Modeling and Validation of an Unbalanced LV Network Using Smart Meter and SCADA Inputs

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***Abstract*—As new technologies such as Photovoltaics (PVs), Embedded Generators (EGs) and Electric Vehicles (EVs) penetrate Low Voltage (LV) distribution networks, the need to understand the constraints and real time system state of LV networks becomes essential for smart grid development. This paper demonstrates that, given household Smart Meter demand data combined with 66kV/22kV zone substation SCADA voltage data, it is possible to model LV networks on a per-phase basis to a high degree of accuracy in near real time. Our model is based on a real suburb in urban northern Melbourne consisting of 113 customers, and is populated with real conductor properties, route lengths and customer phase allocations to create a true unbalanced three-phase, four-wire model. Time stepped load flow simulations of the model are compared with data loggers installed on the LV network for validation, and on average simulated results differ from real measurements by less than 0.5% for phase voltages and less than 10% for phase currents. Such accuracy allows for evaluation of PV, EV and EG impact mitigation strategies and planning in reference to the Electricity Distribution Code with a strong degree of confidence. This LV model is unique as it has been validated and is the only bottom-up load model that utilizes near real time Smart Meter and SCADA inputs to analyse impacts on distribution assets on a per phase, unbalanced basis.**

I. Introduction

Electricity distribution companies own and operate the infrastructure required to connect customers to the network. Distribution networks utilise different voltage levels: High Voltage (HV 66kV), Medium Voltage (MV 11kV to 22kV) and Low Voltage (LV 400V or 230V). The majority of residential and small business customers are connected to the LV network with single phase or three phase connections. Traditionally distribution companies had no requirement to model the LV network in great detail and only considered the overall aggregate load of each LV distribution transformer. Until recently, this level of granularity was sufficient for distribution network planning and analysis. However as disruptive technologies such as PVs, EGs and EVs are connected to LV networks [1][2][3], the need to understand the physical constraints and real-time system state have become crucial to designing a stable, efficient network facilitating smart grid development.

The two key components required to better understand LV networks are accurate network models and smart meter consumption data to provide real inputs into the model. This work aims to do this by modeling a three-phase, four-wire unbalanced model [4] of an urban network in northern Melbourne consisting of 113 customers (Fig. 1). By linking each customer's National Metering Identifier (NMI) to the smart meter consumption database, real load data per customer is integrated into the LV model. Combining an accurate LV model with real world and near real-time smart meter and SCADA data, a solid foundation for EV and EG optimisation and planning applications can be developed to better plan and manage LV networks.

II. LV Model Configuration

A. LV Model Layout

The LV model was created using the load flow package DigSilent PowerFactory.[1] Conductor properties were entered into the model using conductor specification data sheets for the conductors used in the LV Network. In a similar manner, the distribution transformer was modeled according to the specification datasheet. Conductor route lengths for the LV backbone (conductors between distribution poles) and the service cables to each customer were determined via physical onsite inspection and using GIS software cross-referenced with satellite photos of the LV Network. The model also imports the 22kV conductor and zone substation data from available HV models. The infinite bus is defined at the 66kV bus into the zone substation.

Each house (indicated by triangles in Fig. 2) is connected to a distribution pole via service cables. The colour of each service cable indicates the phase that

[1]DIgSILENT PowerFactory http://www.digsilent.com.au/

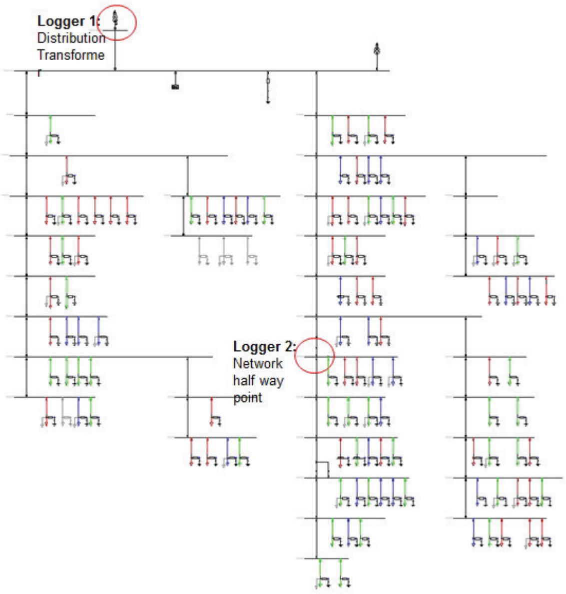

Fig. 1. Model Topology (113 customers) - Red circles indicate locations of LV Data Loggers used as reference for validation.

