ACCURATE DETERMINATION OF DISTRIBUTION NETWORK LOSSES

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ABSTRACT

Distribution losses can be difficult to measure when the loss power has a similar proportion to monitoring equipment sensor tolerances. Measurements for the Western Power Distribution Losses Investigation project have addressed this problem by using high resolution demand measurements combined with loss calculations with an I^2R method. This is combined with additional measurements to verify accuracy of the network database used to calculate losses in each network branch.

INTRODUCTION

Distribution operators are interested in reducing losses due to their impact on customer bills. Distribution losses in the UK have been estimated at between 5.8% and 6.6% of electricity delivered [1] but operators have limited knowledge of the contribution from each voltage layer or from specific feeders. Further investigation is required so that measures to reduce losses can be effectively targeted.

The Western Power Distribution (WPD) Losses Investigation project, undertaken in collaboration with Manx Utilities Authority, aims to make measurements of technical losses on a selected set of HV and LV feeders [2]. The measurements will be used to develop methods to provide accurate estimates of losses for a wide range of network feeders. This differs from previous work in which losses have been estimated on average over multiple feeders, or for average demand profiles. These estimates have limited data on the power factor, unbalance, or stochastic time variation of real customer loads. Recent developments in logging instrumentation and metering have made more detailed measurements feasible. A practical benefit of making measurements on individual feeders is that the number of nodes needing instrumentation is manageable. However, the percentage losses are then relatively small and measurement tolerances become a critical concern.

This paper compares loss calculations using a power difference method with calculations based on power-flow analysis. The uncertainty of each method is investigated, together with techniques that can be used to validate the network database on which the calculations depend.

LOSS MEASUREMENTS

Measurement setup

Monitoring equipment has been installed on a number of HV and LV feeders. In each case, the current and voltage are recorded at all of the nodes at which power enters or leaves the feeder networks, as shown in Fig. 1 and Fig. 2.
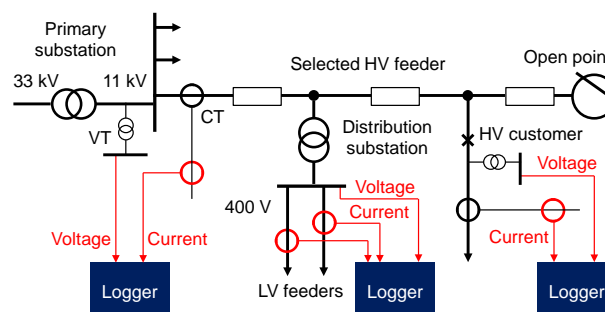

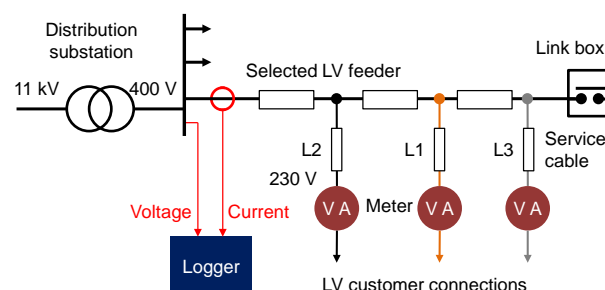Fig. 1 HV feeder measurement configuration

Fig. 2 LV feeder measurement configuration

On the HV test feeders, the current and voltage are recorded by a GridKey or Sub.net logger at the primary substation. Measurements at the primary substation or at HV customer connections use existing voltage transformer (VT) and current transformer (CT) circuits. The use of the existing CT wiring has been necessary as it is not straight forward to fit sensors directly onto the feeder cable cores without also including currents in the sheaths. The current and voltage are also measured at each distribution substation using GridKey loggers fitted to the LV cabinet.

The HV test feeders are located in the WPD operating area in Milton Keynes, UK but the LV test feeders are located in the Isle of Man where the vertically integrated authority can install appropriate metering at customer connections. Measurements are recorded with a 1-minute resolution and the clocks of the logging instruments can be synchronised to within a few seconds.

