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A Quantitative Method for Establishing Field Measurement-Based Voltage Dependence Load Parameters

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Abstract: Static load models of voltage dependence are frequently used in low voltage network simulation research. However, there is usually a lack of defined main parameters for static load models for voltage dependence to represent commonly used loads in residential premises. This paper presents a statistical approach for determining key parameters in models of static load dependence on voltage. Eleven (11) single-phase load types were investigated based on field measurements corresponding to 33 kV upstream on-load tap-changer operations. Changes in the individual loads' active and reactive power due to changes in input voltages were recorded and statistically analyzed to determine the parameters used for the static load model of the voltage dependence. The findings were validated by laboratory measurements of the individual loads and were discovered to be compatible and in close agreement with the statistical analysis outcomes. A simulation case study conducted on a low voltage network with solar photovoltaic penetration shows important deviations in peak power supply, power losses, inverse power flow and energy consumption in the network between steady power load model and LTV model, particularly when the source voltage is set at above 1.0 per unit.

Keywords: Exponential load model, power system study, low voltage distribution network, LTV, Voltage dependency load modeling.

1. INTRODUCTION

Medium and low voltage distribution networks are being introduced to the scheme from the traditional passive form to the active network as distributed generation, electric vehicle charging systems, volt-var optimized operation (VVO), storage devices and other smart grid technologies. Therefore, even at low voltage (LV) networks, loads need to be more accurately represented using voltage-dependent models for simulation studies. To study the LV network in detail, several research and pilot projects were launched. For instance, voltage measurements at LV busbars, LV voltage network solutions, LV embedded automation, LV protection, and communications were performed by Electricity North West Limited in the United Kingdom, while LV network modeling and evaluation environment were performed by Scottish energy and UK power network smart urban LV.

It becomes necessary to perform power flow simulations using quasi-dynamic loads as input to obtain a more meaningful and strategic solution with the introduction of an active distribution network. The selection of the appropriate load models for simulation studies is one of the main challenges for network modeling. The modeling of medium voltage loads[1]–[4] put a lot of effort into accurately representing different types of loads. Electrical characteristics of consumer appliances with time-varying residential load models suitable for analyzing smart grid applications and LV demand-side management were developed and reported at the level of the LV distribution network in [5].

In the study of the power system, the imports of the appropriate load model are mentioned in [6]. Stability studies require dynamic load models while load flow studies require static load models. A survey was conducted in [7] to investigate the load modeling industry practices. Most utilities (about 84% world) still use the simplest load model, the constant power model for load flow studies that do not accurately reflect the actual system behavior in terms of voltage fluctuations throughout the day. For power flow simulations, load-to-voltage (LTV) dependence models are required to achieve results that truly reflect network capacity and behavior. They are generally three common types of LTV dependence models; namely ZIP, also known as a polynomial model [8], exponential model [4], and composite model[9].

2. LITERATURE REVIEW

Most of the literature's suggested load modeling methods are based on real measurements [1], [3], [8],

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[10].Typically, these measurements are based on costly fault recorders installed at main substations that collect the load reaction during disturbance occurrences and then use the information to model the LTV loads [9], [10].However, this approach has a limitation as the generation of sample data requires fault events, and fault events are usually rare. It is usually sufficient to assess the impact of voltage changes on the power flow in the network for LV power flow simulations.

This paper proposes a statistical approach based on 33 kV upstream load tap changer (OLTC) operations to determine key parameters of static loads of voltage dependence in representing single-phase loads commonly found in residential premises. Laboratory studies have been conducted to validate the mean value of the parameters acquired from the field measurement information statistical analysis. Using the LTV model to represent customer loads, an LV network with solar photovoltaic (PV) penetration is used as a case study to determine the effect on maximum power demand, peak power losses, and reverse power flow and network energy consumption.

This paper's organization is the following. Section III discusses the methodology for determining the LTV model's key parameters and power coefficients. Section IV presents the results of the statistical analysis of field measurement data and compares them to the results of laboratory experiments. The application of the LTV model for a case study on an LV network with solar PV penetration is discussed in Section. Section VI concludes the results of this article.

