CHARACTERISATION OF PHASE CURRENT IMBALANCE ON THREE-PHASE LV FEEDERS TO IDENTIFY OPPORTUNITIES FOR REBALANCING

Sarah WEATHERHEAD
TNEI Services - UK
sarah.weatherhead@tnei.co.uk

Charlotte HIGGINS
TNEI Services - UK
charlotte.higgins@tnei.co.uk

Alan COLLINSON
Scottish Power Energy Networks- UK
alan.collinson@sppowersystems.com

ABSTRACT

A new methodology and metric were developed to characterise the phase imbalance in currents on three-phase LV feeders. These focus on the factors most relevant to network capacity headroom: degree of imbalance at peak loaded times, and persistence over time of imbalance towards a particular phase. Phase current data from 233 LV feeders was analysed over the winter period, which correlates with high loading. A total of 23 feeders (10%) were identified with good potential to increase capacity headroom by rebalancing. This was based on providing a capacity headroom increase of at least 20% and high existing loading.

A representative cost-benefit analysis was performed to identify preferred solutions for phase imbalance and compare rebalancing with network reinforcement. For LV OHLs with imbalance, redistributing customers between phases is the most techno-economic approach to release network capacity. For imbalanced LV cables, a change of link-box configuration is the preferred solution.

INTRODUCTION

Phase Imbalance at Low Voltage

Most customers are connected to a single phase of a three phase feeder on the low voltage (LV) distribution network in the UK. This can lead to significant load imbalance if customers and/or loading are not distributed evenly between phases. This can occur during installation or due to unforeseen load differences despite network design intention to achieve relative phase balance. Imbalance of current between phases reduces the capacity headroom of a feeder, increases losses, and accelerates the need for network reinforcement. It can also lead to voltage imbalance along the feeder although this is not assessed here.

There is typically little visibility of the power flows on the LV networks. Network planners will generally assume phases to be balanced with margins included when specifying LV cable ratings to manage the risk of phase imbalance.

Flexible Networks for a Low Carbon Future

The research presented here forms part of the Low Carbon Network Fund Tier 2 project *Flexible Networks for a Low Carbon Future*. The project aims to provide a **20% increase in network capacity** on Scottish Power Energy Network (SPEN)'s UK distribution network, by applying innovative solutions that can:

- Determine more accurately the capacity headroom while maintaining licence obligations;
- Allow that headroom to be exploited in a safe, reliable and cost-effective manner; and
- Provide incremental increases in headroom in a timely and cost-effective manner.

As part of Flexible Networks, in 2013 SPEN installed monitoring on low voltage feeders in three trial areas: St Andrews in Scotland, Wrexham in Wales and Whitchurch in England. Ten-minute current snapshot measurements were taken at 166 secondary substations for all three phases of each LV feeder.

Aims

The aims of this work were to:

- develop a methodology to characterise LV current imbalance from large volumes of monitored data;
- identify LV feeders on SPEN's network where capacity headroom could be increased by rebalancing (i.e. permanently redistributing customers between the phases); and
- assess the typical costs and benefits of rebalancing SPEN's LV feeders.

CHARACTERISING CURRENT IMBALANCE

Phase imbalance in a three-phase LV feeder is a complex, time varying phenomenon. The monitored data for an LV feeder over six months contains over 26,000 current measurements for each phase. A simple metric is needed to condense this data into useful information for network planners for the purposes of assessing whether a permanent rebalancing of the feeder would be advantageous,

A new metric for current imbalance

Existing phase imbalance metrics are mainly used to describe voltage imbalance, and are defined analogously for current imbalance. Three commonly-used definitions of phase imbalance are [1, 2]:

IEEE Standard 112 (1991) (A)

$$= \frac{max\ voltage\ deviation\ from\ the\ avg\ line\ voltage}{avg\ line\ voltage}\ x\ 100$$

NEMA (National Equipment Manufacturer's Association) Standard (1993) (B)

$$= \frac{max\ voltage\ deviation\ from\ the\ avg\ phase\ voltage}{avg\ phase\ voltage}\ x\ 100$$

IEEE True Definition (1996) (C)

$$= \frac{negative\ sequence\ component}{positive\ sequence\ component}\ x\ 100$$

In some unbalanced feeders, one particular phase is always more highly loaded than the others; in others the highest loaded phase changes as large single phase loads turn on and off. Network planners need to know whether or not the feeder is persistently imbalanced towards the same phase, because this information will determine whether permanently redistributing customers between the phases would resolve the problem. (A) and (B) are unsuitable because they do not retain information about which of the phases is the highest loaded and which is the lowest loaded. (C) does not retain information about zero sequence components, which can be significant in four-wire systems such as LV networks.