The logging data provides limited data on distortion and so the analysis has assumed operation at 50 Hz. It is recognised that the actual losses will be slightly higher due to current harmonics and due to demand variation within the 1 minute intervals [3]. However, the initial measurements suggest that these are minor effects.

Loss calculations using power difference method

Losses can be calculated as the difference between the power input at the upstream substation and the sum of the power that is delivered to the downstream nodes. This 'power difference' method has the advantage that no knowledge of the internal impedances or transformer functions is required. However, it is therefore not possible to apportion losses to different cable branches or to the load-losses and no-load losses of the transformers.

A further disadvantage of the power difference method is that the calculated losses are highly dependent on the tolerances of the current and voltage sensors. Taking a hypothetical case of a feeder with 1% losses and perfect measurements at the network outfeeds, an error of ±2% at the input node could result in an apparent loss of 3% of the power delivered, or alternatively a 1% power gain.

The power difference is also highly vulnerable to errors if one or more nodes are omitted from the metering installation. Any unmetered demand then appears as a contribution to the technical losses. This is a particular issue for the LV trials where there are many more nodes and potential inaccuracies of the network database and phase allocation data.

Loss calculations using I^2R method

An alternative approach is to measure the current and then to use prior knowledge of the network topology and the impedances to calculate the losses. The current is measured at each of the downstream nodes and the voltage is measured at the upstream node. Additional currents due to the shunt impedance of the transformers and due to the cable capacitance are included in the analysis for the HV feeders. The currents in each of the branches within the network are solved using a power-flow analysis and the losses in each branch or transformer can then be calculated using an I^2R calculation.

Taking the example quoted above, a current measurement error of ±2% would cause the losses to appear between 0.96% and 1.04% of the delivered power. The errors apply to the power difference rather than to the power delivered and so have a much lower impact.

However, input data is needed to specify the network topology and the impedances and lengths of each cable branch, each of which has some degree of uncertainty. In order to minimise errors in the cable impedance data, a finite element method has been used to provide the full matrix of self- and mutual complex impedances [4].

The power-flow analysis for the HV feeders includes the impact of the Dy11 distribution transformers. Input data is therefore also needed to specify their impedance and the copper and iron losses. It is assumed that the series reactance of the transformer can be determined from the magnitude of the transformer impedance and the

resistance due to copper losses. The shunt reactance is estimated from the iron losses using typical per-unit values for the magnetising current [5] although this is very small compared to the load currents.

The I^2R method only calculates technical losses due to measured currents and so does not include non-technical losses or inadvertently unmonitored currents. Any errors due to unmetered demand apply to the loss power rather than the unmetered power itself. Therefore the I^2R method is much less sensitive to instrumentation errors than the power difference method.

NETWORK DATABASE VALIDATION

The power difference method requires measurements of both the current and voltage at each edge node of the test network. Conversely, the I^2R method only makes use of the current data from the outfeed nodes and the voltage data from the infeed node. The unused data can therefore be used for consistency checking, either by comparing the calculated and measured current at the infeed node, or by comparing the calculated and measured voltages at the outfeed nodes. This can identify errors in the measurement setup, either due to incorrect installation of the sensors or to errors in the original network database.

Pilot trial LV feeder

Monitoring equipment has been installed on a pilot LV feeder as shown in Fig. 3 with 11 single-phase domestic customers and 2 public lighting circuits.
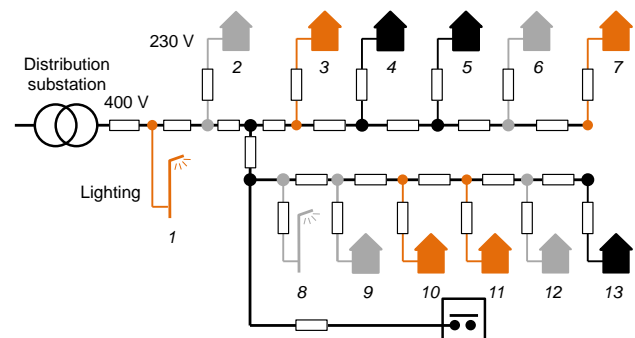

