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Secondary Circuit Model Creation and Validation with AMI and Transformer Measurements

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***Abstract*— Accurate distribution secondary circuit models are needed to effectively monitor and coordinate the distributed energy resources located in the secondary circuits and to enhance overall distribution system operations and planning. Accurate secondary models are also needed to fully leverage the measurement data received from smart meters and distributed energy resources at the customer premises. This paper discusses approaches for creating distribution system secondary low-voltage circuit models utilizing smart meter measurements. This paper also discusses methods to model secondary circuits when the loads and distributed energy resources are only partially metered. The presented methods are demonstrated on a real distribution secondary circuit with smart meter measurements and transformer low voltage measurements. Practical challenges related to real measurement data are discussed.**

***Index Terms*—Load Modeling, Power Distribution, Power System Measurements, Smart Grids**

I. INTRODUCTION

Electric utilities have an increased need to improve the accuracy and detail of the distribution models used to plan, analyze, monitor, coordinate, and control the distribution system and distributed energy resources (DERs). The vast majority of existing utility feeder models do not include the secondary circuits at all. When modeled, they are represented with limited detail and default assumptions. It is becoming particularly important to accurately model the secondary circuit models where a large share of the DERs are located [1]-[4]. The low-voltage secondary circuits also have higher per unit impedances, which result in a large share of the feeder per unit voltage drop or rise as well as losses [4].

The extensive roll-out of smart meters and other modern distribution system sensors is rapidly increasing the available measured data. This new data can be leveraged to increase the accuracy and detail of existing utility models, and automated methods are needed in order to achieve this in a cost-effective way. The Big Data available from smart meters and other emerging sensors has raised the interest in new methods for distribution system topology estimation (DSTE) and parameter estimation (DSPE) [3], [5], [6]. In our past work, we have presented methods to estimate secondary circuit topology and parameters when a dense grid of smart meter measurements is available [7]-[9]. In [7], [8], we have also presented a method to handle the common case when some meters do not transmit voltage measurements. In [8], [10], we have shown alternative methods to generate simplified secondary circuit models when only very limited sensor data is available in the secondary circuits.

In this paper, we extend our previous work on secondary circuit model generation to the case when a dense but incomplete network of sensors is available in the secondary circuits. In particular, this paper further analyzes the methods from [7]-[10] to generate secondary circuit models on a real utility secondary circuit where smart meter measurements are missing. This paper focuses on the case when both the topology and the component parameters are not available. Moreover, this paper discusses approaches to validate the results with service transformer secondary measurements. While there has been increased attention to using measurement for topology estimation [11], [12], this paper discusses practical issues related to real smart meter measurements and transformer measurements (low-voltage side) with errors.

This paper has the following structure. Section II briefly summarizes the key principles of the different secondary circuit model generation methods used in this paper. Section III presents the analyzed real secondary circuit and the related measurement data. Section IV presents different approaches to deal with offset in the transformer voltage measurements. Section V shows the results for the different secondary modeling approaches. Section VI concludes the paper.

II. SECONDARY CIRCUIT MODEL GENERATION

Availability of secondary circuit models can improve the voltage simulation accuracy at the metered loads and DERs in the secondary circuits. This is critical for many emerging distribution system applications. This section discusses secondary model generation in two cases. First, the case of fully available load/DER measurements is examined. Then, we present methods to handle unmetered loads/DERs in the secondary circuit.

The overall objective of distribution system secondary circuit topology and parameter estimation problem (DSTE) is to find the most likely topology and resistance (R) and reactance (X) parameters of a secondary circuit (shown in red in Fig. 1) by leveraging the smart meter and DER measurements (shown in blue in Fig. 1).

