APPLICATION OF DISTRIBUTION SYSTEM STATE ESTIMATION ON ENGINEERING INSTRUMENTATION ZONES OF LOW CARBON LONDON

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ABSTRACT
This paper discusses the performance and presents potential benefits of the application of State Estimation on real distribution network. The application is tested using real network measurements obtained during Low Carbon London project. It demonstrates that the deployed distribution system state estimation, through a limited number of optimally placed sensors with adequate accuracy, can robustly estimate voltage and power flows in high voltage distribution networks.

INTRODUCTION
Low Carbon London (LCL) [1] is a £28.3 million project funded by the Low Carbon Networks Fund (LNCF) [2] to identify innovative solutions to maximise the benefits of a wide range of Low Carbon Technologies (LCT) on London’s electricity distribution network (DN). The deployment of LCT controlled by active network management requires voltages and power flows across the network to be monitored closely in order to enable optimized control actions of LCTs and network control devices, in a coordinated manner in real time. However, in contrast to the national transmission system, where measurements are widely deployed [3], available measurement infrastructure in High Voltage (HV) DNs, is not sufficient to facilitate real time control, essential for the evolution to the smart-grid paradigm. Thus, additional measurements will need to be established to support the implementation of innovative real time active DN management practices necessary to facilitate cost effective integration of low carbon demand and generation technologies. Due to vast number of nodes in a DN, fully instrumenting the network would have a prohibitive cost. A special tool is required for Distribution System State Estimation (DSSE) which could be used to reduce the number of meters needed in a way to ensure that adequate network observability and the accuracy of state estimation (SE) can be achieved over a range of different operating scenarios.

Although transmission SE algorithms have a central role in the operation of the transmission system for some decades [3], they cannot be applied directly to the DNs because of their different design and operating practices. There are a number of methodologies for DSSE proposed in the literature. A good overview of transmission and distribution SE can be found in [3]-[5]. The majority of the existing research on DSSE is performed on generic networks which have ideal network parameters data and measurements. However, when applied on the real network, the user of DSSE faces multiple practical issues. This work presents an effort in examining the role and possible application of DSSE in the UK DNs. Measurements carried out within LCL Engineering Instrumentation Zones (EIZs) demonstrate that the developed prototype DSSE, through a limited number of optimally placed sensors could robustly estimate voltage and power flows in HV DNs. This paper firstly introduces the methodology applied. Secondly, it discusses the results of DSSE in terms of voltage, consumption and power flow and the accuracy of estimation for the peak demand condition. Thirdly, the results of rigorous testing of DSSE model and analysis on the accuracy and robustness of voltage and power flow estimates using half-hourly data across one year are presented. This is followed with a study demonstrating that the way the pseudo measurements, as alternative for the missing real measurement data, are modelled has an important impact on estimation quality. Impact of sensors availability and quality to SE is discussed afterwards. Finally, it demonstrates the application of DSSE along EIZ feeders to determine the optimal number and locations of new sensors and recommends rules of thumb for their location.

METHODOLOGY
Having in mind the limited number of real measurements, the basic task of a DSSE is to estimate as accurately as possible the true state of a system (i.e. voltage and power flow profiles), using any relevant available information. The DSSE model deployed in this work is based on the maximum-likelihood estimation of state variables which employs Weighted Least Square (WLS) formulation, and is recognised as one of the most suitable techniques for state estimation in DNs [5]. WLS methodology works on the principle that the difference between measured and true values is minimised taking in consideration weight of each measurement, which is inversely proportional to the accuracy of the measurement. The Newton iterative
technique is employed to solve SE non-linear equations [3]. The input data required by the DSSE model are:

- **Network topology** - the single phase positive sequence equivalent circuit is used to model the networks under study, assuming steady state balanced conditions;
- **Network parameters** - such as impedance, susceptance and tap changer positions;
- **Measurements**:  
  - **Real measurements** - measurements of rms voltage (V), active and reactive (P&Q) power injections and flows. Data accuracy depends on the accuracy of the measuring equipment and communication system.
  - **Pseudo-measurements** - the approximations of the quantity when real measurement data are not available. They are derived heuristically by using available relevant data, historical data, or any other quantifiable network information associated with the input data in question. Consequently, the accuracy of pseudo measurements is relatively low. However, this approach is necessary to compensate for the lack of real network measurements and to ensure the solvability of the DSSE mathematical model.
  - **Virtual measurements** - assumed zero power injections at the joint points with very high accuracy.
  - **Weighting factor of the measurements** - The higher the meter’s accuracy, the higher the weight. This implies that the algorithm gives more importance to the accurate measurements.