Fig. 3 Pilot trial LV feeder

The connection to house 4 was omitted initially due to an error in the provided network information. The impact of this is shown in Fig. 4 comparing the measured current at the distribution substation with the current calculated by power-flow analysis. There are slight differences throughout due to measurement tolerances but the results clearly indicate that further un-metered loads were connected to phase L1. This is revealed due to the stochastic nature of the demand which mostly varies independently between customers. Using these results, the feeder information was re-checked and the instrumentation was added for the missing connection
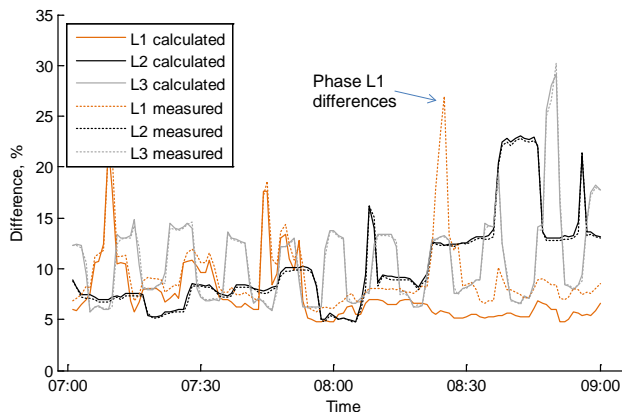
Fig. 4 Difference between LV substation currents from power-flow analysis and from measurement

Also, the time-series of voltages measured at the customer nodes have been correlated against the voltages measured on each of the three phases at the substation. In addition to identifying any time offsets between the two sets of measurement data (which have been corrected if necessary), it is possible to determine the phase allocation of the single-phase customers. Fig. 5 shows results for voltage correlations over a 24-hour period. The plot shows that the correlation to the correct phase allocation is consistently greater than the maximum correlation to either of the other two phases. Similar results were obtained for correlations over a longer period of a week or with the period reduced to one hour, in each case correctly identifying the phase allocations.

These results have been validated against on-site testing of the phase allocations when the meters were installed for the measurement trial and an error in the original phase allocation data was found and corrected.
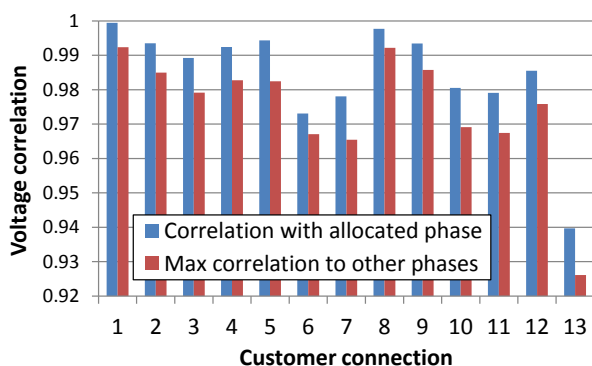

Fig. 5 Voltage correlation between customer node voltage and substation voltages

HV feeder

Monitoring equipment has so far been installed on six HV feeders, one of which is shown in Fig. 6 and consists of an 11 kV feeder with eleven distribution substations.
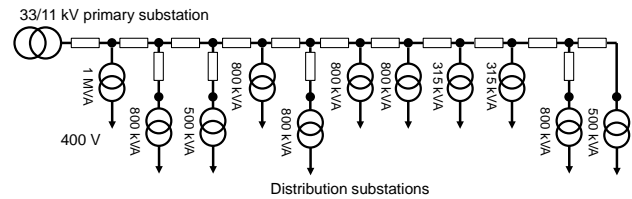

Fig. 6 HV feeder 1

In a similar manner to the LV feeder analysis, the current measured at the primary substation was compared with the expected value found by summation of the measured currents from the distribution substations.

