DESIGN PARAMETERS FOR LV FEEDERS TO MEET REGULATORY LIMITS OF VOLTAGE MAGNITUDE

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ABSTRACT

Various algorithms are used by utilities and independent designers for the design of LV feeders to meet voltage magnitude requirements of low voltage feeders, but until now none have been linked formally to the measurement assessment incorporated in quality of supply standards. This paper addresses the link between design and expected performance relative to quality of supply regulations.

INTRODUCTION

Research into customer load models and their application to designing LV feeders has a long history. The work is necessary because limits are imposed by governments and regulators on the voltage variation of electricity supplies to customers, one aspect of the quality of supply (QOS). The variations and violations of the limit values can be measured and the methods of assessment are specified in standards. Therefore, planners and designers of the distribution networks need to predict the variation, particularly the lowest voltage, before feeders are installed. To do this, they need load models and algorithms to transform the load models to voltage drop, according to which decisions are taken about the adequacy of the proposed network.

Efforts to improve the quality of voltage drop prediction have led to different models and calculation methods evolving with time and being adopted in various countries. Most models are based on experience and incorporate many assumptions with large 'factors of safety'. The evolutionary development of empirical methods might be satisfactory under steady or slowly changing conditions, but electricity distributors now face rapid change in four key areas:

- The nature of electrical loads is changing with attention being given to energy efficiency and renewable energy.
- Regulations for QOS change because of pressures from other countries to harmonise standards and because of perceived changes of the needs of customers, especially with competition in the electricity distribution industry.
- Advanced metering will provide much more information about violations of the QOS limits.
- About 25% of the world's population, mostly in developing countries, still lacks access to electricity, and the models that evolved in developed countries are not appropriate to the loads, the distribution networks needed to supply these new customers and, possibly, extravagant 'factors of safety' in the design approaches.

An algorithm that was reported at CIRED [1] has been used in conjunction with extensive load data to develop an approach to identifying the characteristic design parameters for low voltage feeders that will give quantifiable, risk-based performance in the same terms used to specify allowable voltage drop on a feeder. The approach extends the effect of the reported algorithm, based on the load at the time of system maximum demand, to cover the loads during any time of the year, as they might be assessed by a QOS measurement.

The approach allows different formulations of voltage variation standards and regulations to be tested in relation to each other, such as with measurements over shorter or longer averaging periods and the exclusion of 'extreme' values from the assessment.

The benefit of the new approach is that a consistent and reproducible definition of the limits of (steady state) voltage variation can be adopted by regulators. Designers can plan feeders that meet the requirements of the regulations.

KEY ASPECTS ALREADY REPORTED

The following details have already been reported at CIRED [1] but are summarised here for elucidation:

- Characteristic loads on LV feeders can be conveniently and appropriately modelled as currents.
- The distributions of the magnitudes of loads are not modelled well by a Gaussian probability density function (pdf) but Beta pdfs have been shown to fit measured data well.
- A Beta pdf load model of future expected customer groups can be based on measurements of existing customers with similar characteristics.
- An algorithm was developed that transforms a Beta pdf model of loads into a Beta pdf model of voltage drop, from which a design value can be chosen representing a level of confidence that the voltage drop will not be greater than calculated. The algorithm is usually applied in design using parameters of a load model of the ***after diversity maximum demand*** (admd), but can be applied with any set of parameters modelling conditions during any other period. After rigorous testing, this 'Herman-Beta' (HB) algorithm was adopted in the South African national guideline for electrification as the standard method for calculating voltage drop.
- A method, termed a beta parameter plot, was developed that can show all load measurements during an extended period.

Later, a relationship was identified between the admd and the coefficient of variation of the customer loads [2].

QOS REQUIREMENTS

Since the terms, values and processes of assessment of the limits for voltage variation in QOS specifications are not the same in all jurisdictions, the following general approach is used here as an example.