Additionally, the percentage values in (A), (B) and (C) are more intuitive for voltage imbalance, as values will typically be a few percent. However, for current imbalance on the LV network, instances are seen where one phase is more than twice as highly loaded as the average, leading to values >100%. Arguably a ratio rather than a percentage would be more suitable.

Therefore we have developed new metric for current imbalance, which is particularly suited to the requirements of network planners.

Imbalance ratio for phase X:

$$= \frac{current\ on\ phase\ X}{average\ current\ of\ the\ three\ phases}$$

This gives a dimensionless measure that is comparable between feeders with different loading. Compared with other methods, this method retains information about which phase is highest loaded at each time-point.

Phases with an imbalance ratio >1 have higher than average loading, and phases with imbalance ratio <1 have lower than average loading. If all phases have imbalance ratios close to 1, the feeder is well balanced.

Characterising current imbalance over an extended time-period

An imbalance assessment tool was then developed to process the time-series current data from LV feeder phase monitoring and output characteristic values to describe the phase imbalance.

A network planner will be most interested in phase imbalance during periods of high loading, as this is when the highest losses occur and when the asset is operating closest to rating. The tool selects the 100 timestamps of highest loading for the highest loaded phase (approximately the top 0.5% for a 6 month dataset). The tool then outputs the mean, maximum and minimum imbalance ratio over these 100 highest loaded timestamps. The tool also gives a graphical output to enable the user to visualize the phase imbalance.

Figures 1, 2 and Table 1 demonstrate results from the imbalance assessment tool for Feeder 1, a representative balanced LV feeder on SPEN's St Andrews network. Figures 3, 4 and Table 2 demonstrate results for Feeder 2, a very imbalanced feeder supplied by the same secondary substation. Figures 1 and 3 show raw time series current data for a typical day. Figures 2 and 4 show the graphical output from the imbalance assessment tool indicating the phase imbalance at the highest loading times over the assessment period (October 2013 to March 2014). Tables 1 and 2 show the imbalance ratios calculated by the imbalance assessment tool.

By comparing the mean, maximum and minimum phase imbalance metric for each phase, it is possible to build up a characterisation of the magnitude and persistence of phase imbalance under high loading conditions. This also provides an indication of whether phase rebalancing should be considered.

For example, Table 1 shows that all phases on feeder 1 have mean imbalance ratios close to 1, maximum imbalance ratios > 1 and minimum imbalance ratios <1. This indicates a well balanced feeder. By contrast, Table 2 shows that the mean imbalance ratio for phase 2 is > 2, indicating a high level of imbalance. The minimum imbalance ratio for phase 2 is > 1, indicating that this phase is more highly loaded than the feeder average for all the 100 highest loaded datapoints. This shows that the phase imbalance is persistent, and therefore rebalancing should be considered. The maximum imbalance ratios for phases 1 and 3 are < 1, again demonstrating the persistence of the imbalance.

