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Energy Savings for Various Residential Appliances and Distribution Networks in a Malaysian Scenario

Mithila Seva Bala Sundaram *, ChiaKwang Tan, Jeyraj Selvaraj and Ab. Halim Abu Bakar

UM Power Energy Dedicated Advanced Centre, University of Malaya, Wilayah Persekutuan Kuala Lumpur 59990, Malaysia
* Correspondence: smithila_88@yahoo.com

Abstract: This paper presents a detailed study of the energy savings that can be achieved through residential appliances by implementing conservation voltage reduction (CVR). The computed energy savings are derived from the ZIP coefficients of a load model (static) under varying voltage conditions that represent the power consumed by each appliance tested. Multiple studies have shown energy savings at the substation level but not at the level of a specific residence and appliance; hence, the latter is the focus of this analysis. The appliances are determined based on the type of heating and cooling loads, and the daily duration of use for each appliance, which contributes to the total monthly consumption that is billed for a household are included in this study. Energy savings in Malaysia has been a focus of many current studies, and this study is the first attempt to achieve energy savings through the implementation of CVR. No published work has compared individual appliances that truly benefits from CVR, and this is addressed in this study. The main contribution of this study is that it provides very detailed and measured data that are used to analyze and generate energy savings for very specific residential appliances intended to meet every 1% voltage drop. The load model is developed for the common household appliances in Malaysia, and then a voltage reduction study is applied to the appliances as well as the Malaysian distribution networks. Here, we also provide insight for performing voltage reduction at an electric vehicle (EV) charging station in Malaysia. The results of this study should serve as a foundation for all practicing utilities engineers to address the issue of CVR in Malaysia. The CVR factors for residential, commercial, and industrial networks in Malaysia are also published in this paper.

Keywords: conservation of voltage reduction; energy savings; ZIP load model; cost savings; distribution network

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1. Introduction

Conservation voltage reduction (CVR) is a method of reducing the voltage supplied to electrical loads during periods of low demand in order to increase energy efficiency and to reduce electricity consumption. This technique has been widely used in the power industry to help utilities meet energy efficiency targets, to reduce peak demands, and to minimize environmental impacts. The aim of conservation voltage reduction is to reduce the amount of energy lost through electrical transmission and distribution systems. Through voltage reduction, it is possible to reduce system losses and to improve the overall efficiency of electrical systems that contain various types of electrical loads [1]. The main factors that contribute to energy losses in electrical systems include the resistance of the electrical components, the reactive power flow, and the voltage level of the electrical system. By reducing the voltage level of an electrical system, the reactive power flow can be minimized, which, in turn, reduces energy losses and improves system efficiency. In addition to a reduction in energy losses, CVR also reduces CO_2 emissions. This is crucial, as, the time that city dwellers spend in their living space has increased since the COVID-19 pandemic, and the daily global CO_2 emissions from fossil fuels in the residential sector have also increased by 2.8% [2].

CVR works by reducing the voltage supplied to electrical loads by a small amount, typically between 1% and 6%, according to the Tenaga Nasional Berhad (TNB) Standard. Voltages at consumer premises should be kept at 1 (pu) volts within the range of -6% to +10% [3]. The reduced voltage results in lower power consumption, since most electrical loads are designed to operate within a certain voltage range. In addition to reducing energy consumption, CVR can also help to improve the quality of power supplied to customers, to reduce line losses, and to extend the life of electrical equipment. In addition, CVR requires careful planning and coordination, as voltage reductions can affect the performances of certain types of electrical loads, such as motors and electronic equipment. Different (bus) systems have undergone comparative analysis considering various electrical load model types. The benefits of CVR were found to be maximum on constant impedance loads; however, on constant power loads, more current was drawn and the impact of CVR was minimal [4].

Residential appliances have a significant impact on energy consumption in households [5–7]. Various types of appliances have different levels of energy consumption and they contribute differently to overall energy consumption. For example, heating and cooling appliances such as water heaters, irons, and refrigerators typically consume the most energy, followed by lighting. The impact of appliances on energy consumption can vary depending on several factors, which include the type and efficiency of an appliance, the frequency and duration of use, and the behaviors of the users. The impact of residential appliances on energy consumption is an important topic of discussion, as, households and policymakers seek to reduce energy usage.

This paper is organized as follows: In Section 2, we provide a comprehensive summary of the literature review; in Section 3, we describe the methodology used in the study, including data collection for the residential appliances and substations; in Section 4, we discuss the results of the analysis performed on CVR and energy savings; and in Section 5, we state the conclusions that have been derived from this study.

2. Literature Review

Energy conservation efforts in Malaysia have been ongoing, with various initiatives and programs aimed at reducing energy losses in the country's electrical transmission and distribution systems. In addition, Malaysian Utilities have also implemented various programs to promote the use of energy-efficient appliances through their Smart Utility Program.

CVR is an established method that has been implemented by various countries to save electricity. It is a simple technique that involves reducing voltage supply within an allowed range in order to reduce consumption by consumers. The CVR implementation is the goal of most electrical appliance providers [8]. Several CVR implementation strategies have been discussed in studies by [4,9,10], and studies on the advantages of CVR in terms of energy savings and loss reductions have been conducted by [11–13]. Peak load shaving that is achieved through implementing CVR can benefit utilities; the reduction in endpoint voltages (through CVR) reduces the power consumption of resistive loads (incandescent lights) and constant current loads which benefits end consumers. There are also constant power loads (large motor loads) that do not maximize the benefits from CVR, as the voltage reduction does not affect the power consumed by these loads. Many countries, such as the United Kingdom [14], Korea [15], and the United States of America [16] have implemented CVR with constructive results; however, CVR has not been implemented throughout the countries. It has been executed within a small vicinity on a few feeders. It helps to reduce the strain on the network during peak load periods by managing load profiles, and therefore, can defer network reinforcement.

Electricity distribution utilities have two ways to control high demand. The first approach is to coordinate supply with demand; however, this may not always be practical. The second best option, which might be a more practical one, is to reduce the peak load [17–19]. It is possible to achieve this reduction by lowering the voltage level on the distribution feeder line. One of the most efficient ways to lower energy losses, to reduce peak demand, and to increase energy efficiency is through CVR [20]. CVR is based on the concept that voltage-dependent loads will consume less power if the voltage is reduced while remaining within a reasonable range from −6% to +10% [18].

Since CVR efficiency depends on the types of devices connected, we can categorize electrical devices into four load groups as stated below [21,22]:

(a) constant resistance loads without a feedback loop, which is also known as constant resistance loads that reduce the energy consumption for both the loads and the lines;
(b) constant resistance loads with a feedback loop, which is also known as constant energy loads with a constant energy consumption (for timescales that are longer than the duration of the feedback loop);
(c) constant power loads that increase the energy consumption, because of increasing line losses due to an increase in current draw based on a reduction in voltage;
(d) constant current loads that reduce the energy consumption for the loads.

A crucial finding that was published in [23] indicated that motor loads could also generate energy savings despite a low CVR factor. Based on simulation results obtained for a residential feeder by [19], CVR factors of 1.63 and 1.55 are possible in summer and winter, respectively. CVR was proven to be productive by reducing network peak demand; active power savings of 6 kW and 9 kW were obtained for the summer and winter cases, respectively. An analysis of CVR was also conducted by [24] to study the impact of CVR on the 44 bus Finnish DN in the overload condition. Based on the results, it was concluded that CVR alone led to a 38.45% cost reduction during peak hours, whereas CVR considering dynamic thermal rating (DTR) reduced cost by 89.2% for the same peak duration. Energy saving efforts have been conducted in Malaysia at the university level [24] and the building level [25]. However, these studies did not perform CVR as an option. Regarding [25], the energy savings methods that were used included replacing existing lights with LED lights and performing an energy audit on the wastage of energy consumed by the building. In a study by [24], the proposed conservation methods included load balancing and scheduling that involved planning classes at various times of the day. This also subsequently addressed the peak demand issue faced by the university. The other proposed method was to install solar photovoltaic to sustain the power demand of the university. Voltage reduction must be ensured in order to not affect the last load in a distribution network in terms of a low voltage situation [26]. In other studies by [27,28], CVR initiatives reported kWh energy savings of 3–4% at the distribution network level, and in order to examine the effects of multiple scenarios with large penetrations of PV and EV charging was simulated with the proposed CVR strategy. Based on [28], an analysis of residential appliances was performed and the thermal factor was incorporated into the calculation, as the analysis was performed during winter and the developed model captured, in detail, the thermal electrical behavior of each individual household load. This was used to assess CVR in a residential distribution network. However, there have not been many analyses performed of the impact of specific appliances on energy savings in a residential setting, which is the aim of this study.

