A TALE OF TWO TRANSFORMERS: AN ALGORITHM FOR ESTIMATING DISTRIBUTION SECONDARY ELECTRIC PARAMETERS USING SMART METER DATA

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ABSTRACT

One of the main objectives for the Smart Metering and Infrastructure (SMI) System currently being installed at BC Hydro, is to improve the company's ability to detect and locate electricity theft [1]. Some of the methods used to detect theft depend on accurate topology data for distribution transformer secondary networks and accurate estimates of the voltage at the transformer. The topology data from the Geographic Information System (GIS) is sometimes inaccurate. This paper describes a methodology to confirm the accuracy of the topology and to estimate the transformer secondary voltage, based only on the topology structure and hourly load and voltage data from each smart meter connected to the transformer. The method uses Linear Programming (LP) optimization and simultaneously provides estimates of the impedances of each segment of the secondary line. The degree of convergence indicates the accuracy of the given topology, and in many cases the locations of topology errors can be identified. Copyright IEEE 2013.

***Index Terms*—** Smart Meters, Smart Grid, Distribution Secondary, Distribution Network Topology, Data Analytics

1. INTRODUCTION

This paper presents one of several [2] analytic methods for checking the accuracy of distribution secondary topology being evaluated at BC Hydro. Many of the benefits of the SMI system, including theft detection [1], depend on an accurate representation of the actual distribution topology in the GIS. The same applies to future Smart Grid (SG) applications. Improving the accuracy of the data in the GIS, or at least being able to identify incorrect GIS data, is therefore of vital importance. Similarly, many SG benefits can be realized by knowing the voltage at various points along a distribution feeder. Hardware for making these measurements is expensive. If one could determine the voltage on the primary side of all the distribution transformers without hardware, the need for primary voltage meters could be reduced. A first step to determining the transformer's primary voltage would be to estimate its secondary voltage.

One of the roles of the Load Analysis Group is to develop applications for the new SMI data to support company needs. For the first time BC Hydro has hourly average load and voltage values for each meter connected to the grid, available the next day. This algorithm stems from the Group's efforts to apply the new data to find solutions to the following issues:

1) Can we use the SMI interval data to identify topology errors?
2) Can we use SMI interval data to estimate a transformer's secondary voltage accurately?

The Group has hourly interval data from SMI pilot projects carried out over several years, and some datasets are well known and understood, including the two transformers 'A' and 'B' chosen to test the concept. These transformers are adjacent to each other in an urban residential neighborhood. Although the term 'impedance' is used throughout, only the resistive load component at each meter is currently known and used. Future firmware revisions to the meters will include reactive load data.

2. TRANSFORMER 'A'

Transformer 'A' serves five residential customers, one of

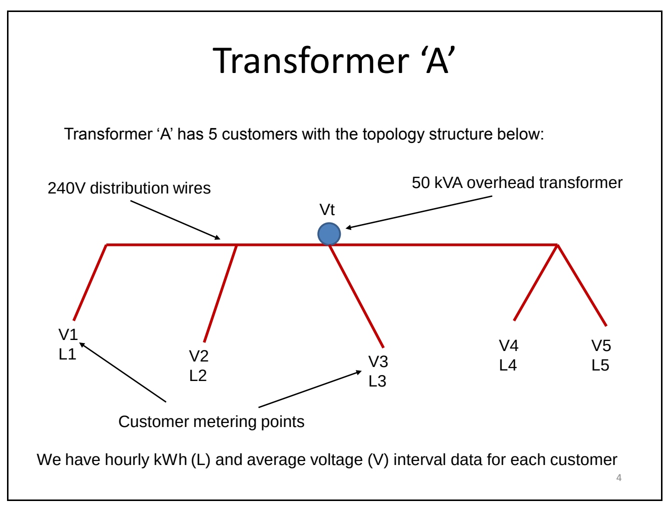

Fig. 1. Topology of Transformer 'A'

whom is connected directly to the transformer, with two connected to one side via a shared secondary line (See Fig. 1), and the other two to the other side, also with a shared secondary.