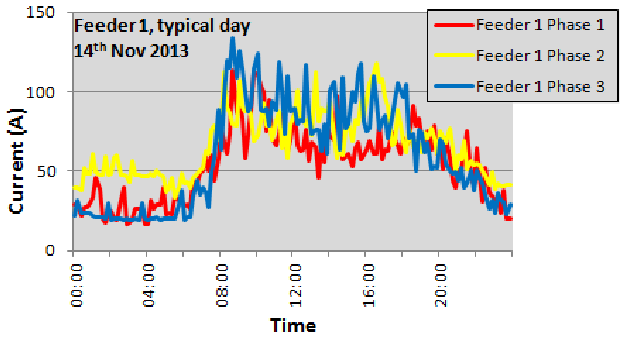

Figure 1: Time-series data for a balanced LV feeder

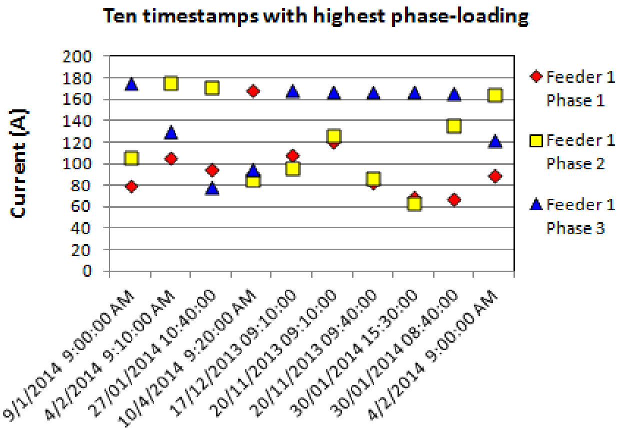

Figure 2: Graphical output of imbalance assessment tool for a balanced LV feeder

Table 1: Mean, highest and lowest imbalance ratios among 100 highest loaded timestamps for a balanced feeder.

For one hundred timestamps with highest phase-loading

	Mean imbalance ratio	Highest imbalance ratio	Lowest imbalance ratio	Maximum current (A)
Phase 1	0.85	1.61	0.48	169
Phase 2	0.93	1.51	0.62	175
Phase 3	1.22	1.71	0.66	175

Balanced feeder so ratios are on average close to 1.

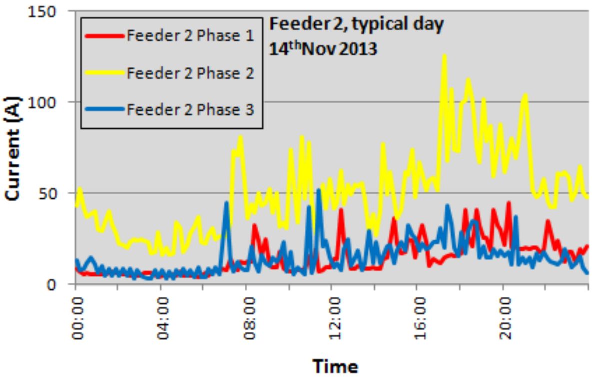

Figure 3: Time-series data for an imbalanced LV feeder

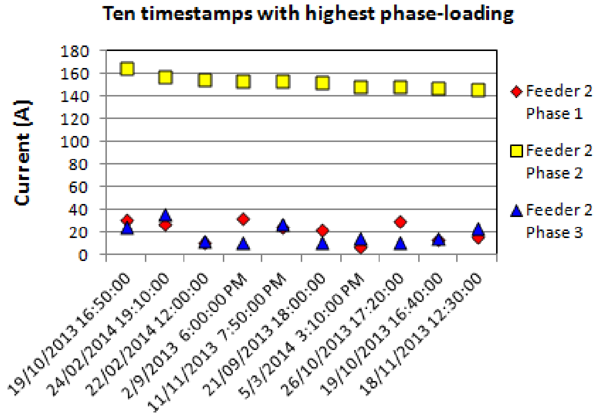

Figure 4: Graphical output of imbalance assessment tool for an imbalanced LV feeder

Table 2: Mean, highest and lowest imbalance ratios among 100 highest loaded timepoints for an imbalanced LV feeder.

For one hundred timestamps with highest phase-loading

	Mean imbalance ratio	Highest imbalance ratio	Lowest imbalance ratio	Maximum current (A)
Phase 1	0.35	0.78	0.10	83.9
Phase 2	2.34	2.75	1.87	164
Phase 3	0.32	0.76	0.09	74.6

Phase 2 more than twice as highly loaded than in a balanced situation.

Phase 2 persists in being the highest loaded for all the top 100 timepoints.

IDENTIFYING FEEDERS FOR PHASE REBALANCING

The imbalance assessment tool was run for 233 LV feeders from 89 secondary substations in the SPEN distribution network licence areas, for the period October 2013 to March 2014. Then feeders were selected which had:

- a phase with mean imbalance ratio >1.3 (indicating a significant imbalance), and
- the minimum imbalance ratio of the top 100 highest loaded datapoints for that phase was >1 (indicating a persistent imbalance towards the same phase during high loading conditions).