In terms of additional comparisons, one potential area of exploration is the effectiveness of different CVR techniques and technologies in different contexts. For example, some techniques may be more effective in urban areas with high population density and complex electrical grids, while other techniques may be more effective in rural areas with simpler grids and lower demand. Additionally, there may be variations in the cost-effectiveness of different techniques and technologies, depending on local energy pricing, regulatory frameworks, and consumer behaviors. In terms of suggestions for improving the study of CVR, one potential area of exploration is the development of more accurate and detailed models of residential energy consumption. In multiple studies, researchers have typically modeled the response of residential loads to different levels of voltage reduction using computer simulations. In this study, however, we attempt to reduce assumptions made by performing measurements on multiple appliances with direct voltage reduction and studying the impact on the power consumed. Many consumers may be unaware of the potential benefits of CVR, or may be resistant to changing their energy consumption behaviors. Therefore, the simplest way to broadcast the benefits of CVR would be to emphasize the possible cost savings. This can be done by implementing CVR for every 1% reduction in voltage for a Malaysian scenario.

Despite numerous efforts to improve CVR, there are still limitations in studies on CVR, because some studies have only considered a limited range of loads, such as residential or commercial loads, which do not reflect the diverse range of loads that exist in modern power systems. The effectiveness of CVR depends on the specific characteristics of the power systems, such as the impedance of the distribution network, the types of loads connected, and the distribution of loads. As a result, the findings of individual studies may not be applicable to all power systems at other settings nor the temperatures of other countries.

The main contribution of this study is that it provides very detailed measured data that are used to analyze and generate energy savings for very specific residential appliances for every 1% voltage drop. A load model is developed for the common residential appliances in Malaysia, and then a voltage reduction study is applied to the appliances in a residence. Implementation of voltage reduction in the Malaysian distribution network is also analyzed. In addition, the results provide insight for performing voltage reduction at an electric vehicle (EV) charging station in Malaysia. This study should serve as a foundation for all practicing utilities engineers to address the issue of CVR in Malaysia, since this is the first attempt to generate CVR factors for residential, commercial, and industrial networks in Malaysia. CVR factors generated for individual appliances and how the cost savings can be appreciated are also included in this paper.

3. Methodology

3.1. Data Collection and Experimental Scenario

In this paper, we focus on a Malaysian residential scenario. The appliances that were used to collect the data were basic appliances that exist in most residential households with regards to all residential class types. Heating and cooling [29] are the largest components of residential electricity consumption. The data for analysis were obtained from measurements conducted at the laboratory. Studies by [30,31] were used as references to determine the crucial appliances for this analysis, which were detailed studies that were conducted in Malaysia, with surveys by residential customers to perform an energy study with respect to occupants' behaviors, appliance characteristics, building characteristics, and socio-demographics. There were 16 common household appliances used for the CVR measurements. The load profile was obtained by changing the input voltage from 215 V to 250 V. The voltage supply was varied every 5 V, and a voltage stabilizer was used to maintain the voltage. A Fluke 1730 Power Quality recorder was used to measure power changes every second. The appliances that were tested included an air-conditioner (new), an air-conditioner (old), a CFL light, a fluorescent light, an incandescent light, an LED light, a fan, a laptop (charging), a personal computer, a phone, a tablet, a television (LED), a microwave, a rice cooker, a shower heater, and a refrigerator [30]. Heating and cooling are important for the Malaysian climate because of the high temperatures and humidity levels that are experienced throughout the year. Malaysia has a tropical climate, with an average temperature ranging from 23 °C to 32 °C, and high levels of humidity. Therefore, heating and cooling appliances are important for maintaining indoor comfort and air quality in Malaysian homes and buildings. Air conditioning is a crucial appliance for many people in Malaysia to help combat the high temperatures and humidity levels. However, the energy consumption of cooling appliances is significant, leading to high electricity bills and contributing to greenhouse gas emissions. Therefore, efficient and sustainable heating and cooling solutions, such as energy-efficient appliances and CVR [32] can help to reduce energy consumption and costs, while maintaining a comfortable indoor environment. Figure 1 displays the percentage of heating and cooling appliances that contribute to the total energy consumption of a residence for this analysis. The impact of CVR on residential heating and cooling appliances is analyzed in this study and will be discussed in the next section.

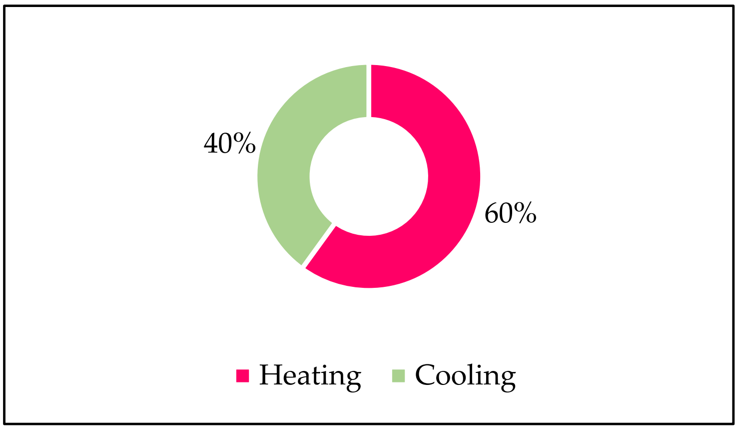


Figure 1. Contribution of heating and cooling appliances to the total energy.

Customers are present in their homes during the weekend and make extensive use of electrical appliances, resulting in significant electricity consumption. The data demonstrate that peak periods are on weekdays from 4 pm to 11 pm and at various times during the weekends. The measured daily energy consumption for weekdays was 21.9 kWh/day, and during the weekend, it was 25.8 kWh/day. A similar analysis had been performed by [33] which was used as a reference for this study to design the household load consumption.

Site measurements were also performed to study the feasibility of implementing CVR at the substation level. Several substations (7 substations) were selected in Melaka, a state in Malaysia, to perform this CVR study which included 100% residential, 100% commercial, 100% industrial, and mixed load types of feeders. Voltage reductions of 1% and 2% were used to compute the CVR factors for this study at the residential, commercial, and industrial substations [34]. Then, with the reduction in voltage, the power was measured to observe the changes to account for the CVR factor value. Figure 2 shows a simplified single line diagram for a measured residential substation.

