of missing and flagged data is not allowed to be more than 10% of the data. For short-term (investigational) assessments, this requirement tightens to 2%.

**The additional retained values allows for proper investigation and visualisation of the efficacy of voltage regulation. It can also be used in benchmarking exercises to more precisely determine the extent of the non-compliance. Without the exclusion of records flagged due to voltage dips removes the masking effect of (specifically type Y) voltage dips and swells on the voltage regulation assessment, where a fixed nominal is employed for dip triggering.*

The visualisation below is now possible with the additional retained values and is used to enrich the assessment values as was obtained from the NRS 048-2 assessment methodology. Real network data is used in this example.

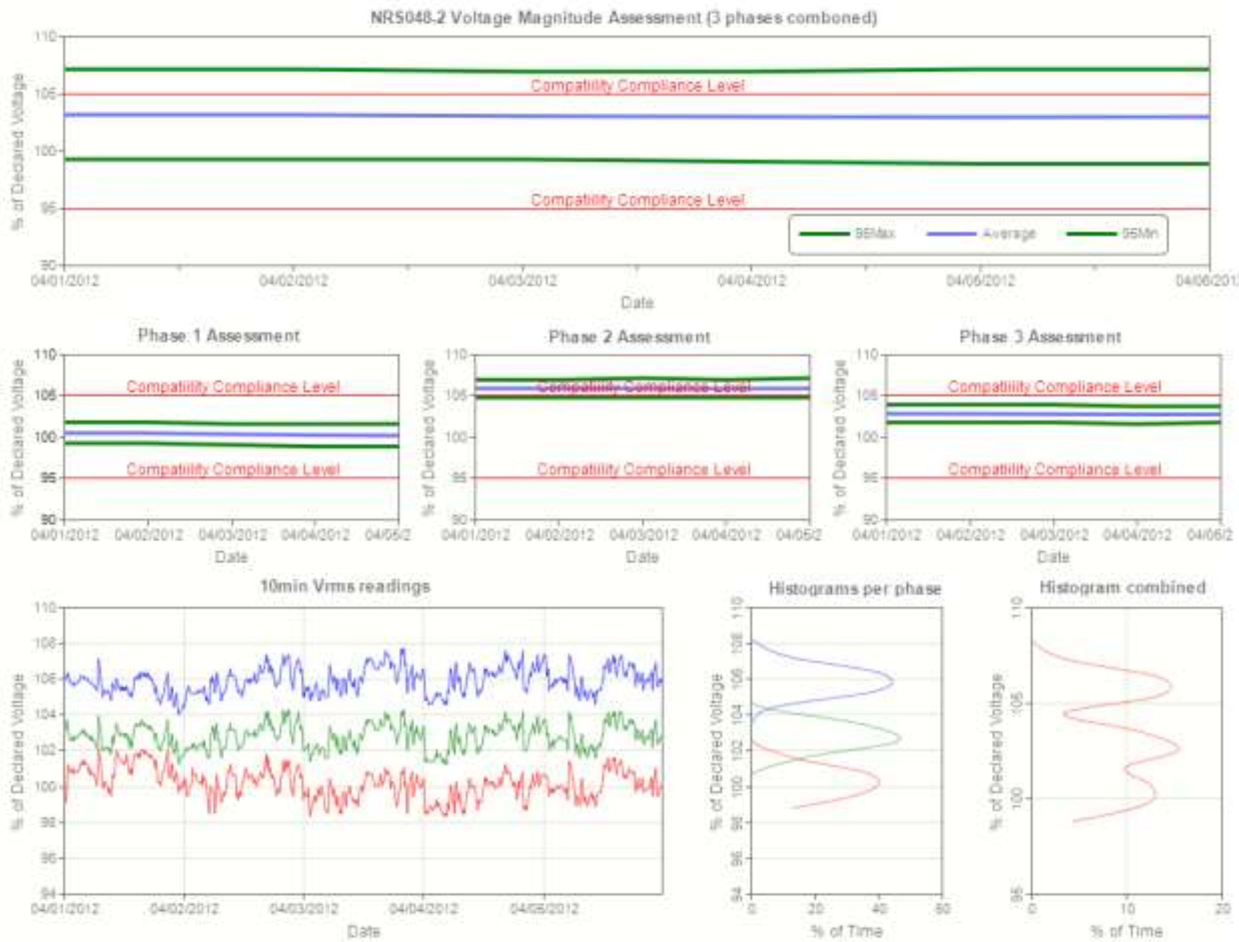


Figure 3-16 Additional NRS048 voltage magnitude assessment visualisations

The top graph in Figure 3-16 is the visualisation of retained values obtained from plotting the retained values from the original assessment over time. From this visualisation, one can see that the supply is out of compliance and that it seems like the voltage regulation isn't very good (the spread of values between the V95max and V95min lines looks to be around 8%).

The individual per-phase assessments were made possible by the additional retained values as proposed. A different perspective on the ability of this supply point to regulate voltage results:

- Regulation per phase is very good: observe how well the spread of values for V_{95max} and V_{95min} is contained (per phase).
- The non-compliance is due to phase 2 only.
- The reason to non-compliance is voltage asymmetry. It was masked in the standard NRS048-2 visualisation.
- Understanding that non-compliance is due to voltage asymmetry empowers the utility to devise useful intervention measures.

The additional use of histogram plots per phase is shown lastly to be as useful as it reveals the working point of each phase.

3.3 Analysis of Voltage Magnitude in Context

3.3.1 Time as context

Because all measurements and assessments are time-stamped, time is already inherently part of the measurement. It might therefore seem strange to use time as separate contextual information.

The 7day sliding method of assessing voltage magnitude is specifically designed to account for the cyclical nature of weekly activity from the assessment. Cycles having longer periods, like monthly, seasonal or yearly cycles could still be investigated by means of the retained assessment values. To investigate the weekly cycle one will however need to inspect the 10minute V_{rms} values.

The "*95% of the time*" requirement for compliance to voltage magnitude is insufficient to adequately protect consumers. What could be gained from investigating exactly *when* the discarded 5% (in essence the worst performing) of values occurs? Armed with a pattern for non-compliance of a specific parameter, an industrial client could possibly re-design the scheduling of its processes, to give processes sensitive to specific power quality problems the highest probability of not experiencing the problem. The availability of such information when an industrial client designs a plant could be valuable.

For a consumer of electricity, the PQ is only important when it is consumed. Operational-hours could be another useful context. Assigning each non-compliant 10-min V_{rms} value as a non-compliance event and listing these events against the hour-of-the-day, day-of-the-week, month-of-the-year and against operational hours can further a different perspective on non-compliance. For an industrial client, using the non-compliance criteria for each parameter should only be a starting point. Identifying the tolerance level for each power quality disturbance for each production process can be used in addition to the power quality standard.

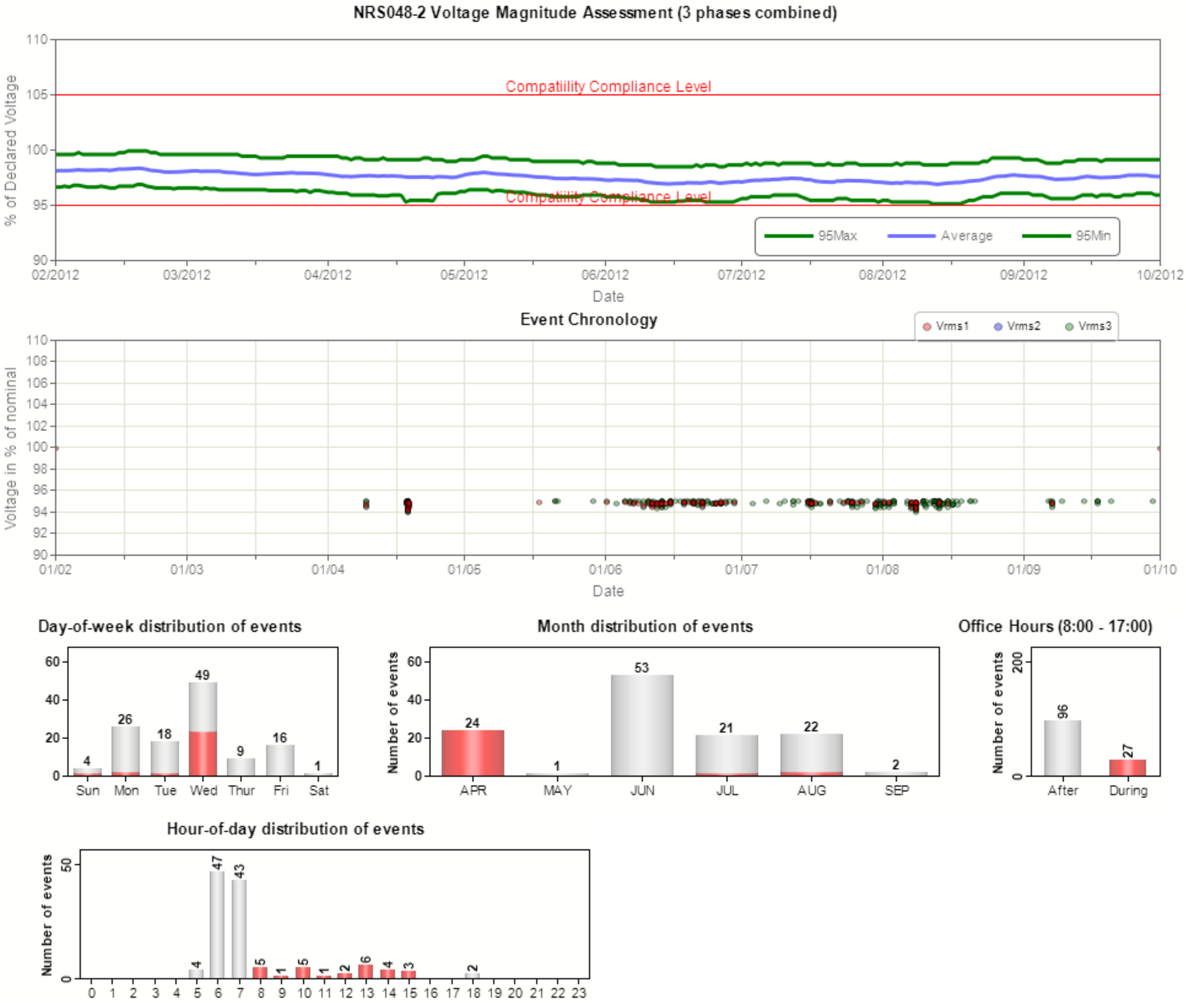


Figure 3-17 Example investigation of voltage magnitude non-compliance events

Figure 3-17 shows an investigation into the voltage magnitude non-compliance events for a specific site. Observe the 7-day sliding assessment at the top. This site is never in non-compliance, although it is near non-compliance from June 2012 onward.

The event chronology graph is a plot of each sample value that exceeded the voltage magnitude compliance criteria. Each phase is identified by a different colour. It can be seen that, although the site is in compliance with the standard, several 10-min values are out of compliance. These values are included in the 5% values discarded as dictated by NRS 048-2 assessment.

The last 4 graphs investigate cyclic patterns. Most events occur on Wednesdays. June had about double the number of events than other months. Most events occur after hours. Most of the events occur between 6 and 8 in the morning.

Brushing and linking (discussed in section 2.6.3.6) has also been used in this example. All events during office hours were selected and are represented by red parts in the bar charts. Most events occur during office hours, on Wednesdays and in April. A cluster of events occur on a specific Wednesday in April, the bulk of the during-office-hours events. The influence of this cluster of out-of-compliance events can also be seen on the assessment graph, as the V_{95min} values “dip” during April.

To investigate what information can be gained from the 5% discarded values, the following aspects were considered:

- What is the time distribution of voltage magnitude non-compliance events?
- Does the distribution differ significantly between utilities?
- How poor is the performance of the values being ignored during the assessment?
- Could any knowledge be gained to support voltage magnitude management?

Figure 3-18 shows the hour-of-the-day of events where voltage magnitude was exceeded at 4 utilities. Events exceeding upper and lower thresholds are shown separately. The event count is normalised by the number of measurement sites at each utility. Observe:

- At all utilities, the number of events exceeding the lower threshold is an order of magnitude less than those exceeding the upper threshold.
- At all utilities, exceeding the upper threshold is less during the day than the night, with two periods of least events around the start of the business day (around 8:00) and early evening (around 18:00 - 19:00).
- No common pattern can be seen in exceeding the lower limit.

The above observation is the result of managing voltage magnitude such that it does not drop too low during maximum loading. The lower voltage magnitude threshold is given priority.

Exceeding the upper threshold illustrates typical loading patterns in industrialised countries. Load increase (and voltage drops, resulting in less events exceeding the upper threshold) early in the morning when industrial processes start up (8:00 – 9:00). A residential load peak is noted around 18:00 – 19:00 with a similar decrease in events exceeding the upper threshold.

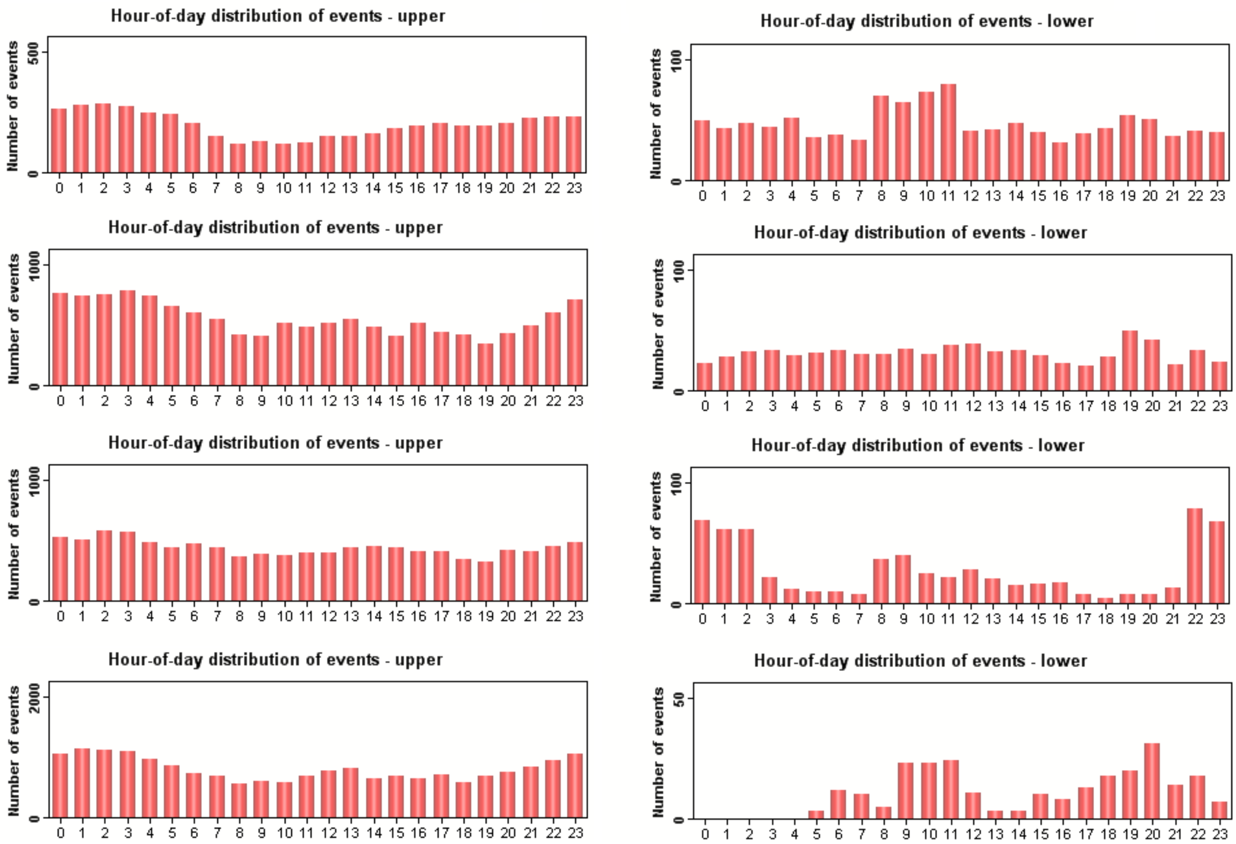


Figure 3-18 Hour of day distribution of voltage magnitude noncompliance events for several utilities

The extent of the events exceeding the thresholds was quantified by the deviation from nominal value and averaged per utility, resulting in an average deviation from nominal per utility. Events exceeding upper and lower thresholds are shown in Figure 3-19.

The average for events exceeding upper thresholds is around 6%. The upper limit is exceeded by 1% and similar for the lower threshold. A value of 8% is noted in the events exceeding the upper threshold. It was found that bar represents a single customer (not a utility) where voltage was set to be high to compensate for voltage sags during start-up of a rotating load.

An additional variable was added, the deviation from the average voltage (set point) at a site for events for exceeding voltage at other utilities. The average value of a 7-day assessment was used. The light blue bars in Figure 3-19 presents this new information.

It can be seen that for most utilities, the difference between the two variables for the upper level is large. The difference between these two variables represents the average distance from nominal for each utility.

The average distance from the set point is larger than the average distance from the nominal value during events exceeding the lower limit, and smaller during events exceeding the upper limit. Therefore, it is concluded that these sites operate at a level above nominal for most of the time.

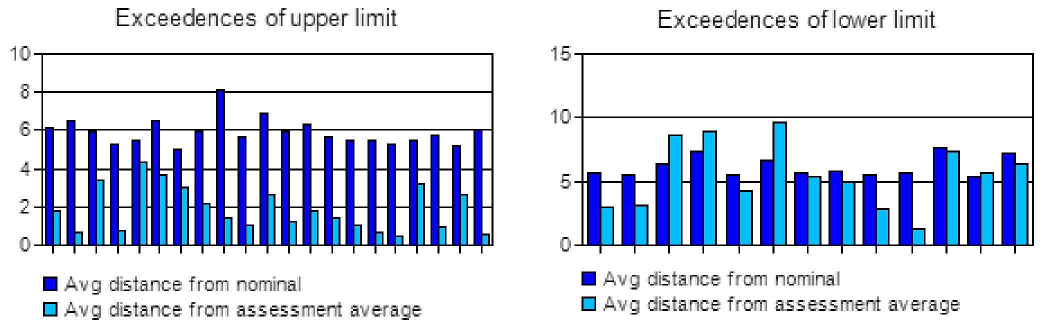


Figure 3-19 Assessing the extent of events exceeding voltage magnitude at several utilities

In Figure 3-20, the voltage magnitude assessment for specific sites and dates when the events of exceeding compatibility thresholds occur, are shown for 4 South African utilities. It was grouped and plotted separately for each utility, based on the visualisation principle of voltage regulation developed in this dissertation. This principle is presented in section 3.2.4.5:

- The majority of assessments indicate higher that nominal operating voltages.
- The majority of assessments do not comply with the NRS048 compatibility criteria on voltage magnitude (dots in the red zone).
- The number of assessments that does comply is not negligible. This represents the cases where the non-compliance of 10-min V_{rms} values were part of the 5% values discarded.

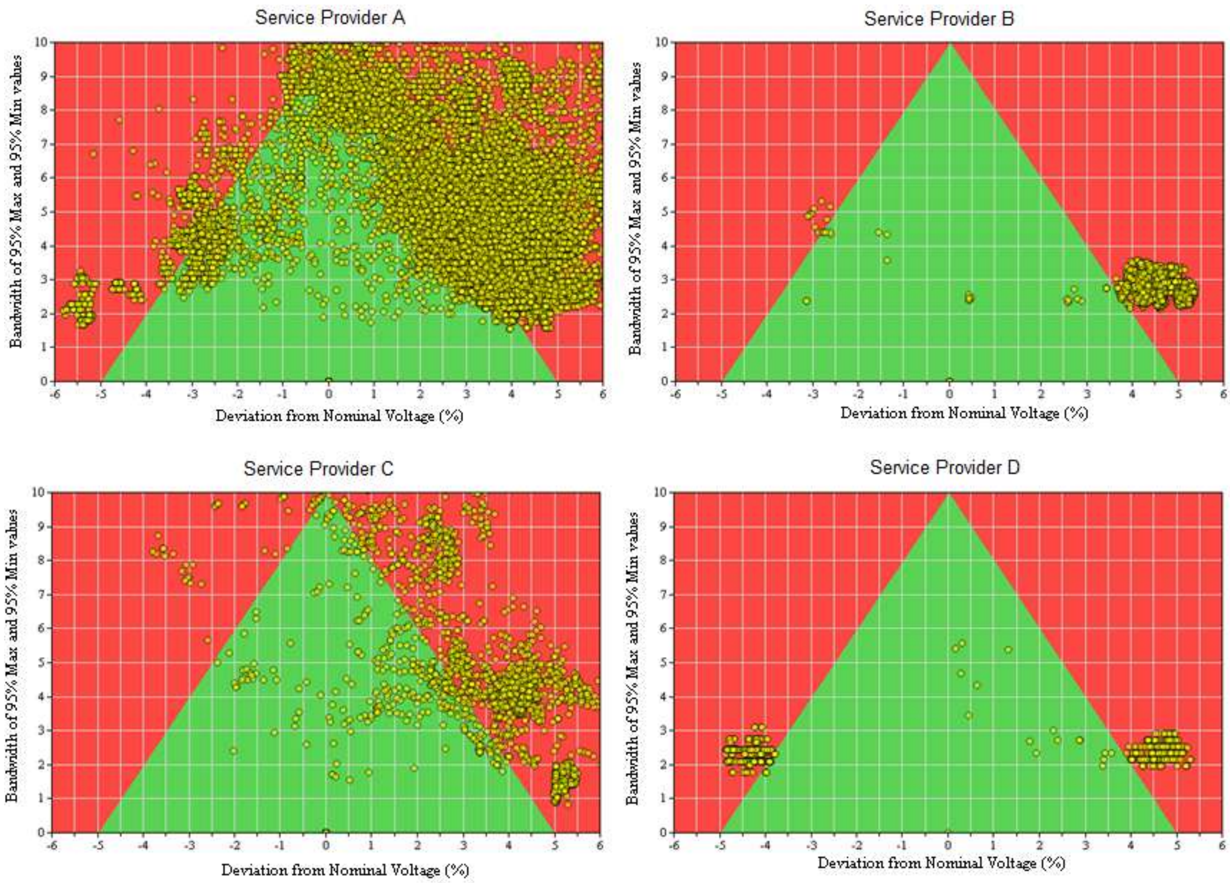


Figure 3-20 Voltage magnitude assessments coinciding with non-compliance events

Observe that the utility has control over the deviation from nominal voltage. The setting of voltage tap changers can be changed or the set-point and/or declared as an operational decision to be high. Provision is made in the NRS048 standard for setting the voltage of a transformer up to 5% higher or lower than the nominal (rated) voltage of the transformer, given that users acknowledge such change.

This means that, through the aid of these two processes, the utility has the ability to relocate the dots in assessments in the horizontal direction, getting them to be compliant with the standard. This will then take care of the majority of the events where the voltage magnitude was exceeded.

Unfortunately, moving the working point to minimize the upper exceedance events could introduce more instances of lower exceedance events, and vice versa. A compromise will have to be made in some cases. Normally, this will mean allowing for exceedance of the upper limit and safeguarding the lower limit.

A final evaluation was done on the date of the assessment and the difference between the absolute minimum and maximum voltage magnitude readings for the 7 days representing each assessment. If the difference between those values where less than 10%, it means the utility could have, by the options discussed above, attained full compatibility. This is because the distance between the upper and lower compatibility thresholds is 10% and thus by keeping the average around the nominal or declared voltage, a spread of less than 10% will avoid exceedances. Table 6 summarises the results for 6 different South African utilities.

Table 6: Voltage magnitude non-compliance analysis

Utility	% Non-compliant assessments	% Assessments with min-max spread of less than 10%
1	82.13 %	100%
2	85.91 %	97.41%
3	97.74%	98.35%
4	100%	100%
5	96.47	100%
6	88.53%	76.70%

The *"% Non-compliant assessments*" column shows the percentage of assessments that failed the NRS048 compatibility criteria. Failing the compatibility compliance means that after discarding the 5% highest V_{RMS} values and the 5% lowest V_{RMS} values, at least one V_{RMS} value remained not within the compatibility statement.

Column 3 indicates the opportunity for being compliant to the NRS compatibility criteria on voltage magnitude. The % of the time for which the spread of V_{RMS} was less than 10% is indicated. It represents the opportunity to adjust the voltage to be within compatibility.

The following can be concluded from this:

- South African utilities tend to operate transformers at voltages higher than their nominal voltage, either to prevent loading of the transformers to cause the voltage to drop below the compatibility level, or because they are supplied with this high voltage and tap changer settings alone cannot compensate sufficiently.
- The first of these reasons (to prevent loading of the transformers to cause the voltage to drop below the compatibility level), could indicate that utilities do not analyse voltage regulation under operational conditions and set points remain unchanged.

- Re-declaring the operating voltage of the transformer can negate the second of these reasons (transformers that are supplied with this high voltage and tap changer settings alone cannot compensate sufficiently).
- Most cases of non-compliance to voltage magnitude compatibility can be mitigated, by utilities integrating the voltage performance of a network into the daily operational procedures.

3.3.2 Load as context

The influence of loading on voltage magnitude was evaluated by scatterplots of V_{rms} against total real power (in kW), total reactive power (in KVAR) and total apparent power (in KVA) at different utilities and large power users in South Africa. More than 100 sites were used.

Some PQ monitoring instruments records voltage parameters only, as PQ standards are QoS (voltage only) based. Loading had to be obtained in some cases from billing data. Careful consideration is needed of time to accounting for clock differences between instruments.

The vast majority of sites showed the same uninteresting pattern as shown in Figure 3-21 - what looks like little to no influence of the measured load on the supply voltage. Node A shows just about no influence, while Node B shows a slight decrease in supply voltage as loading increases.

Allowing the Y-axis to auto-scale however, showed in most cases the definite influence of loading on voltage magnitude, with some cases showing a much stronger negative correlation than others. Some examples are shown in Figure 3-22. Voltage simply drops as loading increase.