Fig. 2 shows the hourly load profiles (L1 to L5) for the five customers over a (almost) three day period. One of the customers (L1) has a load much higher than the others.

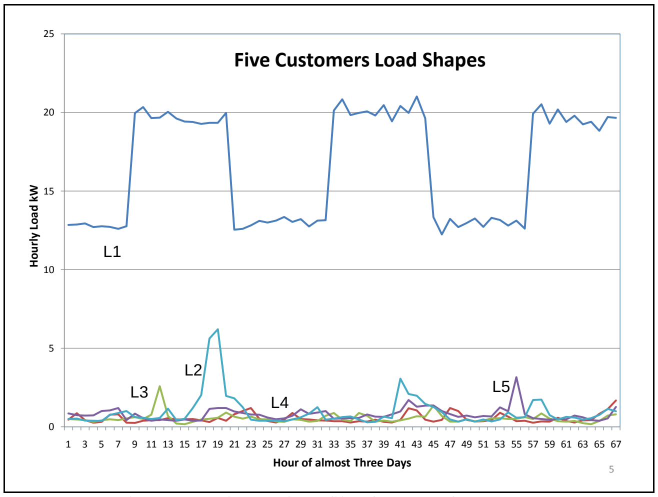

Fig. 2. Hourly Load Profiles for Transformer ‘A’

Fig. 3 shows the average hourly voltage profiles for the five customers (V1 to V5) over the same three day period.

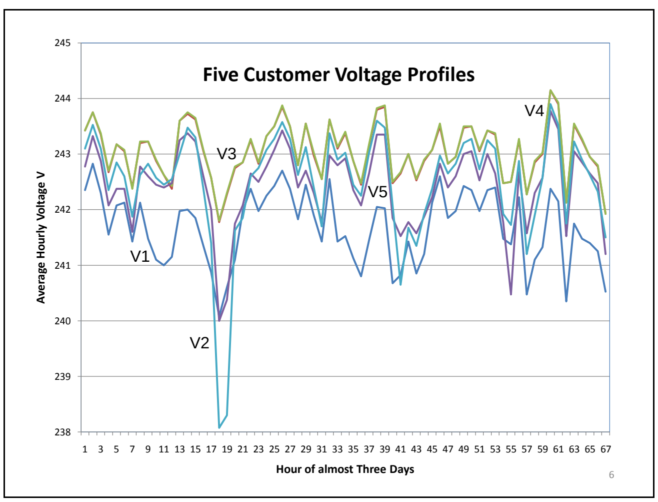

Fig. 3. Hourly Voltage Profiles for Transformer ‘A’

2.1. The Algorithm Concept

The average voltage at the transformer for any given hour should be the sum of the average voltage at any meter and the average volt drop between the meter and transformer. Estimating the transformer voltage from meter 3, for example, the transformer voltage Vt_3 would be the sum of the voltage at meter 3 (V3) and the volt drop across the line Z3 to the transformer (Fig. 4). This can be described as:

$$Vt_3 = V3 + (Z3 \times L3 / V3) \qquad (1)$$

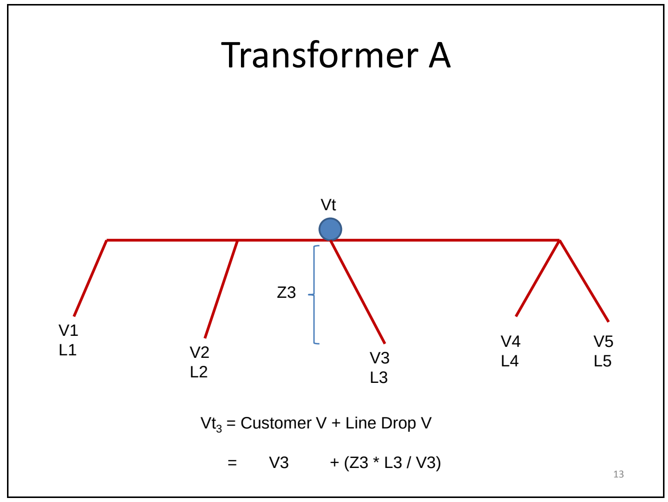

Fig. 4. Meter 3 Volt Drop Calculation for Transformer ‘A’

