Correlation Based Method for Phase Identification in a Three Phase LV Distribution Network

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Abstract—**Low voltage distribution networks feature a high degree of load unbalance and the addition of rooftop photovoltaic is driving further unbalances in the network. Single phase consumers are distributed across the phases but even if the consumer distribution was well balanced when the network was constructed changes will occur over time. Distribution transformer losses are increased by unbalanced loadings. The estimation of transformer losses is a necessary part of the routine upgrading and replacement of transformers and the identification of the phase connections of households allows a precise estimation of the phase loadings and total transformer loss. This paper presents a new technique and preliminary test results for a method of automatically identifying the phase of each customer by correlating voltage information from the utility's transformer system with voltage information from customer smart meters. The techniques are novel as they are purely based upon a time series of electrical voltage measurements taken at the household and at the distribution transformer. Experimental results using a combination of electrical power and current of the real smart meter datasets demonstrate the performance of our techniques.**

Keywords-Phase identification; Correlation; Distribution Network; Unbalance.

I. INTRODUCTION

While utilities usually have knowledge of the grid topology at its core, accurate information regarding the connectivity at the LV consumer side of the network is variable. In some cases the phase may be recorded when connecting a new house however this is not always possible due to remoteness of distribution transformer or a lack of phase identification in cables or bundled conductor systems. Furthermore the information typically deteriorates over time due to maintenance and repair There is considerable motivation to ensure an accurate record of phase per household. These are based on improving the efficiency of the electrical network, extending lifetime of assets and facilitating the infusion of renewable energy within the grid.

The operator may manually compute the load carried by a transformer as a collective 3-phase load. Unfortunately this does not highlight that one phase may be experiencing a significantly higher load in comparison to the other phases. Depending on customer demands, and how they are assigned to different phases, loads on the three phases of a transformer can remain continually unbalanced. By identifying their phase, households may be reassigned to a different phase so that load is more evenly balanced between the phases, thus reducing power loss and improving the operational efficiency of the network.

In order to improve the reliability and efficiency of the electric power grid, utility distribution systems are being made increasingly intelligent. Advanced monitoring and management technologies are being deployed. More recently energy distributors have commenced upgrades of manually-read analogue household meters with automated smart meters that communicate meter readings with greater frequency back to the distributors [1-3]. Collectively these initiatives form a key component of many smart grid transformations that energy distributors are undertaking.

With smart grid driving the uptake of artificial intelligence, telecommunication and power electronics equipment in power systems, it is becoming easier to envisage automation of the phase and load balancing problem [2]. The automation implementation will be technically advantageous as well as economical for the utilities and the customers, in terms of the variable costs reduction and better service quality, respectively [1].

Unbalanced feeders not only increase power losses but also affect power quality. Imbalances also lead to overheating and consequently, shorten the lifespan of the grid assets such as transformers [4-11]. Another outcome for phase identification is to facilitate introduction of distributed energy generation [12] at the households. The excess energy generated at the households can be injected back into the network over one of the three phases. Hence the need to determine phase is important to ensure a balanced infusion of power into the grid. The reasoning for balancing this is similar to the distribution of energy in the other direction - from the grid to the households.

Accurate knowledge of the phase connection at the household level allows operational improvements such as rebalancing three phase distribution transformers and feeders to reduce system losses and reduce voltage unbalance factors. Selective rebalancing will allow higher levels of rooftop PV generation to be accepted into residential networks. Automatic phase identification is the precursor to intelligent automated systems that will detect unbalance issues and recommend optimal reconfiguration solutions.

The literature on phase identification at the household level is limited. Chen [13] describes a system and method for phase identification by measuring voltage phase angles on the secondary side of underground distribution transformers to determine the connecting phase of the transformers. Works by [14, 15] perform phase identification with suitably enhanced automated meters that can detect phases based upon a unique signal injected into the phase line. The disadvantage of both of the methods is that they require enhanced hardware to transmit and receive special signals at different points of the grid, increasing capital and maintenance costs.