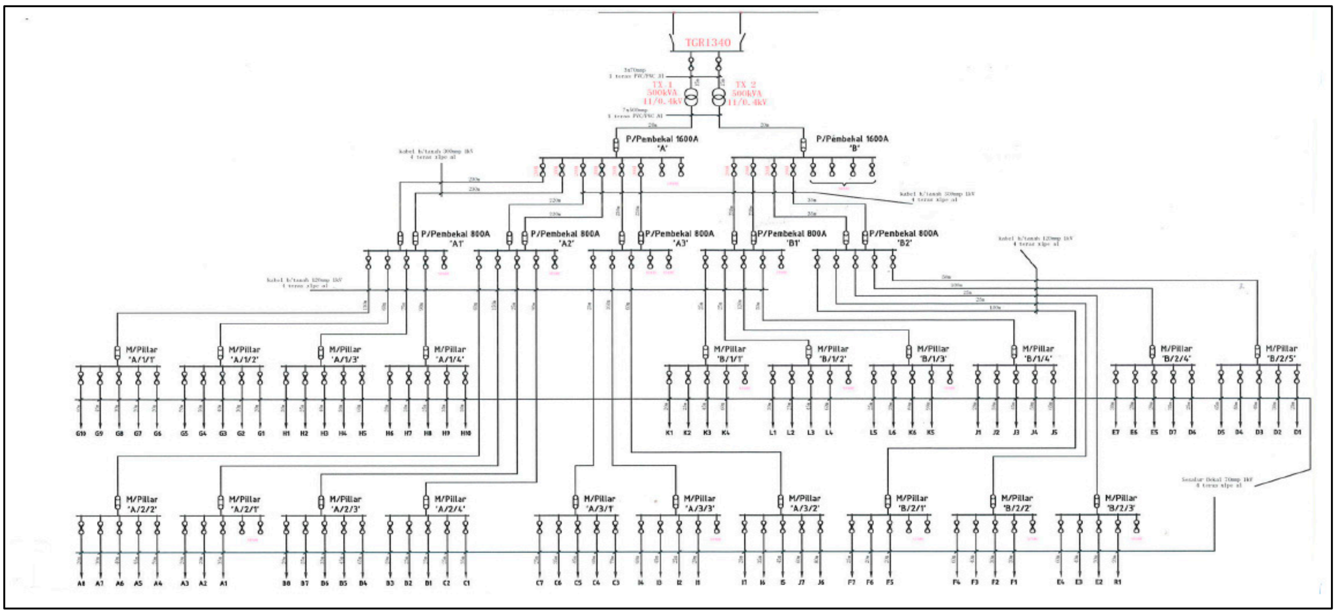


Figure 2. Single line diagram for a residential substation.

3.2. ZIP Load Model Analysis

There are three different methods for load modeling, which are, measurement-based, disturbance-based, and component-based models. This study implemented the measurement-based model which is a common load modeling technique that gathers load data from data acquisition equipment to deduce the load characteristics. The polynomial load model represents a mix of the three types of load characteristics known as constant power, constant current, and constant impedance load. This model is commonly known as the ZIP model. Equation (1) shows Zp, Ip, and Pp, the model parameters which represent the percentages of constant impedance load, constant current load, and constant power load, respectively. Equation (2) shows the constrains of the 100% load types which are equal to 1 [35]. All loads have some variability with different voltage levels based on the composition of constant impedance (Z), constant current (I), and constant power (P) percentages. In this study, the ZIP load model shows the voltage dependency of each load. P is the active power; V is the operating voltage; P_0 and V_0 are the rated active power and the rated voltage, respectively. The model is solved by using the sequential least squares programming optimizer in Python.

$$P_{ZIP} = P_0[Z_P\left(\frac{V}{V_0}\right)^2 + I_P\left(\frac{V}{V_0}\right) + P_P] \quad (1)$$

$$Z_P + I_P + P_P = 1 \quad (2)$$

ZIP models can also be used to gain insights into the electricity consumption behaviors of individual households and to identify which appliances are contributing the most to electricity usage. This information can be used to develop targeted energy conservation programs that are tailored to the specific needs of each household, and to encourage the adoption of more energy-efficient appliances and behaviors.

3.3. CVR Analysis

Figure 3 displays the flow chart that was used to generate the CVR factors by calculating the difference between the percentage power change divided by the percentage change in voltage.

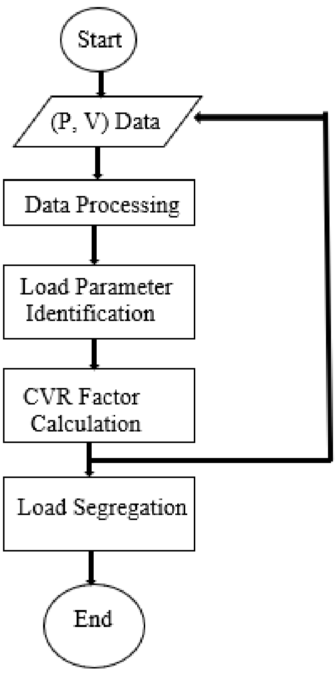


Figure 3. Flow chart of CVR calculation.

The CVR values are calculated using Equations (3) and (4):

$$\text{Active Power CVR Factor} = CVR_f = \frac{\%\ \Delta\ P}{\%\ \Delta\ V} \quad (3)$$

$$\text{Apparent Power CVR Factor} = CVR_f = \frac{\%\ \Delta\ S}{\%\ \Delta\ V} \quad (4)$$

The characteristics of the appliances' four elements mentioned in Section 2 and how they respond to voltage reduction are summarized in Table 1. Most of the feeders' load compositions in a substation are unknown and vary with time, where an accurate estimate of the energy savings made by CVR is difficult. Among the residential, commercial, and industrial sectors, there are differences in load composition and how they are impacted by voltage reductions is very subjective. Hence, for this study, the energy and cost savings are focused on the residential load based on specific appliances that are measured at the lab. For this study, we use the bottom-up load method that reduces assumptions in the results. Table 1 is used as a reference to determine the type of load based on the CVR factor calculated. The ZIP load model values are cross-checked with the CVR factor that is calculated.

Table 1. Load behavior with voltage reduction [34].

Element	Basic Equations and Relationships	P: Power (kW) Q: Reactive Power (kVAR)		Volatge Sensitivity	CVAR Factor (CVR_f)	Comments
Constant impedance($\bar{Z}$) $\bar{Z} = R \pm jX$	$\bar{V} = \bar{I} \cdot \bar{Z}$ $\bar{S} = \bar{V} \cdot \vec{I} = P \pm jQ = \bar{V}^2 / \bar{Z}$ $Power factor = cos\theta = tan^{-1}(Q/P)$	$P = I^2R$	$\pm Q = I^2X$	$P \alpha V^2; Q \alpha V^2$ Lower voltage results proportionately lower current	$CVR_{f(kW)} = 2.0$ $CVR_{f(kVAR)} = 2.0$ $CVR_{f(kWh)} = 2.0$	Constant resistance "R" is a special application, when $X = 0$; $CVR_{f(kVAR)} = 0$
Constant current($\bar{I}$)	$\bar{S} = \bar{V} \cdot \vec{I} = P \pm jQ$	$P = VI\cos\theta$	$\pm Q = VI\sin\theta$	$P \alpha V^1$ $Q \alpha V^1$	$CVR_{f(kW)} = 1.0$ $CVR_{f(kVAR)} = 1.0$ $CVR_{f(kWh)} = 1.0$	
Constant power($\bar{S}$)	$\bar{S} = \bar{V} \cdot \vec{I} = P \pm jQ$	$P = VI\cos\theta$	$\pm Q = VI\sin\theta$	$P = V^o; Q = V^0$ Lower voltage increases current, product remains same	$CVR_{f(kW)} = 0.0$ $CVR_{f(kVAR)} = 0.0$ $CVR_{f(kWh)} = 0.0$	Constant resistance "P" is a special application, when Q = 0
Constant energy: "resistive" element (E)	$V = I \cdot R$ $E = P \cdot \Delta t$	$P = I^2R = V^2/R$		One	$CVR_{f(kWh)} = 0.0$	$\Delta t : time$

For the measurement and verification of CVR, there are four methods that can be used which include: comparison method, regression-based method, synthesis method, and simulation-based methods, as explained in detail in [32]. To achieve the aim of this study, the comparison method is used for the distribution network and CVR analysis, and Equation (5) is used to calculate the energy for the residential appliances ($P_i(V)$ represents the power consumption of appliance i at voltage V and Ti is the load share in terms of duration of use of each appliance which is obtained from the survey [32].

$$E(V) = \sum_i P_i(V) T_i \quad (5)$$

Figure 4 shows a sample measurement result for the voltage and real power of a fan. The graphical results show that with every 5 V reduction, there is a reduction in the power consumed. This implies that the CVR factor will be high, where a decrease in voltage will reduce the energy consumed by the appliance. For the sample of a constant power appliance (air conditioning), with a reduction in voltage, the power remains constant. This will give a low CVR factor which is closer to 0. Inverter-based appliances are also constant power loads as the power drawn remains constant to avoid a sudden spike in energy. The appliance functions based on the load it carries and the power is drawn accordingly and is not voltage dependent.