3. METHODOLOGY

Voltage Dependency Load Model

Previous researchers have developed three models of voltage-dependent loads, namely the models of polynomial, exponential and composite. The polynomial model consists of constant impedance mixed, constant current and constant loads of power. The equations representing the polynomial model's active and reactive power are shown respectively in (1) and (2).

$$P = P_o\left(\alpha_1\left(\frac{V}{V_0}\right)^2 + \alpha_2\left(\frac{V}{V_0}\right) + \alpha_3\right) \quad (1)$$

$$Q = Q_o\left(\beta_1\left(\frac{V}{V_0}\right)^2 + \beta_2\left(\frac{V}{V_0}\right) + \beta_3\right) \quad (2)$$

Where α_1, α_2, and α_3, β_1, β_2, β_3 these are the active and reactive power composition of constant impedance, constant current and constant power respectively, with $\alpha_1+\alpha_2+\alpha_3 = 1.0$, and $\beta_1+\beta_2+\beta_3 = 1.0$.

V_0 is the nominal voltage and V is the voltage of the supply. P_0, P and Q_0, Q, respectively, are the active and reactive power at the nominal voltage and supply voltage. The equations of the linear load model are shown in (3) and (4).

$$P = P_0\left(\frac{V}{V_0}\right)^{z_p} \quad (3)$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{z_q} \quad (4)$$

Where z_p and z_q are the load coefficients for the active and reactive power components, and where α_1, α_2, α_3 and β_1, β_2, β_3[7] could be determined.

Field Measurement Set-Up

In Malaysia, the operation of OLTC is at 1,67 percent for the 33/11 kV transformers. 11/0.4 kV distribution transformers do not have a load tap changer and therefore do not add to dynamic voltage regulations. Besides, variations in voltage are due to ON / OFF loads switching.

Due to load change and OLTC operations, the supply voltage from the utility fluctuates all day. For recording supply voltage (V), active power (P), and reactive power (Q) consumption of individual appliances in a residential home for two consecutive days, high-resolution energy loggers with a second-time interval were used to capture sufficient data samples for the load model.

Power and voltage measurements were performed on home appliances including fluorescent lamps, compact fluorescent light (CFL), LED light, computer workstation, laptop, table fan, tablet, conventional air conditioner, air conditioner type inverter, refrigerator type inverter and LCD television with power recorders. See Fig. 1.

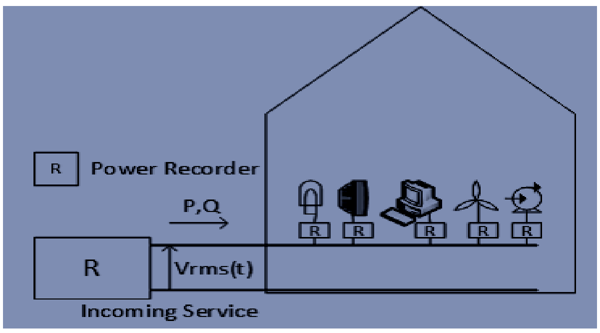

Figure 1. Field measurement set up

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A profile of 24-hour voltage as shown in Fig. 2 Indicates changes in the voltage supply to home appliances as a result of OLTC operations and load switching.

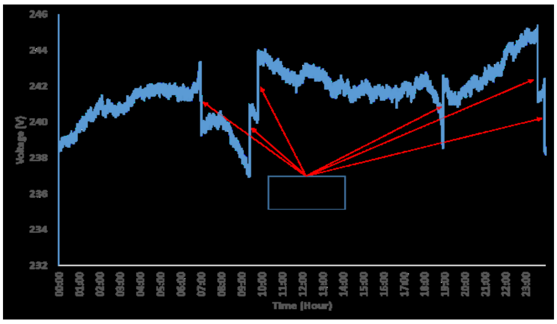

Figure 2. Changes in OLTC operation in 24 hours

Data Processing

The recorded information was processed for each load according to the steps outlined below corresponding to the flow chart shown in Fig. 3.