For the purpose of this work the following values of **measurement errors are assumed**, based on UK Power Networks’ empirical data:

- Virtual measurements - assumed to be 0.001%;
- Pseudo measurements, consumption at substations with no measurement devices, assumed to be 50%;
- Error of measurements at installed meters:
  - Primary Substation: voltage 1.6%, P and Q 2%
  - Secondary substation: voltage 0.3-0.6%; Error in active and reactive power measurements: depends on the current trough CT and goes up to 9.6%, with the quadratic dependency, obtained from the field test results.

**NETWORKS**

One of LCL trial objectives was to instrument the selected four 11kV feeders from three EIIZs, in order to have solid test platforms for this work. These feeders represent typical London 11kV distribution feeders. Feeder BRXB-SE3 total length is 2.6km and supplies around 2000 domestic, industrial and commercial (I&C) customers via ten 11/0.4kV transformers at secondary substations. Seven out of ten secondary substations are instrumented with RTUs, which provide measurements of voltage and consumption measured on LV side. Feeders AMBL-NW1, BRXB-NF2 and MERT-E2 are long from 1.9 to 7.3 km, and supply from 1520-3720 domestic and I&C customers.

Although full instrumentation of EIIZs was planned, due to practical issues some substations are not instrumented, e.g., due to being underground with limited space or having inadequate GPRS coverage to allow data transfer. Feeder’s diagrams with equidistant substations representation of BRXB-SE3 and MERT-E2 are given in Figure 1 and Figure 2, respectively. The substations instrumented by RTUs are marked blue and non-instrumented red.

**RESULTS**

The state of the EIIZ feeders is estimated for each half-hourly period from 01 March 2013 to 01 March 2014. The key outputs of the DSSE model are the expected values and confidence intervals of voltages, angles, P&Q demand and P&Q flows. The following examples demonstrate the outcome of DSSE for the peak demand condition operating regime of BRXB-SE3. The measurements of V, P&Q demand were available for all substations, except for 6, 8 and 10 (90625, 94356 and 91143), for which pseudo measurements are used.

*Figure 4 demonstrates how DSSE can improve the accuracy of the voltage. Measured voltage values are denoted with blue squares. Estimated mean voltages are denoted by red circuits on the thick red line. The red dotted and dashed lines represent the boundaries within which the true value voltage is expected i.e. within ±3 standard deviations of the average estimates. The black lines represent the measuring equipment error margin of ±0.6% at secondary and ±1% at primary substations. The measured voltages do not follow the expected pattern of a constant drop down the feeder, although the feeder is radial with just one lateral branch; however, the estimated voltages do follow the expected pattern.*
The results demonstrate that the level of estimates of voltage error is relatively small and does not exceed 0.22%, as presented with 3 standard deviation lines, while a larger mismatch is obtained from measurement. This indicates that the system cannot rely solely on the sensors and DSSE is necessary to improve the accuracy and robustness of the monitoring system.

Application of DSSE improves estimates of P&Q consumption as well. The uncertainty of consumption of un-monitored substations is lowered from 50% down to up to 30%. Although the error margin is relatively high, the application of DSSE actually improves the visibility of these substations, which were not previously visible.

Furthermore, even if the uncertainty of the estimated load is relatively high, the rating of unmonitored substations is typically sufficient to comfortably supply the maximum load, as demonstrated in Figure 5.

The level of active power flow uncertainty is less than 10% on the main sections of the feeder and less than 2% for the first 4 and the last 2 sections, since the data from the measurements is relatively accurate, although the level of error of pseudo measurement data for unmonitored substations is 50%. Comparing estimated maximum power flows and the circuit’s rating shows that there is an adequate capacity in this system as the maximum loading of the circuits is below 50%, even after taking into account the possible error in the estimation. Therefore, we can conclude that, as long as the capacity of the circuit can cope with the forecasted maximum flow taking into account the uncertainty in the estimation, there is no need to place an additional measurement for the respective circuit.