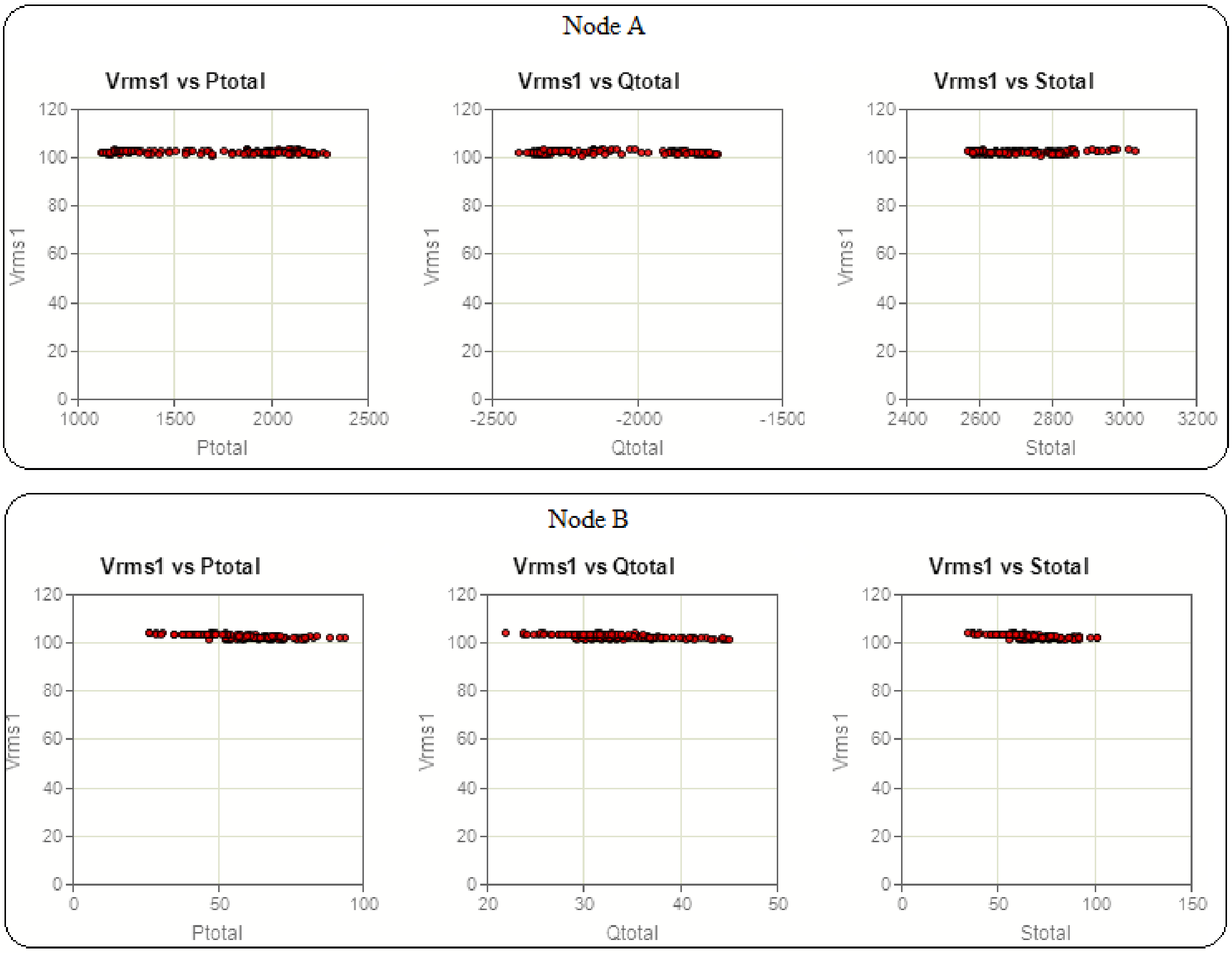


Figure 3-21 Example of influence of loading on supply voltage

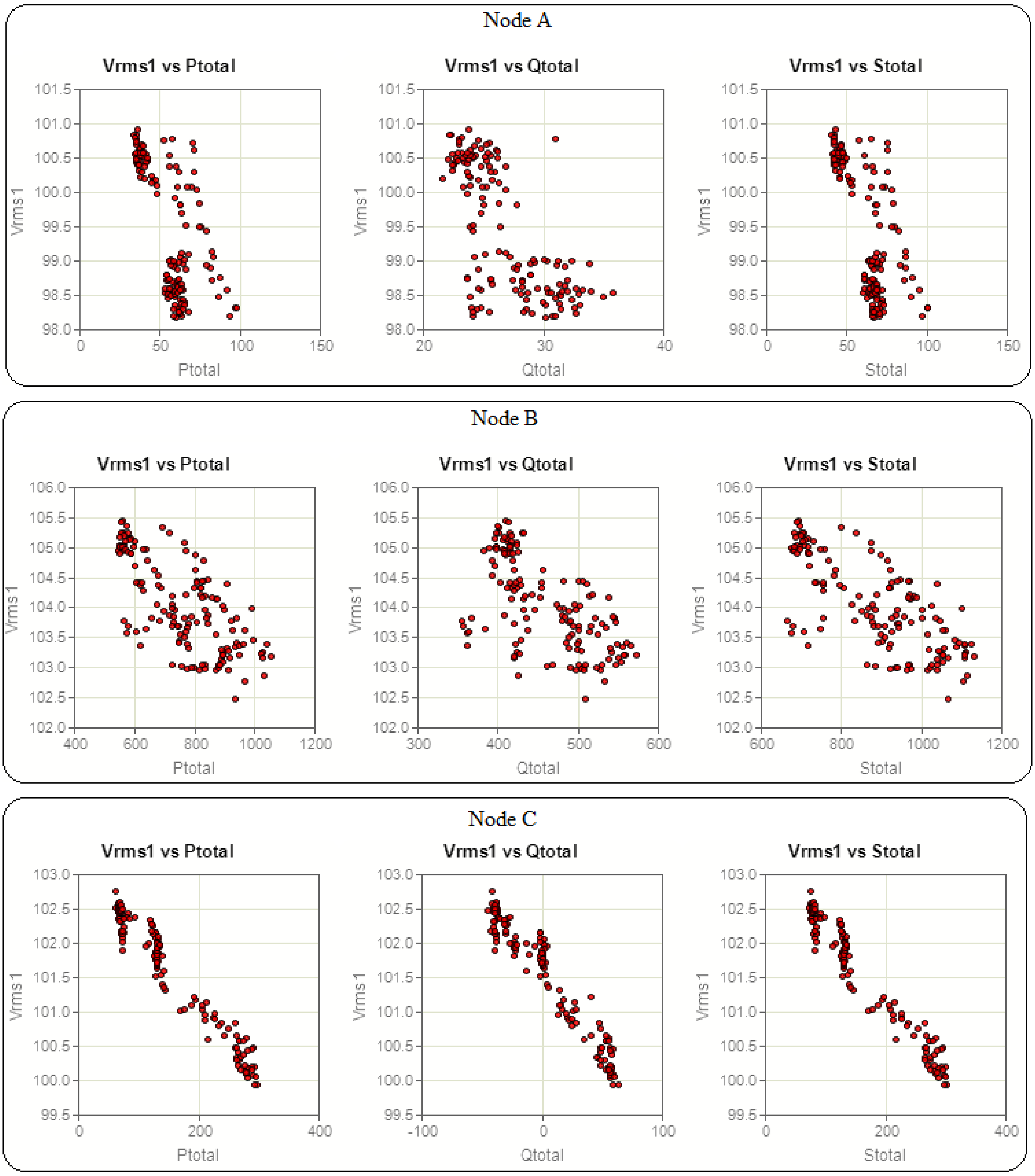


Figure 3-22 Auto-scaled examples of influence of loading on supply voltage

Some cases displayed a different character and are briefly discussed.

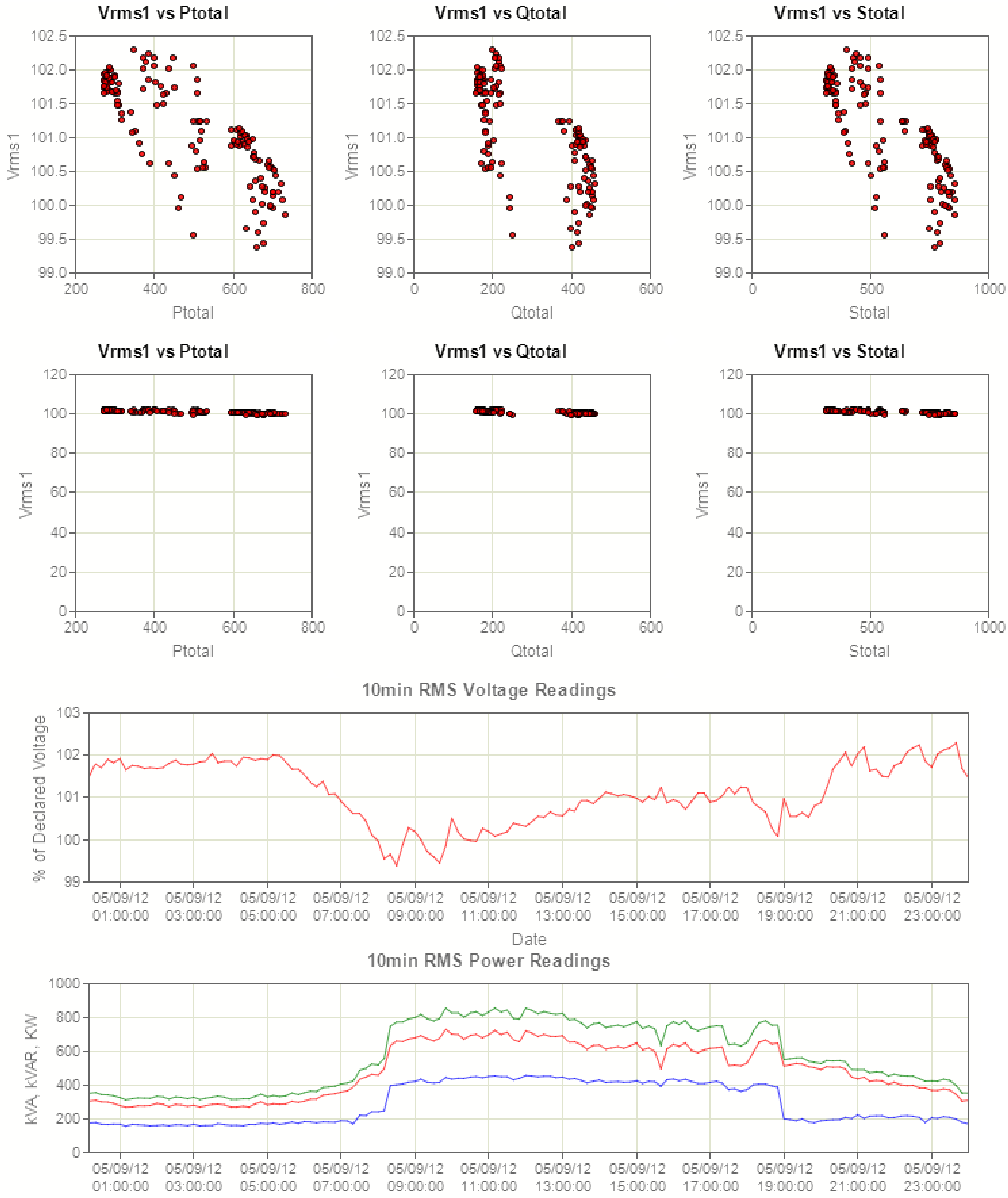


Figure 3-23 Load vs. voltage magnitude special case 1

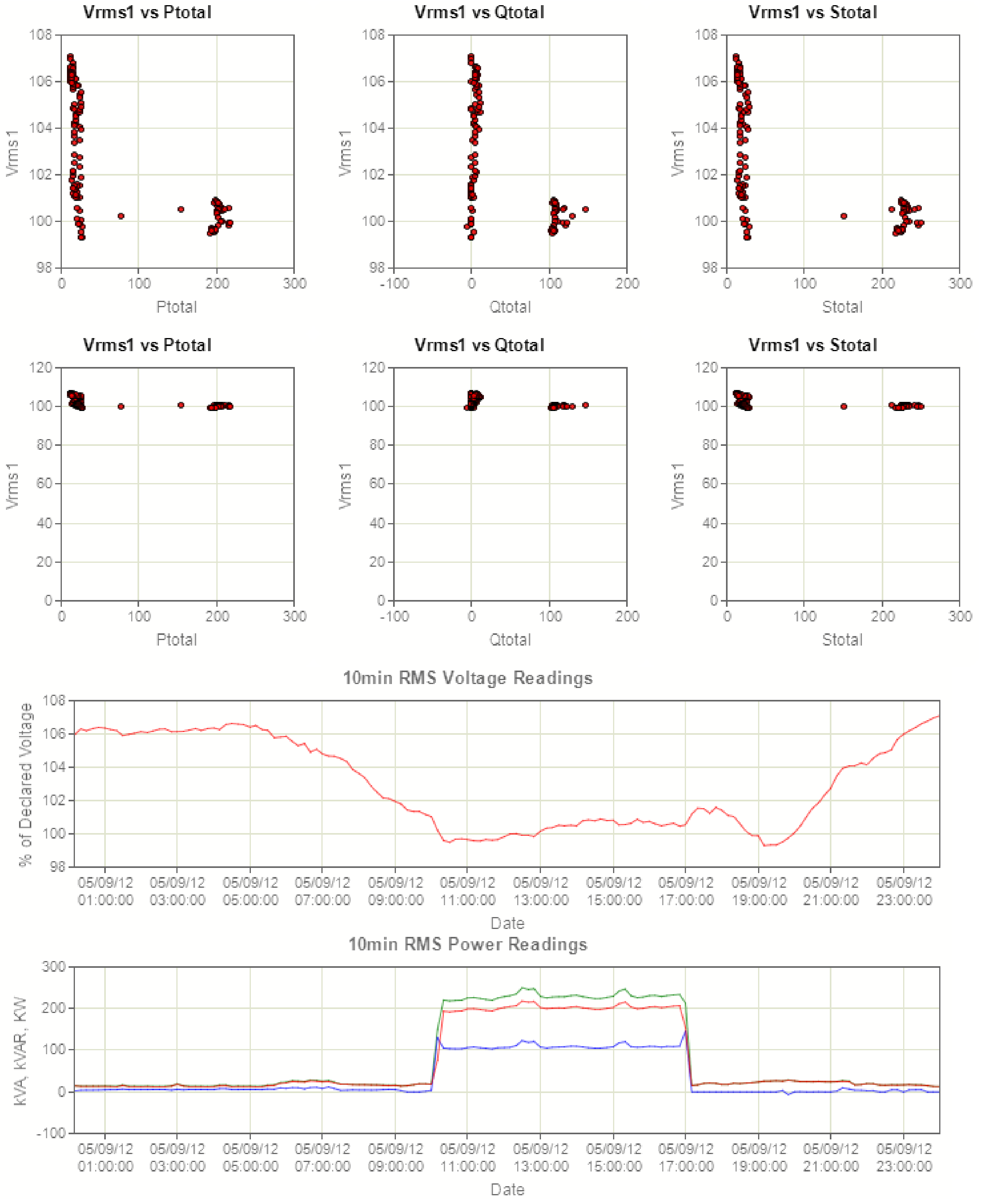


Figure 3-24 Load vs. voltage magnitude special case 2

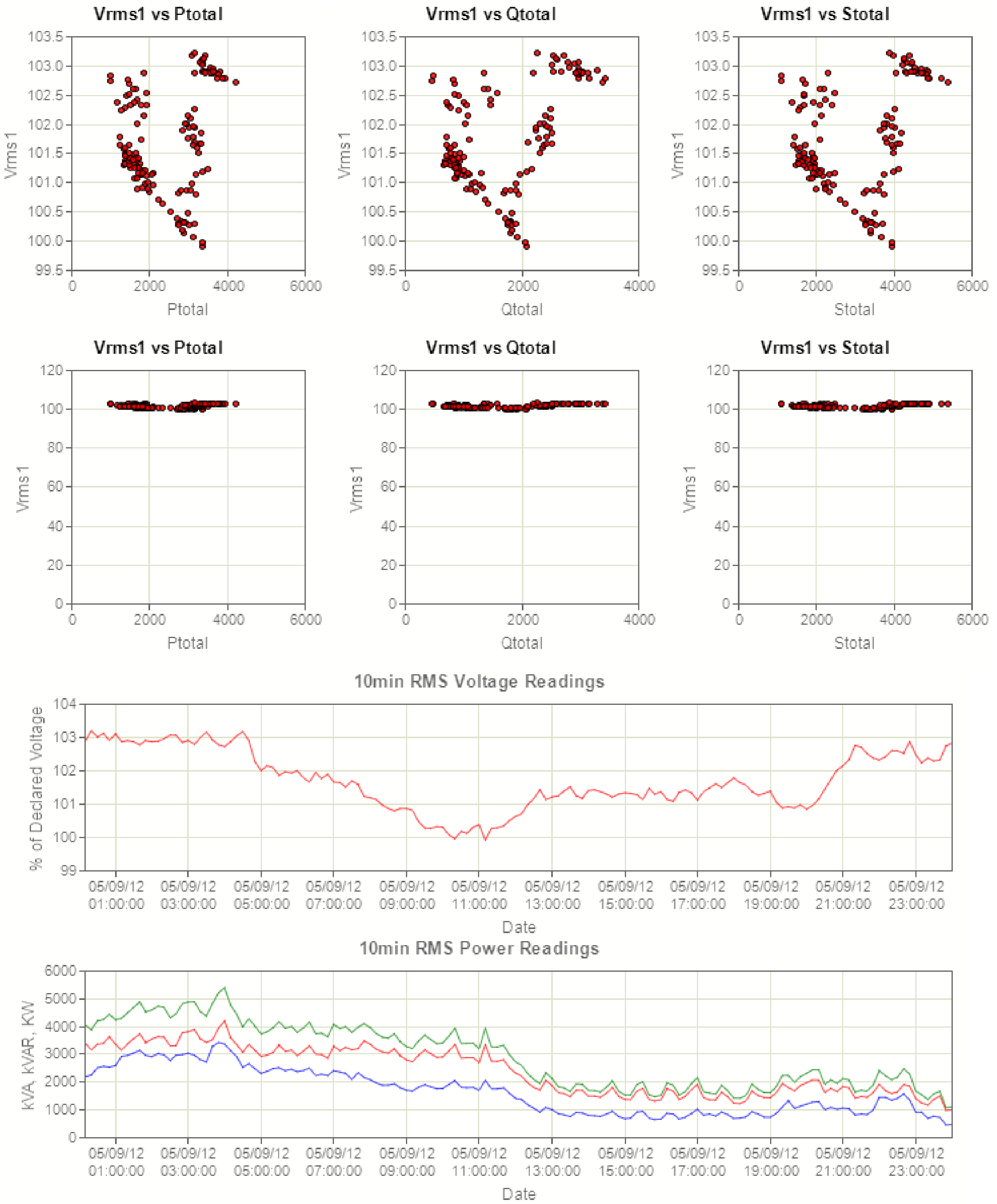


Figure 3-25 Load vs. voltage magnitude special case 3

Figure 3-23 and Figure 3-24 are examples with 2 clusters of values instead of a line. The voltage and power profiles are also shown. The reason of the clusters is the 2 load levels, both constant for a period of time.

Figure 3-25 presents a V-shaped scatterplot. The voltage and power profiles show this to be due to a slower transition from one load level to another.

This confirmed the known relation between loading and voltage magnitude, but no useful information to aid the management of voltage magnitude could be identified.

3.4 PQ Dashboards

PQ dashboards can contain a combination of the following views on the data under investigation:

- Change over time
- Emphasis on the current (latest) situation
- Part of whole view, i.e. what is the contribution of a specific site to the utility ranking for example
- Ranking and distribution of values

3.4.1 Site level

The different users of the PQ information presented by the dashboard will have different needs:

The industrial user:

- Do I receive the voltage level agreed upon?
- How well is this voltage regulated? - How can this affect me?
- When do these exceedances happen? - Are they related to my load perhaps?
- How does my supply voltage compare to a national and/or local benchmark?
- Are there any identifiable trends developing?

The utility:

- Is this site compliant to the minimum standards of the NRS 048-2? - If not, what intervention measures are possible?
- Are any concerns/trends on QoS noted?
- Sudden changes in performance are of special significance and should be easily identified.
- How does this site benchmark to:
    - Similar sites in the same network/voltage level
    - The national norm.

Figure 3-26 is a proposal for a PQ dashboard on voltage regulation per site.

It is divided into a left-hand side of about 2/3 of the page and a right hand side of 1/3 of the page. The left-hand side of the page shows information for the last 365 days. The right hand side of the assessment shows information on the last single assessment (thus the last 7 days).

From top to bottom, the right hand side consists of:

- A table containing details of the latest assessment. It indicates compliance with both the limit and compatibility criteria. It then indicates the percentage of 10-minute values that exceeded the compliance criteria. To fail the compatibility compliance, more than 5% of the measurements need to exceed either the upper threshold or more than 5% of the measurements need to exceed the lower threshold. Lastly the number of 10-minute values that exceeded the limit criteria is shown. A single measurement exceeding the limit criteria results in failing the limit compliance.
- A graph of the 10-minute values used for the assessment, thus 7 days of measurements for all three phases.
- A $V_{\Delta nom}$ vs $V_{spread\,90}$ plot of the latest assessment for each site of the utility/customer. The assessment for the site under investigation is shown in red.

From top to bottom, the left-hand site consists of:

- A table with exactly the same details as for the right-hand side (latest assessment), except that the assessment is made over the last 365 days.
- Three graphs trending the NRS048 assessments of the last 365 days, on a per phase basis. Note these are the new retained values suggested, not the retained values as prescribed by the standard (which would result in a single graph, not one per phase).
- Three bar charts, indicating the time distribution of the 10-minute values exceeding the compatibility compliance over the last 365 days.
- A $V_{\Delta nom}$ vs $V_{spread\,90}$ plot for each assessment of the last 365 days for the site under investigation. The latest assessment is once again shown in red.

The example shown is data from a utility. The following information can be gathered from the dashboard:

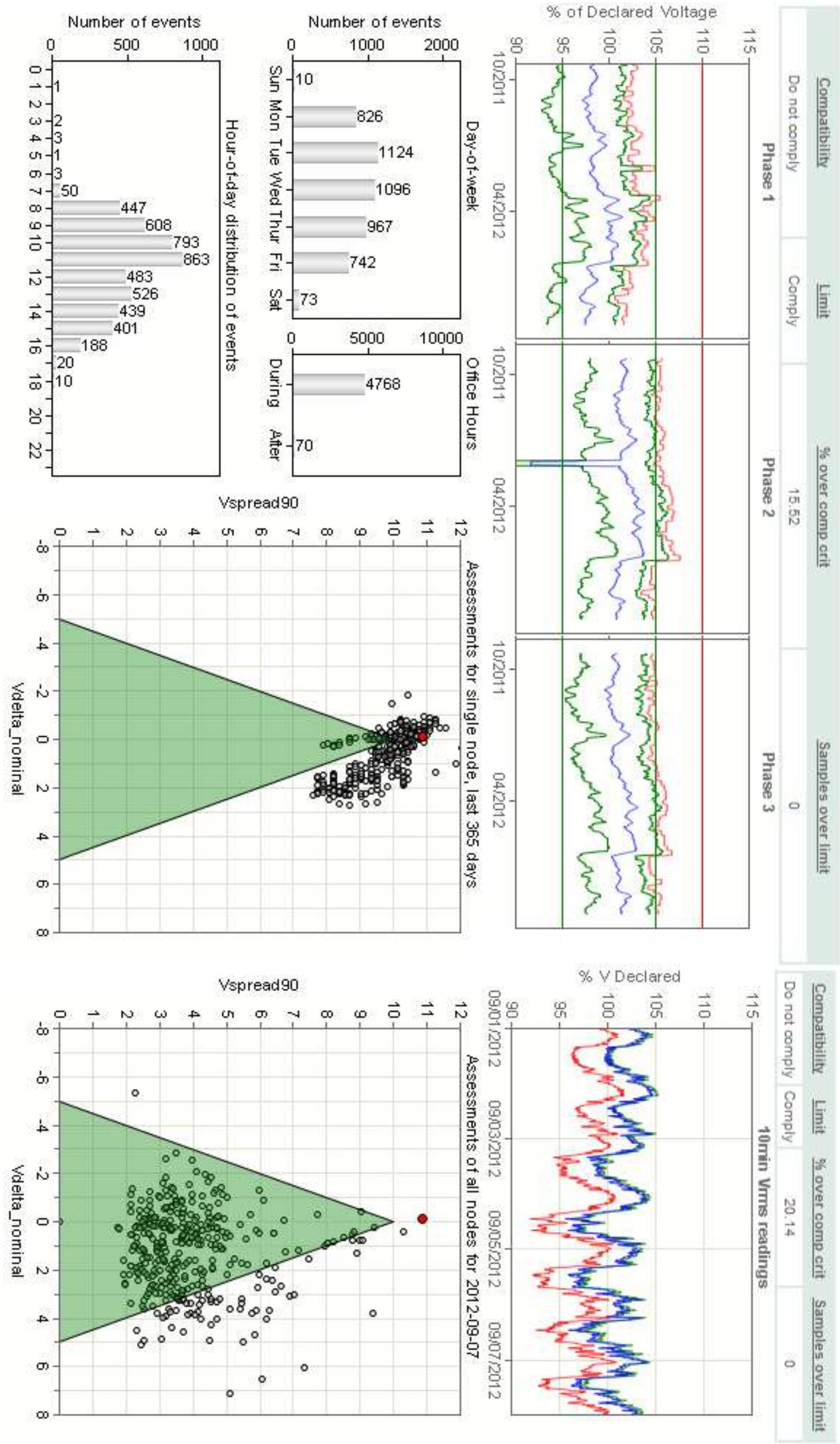


Figure 3-26 Site level dashboard for voltage magnitude

By comparing the two assessment tables at the top of the two sections one sees that:

- The limit compatibility level has not once been exceeded during the past 365 (and thus also the last assessment).
- This site is out of compliance with the compatibility criteria for the current assessment and also fails for that past 365 days. 20% of the 10-minute values for the last 7 days exceed the compatibility criteria vs. 15% of the values over the last 365 days. This could be interpreted as worsening performance, but more metrics is needed to confirm. It does however show that 15-20 % of the time this site is out of compliance. This translates to 3.6 to 4.8 hours per day on average, which is a significant portion of the day.

The trend-graphs for the 10-minute values of the last 7 days and the trend-based assessments for the last 365 days show:

- There is a definite and consistent voltage unbalance present, that complicates compliance to the voltage magnitude compatibility criteria. This unbalance needs to be corrected.
- The average values, or working point, of this site is not very stable over time (seen from the blue line on the individual phase graphs). Further knowledge of the site is needed to make sense of this. This does not look like a site with automatic tap-changing abilities and its voltage magnitude performance could thus be determined both by the loading of this specific transformer, as well as the performance of the transformer feeding it. Investigation into the upstream transformer would be required here to make a proper assessment of the problem.
- The last ¼ or so of the graphs (from the sudden large drop in assessment values) shows the individual spread of each phase to be small enough to comply with the standard. The unbalance however causes the first phase to be out of compliance.