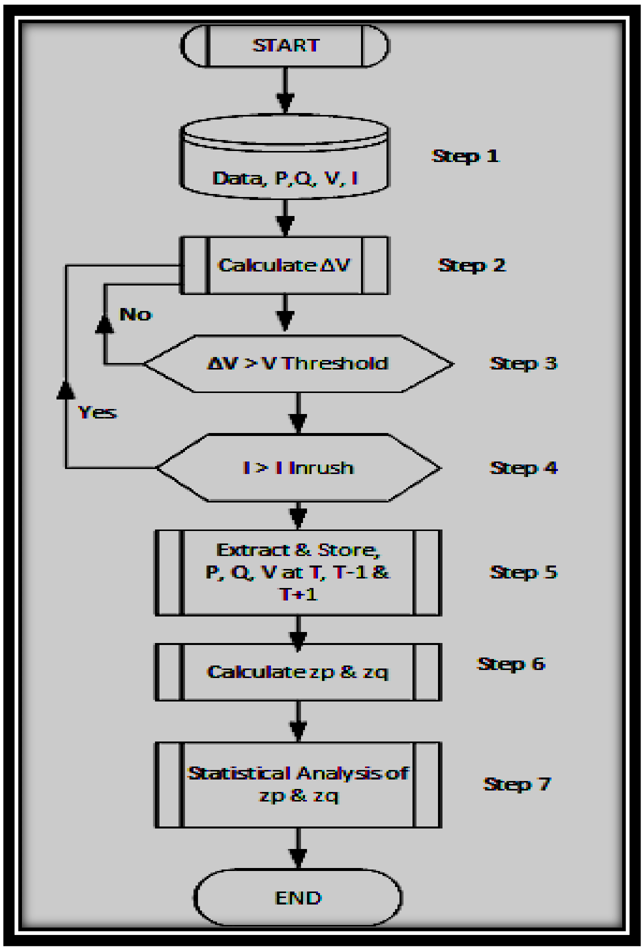

Figure 3. Data process flow chart

Step 1. Import power recorder data; a second resolution voltage (V), current (I), active power (P) and reactive power (Q). OLTC's operating time is within a second.

Step 2.Calculate voltage change, ΔV which is the distinction in voltage before and after each OLTC procedure, or a temporary voltage arising from network switching.

Step 3.A threshold voltage, ΔVTH of 0.2% is chosen and used to filter negligible voltage changes. Variations in voltage due to OLTC operation range from 0.5 to 2.5% [6]. A 0.2% is selected to include minor voltage changes due to the network load/equipment switch.

Step 4.Changes in the current before and after voltage change are used to filter events associated with the load inrush current being investigated. For example, the voltage drop due to a water heater's inrush current is considered as invalid data for the water heater load itself but is valid for other loads.

Step 5.Extraction of data in the form of V, P and Q corresponding to T, T-1, and T+1 as described in (5) and (6) each time.

Step 6.Calculate the coefficient of active and reactive power, z_p and z_q from the data extracted by (5) and (6) in Step 5.

Step 7: Perform statistical analysis on z_p and z_q.

$$P_T = P_{T-1}\left(\left[\frac{V_T}{V_{T-1}}\right]^{zp}\right) \quad (5)$$

$$Q_T = Q_{T-1}\left(\left[\frac{V_T}{V_{T-1}}\right]^{zq}\right) \quad (6)$$

The statistical output of a CFL load's active and reactive energy coefficients is shown in Fig. 4 and fig. 5. The ordinary Gaussian distribution curve was shown by both coefficients. The mean and standard deviation is calculated for both coefficients.