The transformer voltage, as estimated from any of the other meters, is more complex due to the shared line. From meter 4, the transformer voltage would be the meter voltage V4 plus the volt drop across the line segment Z4, plus the volt drop across the shared line segment Z45 (Fig. 5). This can be represented as:

$$Vt_4 = V4 + (Z4 \times L4/V4) + (Z45 \times (L4/V4+L5/V5)) \qquad (2)$$

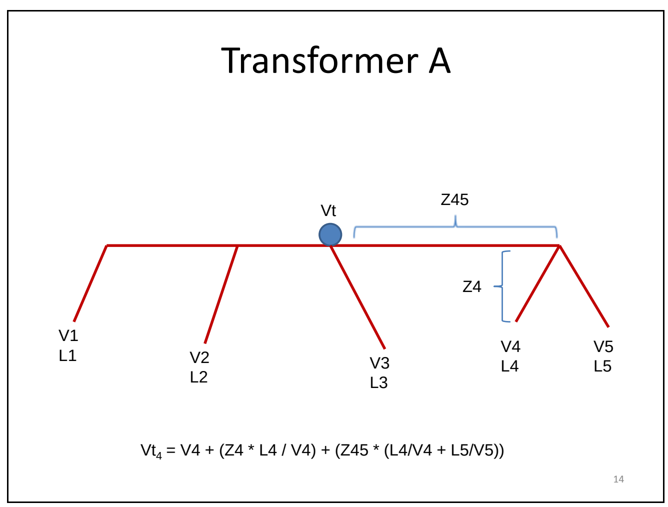

Fig. 5. Meter 4 Volt Drop Calculation for Transformer ‘A’

Similarly, equations representing the transformer voltage as ‘seen’ from each of the other connected meters can be constructed, as follows:

$$Vt_1 = V1 + (Z1 \times L1/V1) + (Z12 \times (L1/V1+L2/V2)) \qquad (3)$$
$$Vt_2 = V2 + (Z2 \times L2/V2) + (Z12 \times (L1/V1+L2/V2)) \qquad (4)$$

$$Vt_5 = V5 + (Z5×L5/V5) + (Z45×(L4/V4+L5/V5)) \quad (5)$$

This provides a set of five estimates of the transformer voltage (Vt_1 to Vt_5), for any hour. The voltages V1 to V5 and loads L1 to L5 are all known, and the impedances Z1 to Z5, Z12, and Z45 are unknown. The variance between the transformer voltage estimates Vt_1 to Vt_5 will be a minimum when the impedances are most accurate. The impedances can be estimated using a goal seeking algorithm or Linear Programming (LP), with the objective of minimizing the variance between the Vt estimates, and the accuracy can be improved by using several sets of hourly equations – see Fig. 6. The initial tests used data sets of a week (168 hours).

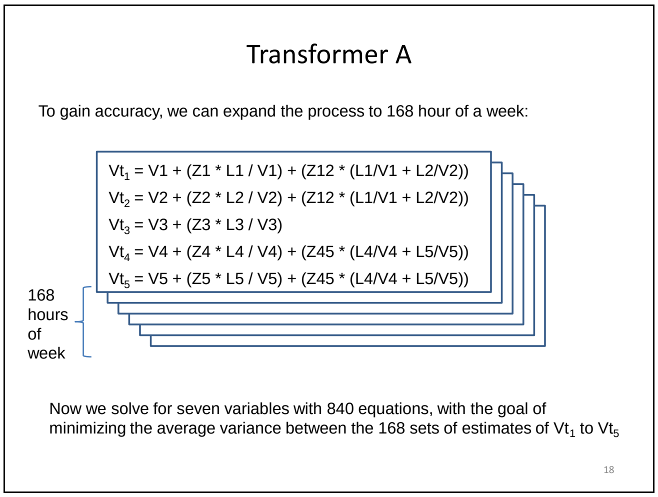

Fig. 6. Increasing Accuracy by using Many Observations

2.2. Implementing the Algorithm in Excel

Excel Solver is ideal for testing the idea. The model was implemented as a set of tables (Fig. 7). The hourly voltage