The bar charts indicating the distribution of voltage magnitude exceedances shows:

- All three graphs show that the exceedances occur predominantly during office-hours - 8:00 – 16:00, Monday to Friday.
- The 3.6 – 4.8 hours on average that is out of compliance thus translates to 45% – to 57.5% of the 8 hour South African workday.

The $V_{\Delta nom}$ vs $V_{spread\ 90}$ plots show:

- Out of all sites for the utility, the site under investigation is the worst performer with regard to voltage magnitude compatibility over the last seven days, with tap changer settings or change in declared voltage unable to bring the site into compliance during that period (the red dot is already in the optimum spot on the horizontal axis – almost 0 deviation from nominal. The combined spread of voltage readings is so big (more than 10%) that it is impossible to comply. Reducing this spread by fixing the unbalance situation and investigating the voltage regulation of the upstream transformer are the only two viable avenues to bring the site into permanent compliance. Other less viable options are reducing the load or fitting a replacement transformer of higher capacity.

- Over the last 365 days, the site has rarely been in compliance, with the spread of the voltage readings the major culprit.

This PQ dashboard revealed a lot of information in an easy-to-interpret manner, on the voltage magnitude performance of a single site and when compared to other sites at the same utility. This dashboard can be used for an industrial client as well, with one minor change. The $V_{\Delta nom}$ vs $V_{spread\ 90}$ plot on the right hand side (relating to all the sites in the network) can be replaced with a graph (or graphs) to show the 10minute power readings for the last 7 days. From this, the client can answer the question whether his load influences the voltage magnitude readings. A V_{rms} against P_{total} scatterplot or even a simpler correlation calculation can also be added to aid in this.

3.4.2 PQ dashboard for the voltage magnitude assessment of a network

A network level dashboard will be useful mostly for utilities. Questions to be answered by such a dashboard could include:

- How are we performing with compliance to the parameter, network wide?
- What is the ranking of site X within our collection of sites?
- Which sites are failing / performing the worst?
- Can we correct these sites? How?

Figure 3-27 is an example of dashboard design aiming to answer these questions.

The dashboard consists of a left-hand side with graphs and a right-hand side with three tables. From top to bottom, the left-hand side contains:

- $V_{\Delta nom}$ vs $V_{spread\ 90}$ plot for the latest assessment of each site of the utility
- A set of three bar graphs showing the distributions of some attributes of the assessment – the distribution of the sites over nominal levels, the number of sites passing and failing the compliances assessment and the salvage ability of the sites that failed the assessment.
- Another set of three bar graphs indicating the time distribution of the 10-minute values exceeding the compatibility compliance over all sites

From top to bottom, the right-hand side contains:

- A ranked table containing the compliance status, 5th and 95th percentile values with regards to the latest (last 7 days) NRS048 voltage magnitude assessment for all network sites. The compliance status indicates which compatibility criteria (upper, lower, both upper and lower or neither of the two) are exceeded. Default ranking is based on the exceedence of the lower threshold, but clicking on the V95Max column header will sort it according to the exceedence of the higher threshold. The last column in the table is a review of the assessments of the site for the past 180 days, to help identify whether an exceedence is spurios or longstanding.
- A table ranking all sites with regards to the new Vspread90 parameter (difference between the 5th and 95th percentile). Ranking is from worst (highest spread) to best (lowest spread) performance. The sites at the top of this least needs special attention, since they cannot be made to comply by the processes of declaring a new operating voltage or by setting tap changer settings alone. The last column of the table shows historical performance of the site with regards to this parameter.
- A table ranking all sites with regards to the new Vdeltanom parameter (difference between nominal and the average voltage of the assessment). Ranking is from highest to lowest. The extremes at both ends (top and bottom) of this table needs to be investigated for possible alternate tapchanger settings or declaration of a different operating voltage. The last column of the table shows historical performance of the site with regards to this parameter.

To act as a dashboard, the whole view needs to fit on a single computer screen. To accommodate this, all the tables are scrollable, since the data for all sites cannot fit on a single screen. The following information can be gathered from the example data shown in the dashboard:

- From the $V_{\Delta nom}$ vs $V_{spread\,90}$ plot we can see the utility have several sites currently out of compliance. Most of these exceed the upper compliance level. We can see that most of the non-compliant sites should be able to be brought into compliance by correcting the operating point of the site.

The first set of three bar charts shows:

- The utility distributes electricity mainly at 11kv and 6.6kV
- 53 out of 378 sites failed compliance with the latest assessment.
- 46 out of those 53 are definitely salvageable, with 7 needing special attention get them to compliance.

The salvageability is determined by inspecting the $V_{spread\,90}$ parameter. In the range 0 to 7 it is giving a rating of 'yes' – definitely possible to salvage. In the range 7 – 9 it is giving a rating of 'maybe'. It is probable that by setting the operating voltage of the site to bring it into compliance. When the value is greater than 9, it is given a rating of 'no'. This does not say there is no way to get that site into compliance. It moreso indicates that apart from setting the operating point of the site, additional measures would probably be required to keep it in permanent compliance, such as correcting any voltage unbalance problems or tightening upstream voltage regulation. These ranges have been arbitrarily chosen as a starting point and should be refined with experience. The goal of the rating is more to indicate the amount of effort to get the sites into compliance than to make a definitive judgement on it. The wording of the ratings could be updated to reflect that.

The second set of three bar graphs shows:

- voltage magnitude compatibilty exceedances occurs more after office hours than during
- occured more over the weekend than during the week (which fits with the first observation)
- when interpreting this with the observation from the first graph that indicates exceedances occurs mostly on the upper criteria, it makes sense that the loading of transformers during office hours will drag the voltage down, into compliance.
- Interestingly, Tuesday had the lowest number of exceedencas. Further investigation would be required to make sense of this.

All the information available in the ranking tables are unfortunately not visible in a static picture, as one needs to scroll through the data. Only observations made from the visible data are given here.

From the table ranking V95min and V95max:

- The site ranking worst for V95min also has a bad rating for V95max (in fact, it is also the worst ranked site with regards to Vspread90). One can see the utility made a change to attempt to correct the exceedance of the upper criteria, only to cause the exceedance of the lower criteria. On the $V_{\Delta nom}$ vs $V_{spread\,90}$ plot, this assessment is the dot above the highest point of the triangle and as such would fall in the "no" salvageabiliy rating.
- The site rated second worst for V95min has in fact a very good Vspread90 rating (this assessment is the lone outside dot on the lower left-hand side of the $V_{\Delta nom}$ vs $V_{spread\,90}$ plot). A definitely salvageable site. We can see that the utility fixed this site from exceeding the upper threshold 3 to 4 months ago. Unfortunately, about 2 to 3 months

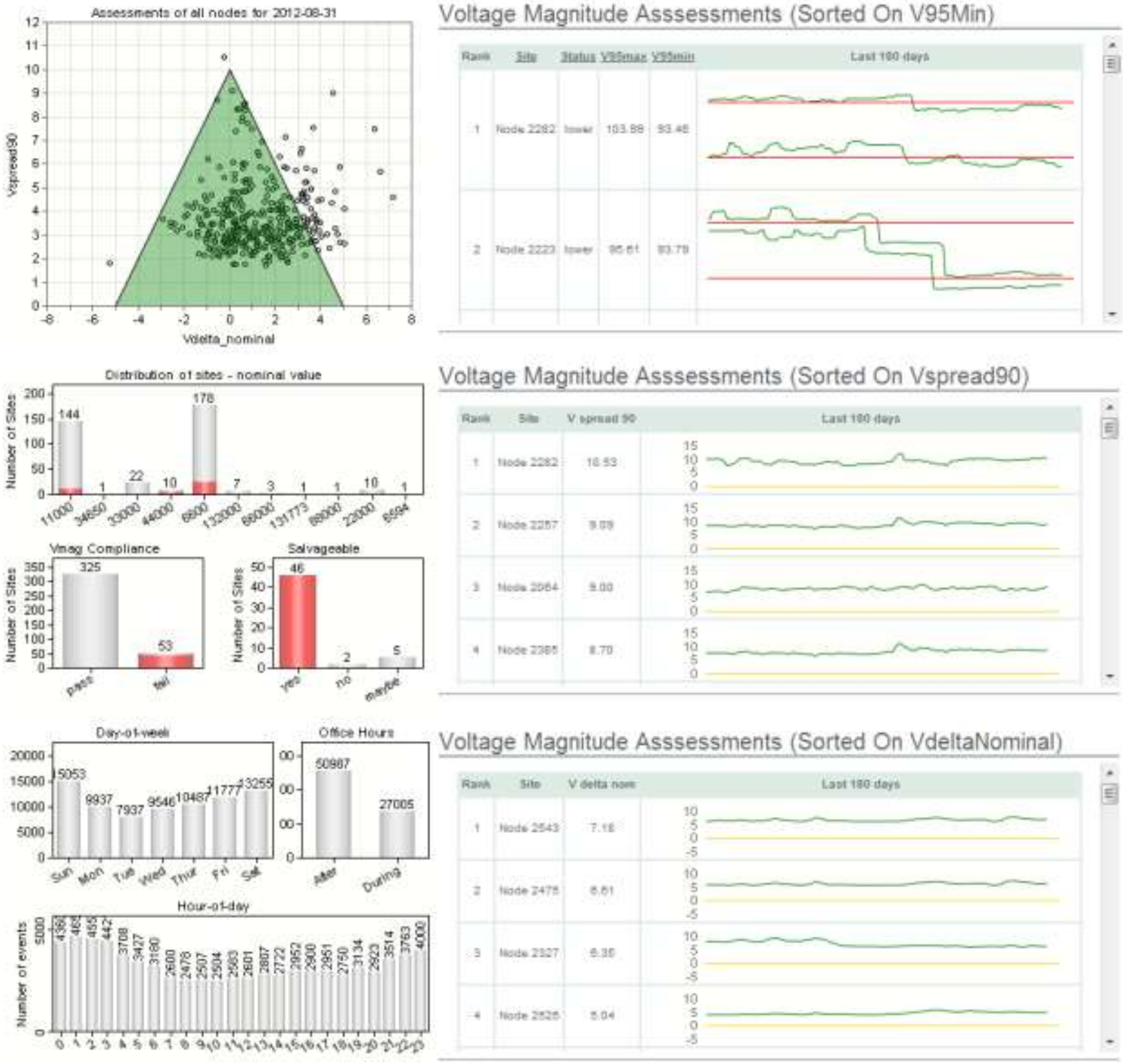
ago another uncalled for large step down in supply voltage forced the site into non-compliance with the lower threshold.

From the table ranking Vspread90:

- This parameter seems rather stable over time for most sites.
- A significant bump can be seen for 3 out of 4 of the visible sites during a short period about 2 – 3 months ago. This could indicate a common transformer or bus feeding these sites that experienced a problem during that period.

From the table ranking VdeltaNominal it can be seen that:

- the parameter is pretty stable over time and thus getting non-compliant sites into compliance by a once-off change to the operational voltage should keep them in compliance. It shows that it will not be necessary to constantly fiddle with tap-changer of declared voltage settings to keep sites in compliance – setting it optimally once should be all that is required.



[2]

Figure 3-27 Utility/network level dashboard for voltage magnitude

3.5 Summary

In this section, an alternative visualisation of the NRS 048-2 assessment of voltage magnitude was developed. The method was applied to practical case studies to demonstrate the advantages in analysing the voltage magnitude performance of a network. It was demonstrated to be useful for improving the operation of an electrical network. This is because the deficiencies of the standardised NRS 048-2 reporting of voltage magnitude assessment by means of the 7-day sliding principle, was eliminated.

Time was proposed to add context when reporting voltage regulation. Understanding of when non-compliance occurs can help to prioritise intervention measures, if deemed necessary at all.

Scatterplots depicting the relation between voltage magnitude and loading added limited value in managing voltage magnitude. A QoS (voltage only) approach can be effective from a cost (“*voltage only”* PQ recorders cost less) and operational point of view, as demonstrated in this chapter.

Customised dashboards to aid the analysis of voltage magnitude performance were proposed and shown to provide powerful additional information as the historical and statistical behaviour of sites in terms of voltage magnitude can be made easy by the visualisation and ranking methodology built into these dashboards. Limited knowledge of PQ is needed to optimise the voltage magnitude performance of the network when using these dashboards in context of a known network. A specific PQ standard such as NRS 048-2 is the basis on which the dashboard operates.

4 Voltage Dips

In this section, the NRS048 voltage dip categorisation and management principle is analysed and an improvement in reporting and analysis is suggested by means of additional visualisation of the depth-duration information.

Alternative dip indices and aggregation dip events are investigated. Case studies are used to demonstrate the principles. Benchmarking the dip performance of single sites and of different distribution networks within a utility is developed and demonstrated.

Context is shown to be important for a comprehensive analysis of the voltage dip performance of a network and practical application is presented

The section and the chapter will conclude with proposed interactive dashboards useful for voltage dip analysis and management.

4.1 Analysis of NRS 048-2 Voltage Dip Assessment

The NRS 048-2 [6] approach to voltage dip classification aims to apportion probable causes, effects and responsibilities to different role-players, because it can aid in the management of the dip performance of a network. Classification principles recognise network protection characteristics and customer load compatibility.

The NRS 048-2 standards document [6] states:

a) licensees should manage protection performance times (for example, the number of X-type dips allowed is more than the number of S-type dips);
b) licensees should place particular emphasis on managing the number of faults that occur close to a particular customer (for example the sum of the number of T-type dips is less than the sum of the number of X-type and S-type dips); and
c) customers should specify the dip sensitivity of their process equipment to enable appropriate mitigation measures to be considered, to limit the number of licensee fault events that actually affect the plant.

The above defines the responsibilities of supplier and user in the management of voltage dips. No limits are set to voltage dips because the occurrence of dips cannot be fully controlled by the utility.

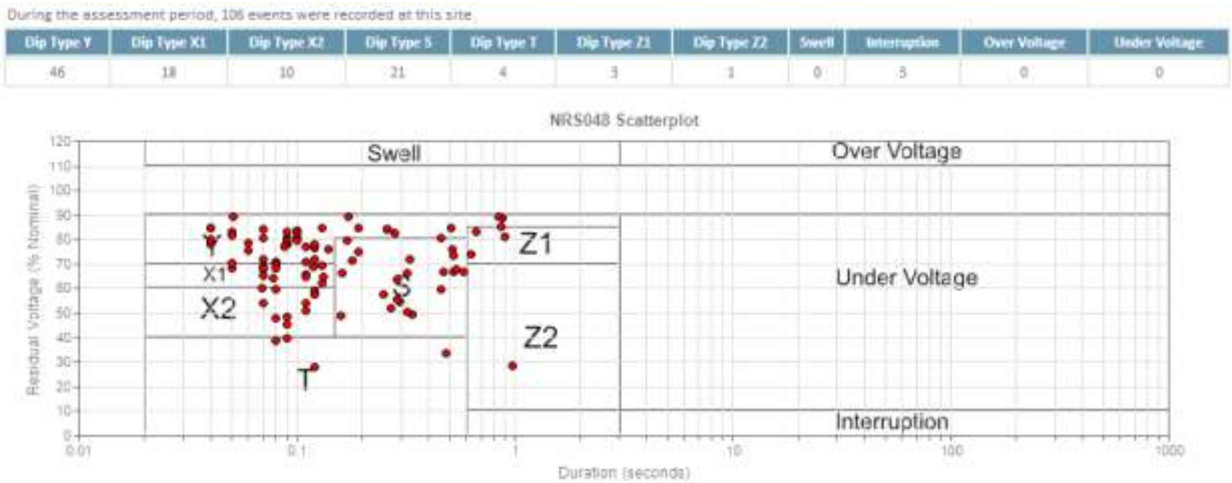
Voltage dip management requires the classification of voltage dip events, finding the root cause and then reducing the probability of future occurrence of the same root cause where possible. Limited means exist, for example, to completely contain voltage dips resulting from lightning activity.

The standards document (NRS 048-2) proposes the benchmarking of a specific site or a network to characteristic values for dip performance. NERSA should regularly publish updated values based on the dip statistics submitted by licensees annually. Most utilities in South Africa do not submit these statistics although it is part of the license agreement. NERSA has since the publication of the PQ Directive in 2002, which declared the recording of PQ data and the submittal of the statistics obligatory, not acted upon the mandate given by government to NERSA to actively manage risk in the Electricity Supply Industry (ESI) by PQ. No license has been revoked based on the absence of PQ monitoring at licensees.

It is only Eskom who published characteristic numbers on dips. It is listed in the NRS048-2 of 2007 and based on data collected up to year 2000. It is largely irrelevant to other licensees, which are operating distribution networks completely different (voltage level, geography, loading) to Eskom's network. Also, conditions in power systems in general, are significantly different in 2013 compared to the year 2000. Diligence and annual updating of the characteristic numbers is required to manage dips effectively.

Voltage dips are the most important PQ parameter due to the financial losses attributed to. The European Union lost 150 billion Euro in 2006 due to voltage dips [9]. South Africa is a developing country and well known for neglected electrical networks and poor dip performance. This chapter will propose a dip management solution to alleviate some of the concerns in a practical manner with a low premium on specialist PQ knowledge.

Dip performance are typically visualised with a tabular count of event types, together with a depth-duration plot with the dip categories overlaid as shown in Figure 4-1.



During the assessment period, 106 events were recorded at this site

Dip Type Y	Dip Type X1	Dip Type X2	Dip Type S	Dip Type T	Dip Type Z1	Dip Type Z2	Swell	Interruption	Over Voltage	Under Voltage
46	18	10	21	4	3	1	0	5	0	0

Figure 4-1 Typical voltage dip assessment visualisation

The standard visualisation contains only dip categories, but has been extended in the above visualisation to include other voltage event categories (swells, over/under voltage and interruption).

Three additional views on voltage dips are presented, pertaining to the distribution of duration, dip residual voltage and classified dip types.

Duration of dips (NRS 048-2) is related to protection settings:

- 20 ms to 150 ms: typical protection zone 1 clearance settings
- 150 ms to 600 ms: typical protection zone 2 clearance settings
- 600 ms to 3 seconds: backup and thermal protection settings.

Dip residual voltages (or depth) are determined by how “far” the point of measurement is from the network fault. Most dips are the result of short-circuit conditions (faults) and the impedance (distance) between the fault and the point of measurement will determine how deep the voltage sag manifest at the recording instrument. Shallow dips could be “far” away but a shallow 3-phase dip could be due to a local 3-phase load being energised. Depth therefore does not allow concise conclusions.

Distribution of event types can be considered. . One could simply show the distribution over the dip categories, but a more enlightening visualisation can be obtained by recognising the dip categories are divided into three further categories of responsibility – customer, combined and utility.

- The customer’s plant is required to withstand dip type Y.
- The utility is responsible to minimize the occurrence of dip types T and Z2 (very deep dips).

- A combined approach is suggested for dip types X1, X2, S and Z1. The customer could immunise plants against these dips whilst the utility should minimize the occurrence.

Figure 4-2 presents the distribution strategy discussed above for two different utilities in South Africa for all dips recorded at all voltage levels in these networks over a 6-month period. A different perspective results:

- The number of dips the utility is “responsible” for is by far the lowest.
- Assuming that user equipment is indeed compatible (immune) to Y dips, it could be cost-effective to both the utility and the user if a cost-sharing model for dip mitigation can attain the “shared” responsibility. For example, it is mostly very expensive to significantly change the network dip performance from a utility perspective, because it requires changes to transmission/distribution lines, fault impedance and others. Dip mitigation at the point in the network where a sensitive user is located, could be very cost-effective if both parties contribute to the costs.

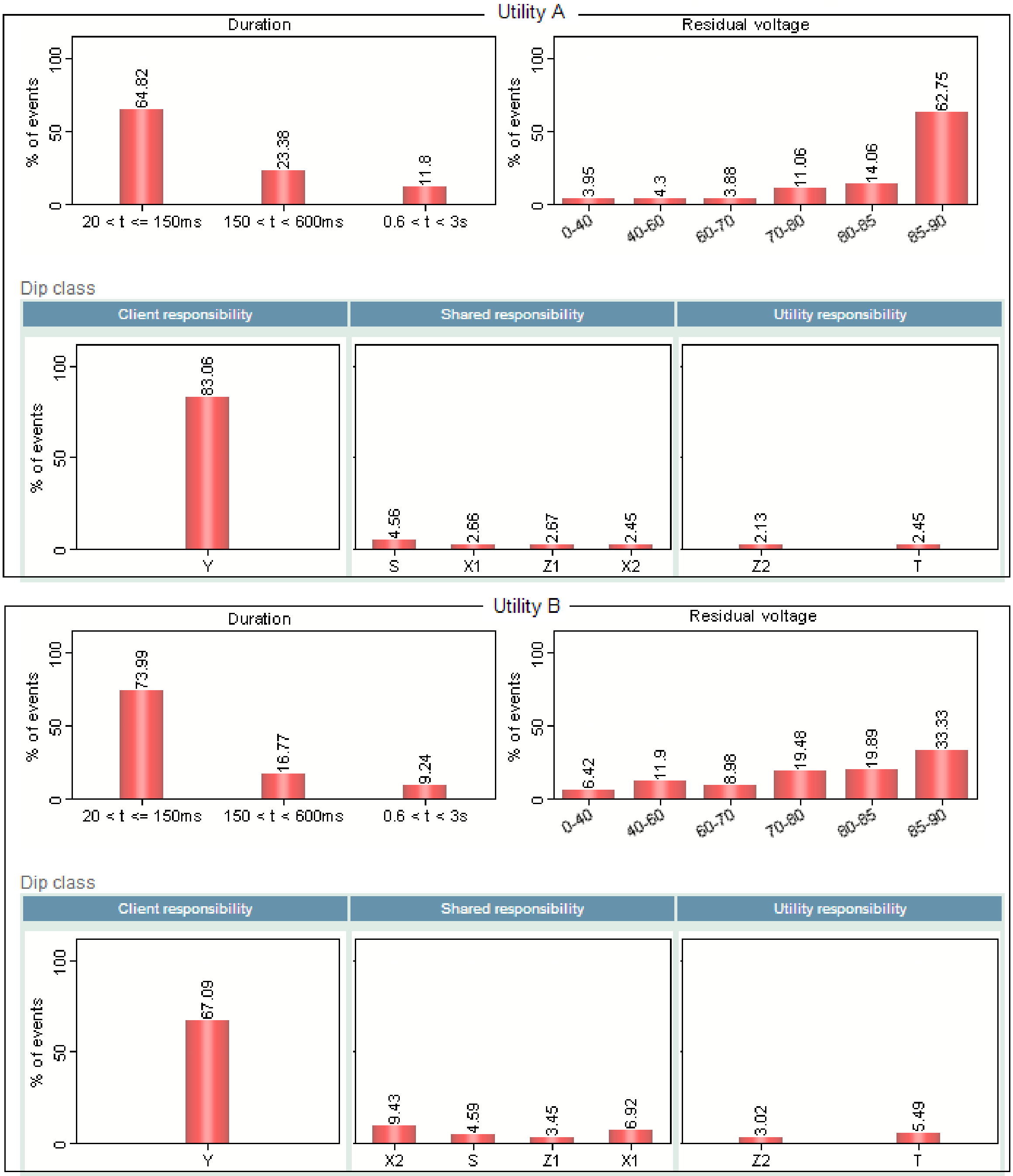


Figure 4-2 Dip Depth, Duration and Class distributions

4.1.1 Alternative dip assessments

Some voltage dip indices produce a single value for a dip, in contrast to the 2-value depth-duration indices. These indices are particularly useful to aggregate into site and system indices, albeit to the loss of information regarding the individual dips.

Two such indices are the Voltage Sag Energy (VSE) and Voltage Sag Severity (VSS) indices discussed in chapter 2. VSE is an indication of the energy lost during an event and VSS is an indication of the severity of a dip. The distance between the retained voltage and a dip reference curve, such as the CBEMA or SEMI curve, represents dip severity.

VSS is less than 1 when the retained voltage is above the curve, equal to 1 when on the curve and greater than 1 when below the curve. VSS can be used to determine whether a dip falls above or below the CBEMA or SEMI curve. NRS 048-2 dip information can be enriched using colour or shape to differentiate between above and below the CBEMA/SEMI curve when plotting dips.

This additional information on the NRS 048-2 dip diagram should be useful to both utility and user, because the intention of the CBEMA/SEMI curve is to visualise the condition of compatibility between supply and use conditions. Suppliers of user equipment are expected to supply equipment such that it operates as designed when a dip is above the curve.

Single value indices can be used in ranking the severity of the voltage dips that occurred at a site for a given period. This principle is applied in Figure 4-3.

It can be even more useful in ranking the dips recorded by several instruments for the same network fault, with the most severe ranking an indication of the site closest to the fault. This principle is applied in Figure 4-4.

Event Date	Duration (s)	Residual Voltage (%)	NRS Class	Voltage Sag Severity (VSS)	Voltage Sag Energy (VSE)
2012/01/23 16:18:31	1.34	52.32	Dip Class Z2	2.384	0.772
2012/01/13 16:00:54	0.39	58.13	Dip Class S	1.382	0.192
2012/01/21 21:17:25	1.16	73.42	Dip Class Z1	1.329	0.14
2012/01/13 14:35:29	1.09	80.41	Dip Class Z1	0.979	0.091
2012/01/21 21:07:45	1.07	78.67	Dip Class Z1	1.056	0.082
2012/01/15 19:29:29	0.89	78.39	Dip Class Z1	1.065	0.063
2012/01/21 21:20:41	1.99	83.13	Dip Class Z1	0.844	0.033
2012/01/22 14:42:04	0.08	59.49	Dip Class X2	0.81	0.018
2012/01/15 11:52:49	0.61	84.10	Dip Class Z1	0.795	0.015
2012/01/23 16:53:03	0.08	65.11	Dip Class X1	0.898	0.014
2012/01/29 06:57:17	0.04	55.35	Dip Class X2	0.893	0.008

Figure 4-3 Dips at a site over a 1 month period, ranked on VSE

Site Name	Event Date	Duration (s)	Residual Voltage (%)	NRS Class	Voltage Sag Severity (VSS)	Voltage Sag Energy (VSE)
Node 2243	2013/01/28 17:25:31	0.07	7.78	Dip Class T	1.844	0.179
Node 2241	2013/01/28 17:24:28	0.07	12.38	Dip Class T	1.752	0.161
Node 2226	2013/01/28 17:24:26	0.07	12.88	Dip Class T	1.742	0.159
Node 2223	2013/01/28 17:24:57	0.06	79.48	Dip Class Y	0.411	0.008
Node 128	2013/01/28 17:25:26	0.04	83.89	Dip Class Y	0.322	0.003
Node 2145	2013/01/28 17:25:26	0.04	84.16	Dip Class Y	0.317	0.003

Figure 4-4 The same network fault measured at different sites, ranked on VSE

4.1.2 Aggregation of voltage waveform events

Voltage swells, over voltages, dips and interruptions are all voltage waveform events, but voltage events refer to voltage sag conditions (or dips) in this document.