the customer is connected to. Phase allocation for each customer in the model reflects the actual connection to the LV network in order to establish a true unbalanced model.

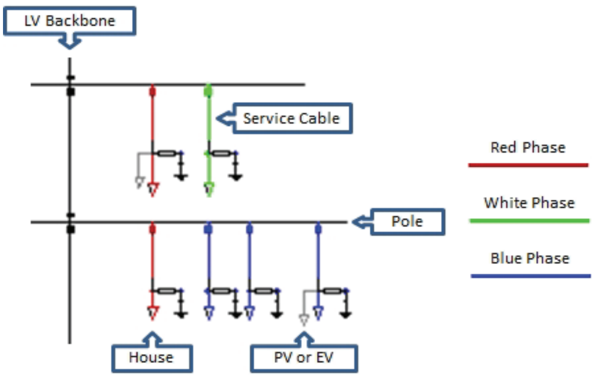

Fig. 2. Phase allocation Red refers to Red Phase, Blue refers to Blue Phase and Green refers to White Phase

B. Smart Meter / SCADA Data Integration

Each house in the LV model is integrated with a data stream from the individual customer's smart meter. This allows the model to access actual and near real time demand data at a granular level. Each smart meter provides voltage, current and consumption data at 30-minute intervals. The zone substation component of the model is fed with a SCADA voltage data stream from the 66kV/22kV transformers (Fig. 3).

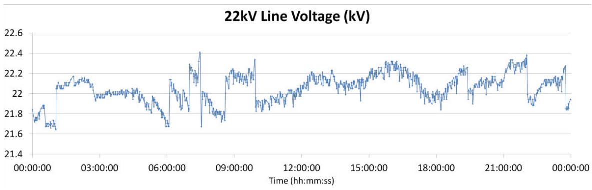

Fig. 3. Voltage as measured via SCADA from the 22kV conductors originating from the Zone Substation.

C. LV Data Loggers

Two GridSense PowerMonic PM45 loggers (Fig. 4) were installed at two locations on the LV network as shown by red circles in Fig. 1. The loggers measure key parameters such as Voltage and Current at one-minute intervals for all three phases and neutral. This data serves as a reference point for the real state of the LV backbone.

Fig. 4. Data loggers Records Voltage and Current parameters on the LV backbone

III. VALIDATION

The LV model is said to be valid if the model outputs match the current and voltage measurements of each phase recorded via the loggers for each 30-minute time interval over a period of one day. This is achieved by importing the demand data from all 113 homes in the LV network into the model at time 00:00:00. Load flow analysis is conducted to determine the LV system state. The voltage and current model outputs are recorded at the two positions where the loggers are installed (Logger

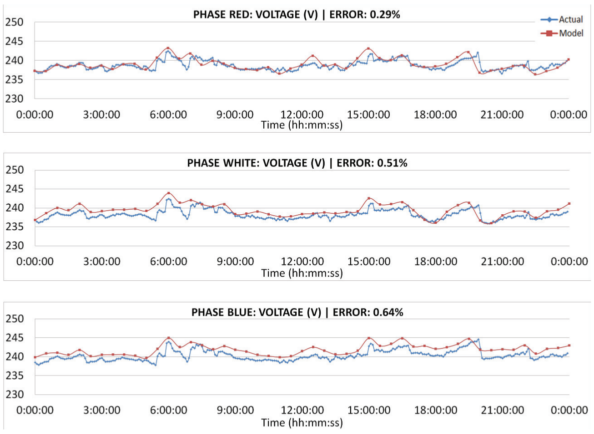

Fig. 5. Voltage Validation at Distribution Transformer - Blue line represents the voltage measured at the distribution transformer via the LV Data Loggers. The red line is the LV model estimation of the voltage at the same point.