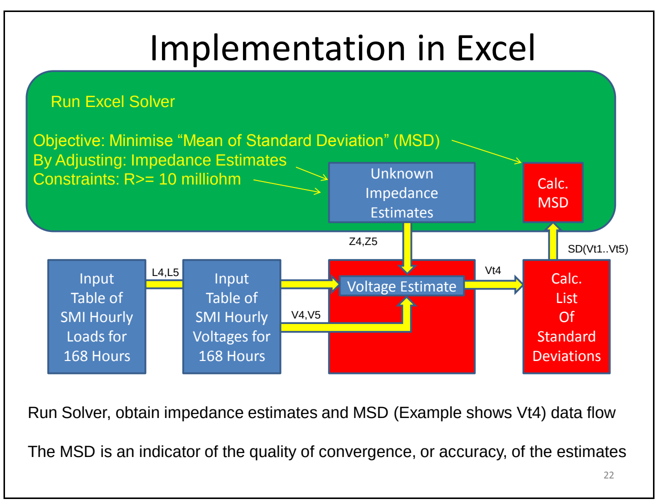

Fig. 7. Structure of the Model in Excel

and load tables feed into a table of formulae, each estimating the transformer voltage for a meter for an hour. The standard deviation (SD) of the estimates for each hour forms an adjacent column, and the Mean Standard Deviation (MSD), which is the objective function, is above it.

The most complex part of the process is the conversion of the topology to a set of equations for each transformer. As a manual process in Excel, this is prone to error.

2.3. Voltage Estimates for Transformer A

The goal for the LP algorithm is to minimize the variance between the estimates of the transformer secondary voltage from the sets of equations. (Minimum impedance constraints of 0.010 Ω were applied for the initial tests). The lower the MSD of these estimates, the more confident one can be of the mean estimate.

The test data for a month was divided into four weekly sets. Each set was passed through the model separately. This provided four sets of transformer secondary voltage estimates with their MSDs, as well as four sets of estimates for each secondary line segment impedance. The first week of test data for Transformer A yielded a MSD of 0.039V, or 0.016%. The hourly transformer voltage, as estimated by each meter equation for the first (almost) 3 days are shown in Fig. 8.

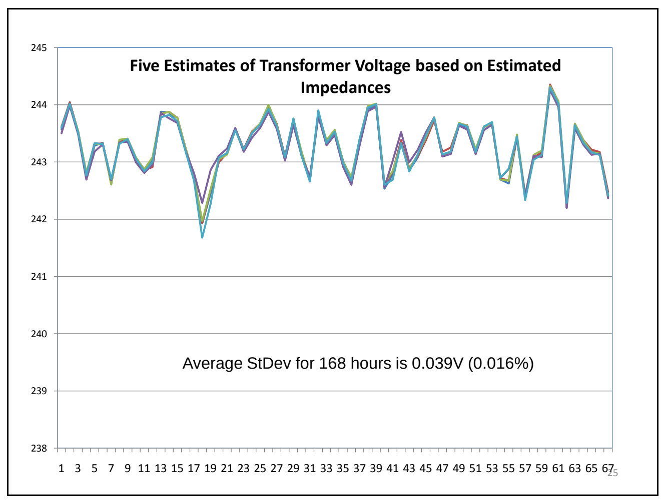

Fig. 8. Transformer Voltage Estimates for Transformer A

Clearly, for most of the hours in the period, the five estimates are very close to each other. A few hours give poor convergence, such as hours 18 and 55. This may be due to meter reading errors or an electrical disturbance on the distribution system.