Aggregation of events is employed to either characterise a specific network operation or fault condition or, through benchmarking, characterise and compare the overall dip performance of sites or networks over a period of time.

Time aggregation over short intervals (minute or less) is applied on a per site, network or utility basis to consolidate measured event data into incident information. For example, multiple short events occurring close together in time can mostly be attributed to a single fault or operation and can be aggregated into a new single event. The multiple attempts of a protection auto recloser to clear a fault motivate this type of aggregation on a per site basis.

The net effect is that the number of events after aggregation resembles the number of actual network faults and operations. Simply counting the dips that was recorded, masks the real dip performance. Network or utility level aggregation should be applied over longer periods than site level aggregation to compensate for clock differences between multiple instruments.

Figure 4-5 shows the effect of aggregation at utility level. The dip events recorded at 47 locations over a one-month period were sorted on their start date. All consecutive events with a less than 30 second difference in their start times were aggregated into a single event. The worst depth and duration over each group of events were chosen as the depth and duration of the new aggregated event. Another option to the properties of the aggregated event is to choose the specific event with the most severe VSS or VSE to represent the aggregated event.

Aggregation has reduced the number of events from 677 to 56, a 91.7% reduction. This translates to about 2 network faults/operations per day, which is now a manageable number to properly investigate and record the details of.

The bottom set of graphs in Figure 4-5 shows the number of events before and after aggregation without Y dips and swells, which can dominate the visualisation and mask the change in the other dip categories. Voltage dips of type Y and swells should not affect the normal operation of equipment. Aggregation almost completely eliminates the X1 and X2 dip types, which were the most prevalent before aggregation. The more serious S, T and interruption event types remained. This is to proof that aggregation emphasise those events that are closest to the fault of network disturbances.

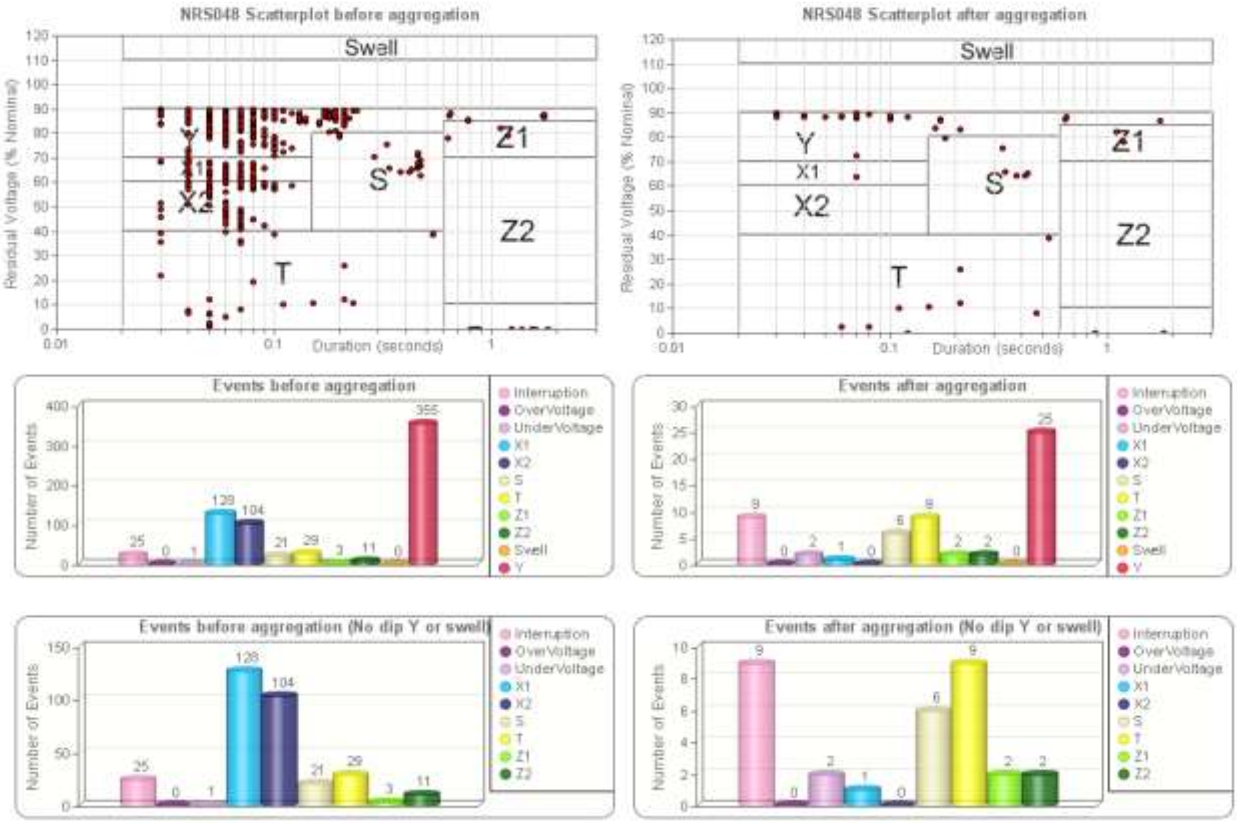


Figure 4-5 Comparison of events for a one month period captured by 47 instruments before and after time aggregation

The second use of aggregation is for benchmarking efforts, where events are aggregated over e.g. a period of year per site, per network or per utility into singular indices to enable comparisons between sites, networks or utilities. Percentile or SARFI values are employed here to represent the aggregated indices. The sums and averages of VSS and VSE are also aggregations that can be used in benchmarking efforts.

Figure 4-6 shows several aggregated indexes for all measured sites of a utility over a period of 3 months. The data is sorted in the first data column, Total VSS. Combining several different aggregated indices into a single visualisation aids in forming a more complete view on the relative performance of each site.

Node 2616 is ranked top (worst performer) with regards to Total VSS. Interpreting this in isolation could lead to assessing that clients connected to this network point were subjected to the most severe voltage dip events of all network points. The average VSS for Node 2616 however shows that most events can be allocated to the safe region of the CBEMA/ITIC curves. The low value for average VSEI supports this conclusion.

Site name	Total VSS	Average VSS	VSEI	Average VSEI	SARFI 80	SARFI 60
Node 2616	747.69	0.341	26.511	0.012	90	40
Node 2599	487.943	1.217	294.667	0.735	246	112
Node 2613	295.029	0.865	22.749	0.067	165	69
Node 2614	239.376	0.684	10.017	0.029	124	52
Node 2597	238.142	0.783	9.18	0.03	172	66
Node 2615	207.667	0.688	8.161	0.027	108	51
Node 2592	155.571	0.714	6.794	0.031	132	42
Node 2833	127.055	0.914	52.964	0.381	72	26
Node 2591	124.771	0.682	4.968	0.027	109	37
Node 2831	119.234	1.055	52.841	0.468	56	26
Node 2598	98.41	0.751	3.166	0.024	72	24
Node 2611	95.999	0.309	1.995	0.006	29	17
Node 2604	44.983	0.692	2.236	0.034	45	8
Node 2605	43.807	0.742	2.088	0.035	40	8
Node 2617	39.137	0.932	0.654	0.016	22	17
Node 2593	38.299	0.618	1.217	0.02	24	10
Node 2603	37.308	0.602	1.804	0.029	38	6
Node 2618	34.746	0.457	0.572	0.008	32	7
Node 2606	32.617	0.476	0.33	0.005	44	4
Node 3058	31.669	0.446	0.334	0.005	28	5
Node 2612	31.074	0.691	1.108	0.025	27	15
Node 2600	26.836	0.703	1.029	0.025	21	6
Node 2587	10.121	2.024	0.885	0.177	5	3

Figure 4-6 Aggregations for benchmarking purposes, sorted on Total Voltage Sag Severity

Node 2599, which is ranked 2nd with regards to Total VSS, is identified as the worst performer when evaluating all indices. Average VSS shows that the average event at Node 2599 fell below the CBEMA/ITIC curve and most probably have affected normal operation of equipment. Node 2599 has the highest VSEI, which indicates it lost the most energy during dip events for the period.

Average VSEI is also the highest at Node 2599, indicating energy lost per event was, on average, significant. The SARFI80 and SARFI60 counts indicates that Node 2599 experienced the highest number of events with residual voltages less than 80% and 60% of all sites for this utility.

The site ranked as performing best with regards to total VSS is Node 2997. The SARFI values indicate a small number of events recorded at Node 2997. It explains the low totals (Total VSS and VSEI). Average VSS at Node 2997 is the highest of all, indicating that events at this site are almost always very deep. Average VSEI are the 4th highest for this site, confirming that a high loss of energy per event is the norm at Node 2997.

Aggregation benefits both consumer and utility by the reduction of recorded dip data into useful network information relating to actual faults and network operations. Intervention measures can be adapted, and prioritised to the root cause of the dip performance.

Characteristic dip numbers for a network can be deduced by benchmarking efforts that helps in characterising dip performance for a specific site or segment of a network. Publishing characteristic values can aid potential investors in an area to determine their risk when planning, or setting compatibility specifications when designing a new plant.

4.1.3 Application: Finding characteristic dip numbers for Utility A

The methodology described above was applied to 3 years of recorded QoS data for a utility in South Africa. All energy is delivered to this reseller of energy distributing it to a range of industrial, commercial and residential users. A vast amount of data resulted from more than 400 PQ recorders located all over this network at various voltage levels. Instruments were placed according to strategic reasons in managing the PQ of energy into this distribution network, and delivered from this network to end-users.

The characteristic values available in South Africa are those published in the NRS 048 part 2 of 2008. Take note that it represents Eskom networks and only up to the year 2000.

The application for “characteristic” values in dip types is that the dip performance of a specific site can then be benchmarked against that characteristic performance of either 50% or 95% of the sites. Using as much historic data as possible will enhance the reliability of characteristic values.

Since networks change with time in terms of loading, configuration, nature of loads, ageing of equipment and others, it is important that “characteristic” values are indeed “characteristic” of that network. This requirement on relevance necessitates continuous analysis of network event data to ensure that characteristic values for dips are characteristically reliable. The characteristic values published in the NRS 048-2007 part 2 is listed (verbatim), below:

Table 7: NRS 048 Characteristic values for the number of voltage dips per year for each category of dip window (95 % of sites)

Network voltage range (nominal voltages)	Number of voltage dips per year					
	Dip window category					
	X1	X2	T	S	Z1	Z2
6,6 kV to 44 kV extended overhead	85	210	115	400	450	450
6,6 kV to 44 kV	20	30	110	30	20	45
> 44 kV to 220 kV	35	35	25	40	40	10
220 kV to 765 kV	30	30	20	20	10	5

Table 8: NRS 048 Characteristic values for the number of voltage dips per year for each category of dip window (50 % of sites)

Network voltage range (nominal voltages)	Number of voltage dips per year					
	Dip window category					
	X1	X2	T	S	Z1	Z2
6,6 kV to 44 kV extended overhead	13	12	10	13	11	10
6,6 kV to 44 kV	7	7	7	6	3	4
> 44 kV to 220 kV	13	10	5	7	4	2
220 kV to 765 kV	8	9	3	2	1	1

The Eskom characteristic values represent diversity in type of network, loading, climatic and geographical diversity between sites, because it represents all of South Africa. Utility A is geographically a smaller area with networks of different character (voltage levels, overhead/cable). The Eskom data used in NRS048 was collected up to the year 2000, which is not representative of Eskom network conditions in 2013.

Towns in Utility A are exposed to similar climatic conditions and types of networks between towns are similar. It is expected that characteristic numbers of dips for Utility A will be useful for benchmarking the performance of any site in any town when assessing dip performance of a singular site anywhere.

The resultant characteristic values for Utility A are based on dip data recorded during 2009 – 2012.

Voltage levels for which the characteristic numbers were calculated required consideration. It was decided to use only 3 groupings:

1. **Networks < 11 kV**: 197 sites
2. **Networks at 11 kV:** 163 sites
3. **Networks > 11 kV:** 57 sites

Information on which sites represent cable networks was not available. It is in the process of collection and will be used in future to distinguish between overhead and cable networks, because notable differences are expected.

A normalised principle is in use. It means that the dip numbers tabled below refer to the characteristic annual dip performance of a single site at that voltage level for either 50% or 95% of the best performers in the sample of sites used.

The characteristic numbers for Utility A is listed in Table 9 and Table 10.

Table 9: Utility A number of voltage dips for 2009 - 2012 (95 % of sites)

Nominal Voltage	X1	X2	S	T	Z1	Z2
< 11kV	7	8	10	7	9	8
11kV	11	11	25	13	6	8
> 11 kV	10	12	14	16	8	7

Table 10: Utility A number of voltage dips for 2009 - 2012 (50 % of sites)

Nominal Voltage	X1	X2	S	T	Z1	Z2
< 11kV	3	2	3	2	2	2
11kV	4	4	4	3	2	2
> 11 kV	4	3	3	2	3	2

Application of this result is to consider for example a site (site A in Utility A, a hypothetical site) at 11 kV for which the annual dip data is available and found that 18 dips of type S has occurred at this example site. Since dip S is a relatively deep and long voltage sag condition, failure of electrical equipment at site A is expected and at a rate of 1.5 incidences per month. It is of concern, but application of the characteristic numbers in dip performance for Utility A enables interpretation of the dip performance of site A in proper context.

Since 50% of the sites in Utility A at 11 kV are exposed to only 4 dips of type S per year, site A is performing significantly worse than 50% of the better performers and can be regarded as located within a network with rather poor dip S performance.

Graphical presentation of the characteristic values further useful visual appreciation of how different types of dips affect the overall dip performance of Utility A.

- Figure 4-7 graphically indicates the dip performance for networks below 11 kV.
- Networks in Utility A at 11 kV experienced dips during 2009 – 2012 as shown in Figure 4-8.
- Networks in Utility A above 11 kV experienced dips during 2009 – 2012 as shown in Figure 4-9.

The characteristic dip values are useful for new clients to understand what to specify in tender documents when new plants are set up with dip-sensitive equipment in use. Advice by the utility on a location in a specific network can be provided in terms of what to expect on dip performance. Existing clients can use these numbers when considering/specifying dip mitigation equipment.

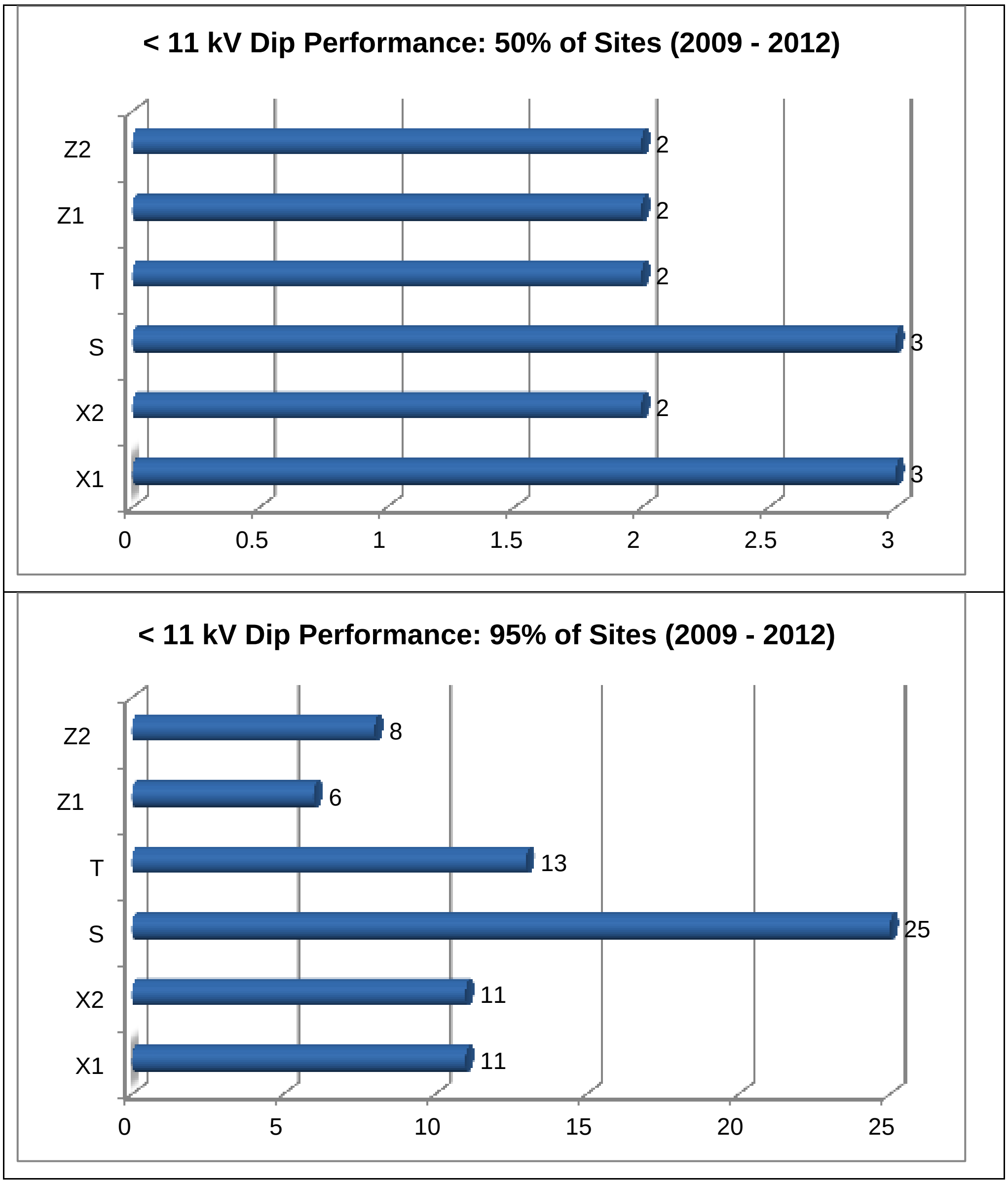


Figure 4-7: Comparison of characteristic dip numbers for networks < 11 kV

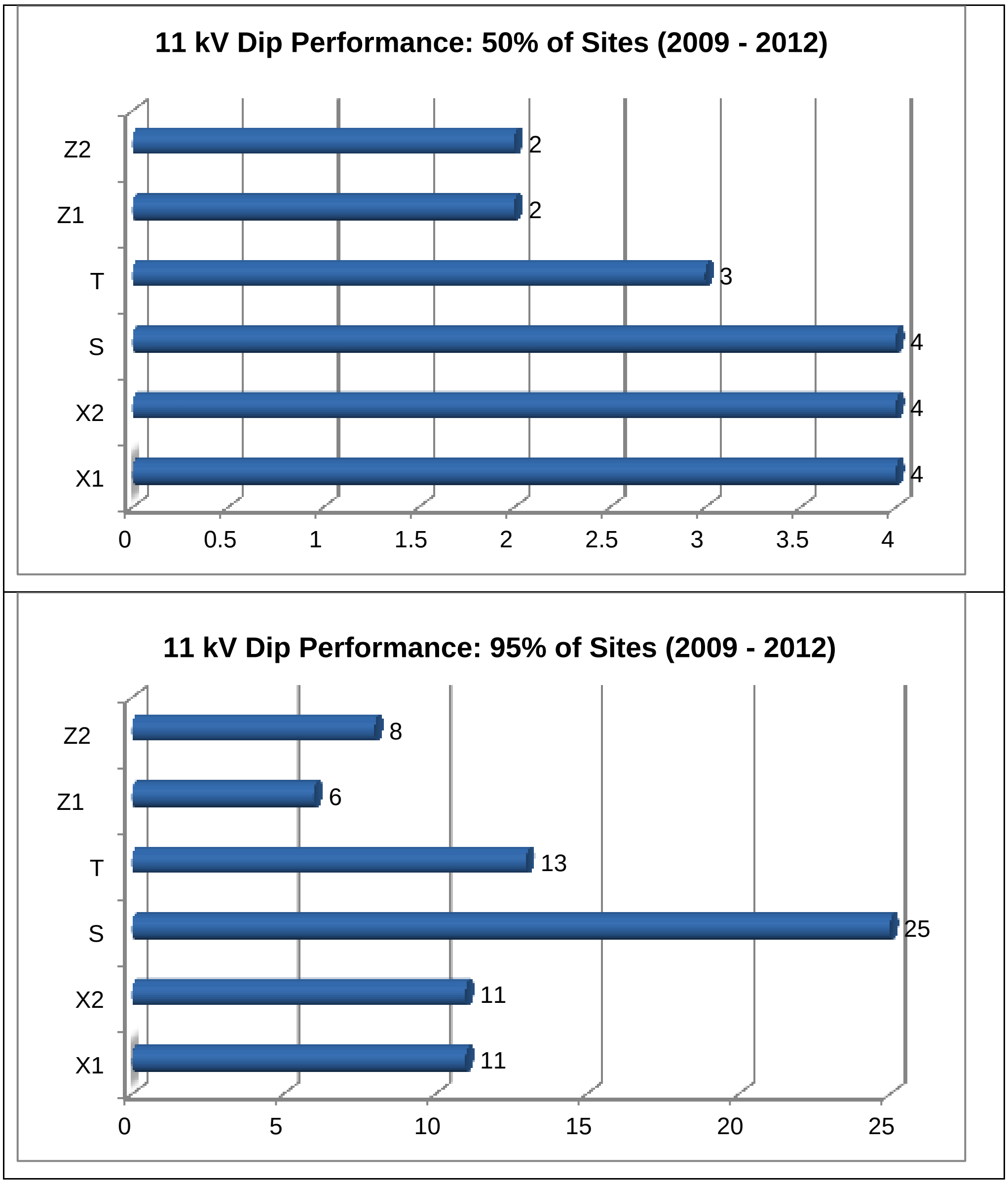


Figure 4-8: Comparison of characteristic dip numbers for 11 kV networks

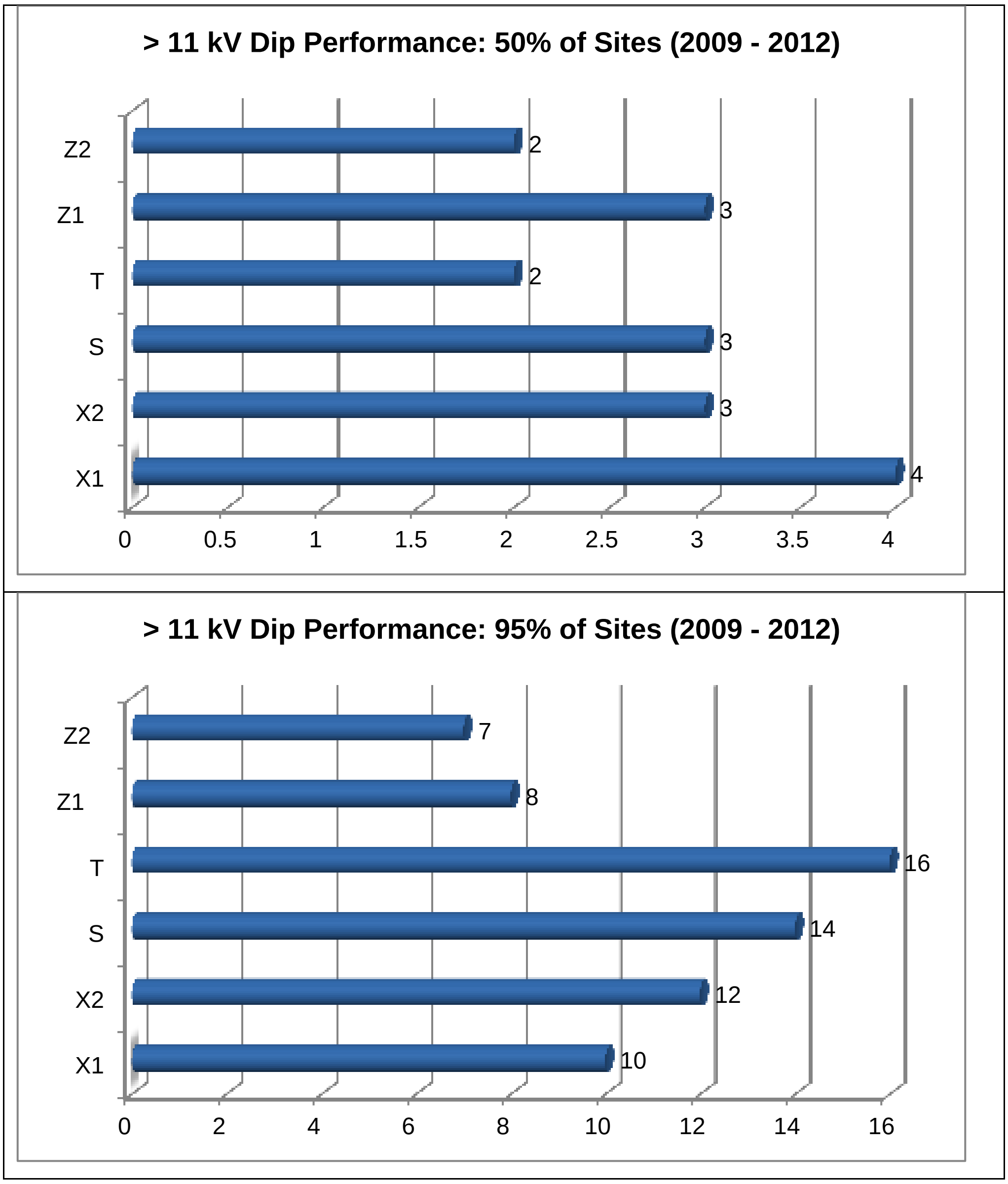


Figure 4-9: Comparison of characteristic dip numbers for networks = 11 kV

Sufficient data (long enough period) will allow "indicative" sag values to be regarded as "characteristic", representing the "to be expected" behaviour of the network. Data representing a limited number of years is affected by anomalies such as major network incidents, upgrades, adverse climatic conditions and others.

A direct comparison (Eskom and Utility A tables) is not possible due to the different voltage levels in use in the Eskom data, the "age" of the Eskom data, and, due to the different geographical and electrical character of the Eskom and the Utility A network. Comparison of Utility A dip numbers with Eskom characteristic dip number indicate that Utility A performed much better than the Eskom characteristic levels on average.