Thirty-six feeders met these criteria.

These feeders were then assessed to estimate the percentage capacity headroom which could be released by phase rebalancing. It was assumed that load would be moved from the highest loaded phase to the lowest loaded phase until these two phases were evenly loaded- this is the simplest intervention though a more complex change could release more capacity. It is recognised that transient imbalance will always remain after rebalancing. A figure was obtained for the percentage reduction in maximum phase loading that could be achieved by this method, i.e. the potential capacity release.

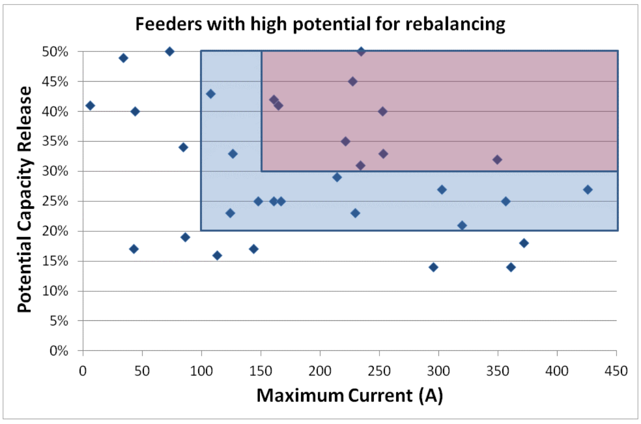

Figure 5: Feeders with a mean imbalance ratio >1.3 for the highest loaded phase, and with persistent imbalance towards the same phase over 100 highest loaded time-points. The blue box highlights candidate feeders for rebalancing, the purple box highlights the most promising candidates.

For these feeders, Figure 5 shows the existing maximum phase loading, and the potential percentage reduction in maximum phase loading. The feeders which should be considered for rebalancing have high loading (as this suggests these feeders are closer to rating and thus more benefit will be gained), and high potential capacity release. Twenty-two feeders were identified with loading >100A and potential capacity release >30% (shown in the blue box in Figure 5). Nine of these feeders have loading >150A and potential capacity release >30% (shown in the purple box in Figure 5).

COST-BENEFIT ASSESSMENT

A cost-benefit analysis was undertaken for various reinforcement options to assess the most techno-economic solutions, once a candidate feeder for phase re-balancing has been identified. It is assumed that the feeder is approaching capacity, and that either reinforcement or rebalancing is required to increase capacity headroom. This cost-benefit assessment focuses on LV feeders supplying domestic customers.

Table 3 gives estimates of the cost for LV feeder monitoring and various phase imbalance solutions for the LV network. The cost of an engineer to investigate and design the most appropriate network reinforcement will be common to all network solutions although for a simple LV connection, this will be minimal.

Table 3: LV phase imbalance typical solution costs

Activities	**Estimated Cost**
Common to all solutions	
LV Monitoring at secondary substation, 4-5 feeders (all phases)	£3000 [3]
Engineering time to analyse monitoring data and characterise phase imbalance	£500
Phase Rebalancing Solutions	
Per Domestic Customer	£2000 for cables; £500 for OHLs
Change link box configuration	£2000 radial; £4000 interconnected
New LV Cable, Uprating or Overlay	£50k-£75k‡

‡ Based on £100-£150/m cost of cable and installation (dependent on ground conditions) and typical LV feeder length of 500m

Rebalancing Solutions

In order to change the phase connection of a typical suburban domestic customer supplied by LV cable, it is necessary to excavate the joint bay, sever and then rejoint the customer service cable. Records of which phase customers are connected to are not available but the cost of identifying the phase connection of the customer is minimal compared to the installation works cost. Possible methods include signal injection, metering, or analysis of smart-meter data [4, 5]. Changing the phase connection of a customer connected to an LV OHL is by comparison a much simpler and less costly process.

If there is a link box located along the LV feeder, jointing works can be undertaken to swap phase cores. If the LV feeder is in an interconnected mesh then this will need to be carried out at both ends of the feeder-link box connection. For both radial and interconnected LV feeders, the re-jointing procedure will result in loss of supply for several hours.