The four sets of line segment impedances for the four test weeks are compared in Fig. 9. The minimum constraint of 0.010 Ω was reached for Z4 and Z5 for three of the four weekly datasets. Later testing indicated that valid impedance values could be as low as 0.001 Ω, and the constraint was removed. The consistency of the estimates across all four weeks lends confidence to the accuracy of the estimates. Both the transformer voltage estimate and the secondary impedance estimates would be useful for various SG applications.

These results indicated that the algorithm produced good results for a transformer with accurate topology data. Poor convergence would indicate topology errors (missing or incorrectly mapped load), theft of electricity, or bad load or voltage data. The next challenge was to test the algorithm with an inaccurate topology.

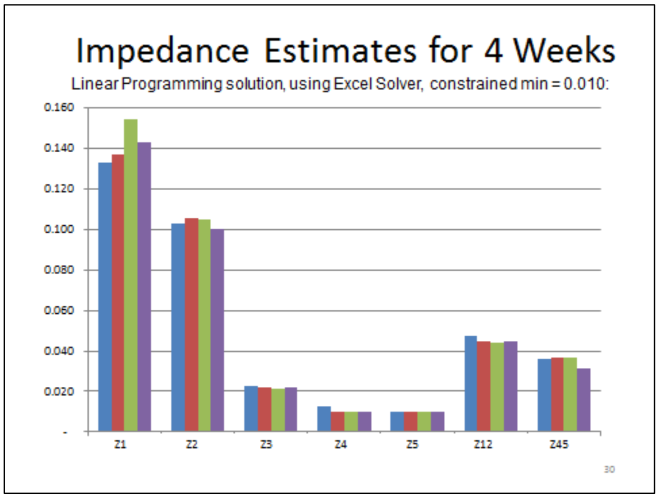

Fig. 9. Line Segment Impedance Estimates for Transformer A

3. TRANSFORMER 'B'

Transformer B, according to the GIS system, supplied 7 meters with the topology shown in Fig 10. Four meters were connected directly to the transformer, and three had a

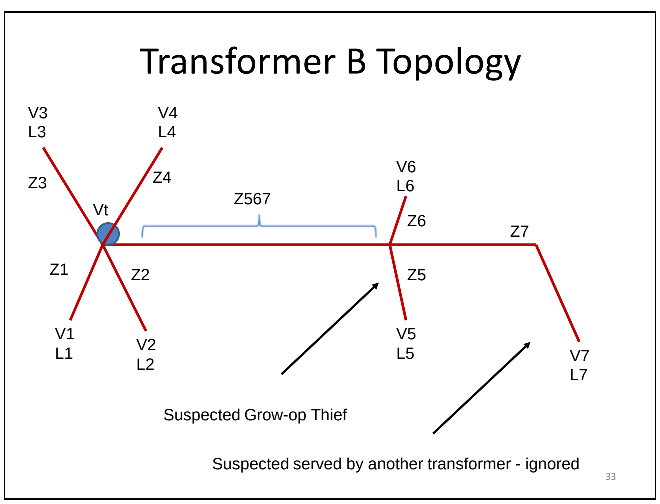

Fig. 10. Transformer B Topology

shared line segment. Previous analysis had indicated that meter 7 was actually connected to a different transformer. (This topology error has since been corrected in the GIS). Also, it was suspected that the customer at meter 5 was stealing electricity. These complications would present a challenge to the voltage estimation algorithm.

3.1. Transformer 'B' with Seven Meters

The model for all 7 meters was built and executed, resulting in a poor convergence with a MSD of 0.437V, and the 7 sets of voltage estimates shown in Fig. 11.

