DATA COLLECTION, LOAD MODELLING AND PROBABILISTIC ANALYSIS FOR LV DOMESTIC ELECTRIFICATION

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SUMMARY
The paper describes the process and findings of the load data collection project in South Africa, the analysis of the data, and the Herman Beta algorithm for calculating voltage drop in LV feeders. It discusses some of the significant differences of these approaches from other existing methods. Case studies of practical applications illustrate the importance of this work for electrification programmes.
Keywords
Electrification, statistical load models, domestic customers, data collection, probabilistic analysis

1. INTRODUCTION

Synchronous data collection of large groups of domestic customers commenced in 1988, using a logger described in a previous CIRED (1991) paper. A microprocessor based, eight channel logger measured and recorded load currents in the connections to domestic customers [1]. Currents were sampled at 2 sec intervals and averaged over 5 min. Internal clocks synchronised the loggers. Phase-neutral voltages were also recorded for one of the phases. Stored data was transferred to a laptop computer every month.

Key findings of the initial load surveys reported in 1991 were:

- The distribution of individual customer loads at the time of system maximum demand was not Gaussian (normal), and can be substantially skewed.
- The load appeared to comprise customers with low load connected or high load connected, with relatively few medium sized loads.

At about the same time, South Africa embarked on an Electricity-for-All electrification programme, with a target of connecting 450'000 new customers each year. Many of the connections are not financially viable for the utilities, but the programme is socially, economically and politically desirable. Therefore utilities need to minimise total costs within the constraints of safety and quality of supply standards.

The utilities' needs and the findings of the initial load studies led to intense reviews of the load models and methods used to analyse and design LV feeders. The load surveys were extended to several communities of different socio-economic groups and the number of customers being monitored has increased each year since 1992. A substantial quantity of data has now been collected. The initial results of the project led to the formulation of load models in which the customer currents are represented as a Beta probability distribution.

Analysis of the collected data allows correlation between the household income, time since electrification, customer maximum demand and dispersion, and circuit breaker size. Appropriate parameters for the calculation of voltage drop on low voltage feeders can be derived from the data. Forecasts of future parameters in an electrification programme can be prepared. The data also provides practical information about energy losses, enabling optimisation of capital and operating costs at the design stage of an electrification programme.

The Beta load models were incorporated into voltage drop and feeder current calculations for design purposes. Beta distributed load currents are transformed into a different beta distributed set of feeder voltages. The alpha and beta parameters of the voltages are derived using statistical moments. Application of the theorem of superposition adequately deals with the problem of successive sections.

Independent investigations revealed that the new Herman Beta method is superior to previous methods of calculating voltage drop. It is now the recommended method for use in the South African LV design guidelines.

2. REPRESENTATION OF DOMESTIC CUSTOMER LOADS

Many domestic loads are resistances. Others, thermostatically switched, are constant energy devices and, when measured over discrete time periods, behave as constant power loads. We chose to model the loads as currents, representing a combination of the resistance and power models. The customer load may be defined as 9 A, equivalent to a load of 2 kVA at a nominal voltage of 230 V. Recent results from the load survey indicate that loads do behave as constant currents in spite of voltage variation.

The representation of loads as currents also simplifies the analysis of feeders. There are very few inductive appliances in most households and the load may be assumed to be at unity power factor.

The customer currents are measured over periods of five minutes. Five minutes is a suitable period for calculating the voltage drop on a feeder. Periods can be combined to build model loads of longer period, such as half-hour loads.

The domestic loads are behaviourally driven. Therefore, the social and demographic characteristics of the community can be used to predict the probability density of the individual loads connected to the system in any period.

3. NATIONAL LOAD SURVEY

A national load survey was established in 1994 by municipal electricity utilities, Eskom, universities and consulting engineers. The minimum number of customers monitored at a site is 60, to reduce the sampling error to below 1 A, and several sites with over 100 customers have been established.

The loggers are usually moved to a new site after two years. In some instances, a longer period has been allowed as part of other longitudinal studies. We now have useful data from about 30 site-years.

Sociometric data is collected by interview from each household being monitored, and this data can be linked to the load readings.