Our approach on the other hand, does not require any additional hardware other than household and transformer meters. Moreover, there is no requirement for interventions through signal injection or physical access to record measurements. The technique is based on the use of voltage data from the utility's distribution transformer system and on correlating this data over time with voltage data from customer meters to assess the phase to which each customer is connected

Seal's [16] work on phase prediction uses comparisons of voltage magnitude and detects significant instances of voltage changes to determine the phases of various loads in respect to the distribution SCADA meter data. This paper applies correlation from a formal signal processing perspective. As such it offers optimal solutions for both single and three phase customers and is capable of identifying the phase to which each customer is connected for large number of residential customers (75 in this case).

The organization of this paper is as follows: Section II presents motivation and related work and some background about the study. The mathematical models and solutions techniques fir phase identification approach based on a time series of voltage measurements is introduced in section III. Section IV discusses experimental results. We conclude in section V with key observations and opportunities for further work.

II. THE PERTH SOLAR CITY PROJECT

Perth Solar City is research program funded by the Australian Government Department of Climate Change and Energy Efficiency. As part of the Perth Solar City program, Western Power, the regional transmission and distribution network services provider, is undertaking a technical trial to understand the impact of large numbers of solar photovoltaic systems on the electricity distribution network. A low voltage feeder, "Paveta 1", in the suburb of Forrestfield was selected by Western Power after desk top audits and site visits for the high penetration trial. The 400/230V feeder, shown in Figure 1, is supplied from a 200kVA 22kV/400V distribution transformer and includes 77 consumers. Of these 31 consumers have roof top PV systems which have typical ratings of 1.88kW. Total rated PV installation capacity is 58.28 kW representing a branch penetration of 29.14%.

Figure 1. Perth Solar City High Penetration Feeder Site, image courtesy of Western Power.

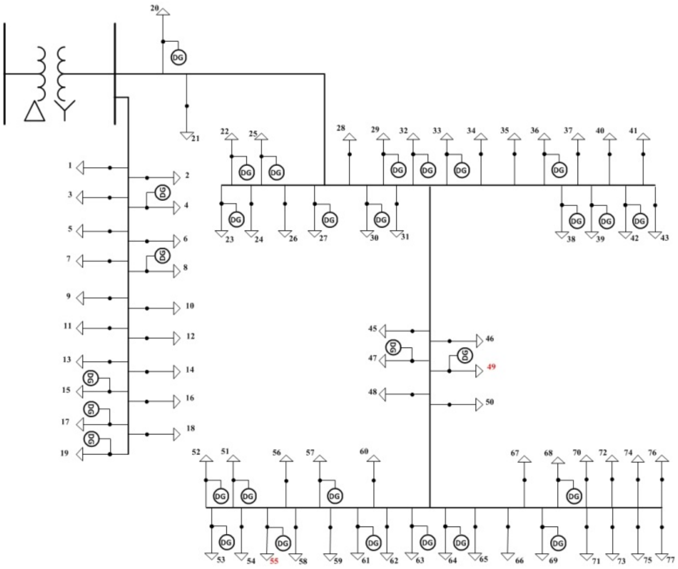


Figure 2. Pavetta feeder diagram

The feeder under study is an aerial, three phase, multiply earthed neutral (MEN) construction (Figure 2). Load data, including energy consumption, voltage and current is recorded by smart meters on the Western Power network at the point of connection to each consumer switchboard at 15 minute intervals. Smart meter data has been collected since July 2011, transformer data logging system also from July 2011 at 5 minute intervals. At the time of the recording there was two three phase meters (49 and 55, highlighted in red in Figure 2.) that were not active and no recording available for these meters.

III. DESIGN METHODS AND TOOLS

A. Phase Identification Approach

Several potential methods for customer phase identification were considered before voltage correlation was selected for further study. The present approach was selected for initial study because it did not necessarily require any additional field equipment or functionality that could not possibly be supported by existing smart systems.

This study is constructed on the hypothesis that voltage profile of consumer is well correlated with the voltage profile on the same phase of the transformer. The correlation between two signals (cross correlation) is a standard approach to feature and signal detection [20-22] as well as a component of more sophisticated techniques [23]. In this paper we consider the short time variation in the voltage signal, if the transformer voltage profile is x(t) and y(t) is the consumer main voltage profile it could be described by:

$$x_i(t)= X_i + \tilde{x}_i(t) \tag{1}$$

Where $X_i=1/T\int_0^T x(t)dt$ and T is our observation period.

$$y_i(t)= Y_i + \tilde{y}_i(t) \tag{2}$$

Where $Y_i=1/T\int_0^T y(t)dt$ and T is our observation period.