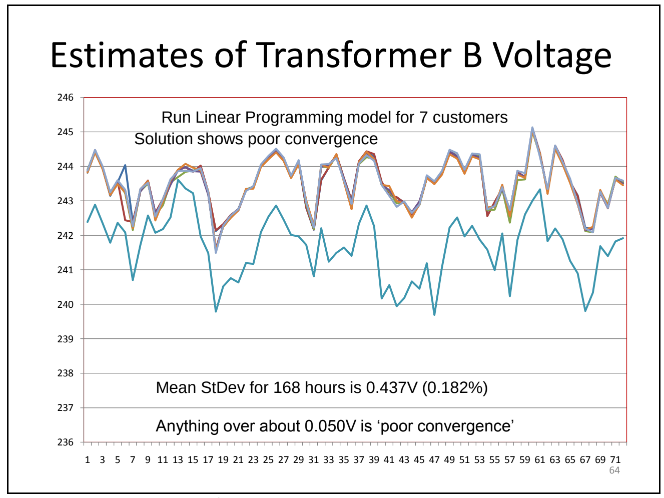

Fig. 11. Transformer B Voltage Estimation, seven meters

Six of the seven meters follow a similar trend, while the seventh follows a different trend altogether. This result clearly indicates that meter 7 was supplied by another transformer.

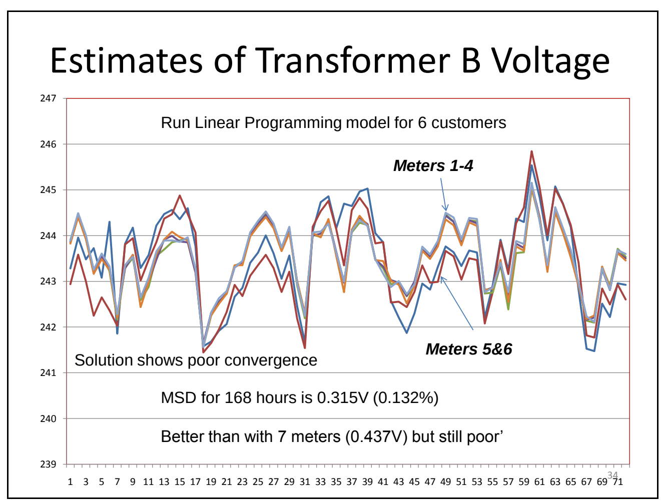

Fig. 12. Transformer B Voltage Estimation, six meters

3.2. Transformer 'B' with Six Meters

The meter was removed from the transformer B model, which was again executed. Removing meter 7 improved the

MSD from 0.437V to 0.315V (Fig. 12), but the hourly voltage estimates for two of the meters (meters 5 and 6) are not in step with the other four meters. This implies that there is a problem with one or both of these meters or the common node that they share.

The model was rerun with only the four 'good' meters connected directly to the transformer (Fig. 13). The resulting MSD of 0.059V indicated a good convergence, and confirmed that the problem was located at meter 5 or 6.

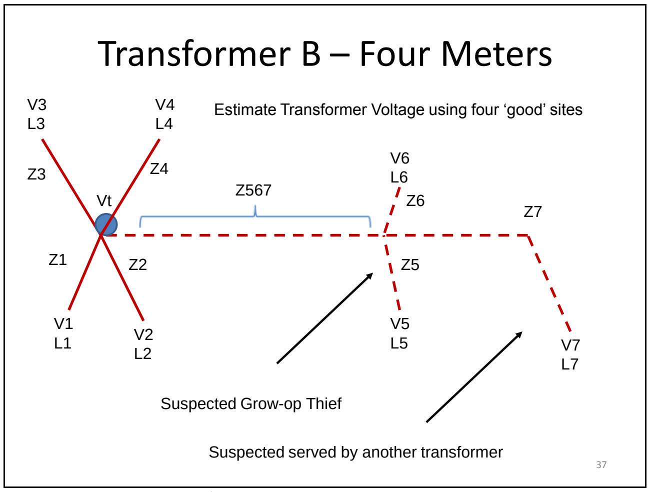

Fig. 13. Transformer B Voltage Estimation, Four Meters

3.3. Modeling the Theft

The suspected theft at meter 5 was the problem. It was a load that the model could not represent. The theft was modeled as an additional virtual meter 8 located at meter 5, with an unknown load L8 that was initially 'on' during the

