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LED ZIP Model Development

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LED ZIP MODEL DEVELOPMENT

by

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LED ZIP MODEL DEVELOPMENT

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The representation of load components deemed to be an essential factor for power system studies as the load characteristics influence the system performance. Thus, choosing an appropriate load model for load behavior studies is very significant for system analysis purposes. Load models can be categorized into three types: static, dynamic, and composite models. Static ZIP load model is a well-known model in the power industry, it represents the relationship between the active and reactive power as a function of the applied voltage. In this paper, a detailed review of the existing static ZIP model coefficients for load components achieved by the work researches over time is provided. Then, the documented ZIP coefficients were grouped into end-use types to plot and visualize the load components in terms of the voltage-power relationship, and the ZIP coefficients for each end-use type are determined for three cases: minimum, maximum, and typical case. In addition, to update the load model for modern lighting and have a better load representation, ZIP load model is developed for LED lights, and the model coefficients is experimentally determined for each light fixture. Next, conservation voltage reduction (CVR) impact on LED lights is investigated, and power reduction estimation based on ZIP coefficients is validated against the actual measurement data of load variations under CVR technique.

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NOMENCLATURE

TV:

LCD	Liquid Crystal Display
LED	Light-Emitting Diodes
CRT	Cathode Ray Tubee
BL	Backlight
sc	Screen
ss	Static screen
v	Volume

Motors:

CT	Constant Torque Loads
LT	Linear Torque Loads
QT	Quadratic Torque Loads
CP	Constant Mechanical Power Load
SMPS	Switch Mode Power Supply
RSIR	Resistive Start-Inductive Run
RSCR	Resistive Start-Capacitor Run
ASD	Adjustable Speed Drive
PFC	Power Factor Correction
VSD	Variable Speed Drive
SASD	Single-phase Adjustable Speed Drive
SPIM	Single-phase Induction Motor

Lighting:

Fluor	Fluorescent
CFL	Compact Fluorescent Lamp
LFL	Linear Fluorescent Lamp
HID	High Intensity Discharge
LED	Light Emitting Diode

Dish washer:

HD	Heat and Dry
NW	Normal Wash
PP	Pot and Pan

CHAPTER 1

INTRODUCTION

1.1 General

This chapter overviews the motivation of the research conducted in this thesis. The chapter also outlines the main objectives of the research and the structure of each chapter.

1.2 Motivation

Several works of ZIP model development were adopted by many researchers to develop ZIP model for lighting loads, and most of the previous works were primarily concentrated on modeling the common lighting types in 2013 and 2014, such as incandescent, compact fluorescent lamp, and halogen, which are not used nowadays anymore.

However, with the rapid development of technologies, LED has been the most common lighting fixture that used in the market, hence LED ZIP model development has not been deeply investigated by researchers for differences, such as power consumption and lighting types. Thus, our goal is to update the load model for the LED lights in order to have a better representation. This can be accomplished by developing the ZIP load model under the conservation voltage reduction (CVR) technique, investigating how CVR impacts the behavior of LED lights and validating the power reduction estimation based on ZIP model against the actual measurement obtained from the experiment.

1.3 Thesis Objectives

The main objective of this research is to review and document the existing work of developing the component-based ZIP model. The ZIP coefficients for collected load components are documented and grouped into end-use types to be visualized, then the ZIP coefficients identification for each end-use type is achieved for three potential cases.

One of the main thesis objectives also is to develop the ZIP load model for LED lights to update the load model for the considerable changes in load characteristics with the development of modern lighting. Experimental determination of ZIP load model for LED lights is adopted in order to represent the power demand of LED lights under the conservation voltage reduction (CVR) technique. Also, the power reduction of LED lights achieved by CVR technique is estimated based on ZIP load model coefficients, and then validated against the actual measurement for LED lights.

1.4 Thesis Organization

This research will start by providing a general background of the load model, the load model types, and the two approaches of load model identification. Next, the applications of the static ZIP model are presented, including the load behavior analysis, power system stability, and conservation voltage reduction. Then, a literature review of the existing ZIP model coefficients is offered, mapping and visualization of the collected load components are drawn for each end-use type, and three cases of ZIP coefficients for end-use types are identified. Later, the ZIP model for LED lights is developed, and the ZIP coefficients for each LED light is determined under the conservation voltage reduction technique. Then, power reduction for LED lights is estimated based on the ZIP model coefficients for each LED light and compared with the actual recordings obtained from the experiments. Finally, the conclusion and future work are provided in the last chapter. A brief outline of the thesis is as follows:

1. Chapter 1 is an introduction
2. Chapter 2 overviews the fundamental knowledge in load model, providing the three types of load model and their applications. Next, a general overview of load model identification approaches is explained in this chapter.
3. Chapter 3 discusses the ZIP load model applications for load behavior analysis, power system stability, and conservation voltage reduction, and provides a literature review of the previous works on ZIP model implementations.
4. Chapter 4 documents all the existing ZIP model coefficients adopted by previous studies, and plots visualizations for load components. Next, this chapter displays the analysis adopted to determine the ZIP coefficients for end-use types.
5. Chapter 5 develops the ZIP model for LED lights, and determines the ZIP coefficients for each light fixture. Next, the impact of conservation voltage reduction on the LED lights is predicted and analyzed based on ZIP model coefficients.
6. Chapter 6 discusses the conclusion and future work, and summarizes the achievements in this research.

CHAPTER 2

LOAD MODEL

2.1. General Background

Load could be defined as a single device that is connected to the system, or a group of load types that are connected to the supply system [1]. A load has multiple meanings, which rely on the focus of the study or the level of analysis that is implemented, but it could be defined as an active power and reactive power consumed by the devices and appliances connected to the system. Load can be called the power consumption of single electrical components or the total power consumed in the system. The load can be shown as a power consumed by part of the system that has not been represented in detail. Load may be presented in a mathematical relationship as shown in equations (1), or it can be expressed as a function of theta θ, where θ is the angular displacement between the applied voltage and current of the load, which is employed to calculate the power factor [2].

$$S = P + JQ \qquad (1)$$

$$P = S\cos\ (\theta) \qquad (2)$$

$$Q = S\sin\ (\theta) \qquad (3)$$

Where

- S: apparent power (VA)
- P: active power (W)
- Q: reactive power (VAr)
- θ: angular displacement

Load model is significant for power system stability as it matches between the electrical generation unit supplies and the demands of electrical loads that are connected to the system [3]. It also has a key role in different implementations such as the study of stability in voltage and frequency and power quality analysis in load classes (residential, commercial, and industrial) [4].

Load modeling has the same significance as the rest of the power system models. A lot of work has been done over the last decades according to load modeling [5]. In the 1990s, reference [6] introduced initial directions regarding the load representation. In addition, the Load model has been an area of focus since the 1997s with the investigation of the impact of load coefficients and load composite on the distribution transformers in the power system [4].

Load model is defined as a mathematical relationship that represents the change in active power demand or reactive power demand as a function of the variation of power system voltage and frequency [7]. It is used to predict the load behavior under the normal operation & sudden changes in voltages and frequency in the shape of analytical representation that express the power-voltage dependency [2], as shown in equations (4-5), where V is the rated voltages, f is the rated frequency, P and Q are active power and reactive power respectively.

$$\mathrm{P} = \mathrm{f}\,(V, f) \qquad (4)$$
$$\mathrm{Q} = \mathrm{f}\,(V, f) \qquad (5)$$

It is very essential to understand the load characteristics in order to build a reliable system based on categorizing loads, then grouping them depending on the similarity of these characteristics. This is because that the load model process could be complicated due to the substantial amount of load components, the variety of loads behavior of each appliance and equipment, the difficulties of getting an accurate load composition estimation, and each one of the devices and appliances has its own characteristics such as response to the variation of voltage and frequency, capacity, and duty cycle [3]. Load models can have different categories such as polynomial and exponential models, hence when choosing the load model for the application process, the model has to be simple and capable enough to represent several load response cases [2].

2.2 Load Model Types

2.2.1. Static Load Model

Load model is classified into two types: static model and dynamic model [3]. static load models are time-independent models that represent the load behavior in the steady-state with reference to the characteristics of the power system [4]. Static load models may be introduced by a mathematical relationship that is predicated based on the voltage dependency of the load in equations (4) and (5) [5].

Static load models can be expressed by the active power and reactive power of load components as a function of supply voltage and the frequency at a given instant time, which means that the relationship between power and voltage is the same at any moment [1]. It can express the electrical characteristics of the loads that can be modeled as a function of specific coefficients in the system bearing in mind that static load modeling uses solely in instantaneous state conditions to identify the characteristic of load [8]. Static models also represent the static load components in a steady-state, which varies instantaneously with voltage variation at the load bus, such as resistive loads. Furthermore, the simulation of the static load model can be used for both static and dynamic loads, e.g., the static model can roughly represent some of the dynamic load components characteristics such as induction motors [7].