$$R_{\tilde{x}_i\tilde{y}_i}(t)=\tilde{x}_i(t) * \tilde{y}_i(t) \tag{3}$$

$$R_{\tilde{x}_i\tilde{y}_i}(t)=\frac{1}{T}\int_0^t \tilde{x}_i(t-\tau)\tilde{y}_i(t) \tag{4}$$

Where T is the observation time and it could be normalized as follow:

$$-1 \le \frac{R_{\tilde{x}\tilde{y}}(\tau)}{[R_{\tilde{x}\tilde{x}}(0)R_{\tilde{y}\tilde{y}}(0)]^{1/2}} \le 1 \tag{5}$$

Where $R_{\tilde{y}\tilde{y}}(0)$ and $R_{\tilde{x}\tilde{x}}(0)$ are the mean square values of the signals ỹ and x̃, respectively.

Correlation is the optimal technique for detecting a known waveform in random noise. That is, the peak is higher above the noise using correlation than can be produced by any other linear system. (To be perfectly correct, it is only optimal for random white noise). The cross correlation function measures the dependence of the values of one signal on another signal. The voltage measurements contain a wanted component and a disturbance component. In regard to the noise the resulting cross-correlation is:

$$\tilde{x}(t) = x_\omega(t) + z(t) \tag{6}$$

$$\tilde{y}(t) = y_\omega(t) + z'(t) \tag{7}$$

Where $x_\omega(t)$ and $y_\omega(t)$ are the desired signals and $z(t)$ $z'(t)$ are the Gaussian noise.

$$R_{\tilde{x}\tilde{y}}(t)=R_{x_\omega y_\omega}+R_{x_\omega z'}+R_{y_\omega z}+R_{zz'} \tag{8}$$

Impedance based voltage drops contribute significantly to disturbances z(t) and ź(t) but a Gaussian component occurs in any physical measurement (Figure 23). The above formula does converge to $R_{x_\omega y_\omega}$ for increasing integration time, because the other terms have an expected value of zero when the signal and the noise sources are uncorrelated. It can be shown that the effective noise power added by the system decreases with 1.5 dB for every doubling of measurement time [24], [25] and can be reduced by as much as 50 dB [24].

B. Measurement Setup and Errors

Consumer smart meters can record and report periodic measurements of power consumed in Watt-hours (Wh) over small time intervals of Δt = 15 minutes. Government regulations require that the watt-hours reported by consumer meters be accurate, typically of the order of 99.5% accuracy [17-19].

A meter records readings based on its internal clock and this clock may be out of synchronism with respect to the true clock. For e.g. if a meter reports that 100Wh were consumed from 9:00:00 to 9:15:00 PM and its clock lags the true clock by 5 seconds, in reality the 100Wh were consumed from 9:00:05 to 9:15:05 PM. Therefore even if all consumer meters are setup to report over the same time intervals, each may suffer from a different clock drift and report Watt-hours consumed over a slightly different time interval.

Meters deployed at transformers are much more complex devices. Unlike consumer meters, they measure several parameters needed to monitor a transformer, such as voltage, current, power factor, active and reactive power, etc at finer time resolution. Typically the meters publish average values of parameters over small time intervals. Therefore the watt-hours computed from these parameters for each phase are estimates of the actual watt hours supplied and may contain errors. (The real power supplied by a phase can be computed as the time average of the instantaneous voltage and current product). In addition, similar to a consumer meters, clock synchronization problems may also occur at the transformer meter.

Another source of error is line losses, since power lines connecting transformer phases to homes possess a certain amount of electrical resistance; some of the transferred energy is lost as heat. These losses primarily vary with load and also with ambient temperature.

IV. EXPERIMENTAL RESULTS

A. Phase Allocation

The correct phase of houses was not originally confirmed by the utility provider in the region (Western Power). Also there were eight units (Figure 2, load 69-77), each with individual smart meters, connected to the distribution pole by one three phase overhead consumer mains but for which the phase was not known. For these reasons the phases of all meters had to be verified. This was done by attempting to profile voltage of each individual house along the feeder and verifying phase voltages as against known phase voltages of the transformer.

To confirm that the correlation between the phases exist an auto correlation and cross correlation have been performed on the voltage profile of the three phase transformer over the period of week and the results are shown in Figure 4.