**Year-round study to test the robustness and performance of the DSSE model**

To test the robustness and performance of the model, results of DSSE are analysed across one year period. The half-hourly voltages data and the estimated voltages are compared. In more than 90% cases, for all instrumented distribution transformers, the mismatch between the recorded and results of DSSE model is considerably smaller than the level of errors of the measurements, which are respectively 1% for the primary node and 0.6(0.3)% for the secondary substations. This difference typically exhibits constant value for secondary substations. These trends are observed for the whole of the year, apart from the few cases where due to recording errors majority of measurements were unavailable, or/and clearly wrong.

In the case of BRXB-SE3, the differences between estimated and measured voltages are the highest for the substation 94192 (node 11). Sorted in ascending order they are presented in Figure 6. For the majority of the half-hourly periods differences are mainly at the level of about 0.5%. This suggests that the accuracy of some of the recorded quantities may not be as good as specified in their technical parameters, e.g. the meter is not tuned, or the parameters of distribution transformer, e.g. impedances, transformer ratio, tap-position, might differ from the typical values anticipated in this study.

If the voltage measurements at substation 94192 are increased by 0.5%, the mismatch between estimates and adjusted measurements is less than 0.1% in majority of the cases. However, this correction does not noticeably affect the values of estimates of any other node. This is due to high level of instrumentation of this feeder with sensors. If the instrumentation is not high enough this inaccuracy can significantly affect DSSE, as explained later.

**Enhancing the accuracy of DSSE using improved pseudo measurements**

The following examples demonstrate the importance of the pseudo measurements choice. Due to a malfunction of
on the system on the 16/09/2013, the recording of some measurements failed to work leaving only 4 out of 10 substations monitored, mainly on the beginning of the feeder. For the purpose of the estimation, the gap in the real measurements has to be filled with pseudo measurements. There are two approaches investigated: Approach 1- if the typical load profiles of the substations are unknown, the best approximation of the substations loadings can be calculated as the difference between the known loadings of the feeder and the known loadings of the substations, and distributed among the substations without measurements based on their capacity; Approach 2 uses the typical load profiles of the substation as the basis for distributing the load obtained by subtracting the load at primary substation with the recorded load from secondary substations. The estimated active power consumption for both cases is compared and the results for the substations 90043 are presented in Figure 7. The blue colour line denotes the measured data, magenta outcome of DSSE for Approach 1 and the red the output for Approach 2.

In the periods when data from real measurements are available, the estimate values are similar to the recorded data with relatively small error margin. However, as shown in Figure 7, in the moment of loss of the measurements, for Approach 1, there is no smooth transition from previously recorded values, and the uncertainty of the estimate values increase significantly. However, by using the information from the typical load profile (Approach 2) to calculate the pseudo measurements, this transition is smooth and gives more meaningful estimates even though the uncertainty is still high due to insufficient measurements which are distributed only on the beginning of the feeder. The way the pseudo measurements are modelled has an important impact on estimation quality.

**Impact of sensors availability to SE**

In order to evaluate impact of sensors availability to SE, a set of studies assuming a smaller number of measurement points than those available has been carried out. The studies have been performed by excluding the measurement data from 1 up to all-1 secondary substations which have real measurements. All network operating conditions occurred in last 2 weeks of January 2014 have been evaluated. The estimated voltages and active power flows are compared with the “true” values obtained by running the DSSE model taking into account all available measurement data. The “true” values are used as reference values. The impact on estimates is evaluated as the average deviation of the estimates from the reference value at each node across all samples for each scenario.

The results demonstrate increased deviation in the cases with less number of measurements available. However, it does not only depend on the number but on the location of the measurements and it is case specific. In general, the smallest deviation is shown in the cases which include measurements in the end of the feeder. For the feeder BRXB-SE3, in the case of only one monitored secondary substation, the smallest deviation is when the last substation, node 12, is monitored; in the case of monitored 2 secondary substations, node 7 and 12, etc. It is interesting to observe that additional measurements will not always improve the estimation. The comparison between the estimates and the reference values of voltages for a few measurement configurations is presented in Figure 8, for a snapshot of network operating condition on 31 January 2014 at 23:30.