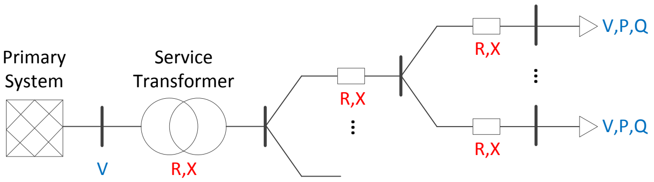

Fig. 1 Secondary circuit topology and parameter estimation problem

A. Secondary Circuit Parameter Estimation with Fully Available Measurements

In [7], [8], we have shown a linear regression parameter estimation (LRPE) method for the case when all secondary circuit loads and DERs are metered and the secondary circuit topology is known. Moreover in [7], we have also shown a method to handle some meters not reporting voltage measurements.

The LRPE method utilizes the well-known linear approximation of voltage drop ($V_{drop} = |V_1| - |V_2|$) over a series impedance $R + jX$ (on the right in Fig. 2)

$$V_{drop} = |V_1| - |V_2| \approx (RP + XQ)/V_2 = RI_R + XI_X, \quad (1)$$

where P, Q, I_R and I_X are the active power, reactive power, real current ($I_R = I(PF)$), and reactive current ($I_X = I\sqrt{1-(PF)^2}$) flowing over the branch, respectively [13]. For transformers, all values must be referred to the same voltage level. In 3-phase systems, line-line voltages and 3-phase powers are used whereas in 1-phase systems, line-to-neutral voltages are utilized.

The LRPE method algorithm estimates the secondary circuit parameters by proceeding from the tree leaf nodes towards the tree root node. At a given iteration the algorithm utilizes (1) to generate linear regression models

$$\boldsymbol{y} = \boldsymbol{\mathcal{X}}\boldsymbol{\beta} + \boldsymbol{\epsilon} \quad (2)$$

to estimate the branch impedances of a circuit subsection consisting of either two series meters (on the right in Fig. 2) or M parallel meters (on the left in Fig. 2 for two meters):

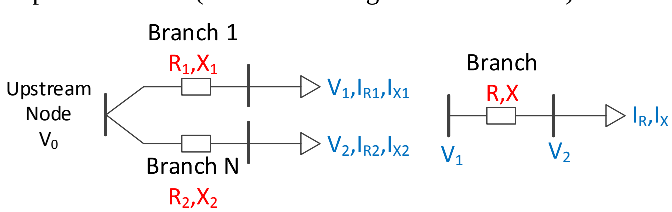

Fig. 2 Two meters connected in parallel (left) and in series (right)

For two series meters, the linear regression (2) variables are

$$\boldsymbol{y} = \boldsymbol{V}_1 - \boldsymbol{V}_2, \boldsymbol{\mathcal{X}} = [\boldsymbol{I}_R \quad \boldsymbol{I}_X], \text{ and } \boldsymbol{\beta} = [R \quad X]^{\mathrm{T}}. \quad (3)$$

For M parallel meters, the variables are

$$\boldsymbol{\beta} = \left[V_{0,1}, \dots, V_{0,M}, R_1, X_1, \dots, R_N, X_N\right]^{\mathrm{T}}, \quad (4)$$

$$\boldsymbol{y} = \left[V_{1,1}, \dots, V_{1,M}, \dots, V_{N,1}, \dots, V_{N,M}\right]^{\mathrm{T}}, \quad (5)$$

and

$$\boldsymbol{\mathcal{X}} = \begin{bmatrix} \mathrm{I} & [-\boldsymbol{I}_{R,1} \quad -\boldsymbol{I}_{X,1}] & \cdots & \boldsymbol{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathrm{I} & \boldsymbol{0} & \cdots & [-\boldsymbol{I}_{R,N} \quad -\boldsymbol{I}_{X,N}] \end{bmatrix}. \quad (6)$$

