ON THE ADEQUACY OF ELECTRICITY RELIABILITY INDICES IN SOUTH AFRICA

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Abstract: This paper investigates ways of describing the reliability performance of an electric power grid. Traditional indices such as SAIDI, SAIFI and MAIFI are inadequate for many comparisons and assessments of reliability. They do not reflect financial, economic or socio-political effects of poor reliability. Southern African decision makers in the supply industry, in the national regulator and among customers urgently need clarity on the subject of reliability and guidance on appropriate methods to manage it. This paper examines the extension of existing approaches to reliability indices and describes alternatives based on recent research in the areas of reliability assessment, costs of interruptions and social response to interruptions.

Keywords: Reliability indices, power system reliability, cost of interruptions.

1. INTRODUCTION

In November 2014 the financial analysts, Moody's, downgraded the South African economy citing among its reasons the threat of electrical power shortfall. Also in November, a collapsed coal silo at an Eskom power station lead to load shedding. Clearly, the electrical supply structure in South Africa is weak and vulnerable. In this paradigm it is vitally important to use accurate, effective and appropriate grid performance indicators for making management decisions. These decisions have significant financial implications. In an economy that is already strained by world markets, labour issues and huge debts it is imperative that decisions are made that will result in the greatest benefit for all the stakeholders. These include the users of electricity, from which wealth is derived and the power supply entities, including Eskom. To lend confidence to investors and local industry the supply should be seen as both sustainable and of an acceptable quality. The South African Regulator has the responsibility to monitor the supply and issue regulations, and for this purpose indicators must be employed to monitor both sustainability and quality. In this case the mechanism is the regulation of tariffs and some cases the imposition of penalties. To compound the problem energy theft and non-payment of electricity bills is still rampant in South Africa.

In this paper we look at traditional grid performance indicators, or reliability indices, and examine their usefulness in guiding decisions relating to grid operation and planning. We refer to research done and some publications that suggest a fresh approach that is probabilistic and time-dependent. It combines both frequency and duration of failures resulting in a measure that is amenable to interpretation by non-technical financial managers. The proposed reliability index expresses the expected performance at load points in the system in terms of value at risk.

2. INTERRUPTIONS: STAKEHOLDERS AND ROLE PLAYERS

Faults on power systems affect the consumer as well as the supplier and also involves body responsible for monitoring and regulating the supply process – the national regulator.

Figure 1 shows the entities affected by and contributing to the overall reliability of the power delivery system. In the past the generation and transmission in South Africa were closely linked and operated by Eskom, while the distribution to industrial, commercial and residential customers was shared by municipal undertakings and Eskom. Generation now includes independent power producers, especially employing wind and solar energy sources, while non-traditional distributors serve some customers.

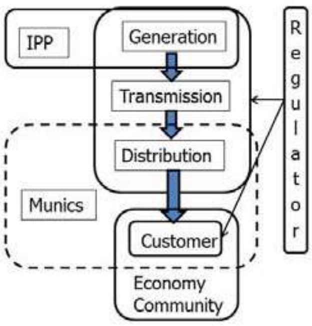

Figure 1. Stakeholders and role players in power system reliability.

The following causes of faults have been identified and characterised for failures on transmission lines in South Africa [1]:

- Lightning
- Fires
- Pollution
- Bird streamers
- Wind storm damage
- Other

However, interruptions can occur in generation simply through inadequacy to meet the load demand, or through external causes or equipment failure throughout the system of generation, transmission and distribution. These interruptions affect the utilities, the customers, the economy and the society.

The utilities experience loss of revenue through energy not served and incur expenses in repairing or replacing damaged equipment. The National Regulator monitors the supply process and responds to complaints about continuity and quality. It regulates tariffs and might also impose penalties for failure to meet supply agreements.

Irrespective of the cause of the outages, the customers suffer loss through damage or lost production and/or sales. Certain customers are more heavily affected than others due to the nature of their application of electrical energy. The effects of the disruption of supplies to customers can be measured by evaluating customer interruption costs (CIC).