Static load model is a well-known model in the power industry and helpful in transient stability studies as it primarily relies on the load's power behavior within and after the disturbance. Thus, the proper load model can be very sufficient for transient stability analysis taking into account the dynamic load models in the voltage stability study as the static load model may not be able to sufficiently present the load behavior under a voltage collapse. Thus, the dynamic load model has a better representation of the voltage stability analysis than the static load model [5]. The survey that was done in [9] found that the static load model was used in 70% of the power system in order to model loads in their dynamic stability analysis utilities. it was also demonstrated that the constant power was used in 82% of the utilities for in the load flow studies [2]. Static models have several characteristics such as the response steady-state could be reached very fast, and the rapid load response to the voltage and frequency variations [3]. The static model applications can be effective for the steady-state power flow studies, where it can represent the loads that are connected to the power system [8]. Static models are defined as one of three general load models [1]:

2.2.1.1 Constant impedance load model

The constant impedance load model represents the active power and reactive power as a function of the square of voltage magnitude. This model can also be called the admittance load model.

2.2.1.2 Constant current load model

The constant current load model represents the active and reactive power which are varying linearly with voltage magnitude.

2.2.1.3 Constant power load model

In the constant power load model, the load will draw constant active and reactive power, regardless of the change in the supply voltage magnitude. This model can be called a constant PQ load model (or constant MVA load model).

2.2.1.4 Polynomial Load Model (ZIP Model)

The polynomial load model can be generally called ZIP model, which expresses the relationship between the active and reactive power with voltage [10]. ZIP model represents the relationship between the applied voltage and the characteristic of the load power in a polynomial equation as the sum of Constant Impedance (Zp), Constant Current (Ip), and Constant Power (Pp) to identify the real power (active power); in a similar way, the reactive power is defined by the following equation (7) using the coefficients: Constant Impedance (Zq), Constant Current (Iq), and Constant Power (Pq). algebraically, the ZIP model is represented by the equations (6-7) shown below [1]:

$$P = P_o\left[Z_p\left(\frac{V}{V_0}\right)^2 + I_p\left(\frac{V}{V_o}\right) + P_p\right] \qquad (6)$$

$$Q = Q_o\left[Z_q\left(\frac{V}{V_0}\right)^2 + I_q\left(\frac{V}{V_o}\right) + P_q\right] \qquad (7)$$

Where Z_p, I_p, P_p are ZIP load model coefficients for active power, Z_q, I_q, P_q are ZIP load model coefficients for reactive power, P is actual active power demand of the load, Q is actual reactive power demand of the load, V is actual voltage at the load bus, V_0 is nominal voltage, P_o is nominal active power of the load, and Q_0 is nominal reactive power of the load.

ZIP model is generally employed in both steady-state and dynamic studies [11], and it is one of the static load models generally recognized among power industries [5]. This model is the most widely used form in power system stability studies [7]. ZIP model may deliver a better fit to non-linear loads than the exponential load model as the polynomial model has a general quadratic form

[1]. In this study, the frequency was not discussed like the voltage since the voltage changes in per-unit are significantly higher than the per-unit frequency changes [5].

Phase angle-based ZIP Model

Besides the three constants of the ZIP model (constant impedance, constant current, and constant power), another form of ZIP model is “Phase angle based-ZIP Model". This form can be described by the active and reactive power with the phase angle of load components, which can be measured at each voltage level. Thus, the active and reactive power of ZIP loads can be calculated by the given equations (8-9). The constants are limited with the constraint in (10).

$$P_i = \frac{V_a^2}{V_o^2} . S_o . Z_\% . \cos(Z_\theta) + \frac{V_a}{V_o} . S_o . I_\% . \cos(I_\theta) + S_o . P_\% . \cos(P_\theta) \quad (8)$$

$$Q_i = \frac{V_a^2}{V_o^2} . S_o . Z_\% . \mathrm{Sin}(Z_\theta) + \frac{V_a}{V_o} . S_o . I_\% . \mathrm{Sin}(I_\theta) + S_o . P_\% . \mathrm{Sin}(P_\theta) \quad (9)$$

$$Z_\% + I_\% + P_\% = 1 \quad (10)$$

Where P_i is active power consumption of the i^{th} load, Q_i is reactive power consumption of the i^{th} load, V_a is actual terminal voltage, V_o is nominal terminal voltage, S_o is apparent power consumption at nominal voltage, $Z_\%$ is fraction of load that is constant impedance, $I_\%$ fraction of load that is constant current, $P_\%$ is fraction of load that is constant power, Z_θ phase angle of the constant impedance component, I_θ is phase angle of the constant current component, P_θ is phase angle of the constant power component.

The six constants in the following equations are representing the ZIP loads behavior as a function of the applied voltage. Once the six values of constants are experimentally determined, they can be inserted to (8) and (9) to calculate P and Q for each load component.

Phase angle based-ZIP model can be employed for CVR analysis, as it is crucial to evaluate the load response to the CVR technique. Furthermore, the six constants can precisely represent the load components behavior, primarily for some complicated loads, e.g., LCD or CFL where the ratios of Z, I, and P are not as obvious. Unlike the heating loads that are undoubtedly know to be 100% of constant impedance Z [12].

2.2.1.5 Exponential Load Model

The exponential load model is one of the most common models used in the static load model, and considered to be a good fit for some of the dynamic load components characteristics such as induction motors [7]. Exponential model represents the relationship between the power and voltage at the load bus by exponential equations. These equations have less coefficients that are basically presented in the ZIP model [11]. Exponential load model has two coefficients (exponents), which is called np and nq, to express the algebraic relationship between active & reactive power with applied voltage V, (equation 11-12) [8].

$$P = P_0 \left(\frac{V}{V_0}\right)^{n_p} \qquad (11)$$

$$Q = Q_0 \left(\frac{V}{V_0}\right)^{n_q} \qquad (12)$$

Where P, Q are actual active and reactive power of the load, V is applied voltage and the load bus where the load is connected, V_0 is nominal voltage, P_0, Q_0 are nominal active and reactive power of the load, and n_p, n_q are exponential model coefficients.

The exponential models employ the exponents np and nq to express the load behavior as the following [8]:

- When $n_p = n_q = 2$, the load behaves as a constant impedance load.
- When $n_p = n_q = 1$, the load behaves as a constant current load.

– When $n_p = n_q = 0$, the load behaves as a constant power load.

Similar to the ZIP model, the exponential model eliminates the frequency changes in the system since the frequency variations are normally much smaller than the voltage changes. Nevertheless, frequency variations could be not excluded from the load model studies by multiplying the model with a frequency term as shown in the equation (13) below [8], where f is frequency value at the load bus, f_0 is nominal frequency, and k_f is frequency-dependent coefficient in the load model.

$$1 + k_f\,(f - f_0) \qquad (13)$$

2.2.2 Dynamic Load Model

Dynamic load models account for the dynamics of load components and it is considered to be time-dependent models [5]. In contrast, static load models are time-independent models that represent the load behavior in the steady-state with reference to the characteristics of the power system [4]. Dynamic load models represent the power demand of the load (both active and reactive power) as a function of voltage and time [11]. This type of model also expresses the variations of load characteristics as a function of supply conditions state (either past or existing state) such as the response to time-related transient variations in the supply conditions [8].

Dynamic load models have a better representation of the voltage stability analysis than the static load model, hence dynamic models shall be taken into consideration when studying the voltage stability as the static load model may not be able to sufficiently present the load behavior under a voltage collapse [5].

The induction motor model is one of the most frequent dynamic load models, and it is considered to be the major part of the dynamic load parts [10]. as mentioned in [13], induction motors consume around 60% of the total power demand [7]. However, it was indicated by [14] that there has not been adequate research done on the dynamic motor models because of the different results between the simulation and the field measurements.

2.2.3 Composite Load Model

The primary difference between both static & dynamic models is based on the voltage impact on the load. The Static load model is executed when the changes in load behavior only based on the instantaneous voltage input, not on the other input variables (e.g., electric lamp). However, the dynamic load model can be implemented when the load behavior is impacted by all of the voltage inputs over time (e.g., induction motor). Thus, the composite load model is broadly implemented as the practical loads consist of multiple components. The composite load model is considered to be a physical load model that combines between the static load model, which is presented by the ZIP model (constant impedance, constant current, and constant power), and the dynamic load model, generally an induction motor model, connected in parallel.

The composite load model (a combination of the ZIP model and induction motor) is the predominant model all over the United States, whereas the static load model (ZIP model) is mostly used by the rest of the world. This is stated in [15] according to the global survey done in 2013 about which of load modeling types is the most frequently used by the utilities for the power system stability.

2.3 Load Model Identification

The determination process of the static load model coefficients (polynomial or exponential) is particularly significant prior to employ these models in the power system analysis, where these coefficients must be precise enough to express the load characteristics [1]. There are two approaches in the coefficients identification of load modeling: component-based approach, which is dependent on the components information that are connected to the power system, and measurement-based approach, which counts on the field-measurements of the load power (active and reactive), the voltage and frequency at the load bus. The load model coefficients are then found by applying the range of voltage values predicated on the codes and standards [4].

2.3.1 Component-based Approach

2.3.1.1 General Background

The component-based approach is a ‘‘bottom-up’’ approach, which implies that it starts from the bottom where the load components are connected to the system, and aggregates all the models of the load components to develop one aggregated load model. Contrary to the measurement-based approach which starts from the information collected by the field-measurements. Consequently, the data about the load compositions, for instance, the portion of load power consumption of each of the individual components, shall be taken into account to apply this approach [11]. This load model approach requires information that is obtained from the electricity consumption of the customers, which are divided into residential, commercial, and industrial [2].