![Figure 7 The estimated active power consumption comparison of Approach 1 and Approach 2, for substation 90043](image)

**Figure 7** The estimated active power consumption comparison of Approach 1 and Approach 2, for substation 90043.

![Figure 8 Comparison of estimated and “true” voltage in the case of availability of sensors on various locations](image)

**Figure 8** Comparison of estimated and “true” voltage in the case of availability of sensors on various locations.

E.g. the results of the study using measurement data from node 1, 11 and 12, as presented with green colour, show further deviation to the reference values in comparison with the results of using measurements from nodes 1 and 12 only. This increased deviation is caused by the characteristic of measurements at node 11. The measured voltage at node 11 is further down below the reference value, and therefore, by including this measurement in the DSSE calculation will pull down the estimated voltages. The reason for this is that the same accuracy is given to both measurements at node 11 and node 12, the one at point 11 is consistently showing lower value of voltage for the whole trial period.

The state of the system can be estimated only by using a few measurements. Additional measurement data on the one hand, will generally improve the quality of the estimation. On the other hand, less accurate measurement data, whose accuracy is considered to be the same as the more accurate measurements reduce the quality of estimation, thus the accuracy of the measurement is the key factor in the implementation of SE.
Studies of Meter Placement along EIZ Feeders

Due to vast number of nodes in a DN, it is neither practical nor economically justified to have a fully instrumented network. DSSE can be used to reduce the number of meters needed but strategically located to ensure that adequate network observability and the accuracy of state estimation can be achieved over a range of different operating scenarios.

The applied meter placement methodology in this paper is based on the work referenced in [6]. It deploys the idea of sequentially improving a bivariate probability index, based on the relative estimation errors in voltage and angle at each substation, by reduction in the Chebyshev bound, which is achieved by reducing the area of the mean error ellipse generated by the error covariance matrix over the comprehensive set of different scenarios simulations. The sequence starts with the situation without any meter deployed. Placing meter on almost any location can contribute to the reduction in the error ellipse of the feeder nodes, however, this location should be such to reduce it in the best way for the whole of the feeder, not only individual nodes. Therefore, the meters are introduced at the locations where the error ellipse is the largest. This is repeated until the relative errors in the voltages and angles estimates for the whole feeder are below their pre-specified thresholds respectively in more than 95% of the cases.

The methodology is implemented on all 4 EIZ feeders, on the all operational scenarios for the period of the last two weeks of January 2014 for diversity.

The results obtained suggest that proposed meter placement methodology is robust and that with a relatively small number of real measurements the level of network visibility can be improved significantly. For example:

- The high quality of voltage estimates of Feeder BRXB-SE3 can be achieved only with 2 sensors measuring voltage and power consumption – on the beginning and on the end of the feeder. On the other hand, the accurate voltage magnitude estimation does not guarantee good active line flow estimation. The farther from the measured nodes, the level of estimation errors typically increases. Adding the flow measurement in the branch §-9 the level of error in estimated power flows and voltage angles along the feeder decreased. However, in this case, the voltage estimation has not improved.
- In the case of voltage and consumption measurements available on the first, next to the last and the last node, the accuracy of estimated voltage has been improved significantly. Still, the improvement of angles and flow is smaller in comparison to the results of the case with the flow sensor.

The results from all 4 EIZ feeders demonstrate:

- Placing sensors in the ends of the feeder is of strategic significance not only for estimation in business as usual situations, but specially in the cases of network reconfiguration when there is a need of the parts of other feeders to be supplied as well. This is especially important if the feeders are tapered and there is need to avoid overloading the particular sections.
- It is important to understand the DNO’s objectives in sensors placement, if it is improvement of voltages and/or flow estimation accuracy or overall state of the network. If there are some parts of the network more important than others, their observability is of higher importance, and instrumentation of that part could be more preferred.
- In the case of possible reconfiguration of the feeder it would be necessary to have flow and voltage measurements at every Normally Open Point.

CONCLUSIONS

This paper analyses the performance and presents potential benefits of the application of DSSE. Measurements carried out within LCL EIZs demonstrate that the prototype DSSE, through a limited number of optimally placed sensors with adequate accuracy, could robustly estimate voltage and power flows in HV DNs.

It is important to highlight that the main barriers for effective implementation of state estimation lie in the availability and quality of network data. Improvement and standardisation of measurement and recording practice, as well as further enhancement of the DSSE algorithm will contribute to more effective and efficient DN system monitoring and control. In order to facilitate the application of DSSE, additional measurements may need to be installed. It is recommended that DSSE is employed in stressed parts of DN's that are operated close to the operating voltage and/or thermal limits, and then be subject to close monitoring.

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REFERENCES