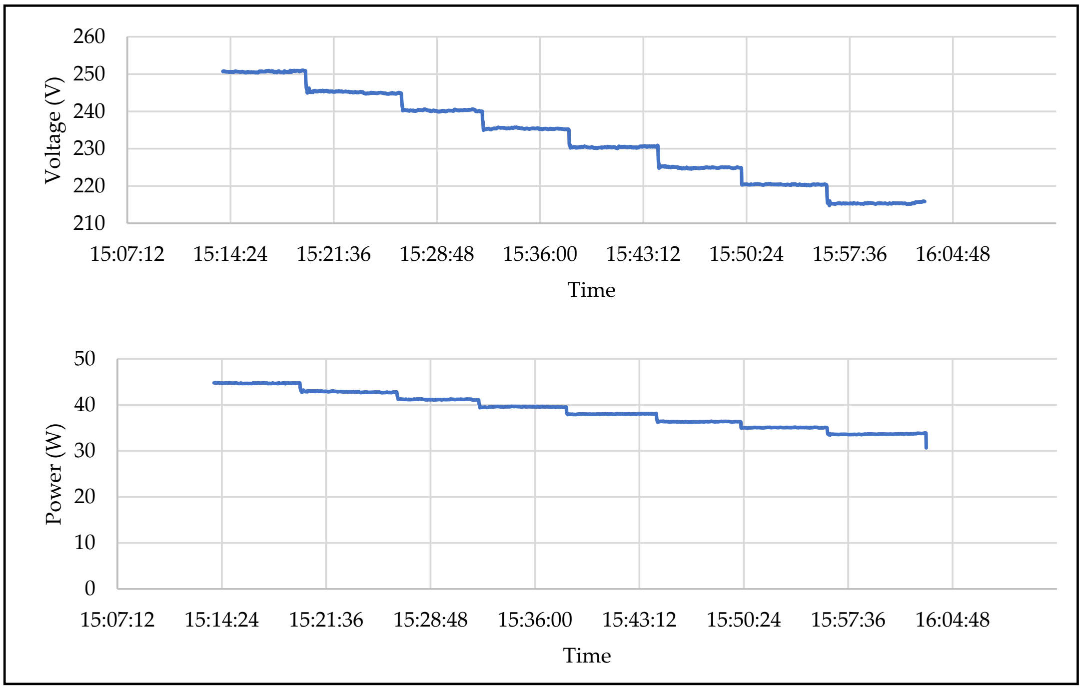


Figure 4. Measured data for a fan.

A sample graphical load profile of a 100% residential load is presented in Figure 5. In this study, the voltage drop is performed for a short duration and the CVR is calculated with voltage reductions of 1% and 2% [36]. The data are all combined and averaged to gain the CVR factor for a specific substation.

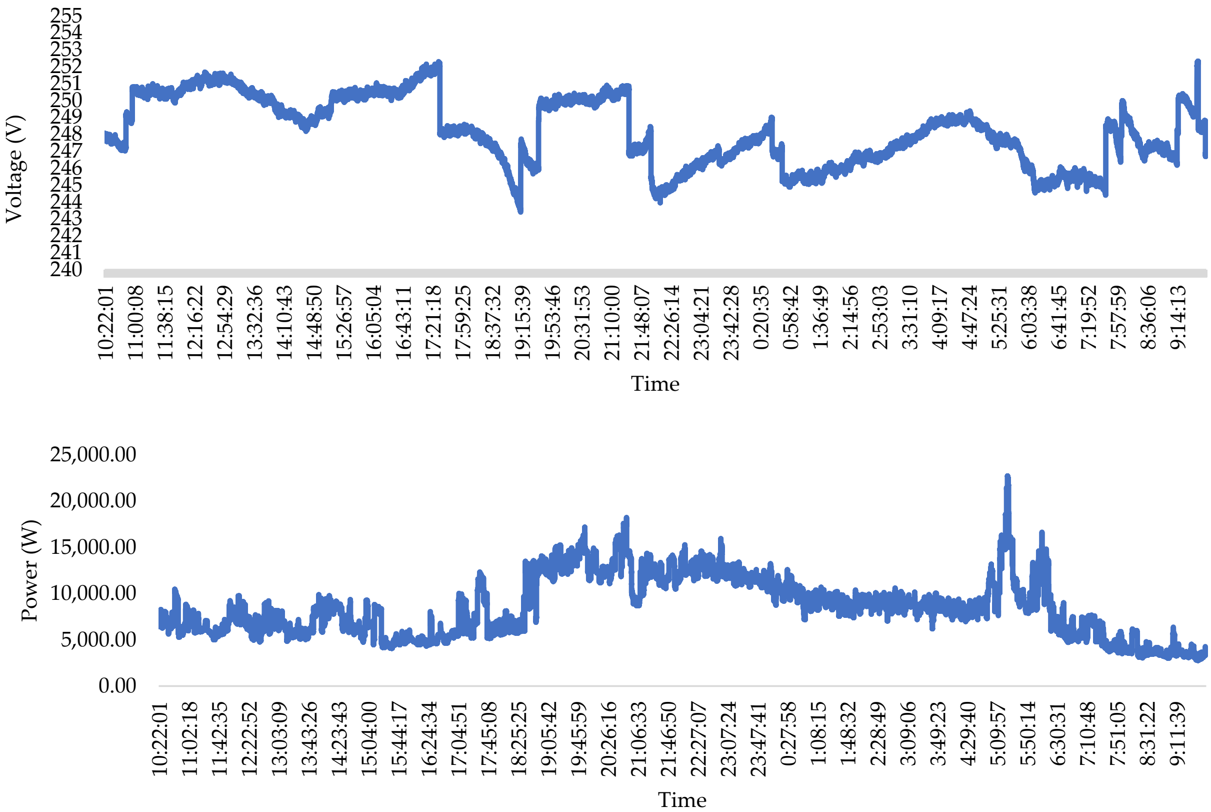
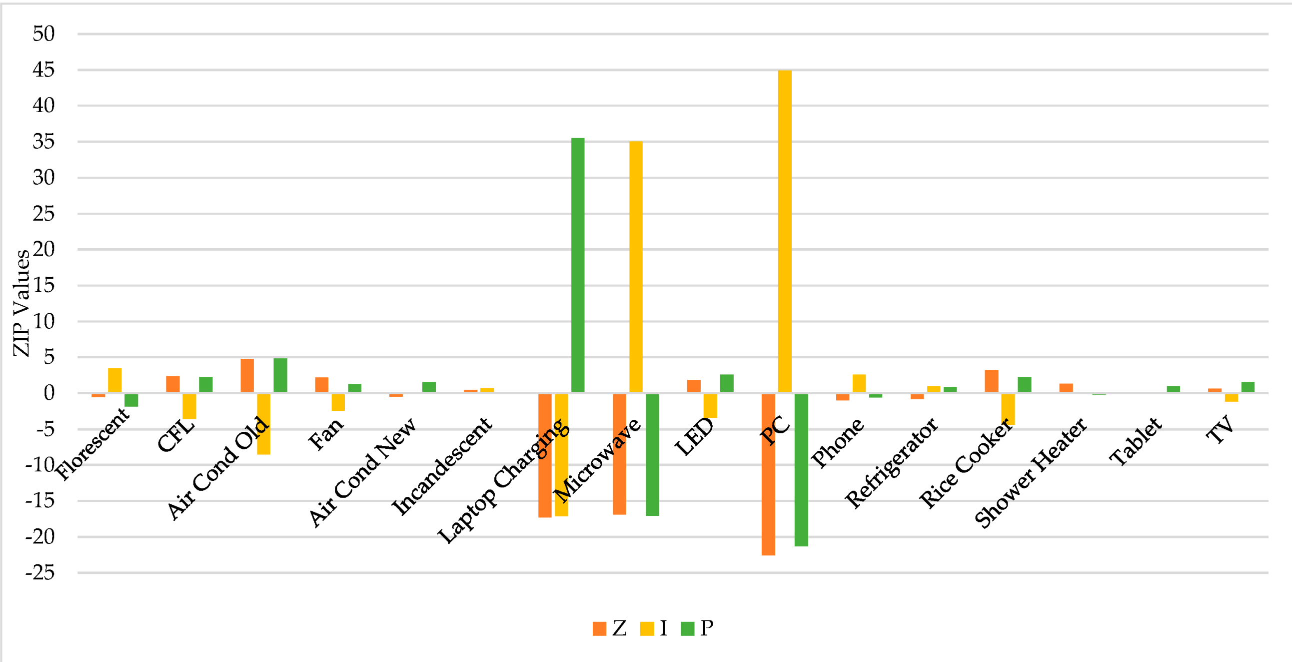


Figure 5. The 24 h residential graphical results from feeder X.