Therefore, the static and dynamic models are a good expression of the individual load components. This representation can be adopted through the load coefficients obtained by the experimental determination. i.e., resistive heaters can be modeled as constant impedance loads [11]. Therefore, the following data shall be collected to identify the load composition of the aggregated load model [8]:

- models of individual components
- component composition, such as the power consumption for each load components.

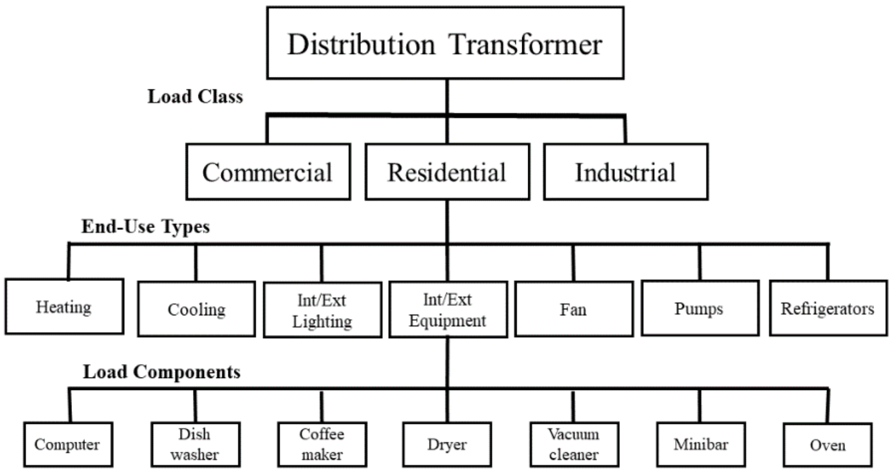

Figure 2.1 Component-based load model approach

2.3.1.2 Advantages

The main advantage of the component-based approach is that the field measurement is not required for applying this approach, which makes the approach fairly cost-effective and easy to apply. Also, the approach could be implemented in different conditions of operation (steady-state or dynamic). Finally, the component-based approach can represent the appliances and devices characteristics that are connected to the power system [11].

2.3.1.3 Disadvantages

The main disadvantage of this approach is that the component-based approach requires the characteristics of loads that need to be modeled. Also, it is hard to get an accurate and extensive information related to the load composition. Additionally, this approach does not have the adjustability to integrate with the modern loads [11].

2.3.2 Measurement-based Approach

2.3.2.1 General Background

A measurement-based approach is a straightforward approach comparing with the component-based approach as the coefficients are obtained directly from the measured data [2]. In other words, the measurement-based approach is another method of identifying the model coefficients mathematically. This approach gets benefits from the data measured by gauges such as smart meters, where the gauges measure the active and reactive power changes, as an output, with the variations of applied voltage and frequency, as an output, at the load bus [11]. These previous changes can be resulted from intentional voltage changes that are done in the laboratory for research purposes, or due to the natural disturbances in the power system. Once the recorded data are obtained, it is used to calculate the model coefficients [1]. The approach can be outlined in the following steps: obtain data from the field-measurements, choose the appropriate load model, calculate the load coefficients, and validate the load model [11].

According to the transient stability studies, the model coefficients obtained by the measurement-based approach can be simply updated within the variation of load characteristics as this approach has the direct observation of the dynamic load response, which is fundamental to determine the load model coefficients in the shape needed for the transient stability. Despite that, there are still some obstacles that are considered one of the approach disadvantages regarding transient stability studies. One of these disadvantages is that the reactive power of dynamic loads cannot be described by the constant impedance of the dynamic load models [16].

It might be functional to merge between both identification approaches, component-based and measurement-based, by utilizing ‘load signatures’. The great illustration of that is the employment of known loads characteristics to identify the load composition from the recorded data [8].

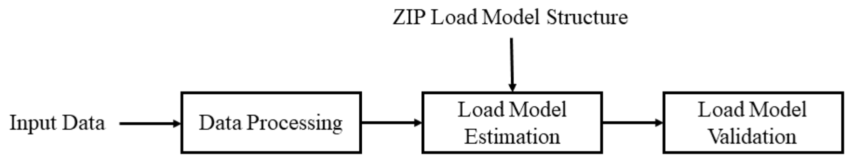

Figure 2.2 Measurement-based load model approach (source [11])

2.3.2.2 Advantages

Unlike the component-based approach, measurement-based approach does not require a lot of information about the load components, and it can be implemented for several models [11]. Also, it provides a precise model as it is based on the actual data, and considered to be an accurate approach to model the current load components, as it relies on the load's physical data [1].

2.3.2.3 Disadvantages

The measured data may not be accurate when enormous disturbances occur. Also, this approach is not applicable in all conditions, and it cannot be generalized since it is performed only for a specific duration of time and a certain place, which means it might not be applicable for other systems [1]. Considerable costs should be considered for this approach for the measurement process. Additionally, it is difficult to know the way of load response to the huge variations that might occur in the system [1]. One of the approach obstructions is the difficulties of considering the seasonal changes in the loads without load composition data [8]. The measurement-based is generally not that prevailing approach due to some issues that are relevant to the measurement devices, especially with some situations when the huge change of voltages and frequency does not exist steadily so as to define the voltage and frequency behavior for the load [7].

CHAPTER 3

ZIP MODEL APPLICATIONS

3.1 Load Behavior Analysis

3.1.1 General Background

Load components can be identified as a group of different equipment, connected to the power system, that converts the electric energy withdrawing from the system into another form of energy, such as heaters, fridge, washing machines, etc. Several models have been implemented to represent the characteristics of load components, and these models have the ability to display the characteristics of a group of loads that are connected to certain buss. It can also represent the features of load classes (residential, commercial, and industrial) [7].

The representation of these load components is considered to be an essential factor for power system studies as the load characteristics influence the system performance. Thus, choosing an appropriate load model for load behavior studies is very momentous for system analysis purposes. Numerous works have been done by utilities for the sake of identifying the load characteristics behavior through the variation of power consumed by loads with different voltage and frequency levels. Moreover, the advancement of loads over recent years raises the challenges of developing a standard structure of the component-based model, like the main system components; generators, transformers, and transmission lines. Therefore, this evolution of load components and emerging some new technologies into the market make the update of the component-based models is very imperative in order to have a dependable model that affords an accurate representation of load characteristics [17].

Component-based models can be defined as the models that depend on the characteristics and detailed properties of load components. This type of model is recognized to be one of the primary power system modeling approaches. Component-based models are implemented by conducting a physical experiment. The way of achieving the type of model can be done through the integration of the load components that are connected to the system, distribution network, under a certain level of an applied voltage to an equivalent model [7].

The ZIP load model is one of the best models to be fit for the behavior analysis studies. ZIP Model represents the sum of three categories; which are the static load characteristics that can be categorized into a constant impedance, constant current, and constant power load. The difference between the three constants is associated with the power-voltage relationship; the power dependency on voltage is quadratic, for constant current it is linear, and for constant power, it is independent of voltage [18].

3.1.2 Related Work

Diverse works of load modeling were implemented by using the ZIP load model in the interest of analyzing the load behavior and their impact on the power system. Authors in [17] studied the performance of game consoles and TVs and updated the ZIP load model for the new version of these appliances that have released recently. Several tests were carried out on game consoles such as PS3, Xbox, and ZIP load model was developed for these measured values obtained from the laboratory tests. On the other hand, [1] developed aggregated load models for the sake of more accuracy in forecasting active and reactive power for the latest, non-linear, and most frequently used loads, such as drive-controlled motors and electronic devices. ZIP load model has been chosen for the developed approach and component-based method was selected to identify the coefficients of this model. Work in [8] intended to update the load modeling for non-traditional loads, such as power electronic interfaced loads, by conducting aggregation of load modeling for the residential and commercial classes in the UK, taking into account the development of some load modeling methodologies.

Research in [7] intended to do a comparison between the two static load models (ZIP & Exponential) by analyzing the outcome of each one of these models on the selected loads under normal operation and abnormal conditions, such as a short circuit fault. It was demonstrated that two models for incandescent light almost have the same accurate representation, but they are different for the fluorescent light. [19] aimed to improve the load model by studying the model performance on the end-use components taking into consideration the loads details like demand response and energy efficiency programs which have a significant impact on energy consumption. ZIP load model was executed to find out the model coefficients for different end-use loads.

[20] proposed an approach that can be implemented in many sectors and different countries to improve the load modeling of the low voltage LV network in the power system. The modeled aggregated load was connected to the medium voltage MV, and ZIP load model was selected to investigate this proposed approach. The work in [21] planned to determine the ZIP load model parameters to prove the reliability of the Transmission-Distribution co-simulation approach, which is a developed model that is considering both transmission and distribution systems. ZIP load model was fitted to validate the suggested approach. Furthermore, the suggested work was also justified by comparing co-simulation to Transmission only simulation using the coefficients that are obtained from the new approach for the purpose of displaying the adequacy of this method in describing the loads' behavior in the distribution system.