Hourly air temperature readings are collected from the nearest weather station of the national weather bureau.

The record from each logger (raw load data) includes the logger ID, date/time, and voltage and current readings. The files of raw load data are never over-written after processing, to minimise the introduction of errors. Errors, however, do arise from:

- channel failure within the logger, usually to either a high or nearly zero value,
- faulty connection from the current transducer to the logger, and
- errors in data transmission from the logger to the laptop computer.

Therefore, it is necessary to screen the data before storing it in tables; one table per logger for each year. The tables for all the loggers at a site are kept in one directory. The accumulated data takes approximately 3 GB of memory.

Experience with data collection has indicated the importance of the following:

- Data must be collected from the loggers regularly to avoid loss of data by memory overflow or logger failure. Problems arise from periods of leave, inclement weather and even snakes.
- Loggers operate in extreme environments and both the loggers and the connections fail. Data must be inspected promptly to identify failure, and initiate field maintenance or logger replacement.
- Errors can be introduced when downloading the loggers, such as by not re-setting properly, and can be reduced by training the operators, improving the operating software and possibly by remote monitoring (under investigation).

Lost or bad data cannot be replaced.

4. PROBABILITY DISTRIBUTIONS OF LOAD

Rusck [2] and Hamilton [3] based their work on an assumption that the loads at the time of system maximum demand were normally distributed (Gaussian), and much subsequent work [4] was based on the same assumption. The assumption is valid for large groups of customers, but feeders typically supply fewer than 30 customers. The loading and voltage drop on the feeder is not be well represented by a Gaussian distribution, as reported in 1991.

Various alternatives to the Gaussian distribution were investigated. The Beta probability distribution function (pdf) was found to have the following advantages:

- It is one of few distributions which represent location, dispersion and shape.
- The range of values is from 0 (below which the loads would be generators) to a scaling factor, c. The rating of the customers' breakers is a convenient scaling factor.
- It represents significantly skewed distributions, including the effect of current limiting.
- The Beta pdf was found to fit measured data to a significant goodness of fit level [5].

The range of load distributions represented by a beta pdf, and typical of loads measured in the survey, is illustrated in Figure 1.

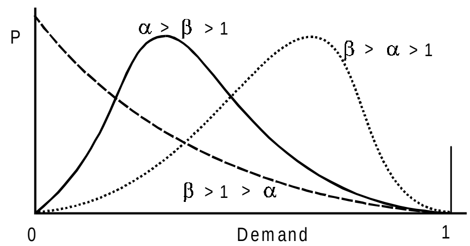

Figure 1: Beta pdf's model a variety of load distributions

Measurement of neutral currents

We are frequently asked why the neutral currents in the feeders are not measured. The neutral current is relevant only to a group of customers, being the sum of the currents in the phases, and depending on the number of the customers beyond the point of measurement. During a 5-minute period the current in the neutral changes in both magnitude, which can be recorded easily, and angle, which cannot. As a result it is neither practical nor useful to measure the currents in feeder neutrals.

Measurement of bulk demands and longer periods

Similarly, it is not useful to measure the bulk supply to a community. Reconciliation of the records of bulk and individual loads is impossible without knowing the feeder losses and the loads on customers not measured. Bulk measurements cannot be disaggregated into individual customer data except by a probabilistic method based on studies of similar loads.

Load profiles based on longer measurement periods (eg half-hour data) can be compiled from 5-minute data. Data collected over longer periods cannot be disaggregated into shorter periods. We have experimented with periods shorter than five minutes. The shorter period generates significantly more data, without a corresponding increase in the accuracy or sensitivity of the parameters describing the distribution of loads needed for voltage drop and losses calculations.

5. MEASURED LOAD PARAMETERS

The measurements during each 5-minute period are a sample of the population of customers at that time. The mean customer demand (μ), often referred to as the after diversity demand, is derived from the measurements by adding all the individual loads recorded in valid logger channels and dividing by the number of channels. The standard deviation (σ) is also derived from the load measurements.