B. Secondary Circuit Topology and Parameter Estimation with Fully Available Measurements

Many utilities do not know the secondary circuit topologies. In we apply linear regression topology and parameter estimation (LRTE) algorithm to generate secondary circuit models [9]. Similarly to LRPE, the LRTE algorithm utilizes (1) to construct linear regression models. The algorithm processes one secondary circuit at a time using the list of all the meters of the secondary circuit. For each meter pair, the algorithm solves a linear regression problem for the parallel circuit type (on the left in Fig. 2)

$$\boldsymbol{V}_1 - \boldsymbol{V}_2 = \boldsymbol{I}_{R1}R_1 + \boldsymbol{I}_{X1}X_1 + \boldsymbol{I}_{R2}R_2 + \boldsymbol{I}_{X2}X_2 + \boldsymbol{\epsilon} \quad (7)$$

and a linear regression problem for the series circuit type (on the right in Fig. 2)

$$\boldsymbol{V}_1 - \boldsymbol{V}_2 = \boldsymbol{I}_R R + \boldsymbol{I}_X X + \boldsymbol{\epsilon}. \quad (8)$$

The order of meters 1 and 2 is irrelevant in regression model (7). If the secondary circuit does not have distributed generation causing reverse power flows, regression model (8) is solved only for the meter order with positive average voltage drop $\sum_{t=1}^{T}(V_{1,t} - V_{2,t}) > 0$. A wrong meter order simply results in negative estimated parameters.

C. Secondary Circuit Model Generation with Unmetered Loads or DERs

The LRPE and LRTE methods summarized in II.A. and II.B. require that all the secondary circuit loads and DERs are metered. This section discusses the common case when some of the secondary circuit loads are not measured. If the share (of the load/generation) of the unmeasured secondary circuit loads and DERs is small (<5-10%), the unmeasured load can simply be ignored in the LRPE and LRTE methods. However, if the share of the unmeasured load is larger, the unmeasured load can have a significant impact on the secondary circuit topology and parameter estimation. If the number of unmetered customers connected to the transformer is not known, for example not in the Outage Management System (OMS), the secondary circuit topology and parameter estimation problem is very hard (if not impossible) due to the exponential number of possible connections [9] and the infinite number of possible load profiles.

In [8], [10], we have shown a simplified linear regression parameter estimation (SLRPE) method to generate simplified secondary circuit models when measurement data is not available from all loads in the secondary circuits. This is quite simple in the case when measurement data is only available from one or a few sensors in the secondary circuit. However, when the measurements are available from most (but not all) loads and DERs in the secondary circuit, the SLRPE method makes unnecessary simplifications. Instead, it is better to assume a certain secondary topology (such as single service drop to each customer) and to utilize the LRPE method to estimate the secondary parameters. TABLE I summarizes the discussed secondary circuit modeling approaches.

TABLE I. SECONDARY MODEL GENERATION APPROACHES

Algorithm	Requires Known Topology	Requires Power Meas.	Requires Voltage Meas.	Can Handle Missing Meas.
LRPE (ignore missing meas.)	Yes	Yes	Yes	Small fraction
LRTE (ignore missing meas.)	No	Yes	Yes	Small fraction
SLRPE	No	Preferably	At least one sensor	Yes

III. STUDIED SECONDARY CIRCUIT AND MEASUREMENT DATA

This paper analyzes one of the underground secondary circuits located in the Mueller community in Austin, Texas that is served by Austin Energy [14]. The secondary circuit is illustrated in Fig. 3. The secondary is fed by a 7.2kV/240/120V 25kVA service transformer [15]. No secondary circuit topology, cable types, or cable lengths were received.

The transformer secondary voltage V_1, V_2 and current I_1, I_2 measurements were available. The customer phase voltage measurements V_{L1}, V_{L2} and the customer total customer 1-minute active and reactive power readings $P_L = P_{L1} + P_{L2} + P_{L3}$ and $Q_L = Q_{L1} + Q_{L2} + Q_{L3}$ were also received for five of the total eight secondary circuit customers. Since the customer phase powers $P_{L1}, P_{L2}, P_{L3}, Q_{L1}, Q_{L2}, Q_{L3}$ are not available, this paper focuses on generating a single-phase equivalent model for the secondary circuit.