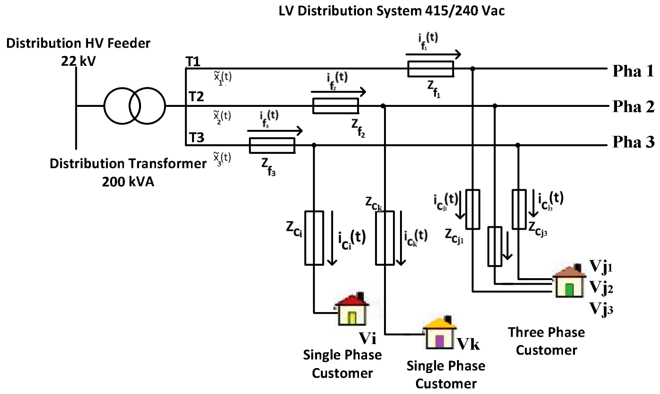


Figure 3. Simplified diagram of network under study

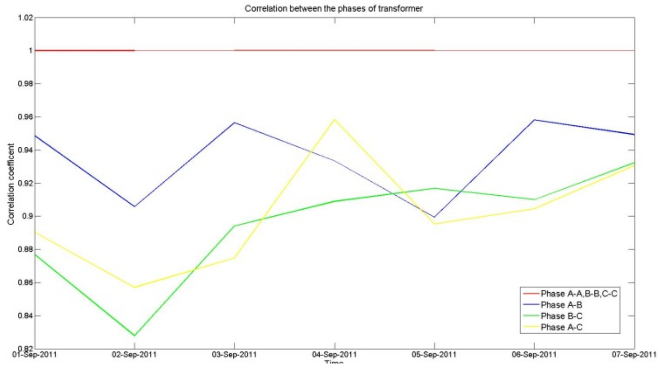


Figure 4. Auto-correlation & cross-correlation of transformer phase voltages 1^{st}-7^{th} September 2011.

In order to compare the smart meter and transformer voltage signal cross-correlation, the seven-day voltage profiles of the 51 single phase houses, 24 three phase houses and the voltage profile on each phase of the distribution transformer were recorded. The average series voltage for each phase of the transformer over the seven day was calculated, as well as their variant. Next, the signal segments that contain the transformer average voltage sequence were extracted from the simultaneously received smart meter voltage signals and were cross correlated with variable signal of phase A, B and C of the transformer.

The amplitude of each sample in the cross-correlation signal is a measure of how much the received signal resembles the target signal, at that location. This means that a peak will occur in the cross-correlation signal for every target signal that is present in the received signal. The value of the cross-correlation is maximized when the target signal is aligned with the same features in the received signal.

Figure 5 illustrates the procedure to perform the cross correlation. For the single phase load, it is a simple three way correlation test with each phase of the transformer (Figure 26a). In case of the three phase load the cross correlation will be performed on the six combinations shown on Figure 26b and the three combinations with highest cross correlation will be picked as the correct phases.