[22] looks into the non-linear loads and their impact on the system for the purpose of developing a PC program. The main features of this program are the investigation of non-linear components behavior according to the active and reactive power under voltage variations, and the ability to study combined loads. Experimental measurements were conducted and ZIP model was fitted into the data obtained from the measurements. On the other hand, authors in [4] did not develop a load model through the laboratory measurement method used as used in [6], [22], [23]. Taylor Series Approximation was the proposed approach for the estimation of the load coefficients.

The suggested method relies mainly on the in-situ measurements for defining the load parameters, which represent the active and reactive power based on the nominal values that applied in the utility voltage. [18] also used the ZIP model to identify the impact of voltage variations on the loads in the micro-grid under abnormal conditions, such as a three-phase short fault. It was found that ZIP models can have several power characteristics and the required load characteristics could be achieved by varying the percentages of ZIP parameters. From another point of view, [24] was mainly focused on studying the home-grid system and investigating the possibility of developing it more efficiently. The research proposed a new home-grid system based on solar energy which is called a hybrid AC/DC solar powered Home grid model. Experiments were done to study loads behavior. Then, ZIP model coefficients were identified to present the loads' characteristics.

3.2 Power System Stability

3.2.1 General Background

Power system stability is described as the ability of the synchronous machines of coming over the system disturbance to the steady-state operating point, without missing synchronism. It may be classified into three types: steady-state stability, transient stability, and dynamic stability [25].

Steady-state stability still has some gradual variations in the operating conditions. However, the stability analysis performed on the power system guarantees that these changes don't negatively impact system stability by making sure that the bus voltage is still close to the rated voltage, and the other parts of the system such as generators, transmission losses, and equipment are not overloaded. Regarding transient stability, which includes primary disturbances like faults, generation, and sudden load changes, synchronous machine, after occurring disturbances, are exposed to variation in machine power angle and transient deviations from frequency (60 Hz). The goal of transient stability analysis is to figure out if the machine will return to the synchronous frequency with new steady-state power angles [25].

Power system representation is very essential for analysis purposes. Thus, modeling of different parts of the system equipment, e.g., generation, transmission, distribution system, can be performed by the power industries or researchers or can be approximated through on-site measurements and mathematical analysis [49]. The uncertainty of load representation is one of the prime challenging issues that face the load modeling analysis, and this challenge is caused by the time-varying physical characteristics associated with loads. For this reason, most researches and related works were focused on the modeling of generation and transmission equipment more than load modeling. As a consequence, it is very imperative to investigate the load modeling impact on power system stability [26].

Load model determination for presenting the load is a very critical matter as the load representation has a considerable influence on the power system analysis and transient stability is one of the main essential topics to be studied in the power system. Static and dynamic load models are well-known models in the power industry when it comes to transient stability analysis and static model performance has been investigated in several works [27]. Numerous work and investigations have been done by the industries and academia regarding load modeling due to its effectiveness. Consequently, an accurate load model carries out remarkable outcomes for the power system in terms of raising the flexibility of system operation cost-savings of system reinforcement. However, the inappropriate load model causes various issues that lead to the system collapse [28].

3.2.2 Related Work

According to the [27], it was shown that the ZIP model is an appropriate and sufficient model for transient stability studies and can be considered as an accurate representation of the dynamic behavior of real power throughout the system disturbances. Authors in [27] examined the adequacy of static load models of representing transient stability by using on-line measurement data. Similar work in [26] was done in China where authors aimed to study the load modeling impact under different conditions of faults during the transient stability. It has been demonstrated that the load model is significantly crucial for analyzing transient stability although the load model can be considered as a conservative model in some abnormal cases such as transient stability and has a notable impact on study results at the power system.

Work in [29] intended to develop the ZIP model to analyze its impact on the power flow solutions, taking into account the voltage parameter as one of the load variables, at the MV level. The data for this study is based on real-time measurement data obtained from the power system in Cyprus.

Data were experimentally measured and collected on-site and the results concluded that the ZIP model that relies on real and accurate data for power flow solutions is deemed to be a suitable model for power flow.

The author in [6] also employed the data obtained from the laboratory experiment in order to derive the model of modern loads in 1998, which can evaluate the power system behavior when it is exposed to unexpected variations such as voltage reduction during the operation conditions. ZIP model is the best fit to develop for these modern loads since the study focuses on the load behavior under varying voltages for a long time. The author referred to the importance of using an accurate load model when the load composition can be identified.

Authors in [3] aimed to update the loads' measurements in the previous work [6] taking into consideration the technology advancement and the modern devices that are recently used in the residential and commercial classes, specifically in the small offices, and that had not been tested and modeled yet. Laboratory measurements of the recent appliances and the derived ZIP load model were investigated. It revealed that ZIP model is able to represent the behavior of the small motors and the power electronic conversion devices.

While [17] worked on developing a model for the modern generation of appliances, research in [5] also tended to do a similar study on modern flat TVs. The authors' focus was on studying its behavior and investigating the energy consumption of these components and their impact on power system stability. Different types of TVs such as LCD and LED with several sizes were tested in the laboratory and subjected to different voltage variations in order to develop the ZIP load model and derive the coefficients.

3.3 Conservation Voltage Reduction

3.3.1 General Background

Utilities practice principle of CVR to conserve energy and minimize losses by operating the end-user load on the lower half of the ANSI standard without exposing customers to unacceptable under-voltage conditions. Reduction of voltage may reduce or increase total power consumption depending on the end-user load type and local reactive power compensation. CVR implies that the load will require less energy (less peak demand and energy losses) when the applied voltage is reduced. So the object of this technique is to reduce the power consumption of the system. This can be done by reducing the voltage supplied from the feeder, so the applied voltage at the end-user will be the lowest acceptable level of voltage corresponding to the rated values of the equipment and the voltage margins specified by the international standards [30].

CVR is one of the frequently used methods for power-conserve purpose in the utilities. Even though the CVR technique has been implemented in most of the systems in North America, one of the main CVR challenges is that it is hard to find out how CVR will perform on different sorts of distribution feeders. So, most of the published researches are predicated on the experimental field measurements and little of works is an essential analysis of CVR impact [12]. CVR is categorized into two kinds of performance: short term, where the CVR is deployed employed to conserve power at the peak time of a day, and long term, where it is employed permanently [31].

3.3.2 National Standards of CVR Ranges

End-use equipment and appliances can be fed by the applied voltage levels lower than the nominal voltage without any shutdown or failures of this equipment. This reduction of voltage levels is allowed within a range of voltage levels which is determined by the International Standards ANSI

C84.1–2006 and IEEE std 1250-1995 [30]. As stated in the American National Standards Institute (ANSI) Standard C84.1, voltages at consumer levels must remain at 1 p.u. volts 5% [32].

According to the voltage variations range that is used for the ZIP model solution and looking back to the references and based on the review, it was noted that different ranges of voltage variations were typically imposed to obtain the voltage power functions used to compute the ZIP coefficients, e.g., voltage variations from Vmin% to 110% of the nominal voltage was imposed in [6], where Vmin is between 25% - 27%. Two voltage variations were imposed in [23]: 83% to 110% which is called the 100-v cutoff voltage, and Vmin% to 110% which is called the actual cutoff voltage, where Vmin is defined as the voltage where the load can no longer functioning. The purpose of finding the Vmin is that the importance of determining the shutdown minimum voltage, e.g. In some cases, if the Vmin value is bigger than voltage step, the lowest voltage levels will be redefined in the test. Voltage variations from 80% to 110% were imposed in [30] as the reference investigation is about the Conservation Voltage Reduction (CVR). Voltage variations from 50% to 110% were imposed in [17]. Voltage variations from 0% to 100% were imposed in [3].

In conclusion, voltage variation range selection is dependent on the work interests. However, the range of voltage, which is between 80% - 110%, is adopted in our research since the work purpose is to evaluate the load behavior under Conservation Voltage Reduction studies. Also, these ZIP coefficients obtained from different voltage ranges can be used together for our work interests as there are many works such as [2], [4] used the obtained ZIP coefficients from different previous measurements.

3.3.3 CVR Economic Advantages

Numerous companies are attracted by the economic advantages of CVR regarding power consumption reduction. Many companies, such as BC Hydro, Hydro Quebec (HQ), Southern California Edison (SCE), Northeast Utilities (NU), Dominion Virginia Power, and Bonneville Power Administration (BPA) have applied CVR and observed that a range of power reduction between 0.3% to 1% was achieved for 1% of voltage reduction [31]. Another study shows that 3.04% of the power consumption can be saved if the CVR is implemented across the distribution feeders of the USA [12]. Another study of a utility company, BC hydro, demonstrates that CVR application has led to reducing 1% of energy losses when 1% of the voltage reduction was implemented [33].

3.3.4 CVR implementation methods

CVR can be implemented utilizing the three means [34]:

- Line Drop Compensator (LDC) with the adjustment of Load tap changers (LTC) supported with a controller that changes the tap position to keep the voltage within the allowed margins
- Deploying voltage spread reduction, which is similar to the LDC method except it reduces the voltage in lower percentages. This method requires line reconfiguration to maintain the voltage within the permitted range.
- Adaptive voltage control (AVC) by using Line Voltage Monitor (LVM), data collector, and controller.