4.1.4 Application of characteristic numbers to benchmark annual dip performance

The characteristic numbers discussed in the section above was used to benchmark the dip performance of 2012. A graphical presentation is done in Figure 4-10, Figure 4-11 and Figure 4-12.

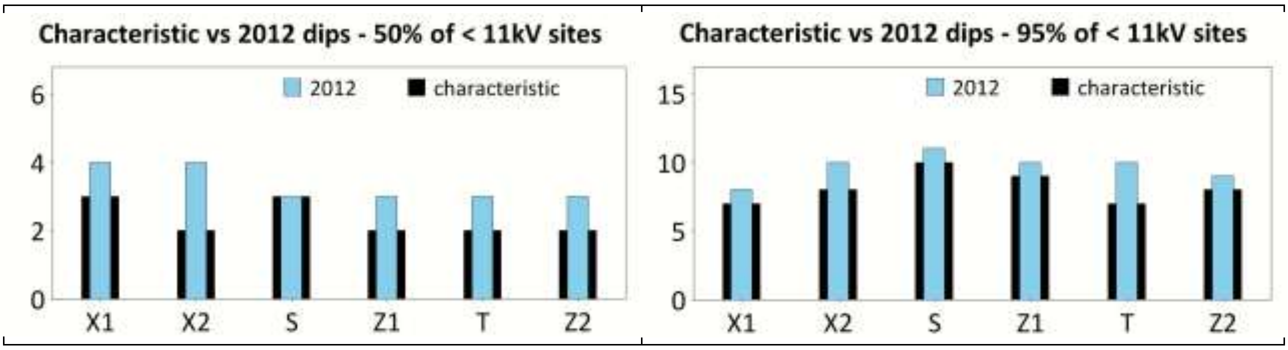


Figure 4-10: Dip performance 2012: Sites < 11 kV

- 95% of the sites operated < 11 kV performed worse than the characteristic number for all dip types during 2012.
- The 50% best performers operated < 11 kV also performed worse than the characteristic number. It is only dip S, which, for 2012, was at the same level then the characteristic number.
- It is concluded that sites < 11 kV experienced a relative bad 2012 dip season.

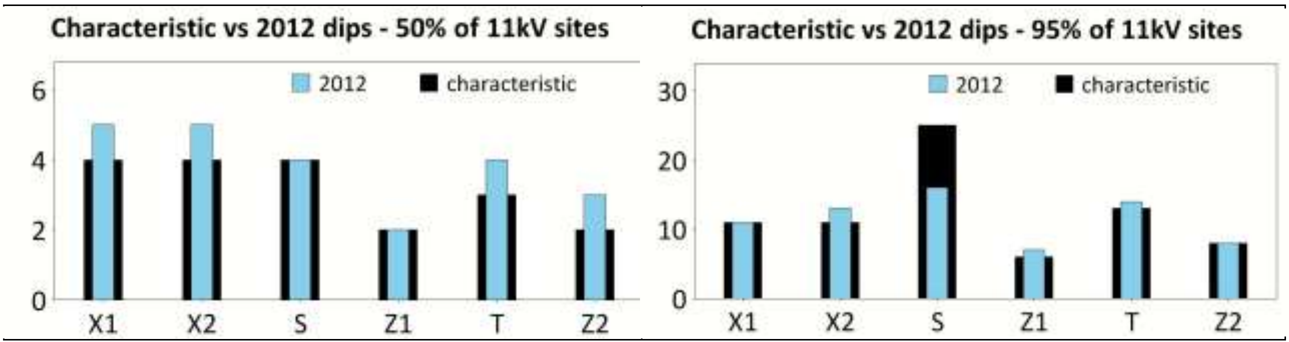


Figure 4-11: Dip performance 2012: Sites @11 kV

- It is only dip S, which for 95% of the best performers, operated at 11 kV, and performed better than the characteristic number. The rest (dip types) performed worse.
- Dip S and Z1 performed at the same level than the characteristic numbers for the 50% best performers operated at 11 kV, the rest (dip types) performed worse.
- It is concluded, that also for sites at 11 kV, that 2012 was a relative bad dip season for sites at 11 kV.

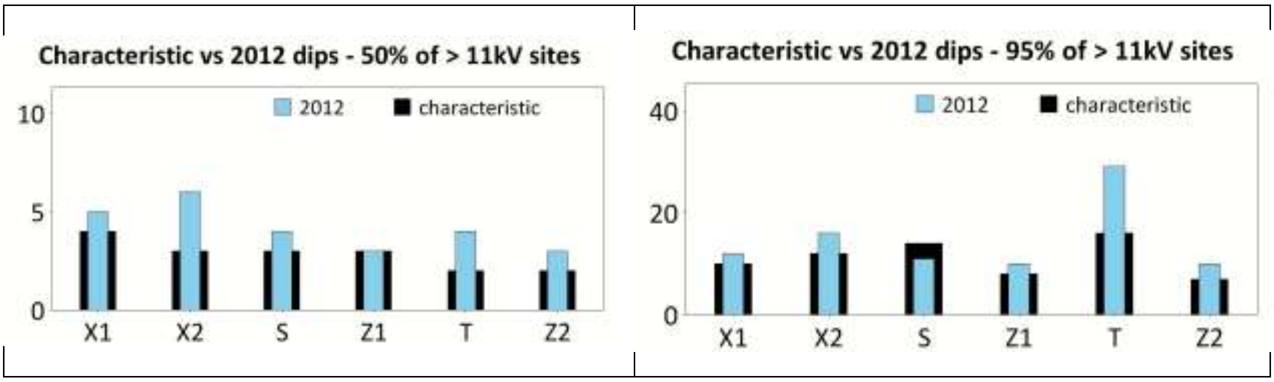


Figure 4-12: Dip performance 2012: Sites >11 kV

- It is only dip S for 95% of the best performers operated > 11 kV which performed better than the characteristic number. The rest (dip types) performed worse.
- It is only dip Z1 for 50% of the best performers operated > 11 kV which performed at the same level than the characteristic number. The rest (dip types) performed worse.
- It is concluded, that overall, for all sites within Utility A, that 2012 was indeed a bad dip season.

The dip types contributing to the dip performance of Utility A can now be made visible as shown in Figure 4-13

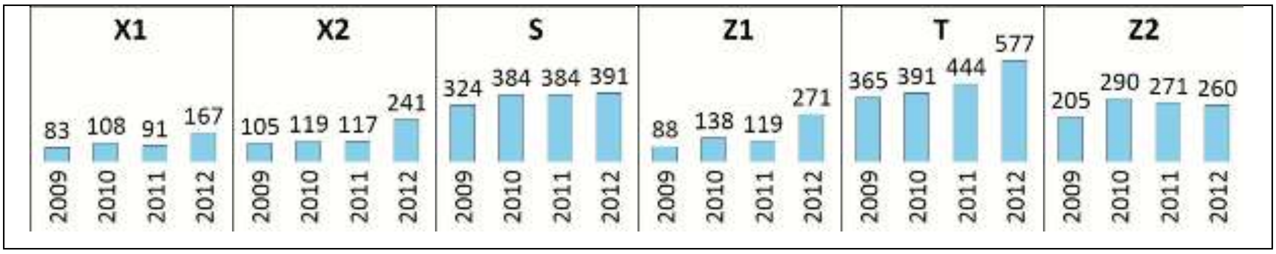


Figure 4-13: Dip types in Utility A: 2009 - 2012

Root cause to the above is unknown. Knowledge on the root cause of the dip events resulting (at least) in the S, T, Z1 and Z2 will be helpful in formulating possible intervention measures.

It is an explainable and “acceptable” condition if lightning is the driving parameter of dip performance in a network. Seasonal variation in dip performance is analysed in the next section as a context to the dip performance of a network.

4.2 PQ Analysis in Context

4.2.1 Time as context

Time can be used as context to extract additional information on dip performance:

- Analysis of the distributions of dip depth, dip category, or the number of dip and swell events that are outside the SEMIF47 or CBEMA curves over different time intervals. The influence of seasonal factors, residential, commercial and industrial loading will be revealed. A “longer” time interval is used in the aggregation.
- Aggregation over a “shorter” time interval to group dip events was described in section 4.1.2 can help to attribute the root cause to a single network fault or operation.

Figure 4-14 to Figure 4-16 shows the distribution of several voltage dip related parameters over different time intervals. Hour of the day and weekday can be used to investigate the relation to residential and industrial load cycles whilst month-of the-year can be used to identify seasonal influence on dip parameters used.

Observations made possible:

- The most (and most severe) dips occur during 14:00 to 18:00, 1:00 and 21:00. The period between 14:00 and 18:00 can be attributed to industrial loads, but the 1:00 and 21:00 periods are of special interest, because they contain severe dips with no logical explanation except cable theft.
- Tuesdays and Thursdays experience the most dips, with Z1 dip type being most prominent on Tuesdays and Z2 most prominent on Thursdays.
- November experienced double the number of dips than the second worst affected month. Since this data if for one year only, a valid conclusions is not possible.
- Brushing and linking of the 1:00 and 21:00 periods, as well as the November period can reveal relation such as a behavioural pattern, or if it were a small number of instances but of high dip activity.

Hour of day	Total	Avg duration	Avg Res Volts (%)	Below CBEMA	X1	X2	S	T	Z1	Z2
00	8	0.5	53.26	6	1		4			3
01	46	0.79	68.13	40	1		5		34	6
02	13	0.8	28.53	11			3		1	9
03	2	0.6	52.82	2						2
04	3	0.47	52.47	3		1				2
05	6	0.39	57.65	3			5			1
06	8	0.47	64.17	6	1		6			1
07	18	0.81	43.31	16	1		3	1	1	12
08	16	1.09	35.95	15	1					15
09	21	0.82	46.07	18	3		5			13
10	20	0.56	53.61	16		3	11			6
11	14	0.49	58.82	10	2		8			4
12	23	0.33	54.89	17	3	4	10	2		4
13	16	0.59	56.91	11	1	1	4			10
14	39	0.92	45.23	33	2	1	5	1	2	28
15	41	0.45	55.54	30	8	5	14	5	5	6
16	54	0.49	54.16	33	7	11	12	4	5	15
17	50	0.6	50.47	41	4	1	21	3	4	17
18	31	0.53	49.08	25	3	3	10	5	2	8
19	25	0.34	56.98	13	8	2	6	6	2	1
20	16	0.49	63.55	9	2	1	8		3	2
21	45	0.52	52.81	40	2	2	28	2	1	10
22	15	0.49	54.37	13	2		10			3
23	7	0.44	52.33	6		1	2	1		3

Figure 4-14 Dip parameter distributions over hour-of-day for a single site over the period of a year

Day of Week	Total	Avg duration	Avg Res Volts (%)	Below CBEMA	X1	X2	S	T	Z1	Z2
SUNDAY	47	0.35	59.21	24	9	7	17	2	4	8
MONDAY	54	0.64	55.98	40	2	5	18	2	7	20
TUESDAY	106	0.63	58.04	92	4	5	37	5	34	21
WEDNESDAY	75	0.62	51.88	62	4	4	31	4	3	29
THURSDAY	99	0.71	48.21	89	4	5	29	6	4	51
FRIDAY	84	0.55	52.16	55	14	8	23	6	5	28
SATURDAY	72	0.55	47.96	55	13	2	25	5	3	24

Figure 4-15 Dip parameter distributions over day-of-the-week for a single site over the period of a year

Month of Year	Total	Avg duration	Avg Res Volts (%)	Below CBEMA	X1	X2	S	T	Z1	Z2
JANUARY	43	0.39	53.24	26	7	4	18	7	1	6
FEBRUARY	75	0.68	45.73	66	5	4	28	1	3	34
MARCH	48	0.61	50.59	38	3	4	10	5	5	21
APRIL	25	0.58	61.53	18	4	4	4		3	10
MAY	15	0.63	55.93	12	1		3		1	10
JUNE	26	0.71	45.27	18	3	2	6		1	14
JULY	21	0.88	45.67	19			6	1	1	13
AUGUST	5	0.59	65.11	3			3		1	1
SEPTEMBER	10	0.56	43.55	6	1	3	1	1		4
OCTOBER	51	0.76	47.06	46	3	1	19	2	1	25
NOVEMBER	150	0.56	60.84	115	18	4	60	5	36	27
DECEMBER	68	0.47	51.58	50	5	10	22	8	7	16

Figure 4-16 Dip parameter distributions over month-of-the-year for a single site over the period of a year

Figure 4-17 Time distribution of dips below the CBEMA curve for several sites of a utility over a period of 4 years

Figure 4-17 presents detail on the dip performance of several sites of a utility over a period of 4 years. Users (current and potential future users) will gain information on the risk to normal operation of equipment due to dip sensitivity based on the CBEMA curve.

The 7 worst performers and the 3 best performers are shown in Figure 4-17. The diversity between the dip performances of sites within the same network is evident.

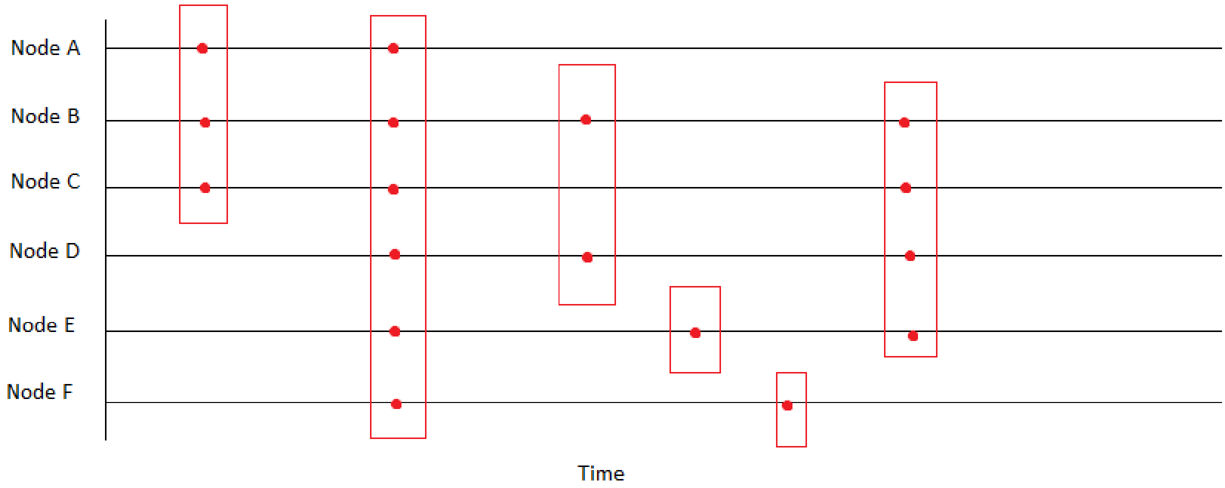
Options to mitigate dips can be analysed. Hardware mitigation equipment can be installed and a reliable projection on cost against benefit is possible based on the statistics shown.

Another powerful application of time as context is shown in Figure 4-18. Each dot represents a voltage dip event as recorded at different nodes in the network. Grouping dip events that happened within a pre-defined time period as a single entity can be attributed to be a single network incident.

This time-period will depend on the ability of PQ recorders to contain clock-drift. If instruments are not synchronised continuously to for example a GPS time stamp, the drift in the real-time clock at each instrument could result in different time stamping at different nodes for the exact same network event recorded at a number of nodes.

The difference in time was found to be not that significant by rigorous analysis of data recorded at different utilities in Southern Africa. A timing difference of less than 60 seconds was the norm with rare instances of 2 minutes and more.

In an Oracle database application developed for this purpose by the author, an incident with a unique ID were used to record attributes and statistics of the network disturbance. Attributes such as the party responsible, network segment where the fault occurred, network voltage level where the fault occurred and the specific root cause of the disturbance were recorded.



[3]

Figure 4-18 Grouping events into incidents

Figure 4-18 demonstrates how 17 individual dips were reduced to 6 network incidents. The more instruments a utility have installed in a network, the more pronounced this data reduction will be.

Figure 4-19 illustrates this reduction rate for several utilities as well as individual large electricity users as obtained in a dataset, which was available for analysis to the author. This dataset represent data recorded at a number of utilities all over Southern Africa. The reduction percentage is defined as:

$$\%\ Reduction = 100\ x\ \frac{\sum Individual\ measured\ dip\ events - \sum Grouped\ incidents}{\sum Individual\ measured\ dip\ events}$$

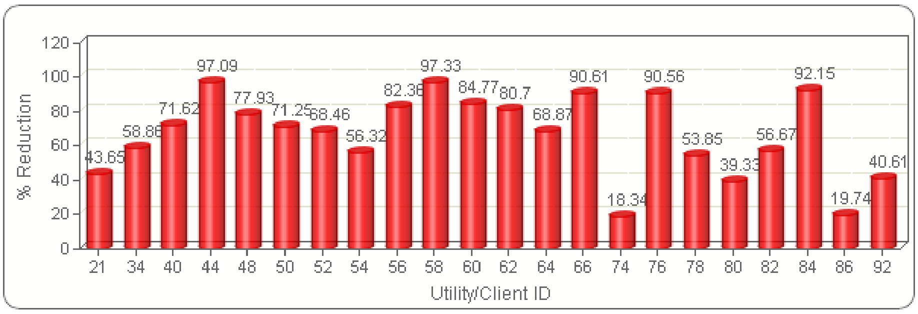


Figure 4-19 Percentage reduction that grouping events into incidents achieved for several utilities and clients

This reduction is significant, because it also represents the reduction in effort for the utility to fully investigate and declare the cause of each dip recorded by each instrument in its network. Such information is needed to manage PQ. If PQ management remain at PQ monitoring and merely reporting the statistics, no gain in managing the risk in the ESI will be seen.

A powerful opportunity to manage PQ exist in the aggregation of voltage dip events to voltage dip incidents as the impact of a single network fault can now be analysed in context of the network in which it has occurred.

4.2.2 Season as context in distribution of voltage dips

Seasonal factors can affect dip performance if an electrical network is located in an area where lightning occurs during the rainy season. Overhead lines are exposed to atmospheric electrostatic conditions. If voltage induced in line conductors exceeds the insulation strength of insulators, a flashover condition constitutes a short circuit, which should be recognised by protection equipment and be cleared within the set clearance time. It is protection settings that determine the duration of voltage sag events. Minimal intervention of network operators is possible in the reduction of lightning induced voltage sags.

Cable networks should record much less voltage sag events, because the root cause will be due to cable faults, load action, copper theft and other factors which present an opportunity to be managed.

It is expected that lightning will be the major contributor to voltage dips in the overhead networks. Utility A operates a vast network of underground cables (up to 132 kV), which are less susceptible to lightning induced voltage sags. Lightning induced voltage sags should be the dominant aspect at points of feed-in from the transmission network.

The voltage sags recorded all over Utility A is depicted by dip type for each year in Figure 4-20 starting at January on the left hand side with December of each year on the right hand side.

- It is revealed that the absence of seasonal variation is regarded as better than a random pattern.
- The dominance of S, T and Z2 dips each year is a concern.
- The duration of S, T and Z2 dips should relate to the operation of a specific type of protection equipment, such as zone 2 protection.
- Dip X2 is more prominent in 2012 than in previous years.
- Overall, dip performance became significantly worse in 2012.

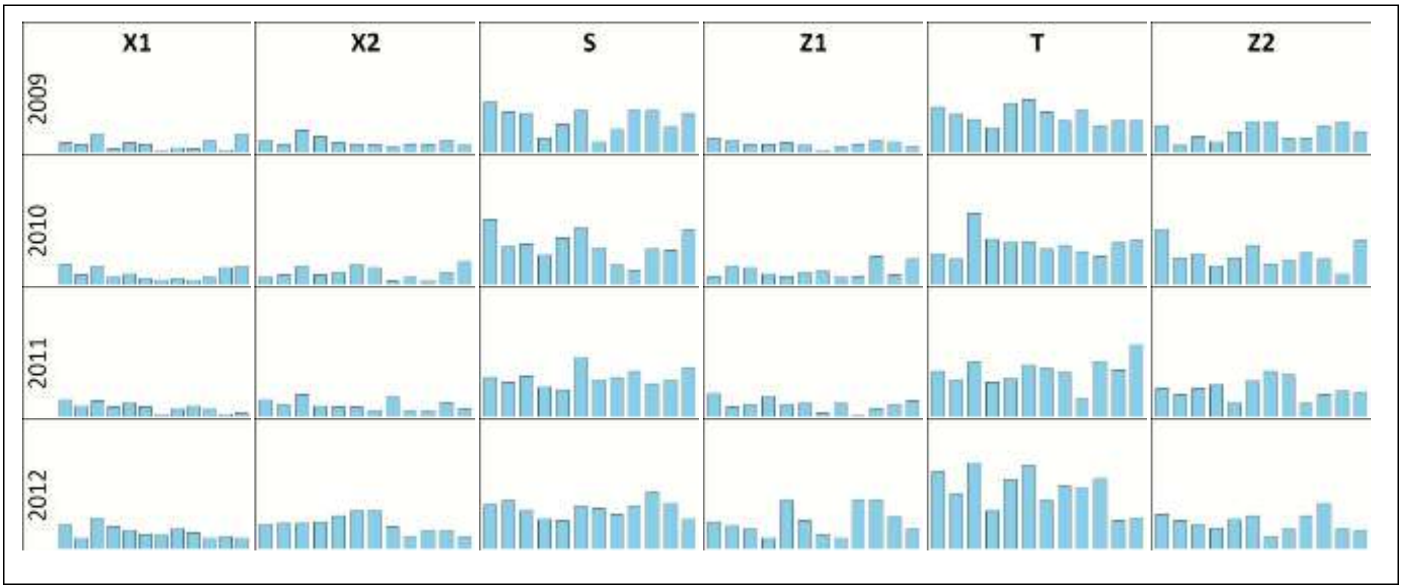


Figure 4-20: Seasonal variation of voltage sag incidents at Utility A: 2009 -2012 (Same scale for each year)

4.2.3 Voltage magnitude as context

In (3.2.3) it was shown that some shallow dips and swells that are recorded by power quality instruments are by-products of poor voltage regulation with a fixed voltage dip threshold instead of real network disturbances. Numerous of these events can be recorded in short succession and can dominate the dip statistics, masking the real dip performance of a site. Figure 4-21 is an example of how the seasonal influence on voltage dips at a specific site is masked by a large number of swells and over voltages during 2 months of the year being reported on.

Solutions for this problem can be implemented on the recording device itself or in post-processing of the recorded data. On the instrument, temporal aggregation of events and/or hysteresis on the dip trigger threshold will ensure the successive events are recorded as a single event of a longer duration. These events can then be accurately classified as under- or over voltages within the NRS 048-2 classification framework.

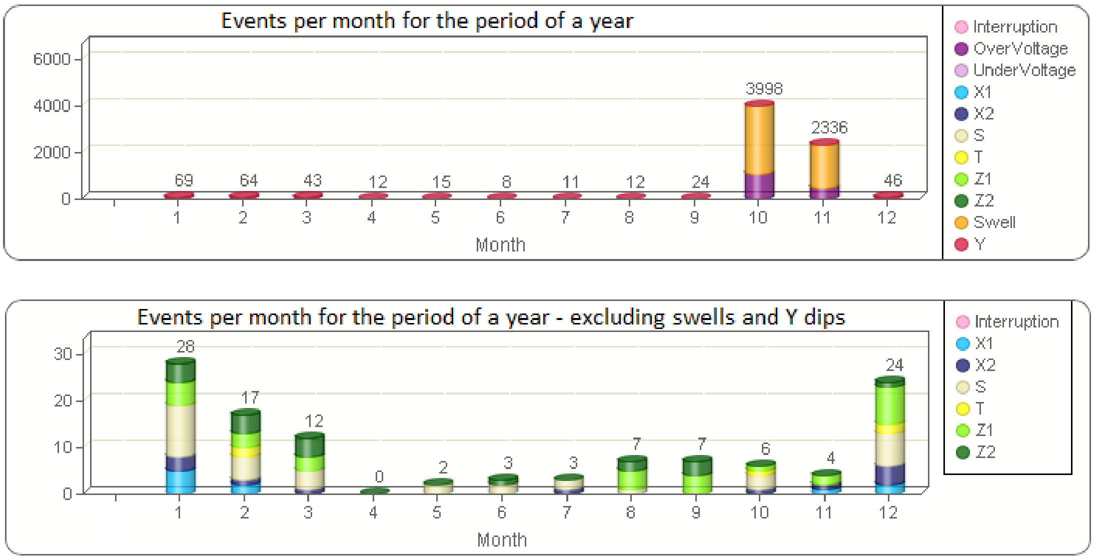


Figure 4-21 Example of how dip events not related to network events masks the true dip performance

In post-processing, the same approach as on the instrument can be used. Another option in post processing is to tag the events where the actual deviation from the moving average voltage at the time of the event is less than an agreed upon percentage, in the region of 2 – 5%. This will identify events where the cause is voltage regulation and not network faults. These fake events can then be filtered out when investigating network faults and rather reported on with voltage magnitude assessment. Ignoring these tagged events in the flagging process will ensure voltage regulation problems are not masked by events.

Lastly, a visualisation that does not allow high values of a specific event type to hide the patterns can be employed to expose the patterns of each event type. Figure 4-22 is an example of such a visualisation, where each event type is independently plotted and scaled to observe patterns rather than compare numbers.