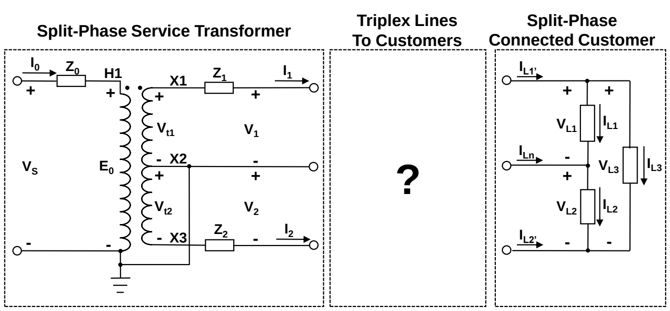

Fig. 3 Secondary circuit measurements

One-minute (43200 samples) active energy, reactive energy, and average voltage readings in June 2015 were obtained for five of the eight customers in the secondary circuit. An overview of the customers is presented in TABLE II. The customer measurements were recorded with eGauge meters that depending on the utilized CT meet either the requirements of ANSI C12.20 0.5% or ANSI 12.1 1.0% accuracy class [16].

TABLE II. OVERVIEW OF THE CUSTOMERS

Data ID	1185	5129	5403	6836	9982
Construction Year	2007	2008	2007	2008	2008
Total Area [sqft]	2122	1439	1720	1217	Unknown
Rooftop PV	X	X	X	X	X
Net Metering	X	X	X	X	X
Electric Vehicle	X	Unknown	X	X	Unknown

In addition to the customer measurements, one month (9836 samples taken roughly every 5 minutes) of service transformer measurements in June 2015 were also obtained. The received measurement data set includes phase voltages, accumulated winding kWh and kvarh, winding currents, and winding power factors. The transformer measurements are recorded with TransformerIQ monitoring device that has ±0.5% accuracy with 0.1 V and 1.0A precision for voltage and current, respectively [17].

Before utilizing the customer and transformer measurement data for secondary model generation, the data was validated for bad and missing data. The transformer data was also interpolated on the customer 1-minute time granularity. The customer and transformer measurements over the first two days are illustrated in Fig. 4 and Fig. 5, respectively.