3.3.5 CVR Factor

The impact of CVR can be assessed by the CVR factor, which is defined as the ratio of the percentage of change in power consumed by the load to the percentage of change in voltage level, expressed in equation (14) [35], where $\mathrm{CVR_f}$ is conservation voltage reduction factor, $\%\Delta\mathrm{P}$ is the change percentage in power consumed by the load, $\%\Delta\mathrm{V}$ is the change percentage in voltage level.

$$\mathrm{CVR_f} = \frac{\%\Delta\mathrm{P}}{\%\Delta\mathrm{V}} \qquad (14)$$

3.3.6 Load Modeling for CVR Studies

load modeling is one of the most substantial means to evaluate the efficiency of the CVR technique in the network system, where load modeling can represent the performance of loads that are connected to the system. Additionally, some of the previous related works indicated the significance of load modeling application on CVR [30]. Load modeling also considered to be an important part of the CVR study. ZIP load model can be used to express the loads performance that are exposed to the CVR technique. The basic concept of CVR is that the loads (end-use components) consume less power when the applied voltage gets decreased. So the modeling process can be a very helpful method for investigating the impact of CVR for end-users and systems. Load modeling is implemented on the loads, then the model coefficients can be obtained and the validation of the model is done by the comparison between the actual laboratory measurements and the ZIP coefficients [23].

3.3.7 Related Works

Some of the previous related works indicated the significance of load modeling application on CVR. Research in [23] aimed to validate the ZIP load model in various customer categories versus the measured values obtained from the laboratory test for analyzing the CVR impact. ZIP load model was the most appropriate for this purpose as it represents the relationship between consuming power and the applied voltage. It was found that the latest loads behave differently than the older appliances. [10] also calculates the ZIP coefficients by the values obtained from the experiment in order to figure out the precision of the ZIP load model under the CVR conditions. It was also revealed that the ZIP load model has high accuracy with calculating the active power for most of the residential home appliances, but not as good as precision with the reactive power.

Work in [36] examined the CVR impact on the behavior of residential appliances in the distribution network in the UK. Authors used the ZIP coefficients obtained in [6] to model 70% of the residential peak demand. Load components behavior was investigated by using the ZIP model due to the ability of this model to define the appropriate range of the voltage variations that could be implemented in the corresponding network. [30] primarily compared the three statics load models (which are polynomial ZIP, phase angle-related ZIP, and Exponential model) and discussed their CVR influence and suggested the ellipsoidal algorithm as an approach to achieve more accurate load models. It was shown that phase angle-related ZIP was the only model who has a better accuracy with showing the V-P relationship. Another work in [37] proves that CVR can be performed well when the aggregated load model is controlled by constant impedance or constant current loads.

[38] conducted a research on the two types of loads, which are the ZIP loads and the Equivalent Thermostatic Loads (ETLs), and their impact on the energy savings of CVR estimations in the distribution network. Loads were subjected to ZIP and ETLs models. Then, a comparison was made between two models to figure out the ability of both models to catch the ambient temperature. Research in [39] tended to concentrate on the harmonic distortion and comprise it with the suggested approach of the updated ZIP load model for the sake of more accurate modeling. On the other hand, in [40], the ZIP load model was conducted for a study that represents a formulation named Mixed-Integer Nonlinear Programming MINLP. This approach expresses a procedure of

measuring the applied voltage for the sake of accurate CVR according to the network infrastructure. The research in [41] employed the ZIP model to investigate the Distributed Energy Resources (DER) as one of the CVR approaches and examine the DER applications in different considerations.

[42] demonstrates that CVR can be concretely optimized by penetrating PV in the distribution network. Loads behavior has to be taken into account for the CVR estimations and this can be achieved by the ZIP modeling of the aggregated loads. From another point of view, work in [43] discussed the CVR applications that can be implemented on future networks, especially with the rising voltage demand of the future loads such as electric vehicles and heat pumps. The authors employed the ZIP load model as the best fit for CVR forecasts and calculations. ZIP model was also used in [44] to study the impact of the electric vehicles penetrated on the distribution network and found that the electric vehicle penetration adversely influences the CVR implementation and weakens its efficacious.

CHAPTER 4

EXISTING ZIP COEFFICIENTS: REVIEW & ANALYSIS

4.1 Framework Description

The framework in this chapter is divided into four stages. The first stage is documenting the existing work of the researchers investigated in the component-based ZIP model and its coefficients. The second stage is grouping the ZIP coefficients of load components obtained from the previous works into end-use types according to a building performance simulation called EnergyPlus, which is an open-source whole-building energy modeling (BEM) that commonly used by engineers, designers, and researchers. It consists of a group of modules that are integrated together to calculate the energy consumption for heating, cooling, lighting, plugged equipment, and the other end-use types in buildings. The calculation is achieved by an integrated simulation of building and associated energy systems under different conditions of operation.

The third stage is mapping and visualizing the documented load components and plotting them with respect to the voltage-power relationship and ZIP coefficients so the load behavior and response to the voltage variations can be visualized. This can be achieved through ZIP model equations for active and reactive power. And finally, the fourth stage is identifying the ZIP coefficients for each end-use category based on the load components documentation and visualization adopted in the previous stages. Three cases of ZIP coefficients determination for each end-use category are investigated in this stage: the minimum, maximum, and typical cases. Two of these cases, which are min & max, of ZIP coefficients are extracted by the load components plots for each end-use type by identifying the most and least sensitive component with respect to the relationship between power and voltage. The third case, which is the typical ZIP coefficients, is achieved by the determination of ZIP coefficients for each end-use type in one residential house based on the documented load components and load composition represented by the share of electricity for each load. Figure 4.1 shows the framework of this paper for the review and visualization adopted in this work.

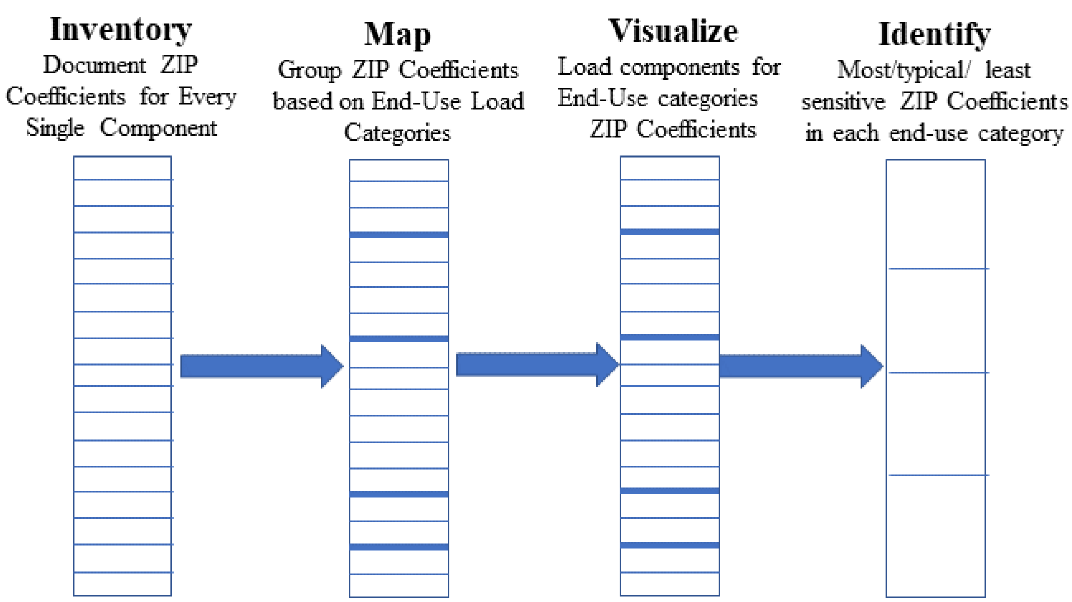

Figure 4.1 framework for ZIP model coefficients: review & visualization

4.2 Inventory: Detailed Review & Discussion

Diverse works were conducted by many researchers to develop the ZIP model and identify its coefficients for different directions of focuses. The summaries of works related to the ZIP coefficients determination has been reviewed and shown in the following sections. The author in [6] employed the data obtained from the laboratory experiment in order to derive the ZIP model coefficients of modern loads in the residential class such as refrigerator, battery charger, microwave oven. The purpose of modeling is to evaluate the power system behavior when it is exposed to unexpected variations such as voltage reduction during the operation conditions. Authors concluded that modern loads can significantly minimize the voltage reduction impact on the power system. Work in [22] looked into the non-linear loads and their impact on the system for the purpose of developing a PC program to investigate the non-linear components behavior. A field survey was done to identify the most common non-linear loads in the residential and commercial classes. Then, experimental measurements of elevator, escalator, pump, fan, and other commercial loads were conducted based on this survey. The ZIP load model was fitted into the data obtained from the measurements. Similar research in [3] aimed to update the ZIP coefficients in [6] taking into consideration the technology advancement and the modern devices used in the residential and commercial classes. It revealed that ZIP model is able to represent the small motors behavior and the power electronic conversion devices, but it is not convenient for presenting the motor loads behavior that carry mechanical loads with constant torque. [19] also aimed to determine the ZIP coefficients by studying the model performance on the end-use components taking into account the loads details such as demand response and energy efficiency programs that have a significant impact on energy consumption. ZIP coefficients of several lighting fixtures, e.g., CFL, LED, and incandescent, were determined in this work.

