IMPACTS OF REACTIVE POWER AND HARMONICS ON LV NETWORK LOSSES

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ABSTRACT

Reactive power and harmonics have been proposed as key factors contributing to losses on LV networks. This paper describes measurements of reactive power phase displacement and harmonic distortion over a large number of LV feeders, demonstrating that low power factors mostly arise when the demand is lowest. Loss calculations for a set of eleven feeders show that distortion has a low impact, less than 10% of the loss power and near zero for feeders with higher losses. Phase displacement can significantly increase losses, particularly for commercial LV feeders. In one example, power factor correction would reduce losses by up to 36%.

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 there is uncertainty relating to the contribution from low voltage networks and on key factors that cause some feeders to have high or low losses.

This paper presents data and results from the Western Power Distribution (WPD) Losses Investigation project, undertaken in collaboration with Manx Utilities Authority, Loughborough University and Lucy Electric [2]. This project has developed methods for estimating losses on LV feeders on a distribution license-area scale. The LV estimation method has been derived and validated on a set of eleven trial feeders fitted with instrumentation at the substation and at customer connection points. Losses are calculated for these trial feeders using a power-flow analysis based on measured current data and using a network model derived from a GIS asset database. The accuracy of the instrumentation installation, customer phase allocations, and network records has been comprehensively verified by comparing the measured currents and voltage differences with those predicted by the power-flow analysis [3]. A demand model, based on the measurements from these trial feeders, has been developed in order to estimate losses more generally on feeders where there is no instrumentation.

The trials measurements provide a more detailed model of the power factors than is typically employed in planning tools by the DNO. This gives a more detailed model than previous approaches where, for example, a constant power factor, such as 0.95 lagging in [4] would be applied. Such constant power factor models also typically assume that the power factor is solely represented by a phase displacement of the 50 Hz waveform with no contribution from distortion.

Improving the power factor on LV networks has been proposed as a means of reducing losses [1]. This paper therefore concludes by evaluating the impact on losses of harmonics and of reactive power phase displacement on the eleven LV trial feeders.

MEASUREMENT DATA

Instrumentation

Fig. 1 shows the measurement configuration for an LV trial feeder. Instrumentation with 1-minute resolution has been installed at the substation and at each of the customer connections. The feeders also supply a number of unmetered connections to public lighting which, for the purposes of the trials, have been fitted with instrumentation and treated as ‘customers’. Capacitance effects in the cables are negligible at LV and so the instrumentation allows for a verification test such that the total current measured at the substation should be equal to the sum of currents delivered to customers.

In addition to the eleven LV trial feeders with instrumentation as shown above, data is also available for a much wider set of 410 LV feeders in Milton Keynes, UK. These feeders have GridKey loggers fitted at the substation, as in Fig. 1, but the customer connections are not monitored. (These loggers provide data for a separate trial in which HV feeder losses are quantified.)

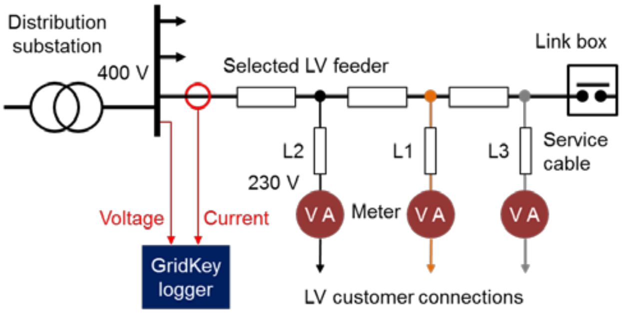

Fig. 1 LV feeder instrumentation

Power factor calculations

Power factors are defined here in terms of a power tetrahedron [5], as shown in Fig. 2. This shows an apparent power $S = V \cdot I$ where V and I are the root-mean-square (rms) amplitudes of voltage and current and include contributions from all frequencies. At the fundamental frequency the power is described by a triangle with active power P_1, reactive power Q_1 and apparent power S_1. There is an angle ϕ between P_1 and S_1 (and between the voltage and current components at the fundamental frequency) such that the phase displacement power factor is given by $\cos\phi$. The distortion power factor is given by the ratio S_1/S.