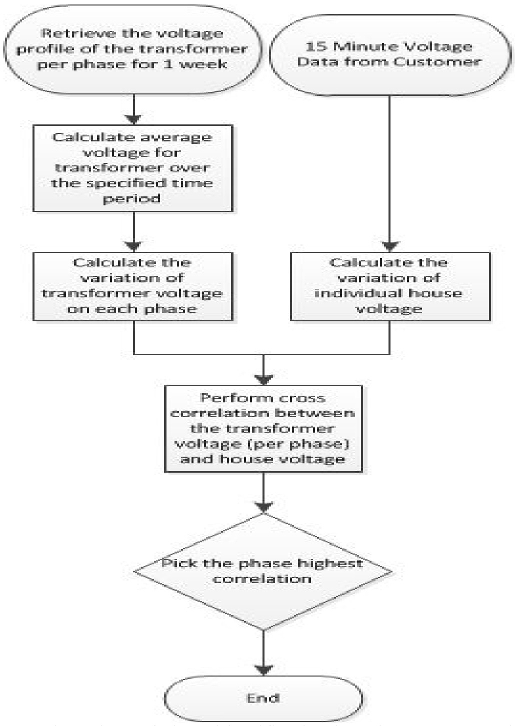
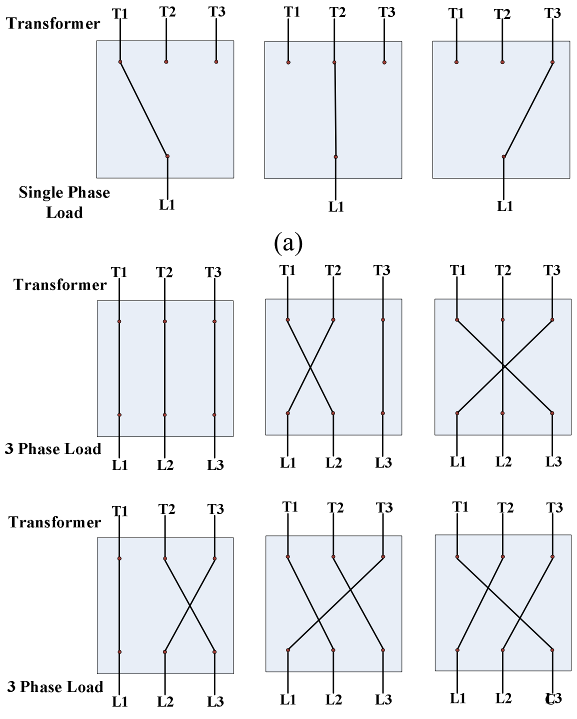


Figure 5. Flow chart of phase identification based on cross correlation



(a)

(b)

Figure 6. Cross correlation of three phase and single phase house with transformer

We performed the above mentioned procedure on all the 75 available (There are 77 houses connected to this feeder but at the time of this work two meters were missing data). Table 1 and Table 2 summarize the allocation of the 51 single phase and 24 three phase meters respectively. Smart meters load data on the Pavetta LV feeder and the result of the phase identification is shown in Figure 7 and Figure 8 for the period of one week (1st -7th September 2011) and one day (1st September 2011) respectively.

In Figure 7 and Figure 8 transformer actual phases A, B and C are illustrated in red, green and blue colours respectively, as the black dotted line shows the estimation of these phases based on the allocated phases assigned using our technique.

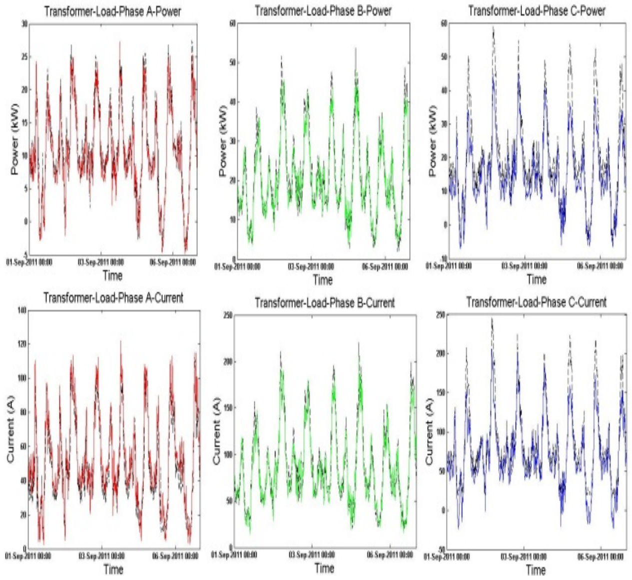


Figure 7. Comparison of aggregation of correlated meters with transformer reading, power and current. (1st-7th September)

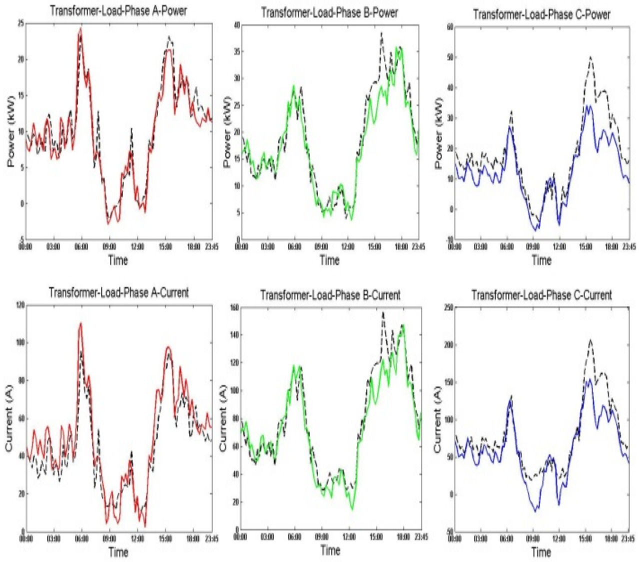


Figure 8. Comparison of aggregation of correlated meters with transformer reading, power and current. (1st September 2011)

Table 1. Allocation of the single phase houses.