Measurement, assessment and compliance

Voltages are measured between the phase and neutral at the point of supply to a customer for a period of at least a week. Measurements at short intervals are averaged over 10 min and recorded.
The most extreme value is identified. Then 5% of the measurements may be regarded as extreme values and their magnitude considered not greater than the limits of 95% of the measurements.
The most extreme voltage measurement shall be within ±15% of the nominal voltage, and no two consecutive values shall be outside the nominal voltage ±10%.

In general, customers subject to low voltages will not also experience very high voltages, so for the purposes of this paper all violations will initially be considered to be conditions of low voltage.
The problem that arises is that no practical link has been identified between the QOS requirements and the parameters used for distribution feeder design.
Many feeders in UK are designed using the expected admd, with correction factors to compensate for unbalance and loss of diversity that are assumed to calculate the voltage limit with 90% confidence, such that voltages will approximately meet the QOS requirements. Similarly, the guidelines for the application of the HB algorithm in South Africa allow the use of 90% confidence (or 10% risk) in the voltage drop calculated using beta parameters of the admd. Another approach, used in Germany, is to calculate the voltage drop using profiles of the average load and allow a substantial margin between the maximum calculated voltage and the permitted limits.
Seemingly then, most design methods are based only on the maximum demand conditions and no specific provision is made for other measurement periods of a QOS assessment or for linking the design to the allowable violations of the voltage limits.

BETA PDF LOAD MODEL

For every measurement interval, the mean (μ) and standard deviation (σ) of the load measurements of all the customers can be calculated. The shape parameters of the Beta pdf are α and β. A scaling factor c is chosen, at least as large as the highest individual load measured. The five parameters μ, σ, α, β and c are related and defining any three of them fixes the other two. Thus, with μ and σ from a sufficiently large sample of measured loads to be statistically relevant, and selecting a suitable value for c, α and β are given by:

$$\alpha = \mu(c\mu - \mu^2 - \sigma^2)/c\sigma^2 \tag{1}$$

and $$\beta = (c-\mu)(c\mu - \mu \ \ - \sigma^2)/c\sigma^2 \tag{2}$$

Eq. 1 can be rearranged to:

$$\alpha = -(s^2+1)\frac{\mu}{c} + s^2 \tag{3}$$

where coefficient of variance, $\gamma = 1/s = \sigma/\mu$ (4)

BETA PARAMETER PLOT

The parameters α and the normalised mean μ/c of Eq. 3 derived from a sample of coincident customer loads measured over a period of 10 minutes represent the whole community for that period of measurement. One week of 10-minute periods yields 1008 measurements and there are slightly more than 50’000 10-minute periods in a year.
A plot of α against μ/c for all the measurements represents the beta pdf of loads at all times of day for the whole of the chosen period of monitoring. The plot is called a beta parameter plot (bpp). A bpp for one week of 10-minute measurements is illustrated in Fig 1. The relevance of the lines of various values of γ will become evident later.

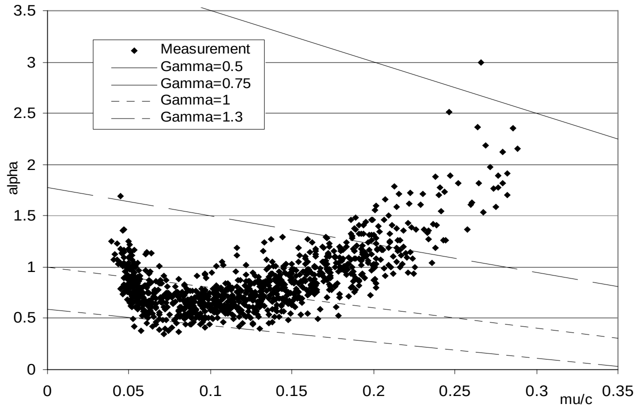

Fig. 1: BPP for Wn, 22-28 Jul 2000. (c=51.1A, n=65)