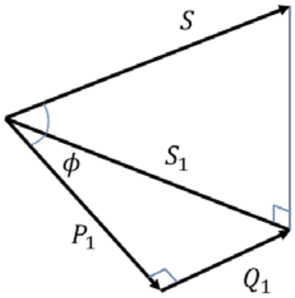

Fig. 2 Power tetrahedron

Current metrics

The instrumentation meters fitted at customer premises provide voltage and current amplitudes, active and reactive power, the total harmonic distortion (THD) of voltage and current, and the apparent power.

The measured rms amplitude includes all frequency components and so

$$I = \sqrt{\sum_{h=1}^{n} {I_\mathrm{h}}^2} \quad (1)$$

The current THD is defined as

$$\mathrm{THD_I} = 100 \cdot \sqrt{\sum_{h=2}^{n} {I_\mathrm{h}}^2} \Big/ I_1 \quad (2)$$

The current amplitude I_1 at the fundamental frequency of 50 Hz can be derived from the total current amplitude I (including harmonics) as

$$I_1 = I / \sqrt{1 + (\mathrm{THD_I}/100)^2} \quad (3)$$

where $\mathrm{THD_I}$ is the percentage total harmonic distortion. An equivalent calculation applies to the voltage.

The voltage distortion is typically low, around 1% - 2% THD. Even with relatively high current distortion, the power represented by the product of harmonic voltages and currents active is therefore also low compared to the power at the fundamental. The phase angle ϕ at the fundamental frequency is then approximately equal to the angle between the measured active and reactive power P and Q which include all frequencies. The fundamental current for each customer connection can then be defined as a phasor quantity $\boldsymbol{I_1}$ where

$$\boldsymbol{I_1} = I_1 \cdot \mathrm{e}^{-\mathrm{j}\angle(P+\mathrm{j}Q)} \quad (4)$$

To assess the impact of reactive power, a real-valued current can also be defined as $\mathrm{re}(\boldsymbol{I_1})$, representing the current that would occur at the fundamental frequency if the customer load had perfect correction of any reactive power demand.

The GridKey loggers at substations provide voltage, and current amplitude data but no direct measure of the distortion. However, the data includes total active and reactive powers, and also harmonic active and reactive powers, and these can be subtracted to find the powers $P_1 + \mathrm{j}Q_1$ at the fundamental frequency.

The current amplitude at the fundamental frequency can then be approximated by assuming that the voltage distortion is low (as indicated by measurements from nearby customer connections) and so $V_1 \approx V$. The fundamental current is then

$$I_1 = |P_1 + \mathrm{j}Q_1| / V_\mathrm{f} \quad (5)$$

and the current THD can then be found from (3).

LV FEEDER MEASUREMENTS

Power factor at 1-minute resolution

Measurements from one phase of an LV feeder serving 54 domestic customers are shown in Fig. 3. This shows the phase displacement and distortion factor contributions to the power factor, as measured by the GridKey logger at the substation. Distortion and phase displacement are both significant at lower levels of demand, and are also highly variable between 1-minute sample periods. However, both measures approach unity when the demand and the losses are highest. High demands tend to be resistive and not to have power electronic converters.

Fig. 4 shows the corresponding levels of current harmonics, expressed as a percentage total harmonic distortion (THD), noting again the limitation of the measurement data here that the voltage distortion is assumed to be zero. At low levels of demand, the aggregated distortion from all 54 domestic customers can still reach considerable levels of up to 50% THD.