A host of associated infrastructure functions that serve a society, such as transport, water supplies, sewerage, emergency services etc. are directly dependent on electrical power. When there are frequent and/or lengthy disruptions the community and the society are very severely affected. This problem is universal and has been widely reported [2, 3].

Lower voltage distribution lines operated by utilities and municipalities in both urban and rural environments are vulnerable to faults caused by weather, birds and animals and even by unintended human interference like vehicle accidents. However, other sources of disruption include theft of energy (illegal connections) and of conductors.

3. CONVENTIONAL RELIABILITY INDICES

A wide variety of indices has been defined to measure the adequacy and interruptions of electricity supplies [4]. In this section we examine only the most common reliability indices based on the following definitions [4] for interruptions of different durations:

- Momentary Interruption – A single operation of an interrupting device that results in a voltage zero
- Momentary Interruption Event – An interruption duration limited to the period required to restore service by an interrupting device. This must be completed in 5 minutes
- Sustained Interruption – Any interruption not classified as a momentary event.

3.1 SAIDI, SAIFI and MAIFI

System Average Interruption Duration Index (SAIDI) indicates the total duration of interruptions for the average customer during a given time period, usually on a monthly or yearly basis. Each interruption to a customer during a sustained interruption is multiplied by the duration experienced and then summed to give the total customer minutes (or hours) during the basis period. It is then divided by the total number of customers on the system. Thus, SAIDI (in minutes) can be expressed as:

$$SAIDI = \Sigma(r_i \times N_i)/N_T \qquad (1)$$

Where
r_i = Restoration time in minutes
N_i = Total number of customers interrupted
N_T = Total number of customers served

Only the sustained interruptions are considered, i.e. those longer than 5 minutes, to allow the utility time for automatic restoration [4]. However, short interruptions can never-the-less adversely affect the customers although the duration is excluded from the index.

The System Average Interruption Frequency Index (SAIFI) describes the average number of times a system customer is interrupted during a given period of time and is expressed as:

$$SAIFI = \Sigma(N_i)/N_T \qquad (2)$$

In essence SAIFI expresses the probability of customers experiencing an outage within a given time frame.

Since customers can be adversely affected by momentary interruption events the Momentary Average Interruption Frequency Index (MAIFI) was introduced, defined in the same way as SAIFI, but only for the momentary interruption events excluded from SAIFI

These three indices may be applicable to the whole power system or any part of it.

Two similar indices, CAIDI and CAIFI, are customer-based instead of system-based. They and others that reflect power or energy interruptions are used widely in reliability analysis.

3.2 Discussion of conventional indices

Some reliability indices are used to compare the performance of the electricity systems of various utilities or countries in so-called 'benchmarking' surveys. In practice, the indices are difficult to compare because they refer to networks with different customer densities, constructed using different technologies, and/or in regions exposed to different intensities of the conditions causing the faults. The disparities between indices can be so large, with ratios of up to 60 between indices for different systems, that it is possible even to confuse comparisons based on annual values of SAIDI expressed in minutes and hours.

Most conventional indices are based on average values. These averages (means) give no indication of the dispersion of the interruption data or the extreme values experienced by the worst served customers. Average value indices can be misleading when used in applications sensitive to the full probabilistic spread of the data. Minnaar *et al*. [1] analysed transmission system fault data and concluded that faults were often time, region and season dependent. For example, in South Africa, outages caused by lightning in the summer rainfall area are most likely to occur during the summer months between 12:00 and 18:00. They also showed that the statistical distributions of fault frequency and duration were often skew with large dispersion and could be modelled with a Beta PDF. A probabilistic approach that includes both a specified level of risk in specific time windows of occurrence, which can be paired with the power or demand on the system, provides a more realistic measure of the likelihood of events on the power system and how serious they might be.