Authors in [17] studied the performance of game consoles and TVs by updating the ZIP model coefficients for the new version of these appliances that have released recently. The model was developed based on several tests were carried out on game consoles such as PS3, Xbox. Research in [5] also tended to do a similar study on modern flat TVs by studying its behavior and investigating the energy consumption of these components and their impact on power system stability. Different types of TVs such as LCD and LED with several sizes were tested in the laboratory and subjected to different voltage variations in order to develop the ZIP model and derive the coefficients. [23] aimed to validate the ZIP model in various customer classes versus the measured values obtained from the laboratory test. Authors also used the information obtained from the previous laboratory experiment to compare between the behavior of the recent and old loads by determining the ZIP model to represent the loads that are exposed to CVR technique. The modeled load in this work are the plugged equipment, lighting fixtures, cooling system, and some commercial loads such as air compressor and fans. It was found that the latest loads behave differently than the older appliances.

According to [10], based on the determination of model coefficients, ZIP model has high accuracy with calculating the active power for most of the residential home appliances, but not as good as precision with the reactive power. On the other hand, [24] proposed a new home-grid system based on solar energy which is called a hybrid AC/DC solar powered Home grid model. This new system was suggested based on the specifications of the most frequently used loads in residential homes. Thus, experiments were done to study loads behavior, and ZIP model coefficients were identified to present the loads' characteristics. [1] developed aggregated load models for the sake of more accuracy in forecasting active and reactive power for the latest, non-linear, most frequently loads, such as drive-controlled motors and electronic devices. ZIP load model has been chosen for the developed approach and component-based method was selected to identify the coefficients of this model.

[30] primarily compared the three statics load models, which are polynomial ZIP, phase angle-related ZIP, and Exponential model, and discussed their CVR influence and suggested the

ellipsoidal algorithm as an approach to achieve more accurate load models. The coefficients of the three models were identified and the results illustrated that phase angle-related ZIP was the only model who has a better accuracy with showing the V-P relationship where the power is decreased by raising the applied voltage. Work in [8] intended to update the load modeling for non-traditional loads, such as power electronic interfaced loads, by conducting aggregation of load modeling for the residential and commercial classes in the UK. Important changes in load characteristics were noticed in this study, which leads to the necessity of more extensive assessment of demand-side management and its association with distributed generation.[12] also extracted ZIP coefficients for the CFL and LED lighting fixtures to study CVR advantages for individual distribution feeder types, and investigate the CVR impact on national levels.

Thus, a comprehensive review of all ZIP coefficients is executed to document all these above-mentioned researches that identified ZIP model coefficients for the loads from 1998 to the present. The ZIP coefficients tables below are classified into two categories: US-based voltage and International based voltage. The US-based voltage is the voltage that is used in the United States, which is a single-phase voltage is 120 V & 277 V with 60 Hz frequency, and the international-based voltage is the voltage used in Europe and Asia, where the single-phase voltage is 220 & 230 V with 50 Hz frequency.

4.2.1 120V / 60 Hz – US Based Voltage

4.2.1.1 Constant-Based ZIP coefficients

The constant-based ZIP coefficients is this section are related to the Constant Impedance Z, Constant Current I, and Constant Power P for the active and reactive power. These ZIP coefficients are grouped according to EnergyPlus, and the energy consumption of facilities in EnergyPlus is grouped according to end-use category type for the purpose of the data collected and the available end-use categories in EnergyPlus, the following are selected and utilized: Heating, Cooling, Interior Lighting, Exterior Lighting, Interior Equipment, Exterior Equipment, Fans, Pumps, Heat Rejection, Humidification, Heat Recovery, water systems, and Refrigerator [45]. Thus, the ZIP coefficients review in this section are sorted based on the US based voltage.

Heating

Heating end-use includes the devices used for heating purposes such as resistive and baseboard heater. Tables 4.1 shows the ZIP coefficients for load components in the heating end-use, where Resistive heater (1) is the ZIP coefficients with 100 V cutoff voltage, Resistive heater (2) is the ZIP coefficients with variable cutoff voltage which is the shut off voltage.

Table 4.1: ZIP Coefficients for Heating components – 120V US based voltage

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Resistive heater (1)	[23]	0.640	0.590	-0.230	0.130	0.750	0.120
Resistive heater (2)	[23]	0.920	0.100	-0.020	0.150	0.860	-0.010
Resistive Load	[22]	1.000	0.000	0.000	0.000	0.000	1.000
Dryer heater	[6]	0.960	0.050	-0.010	0.000	0.000	0.000
Industrial heater/ blower	[6]	0.980	0.020	0.000	0.690	0.250	0.060
Baseboard heater	[6]	1.000	0.000	0.000	0.000	0.000	0.000

Cooling

Cooling end-use includes the systems used in the residential class to cool the place such as air conditioner. Table 4.2 shows the ZIP coefficients for cooling components.

Table 4.2: ZIP Coefficients for Cooling components – 120V US based voltage

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Air conditioner (1)	[23]	1.170	-1.830	1.660	15.680	-27.150	12.470
Air conditioner (2)	[23]	1.600	-2.690	2.090	12.530	-21.110	9.580

Interior/Exterior Lighting

The interior/exterior lighting end-use includes the indoor and outdoor lighting components used in the residential class. Interior light fixtures can be installed in different areas of the house such as bathroom, kitchen, and living room. On the other hand, the exterior light is used to illuminate the outside areas such as garage, porch, and patio. The documented lighting fixtures are fluorescent, compact fluorescent lamp (CFL), incandescent, Light Emitting Diode (LED), high-pressure sodium (HID), Tungsten light, halogen, and induction light. Table 4.3 shows the ZIP coefficients for Interior/Exterior Lighting components.

Table 4.3: ZIP Coefficients for interior/exterior lighting – 120V US based voltage

Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
Fluor lamp (U-shape)	[22]	-0.300	1.270	0.040	-9.230	16.640	-6.400
Fluor lamp (Spot)	[22]	-0.640	2.170	-0.530	-1.020	2.800	-0.780
Fluor lamp (Magnetic)	[22]	-5.240	10.710	-4.470	-5.680	12.270	-5.590
Fluor lamp (Electronic)	[22]	-7.420	13.970	-5.550	7.420	-10.590	4.180
Fluor lamp T8_32W - Instant-on electronic ballast	[3]	0.350	0.720	-0.040	0.280	-0.900	0.030
Fluor lamp T12_40W - Instant-on electronic ballast	[3]	0.340	0.710	-0.030	0.200	-0.760	0.020
Fluor lamp T8_32W- Instant-on no flicker electronic ballast	[3]	-0.030	1.100	-0.050	0.320	-0.750	0.030
Fluor lamp T12_40W- Instant-on no flicker electronic ballast	[3]	0.060	0.970	-0.030	0.240	-0.600	0.020
Electronically ballasted Fluor 1-(composite load)	[6]	-2.480	5.460	-1.970	0.000	0.000	0.000
Electronically ballasted Fluor 2-(composite load)	[6]	-1.600	3.580	-0.980	0.790	-0.160	0.360
CFL(1)	[23]	0.810	-1.030	1.220	0.860	-0.820	0.960
CFL(2)	[23]	-0.630	1.660	-0.030	-0.340	1.400	-0.060
Electronic CFL 1	[6]	0.140	0.770	0.090	-0.060	-0.340	-0.600
Electronic CFL 2	[6]	0.160	0.790	0.050	0.180	-0.830	-0.350

Magnetic CFL	[6]	0.340	1.310	-0.650	3.030	-2.890	0.860
CFL 19W	[3]	-0.420	1.500	-0.060	0.660	-1.160	0.060
CFL 23W	[3]	-0.280	1.350	-0.050	0.580	-1.110	0.050
CFL 20W	[3]	-0.300	1.360	-0.050	0.600	-1.080	0.040
External Fluor dimmer	[6]	-0.480	1.890	-0.410	12.210	-18.380	7.160
Incandescent light(1)	[23]	0.470	0.630	-0.100	0.550	0.380	0.070
Incandescent light(2)	[23]	0.540	0.500	-0.040	0.460	0.510	0.030
Incandescent	[30]	0.690	0.000	0.300	0.000	0.000	0.000
LightBulb 100W	[3]	0.640	0.400	0.000	0.000	0.000	0.000
Incandescent light	[22]	0.430	0.640	-0.080	0.000	0.000	1.000
LED light(1)	[23]	0.580	1.130	-0.710	1.780	-0.800	0.020
LED light(2)	[23]	0.690	0.920	-0.610	1.840	-0.910	0.070
High pressure sodium HID(1)	[23]	0.090	0.700	0.210	16.600	-28.770	13.170
High pressure sodium HID(2)	[23]	-0.160	1.200	-0.040	3.260	-4.110	1.850
High pressure sodium lamps	[6]	0.980	-0.030	0.060	29.840	-45.260	14.410
Mercury vapor HID light(1)	[23]	0.520	1.020	-0.540	-1.330	2.400	-0.070
Mercury vapor HID light(2)	[23]	-0.160	2.330	-1.170	0.420	-1.010	1.590
Halogen(1)	[23]	0.460	0.640	-0.100	4.260	-6.620	3.360
Halogen(2)	[23]	0.510	0.550	-0.050	0.430	0.520	0.050
Halogen_100W	[3]	0.660	0.390	0.000	0.000	0.000	0.000
Halogen	[22]	0.480	0.570	-0.050	-3.570	0.690	0.000
Induction light(1)	[23]	2.960	-6.040	4.080	1.480	-1.290	0.810
Induction light(2)	[23]	0.180	-0.750	1.570	7.510	-12.350	5.840
Tungsten light(1)	[23]	0.430	0.700	-0.130	-0.110	0.660	0.450
Tungsten light(2)	[23]	0.450	0.660	-0.110	0.210	0.110	0.680
Electronic ballast(1)	[23]	0.220	-0.500	1.280	9.640	-21.590	12.950
Metal halide HID electronic ballast(1)	[23]	1.000	-2.020	2.020	8.800	-18.640	10.840
Electronic ballast(2)	[23]	-0.070	0.080	0.990	9.320	-20.960	12.640
Metal halide HID electronic ballast(2)	[23]	-0.030	-0.060	1.090	11.400	-23.500	13.100
Electronic dimming ballast	[6]	-0.160	1.770	-0.620	0.000	0.000	0.000