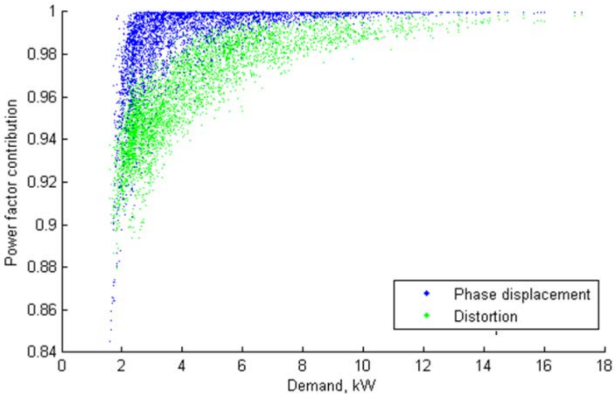

Fig. 3 Power factors for a domestic feeder

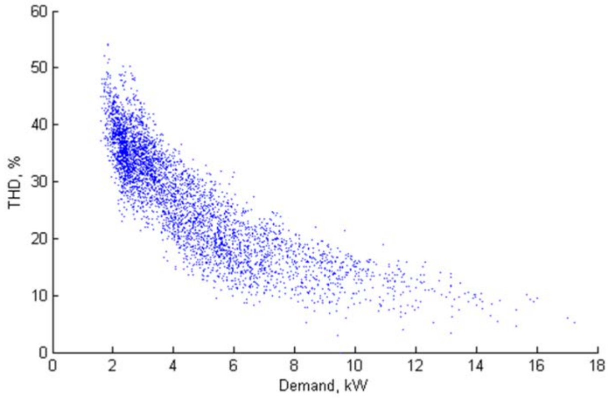

Fig. 4 Current distortion for a domestic feeder

Power factor probability distributions

Data from the 410 LV feeders in Milton Keynes has been used to form probability distributions of the phase displacement due to reactive power. Measurement samples for each feeder were categorised according to the level of active power demand, in bands of width 100 W. Histograms were then created to show the variation of reactive power, for a given active power band. These histograms express the reactive power in terms of a percentage of the active power. This avoids the ambiguity of import/export associated with the power factor, and also avoids the loss of resolution of a phase angle representation (where very high reactive powers are all close to ±90°).

The distribution of reactive power for the full set of Milton Keynes feeders is shown for a range of active powers in Fig. 5. Averaged over all of the 410 feeders and for a 1-year period, the phase displacement power factor is 0.995 lagging.

There is also considerable variation in the reactive power, both positive and negative, and a second peak in the distribution around 100% of the active power (a phase displacement of 45° and power factor near 0.7), particularly when the active power supplied to the feeder is higher. These instances relate to samples from specific feeders, rather than being distributed randomly amongst the full set.

Fig. 6 shows the same results but only with feeders that have been categorised as domestic. These feeders are defined as those for which over 80% of the annual demand is from customers categorised as domestic by the DNO (assigned to UK Elexon profile classes 1 and 2 for non-half-hourly metered domestic customers). For these domestic feeders, the reactive power has a mean around 5% of the active power, corresponding to a phase displacement of 3° and a power factor of near unity. As the level of active power increases, the range of variation reduces, but both reactive powers at low levels of demand can be both capacitive and inductive.

For these domestic feeders, the mean phase displacement power factor is unity.

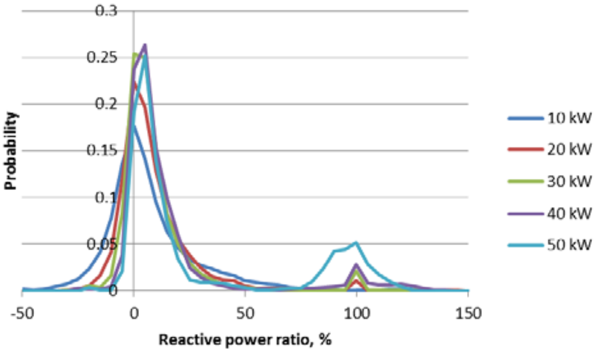

Fig. 5 Reactive power probability distributions for Milton Keynes feeders

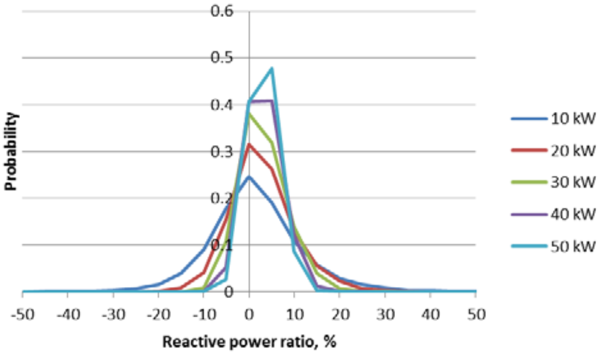

Fig. 6 Reactive power probability distributions for domestic Milton Keynes feeders