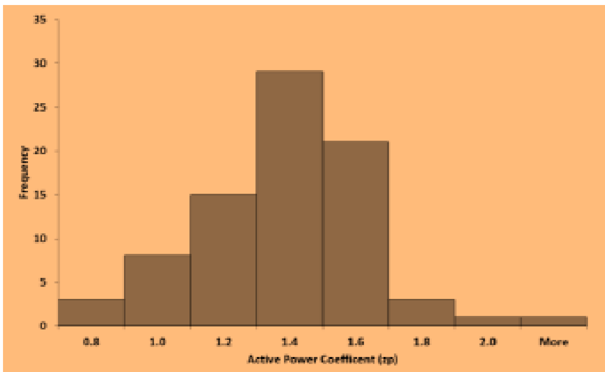

Figure 4. Distribution of calculated active power coefficient, z_p

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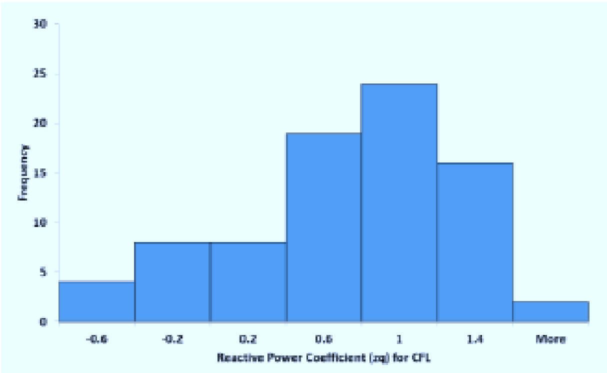

Figure 5. Distribution of calculated reactive power coefficient, z_q

Laboratory Measurement

Experiments have been carried out in the laboratory to determine the relationship between voltage and power changes in each of the loads and the results compared to those obtained from field measurements. The experimental set-up is as shown in Fig. 6.

A voltage stabilizer is used in the experiment to control the AC voltage at a constant level. A variable transformer from 215V to 250V varies input voltage to the load under test. The power recorder records the voltage, current, active and reactive power of the load under test.

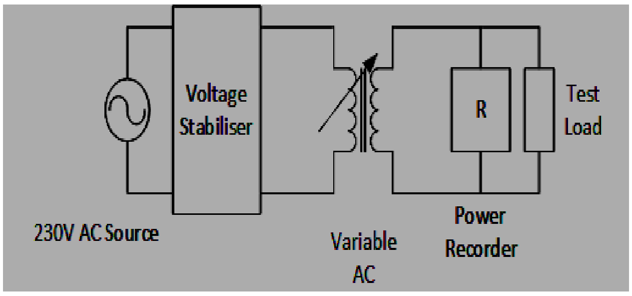

Figure 6. Laboratory measurement

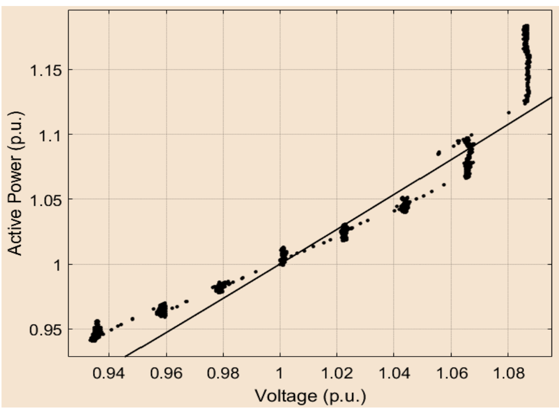

Figure 7. Active power curve fitting for CFL

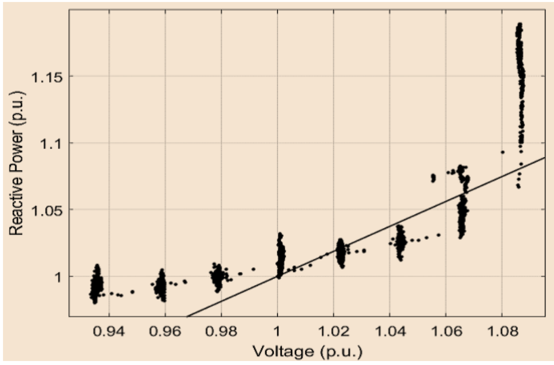

Figure 8. Reactive power curve fitting for CFL

Table I. Goodness of Curve Fitting

Coefficient	SSE	R-square	Adjusted R-square	RMSE
Z_p	1.868	0.8651	0.8651	0.02458
z_q	4.493	0.4598	0.4598	0.03812

The data measured from the experiment is then processed using the curve fitting technique. The active and reactive power coefficient is tuned with confidence boundaries of 95 percent. Figure 7 and Figure 8 show the fitting curve for CFL with fit quality shown in Table I.

4. RESULTS

Data statistical analysis based on field measurements demonstrates that the energy coefficient z_p and z_q acquired for the eleven (11) load kinds are distributed with mean and standard deviations as shown in Table II.

Besides, compared to field measurement outcomes, the energy coefficients acquired from laboratory measurements were discovered to be in close agreement as shown in Table II.