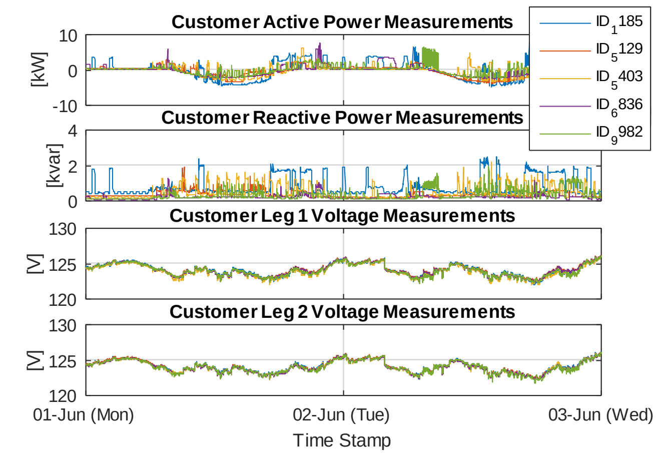

Fig. 4 Customer measurements over the first two days

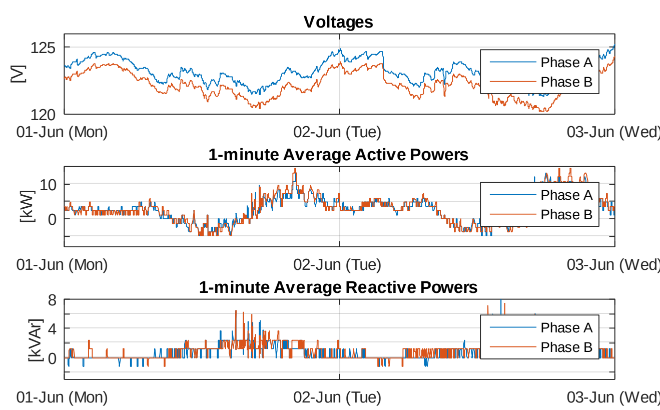

Fig. 5 Transformer measurements over the first two days

As stated above, measurements were only available for five out of the total eight secondary circuit customers. The unmeasured portion of the secondary circuit load is illustrated in Fig. 6 and Fig. 7. Over the one month period, 61.6%, -48.7%, and 49.7% of the kWhr, kvarhr, and kvahr is unmeasured (and losses). The unmeasured kWhr is surprisingly large considering that five out of eight customers are measured. The negative unmeasured kvarhr indicates potential problems in the transformer reactive power measurements.

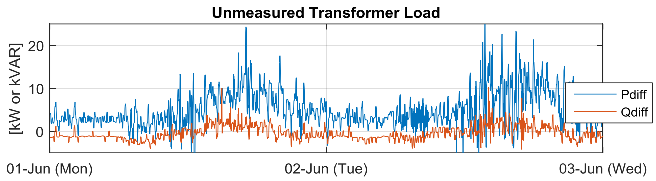

Fig. 6 Unmeasured secondary circuit load over the first two days

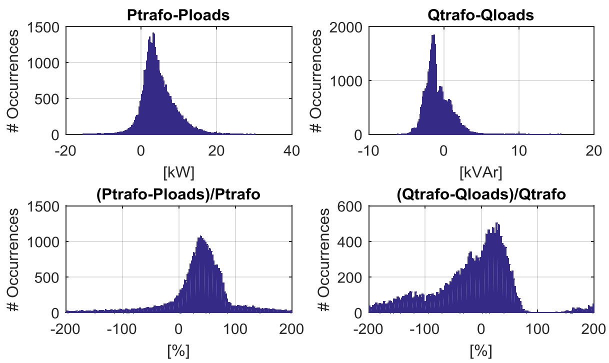

Fig. 7 Unmeasured secondary circuit load over the first two days

IV. Transformer Voltage Measurement Offset Detection

The voltage drops from the transformer secondary to the customers were all negative as illustrated in Fig. 8. Since there should not be a voltage rise to the customer when they are consuming power, the transformer voltage measurements seem to have a considerable offset. Therefore, it was not possible to directly utilize the transformer voltage measurements for the secondary circuit model generation.

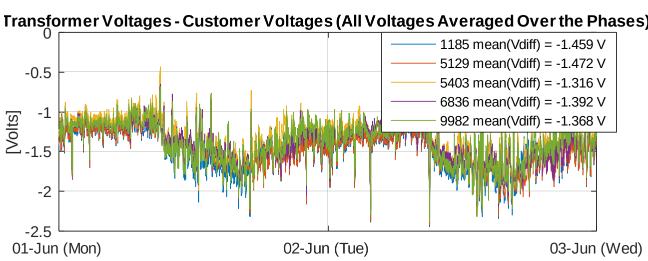

Fig. 8 Measured voltage drops from the transformer secondary to the customers

The remainder of this paper assumes that the transformer voltage measurements have a constant offset. Next, different approaches to estimate the offset are discussed. The simplest approach is to look at the secondary voltage drops during very low load times. Fig. 9 illustrates the secondary voltage drops for the off-PV generation times with the lowest 1% of the absolute load apparent powers. The overall average secondary voltage drop was -1.3368 Volts. Adding this value to the measured secondary voltage drops in Fig. 8 results in only one positive (on average) secondary voltage drop. Thus, the offset estimated in this way appears low.