4. Results and Discussion

4.1. ZIP Load Model

Figure 6 shows the results obtained from the ZIP load model analysis. Each appliance consists of a combination of constant impedance load, constant current load, and constant power load. The ZIP model provides an understanding of the behavior of a load under different operating conditions.



	Flo rescent	CFL	Air Cond Old	Fan	Air Cond New	Incan descent	Laptop Charging	Micro wave	LED	PC	Phone	Refrig erator	Rice Cooker	Shower Heater	Tablet	TV
Z	−0.5533	2.3221	4.7060	2.1595	−0.4865	0.4250	−17.3037	−16.918	1.7928	−22.5913	−0.9991	−0.8228	3.1621	1.2828	0.0220	0.6086
I	3.3989	−3.5416	−8.4912	−2.4021	−0.0251	0.6762	−17.1554	34.998	−3.3690	44.9171	2.5791	0.9562	−4.3583	−0.0987	0.0509	−1.1396
P	−1.8455	2.2194	4.7852	1.2426	1.5116	−0.1013	35.4592	−17.080	2.5761	−21.3257	−0.5799	0.8666	2.1962	−0.1840	0.9269	1.5309

Figure 6. ZIP values for various appliances.

4.2. CVR for Residential Appliances

The CVR factors for all 16 appliances that were measured and calculated are displayed in Figure 7. The constant resistance loads generate the highest CVR factors followed by constant current load and constant power load with lower CVR factors. The behaviors of loads based on the numbers obtained can be determined from Table 1. The values obtained validate the residential appliances that can be related to the ZIP load model generated. Hence, the higher the CVR factor, the lower the power consumed by the appliance, which contributes to higher energy savings for a home.

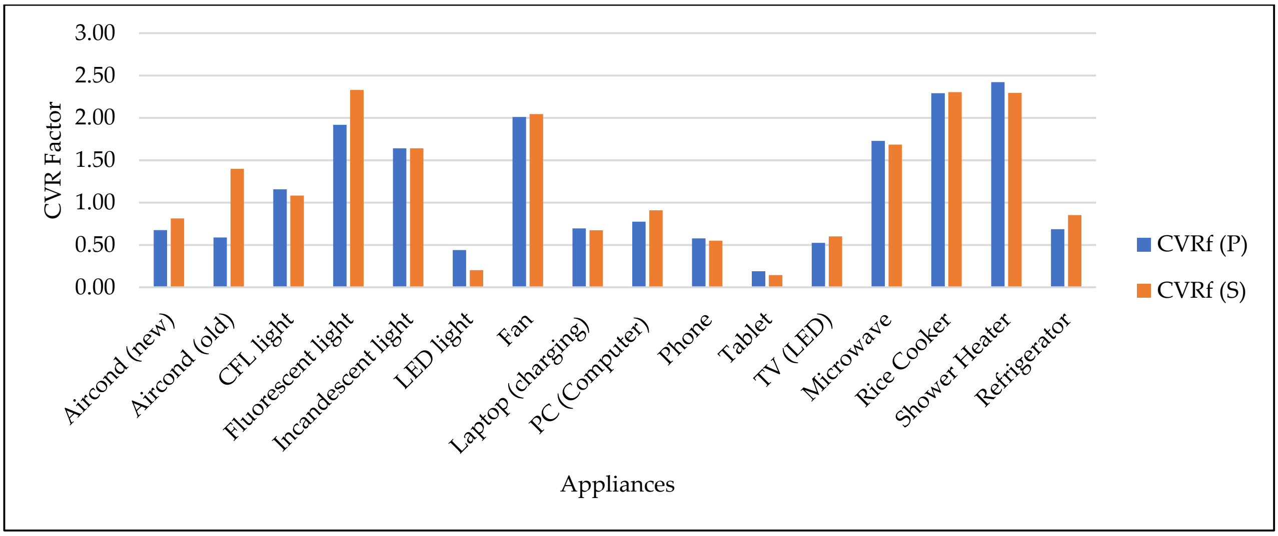


Figure 7. CVR factors for all the measured appliances.

The CVR factor for each load type is used as a reference to calculate the possible cost savings for a residential customer. For the household appliances, the total billing was calculated using the TNB billing calculator which is accurate and constantly updated by the utility. The CVR factor obtained verifies that some domestic appliances can benefit from voltage reduction. The base household voltage was set at 235 V. The cost was calculated for every 1–6% voltage reduction. Applying the CVR factor generated at the laboratory, a model of a residence is replicated with reference to a study performed by Universiti Kebangsaan Malaysia [30] for the duration of use of the appliances which is obtained through a thorough survey conducted. The load model is used to generate the monthly energy savings in kWh. The total energy consumption for an average residential load is approximately 636.55 kWh per month (20 weekdays and 8 weekends) without CVR. This is equivalent to RM 240.18. Equation (6) is derived and is used to compute the monthly energy consumption, where Hw is the duration of use for each appliance during the weekday, He is the duration of use for the appliance during the weekend, P is the power consumed, $Ntot$ is the quantity of each appliance, dw is the number of weekdays (20 days), and de is the number of weekends (8 days for a month).

$$Total\ monthly\ consumption(kWh) = \sum_{n=1}^{n=appliance} [((Hw \times P)(Ntot)(dw)) + ((He \times P)(Ntot)(de))] \quad (6)$$

Table 2 shows the energy savings, for the same residential load upon performing a 2% voltage reduction. The 2% voltage reduction (new voltage is 230.30 V) leads to a total energy conservation of 17.01 kWh per home with a cost savings of RM 9.48 per month.

The cutoff voltage drop is 6%; hence, for calculation purposes, the amount of monthly savings is computed for every 1%. The savings are very significant and customers can benefit from CVR. Customers as well as utilities can further investigate the generation of cost savings with a reduction in voltage supply. From this study, for a 1% voltage reduction, the energy savings is 1.3% and the total cost savings is RM 4.74 per month. For a 2% voltage reduction at 230.30 V, the energy consumption is 619.52 kWh, the energy savings is 2.7%, and the cost savings is RM 9.48 per month. From Figure 8, savings can be realized, i.e., for every increase in voltage reduction there is a linear increase in energy savings as well as cost savings.

Table 2. Load model of a residential load with 2% voltage reduction.

No	Appliance	CVR Factor (P)—Baseline	Measured Power (kW)—Baseline	New Power (kW)—% Voltage Drop	Operation Time—Weekday (Hour)	Operation Time—Weekend (Hour)	No of Appliances	Weekday kWh—Daily (kWh)	Weekend kWh—Daily (kWh)
1	Aircond (new)	0.68	1.06	1.05	5.05	8.00	1	5.28	8.37
2	Aircond (old)	0.59	2.05	2.03	5.05	8.00	0	0.00	0.00
3	CFL light	1.16	0.01	0.01	10.00	13.00	5	0.54	0.70
4	Fluorescent light	1.92	0.03	0.03	10.00	13.00	5	1.35	1.75
5	Incandescent light	1.64	0.10	0.10	10.00	13.00	5	4.79	6.22
6	LED light	0.44	0.01	0.01	10.00	13.00	5	0.45	0.58
7	Fan	2.01	0.04	0.03	11.55	18.00	3	1.20	1.87
8	Laptop (charging)	0.70	0.04	0.04	2.87	3.82	1	0.11	0.15
9	PC	0.77	0.12	0.11	1.97	1.82	1	0.22	0.21
10	Phone	0.58	0.01	0.01	0.00	0.00	1	0.00	0.00
11	Tablet	0.19	0.01	0.01	0.00	0.00	1	0.00	0.00
12	TV (new)	0.53	0.08	0.07	5.70	8.15	1	0.42	0.60
13	Microwave	1.73	1.30	1.26	0.20	0.19	1	0.25	0.23
14	Rice cooker	2.29	0.60	0.57	0.82	0.83	1	0.47	0.48
15	Shower heater	2.42	2.54	2.41	0.16	1.50	2	0.77	7.24
16	Refrigerator	0.69	0.11	0.11	24.00	24.00	1	2.70	2.70
							Total kWh	18.54	31.09