A separate problem arises in the under-reporting of momentary events. MAIFI is not often reported in reliability data because it is difficult to know when the short interruptions occur and, where reported, the index is generally only measured at the substation level. Faults on medium and low voltage feeders could go unrecorded and, importantly, a large number of affected residential and small commercial, industrial and agricultural customers could be ignored. These customers may form a significant component of the community and excluding their reliability assessment can exacerbate negative social sentiments.

Recent research has addressed some of these issues and provides approaches to applying reliability indices in small and large power systems and from high voltage to low voltage. Three of these approaches are described in the following sections:

- Considering the probability density functions (PDFs) of the interruption statistics leads to a time dependent probabilistic approach to reliability analysis.
- Factoring the economic costs of interruptions to customers (CIC) into the reliability analysis leads to estimates of the value at risk, a term widely used in the risk sector.
- Surveying the customers' perceptions of interruptions leads to a different, non-technical view of reliability in terms of social acceptance.

4. TDPA ANALYSIS

Most quality of Supply indices are not averages but 5% or 10% risk values or limits, as for example in respect of voltage magnitude and voltage dips. Edimu *et al.* developed a time-dependent probabilistic approach (TDPA) to reliability analysis of a power system subjected to interruptions caused by the various causes of faults listed in section 2 [5,6]. By taking cognizance of the time and seasonal dependence of faults, a 16-cell time matrix proposed by Herman and Gaunt [7], is used to describe frequency and duration of various fault categories, as shown in Table 1.

Table 1. A 16-cell time matrix with Beta PDF shape parameters defined for all or a specified sub-set of faults

Period or season	**Daily time intervals (hrs)**			
	0000 - 0600	***0600 – 1200***	***1200 – 1800***	***1800 – 2400***
1	$\alpha_{11}\,\beta_{11}\,C_{11}$	$\alpha_{12}\,\beta_{12}\,C_{12}$	$\alpha_{13}\,\beta_{13}\,C_{13}$	$\alpha_{14}\,\beta_{14}\,C_{14}$
2	$\alpha_{21}\,\beta_{21}\,C_{21}$	$\alpha_{22}\,\beta_{22}\,C_{22}$	$\alpha_{23}\,\beta_{23}\,C_{23}$	$\alpha_{24}\,\beta_{24}\,C_{24}$
3	$\alpha_{31}\,\beta_{31}\,C_{31}$	$\alpha_{32}\,\beta_{32}\,C_{32}$	$\alpha_{33}\,\beta_{33}\,C_{33}$	$\alpha_{34}\,\beta_{34}\,C_{34}$
4	$\alpha_{41}\,\beta_{41}\,C_{41}$	$\alpha_{42}\,\beta_{42}\,C_{42}$	$\alpha_{43}\,\beta_{43}\,C_{43}$	$\alpha_{44}\,\beta_{44}\,C_{44}$

Adopting the approach of modelling only the down states of the power system in a Monte Carlo simulation, it became possible to reduce the calculation time for a system reliability study by more than a factor of 30 compared with the conventional approach [5]. Within any 6-hour window of Table 1, probability-based indices may be calculated for any chosen level of risk (or confidence) for use in operational procedures. The application is similar to that of a contingency analysis, except that in contingency analysis a different level of risk is associated with each fault possibility. Deterministic contingency analysis, assessing the effects of an (N-1) event, is appropriate for small systems, but as systems increase in size and complexity the possibilities of concurrent failure of more than one element, and risk of failure of parts of the system, become realistic, and can only by modelled probabilistically. The same TDPA can also be used for planning by extending the window of analysis from 6 hours to a full year, thereby correlating the seasonal and time-of-day availability of generation, likelihood of faults and load demand of the customers. Further, because a probabilistic method is used, selected levels of risk can be included by assigning a level of statistical confidence to the resultant PDFs of system failure.

5. COST OF INTERRUPTIONS

The financial impact of interruptions was briefly mentioned in section 2. Dzobo *et al.* examined the effects of interruptions on various types of customers as well as at different times of the day and season of the year [8]. As in the case of the reliability assessment it was found that the Beta PDF could be used to describe CIC and that the time 16 cell time matrix was appropriate for explaining the variability in cost. Dzobo *et al.* went on to demonstrate that customers could be categorised into segments, each with its characteristic CIC description [9].