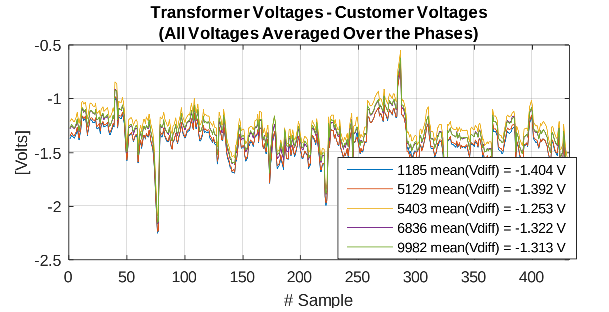

Fig. 9 Secondary circuit voltage drops over the low (lowest 1%) load times

A second way to estimate the transformer voltage measurement offset is to assume that each customer is connected to the transformer secondary over a separate service drop and to estimate the constant offset from the intercepts of the LRPE linear regression models. The results for this are listed in TABLE II. The average (over the five meters) estimated intercept was -1.4019. Adding this to the average secondary voltage drops in Fig. 8, still does not result in average positive secondary voltage drops for all meters.

TABLE III. LRPE Estimated Regression Model parameters

Meter	R_{est}	X_{est}	Intercept
1185	0.0100	-0.0200	-1.4433
5129	0.0083	-0.0427	-1.4311
5403	0.0116	-0.0255	-1.3191
6836	0.0086	-0.0412	-1.4163
9982	0.0159	-0.0430	-1.3995

A third way to estimate the transformer voltage measurement offset is to estimate the secondary circuit topology and parameters with the LRTE method (that does not require the transformer measurements) and to estimate the transformer secondary voltages with the smart meter measurements and the estimated secondary model. Results for this are illustrated in Fig. 10. The estimated voltage measurement offset was -1.5194 Volts, which is somewhat higher than the one given by the previous two approaches and results in positive average secondary circuit voltage drops for all the meters as illustrated in Fig. 11. The remainder of this paper has added the constant offset of 1.5194 Volts to the transformer voltage measurements.

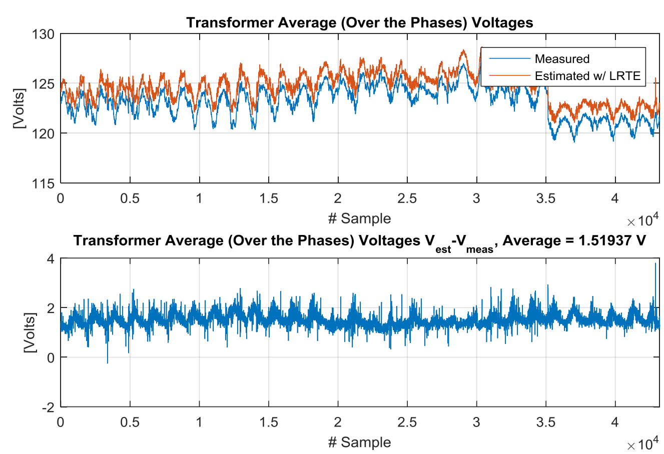

Fig. 10 LRTE estimated transformer voltage measurement offset

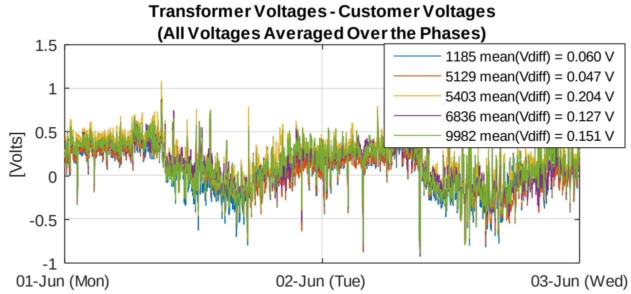

Fig. 11 Secondary voltage drops (LRTE estimated transformer secondary voltages – smart meter measured voltages)

V. SECONDARY MODELING RESULTS

This section shows the secondary model generation results for the secondary circuit discussed in III utilizing the methods discussed in section II.