Probability distributions for the current THD over the set of 410 Milton Keynes feeders, as in Fig. 7, show that higher levels of distortion seen for the example feeder of Fig. 4 are rare when the mean levels of demand are higher. The mean current THD reduces with the feeder demand, as does the variation around the mean.

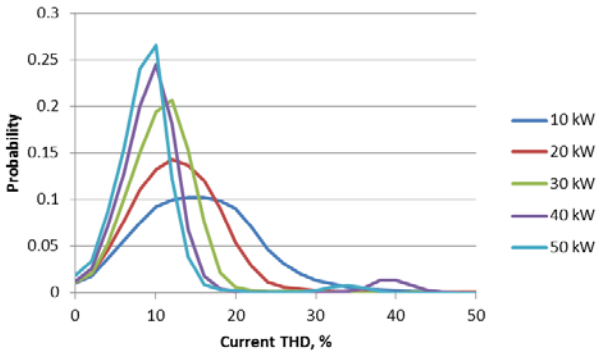

Fig. 7 Current distortion for Milton Keynes feeders

IMPACT ON LOSSES

Losses have been calculated for the eleven trial feeders based on measurement data recorded over a 1-year period. The feeder instrumentation does not provide measurements at individual harmonic frequencies and so the simulation operates at a single-frequency of 50 Hz. Despite this, it is possible to assess the impacts of harmonics and phase displacement by selecting the appropriate current amplitudes for the customer load models. Three different simulation options are compared:

Losses with all frequencies included: The current is modelled using the measured rms amplitude and phase angle ϕ (as for the fundamental current).

Fundamental only: Using the estimated fundamental frequency current, with amplitude and phase angle $\boldsymbol{I_1}$ from (4).

Active fundamental only: Using the active component of the estimated fundamental current, from $\mathrm{re}(\boldsymbol{I_1})$.

The first of these options, using the measured rms current amplitudes, represents the combined current of all frequencies as if it were at the fundamental frequency. This gives a close approximation to the sum of losses that would have been calculated if the individual harmonic components had been known, as demonstrated in previous work where the currents and impedances at each harmonic frequency were considered in detail [6].

For branches directly connected to the customer loads, and neglecting the relatively minor impact of the increased resistance at harmonic frequencies due to AC skin and proximity effects, losses calculated using the measured current amplitudes are equal to the sum of losses for all frequencies. In upstream branches the use of a single frequency model gives an upper bound to the calculated losses. This arises as the currents from each downstream customer are added coherently, whereas in practice there will be some degree of cancellation as some of the harmonic contributions will have different frequencies and phase angles.

The loads are modelled with a constant current characteristic so that the power-flow solution retains the current amplitudes as specified in the input data (rather than using a constant power model where the solved currents may deviate from the measured data).

The feeders are categorised as:

- ‘domestic’ – feeders with underground cables supplying urban or suburban residential customers
- ‘industrial’ - feeders with underground cables to light industrial and commercial customers
- ‘overhead’ - feeders where the network includes some branches with overhead lines or aerial bundled cable supplying more rural residential customers

The calculated cable losses are shown in Fig. 8 and the relative impacts of the different current models are summarised in Table 1. These results show that impact of harmonics on losses in these feeders is relatively minor, with differences ranging from 9% to near zero. The contribution of harmonics to losses is most significant when the total losses are low, and negligible on feeders with the highest losses. This might be expected from the variation of harmonics with the active power in Fig. 4.

The impact of reactive power is also low for the domestic and overhead feeders, but much higher for the feeders with industrial and commercial customers. Although the sample size is small, the results clearly indicate that reactive power can have a significant impact on losses for some LV feeders. These commercial feeders are also found to be those with the highest losses.