Now, by combining the TDPA reliability analysis and the CIC concepts it is possible to consider a geographically located load bus within a power system, calculate the probabilistic frequency and duration statistics of likely faults, aggregate the load types and determine the likely cost of outages. This value at risk can be expressed in monetary terms for a specified level of risk, for example in South Africa as Rands at risk: R@R.

Various combinations of the cost of interruptions to the economy as a whole, a utility's loss revenue, or the costs seen by customers allow the consequences of a probability-based loss of reliability to be assessed. Such information expressed in monetary terms is useful for decision-making in financial and regulatory management.

6. SOCIO-POLITICAL EFFECT

The financial impact of interruptions on industrial and commercial customers can be assessed probabilistically using the R@R measure. When interruptions are long and frequent the collective impact affects the economy of the community. This leads to dissatisfaction with the services followed by the threat of disinvestment and can spill over into the socio-political area. However since there are more individual residential customers the socio-political impact on poor service is even greater. This has been demonstrated in South Africa where protests and even riots have erupted.

In a case study, approximately 230 households were surveyed in two low-income settlements in South Africa. One settlement comprised formal housing and the other only shacks, and both were fully electrified. Households were surveyed about a range of issues related to their energy use, one of which was their perceptions of the number of interruptions they experienced and overall satisfaction with the reliability of their electricity supply. Residents in the communities estimated the typical number of interruptions during winter months as 1.8 to 2.6 incidents per month. Virtually all households reported that there were more frequent interruptions in winter than during summer months. In contrast, data provided by the utility indicates there were only 1 and 3 incidents *per year*, the average values over several years being 1.4 and 2.2 interruptions per year. The average duration of interruptions was 2.7 hours and 2 hours respectively.

More than 90% of respondents in the poorer area expressed dissatisfaction with the reliability of their electricity supply. In comparison, only 25% of the sample in the formal housing settlement expressed dissatisfaction with their supply.

The seeming disparities between the perceptions of survey respondents and the utility's data may arise from a number of reasons. First, the accuracy of self-reported data on recollections about past events in surveys is affected by recall bias. This is especially true for emotive topics, of which the quality of service delivery in South Africa is one. This information error could lead to respondents overestimating the number of outages they experience. Secondly, the utility collects data on interruptions at sub-station level, thus excluding low voltage incidents. Typical events affecting low voltage systems include weather related events, trees or vegetation interfering with lines, theft/vandalism, meter failures and other technical faults. Thirdly, the utility data does not reflect momentary interruptions; only those of longer duration. The utility's measured data could therefore under-estimate the number of interruptions, although the extent of such potential under-estimation cannot be determined. The omission of low voltage system and momentary interruptions from reliability indices is not unusual in South Africa.

Poor reliability may compromise (to a degree) the beneficial societal outcomes of having access to an electricity supply for low-income customers. For low-income residential consumers some of the potential impacts of unreliability may be direct financial loss where it interrupts economic activities, spoilage of food, inconvenience, increased feelings of vulnerability and crime on dark nights. Perhaps most significantly an unreliable electricity supply may increase the usage of and consequent risks associated with alternative fuels like paraffin and candles. Understanding the societal and economic impacts (for all sectors) may give more insight into what appropriate thresholds for an acceptable minimum level of utility's reliability performance may be.

7. DISCUSSION

Conventional reliability measures based on deterministic methods using average values of fault duration and frequency have limitations. Generally, they provide indices that are compared with standards adopted from historical performance or derived from other power systems. Such indices do not reflect the basic purpose of power systems to supply electricity economically or to meet social requirements.

In conventional long term planning approaches, known component failure rates are used in deterministic reliability analyses to predict SAIDI and SAIFI and indices of the energy not supplied, but these are average values and do not indicate the possible extremes that can arise. Similarly, contingency analysis for (N-1) events to examine the operational risk of system interruptions compares possibilities with different probabilities of occurrence.