The parameters of the Beta pdf are α, β and the scaling factor, c, which is the circuit breaker rating (may be referred to as c_b). The five variables μ, σ, α, β and c are related and values of α and α/β can be expressed in terms of μ/c and a slenderness ratio, s = μ/σ, which is an indicator of the dispersion of the loads [6].

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

$$\frac{\alpha}{\beta} = \frac{\mu/c}{1 - \mu/c} \quad (2)$$

The value of α is fixed by the mean normalised customer demand (μ/c) and the slenderness. α/β is a measure of skewing of the distribution; it depends only on μ/c and is independent of α and s.

The parameters α and μ/c derived from the coincident customer loads during a 5-minute period of measurement represent the community as a whole. The parameters for all periods from one site for one year can be represented as 100’000 points on a graph of α against μ/c, referred to as a beta parameter plot. A typical beta parameter plot is illustrated in Figure 2.

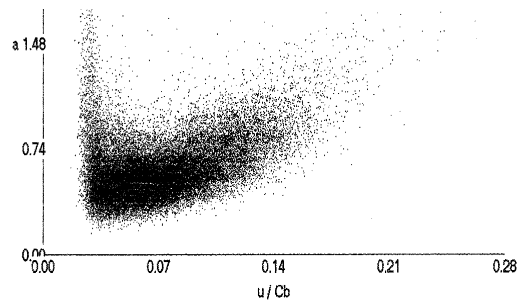

Figure 2: Beta parameter plot for Helderberg ’97 (Jul - Dec)

The highest coincident demand (the system maximum demand) is represented by the data point with the highest value of μ/c. Most designers assume the worst voltage drop conditions on a feeder occur at maximum system load. The assumption is not always valid.

The load parameters of the community of customers can be defined from the data points representing high loading of the network. The maximum value of μ/c and the mean value of α corresponding to the highest 60 loads are recommended as the load parameters for voltage drop calculations.

6. FORECAST LOAD PARAMETERS

The shapes of the beta parameter plots depend on several factors, such as the ratio of the circuit breaker size to the mean current, especially where it imposes current limiting, the type of appliances used by the customers, and the homogeneity of social behaviour.

Accordingly, load forecasting on the basis of projected community parameters should be possible. Analysis of the sociometric data associated with the load data indicates good correlation of mean current with income, availability of water (for water heating) and time since electrification. The weather data shows a strong relation between load increase and fall in temperature over three days. Parameter forecasts based on independent factors are being developed [7]

The load factors and loss load factors associated with different communities and numbers of customers, for the calculation of lifetime operating costs for feeders, are also being identified [8].

7. PROBABILISTIC NETWORK ANALYSIS FOR DESIGN

Appropriate statistical load models have been derived for domestic consumers specifically for application to the design of electrical networks. In developing countries the L.V distribution system can be extensive, requiring careful engineering to meet cost constraints.

Design criteria for feeder sizing

There are first and second order criteria. First order issues relate to the electrical constraints to be met. These are:

- Thermal sizing – current carrying capacity
- Voltage performance and satisfying statutory voltage specifications
- Short-circuit capability

Calculation procedures for the first two criteria require a statistical description of the expected loads. These calculations are therefore probabilistic, while the last one may be calculated deterministically in the conventional way. A second order criterion is the effect of choice of plant on annual losses.

8. THE HERMAN-BETA METHOD

Using the Beta pdf description of consumer loads, a probabilistic approach has been analytically developed [9, 10]. A brief description of the derivation of the algorithms for calculating consumer voltage and feeder currents is described.

Voltage profile analysis for feeders

It can be shown that if the loads are modelled as Beta distributed currents (with parameters: α_I , β_I and scaling value C_b), the consumer voltages are also Beta distributed (with parameters: α_v, β_v and based between voltages V_{min} and V_{max}). The diagram in Figure 3 illustrates the distribution of voltage components for one phase of a conventional three-phase system.