Magnetic ballast (1)	[23]	-1.580	3.790	-1.210	36.180	-67.780	32.600
Metal halide HID magnetic ballast (1)	[23]	0.860	-0.660	0.800	32.540	-59.830	28.290
Magnetic ballast (2)	[23]	-3.160	6.850	-2.690	34.260	-64.040	30.780
Metal halide HID magnetic ballast (2)	[23]	-0.200	1.350	-0.150	1.370	-0.630	0.260

Interior/Exterior Equipment

Interior/exterior equipment includes several sorts of electrical appliances used in the residential house for different functionalities such as cooking and cleaning. Most of this equipment are listed in the following tables according to the review adopted in the last section. Table 4.4 shows ZIP coefficients for equipment and appliances obtained from the literature review, e.g., battery charger, coffee maker, computer, oven, dish washer, iron, and vacuum cleaner. Tables 4.5 and 4.6 also lists the ZIP coefficients for video game console, which are PS4 and Xbox, and TVs such as CRT, LED, and LCD for different sizes.

Table 4.4: ZIP Coefficients for home appliances – 120V US based voltage

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Battery charger	[6]	3.510	-3.940	1.430	5.800	-7.260	2.460
Coffee maker(1)	[23]	0.130	1.620	-0.750	3.890	-6.000	3.110
Coffee maker(2)	[23]	0.980	0.030	-0.010	0.840	-0.300	0.460
PC (Monitor & CPU)(1)	[23]	0.200	-0.300	1.100	0.000	0.600	0.400
PC (Monitor & CPU)(2)	[23]	0.180	-0.260	1.080	-0.190	0.960	0.230
PC	[30]	0.340	0.000	0.650	0.000	0.000	0.990
Computer	[22]	0.270	-0.610	1.340	-0.110	0.020	1.080
Copier(1)	[23]	0.870	-0.210	0.340	2.140	-3.670	2.530
Copier(2)	[23]	0.520	0.450	0.030	0.390	-0.250	0.860
DishWasher_HD	[3]	0.950	0.000	0.000	0.000	0.000	0.000
DishWasher_NW	[3]	0.990	0.000	0.000	0.000	0.000	0.000
DishWasher_PP	[3]	1.000	0.000	0.000	0.000	0.000	0.000

Dryer	[3]	1.020	0.000	0.000	1.000	0.000	0.000
Laptop charger(1)	[23]	-0.280	0.500	0.780	-0.370	1.270	0.130
Laptop charger(2)	[23]	0.250	-0.480	1.230	0.140	0.320	0.540
Microwave(1)	[23]	1.390	-1.960	1.570	50.070	-93.550	44.480
Microwave(2)	[23]	-0.270	1.160	0.110	15.640	-27.740	13.100
Microwave	[22]	0.550	1.860	-1.400	19.740	-31.300	12.560
Microwave	[6]	-2.780	6.060	-2.280	0.000	0.000	0.000
Minibar(1)	[23]	2.500	-4.100	2.600	2.560	-2.760	1.200
Minibar(2)	[23]	3.950	-6.460	3.510	4.840	-6.640	2.800
Office equipment 1	[6]	0.340	-0.320	0.980	0.000	0.000	0.000
Office equipment 2	[6]	0.080	0.070	0.850	0.000	0.000	0.000
Oven	[3]	0.990	0.000	0.000	0.000	0.000	0.000
Projector(1)	[23]	0.230	-0.520	1.290	0.240	-0.170	0.930
Projector(2)	[23]	0.190	-0.450	1.260	10.180	-18.010	8.830
Range	[3]	0.970	0.000	0.000	0.000	0.000	0.000
TV, Printers, Fax	[22]	1.000	0.000	0.000	0.000	0.000	1.000
Vacuum cleaner(1)	[23]	1.180	-0.380	0.200	4.100	-5.870	2.770
Vacuum cleaner(2)	[23]	0.920	0.070	0.010	0.910	-0.020	0.110
Washing machine	[6]	0.050	0.310	0.630	-0.560	2.200	-0.650
Iron	[30]	0.920	0.000	0.070	0.800	0.160	0.040
Mixer	[30]	0.710	0.000	0.280	0.290	0.700	0.000

Table 4.5: ZIP Coefficients for Video Game Console – 120V US based voltage

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Game console (1)	[23]	-0.630	1.230	0.400	0.760	-0.930	1.170
Game console (2)	[23]	0.360	-0.580	1.220	0.340	-0.120	0.780
Xbox 360	[17]	0.115	-0.301	1.186	2.875	-5.912	4.037
Xbox 360 & LCD TV	[17]	0.384	-0.733	1.349	1.890	-3.371	2.481
Xbox 360 & LCD TV ss	[17]	0.307	-0.630	1.323	1.282	-1.857	1.575
Xbox 360 & LED TV	[17]	-0.033	-0.104	1.137	2.304	-4.303	2.998

Xbox 360 & LED TV ss	[17]	0.249	-0.516	1.266	2.104	-3.635	2.531
Wii	[17]	0.318	-0.338	1.019	2.078	-3.468	2.390
Wii & LCD TV	[17]	0.416	-0.798	1.382	-0.377	1.643	-0.266
Wii & LCD TV 50% v	[17]	0.438	-0.795	1.357	-0.344	1.595	-0.251
Wii & LED TV ss	[17]	0.314	-0.568	1.254	0.763	0.156	0.081
Wii & LED TV	[17]	0.789	-1.204	1.415	0.816	0.076	0.108
PS3	[17]	0.376	-0.738	1.362	0.831	0.409	-0.240
PS3 ss	[17]	0.167	-0.269	1.102	0.627	0.719	-0.346
PS3 & LCD TV ss	[17]	0.196	-0.416	1.220	-0.084	1.513	-0.429
PS3 & LCD TV 50% v	[17]	0.232	-0.501	1.268	-0.048	1.477	-0.429
PS3 & LED TV	[17]	0.202	-0.374	1.172	0.490	1.070	-0.560
PS3 & LED TV ss	[17]	0.178	-0.357	1.179	0.615	0.844	-0.459

LCD 22 " (3) is the ZIP coefficients with no constraints, which means that coefficients not bounded to [0,1], LCD 22 " (4) is the ZIP coefficients with one constraints that Zp + Ip + Pp = 1, and LCD 22 " (5) is the ZIP coefficients with two constraints: coefficients bounded to [0,1] and Zp + Ip + Pp.

Table 4.6: ZIP Coefficients for TVs – 120V US based voltage

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
LCD Television (1)	[23]	0.110	-0.170	1.060	1.580	-1.720	1.140
LCD Television (2)	[23]	0.330	-0.570	1.240	19.000	-33.220	15.220
LCD 22 " (3)	[5]	0.473	-0.898	1.427	9.035	-16.732	8.658
LCD 22 " (4)	[5]	0.465	-0.889	1.425	9.225	-16.934	8.709
LCD 22 " (5)	[5]	0.000	0.000	1.000	0.000	0.000	1.000
LCD 40 " (3)	[5]	0.163	-0.325	1.161	0.464	1.000	-0.465
LCD 40 " (4)	[5]	0.170	-0.333	1.164	0.479	0.981	-0.460
LCD 40 " (5)	[5]	0.000	0.000	1.000	1.000	0.000	0.000
LCD 55 " (3)	[5]	0.546	-1.051	1.499	-0.646	2.204	-0.560
LCD 55 " (4)	[5]	0.580	-1.088	1.509	-0.637	2.194	-0.557
LCD 55 " (5)	[5]	0.000	0.000	1.000	0.247	0.753	0.000