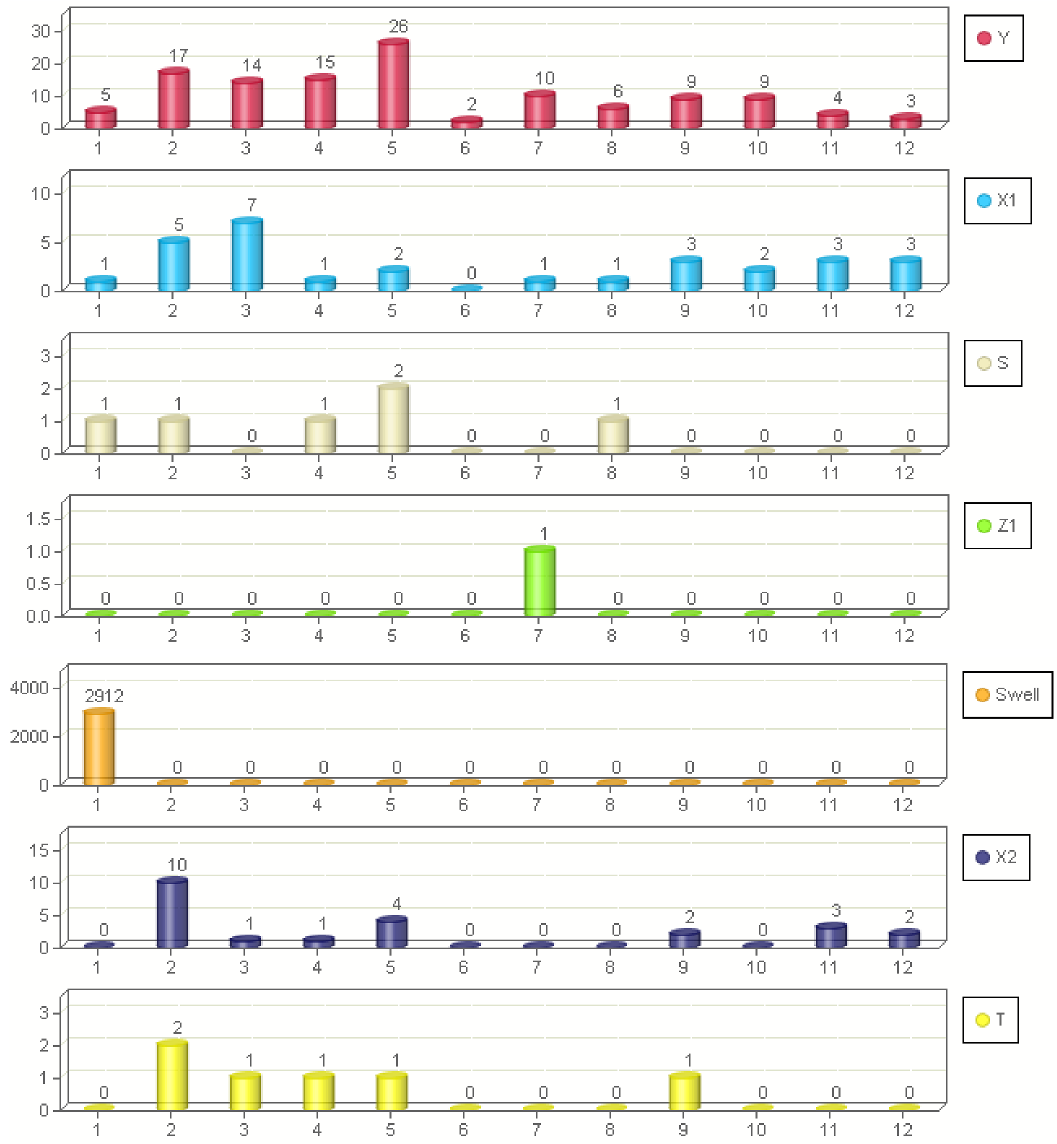


Figure 4-22 Alternative visualisation for events over time

The NRS 048-2 definition of a dip is: "*A sudden reduction in the r.m.s. voltage, for a period of between 20ms and 3s, of any or all of the phase voltages of a single-phase or a poly-phase supply*" [6]. The depth of the dip is then determined as the maximum deviation from the nominal voltage. Identification of dips to be flagged can be based on evaluating the type of "reduction" in voltage:

- a "sudden" component, that can be contributed to a network fault or switching operation,
- a steady state component, that can be contributed to the voltage regulation (being poor) at the measurement point.

As an example of the implication, consider 2 instruments that measure the same network fault at different locations in the network. Network theory dictates that the deeper dip is closer to the fault. The voltage regulation of the two sites however has a direct influence in the difference of the classified depths of the dips at the 2 points. A 10% difference in voltage between the 2 sites can still result in both being compliant to NRS 048-2 voltage magnitude criteria.

The classified depth as defined in the NRS 048-2 standard is therefore not reliable to indicate distance to the fault. Distance to fault could be estimated more reliably if based on the "sudden" component of the voltage deviation (or actual deviation).

Figure 4-23 demonstrates the principle. Graphs A and B are the same dip measured at two different sites. The moving average voltage on graph A is at 105% of nominal and at 98% of nominal on graph B. The dip depth for graph A is calculated as 15% and under represents the actual voltage drop during the dip. The depth for graph B is calculated as 22% and over represents the actual drop in voltage.

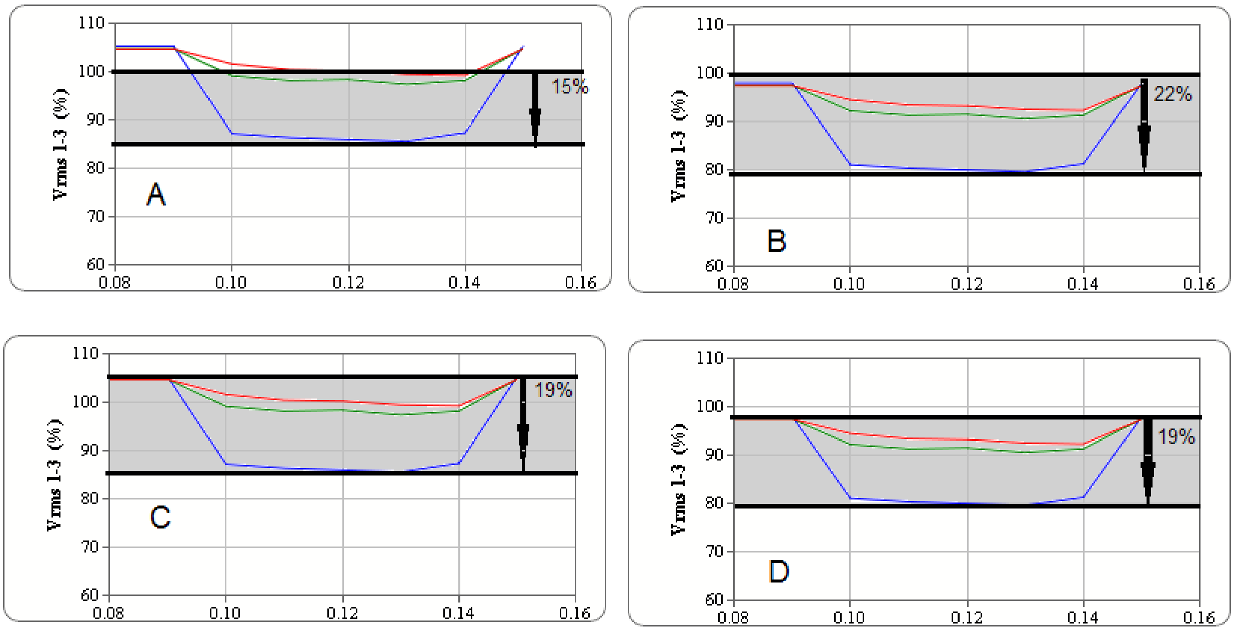


Figure 4-23 Illustration of effect of moving average on dip classification

Graphs C and D are the exact same two events with the dip depths calculated as a percentage deviation from the moving average. Both depths are calculated to be 19% and represent the real voltage drop during the event.

The deviation from the moving average voltage is suggested as an additional parameter to describe a voltage dip. Should the moving average not be available, the 10-minute voltage magnitude reading will be helpful.

The electrical network envisages for the future, the smart grid, will rely on communication between devices and the use of real-time measurement information to make operational decisions. Fake dips as discussed above can be useful in implementing intelligent, centrally coordinated voltage regulation efforts. These fake dips can be useful as early warning of voltage magnitude concerns.

Knowledge of fake dip events can be used in the smart grid:

- A "signature" to be developed for each network node over time, which identifies the 10-minute voltage magnitude levels where these fake dips start to appear. Tap changers throughout the network can be controlled centrally (it is a smart grid) and algorithms then calculate the optimal tap positions to manage voltage magnitude compliance for the network pertaining as far as possible. The inputs for these algorithms will be the "signature" of each site evaluated against the last 10-min V_{RMS} value and the instantaneous V_{RMS} value.
- An alternative algorithm can be developed to make direct use of the occurrence of fake dips to evaluate the optimal tap position. A high number of fake dips are an indication that non-compliance to voltage magnitude compatibility should be expected.

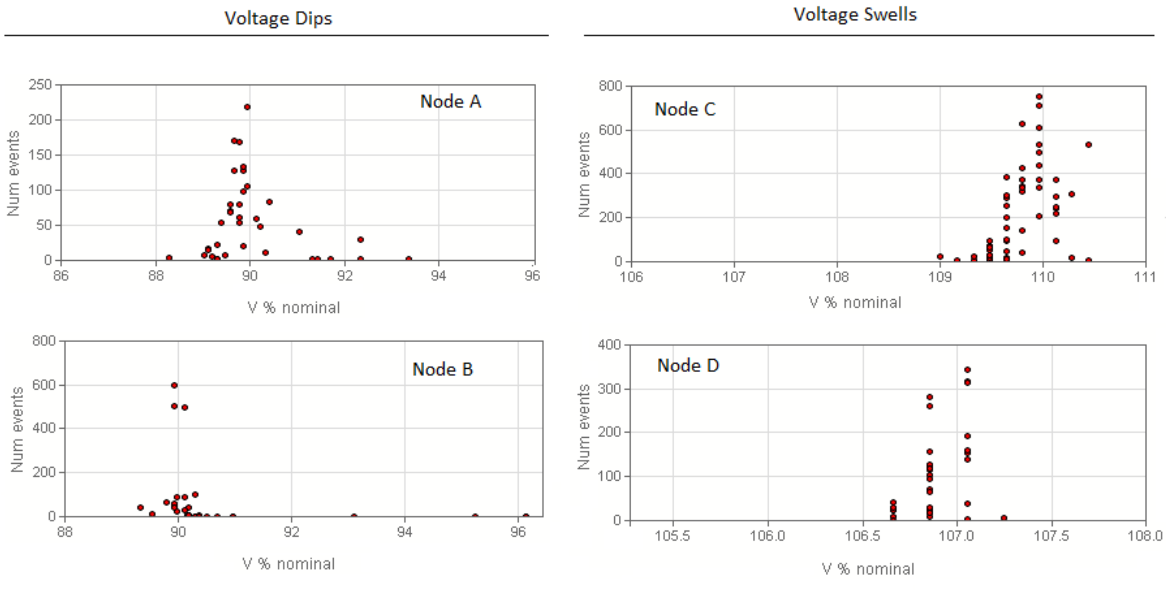


Figure 4-24 Number of events vs. V_{rms} signature (fake dip and swell events)

Figure 4-24 present examples of "signatures". Each dot represents a 10-min V_{rms} value against the number of Y-dips or swells recorded.

Voltage dip definition and classification as defined in NRS 048-2 and other power quality standards indicate how far from the ideal (nominal) voltage the voltage supplied to the client was during the threshold exceedance. The goal set to the utilities therefore is not to exceed certain voltage levels.

A different goal has been identified in the use of voltage dip information – the use of the actual voltage deviation from the moving average in determining proximity to the fault. The definition of dip depth in the power quality standards is not compatible with this goal and an additional depth parameter was identified to satisfy that goal

4.2.4 Voltage waveform incident attributes as context

NRS 048-2 does not require recording any additional attributes of voltage sag and swelling incidents. Investigation of a network incident is needed most of the time to reveal these attributes and few network operators puts priority to it.

The ranking and benchmarking of these attributes is valuable in the management of network voltage disturbances. NERSA requires in theory the submission of per site dip number statistics. Even if it was submitted, such data has limited value, because it is not in context of the network in which it was obtained and in context of the network incident related to.

If the energy regulator shifts the focus to the submission of network incident information, valuable information will be revealed:

- What percentage of faults at users were caused by the utility, were cause by users, third parties, or imported from the transmission provider.
- What percentage of the incidents attributed to the utility were caused by lack of maintenance, network operation, cable theft, lightning, and others.

This presents an opportunity:

- The commitment of the ESI to manage electrical energy in the interest of the economy will become visible and the regulator can influence that commitment by incentives and penalties when application for tariff increase and subsidies are lodged.

Figure 4-25 presents an interactive visualisation to aid the understanding of causes of network incidents. Brushing and linking is employed to allow visual queries.

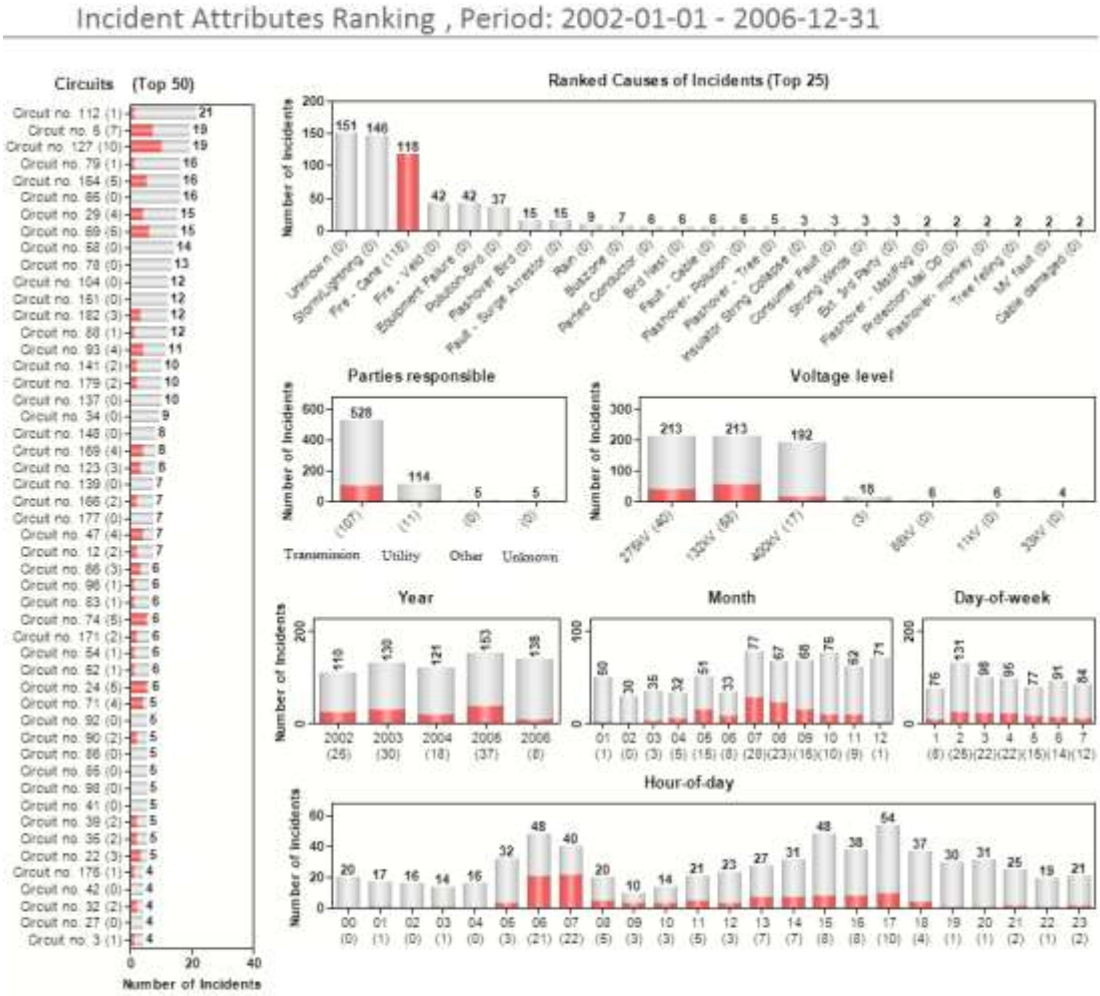


Figure 4-25 Ranking and distribution of incident attributes for a utility over a period of 5 years

The visualisation reveals that:

- The worst performing circuit accounts for 21 incidents per year.
- A large number of the incidents were either not investigated, or the cause could not be determined.
- Fire and lightning makes up a large proportion of the causes of network disturbances for this utility.
- Equipment and surge arrestor failures are both in the top 10 causes of network incidents, indicating a possible need to evaluate maintenance practises.
- The ratio of incidents originating inside the utility's network to incidents imported from the transmission network is about 1:5. This utility therefore has limited control over most of the incidents.

Brushing and linking has been applied in Figure 4-25 to investigate the relation between cane fires and the other attributes. It follows that:

- Cane fires are a small percentage of the causes for the worst performing circuit, but almost 50% of the 2nd and 3rd worst performing circuit.
- 107 out of 118 instances of network incidents caused by cane fires originated at transmission level and thus outside the utility's area of responsibility.
- Faults due to cane fires are experienced from March to November and between 6:00 and 8:00 in the morning.

Brushing and linking several attributes reveals invaluable information and garners insight into the cause of network disturbances and how they could possibly be reduced.

4.2.5 Protection fault-clearing time as context

Protective devices are employed to isolate faulted network circuits from the rest of the network. The result of protection equipment operating is:

- an interruption in the faulted circuit and
- a voltage dip in non-faulted downstream circuits.

The circuit is disconnected from the network within a time determined by the characteristics of that breaker, called the fault-clearing time. If a reclose option exists, then after the reclosing interval, the circuit is again energised. If the fault was transient in nature, such as a lightning strike, the fault would have self-cleared and the circuit will now remain energised. Several recloser operations can be sequenced. A sustained interruption results if the fault has not been cleared after the set recloser sequence.

The time setting of protection equipment is evident in the duration of voltage dips. A large portion of voltage sags is directly related to the fault-clearing time of the protective device. Motor start-up conditions (for example) can cause the recording of a voltage dip, but the duration will be proof of user equipment being the cause and not protection equipment.

Protection can be co-ordinated such that devices closer to the fault will operate first. Devices at higher voltage levels normally operate faster than at lower voltage levels. The duration of a voltage sag can hint to where (voltage level) the fault occurred.

Knowledge of the specific power system protection devices in use is important context information when investigating voltage dips. The fault-clearance time setting for a device in a distribution network for example is useful, since dips of duration shorter than this can be attributed to the transmission network. This cannot be used as a one-to-one mapping unfortunately, since protection devices only operates when the fault is severe enough and are thus not responsible for the duration of all dips.

Figure 4-26 visualises the dip duration distributions of utilities fed from the same transmission network, based on 5 years of event data.

- The bulk of event durations are less than 200 ms. It peaks at 60-80 ms and 100-120 ms.
- Utilities A and F share a peak around 400 ms.
- Utilities C and D share a peak at 500-600 ms, with the peak more prominent at utility D.
- Utility B has 2 peaks at 1.02 s and 2.95 s which are not shared with any other utility.

Conclusion:

- According to [16], typical best-case protection clearance times at distribution level voltages are 100 ms. The peak at 60-80 ms can thus by attributed to transmission level faults. The peak at 100-120 ms cannot be attributed to transmission or distribution, because it is a borderline case.
- The 400 ms peak can be attributed to distribution level faults, with the depths of the events indicating local and remote distribution faults.

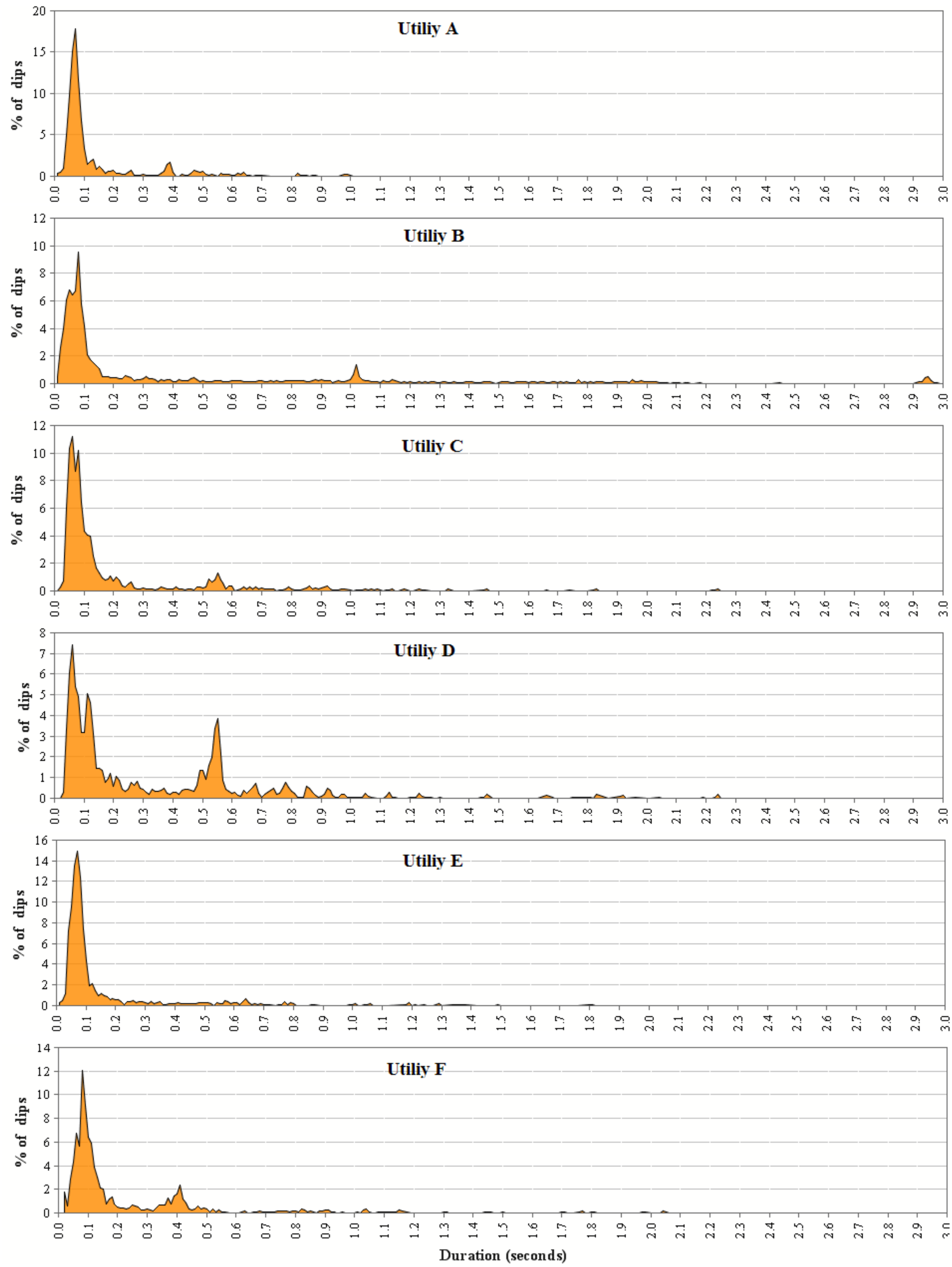


Figure 4-26 Dip duration distributions for several near located utilities fed from the same transmission network

- The 500-600 ms peaks can be attributed to distribution level faults.

- Utility D has more dips attributable to internal faults than the rest. The peak at 60-80 ms (transmission level errors) is lower than the other utilities. This could be due to a different network topology at utility D.
- The 1.02 s and 2.95 s peak at utility B is not understood. It could possibly be attributed to large motors starting or the operation of overcurrent relays with long delay times (as used on long radial lines).

4.2.6 Transformer winding and fault type as context

The voltage dip types recorded at different points throughout a network as a result of the same fault, depend on transformer connections between the fault and the point of recording, as well as the type of fault (for example single line to earth).

Delta and wye connected PQ recorders at the same point will record dip depths and duration differently [47]. It has been found through simulation and confirmed with monitoring that, at transmission and distribution voltage levels, phase-to-neutral (PN) dips are more frequent and severe than phase-to-phase (PP) dips. The performance at low voltage (LV) however is much more similar, indicating that where electricity is consumed, load - or metering connection will not influence the dip performance significantly.

When measuring at transmission or distribution level, the dip performance at a LV load can be predicted by knowing the winding connections of each transformer between the measuring point and the connection of the load of interest. This is possible because the propagation of voltage dips caused by each fault type through transformers of different winding connection types is well known [47], [48], [49].

Fault types are:

- 3 phase symmetrical (3P)
- Single line to ground (SLG)
- Line to line (LL)
- Double line to ground (DLG)

Transformer winding connections are noted with primary side in capital letters and secondary side in lower case:

- YNyn is wye-wye connection, both star points grounded
- YNy and Yyn are wye-wye connected with only one star point grounded
- Yd and Dy are wye-delta and delta-wye transformers, which swop the line and phase voltages from primary to secondary

- Yz and Dz are wye-zigzag and delta zigzag transformers. Zigzag transformers have the advantage that they isolate earth faults between secondary and primary.

Transformer winding connections are classified by their influence on voltage dip phasors [48]:

- Type 1 has no influence on dips. Only transformers configure YNyn fall in this group.
- Type 2 removes zero-sequence voltages and thus transforms the dip phasor diagram since it travels from primary to secondary. Dd, Dz, YNy, Yyn are of type 2.
- Type 3 transformers removes zero-sequence components and swops line and phase voltages – Yd, Dy and Yz

Voltage dip types are classified by Bollen [16] as A, B, C, D, E, F or G according to the phasor placement during the dip as shown in Figure 4-27. The dashed phasor is the pre-event phasor and the solid line the event-phasor.

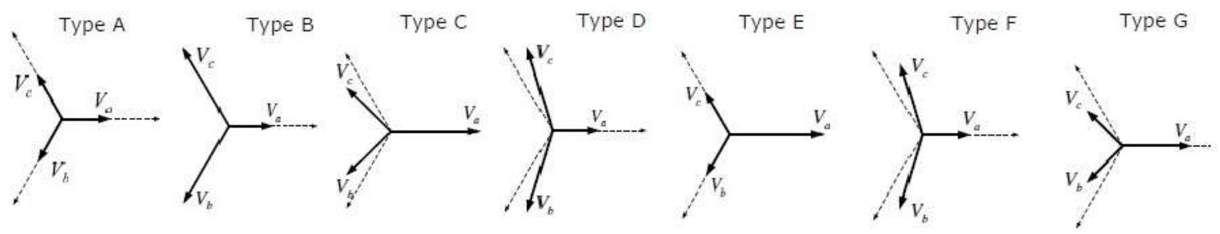


Figure 4-27 ABC dip classification as defined by Bollen [16]

Table 11 summarizes the relation between entities when relating a fault to the dip type with an optional transformer between the fault and the measuring device. Transformer type 0 in the table indicates the fault and measuring device are on the save voltage level, thus no transformer in between.

Observations made from this table:

- Dip Type A are only caused by symmetrical (3P) faults and appear irrespective of the transformer type or measurement connection. When dip type A is measured, the fault type is known, but the location cannot be determined from this information.
- Dip Type B can only be measured when the instrument is connected in wye. It only appears when a SLG fault happens at the same voltage level as the instrument, or a type 1 transformer is between the fault and the instrument. It is noted that when a dip type B is measured after a transformer of type 2 or 3, the fault can be uniquely assigned to the same voltage level as at the instrument. Should a utility have intake transformers of type 2 or 3 – dip type B will identify internal faults.