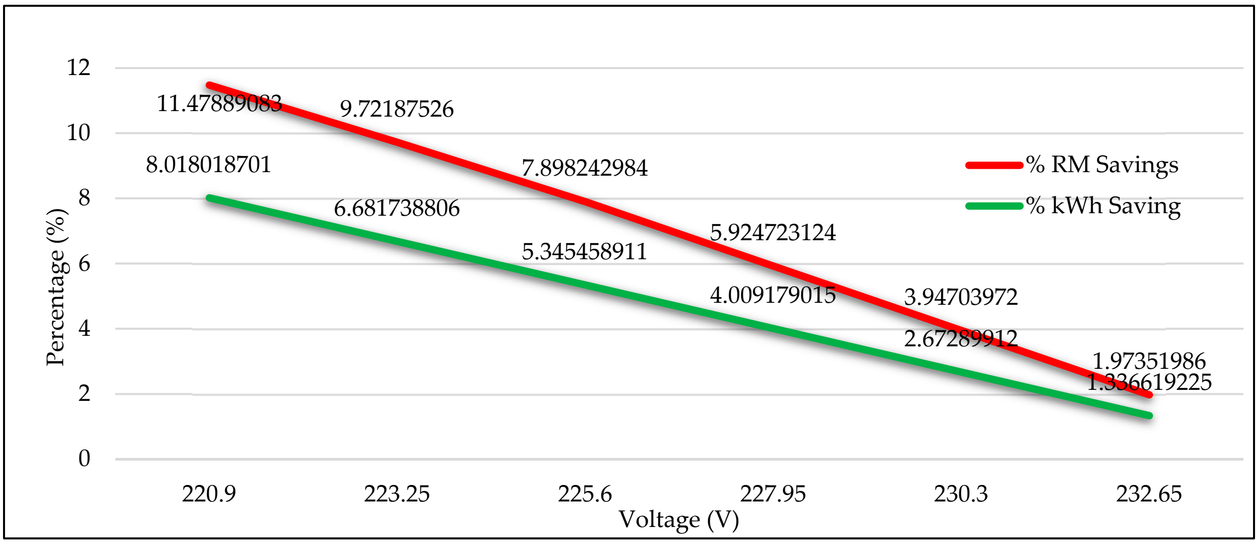


Figure 8. Savings with voltage reduction.

In addition to the savings calculated above, for every 5 V voltage drop that was measured at the lab, the energy savings was calculated, using the new power that was obtained from the measured data. The power was measured at 250 V, 245 V, 240 V, 235 V, 230 V, 225 V, 220 V, and 215 V, and its corresponding monthly consumption is displayed in Table 3. It can be observed that the monthly consumption is very similar to the calculation done using the CVR factor as displayed in Table 2, where the total monthly consumption with a 2% voltage reduction at 619.54 kWh is RM 230.70. Based on the detailed analysis, there is a clear indication that with an increase in voltage there will be an increase in energy consumption.

Table 3. Monthly energy consumption at every 5 V power measured.

Voltage	Monthly Energy Consumption (kWh)	Monthly Bill (RM)	Monthly Bill (Euro)	Savings from Base (235 V) in %
250	697.114	273.94	56.18	−14.01340159
245	678.03	263.3	54.00	−9.585050152
240	659.79	253.14	51.92	−5.356473967
235	636.704	240.27	49.28	0
230	619.84	230.86	47.35	3.916427353
225	609.608	225.16	46.18	6.28875848
220	588.156	213.93	43.88	10.962667
215	568.979	204.41	41.92	14.92487618

4.3. CVR for a Residential Load Network

Despite having substations with mixed loads, the substations with 100% residential, 100% commercial, and 100% industrial loads were used to compute the CVR factors for direct comparison. Based on the CVR factors calculated, residential and commercial substations can benefit from voltage reduction, thus, leading to energy savings with a reduction in the total power consumed. For the substation data, the CVR is calculated separately over three sessions a day, which are 8 a.m.–5 p.m., 5 p.m.–10 p.m., and 10 p.m.–8 a.m. This segregation is to ensure that industrial loads that are actively used during the night are also accounted for, to compute the CVR factor. Cost savings at the substation level are not performed in this study due to the various connected appliances by commercial and industrial customers and numerous combinations of loads in a network. This can be explored in a future study. Figure 9 displays the comparison between the CVR factors for each type of substation loading [mixed load (residential 70% commercial 30%) and 100% types of loads].

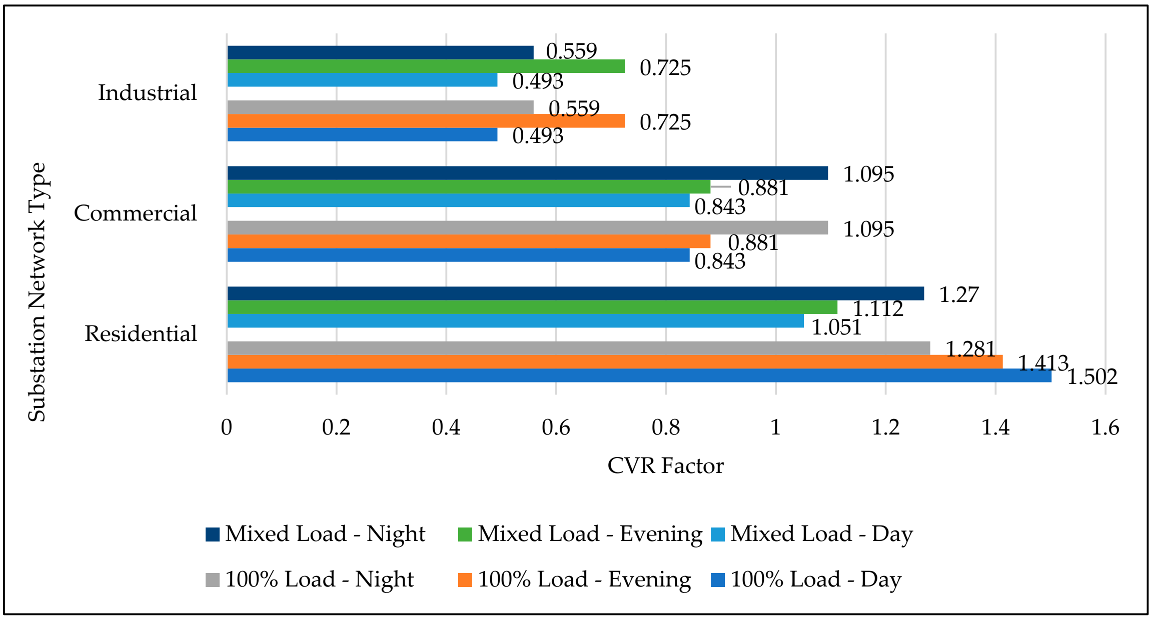


Figure 9. Power CVR factor summary of residential, commercial, and industrial loads.

The results obtained for the residential loads are consistent with the substation CVR factor for 100% residential loads with reference to Table 1. Nonetheless, certainly the loads in every residence differ and cannot be specifically categorized as a majority with constant current type. However, based on the CVR factor that is calculated, it can be established that the residential substation will benefit from voltage reduction. The commercial data indicate that there will be some energy savings from the generated CVR factor and the least amount of energy savings would be from the industrial substation. The industrial load displays an increase in CVR factor from 5 pm to 10 pm. This could be due to the switching off of heavy production machines and change in production shift. Large machines are frequently categorized as constant power loads because the reduction in voltage will increase the current to maintain the inertia of the motor. The CVR factor for real power is also compared to the CVR factor of the apparent power and the results are very coherent.

Table 4 summarizes the published results of CVR factors of each customer class. The table shows a relative comparison of the CVR factors that are calculated and measured for the Malaysian distribution network and those of other utilities around the world.

Table 4. Comparison of CVR factors of different customer classes.