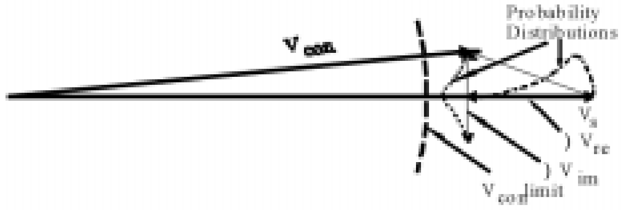

Figure 3 Voltage drop distribution

Parameters α_v and β_v are determined analytically using the first and second statistical moments. The second moment is given by:

$$E(V_{con})^2 = Vs^2 + E[-2Vs\Delta V_{re} + \Delta V_{re}^2 + \Delta V_{im}^2] \quad (3)$$

$$= \alpha_v(\alpha_v + 1)/\{(\alpha_v + \beta_v)(\alpha_v + \beta_v + 1)\} \quad (4)$$

where

V_{con} = customer terminal voltage
Vs = supply voltage
ΔV_{re} = real part of voltage drop
ΔV_{im} = imaginary part of voltage drop

An expression for the first moment is derived from the Taylor expansion:

$$E(V_{con}) = Vs - E(\Delta V_{re}) + {}^1/_2 E(\Delta V_{im})^2 \quad (5)$$

$$= \alpha_v/(\alpha_v + \beta_v) \quad (6)$$

The variables: ΔV_{re} , ΔV_{re}^2 and ΔV_{im}^2 may all be expressed in the following general terms:

$$K_I.\{\alpha_I(\alpha_I+1)/[(\alpha_I + \beta_I + 1)]\} + K_j.\{\alpha_I^{\ 2}/(\alpha_I + \beta_I)^2\} \quad (7)$$

K_I and K_j are constants that can be evaluated in terms of m_a, m_b and m_c with Rp, Rn, and C_b, where

m_a, m_b and m_c = number of customers on phases a, b and c
Rp, Rn = phase and neutral resistance
C_b = load current scaling factor in amps

Multiple feeder sections are analysed using superposition.

A similar, simpler set of linear functions may be derived for the bi-phase (or dual phase) system, while the single phase system is a special case of either the three phase or the bi-phase systems [11].

In all cases V_{min}, V_{max}, α_v and β_v may be evaluated analytically without iterative procedures using standard spreadsheet software – or the calculation steps may be incorporated into a dedicated program.

A single design voltage for a given level of confidence (or risk) is extracted from the resulting statistical distribution of consumer voltages.

Feeder current evaluation

The Beta distributed domestic load currents are statistically summated to give the total Beta distributed feeder currents. A quantile value of this current may be determined for a given level of confidence (or risk). The largest phase current is used to thermally size the feeder conductors.

Transformer sizing

As the number of customers increases the Central Limit phenomenon results in a tendency towards Gaussian statistics.

The mean (μ) and variance (σ^2) can be derived from the load currents. These parameters may be summated to give a total loading for transformer sizing. For a homogeneous residential supply area and a 230V supply voltage the following formulation gives the load in kVA:

$$\text{Load} = 0.23 \times N \times \frac{Cb}{a+b}\left[a + 1.28\sqrt{\frac{ab}{N(a+b+1)}}\right] \ldots (8)$$

Where N = total number of customers and the factor 1.28 refers to a 10% risk.

Evaluation of annual feeder losses

Cost-effective network designs should include the cost of losses over the expected life cycle of the plant. Methods based on the Beta defined load models have been developed and are currently being evaluated [12].

Verification

The Herman-Beta approach has been thoroughly tested using extensive Monte-Carlo simulation methods and is now regarded as the most accurate residential network analysis tool [13, 14]. As a result it is endorsed as the most appropriate design approach in Southern Africa and forms part of the National design guidelines [15].

9. ADVANTAGES OF HERMAN-BETA METHOD

- It can handle skewed load current pdfs – typical in developing countries
- It has been shown to be more accurate than other available methods
- It takes into account the neutral resistance, particularly important in aerial bundle conductors, and unbalanced loading of the phase conductors.
- It correctly models single-phase, bi-phase and three-phase systems and allows accurate comparisons of the alternative technologies

10. ILLUSTRATIVE CASE STUDIES

a) Loads differently skewed with the identical means

At present none of the probabilistic methods address the issue of skewed load distributions. To illustrate the effect of skewing a typical three-phase radial feeder with 6 nodes is considered. The feeder is typically an aerial bundled conductor (ABC) and 4 customers are fed from each pole. For the purposes of this comparison the mean load current per customer is taken as 11 A. This represents a typical lower income group of customers drawing about 2.5 kVA. Load L1 is described by α = 1.65, β = 7.37 and C_b = 60 A. Load L2 has the same mean of 11 A but α = 3.5, β = 2.86 and C_b = 20 A. The second load type is typical of the application of "circuit breaker tariff" in South Africa.