- Dip type E, similar to dip type B, can only be measured when the instrument is connected in wye. Transformer types have the same effect as dip type B. The only difference between the two is the fault type, LLG. In the same fashion as dip type B, a LLG fault after an intake transformer of type 2 or 3 will signify an internal fault. The unifying factor between dip types B en E are the zero sequence components. The presence of zero sequence components, measured by an instrument connected in wye, after a type 2 or 3 transformer, will be due to an internal fault.
- Dip types E, F and G are caused by LLG faults only.
- Dip types C and D are cause by both SLG and LL faults.

Complicating matters is the fact that a fault can originate from a network level higher up than the immediate higher level, resulting in multiple transformers between the fault and the measurement.

Milanovic [48], state for PN connected meters:

- After the first type 2 transformer, further type 2 transformers have no influence on the dip type.
- Consecutive type 3 transformers will alternate between dip types C and D
- Consecutive type 3 transformers will alternate between dip types G and F

In conclusion, zero sequence removing transformers (types 2 and 3) will alter the dip characteristic that is seen at the fault. After removal of zero sequence components, further type 2 transformers will have no influence and type 3 transformers will continue to alternate between 2 dip types because of their swopping of line and phase voltages. Type 1 transformers never have an influence.

Table 11: Relationship between dip type, transformer type, fault type and meter connection

Fault Type	Transformer Type	Meter connection	Dip Type
3P	0	Wye	A
3P	0	Delta	A
3P	1	Wye	A
3P	1	Delta	A
3P	2	Wye	A
3P	2	Delta	A
3P	3	Wye	A
3P	3	Delta	A
SLG	0	Wye	B
SLG	1	Wye	B
LL	0	Wye	C
LL	1	Wye	C
LL	2	Wye	C
LL	3	Delta	C
SLG	0	Delta	C
SLG	1	Delta	C
SLG	2	Delta	C
SLG	3	Wye	C
LL	0	Delta	D
LL	1	Delta	D
LL	2	Delta	D
LL	3	Wye	D
SLG	2	Wye	D
SLG	3	Delta	D
LLG	0	Wye	E
LLG	1	Wye	E
LLG	0	Delta	F
LLG	1	Delta	F
LLG	3	Wye	F
LLG	2	Wye	G
LLG	3	Delta	G

As a consequence of the above, having the network topology and the instrument connection information available, the dip types expected at any location caused by faults at any other location, can be deduced. Identification of dip types from recordings can help to locate the most probable fault locations.

The above principles seems to further practical value for dip management practises, but such information could not be obtained from the utilities at which dip data was recorded. Limited interest in enhancing dip management was noted at utilities from which this information was requested.

4.3 User-defined PQ Dashboards

An attribute of dashboard applications not yet discussed or demonstrated in this dissertation, is enabling the user to choose what is on display. The limited real estate available on a computer monitor places a definite constraint on the amount of information to present concurrently. Enabling the user to define the focus of his interest follows to be a definite requirement when a large selection of contexts and visualisations are available.

A modular approach to the design of such an application is thus needed and will be demonstrated in this section.

The first step in the design of this dashboard application for voltage dips, is to realise that the choices allowed to the user needs to be defined within some framework. The core activity when investigating voltage dips is identified as a relating cause of network disturbances. This relationship is a one-to-many relationship, since a single fault on the network can be measured at several places throughout the network. A further interest is then the classification of the effects, since the same network fault can be experienced differently throughout the network. The choices allowed and the dashboard design should thus be clearly divided in cause and effect, as shown in Figure 4-28.

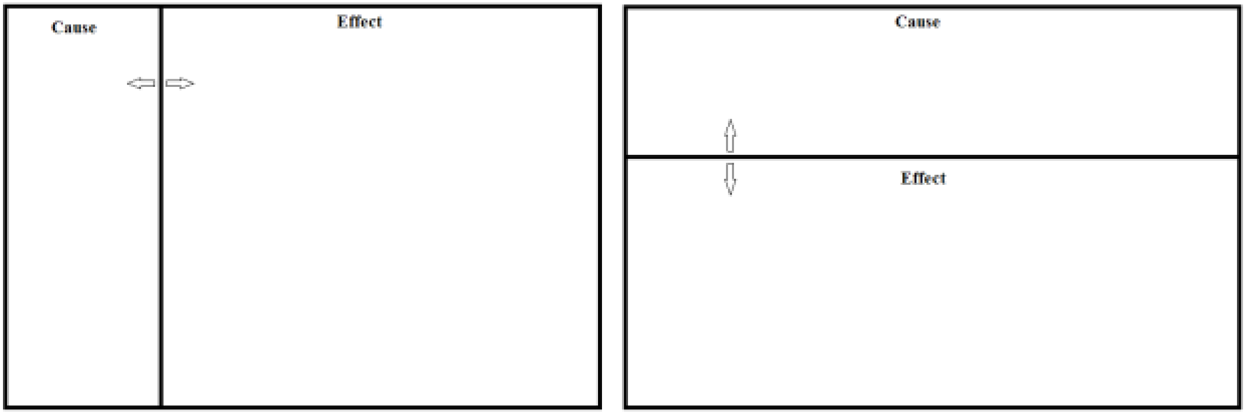


Figure 4-28 Dip dashboard design, separate cause and effect contexts

Collapsing one of the halves will focus the user on inspecting the interrelationships between parameters related to either cause or effect.

Starting off with all parameters identified as observations, labelling several observations as effects and placing them in the allocated area, can reveal a cause-effect relationship between some of them, identifying parameters which can then be used on the cause side.

The principle for this application is to have a data table with a column for each parameter (or observation) to be investigated. The visualisation for each parameter will then aggregate this table regarding the parameter to be displayed. An illustration of this principle follows.

To investigate the time distribution of dips at a specific site, a table is created with a single row for each voltage dip type recorded at the site against the following columns:

- Month of the year (i.e. January to December)
- Day of the week (i.e. Sunday to Saturday)
- Hour of the day (i.e. 1 to 24)

These parameters are all extracted from the recorded date of the event. Three visualisations are then created, each doing a count of the events grouped in a different column. The month of the year visualisation will, therefore, count all events that happened during a given month. The day of the week visualisation will count the events that happened during a given day.

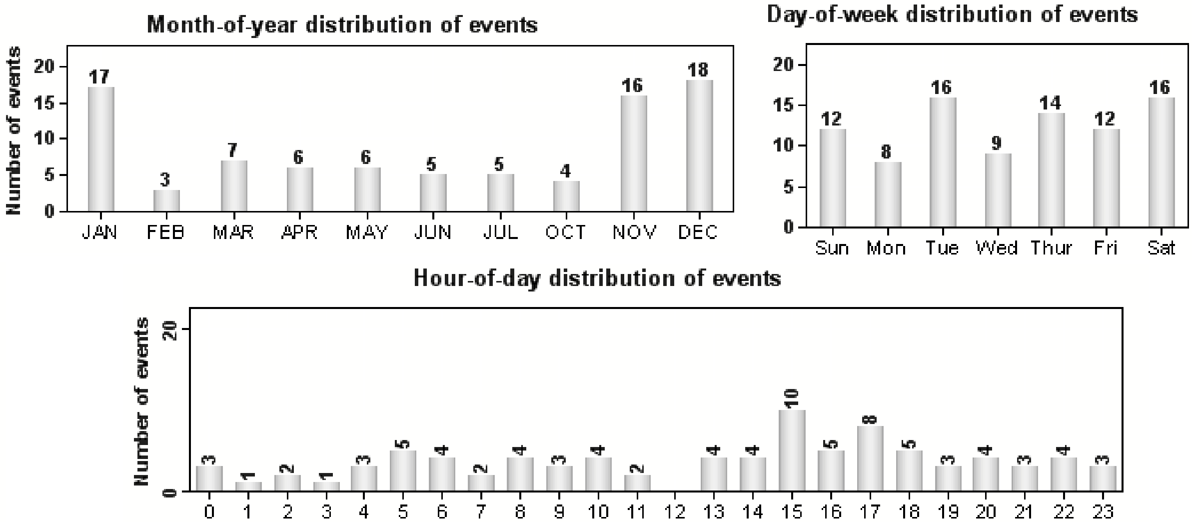


Figure 4-29 Time distribution of voltage dips at a specific site

The results of this can be seen in Figure 4-29. A seasonal influence is evident in the summer months of November, December and January in which the most events were recorded. This could prompt one to identify season (summer, winter, spring and autumn) as a new observation to be added to the data table and placed in the cause side of the dashboard display.

Adding the NRS 048-2 classification (X1, X2, S, T, Z1, Z2 and T) to the table enables the addition of a visualisation of the distribution of dip types, shown in Figure 4-30.

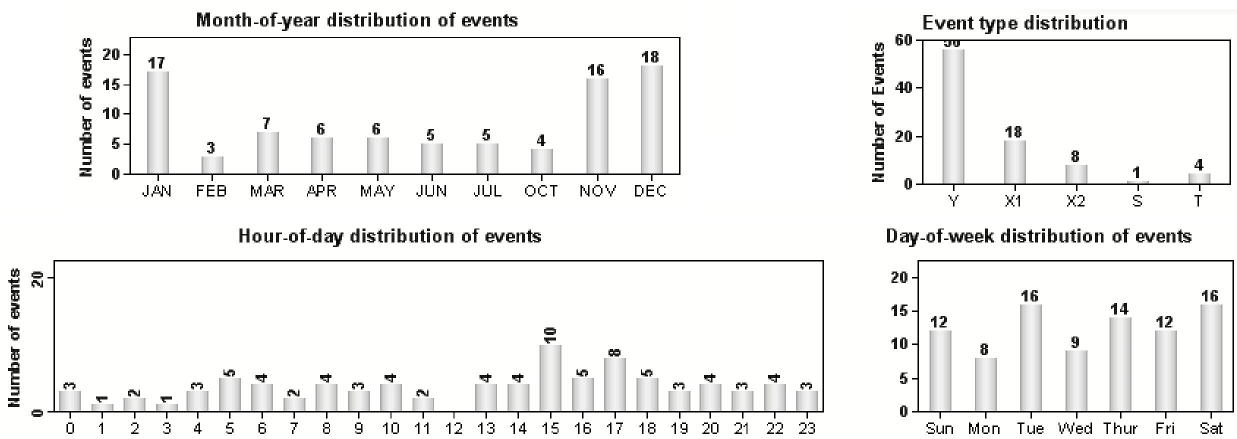


Figure 4-30 Dip type added to visualisation

In Figure 4-30, one can see that, apart from Y-dips, the more serious X1 dip type is the most prominent.

Interactive brushing and linking requires two grouped counts on the parameter of interest. An additional count based on a filter is added for the parameter that has been brushed (selected). Naming the data table containing the 5 parameters “dip_table”, the SQL query will be:

1. The total count of dips per day of the week:

   Select Day-of-week,

   Count (*) as total_number_of_events

   From dip_table

   Group by Day-of-week

2. The distribution of X1 dips over time:

   Select Day-of-week,

   Count(*) as number_of_selected_events

   From dip_table

   Where classification = ‘X1’

   Group by Day-of-week

Similar filters are applied to each visualisation, month-of-the-year, day-of-the-week, hour-of-the-day and the dip type classification. The result is shown in Figure 4-31.

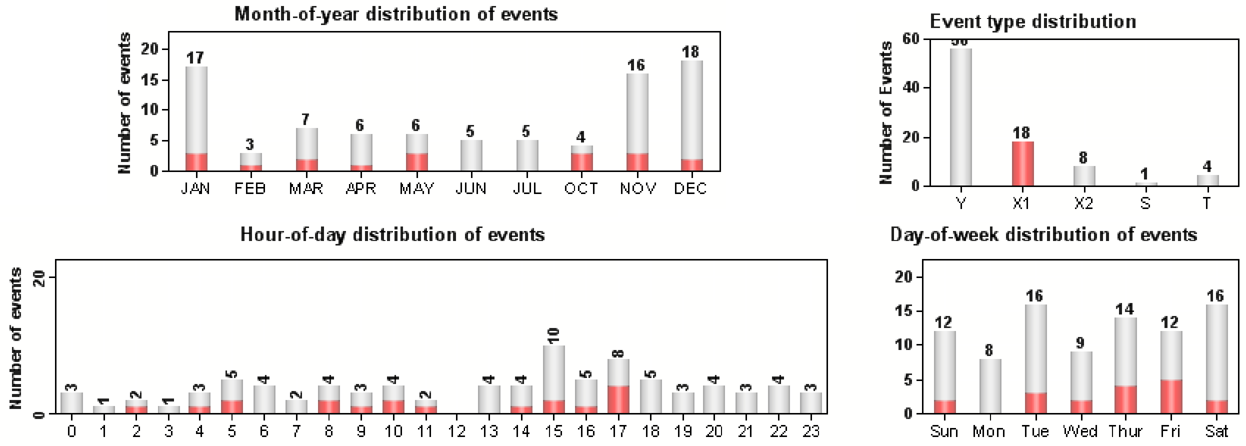


Figure 4-31 Investigating time distribution of X1 dips by brushing and linking

Dip type X1 is “brushed” (selected) and it is revealed that it does not share the seasonal pattern of the total dip distribution in Figure 4-29, indicating that lightning is not the main cause of X1 dips.

Dip type X1 constitutes a significant portion of the dips during May and October. Identifying a further context (such as a maintenance schedule) that could possibly explain this and adding it to the data table, will allow additional insight and develop the cause-effect relationship model.

Identifying the useful context parameter for a specific investigation is not straightforward. Based on experience, a number of pre-designed dashboards is presented below. It was shown to be useful both for utilities and consumers.

4.3.1 Per incident PQ event dashboard

Several Southern African utilities share dip information with key customers. The dashboard presented below assumes the utility shares information from two sites with the user. One instrument is located at the user, a second instrument at the PCC where the user is connected and the third instrument at the upstream point of intake point where the utility connects to the transmission network.

The “*per dip*” dashboard aims to enable the user to answer the following questions:

- Where did the dip originate? - Inside my plant, in the distribution network, or has it been imported from transmission?
- How severe was the dip? - Can any malfunction in my plant be attributed to the dip?
- Is the incident part of a re-occurring pattern?

Similarly, it enables the utility to answer:

- Where did the dip originate? - Inside the network, or has it been imported from transmission?
- How was the dip experienced at different points in the network?
- Could it have affected users?
- Is the incident part of a re-occurring pattern?

Figure 4-32 is a block-level concept design based on the goal of locating the source of the dip event.

A single-line diagram indicates where each dip was measured, with the size of the dot (shown in Figure 4-33) an indication of the depth of the dip experienced at that point. A NRS 048-2 dip-duration scatterplot in the bottom-left corner indicate the location of the events.

In the bottom-middle area, the incidents are classified as part of a re-occurring pattern or not. It contains different time-based distribution of similar incidents over the past year. The value in each distribution relating to the incident under investigation is marked by colour.

In the bottom-right corner, the trend of RMS voltage is shown for each site involved at the day of the event. It can be used to evaluate the influence of voltage regulation on the events recorded.

The top-right corner is a table with additional information on each dip event pertaining to this incident.

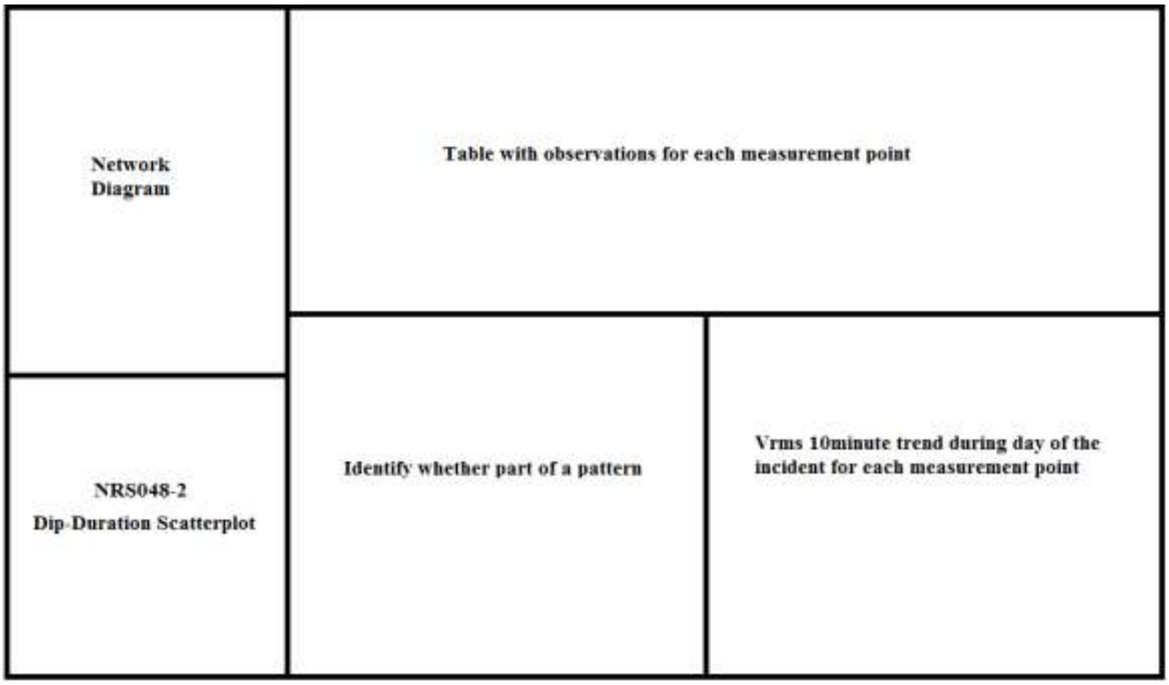


Figure 4-32 Design of dashboard for single dip/incident evaluation

The implementation for a real-life incident is shown in Figure 4-33. The size of the dots on the single-line diagram indicates that a dip of similar magnitude was recorded at all 3 sites. Horizontal spacing on the NRS 048 scatterplot confirms this and the vertical spacing that the duration of each is the same and the reason why all 3 events were classified as dip Type Z1.

No pattern information is revealed. The trend of RMS voltages at all 3 sites confirms the relation between the 3 measurement points with the supply voltage to be 5% below nominal at the time of the incident (incident identified by vertical red line).

The depth of the dip at the 3 sites hint towards an upstream (or at 33 kV) source as the fault impedance at the lower voltages is higher. A fault at the lower voltages will cause voltage sags at the higher voltages be not as deep.

A voltage profile during the dip at 1 site is shown in the table, as the other 2 instruments do not record dip voltage profiles. Only 1 site experienced the severity of the dip below the CBEMA curve.

It is clear that if the voltage at the 3 sites has been at or above nominal, neither would have experience a dip below CBEMA. This is significant as the importance of proper management of voltage regulation in a network is shown in this case to have the ability to contain losses at a user. Dip mitigation is possible without capital expenditure. Best practises in network operation can make the difference, but the information on root-cause is needed and the PQ dashboard demonstrated provided that information.

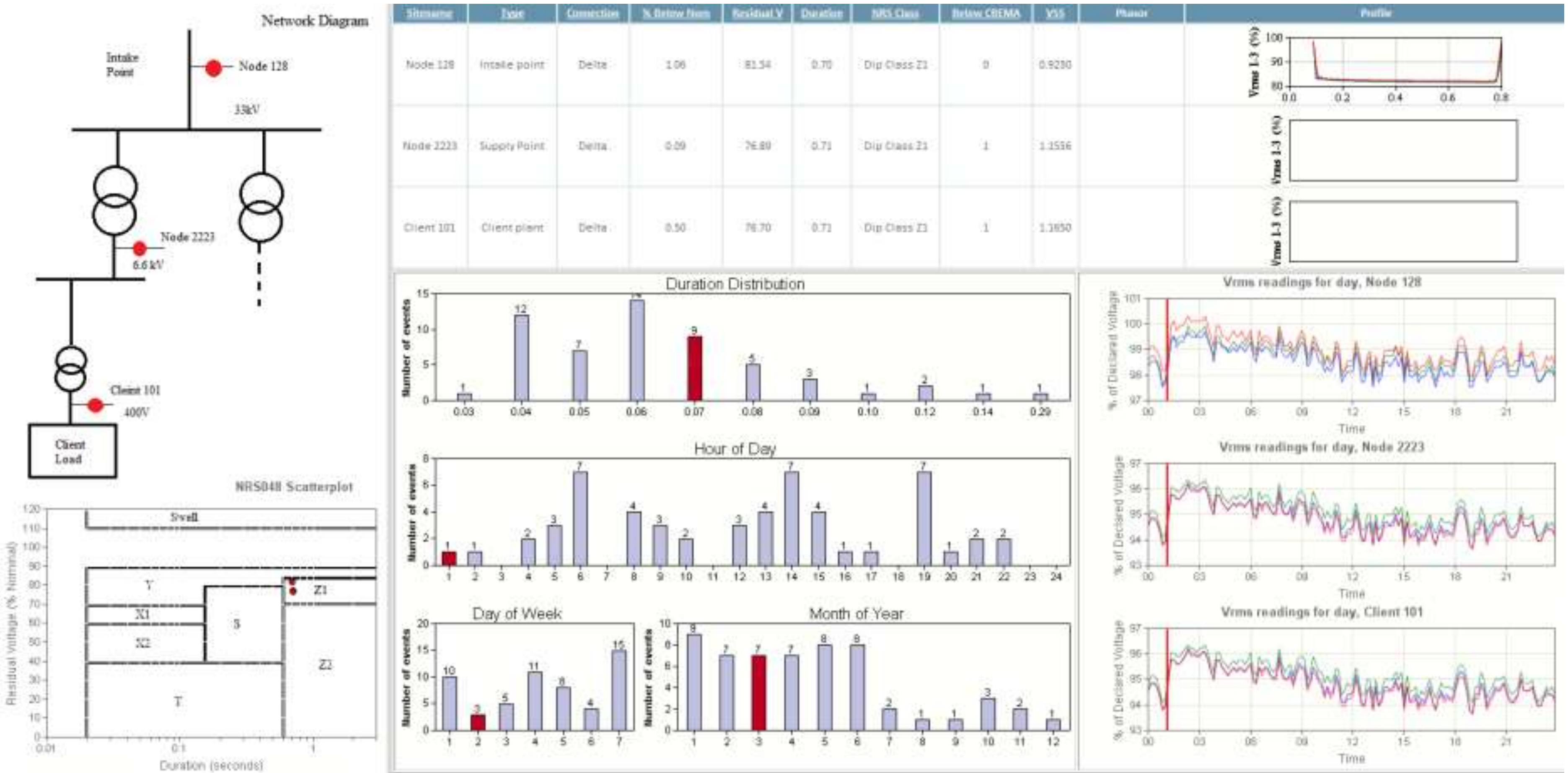


Figure 4-33 Implementation of incident level dashboard design

4.3.2 Per site PQ event dashboard

This dashboard presents the dip performance of a site over time. Brushing and linking simplifies the analysis of root cause. Visibility enables:

- Identification of patterns in the data, such as events of a repetitive nature, similar depth or similar duration.
- Visualisation of dip performance as function of time.
- Should incident attributes be available (results from root cause investigations by client or utility), identify the most common causes of faults.

A self-explanatory conceptual design is shown in Figure 4-34.

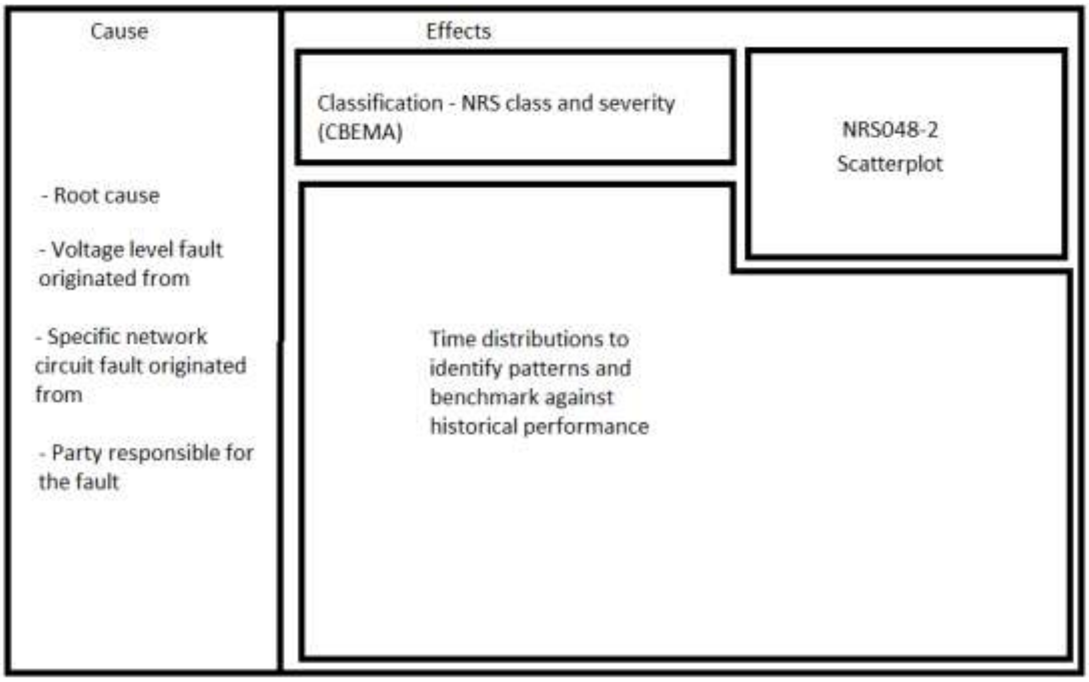


Figure 4-34 Conceptual design for a per site event dashboard

Implementation of a per site PQ dashboard is demonstrated in Figure 4-36

From the "cause" part:

- Most faults originated in the 132 kV transmission network.
- Fire and lightning is a concern.
- Approximately 1/3 of the incidents do not have a cause attributed.

From the "effects" part:

- Dip type X1 dominates (Y-dips are ignored).
- Only 5 dips were recorded during 12 months below the CBEMA-curve, which could have affected user equipment.

- A seasonal influence is noted.
- Time-of-the-day distribution possibly due to late afternoon lightning activity typical of the utility's summer weather conditions.
- 5 dips occurred on a single day during September 2011.

Figure 4-37 employs brushing and linking employed to reveal additional information:

- All but one fault originated in the 132 kV network, with equipment failure related causes prevalent.
- Those dip events below the CBEMA curve can be attributed to internal faults
- September is the worst performing month on average, August 2010 the worst performance over the 5-year period.

4.3.3 Utility PQ event dashboard

This dashboard presents the dip performance of a utility over time. Brushing and linking simplifies the analysis of root cause. Visibility is made possible on:

- Identify re-occurring events.
- Rank the dip performance of all sites.
- Ranking of incident attributes.
- Distribution of NRS048 dip types.