D. Conventional Secondary Modeling Approach

A conventional utility secondary modeling approach is to add a 100ft 1/0 triplex service drop for every customer. After reducing the triplex to an equivalent 1-phase impedance with Kron, the typical equivalent series impedance parameters are $R = 0.03674$ and $X = 0.00786$. Other typical values are listed in TABLE IV.

TABLE IV. TYPICAL TRIPLEX CABLE IMPEDANCES

Service Cable Type	$R\ [\frac{\Omega}{100ft}]$	$X\ [\frac{\Omega}{100ft}]$	X/R-ratio
Typical Reduced Series Impedance	0.0367	0.0079	0.2138
Nexans 600V ACSR Triplex 1/0 Underground Cable at 75°C [18]	0.0201	0.0028	0.1398
Nexans 600V ACSR Triplex 4/0 Underground Cable at 75°C [18]	0.0101	0.0026	0.2535
Alcan Aluminum Multiplexed Triplex 1/0 Overhead Cable at 50°C [19]	0.0184	0.0025	0.1372
Alcan Aluminum Multiplexed Triplex 4/0 Overhead Cable at 50°C [19]	0.0092	0.0026	0.2803

TABLE V lists the simulated (with the conventional approach) and measured voltage drops over the secondary circuit. The table also lists the average absolute differences and correlations between them. The measured voltage drops are unexpectedly low but this may be caused by the uncertain accuracy of the transformer voltage measurements discussed in section IV. The simulated and measured voltage drops also match very poorly as indicated by the high errors and low correlations. The low correlations also hint that the separate service drop per customer may not be able to capture the secondary voltage drop dependency on the loads. Alternatively, the poor correlation may be an indicator of inaccurate transformer voltage measurements.

TABLE V. VOLTAGE DROPS SIMULATED WITH CONVENTIONAL SECONDARY MODELS

Meter	1185	5129	5403	6836	9982
Average Absolute Simulated Voltage Drop	0.6529	0.3902	0.5033	0.3684	0.2898
Average Absolute Measured Voltage Drop	0.2017	0.1840	0.2450	0.1848	0.2052
Average Absolute Error in Simulated Voltage Drop	0.5822	0.3757	0.4164	0.3682	0.2607
Correlations Between Simulated and Measured Voltage Drops	0.5534	0.3634	0.4573	0.3333	0.4779

E. Results for LRPE Ignoring Unmeasured Load

The conventional secondary model results in a low voltage drop simulation accuracy. A better accuracy may be obtained by utilizing the LRPE method to estimate the secondary parameters. Since no topology information was available, each customer was simply assumed to be connected to the service transformer over a separate service drop. Then, the service drop impedances were estimated with the LRPE method. The results are listed in TABLE VI.

The LRPE estimation with linear regression resulted in negative estimates for all the reactances. Thus, the parameters were estimated with the linearly constrained least squares approach (see [7] for details), which resulted in all the reactances to be set to the lower limits. The simulated voltage drops are very low but as expected, the average simulated voltage drop simulation errors are smaller (0.1704-0.1906) compared to the conventional modeling approach (0.2607-0.5822). Also, the correlations are slightly higher compared to the conventional secondary circuit modeling approach. However, the errors in the simulated voltage drops are still high compared to the simulated voltage drops and the simulated voltage drops are unexpectedly low.

TABLE VI. LRPE ESTIMATION RESULTS

Meter	1185	5129	5403	6836	9982
R_{est}	0.0069	0.0055	0.0090	0.0064	0.0118
X_{est}	0.0001	0.0001	0.0001	0.0001	0.0001
Average Absolute Simulated Voltage Drop	0.1156	0.0562	0.1163	0.0627	0.0897
Average Absolute Measured Voltage Drop	0.2017	0.1840	0.2450	0.1848	0.2052
Average Absolute Error in Simulated Voltage Drop	0.1750	0.1750	0.1906	0.1704	0.1714
Correlations Between Simulated and Measured Voltage Drops	0.5655	0.3719	0.4694	0.3388	0.4891

F. Results for LRTE Ignoring Unmeasured Load

Due to the LRPE estimation inaccuracy, the LRTE method was utilized to estimate the secondary circuit topology and parameters. The unmeasured portion of the secondary circuit load was ignored. The advantage of the LRTE approach is that it does not utilize the transformer measurements that are subject to considerably uncertainty.