Initial results for feeder 3 indicated that the measured current at the primary was greater than the sum of the distribution substation currents, indicating either an unmetered load or that the sensor at the primary reads high. Assuming that there are no unknown HV connections this suggested that a distribution substation had an unmetered LV feeder. In some cases it has been possible to identify substations with unmetered demand based on differences between the measured and calculated line-to-neutral voltages. However, these differences are small and subject to voltage sensor tolerances. An improved metric is given by the correlation between variations in the current difference at the primary and the voltage differences at the distribution substations. This metric is less subject to measurement errors which remain relatively constant in proportion to the line-to-neutral voltage. The correlation technique successfully identified the substation at which an LV feeder had been omitted from the instrumentation.

MEASUREMENT RESULTS

Results for a sample day, 14th December 2016, are shown at 1 minute resolution for the pilot LV feeder in Fig. 7 and for the example HV feeder in Fig. 8. For the LV feeder, the power difference results have a very wide spread (and can appear negative) and so are clearly unreliable for the LV feeder. The HV feeder losses have far less spread, and show a degree of agreement between methods
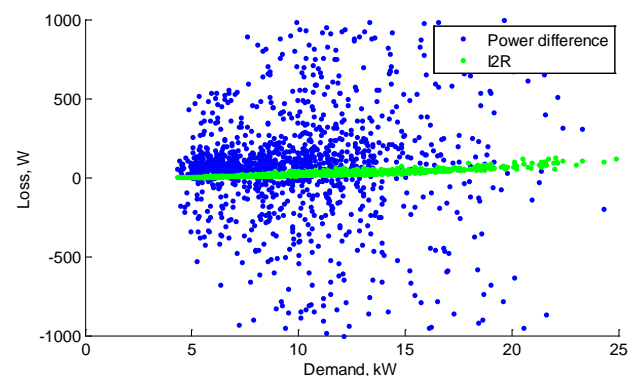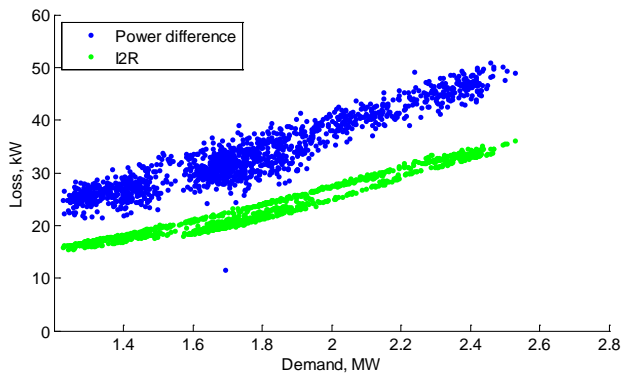

Fig. 7 Pilot trial LV feeder loss vs. load

Fig. 8 HV feeder 1 loss vs. load

The mean losses for the full set of feeders monitored so far are shown in Table 1. In some cases the mean losses from the power difference method are significantly different to those from the I²R method. This is the subject of ongoing work. The next section presents a detailed analysis of the uncertainty in both methods and shows the improvement in accuracy from the I²R calculations.

Table 1 Mean losses over one day

Feeder	Mean demand	Loss, % of input power	
		I²R method	Power difference
LV pilot	10.3 kW	0.23	0.86
HV 1	1.81 MW	1.29	1.96
HV 2	2.53 MW	1.99	2.72
HV 3	0.92 MW	0.91	0.86
HV 4	3.28 MW	1.35	1.43
HV 5	2.92 MW	0.87	1.08
HV 6	1.56 MW	0.59	0.53

UNCERTAINTY ANALYSIS

Although results obtained using the power difference method are more susceptible to measurement tolerances, a more quantitative analysis is required to give a fair comparison of the uncertainties of both methods.