Table 1 Impact of harmonics and reactive power for LV trial feeders

LV feeder	Cable loss, all frequencies, W	Fundamental only	Active fundamental only
Domestic 1	16.4	-4%	-3%
Domestic 2	233.4	-4%	-4%
Domestic 3	43.9	-6%	-2%
Domestic 4	625.5	-3%	0%
Industrial 1	341.6	0%	-32%
Industrial 2	1518.7	0%	-36%
Industrial 3	64.8	-9%	-21%
Industrial 4	211.9	-4%	-7%
Overhead 1	17.5	-4%	-9%
Overhead 2	357.9	-3%	-9%
Overhead 3	83.8	-3%	-1%

In the case of the ‘Industrial 2’ feeder shown in Table 1, a reduction of losses by 36% due to reactive power correction would save mean losses of 550 W. With energy costs of losses at £48/MWh [1] in the UK, this equates to a saving of £230 per annum. For this feeder (as with many), the demand is dominated by one particular customer and so it may be viable to consider fitting power factor correction at this connection point.

As the use of smart meters becomes more commonplace, it will be increasingly practical to identify customer connections where reactive power is high. The UK also has a programme to replace commercial non-half-hourly meters in profile classes 5-8 with half-hourly metering, making reactive power data readily available to DNOs.

Fig. 8 shows the magnitudes of the losses for the three different current models, again demonstrating the impact excluding harmonics and of excluding reactive power at the fundamental frequency. This plot also highlights the significant variation in the losses with order-of-magnitude differences between the feeders.

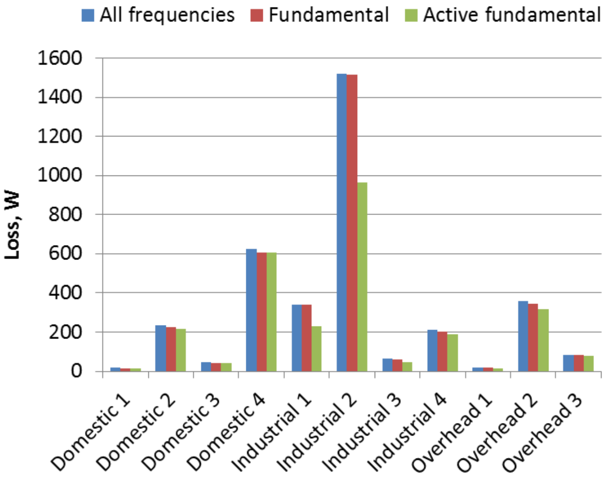

Fig. 8 Calculated losses for LV trial feeders

CONCLUSIONS

Cable losses have been calculated for a set of eleven LV trial feeders fitted with instrumentation to measure the demand at each customer connection.

Harmonics have a low impact on the mean losses for these feeders. If harmonics were to be removed, there would be negligible impact on losses of the heavily-loaded feeders, and less than 10% reduction on the more lightly-loaded feeders.

Reactive power due to phase displacement of the current was found to have a more significant impact on the commercial feeder losses. In one case, 36% of the losses could be avoided, with a cost saving of £230 per annum, if power factor correction were to be fitted.

In addition to these power factor effects, the losses are significantly affected by differences in the network topology and the number and type of loads connected. Within the set of eleven trials feeders, the mean losses range over two orders of magnitude.

Measurements of the aggregated current have also been obtained for a more extensive set of 410 LV feeders. This data shows that reactive power has a mean phase displacement angle of only 3° and that variations around this mean reduce as the active power increases. The mean phase displacement power factor was 0.995, much closer to unity than has been assumed in previous DNO models.

For the domestic feeders, the mean phase displacement factor measured at the substation was found to be unity. Higher domestic power demands tend to be more resistive and have lower harmonic distortion, although this may change in future with increasing uptake of electric vehicles with home chargers. On some of the commercial feeders the aggregated currents have a much greater phase displacement, even at higher levels of demand.

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