Among the eleven (11) types of loads measured, fluorescent lamps with the highest LTV power coefficients are found to be the most sensitive to voltage changes. For typical home appliances, the power coefficients, z_p, and z_q vary from 0.07 to 2.44, and -0.67 to 21.49 respectively. Positive coefficients show that any decrease in voltage would probably decrease energy consumption, while adverse coefficients indicate that any decrease in voltage would boost energy consumption.

5. CASE STUDY

The voltage dependence aggregate load model was created and used in this case study based on field measurements of a residential LV network. The

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measurement was performed in one Malaysian residential house. The aggregated load coefficient has been calculated using the proposed method. As shown in Fig. 9, the load coefficients, z_p and z_q vary time as the voltage and power vary at different times of the day.The aggregate load model is used in this case study to investigate the impact of solar PV system on a residential LV distribution network.

Table II. Active and Reactive Power Coefficient

Appliances	LTV Power Coefficients							
	z_p				z_q			
	Field Measurement		Laboratory Experiment		Field Measurement		Laboratory Experiment	
	Mean Value	Standard Deviation	Best Fit Value	Difference (%)	Mean Value	Standard Deviation	Best Fit Value	Difference (%)
Compact Fluorescent Light	1.24	0.36	1.33	-6.64	0.73	1.29	0.94	-21.92
LED Light	0.24	0.16	0.27	-2.20	-0.67	1.95	-0.68	+1.41
Personal Computer	0.24	1.64	0.23	+6.12	1.69	0.56	1.89	-10.11
Laptop	1.48	1.56	1.56	-5.15	1.68	1.13	1.40	+20.12
Fan	1.99	0.15	1.90	+4.43	3.04	1.86	2.90	+4.84
Fluorescent	2.44	0.14	2.30	+6.26	2.90	0.09	3.46	-16.01
Tablet	0.07	1.77	0.08	-7.58	-1.93	12.77	-1.90	+1.48
Conventional Air Cond.	0.98	0.59	0.89	+4.40	5.30	1.46	5.44	-2.55
Inverter Air Cond.	0.77	0.13	0.53	+2.41	21.49	7.47	15.97	+10.27
Refrigerator	0.12	0.40	0.82	-2.85	3.82	2.89	2.20	+14.38
Television	0.04	0.93	0.05	-3.47	1.81	4.92	1.69	+7.25

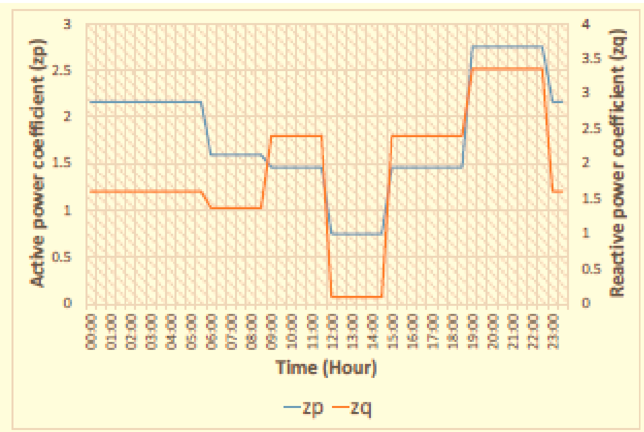

Figure 9. Time-varying power coefficient

Table III. Case Investigated

Case	Source voltage (per unit)	Load model
I	0.94, 1.00, 1.10	Constant power
II	0.94, 1.00, 1.10	LTV

Two (2) cases as shown in Table III were explored to determine the effect on power losses, inverse power as well as energy consumption of distinct load models in the low voltage distribution network with the solar PV system.

LV Reference Network

This case research uses the reference network established in [13]. The network is altered to include different home appliances' active and reactive energy coefficient. Using DIgSILENT Power Factory software, the home appliance is modeled in detail. The LV network's single line diagram is as shown in Fig. 10.