The mean μ associated with each plotted 10-minute measurement is the after diversity demand (add) for that measurement, and the maximum value during the whole period of monitoring is the admd. The ***characteristic admd*** for a community of customers with similar traits in terms of their electricity usage is the admd as the number of customers sampled tends to infinity. In practice, because of the difficulty of defining the traits of customers, the error of estimating the characteristic admd μ_{max} is insignificant once the numbers of customers sampled exceeds about 150 and measurements have been collected for long enough to be likely to include a typical system maximum demand.
It is clear from the bpp that the characteristic admd is a line and not a point, and a wide range of values of α or γ could be associated with a single value of admd. Accordingly it is useful to define the ***characteristic admd parameters***, μ_{max} and γ_{admd}, typically associated with a community or class of customers.

LOAD DATA COLLECTED IN SOUTH AFRICA

The NRS Load Research programme collated more than 500 million measurements of loads from about 2300 households in 33 communities. Measurements were made over 5-minute averaging periods (Nyquist criterion to sample at twice the frequency needed to interpret the measurements) and the basic data can be re-compiled as rolling or discrete data in any multiples of 5 minutes. Extensive analysis of the data provided estimates of beta parameters that characterised the maximum demand periods for all the customers in various groups described by their urban or rural location and electricity use. Data extracted from the results of the analysis provided the typical association between admd μ_{max} and γ_{admd} that has already been reported [2] and is illustrated in Fig. 2.

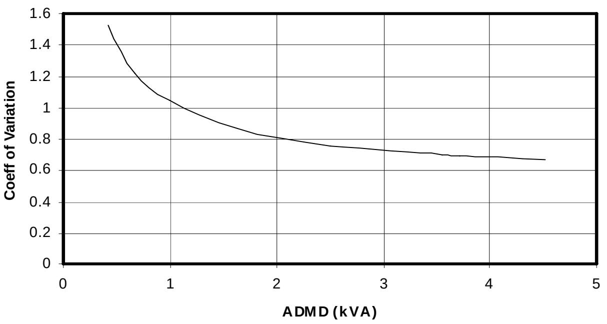

Fig.2: Relation between admd (expressed in kVA at nominal voltage) and coefficient of variation [2]

Fig. 2 represents the association expected at the times of system maximum demand and still does not assist in matching designs to the QOS specifications. The curve of the relationship could be translated onto the bpp, but another approach provides more information about the compliance of a design with the QOS specifications.

ISO-VOLTDROP CURVES

Adding an iso-voltdrop curve

Since each point plotted on a bpp represents the set of parameters for a measurement, applying those same parameters to a typical feeder using the HB algorithm determines the voltage drop associated with that measurement, according to the confidence adopted in the algorithm. A contour of points for which the voltage drop is the same can be plotted, called an iso-voltdrop (IVD) curve. For example, assuming a typical feeder of six equally spaced nodes with four customers connected to each node, an IVD curve of 10% voltage drop and with a confidence level of 90% can be drawn through the point (μ_{max} , γ_{admd}) that defined the characteristic admd parameters.
The points plotted below the IVD curve represent load conditions that are likely to cause a voltage drop greater than the IVD, i.e. violations of the design limits. Such points are likely to result in voltage conditions worse than during the measurement interval with the admd. The highest voltage drop is represented by the point furthest from the IVD curve.
However, the matter is complicated by the uncertainty associated with the confidence level of 90%. Thus it would appear that more than 10% of the measurements would return voltage drop conditions beyond the limit values and this would represent a violation of the 5% of values that are allowed to be classified as extreme. (It is still necessary to check further whether the violations are in consecutive or adjacent intervals.)

Determining threshold of 95% confidence

Since 5% of voltage measurements may be defined as extreme, the IVD curve that represents 5% probability of violations will help to define the voltage for which a feeder should be dimensioned. The 5% risk of violations is a combination of the confidence of the HB algorithm and the confidence the measurements will lie above the IVD curve. A 5% risk can be derived from various combinations, as illustrated in Table 1. (Note: The HB algorithm does not permit a confidence level of 100%.)