Figure 4 shows the resultant voltage drops for the same degree of risk (10%). The difference between the two cases at node 6 is 27%, even though the mean currents are identical.

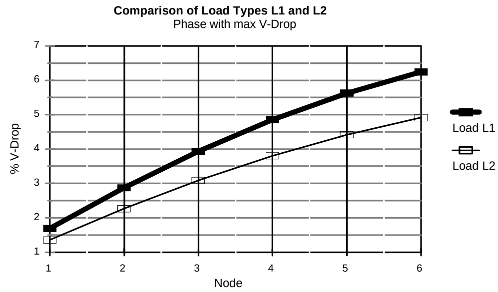

Figure 4: Results for Case 1

b) Effect of phase allocation

This actual case illustrated the effect of allocating customer connections to phases and the importance of software to deal with this phenomenon.

A 13-span ABC feeder with 40 m spans had the following customer connections to the a, b and c phases, respectively:

1	2	3	4	5	6	7	8	9	10	11	12	13
0	0	3	0	0	3	0	0	2	2	0	4	0
0	4	0	0	4	0	0	3	0	0	2	0	0
3	0	0	3	0	0	3	0	0	0	0	0	4

Collectively, the loading appears to be reasonably balanced across the phases: a:14, b:13, c:13. Taking a typical load description and a 95 mm^2 conductor size, the maximum %-voltage drop of 14.98% calculated with the Herman-Beta method was on the a-phase of the **12th node**. After rearrangement of connections the maximum %-voltage drop occurs at node 13 and is 10.293%. The difference in calculated values is 45.54%. This allows downsizing of the conductor.

c) Bi-phase systems can be cost effective options

In this case a bi-phase alternative is shown to be more cost-effective than a conventional three-phase system. The analysis was performed with the Herman-Beta method. The two systems are shown in Figures 5 and 6.

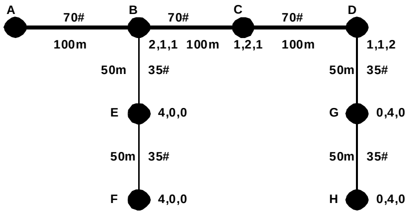

Figure 5: 3-phase Spine

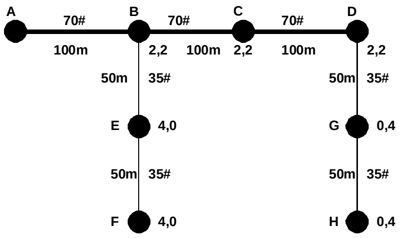

Figure 6: Bi-phase Spine

In both cases A-B-C-D represents a spine with two single-phase spurs (B-E-F) and (D-G-H). In the first case the spur is a 70 mm^2 three-phase, 4-wire feeder and the second a 70 mm^2 bi-phase feeder. The number of customers connected to each node is the same for both cases and the load description is also identical.

The calculated results show that the highest voltage drop for the three-phase case is 11.361% and for the bi-phase case 11.327%. This shows that less conductor material can give an improved voltage performance.

11. CONCLUSION

Substantial progress has been made in South Africa on the characterisation of domestic loads and the analysis of network conditions. Techniques are sufficiently sensitive to allow accurate comparison of the efficiencies of alternative feeder technologies for electricity distribution to domestic customers and to design feeders on a consistent basis. The work allows significant savings in the capital cost of electrification, by reducing the uncertainty associated with the design of LV feeders.

The techniques of load survey and voltage drop calculation could be applied effectively in all countries considering electrification programmes or the need to improve networks supplying domestic customers.

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