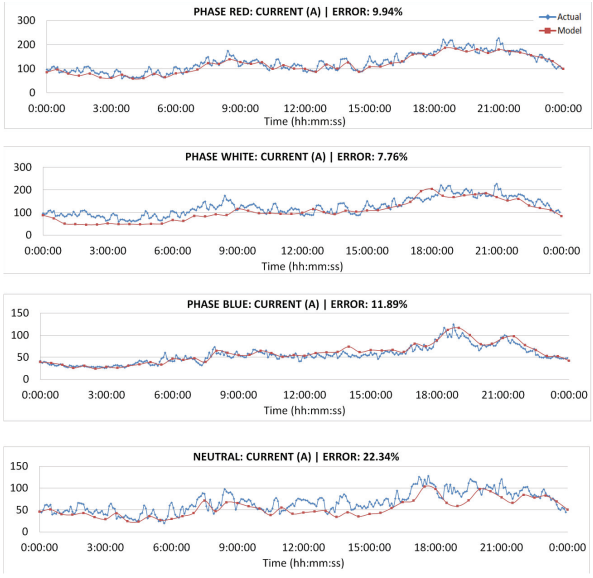

Fig. 6. Current Validation at Distribution Transformer - Blue line represents the voltage measured at the distribution transformer via the LV Data Loggers. The red line is the LV model estimation of the voltage at the same point.

1 and Logger 2 in Fig. 1). This process is repeated for each 30-minute interval (for a total of 48 load flow calculations). The model outputs at the two positions are then compared with the data loggers at the same interval.

Logger 1 in Fig. 1 is installed at the origin of the LV network, i.e. the distribution transformer. This location was selected as it will inform the starting voltage for the LV network before voltage drop occurs along the length of the LV network. By obtaining voltage at this point, the actual voltage of the HV side of the transformer can also be determined by using the tap setting of the transformer. This will contribute to analysis by providing validation reference points for the HV network. In addition, Logger 1 will also log the total current drawn by all the household loads attached to the transformer, a key performance metric for the LV model.

Fig. 5 shows the voltage parameter at the distribution transformer. The blue line represents the measured voltage from Data Logger 1 for July 10th 2012. The Red line is the LV model estimation of the voltage for the same time period as the data logger measurement. It can be seen that the model estimation compared to the actual state has an error of approximately 0.5%.

Fig. 6 shows the corresponding current measurement for current at the distribution transformer. The blue line represents the data measured from the data logger and the red line is the model estimation. The current in the network can vary rapidly at localised locations throughout the network depending on the current draw from each household. Despite this, load flow calculations using smart meter data at each home derived accurate results. On average, the model was able to estimate the current on each phase with an average error of 10%. The neutral has an expected higher error as this is a combination of the phase errors.

Logger 2 in Fig. 1 is installed at the approximate half way point on the LV network. The primary reason for installation at this point is to observe the effects of voltage and current unbalance and to analyse the effect of voltage drop along the LV network. For example, the voltage data points here should indicate an overall voltage drop from the voltages recorded by Logger 1 due to conductor impedance (assuming low to no PV generation).

Fig. 7 shows the voltage parameter at the midway point of the LV network at LV Logger 2 (network midpoint). The error at this point is under 1% for all cases. The green dotted line represents the voltage at the distribution transformer (Logger 1) for comparison purposes. It can be seen that the voltage for the red and white phases drop significantly down the LV network. The blue phase is not as heavily loaded hence the voltage drop is not as pronounced.