House No	Phase	House No	Phase	House No	Phase
1	B	**22**	C	**50**	C
2	A	**24**	A	**51**	B
4	B	**27**	C	**54**	B
5	C	**28**	C	**55**	C
6	A	**29**	B	**57**	C
7	B	**31**	A	**59**	B
8	C	**33**	A	**60**	C
10	B	**34**	A	**62**	C
12	A	**36**	A	**65**	C
13	B	**37**	C	**70**	A
14	C	**39**	C	**71**	B
15	C	**40**	A	**72**	C
16	B	**41**	B	**73**	C
17	A	**42**	C	**74**	B
18	B	**43**	C	**75**	A
19	C	**45**	B	**76**	B
20	C	**48**	B	**77**	A

Table 2. Allocation of the three phase houses.

House No	Phase 1	Phase 2	Phase 3
69	A	B	C
44	A	B	C
49	A	B	C
67	A	B	C
66	A	B	C
3	A	B	C
9	A	B	C
32	A	B	C
58	A	B	C
38	A	B	C
52	A	B	C
25	A	B	C
26	A	B	C
47	A	B	C
11	A	B	C
61	A	B	C
21	A	B	C
23	A	B	C
35	A	B	C
30	A	B	C
53	A	B	C
64	A	B	C
63	A	B	C
68	A	B	C
69	A	B	C
44	A	B	C

B. Unbalanced and Balanced Transformer Loading

It was also identified that the network under study is significantly unbalanced. The level of three phase unbalancing in distribution feeder Pavetta shown in Figure 9 was introduced because of the poor allocation of customer loading among the three phases. For instance, The Power of phase A is much less than phase B and C during day time peak hours.

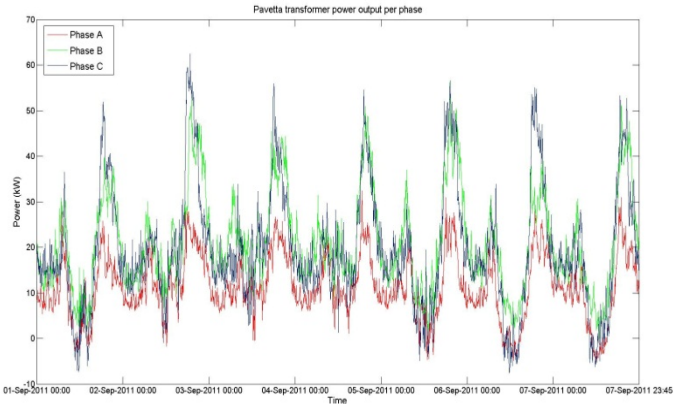


Figure 9. Pavetta transformer power output on three phase, 1st-7th September 2011.

It is possible that most of the over and under voltage incidences would be mitigated by reallocation of PV and load [26]. PV could be allocated to more heavily loaded phases to reduce net load. Alternatively, if all load and all PV were balanced, no one phase would be more or less likely to be subject to noncompliant voltage. Balancing of the network will reduce the occurrence of voltage drop and reduce the instance of voltage rise at higher PV branch penetration.

Transformer losses (P_T) can be divided into two main components: no-load losses (P_{NL}) and load losses (P_{LL}). These types of losses are common to all types of transformers, regardless transformer application or power rating. Load losses, which become more important at high power levels, can be reduced by several methods, including increasing the voltage of the distribution lines, shunt compensation, reduction of harmonics, load balance, and demand side management.

$$P_T=P_{NL}+P_{LL} \tag{9}$$

In order to compute winding currents and induced voltages necessary for loss calculations, the transformer equivalent circuit is defined with 3 buses which separate the primary terminals, magnetization branch and secondary terminals (Figure 10).