References	Residential	Commercial	Industrial
CPUC [32]	1.14	0.26	NA
SCE [37]	1.30	1.20	0.50
Snohomish [32]	0.33–0.68	0.89–1.10	NA
HQ [13]	0.06–0.67	0.80–0.97	0.1
NEEA [38]	0.63	0.37	NA
Detroit [32]	0.96–1.11	0.75–0.80	0.5–0.83
Malaysia	1.399	0.94	0.592

Moreover, to further corroborate these results, the statistics collected from the residential substation and the household loads were compared. The graph in Figure 10 shows a similarity in the pattern of power consumed over 24 hours, based on the appliance usage duration. The total energy is derived based on the number of appliances switched on every 30 min, multiplied by the power consumed by each appliance. The appliances that were measured at the lab were determined based on the probability of availability at every residence.

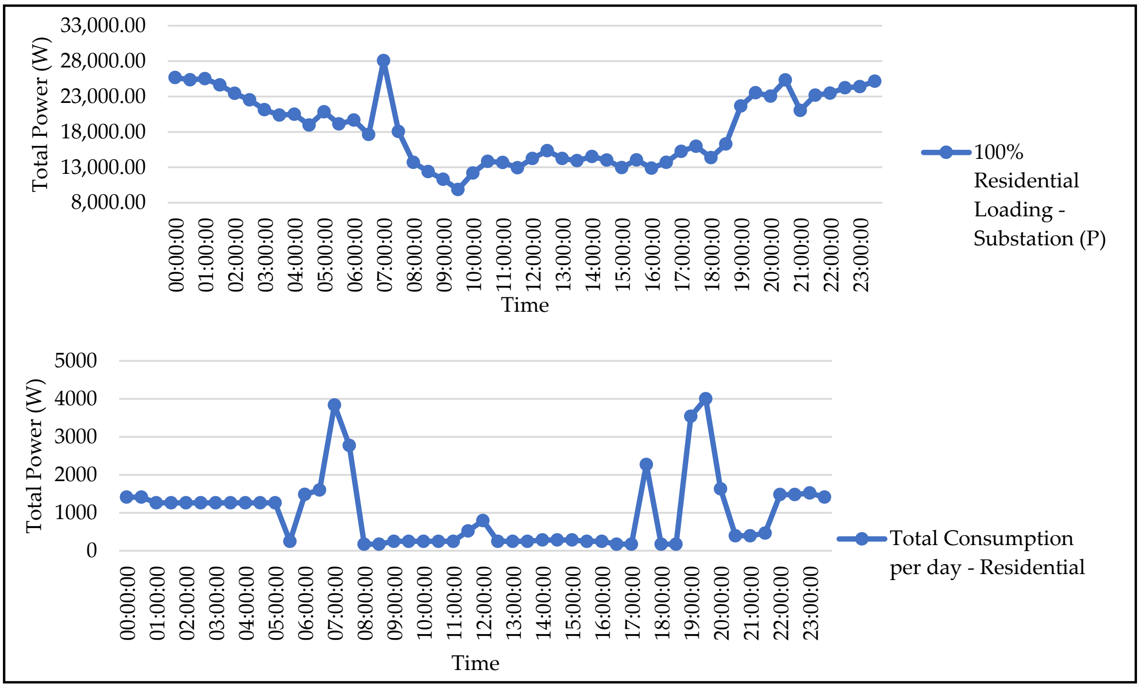


Figure 10. Substation and residence power consumption pattern.

4.4. CVR for an EV Charging Station

With the growing market for electric vehicles (EVs), the CVR application was also analyzed for an EV charger. There are two types of charging points at Tenaga Nasional Berhad Research (TNBR) namely the Chademo and a slow charger. The chargers are both connected to the solar photovoltaic panels and charge at 400 V direct current (DC). CVR for direct current cannot be measured unless the output voltage is varied. However, for this Japanese charging set, the user is not able to manipulate the output voltage. Figure 11 shows the schematic block diagram of the EV charger at TNBR. The only option to perform a CVR measurement is to disconnect the solar battery inverters, bypass the battery storage, and directly connect to the grid supply for the charging purpose, but based on the schematic, the charging port will still be in DC. The results from this charging method were obtained and the graphical results for fast charging are shown in Figure 12 [3].

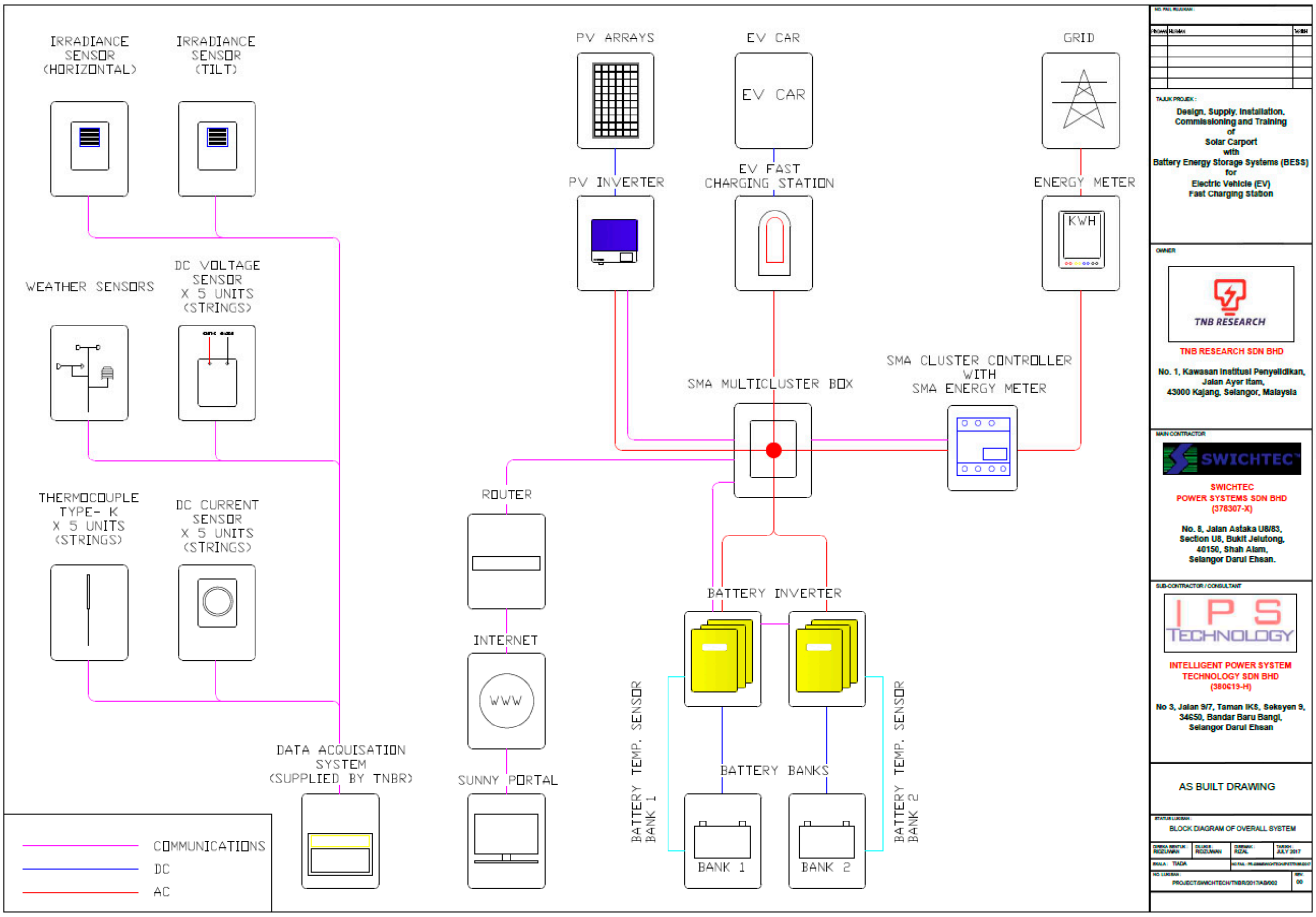


Figure 11. Schematic block diagram of the EV (Courtesy of the TNBR Environment Group).

From the results above, it can be realized that EV charging is constant power with the existence of inverters and converters in the system. Therefore, it can be concluded that EV charging will not benefit from CVR and it is not viable to perform a CVR study for this system. Further analysis could be performed if the manufacturer allows the system to be manipulated to vary the output of the system. Nevertheless, there are a few studies that have been performed to analyze the impact of CVR on EV charging at the residence level, and the results are positive with energy savings.