Fig. 8 shows the current parameter at the midway point of the LV network at Logger 2. The percentage error for the white and blue phase is low. The error for the red phase is high (41.32%) however in absolute terms, the error is on average 1.53 Amps, an insignificant amount. This is due to a small number of houses

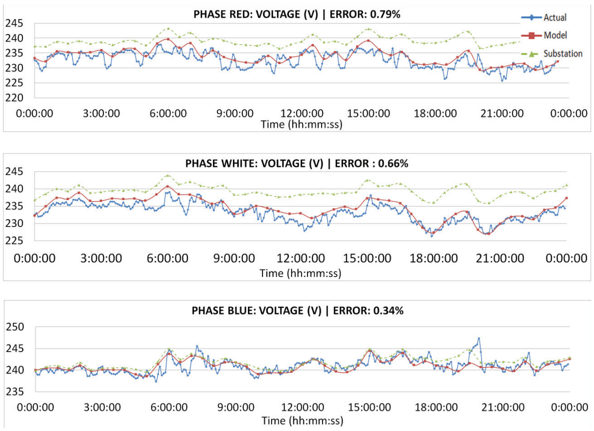

Fig. 7. Voltage Validation at LV Network Midpoint - Blue line represents the voltage measured at the distribution transformer via the LV Data Loggers. The red line is the LV model estimation of the voltage at the same point. Green dotted line represents the voltage at the transformer for comparison purposes

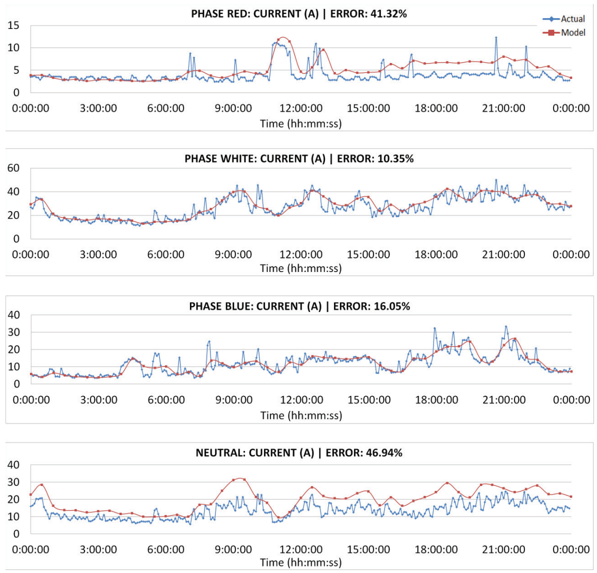

Fig. 8. Current Validation at LV Network Midpoint - Blue line represents the current measured at the LV Network midpoint via the LV Data Loggers. The red line is the LV model estimation of the voltage at the same point.

connected downstream from Logger 2 on the red phase. Again the neutral conductor has an expected high error due to the fact that it is a combination of all errors in the phases.

The main source of error between model outputs and data obtained by the data loggers is believed to be due to 11 smart meters not yet configured to send data. The LV model compensates for this by assigning the average demand of all the houses with smart meter demand data in the LV network to houses with missing smart meter data. This will be amended in future publications once the missing data is available.

IV. Results

Validated LV model outputs are used to determine if key parameters including voltage range limits, negative sequence limits (phase voltage unbalance limits) conductor current limits and transformer capacity limits are within Australian Standards [5] and the Electricity Distribution Code [6] (Fig. 9-12).

Fig.9 shows the voltage profile of the LV network. Three colours represent the phase voltages (red = red phase, green = white phase, blue = blue phase). Light blue lines represent the voltage limits. The transformer is located at 0km and the last house is located approximately 0.5km away from the transformer (x-axis). As houses draw more power, voltage begins to drop along the LV network. Nominal voltage is 1pu volt (230V). Distribution code allows voltage between 1.1pu and 0.94pu volts.

Fig. 10 shows the negative sequence Voltage Profile of the LV network. Negative sequence expressed as a percentage over positive sequence is an indicator of phase balance. The transformer is located at 0km and the last house in the network is approximately 0.5km away (x-axis). Traversing down the network increases negative sequence voltage for each house due to uneven allocation of loads between phases. The distribution code allows for negative sequence voltage up to 1% (light blue line) on average and a maximum of 2% (can go over 2% for a maximum period of 5mins within each 30min time period).

Fig. 11 shows the transformer utilisation represented as a percentage over time. Ideally, this should be below 100% (light blue line) or on average and below 150% (purple line) at all times for safe operation.