For the power difference method, this involves assessing the impact of current and voltage sensor tolerances at infeed and outfeed nodes. For the I²R method, the sensor tolerances only apply at the outfeed current sensors and the infeed voltage sensor, but uncertainties in the impedance data also need to be taken into account.

The uncertainty analysis uses a Monte-Carlo technique in which errors in the input data are selected randomly from pre-defined uniform distributions and the corresponding losses are calculated. It is assumed that the metrology errors apply independently at each sensor but that they remain constant for all time samples. This process is repeated for a series of 100 trials to find the range in loss results that could arise for the given tolerances on the

input data. The baseline network state uses the power-flow analysis defined for the I²R method. Although this state is itself an estimate, it represents a fully self-consistent state onto which the errors can be applied. The tolerances are as follows:

Voltage and current measurements:
Primary substation voltage 100:1 VTs: ±1%.
Primary substation current CTs: ±1%.
Distribution substation Rogowski coils, rating 600 A, IEC 60044-8: ±1% to ±3% according to amplitude.
GridKey logger metrology EN 60253-21: ±1%.
EDMI Mk7c meter current metrology: ±2%.

Transformer parameters:
The analysis uses manufacturer's test data for copper losses, iron losses and impedance. An accuracy of ±0.4% has been proposed [6] but a more conservative ±1% has been assumed here. Much wider tolerances would apply if generic figures were used (such as from purchase specifications) rather than test data for individual assets.

Transformer model:
Load loss conductor temperature: 50 °C ±10 °C
No-load losses for transformers rated 10 to 50 kVA reduce 5%-10% over a 20 °C to 100 °C range [7] so ±5% assumed here for ±10 °C range.

Feeder cables: Length: ±5%; temperature: 20 °C ±10 °C; resistance tolerance BS3988:1970: ±3%.

Results of the uncertainty analysis are shown for the HV feeder in Fig. 9 and Fig. 10. Without errors, the mean loss was 1.2% of the delivered power. Fig. 9 illustrates the wide range of results obtained with the power difference method for which the mean losses vary from -0.8% to 3.2% of the delivered power. This represents an uncertainty -167% to +165% of the percentage losses. These uncertainties make the power difference method unsuitable for the accurate loss calculations required here.
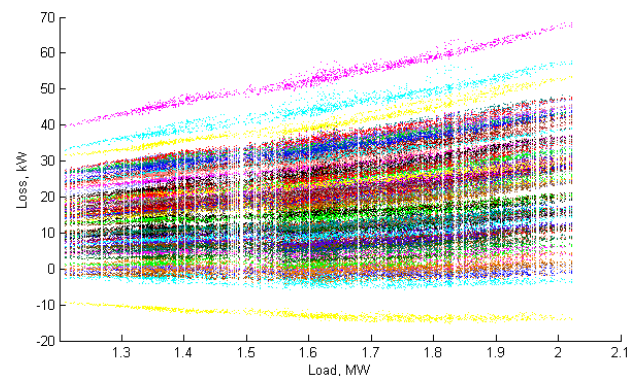

Fig. 9 HV feeder power difference uncertainty analysis (colouring identifies simulation trials)
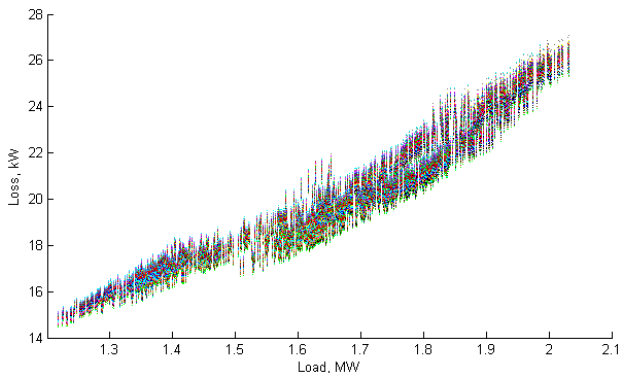
Fig. 10 HV feeder I^2R uncertainty analysis (colouring identifies simulation trials)