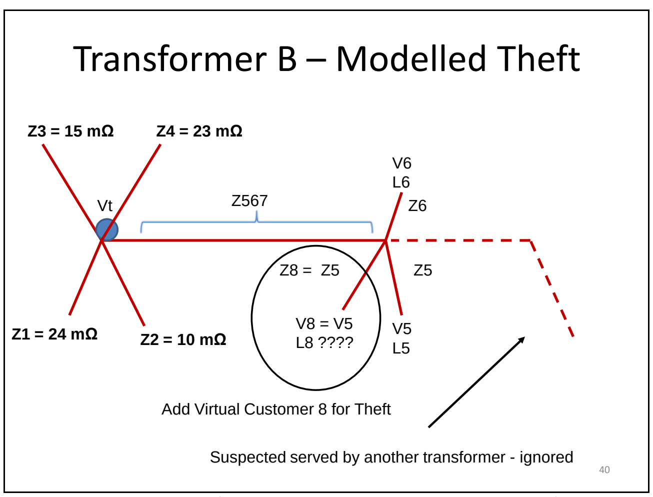

Fig. 14. Transformer B Topology, six meters plus theft

times that marijuana growing operations normally have their growing lamps turned on – 7PM to 7AM. (These times were later refined when it was clear that the virtual load approach worked.) The virtual load was given the same local impedance and hourly voltage as meter 5 (see Fig. 14). The magnitude of the virtual load L8 was unknown and was included as one of the variables for the LP algorithm to estimate.

Figure 15 shows the transformer voltage estimates for the 6 meters and 1 virtual meter for the theft. The MSD has improved to 0.092V, which is not perfect but much better than the original value. The theft load was estimated to be about 3.5 kW running 12 hours per day. The hours during which the modeled theft was turned on or off, or hours where the theft magnitude varied from the average estimate of 3.5kW, showed poorer convergence than the other hours. More accurate modeling of the theft load shape could reduce the MSD.

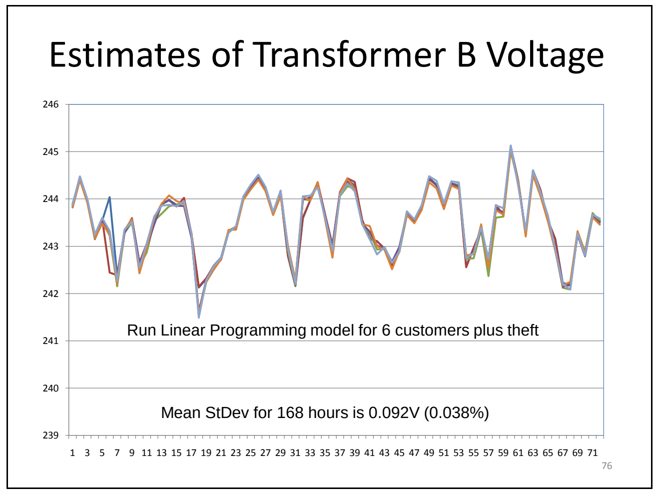

Fig. 15. Transformer B Voltage Estimation, six meters plus theft

The model for Transformer B, with corrected topology and estimated line segment impedances, is shown in Fig. 16.

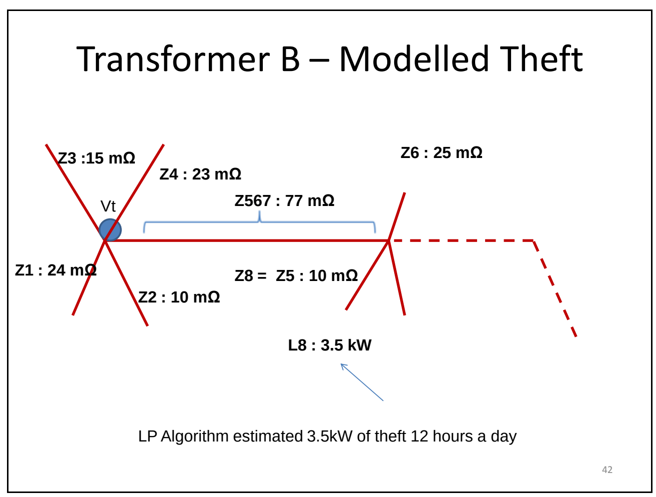

Fig. 16. Transformer B Theft Magnitude and Segment Impedance Estimates

4. FURTHER TESTING AND AUTOMATION

Transformers A and B were the first to be tested with this algorithm. Since then a further 20 transformers have been modeled, with similar results. The algorithm was implemented in the statistics programming language 'R' with results identical to those from Excel Solver. A set of tables defining equations for the most common topology structures was implemented in 'R' to automate this error-prone process. Additional experimental work has been done on estimating the transformer primary voltage and using the primary estimates to identify the feeder phase supplying the transformer. This work is still in the embryonic stages.