Fig. 12 shows the Current on a particular phase conductor. This parameter must be below 230A (purple line) to avoid conductor sag and ground clearance issues for the type of conductor used in the modelled LV network. Furthermore this parameter should be above 0A to avoid reverse power flow (light blue line).

The voltage and negative sequence profile in Fig. 9 and Fig. 10 show the worst case time instant at 6:00pm while the phase current in Fig. 12 shows the white phase current which recorded the worst case highest current amongst the three active phases. It can be seen that all parameters in the modelled LV network, even under worst case instances are within Australian Standards and the Electricity Distribution Code on July 10th 2012 as

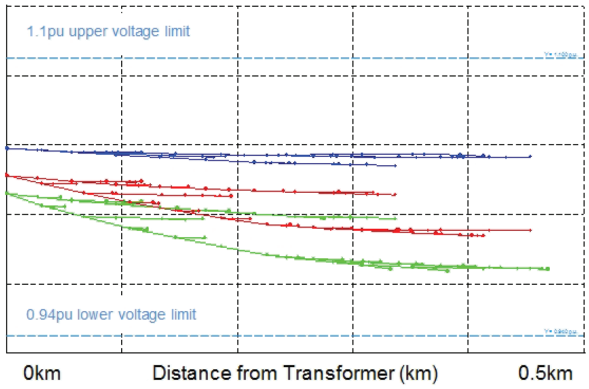

Fig. 9. Voltage profile of the LV network with limits.

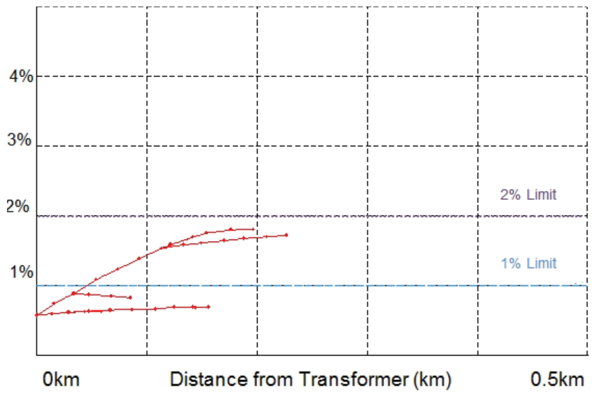

Fig. 10. Negative sequence voltage profile of the LV network with limits.

estimated by the LV model.

Although the modelled LV network performs to code under present conditions, the foreseen problem is the introduction of disruptive technologies such as solar PV and electric vehicles. High penetration of such technologies in LV networks are expected to exceed limits set out by Australian Standards and the Electricity Distribution Code. The next step in the LV model development is to simulate and estimate the impact of disruptive technologies over various penetration and phase unbalance scenarios.

V. Conclusion

The simulation model presented in this paper demonstrates strong correlation with the real network, with simulated outputs closely matching data logger reference measurements for current and voltage at different locations in the network, throughout the day. This shows that this LV model is sufficiently accurate to estimate the real state of LV networks in reference to Australian Standards

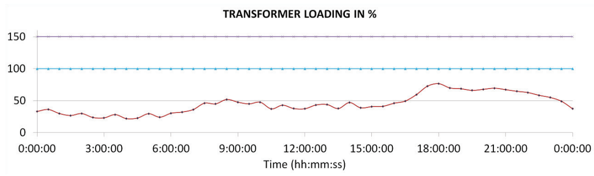

Fig. 11. Transformer utilisation with limits

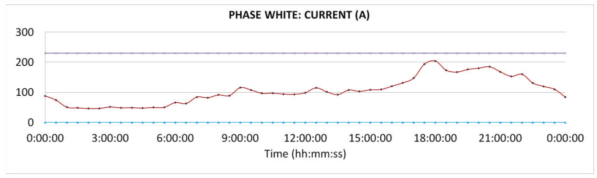

Fig. 12. Phase current with limits

and the Electricity Distribution code. The near real time input from smart meters and zone substation SCADA enhances this unbalanced per-phase LV model beyond assumption-based models often found in the literature. Using this as a baseline, the LV model can be used as an accurate, near real time platform to perform EV and EG optimization and planning strategies going forward.

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