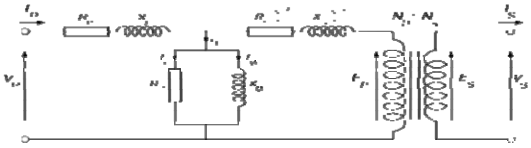


Figure 10. Per-phase equivalent circuit for distribution transformers.

Table 3 provides the summary of differences in power losses of the transformer on a per phase basis for when the transformer is unbalanced versus when it is balanced. The losses on phase A of the transformer increase in comparison to the unbalanced system as more loads would be allocated to phase A to maintain the balance in the system. Loss reduction in the other two phases is more significant than the losses gained in phase A.

Table 3. Energy Saved By Balancing the Transformer Loading.

	Energy				**Power**		
	Pha A-Wh	**Pha B-Wh**	**Pha C-Wh**	**Total-Wh**	**Max-Instan-Pha A-W**	**Max-Instan-Pha B-W**	**Max-Instan-Pha C-W**
Day 1	-862	539	723	401	175	156	297
Day 2	-1288	804	1100	615	294	233	423
Day 3	-1161	1033	629	501	215	195	303
Day 4	-1054	904	602	452	216	196	290
Day 5	-1207	987	799	579	308	252	272
Day 6	-887	344	973	430	161	111	369
Day 7	-953	742	618	408	227	254	277

Per phase power losses in case of unbalance and balance tranformer for the period of 1st September till 7th Septmber 2011 are shown in Figure 11 and Figure 12 respectively. As illustrated in the figures 11 and 12 and Table 3, by balancing the transformer more losses would be incurred on phase A due to low loading of this phase in the first case but this loss would be minimal comparing to power gained by balancing the load on phases B and C.

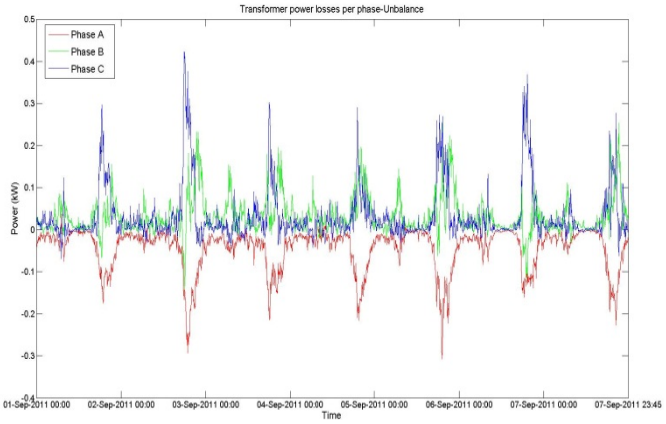


Figure 11. Per phase power losses in the case of unbalanced transformer.

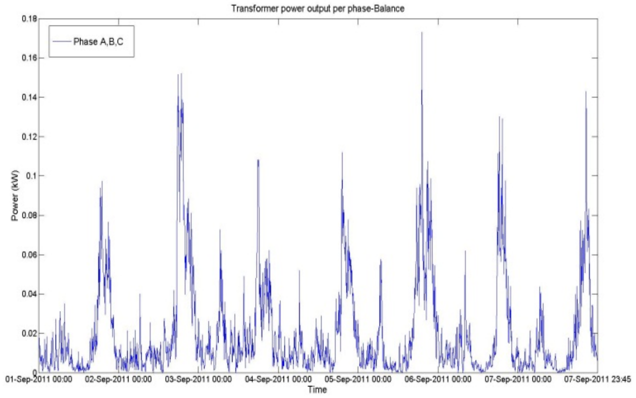


Figure 12. Per phase power losses in the case of balanced transformer.

V. CONCLUSION

This paper has demonstrated that voltage profile of consumer is well correlated with the voltage profile on the same phase of the transformer and established a new method to determine the phase connection of consumer loads on a LV distribution network from smart meter voltage measurements of the consumer and transformer log data. The initial field testing was successful, with fifty one single phase meters and twenty four three phase meter correctly allocated on a residential LV feeder. The next step is to assess the ability of the method to work based on grouping the houses among each other into three separate groups which then would be compared with the phase A,B,C of the transformer. Also, phase identification is the first step towards the larger problem of phase balancing and we shall investigate this problem taking into account various costs associated with phase re-balancing.

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