Figure 4-35 shows a conceptual design with a minor change to the approach used in the per-site dashboard. The "cause" ranks incident attributes:

- Root cause of network faults.
- Network voltage level the faults originate from.
- Network segments faults originate from.
- The party responsible for the network faults originate from.

The "effects" present:

- The dip types.
- The severity (below CBEMA curve)
- Distribution against time.
- NRS 048-2 dip-duration scatterplot

Two visualisations ranking the utility sites with regards to dip performances are also shown.

The left graph shows the amount of times each site was the worst affected site during an incident. The right graph shows the total dip count for each site.

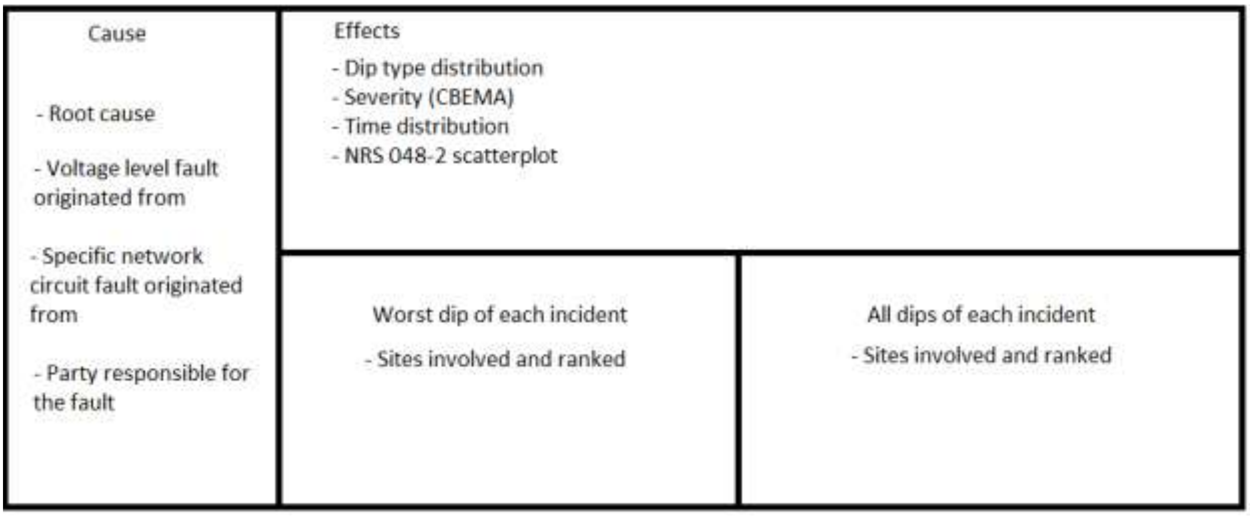


Figure 4-35: Conceptual design for utility PQ event dashboard

The implementation of Figure 4-35 is presented in Figure 4-38:

- More than 2/3 of faults occur outside the utility's network with most of root causes not explained.
- Without the unknown causes, equipment failure and local switching operations dominates internal network incidents.
- Dip type S dominates.
- 1/3 of are below the CBEMA curve.
- The dominance of the winter months shows seasonal influence on voltage dips
- The hour-of-day en day-of-the week distribution of events shows during the 13th hour and on Saturdays, which proved to be related when brushed and linked (not shown here). This suggests a re-occurring event that should be investigated.

Brushing and linking is used in Figure 4-39 to investigate the worst affected site during the highest number of incidents, which is Site 3072:

- The dips mostly originated in a single circuit. .
- A root cause should be possible to find, and to mitigate, as the operators of that network will certainly have dealt with that root cause although it was noted in the database. The importance of such attribute in a PQ database by operational personnel contributing to dip information is obvious.

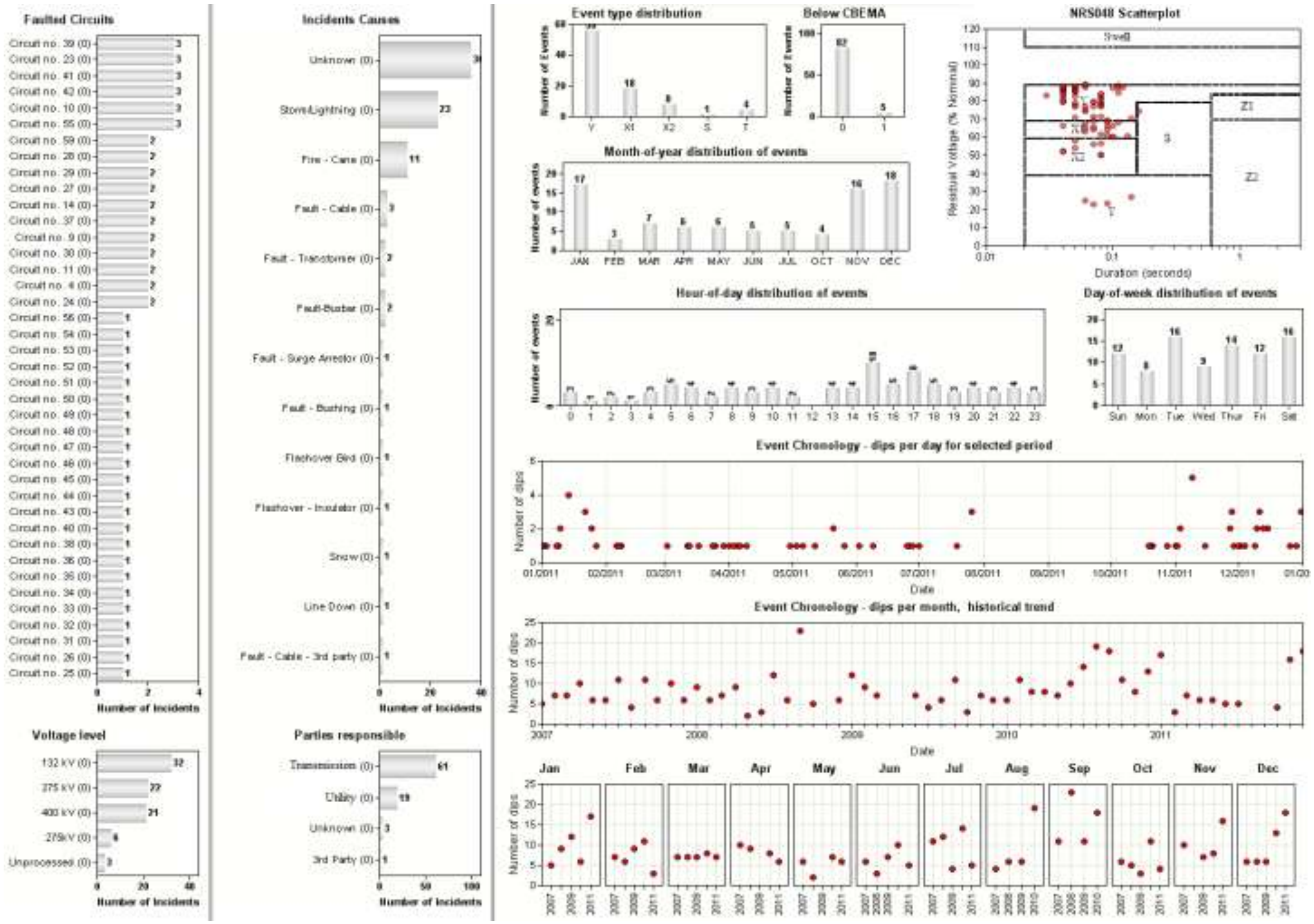


Figure 4-36 Implementation of per site PQ event dashboard

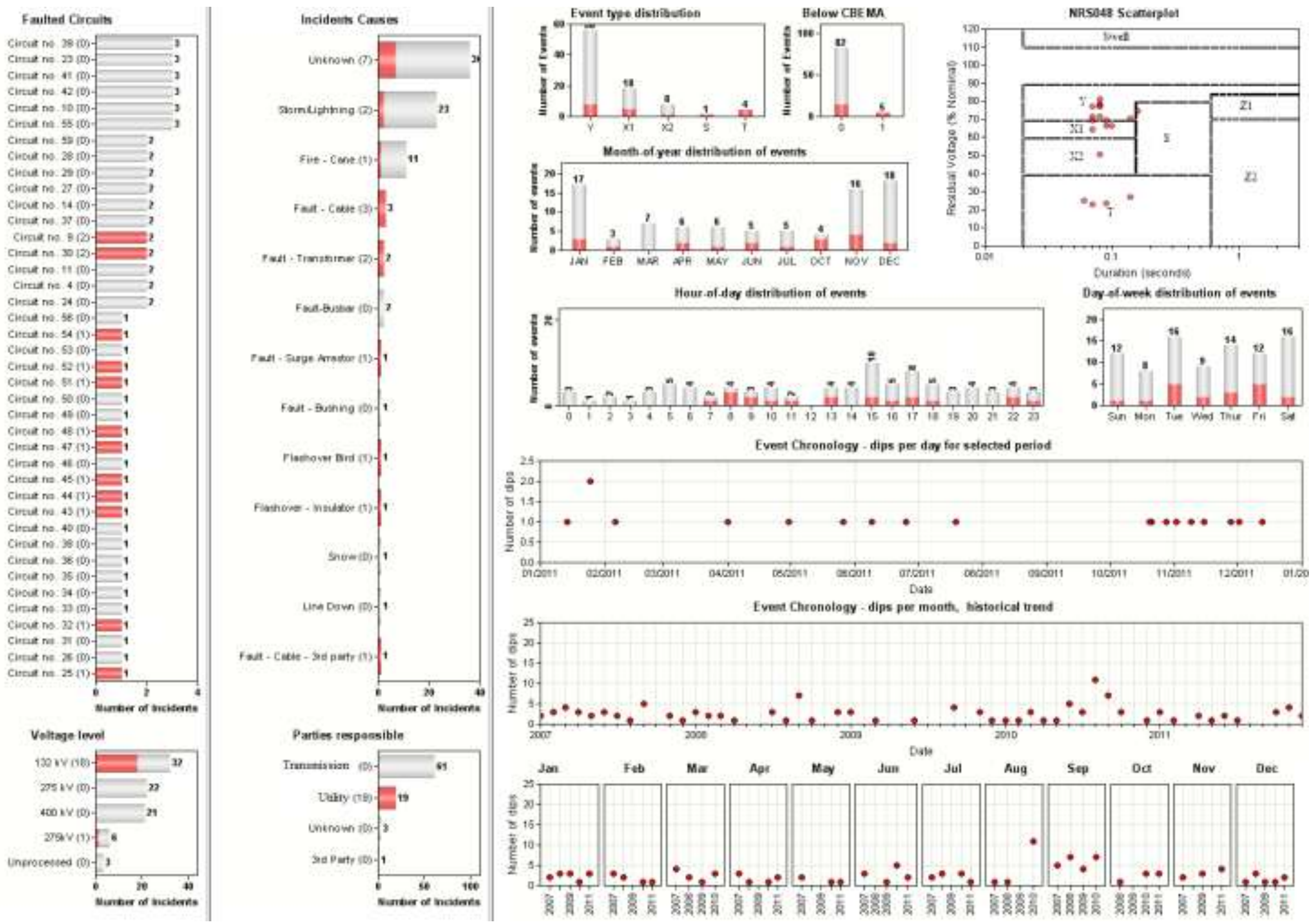


Figure 4-37 Brushing and linking employed in example dip dashboard to investigate utility responsibility

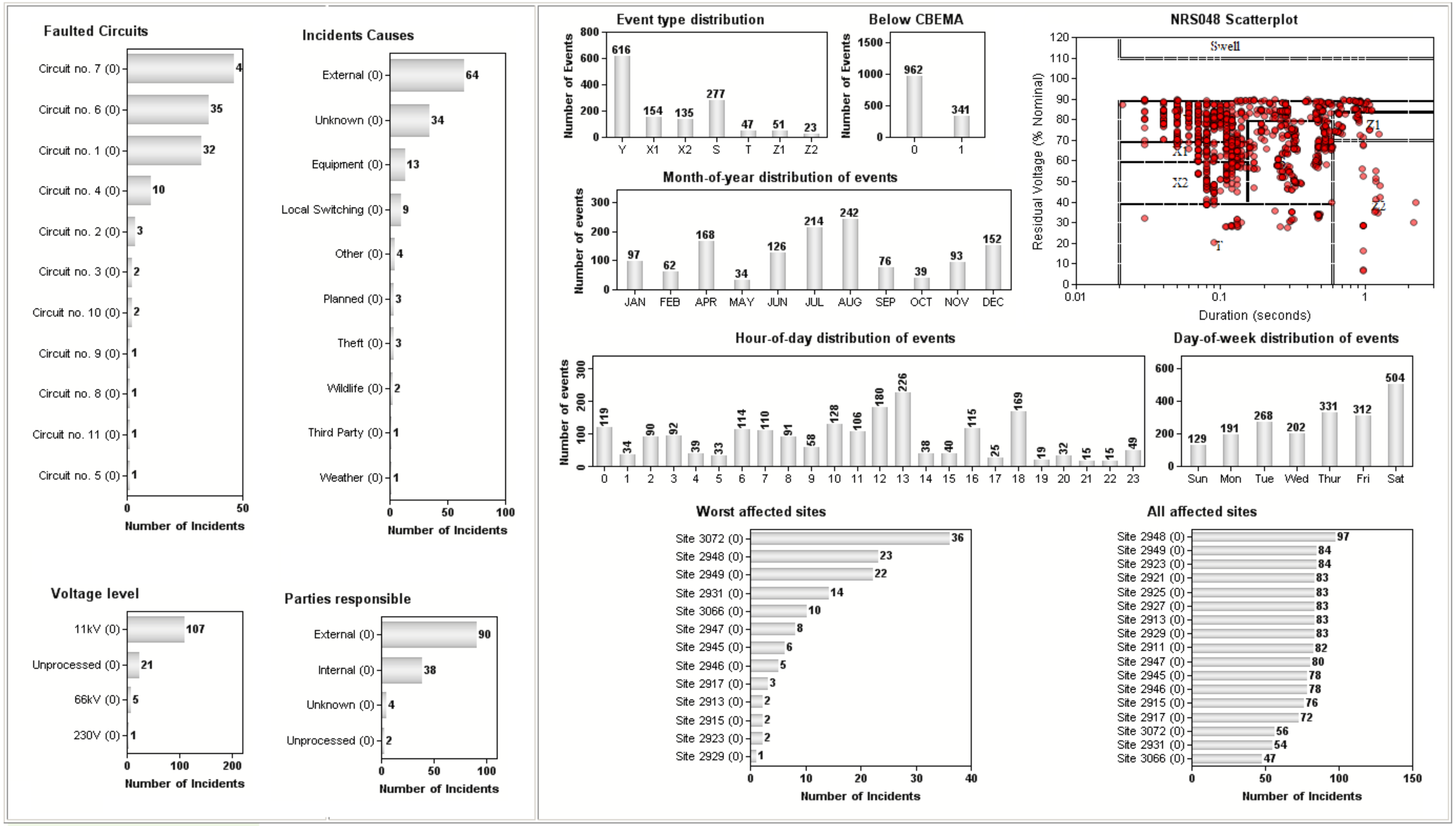


Figure 4-38 Implementation of utility level voltage dip/incident dashboard

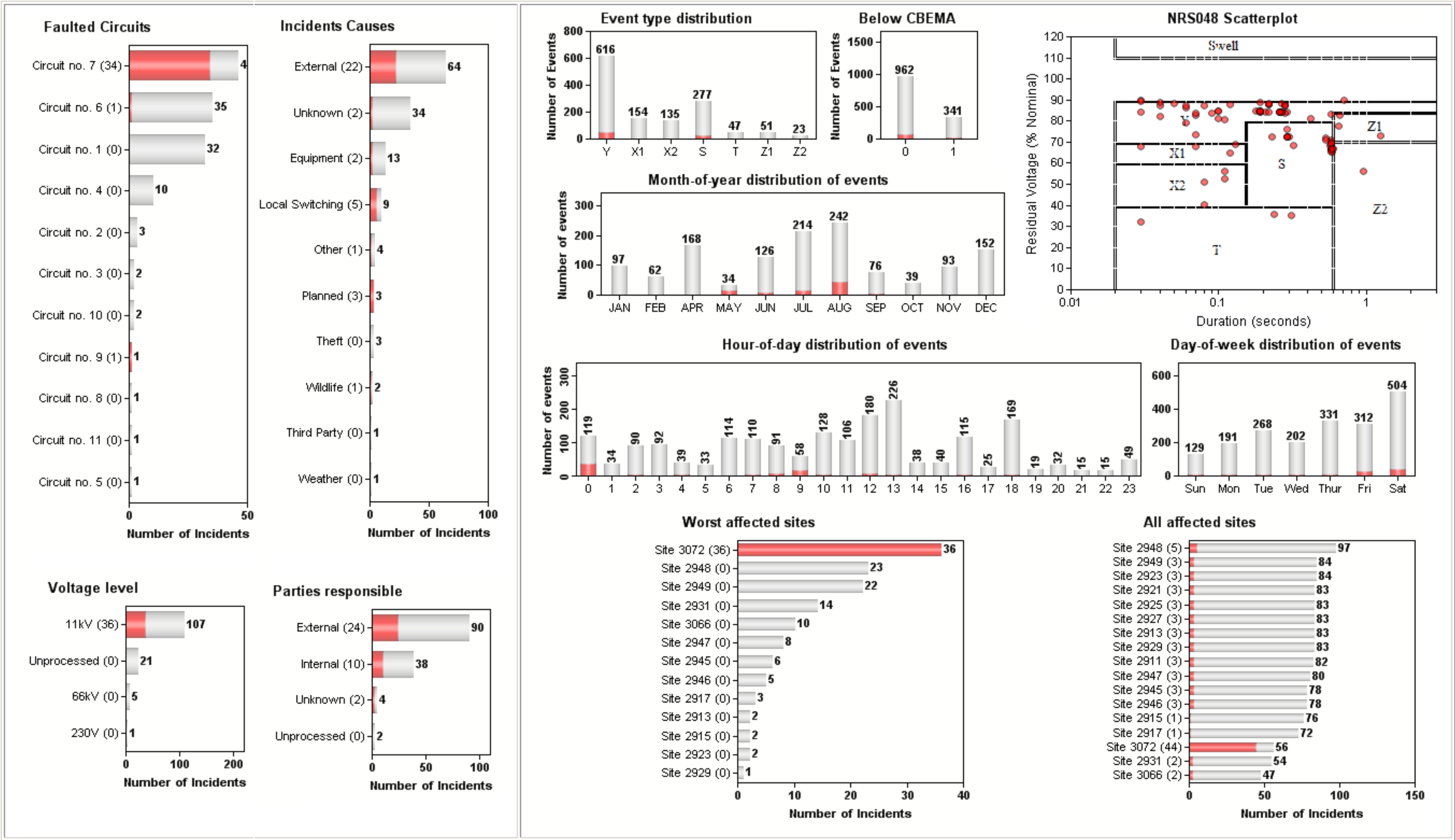


Figure 4-39 Brushing and linking employed in utility level dip/incident dashboard to investigate worst affected site

4.4 Summary

In this chapter, the NRS048 approach to dip classification and management has been presented together with the standard visualisation used during reporting on voltage dips. Further visualisations on the distributions of depth, duration and classification have been suggested. A selection of widely used single parameter dip indices has been presented and their use in ranking of dip events demonstrated in two scenarios.

Dual motivations for the use of event aggregation were given. Aggregation was shown to be useful in exposing the true network fault behaviour as well as in benchmarking performance of individual sites or networks.

The magnitude of the pre-event voltage was identified to be contextually important when investigating dips. Significant difference in the depth expressed as a percentage of nominal and percentage of pre-event voltage, indicates that poor voltage regulation contributes or in some cases is the sole cause of some dips.

Time was presented as context information by providing visualisations aimed to assist in identifying patterns in dip behaviour consistent with known consumption and seasonal cycles. Network faults and voltage dips measured throughout the network concurrently was related to each, as cause and effect through the concept of dip incidents. An interactive visualisation was presented to aid utilities, which investigate and record attributes relating to the cause of each incident, in identifying patterns and relationships in those attributes.

Protection devices were identified as responsible for the duration of a large proportion of voltage dips. Knowledge of the fault-clearing times of the protective devices employed throughout the network, aids in identifying fault location.

The interconnections of transformers, their winding connections and the wye or delta connection of measurement devices have been shown to influence the form and magnitude of voltage dips as they propagate through the network. Having this information on hand when investigating an incident aids in identifying probable fault types and locations.

Finally, example designs of interactive dashboard applications in aid of both utility and consumer management of voltage dips were presented.

5 Conclusion and Recommendation

5.1 From PQ monitoring to PQ management

Although NERSA is not enforcing license requirements, a number of utilities have collected PQ data over a number of years. NERSA requires licensees to **monitor** PQ in return for the ability to resell electrical energy.

The distinct difference between PQ **monitoring** and PQ **management** should be noted, and a move from monitoring to management should be made to attain the government assigned mandate to NERSA to regulate risk in the ESI. The operational value of the information inherently present in existing QoS data is not evident, and therefore to a large extent, not used in the daily operation of networks. Although QoS data is mostly voltage-based, sufficient network performance information can be extracted.

The research conducted and documented in this dissertation, was used to develop solutions to aid the operators of electrical networks to extract the valuable information hidden in QoS data for integration into operational processes.

Data was imported into a database called Oracle. Evaluation of concept designs was done by extensive testing on a database containing 1000+ instrument-years of PQ data recorded at a number of utilities all over Southern Africa.

The final solutions were developed as web tools to interrogate the database in context of various attributes such as time, season, voltage magnitude, voltage level, electrical circuit etc. Powerful information can be extracted and was proven useful for much more than the minimum statistical reporting theoretically required be NERSA. Benchmarking was shown to be possible as an operational tool to be used on a daily basis.

Voltage magnitude was shown as the most significant parameter contributing to non-compliance. Poor voltage regulation was found to be mostly the result of the lack of network operators integrating the visibility of voltage performance into the operation of networks. The common excuse of fault impedance being the culprit was revealed as not true.

Innovative database interrogation was made possible by implementing brushing and linking techniques. It visually revealed powerful information to be used in the forensic analysis of voltage dips.

5.2 Voltage Magnitude

An improvement to the NRS 048-2 assessment method of voltage magnitude was demonstrated by taking cognisance of how voltage unbalance can skew the results obtained. The existing assessment methodology can be a cause to a utility not complying to compatibility criteria on both magnitude and unbalance as the proper context is lacking.

An alternative method for voltage magnitude reporting based on the per-phase voltages was shown to add context to the non-compliance to compatibility. The practical value to network operators is to validate the priority set to sites of concern.

Two parameters were derived from the NRS 048-2 retained values for voltage magnitude, which expresses the performance in terms of attributes under the control of, or at least of practical significance to, the utility. The parameters are the deviation from nominal and the spread of voltages for 90% of the time. An intuitive visualisation was developed for these parameters, which proves successful in communicating performance of both a single site and a network of instruments concisely.

Time was introduced as context information when analysing voltage magnitude performance. It was revealed that the majority of non-compliant sites in the dataset do not have inherent problems with voltage regulation, but with the declaration of the nominal voltage at the site. Sites that have inherent voltage magnitude regulation constraints were identified by the newly introduced $V_{spread\ 90}$ parameter.

Interactive dashboard designs for voltage magnitude management were also demonstrated.

5.3 Voltage Dips

The NRS 048-2 dip assessment methodology defined responsibility for the management of different dip classes, by probable causes for different dip classes. Innovative data visualisations were developed and implemented to aid the forensic investigation of voltage dips.

An improvement in voltage dip recording was proposed and demonstrated as the fixed voltage dip thresholds set by the NRS 048-2 for distribution network operators, introduce fake dips to be recorded. Measurement anomalies are automatically detected by the alternative dip threshold principle and used to flag the 10-min V_{RMS} values during the assessment process. It was tested and shown to remove the masking of bad voltage magnitude performance during dip assessment.

The presence of fake dips was shown to be useful as an opportunity to implement an early-warning system for voltage magnitude problems if smart grid principles are considered.

Single indice dip assessments were presented and demonstrated as effective in the ranking of dips over a period for a single site, as well as identifying the most severely affected measurement point of a network incident.

The aggregation of several dip indices for benchmarking purposes was tested to what constitutes good and bad dip performance. Using combinations of them reveals more about the underlying facts.

The NRS 048-2 assessment of voltage dips in distribution networks was shown to be improved in the interest of network management if the depth of the dip is referenced both from the nominal voltage of that site and from the voltage level immediately prior to the dip.

Time as context was investigated. Visualisations were developed to aid in the identification the influence residential, industrial load cycles, as well as seasonal patterns have on dip performance.

The formal association of several dips observed in a network through the concept of an incident was presented as another use of time as context. The reduction of the count of individual dips to incidents was shown to be significant, especially for utilities with large numbers of instruments. This reduction directly translates to the reduction in effort to investigate every voltage dip occurring in the utility network. Formalising the association in a database application enables the capturing of root cause information for each incident only, which automatically associates that information with each dip.

Interactive visualisation was demonstrated to investigate incident attributes as context information. It enabled the identification of patterns in time distribution of each attribute, as well as the relation between different attributes.

PQ event dashboards recognising network connectivity, transformer-winding configuration was developed in the support of voltage dip management practises. Information on the root cause, type of fault and origin in the network could benefit. A significant conclusion is that the presence of voltage dip type B after a zero-sequence removing type of transformer (all but YNyn transformers) identifies the fault as internal to the network.

5.4 Recommendation

PQ management in Southern Africa at distributors of electrical energy will not realise if PQ data produced by PQ monitoring is not recorded in databases to enable extraction of information to enable network management. Best practises in risk management for the ESI is not developing due to energy regulators not stimulating research and development in PQ at large. Limited knowledge of PQ is needed if network operators can query PQ databases by means of innovative tools made possible by visualisation, brushing and linking, context as attribute etc.

It is recommended that NERSA service the ESI by adopting changes to the PQ Directive to provide clear guidelines on how to grow a PQ monitoring programme to a PQ management programme. Deficiencies in the PQ Directive, the NRS048-2 assessment of PQ and other constraints should first be acknowledged at a regulatory level. Implementation is straightforward since modern computing, communication and database technology has eradicated the barrier-to-entrance.

Investing in research at tertiary institutions to translate the user requirement of the PQ directive to operational requirements is firstly required. Then process-specific solutions should be developed, to meet the requirements which will benefit not only the developing Southern African ESI significantly, but also the transition to a developed region.

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