Table 2 Mean losses for uncertainty analysis

	Loss as % of delivered power		Error in % loss
	No errors	With errors	
LV feeder	0.23%	0.21% to 0.25%	±9%
HV feeder end-to-end	1.20%	1.17% to 1.23%	±3%
HV cable	0.29%	0.26% to 0.32%	±10%
Transformer:			
Load loss	0.35%	0.33% to 0.36%	±5%
No-load	0.58%	0.57% to 0.59%	±2%
Total	0.92%	0.91% to 0.93%	±1%

Fig. 10 shows the very low variation between each simulation trial with the I^2R method. The mean losses are shown in Table 2 and have a range of 1.17% to 1.24% of the delivered power. This represents an uncertainty of ±3% in the percentage losses. The mean losses are shown separately for the HV cable and for the distribution transformers, indicating that the uncertainty is mostly associated with the cable losses.

Table 2 also shows the uncertainty analysis for the LV feeder. The selected feeder is lightly loaded and has low losses and so the results are particularly sensitive to the sensor tolerances. The results with the power difference method can suggest losses that are many multiples of the reference case, again demonstrating that this method does not provide the required accuracy. However, the uncertainty with the I^2R method is low, in this case ±9% on the percentage losses.

CONCLUSIONS

The measurement results for 11 kV and LV feeders demonstrate that losses calculated with the power difference method are highly sensitive to tolerances in the current and voltage sensors. These errors are largely avoided by using an I^2R method, although this is subject to tolerances and errors in the network data. Assuming that the network topology is known correctly, the uncertainty in percentage losses has been assessed as ±9% for the LV feeder and ±3% for the HV feeder.

The network topology can be validated by combining additional current and voltage data with the power-flow analysis. This can detect unmetered demand, errors in the phase allocation records, and errors with the monitoring installation. Correlation methods have been successfully used to identify phase allocation errors of single phase loads or to locate unmetered demand on the HV feeder.

The initial results have demonstrated that the HV and LV feeders can credibly be assessed for technical losses. The instrumentation is now being expanded to cover a wider range of feeder types. Future publications will summarise the measured losses and describe the methods used to apply these results to estimate losses on feeders without the need for detailed measurements.

ACKNOWLEDGEMENTS

REFERENCES

[1] Sohn Associates, Imperial College London, 2014, *Management of electricity distribution network losses*, http://www.westernpower.co.uk/docs /Innovation-and-Low-Carbon/Losses-strategy/SOHN-Losses-Report.aspx

[2] Western Power Distribution Losses Investigation http://www.smarternetworks.org/NIA_PEA_PDF/WPD_NIA_005_3113.pdf

[3] A.J. Urquhart, M.Thomson, 2015, "Impacts of Demand Data Time Resolution on Estimates of Distribution System Energy Losses", *IEEE Trans. Power Syst.*, 2015, 30, (3), pp. 1483–1491.

[4] A.J. Urquhart, M.Thomson, 2015, "Series impedance of distribution cables with sector-shaped conductors", *IET Gener. Transm. Distrib.*, 2015, 9, (16), pp. 2679–2685.

[5] T. Wildi, 2006, *Electrical Machines, Drives and Power Systems,* Pearson Education, New Jersey, USA, 215.

[6] A. B. Damnjanovic, G. Ferguson, 2004, "The measurement and evaluation of distribution transformer losses under nonlinear loading", *IEEE Power Engineering Society General Meeting* pp. 1416–1419

[7] D. Takach, R. Boggavarapu, 1985, "Distribution Transformer No-Load Losses", *IEEE Trans. Power Appar. Syst.*, 1985, PAS-104, (1), pp. 181–193.