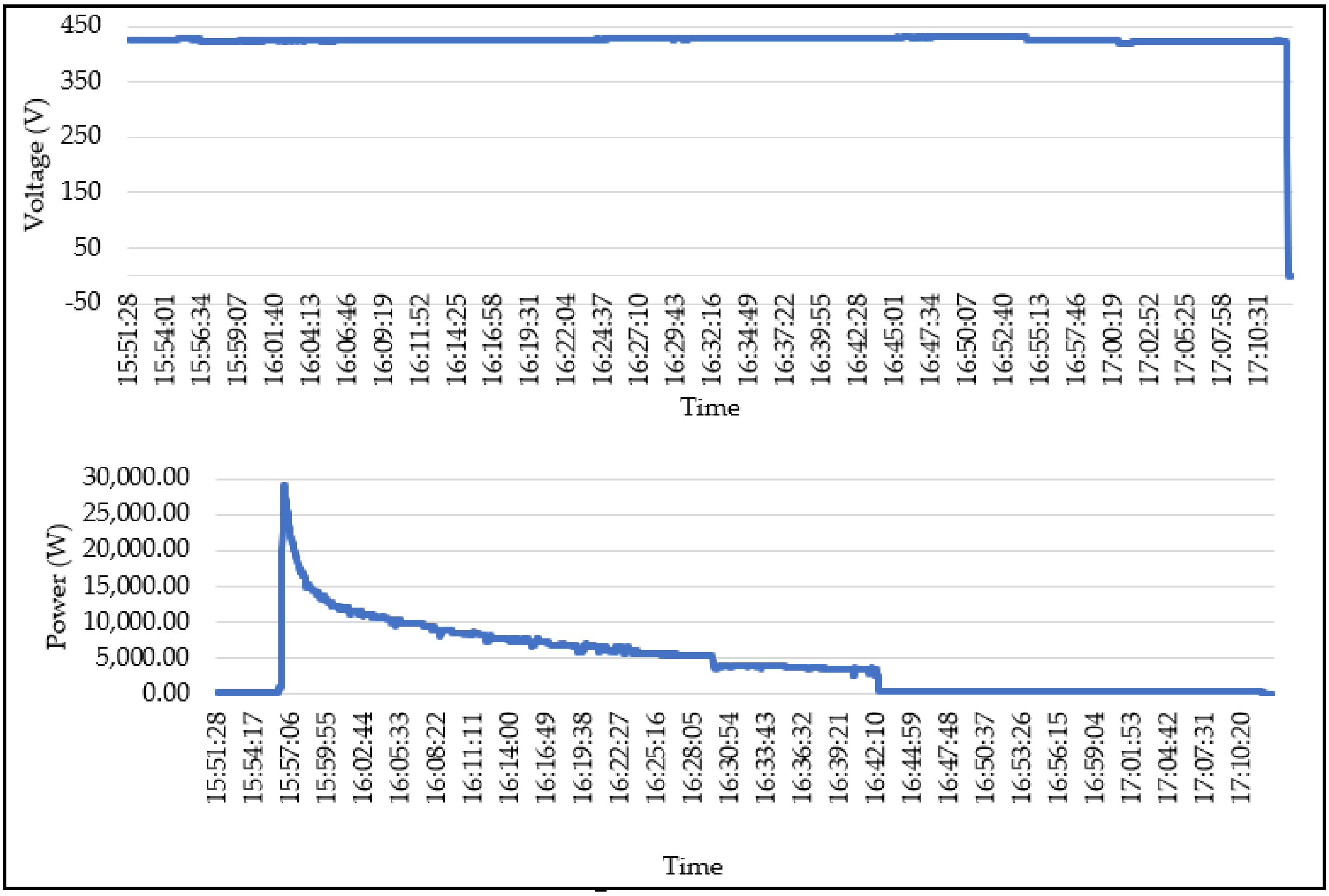


Figure 12. Voltage and Power Graph for EV Fast Charging (Chademo).

4.5. Discussion of Results Obtained

The results gained from the ZIP analysis through Python programming display a close correlation with the CVR factors generated, which show similar load behaviors towards the change of voltage. The use of ZIP models in the context of residential load appliances can lead to more efficient and sustainable energy use, and ultimately can contribute to a reduction in greenhouse gas emissions.

The main aim of this paper is to highlight the actual possible amount of savings that can be achieved by implementing CVR. The CVR and ZIP values are successfully determined in this study, and they can assist in energy savings calculations. Since cost savings is the main priority of every customer, the amount of savings for residential is calculated for every 1% voltage drop up to 6%, as shown in Figure 8. From this study, for a 1% voltage reduction, the energy savings is 1.3% and the cost savings is 1.97% (RM 4.74) per month. For a 2% voltage reduction at 230.30 V, the energy savings is 2.7% and the cost savings is 3.94% (RM 9.48) per month. For a 3% voltage reduction, the energy savings is 4% and the cost savings is 5.92% (RM 14.23) per month. The standards that are to be complied by the Malaysian distribution network are +10% and −6%.

It can be observed that the monthly consumption is very similar to the calculation done using the CVR factor, as displayed in Table 3. The increase in voltage to 240 V (2% voltage increase) will lead to an increase in energy consumption to 659.79 kWh, that is, an increase of RM 5.35 a month. The negative values in Table 4 indicate the percentage increase that the customers will have to sustain if higher voltage is supplied to their dwellings. The increase in voltage by the utility is an ideal power system practice to avoid low voltage during transient.

Figure 9 displays the comparison between the CVR factors for each type of substation, i.e., mixed load (residential 70% and commercial 30%) and 100% residential, commercial, and industrial loads. The results obtained for the 100% residential CVR factor is 18% higher than the average of the mixed load CVR factor. The value of this CVR factor is acceptable, as 30% of commercial load is connected to that feeder. Commercial loads consist of large refrigerators and centralized air conditioners that are constant power loads that could decrease the CVR factor. The CVR value at night is consistent with the 100% residential, since commercial shops would ideally be closed by 10 pm. The industrial load displays an increase in CVR factor from 5 pm to 10 pm. This could be due to the switching off of heavy production machines and change in production shift. Large machines are known to be constant power with motor driven load type.

Nevertheless, based on the CVR factors that are calculated, it can be established that residential substations will benefit from voltage reduction, the commercial network indicates that there will be some percentage of savings for commercial customers, and the least amount of savings would be realized by industrial customers.

5. Conclusions

In this paper, a comprehensive study has been conducted to analyze the impact of voltage reduction on energy savings at the residential level. Many individual appliances are scrutinized based on ZIP load model values which are then compared to the CVR factors that are generated. This is to determine the types of loads and their behaviors toward a change in voltage. This analysis covers the selection of residential loads, ZIP load modeling, CVR factors for individual appliances, energy and cost savings at a residence level, and the CVR factors for various types of power networks. The main contribution of this study is to be able to determine the exact amount of residential savings that is possible with every 1% voltage reduction at the customer level. This study shows that CVR can be implemented to achieve residential savings. Customers can save from RM 4.74 to RM 27.57 monthly with every percentage of voltage reduction. Moreover, the CVR factors that are displayed in Figure 7 can be used to calculate the possible amount of energy savings that can be achieved by each appliance in a household. Therefore, customers as well as utilities can further investigate the generation of cost savings with a reduction in voltage supply.

The CVR factors that are generated in this study range from 0.44 to 2.42 for active power, and the apparent power ranges from 0.2 to 2.3. The real and apparent power CVR factors are very consistent, and reducing the voltage supplied to individual appliances can lead to significant energy savings, particularly for appliances with resistive loads such as electric resistance heating and lighting fixtures.

Conservation voltage reduction has numerous benefits, including reducing greenhouse gas emissions and other pollutants, lowering energy costs, and increasing the reliability and stability of an electrical system. The results of this study can serve as a guide for anyone involved in the design, operation, or maintenance of the electrical infrastructure at a utility for CVR implemention in the Malaysian distribution network.

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Data Availability Statement: The dataset used and/or analyzed during the current study is available from the corresponding authors on reasonable request.

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