The LRTE estimated secondary circuit model is shown in Fig. 12. The estimated impedances are much smaller than the values listed in TABLE IV. The resulting voltage simulation accuracy is not significantly better than with the alternative approaches. However, this may be caused by the inaccurate transformer voltage measurements that are used to calculate the measured voltage drops over the secondary in TABLE IV. Moreover, as illustrated in Fig. 13, the meter voltage measurements follow each other quite closely. This may hinder the accuracy of the LRTE algorithm, since the algorithm is based on (non-constant) voltage differences between meter pairs. Small voltage differences result in higher influence of measurement error that may make it hard to properly estimate the topology and parameters.

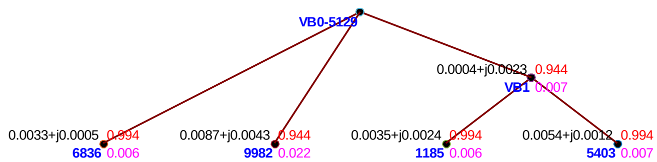

Fig. 12 LRTE estimated secondary circuit: meter name in bold blue, estimated node upstream branch impedance in black, node upstream branch parameter estimation linear regression R-squared values in red, and node upstream branch linear regression root mean squared error values in magenta

TABLE VII. LRTE ESTIMATION RESULTS

Meter	1185	5129	5403	6836	9982
Average Absolute Simulated Voltage Drop	0.6218	0	0.1056	0.0133	0.0726
Average Absolute Measured Voltage Drop	0.2017	0.1840	0.2450	0.1848	0.2052
Average Absolute Error in Simulated Voltage Drop	0.5516	0.1840	0.1908	0.1790	0.1761
Correlations Between Simulated and Measured Voltage Drops	0.5568	Undefined	0.4330	0.3285	0.4623

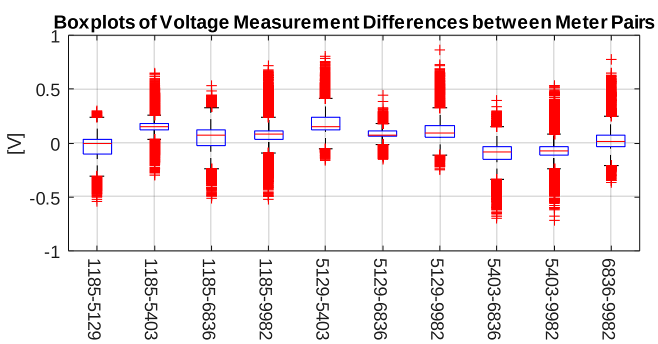

Fig. 13 Boxplots of voltage measurement differences between meter pairs

VI. CONCLUSIONS

Accurate distribution secondary (low-voltage) circuit models are needed leverage smart meter and DER sensor measurements and to coordinate and control the DERs located in the secondary circuits. This paper discusses different approaches to model distribution secondary (low-voltage) circuits. The discussed methods are used to generate a model for a real secondary circuit with smart meter measurements and transformer secondary monitoring device measurements. Issues related to practical smart meter and transformer monitor measurements are highlighted and potential ways to overcome some of the limitations are discussed. Certain realistic problems with measurement data, such as measurement noise and voltage measurement offsets between different types of meters, create significant issues, especially for systems with very little voltage drop between measurement points. The importance of having high-quality (class .2 device or better) smart meter voltage measurements is crucial for accurately estimating the topology and parameters. Future work should evaluate the pros and cons of different algorithms on different types of real secondary circuits with different types of measurement data.

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