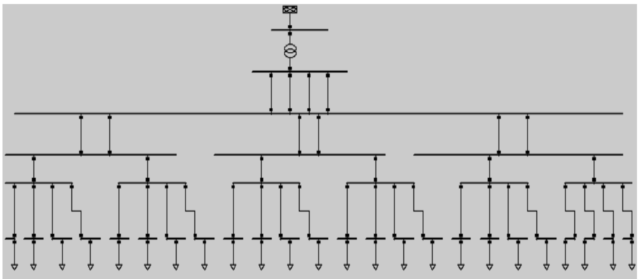

Figure 10. Single line diagram for the residential network with the fully underground system

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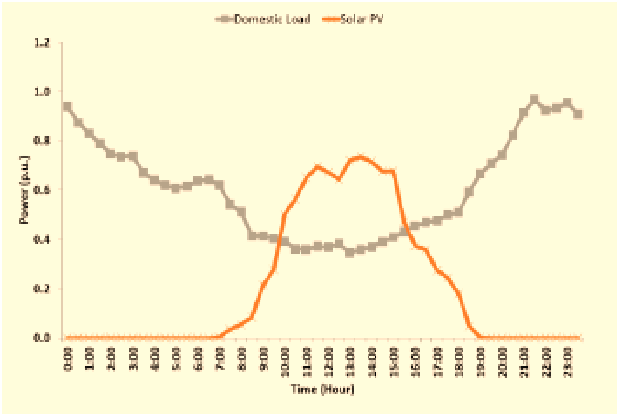

Figure 11. Load demand and PV generation profile.

Fig. 11 shows the profile of the load and PV generation. Using the actual aggregated load profile recorded at the Malaysian utility as well as the PV generation profile, the load profile is generated.

Peak Power Demand and Network Losses

In the distribution substation, the peak power demand is influenced by the type of load model used in the simulation. LTV model results in lower peak power demand compared to the constant power model for source voltage of less than 1.0 p.u as shown in Table IV.
As a result, peak power losses are also lower for the LTV model as shown in Table V. However, the LTV model shows a higher peak power demand and higher power losses than the constant power model when the source voltage is raised to above 1.0 p.u.
Table VI shows the effect of the LTV model on reverse power flow, which is consistent with changes in peak power demand. With source voltage above 1.0 p.u, LTV model shows higher power consumption and therefore a smaller amount of reverse power flow.

Table IV. Load Model Effect on Peak Power Demand

Source Voltage (p.u.)	Maximum demand (kW)		Difference (%)
	Constant power model	LTV load model	
0.94	244.54	208.00	-14.94
1.00	244.30	235.64	-3.54
1.10	244.08	285.53	16.98

Table V. Load Model Effect on Peak Power Losses

Source Voltage (p.u.)	Peak power losses (kW)		Difference (%)
	Constant power model	LTV load model	
0.94	4.54	3.76	-17.18
1.00	4.31	4.13	-4.17
1.10	4.08	4.82	+18.14

Table VI. Load Model Effect on Reverse Power Flow Due To Solar PV

Source Voltage (p.u.)	Maximum reverse power (kW)		Difference (%)
	Constant power model	LTV load model	
0.94	124.18	133.28	+7.33
1.00	124.10	123.87	-0.19
1.10	123.91	106.80	-13.81

Energy

The LTV model shows a lower consumption of energy in consumer loads as shown in Table VII.

Table VII. Energy Consumption Calculated from the Simulation

Source Voltage (p.u.)	Load Model	Grid (kWh)	PV (kWh)	Consumer Energy Consumption (kWh)
0.94	Constant Power	2131	1423	3495
	LTV	1653	1423	3022
1.00	Constant Power	2132	1423	3495
	LTV	2057	1423	3421
1.10	Constant Power	2134	1423	3495
	LTV	2787	1423	4141

6. CONCLUSION

As an LTV model, voltage dependence load parameters were used to conduct case studies to determine the impact of the LTV model on studies of network simulation. The findings show that the LTV model provides a more conservative result in terms of substation peak power supply, network peak power losses and load energy consumption when the source voltage is set at less than or equal to 1.0 p.u.This indicates that energy conservation could be realized when voltage is conservatively set at the grid source and in the distribution network optimally controlled.
In the next part of our research, advanced noise and bad data filtering process will address further improvements

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in the determination of power coefficients. The suggested methodology will also be used to quantify the potential advantages of applying conservative power utility network voltage reduction (CVR) schemes.

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