Table 1: Two combinations of 5% risk of violating voltage limit.

Confidence level in HB algorithm	Measurements above IVD curve	Total confidenc e	Measurements below IVD curve (out of 1008)
95%	100%	95%	0
99.9%	95.54	95%	45

Since the parameter μ_{max} is already defined, only the relevant value of γ needs to be found, and this is called γ_{qos} . Thus, the ***QOS design parameter pair*** (μ_{max} , γ_{qos}) will result in 5% of measurements being 'extreme'.
Fig. 3 illustrates these concepts applied to the bpp shown in Fig. 1. An IVD curve corresponding to a HB confidence of 99.9% has been located such that 45 points lie beneath the curve.

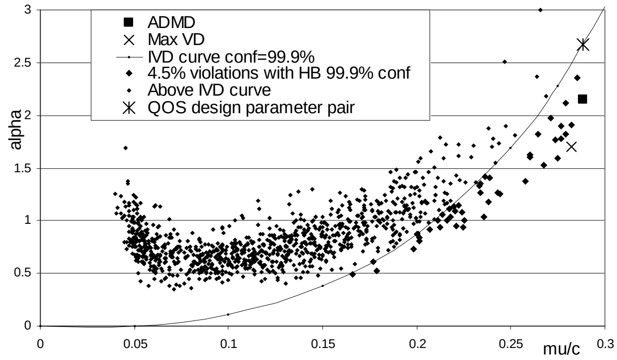

Fig. 3: BPP for Wn, 22-28 Jul 2000. (c=51.1A, n=65), using 10-minute data, with IVD curve for HB conf=99.9%, showing measured admd, and the load point with maximum voltage drop

The maximum voltage drop is associated with a load measurement about 2.2% below the admd, where the voltage drop is about 1.1p.u. of the voltage drop of the IVD curve. In other words, if the feeder is designed to have an IVD curve of 10% below the nominal voltage, then the worst measurement of voltage would be 11% below nominal. In this record of monitoring, the most extreme voltage drop would not exceed the limit of 15%.
It is found that the value of γ_{qos} is lower than the value associated with the admd. This represents a move from the practical measurement (μ_{max} , γ_{admd}) towards the central limit at μ_{max} , illustrated in Fig. 4.

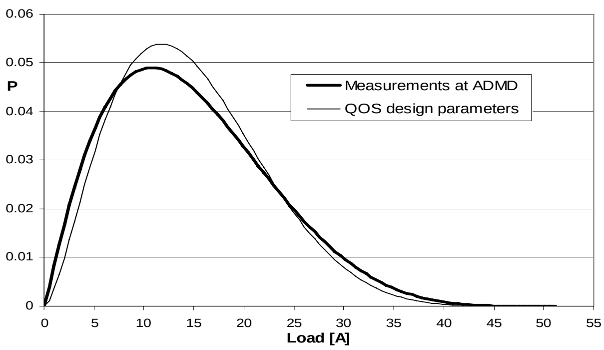

Fig 4: Beta pdfs for (μ_{max} , γ_{admd}) and (μ_{max} , γ_{qos})

APPLYING THE COMPLIANCE TEST

As described in our example of a QOS specification, non-compliance is not related simply to violating the voltage limit in more than 5% of the measurements, or 50 of the 1008 measurements collected during a week. Where compliance requires no two adjacent periods at the limit level, the measurements in question need to be inspected for adjacency. This is possible with measured data collected in a QOS monitoring exercise, but is difficult to predict at the design stage.
The assessment could be approached by interpreting the specification slightly differently: the average voltage level over two consecutive periods (20 minutes) shall not violate the voltage limit.
The original data was recalculated to give 20-minute measurements. All measurements will tend towards the central position because of the averaging, and there should now be no violations of the IVD curve with 99.9% confidence. However, Fig.5 illustrates there still appear to be violations of the IVD curve.