Reinforcement solutions

For cable reinforcement, it is most efficient to retain the existing cable and overlay an additional cable as a split feeder to double the capacity, as long as there is space on the LV board. Up-rating an existing cable would involve removing the old cable and re-jointing all customers, and would thus provide much less benefit for similar cost.

For LV OHLs, it is common SPEN procedure to replace OHLs approaching capacity with LV cables to provide additional headroom whilst reducing future maintenance requirements and improving visual amenity, rather than re-conductor or build additional OHLs.

Results of cost-benefit assessment

Results of the representative cost-benefit analysis in Table 4 indicate that it is most cost-effective to change the link box configuration, if a link box is located along the LV feeder cable. The feasibility of this will depend to an extent on the number of customers connected upstream and downstream of the link box.

Table 4: LV phase imbalance solution cost-benefit

Activities	Estimated Capacity Headroom	£k/Percentage Capacity Headroom
Phase Rebalancing		
*Moving 4 - 8 domestic Customers**	15% - 30%‡	0.55 for cables 0.14 for OHLs
Changing link box configuration	up to 30%	≥0.07 for radial ≥0.14 for interconnected
New LV Cable (replacing OHL)	25% - 50%	1 – 3
LV Cable Uprating	20% – 30%	1.7 - 3.75
LV Cable Overlay	100%	0.5 - 0.75

* Typically up to 50 customers connected per LV feeder with an After Diversity Maximum Demand per domestic property of 2kW [6].

‡ For highly imbalanced LV feeders identified as suitable candidates.

Changing the phase connection of individual customers on LV cables does not appear to be a more techno-economic solution than simply overlaying a new LV cable and potentially moving some customers off the most heavily loaded phase if required. However, this may not always be the case. If the LV feeder board at the secondary substation is already full, then the addition of another LV cable will require a new secondary substation to be built which is a much more costly undertaking. Also, if it is unlikely that the additional capacity of a new LV cable will be fully utilised in future, then the total cost of rebalancing a few customers is less than the total cost of a new LV feeder that will be under-utilised.

For LV OHLs, it is more cost-effective to rebalance existing customer load connections than to increase circuit capacity by laying a new LV cable.

CONCLUSIONS

A new phase imbalance metric to characterise LV current imbalance has been developed and incorporated into a data analysis software tool. The new metric has advantages over existing metrics for use in network planning - identifying the magnitude and persistence of phase imbalance under high loading conditions and opportunities for capacity headroom release through rebalancing. Data from 233 LV feeders was analyzed using the phase imbalance assessment software tool. Twenty-two feeders were identified with high potential to benefit from rebalancing.

A representative cost-benefit assessment has demonstrated that for LV OHLs with imbalance, redistributing customers between phases is a more cost-effective way to release network capacity than LV cable reinforcement. For imbalanced LV cables, a change of link-box configuration is the preferred solution. For LV cables, the costs per unit capacity headroom of redistributing customers are comparable with reinforcement, however customer redistribution is preferable in circumstances where a new secondary substation is required or there is high risk of a stranded LV cable asset. Whilst it is recognized that this cost-benefit analysis is specific to SPEN, there will be some applicability to other DSO LV networks.

REFERENCES

[1] P. Pillay, M. Manyage, 2001, “Definitions of Voltage Unbalance”, *IEEE Power Engineering Review*, May 2001.

[2] M. Tavakoli Bina, A. Kashefi, 2010, “Three-phase unbalance of distribution systems: Complementary analysis and experimental case study”, *Electrical Power and Energy Systems* 33 (2011) 817-826

[3] Scottish Power Energy Networks, March 2014, *RIIO-ED1 LCT Network Monitoring Strategy*.

[4] V. Arya et al, 2011, “Phase Identification in Smart Grids’, *2011 IEEE International Conference on Smart Grid Communications*, Oct 2011.

[5] H. Pezeshki, P. J. Wolfs, 2012, “Customer Phase Identificaiton in a Three Phase Unbalance LV Distribution Network”, *3rd IEEE PES Innovative Smart Grid Technologies Europe*, 2012.

[6] I. Richardson et al, 2010, “Domestic electricity use: a high resolution energy demand model”, *Energy and Buildings*, 42 (10), pp. 1878-1887.