These approaches may no longer be useful decision guides for more complex systems.

The TDPA to reliability analysis incorporates both e dispersion of fault data and presents a range of outcomes according to the risk levels needed by system planners and operators. Adding CIC data allows a value index, R@R, to be derived, which is consistent with other financial indicators associated with investment and risk exposure decisions. The same analytical approach for system operations analysis is appropriate to system planning and is based on consistent data sets and confidence levels.

Even as simple measures of system performance, SAIDI, SAIFI and MAIFI do not adequately reflect the perceptions of customers, partly because some of the interruption data are omitted from the indices by definition. Surveys of the social responses to interruptions indicate discrepancies between utility reliability indices and customer perceptions. It appears more research is needed in this area to inform utilities and regulators, and to establish objective standards of performance. Bringing together the technical and societal elements of reliability poses some interesting problems for researchers and regulators.

In this last respect, there could be a requirement for inexpensive interruption monitors suitable for low voltage feeders. Such monitors would be consistent with the concept of smart grids and fill the data gap not met by smart meters with a sampling cadence of only 15 minutes. The monitors should measure and distinguish between momentary and sustained interruptions as presently defined.

8. RECOMMENDATIONS AND CONCLUSION

The conventional indices for reporting the reliability of electricity supply appear to be inadequate for decision making in modern power systems.

It is recommended that indices more closely related to value-based decision making are needed, and the R@R index derived from the TDPA reliability analysis should be considered in more detail for application in South Africa.

Value based reliability measures will need to be supported by more comprehensive CIC data than already collected by researchers at UCT from residential, commercial and industrial customers, but the techniques for collecting the data efficiently have already been developed and published.

At the same time, utility and regulatory staff will need to be trained in probabilistic reliability assessment.

It also appears that broader assessment of the social and political responses of communities to interruptions is desirable, especially in the context of the present attitudes to electricity supply utilities in South Africa.

9. REFERENCES

[1] U.J. Minnaar, C.T. Gaunt and F. Nicolls: Characterisation of power system events on South African transmission power lines. *Electr. Power Syst. Res.*, Vol 88, 2012, pp 25-32. doi:10.1016/j.epsr.2012.01.015

[2]http://www.energyathaas.wordpress.com/2012/11/04/measuring-the-economic-costs-of-electricity-outages/ (Accessed 14 Nov 2014)

[3] http://www.enca.com/coverage/power-outages-sa?gclid=CIaCy4O2-cECFRMatAod0DsAjA (Accessed 14 Nov 2014)

[4] IEEE Power Engineering Society. *IEEE Std 1366:-2003 IEEE Guide for Electric Power Distribution Reliability Indices*. New York: Institute of Electrical and Electronics Engineers, Inc. 2014. 35 pages.

[5] M.Edimu, C.T. Gaunt and R. Herman: "Using probability distribution functions in reliability analyses", *Electr. Power Syst. Res.*, Vol 81, I (4), April 2011, pp 915-921.

[6] M. Edimu, K. Alvehag, C.T. Gaunt and R. Herman: "Analyzing the performance of a time-dependent probabilistic approach for bulk network reliability assessment", *Electr. Power Syst. Res.*, Vol 104, year 2013, pp. 156 – 163.

[7] R.Herman and C.T.Gaunt: "Probabilistic Interpretation of Customer Interruption Cost (CIC) Applied to South African Systems", *PMAPS2010*, Singapore, June 2010.

[8] O. Dzobo, C.T. Gaunt and R. Herman, "Investigating the use of probability distribution functions in reliability-worth analysis of electric power systems", *International Journal of Electrical Power and Energy Systems*, Vol 37, May 2012, pp110-116.

[9] O. Dzobo, K. Alvehag, C.T. Gaunt and R. Herman: "Multi-dimensional customer segmentation model for power system reliability-worth analysis", *International Journal of Electrical Power & Energy Systems*, Nov 2014, pp 532–539.