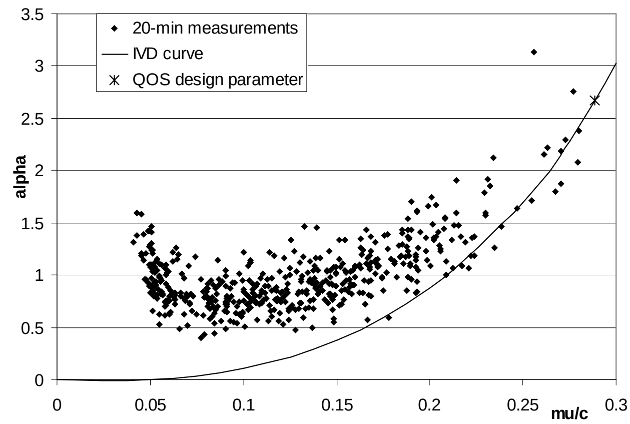

Fig. 5: BPP for same community as Fig. 2, but using 20-minute data.

The 10-minute data shows that 15 load measurements indicated a voltage drop higher than during the admd measurement. 12 events occurred within the same hour on three days centred on the day the admd was measured.
However, the analysis of the adjacent periods must take into account that the transforms from current to voltage drop models are being carried out independently of other measurements. The successive use of high levels of confidence to model several occurrences, introduces a distortion that is not statistically valid. Since there is a typical daily profile, we know there is covariance between the customers. To completely apply the approach of the bpp, it is necessary to assess the extent of the co-variance between customers and the successive application of high levels of confidence.

IMPLICATIONS

Conventionally, designs prepared to meet voltage limits assume the worst case load is the admd. A voltage drop is calculated for that condition, and then factors are applied to allow for variability of loads along a feeder, loss of diversity, unbalanced loading, other uncertainties and, sometimes, a further safety margin is allowed between the calculated voltage drop and the permitted values.
Applying the HB algorithm to the admd period has already been tested against other, conventional design methods and Monte Carlo simulation, and was found to give good agreement when loads are balanced and be better for unbalanced conditions. However, all design methods based only on the loads at admd miss other loads that give even greater voltage drop.
The bpp allows voltage drop to be assigned to all loads for all the intervals measured during a monitoring period.
Although probabilistically calculated voltages based on load measurements are not the same as QOS monitoring of voltage variation compliance, the use of the HB algorithm and bpp enables voltage conditions to be modelled before or independently of taking voltage measurements.
A QOS specification that sets up an acceptance criterion allowing some high values of voltage drop to be disregarded, and requires a design model to replicate a criterion of adjacency, cannot be applied directly to design, because not enough is known about loads and voltages to apply the effects of covariance and successive probability.
A QOS criterion that requires all means of two adjacent measurement intervals to comply with a voltage drop limit and allows no violations can be directly applied to design. A higher limit applied to each individual measurement interval, again without allowing any violations, can be specified also.
The measurement interval, 10 minutes in the example here, could be varied. Shorter measurement intervals will generate more stringent tests of voltage variation because load variation during a measurement interval leads to a mean lower than the maximum. The period of cycling of thermostatically controlled loads such as heaters and refrigerators affects the variability of the loads of individual customers and the moving average of pairs of measurements. Thus the specification of the measurement interval is related to the conditions that authorities want to manage by their regulations.
QOS monitoring outside the week when system maximum demand occurs is extremely unlikely to generate a violation of the limit. To be meaningful, therefore, the monitoring period must include the days around the period when a community's admd occurs.

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REFERENCES

[1] C.T. Gaunt, R. Herman, M. Dekenah, R.L. Sellick, S.W. Heunis, 1999, "Data collection, load modelling and probabilistic analysis for LV domestic electrification". *International Conference on Electricity Distribution* (CIRED), Nice.
[2] R. Herman, C.T. Gaunt, "A practical probabilistic design procedure for LV residential distribution systems". *IEEE Trans on Power Delivery*, vol 23, no 4, Oct 2008, 2247-2254.