The Load Analysis Group does most of their work in the statistics language SAS and in Excel. Although ideal as a prototype testing environment, Excel is not suited to large scale, automated implementation of the algorithm. BC Hydro has about 300,000 distribution transformers in service, and any useful algorithm must be able to check them all automatically.

The planned process is shown in Fig. 17. BC Hydro is installing an 'Energy Analytics System' (EAS) that will make use of SAS and STI (Space Time Insights – like Google Earth on steroids) tools for SMI and SG applications. This algorithm will be implemented in the EAS to support the SG applications that require accurate topology data. The hourly voltage and load data for each meter will be retrieved from the Meter Data Management System. The topology will be extracted from the GIS as a CIM (Common Information Model) file. The secondary line segments will be built up as a tree for each transformer from the CIM file data. Each tree will be transformed into a set of equations, as described above. This could be the most complex part of the algorithm. The set of equations, one for each hour for each meter connected to the transformer, is then solved using a canned LP function or procedure in SAS.

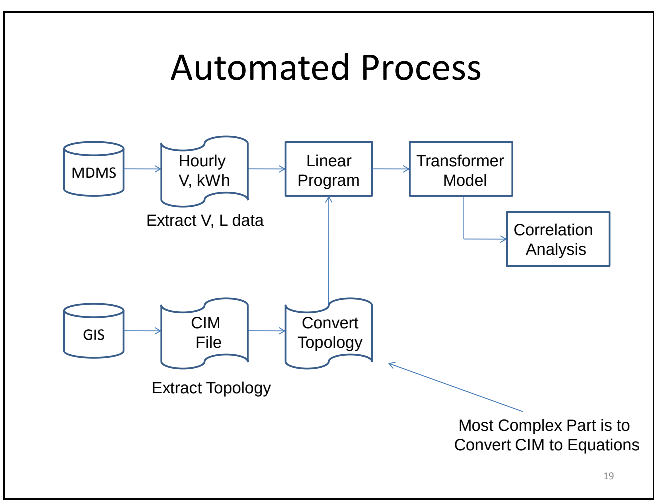

Fig. 17. Automating the Transformer Voltage Estimation Algorithm

This paper covers the development of the LP algorithm for estimating the secondary voltage at the distribution transformer. However, the process can be extended to model the volt drop inside the transformer and then to estimate the hourly primary voltage using correlation analysis, as indicated in Fig. 17. These estimates will have several SG applications, including correct phase identification for the transformer [3], feeder fault location, and primary voltage theft detection.

5. CONCLUSION

Using the average hourly voltage and load data from SMI meters and distribution topology data from the GIS system with a LP optimization algorithm, it is possible to:

1) Estimate the average hourly voltage at the distribution transformer secondary terminals. This estimate is useful for several SG applications.
2) Estimate the impedance of each segment of secondary line connected to the transformer. These estimates can be used to identify topology errors, electricity theft, and high resistance joints.
3) Identify incorrect topology or bad data by poor convergence of the model.
4) Identify unmetered loads, including electricity theft, on the secondary side where topology and data are accurate.
5) Estimate the magnitude of theft once detected.

In addition, the model can be extended to estimate the primary voltage of the distribution transformer, extending its benefits to primary side and feeder SG applications.

6. ACKNOWLEDGEMENTS

The author would like to thank Jing Dong for implementing the algorithm in 'R', testing the algorithm on many transformers, and developing the LP equation building tables.

7. REFERENCES

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