LCD	[30]	0.000	0.000	1.000	0.030	0.000	0.960
LCD TV	[17]	0.497	-0.941	1.444	-0.766	2.398	-0.632
LCD TV - black sc	[17]	0.447	-0.848	1.401	-0.795	2.436	-0.641
LCD TV - black sc 1080	[17]	0.580	-0.976	1.396	-0.636	2.218	-0.582
LCD TV - white sc	[17]	0.540	-0.977	1.437	-0.793	2.452	-0.659
LCD TV - white sc 1080	[17]	0.496	-0.941	1.445	-0.819	2.483	-0.664
LCD	[3]	0.000	0.000	1.000	0.000	0.000	0.150
LED 26 " (3)	[5]	0.285	-0.563	1.278	3.127	-5.580	3.428
LED 26 " (4)	[5]	0.286	-0.564	1.279	3.260	-5.726	3.466
LED 26 " (5)	[5]	0.000	0.000	1.000	0.000	0.000	1.000
LED 32 " (3)	[5]	0.551	-1.026	1.464	6.396	-11.078	5.673
LED 32 " (4)	[5]	0.613	-1.096	1.483	6.453	-11.143	5.690
LED 32 " (5)	[5]	0.000	0.000	1.000	0.000	0.000	1.000
LED 55 " (3)	[5]	0.276	-0.546	1.271	0.546	0.909	-0.482
LED 55 " (4)	[5]	0.271	-0.540	1.269	0.726	0.697	-0.423
LED 55 " (5)	[5]	0.000	0.000	1.000	1.000	0.000	0.000
LED TV	[17]	2.694	-4.291	2.597	0.590	0.866	-0.456
LED TV - BL0	[17]	0.258	-0.334	1.077	0.546	0.680	-0.226
LED TV - BL14	[17]	0.394	-0.690	1.296	0.389	1.193	-0.582
LED TV - BL20	[17]	0.410	-0.721	1.311	0.176	1.664	-0.840
CRT	[3]	0.000	0.000	1.000	0.000	0.000	0.150
TV	[30]	0.000	0.000	0.990	0.040	0.000	0.950

Fan

Fan end-use covers the fan used in the residential appliances as shown in table 4.7

Table 4.7: ZIP Coefficients for Fans – 120V US based voltage

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Fan (1)	[23]	-0.470	1.710	-0.240	2.340	-3.120	1.780
Fan (2)	[23]	0.260	0.900	-0.160	0.500	0.620	-0.120

Fan	[30]	0.870	0.000	0.120	0.750	0.000	0.240
Fan1	[22]	0.610	0.420	-0.040	0.830	0.170	0.000
Fan2 (VSD)	[22]	-0.960	3.050	-1.090	-8.210	14.270	-5.060
Fan - speed 1	[3]	0.870	0.140	-0.010	0.110	0.160	-0.010
Fan - speed 2	[3]	0.740	0.270	-0.020	0.030	0.280	-0.020
Fan - speed 3	[3]	0.390	0.660	-0.050	-0.100	0.460	-0.030
Fan - speed 3B	[3]	0.450	0.570	-0.040	-0.030	0.340	-0.020

Pump

Pump end-use includes the components used in the residential class such as heat pump, as shown in table 4.8 below.

Table 4.8: ZIP Coefficients for Pumps – 120V US based voltage

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Heat pump 1 (split design)	[6]	0.720	-0.980	1.250	14.780	-23.720	9.930
Heat pump 2 blower	[6]	5.460	-14.210	9.760	-14.850	31.590	-15.740
Heat pump 2 compressor	[6]	0.850	-1.400	1.560	22.920	-40.390	18.470
Pump 1	[22]	5.510	-11.300	6.820	11.770	-24.280	13.510
Pump 2 (VSD)	[22]	-35.500	75.710	-39.250	19.230	-40.250	22.020

Refrigerator

The refrigerator end-use presents the loads used for food preservation such as refrigerator and freezer. Table 4.9 shows the ZIP coefficients for the components reviewed in the literature review.

Table 4.9: ZIP Coefficients for Refrigerators – 120V US based voltage

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Refrigerator (1)	[23]	1.170	-1.830	1.660	7.070	-10.940	4.870
Refrigerator (2)	[23]	5.030	-8.480	4.450	17.440	-28.620	12.180
Refrigerator/freezer	[6]	1.190	-0.260	0.070	0.590	0.650	-0.240

Motor

Table 4.10 shows the ZIP coefficients for Adjustable Speed Drive motors (ASD) and dryer motor

Table 4.10: ZIP Coefficients for motors – 120V US based voltage

Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
ASD 1	[6]	0.430	0.610	-0.050	-1.210	3.470	-1.260
ASD 2	[6]	3.190	-3.840	1.650	1.090	-0.180	0.090
Dryer motor	[6]	1.910	-2.230	1.330	2.510	-2.340	0.830

Commercial Loads

Table 4.11: ZIP Coefficients for commercial loads – 120V US based voltage

Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
Air compressor 1 Ph(1)	[23]	0.710	0.460	-0.170	-1.330	4.040	-1.710
Air compressor 3 Ph(1)	[23]	0.240	-0.230	0.990	4.790	-7.610	3.820
Air compressor 1 Ph(2)	[23]	0.730	0.380	-0.110	0.450	0.510	0.040
Air compressor 3 Ph(2)	[23]	1.160	-1.810	1.650	3.580	-5.250	2.670
Elevator(1)	[23]	0.400	-0.720	1.320	3.760	-5.740	2.980
Elevator(2)	[23]	2.360	-4.150	2.790	11.690	-19.500	8.810
Elevator (simulated in lab)	[22]	-2.330	4.950	-1.620	2.500	-3.690	2.180
Escalators (simulated in lab)	[22]	12.580	-26.300	14.670	8.510	-14.210	6.700

4.2.1.2 Phase Angle-Based ZIP Coefficients

This form of ZIP model can be described by the active power and phase angle of load components, which can be measured at each voltage level. Thus, the active and reactive power of ZIP loads can be calculated by the given equations (8-9). The constants are limited with the constraint in equation (10).

$$P_i = \frac{V_a^2}{V_o^2} \,.\, S_o \,.\, Z_{\%} \,.\, \cos(Z_\theta) + \frac{V_a}{V_o} \,.\, S_o \,.\, I_{\%} \,.\, \cos(I_\theta) + S_o \,.\, P_{\%} \,.\, \cos(P_\theta) \qquad (8)$$

$$Q_i = \frac{V_a^2}{V_o^2} . S_o . Z_{\%} . Sin(Z_\theta) + \frac{V_a}{V_o} . S_o . I_{\%} . Sin(I_\theta) + S_o . P_{\%} . Sin(P_\theta) \quad (9)$$

$$Z_{\%} + I_{\%} + P_{\%} = 1 \quad (10)$$

Where P_i is an active power consumption of the i^{th} load, Q_i is reactive power consumption of the i^{th} load, V_a is actual terminal voltage, V_o is nominal terminal voltage, S_o is apparent power consumption at nominal voltage, $Z_{\%}$ is fraction of load that is constant impedance, $I_{\%}$ is fraction of load that is constant current, $P_{\%}$ is fraction of load that is constant power, Z_θ is phase angle of the constant impedance component,$I_\theta$is phase angle of the constant current component, $P_\theta$is phase angle of the constant power component. The six constants in the following equations are representing the ZIP loads behavior as a function of the applied voltage. Once the six values of constants are experimentally determined, they can be inserted to (5) and (6) to calculate P and Q for each load component. The following tables are the review of all the ZIP coefficients determined in the previous researches. Lighting, equipment, and fan end-use are shown in the tables 4.12, 4.13, 4.14 respectively.

Interior/Exterior Lighting

Table 4.12: Phase angle-based ZIP Coefficients for interior/exterior lighting

Component	Ref	Z%	I%	P%	Zpf	Ipf	Ppf
Incandescent	[30]	0.6886	0.0001	0.3015	0.0000	-3.1400	0.0000
Incandescent light 75W	[19]	0.5711	0.4257	0.0032	1.0000	-1.0000	0.9996
Incandescent 75W	[12]	0.5711	0.4257	0.0032	1.0000	-1.0000	1.0000
CFL	[30]	0.2700	0.1600	0.5600	-1.7300	-1.5400	-0.4400
CFL 13W	[19]	0.4085	0.0067	0.5849	-0.8785	0.4208	-0.7792
CFL 42W	[19]	0.4867	-0.3752	0.8884	-0.9702	-0.6980	-0.7895
CFL 20W	[19]	-0.0105	1.0000	0.0105	0.0000	-0.8101	0.8998
CFL-13W	[12]	0.4085	0.0067	0.5849	-0.8800	0.4200	-0.7800

CFL-20W	[12]	-0.0105	1.0000	0.0105	0.0000	-0.8100	0.9000
CFL-42W	[12]	0.4867	-0.3752	0.8884	-0.9700	-0.7000	-0.7900
LED light - High quality	[19]	-0.4280	0.8664	0.5616	0.9990	-0.9990	0.9990
LED light - low quality	[19]	0.9852	0.0094	0.0054	-0.3455	-0.9996	0.7876
LED light - medium quality	[19]	-0.4550	0.4573	0.9977	-0.8191	-0.9843	-0.8613

Interior/Exterior Equipment

Table 4.13: Phase angle-based ZIP Coefficients for interior/exterior equipment

Component	Ref	Z%	I%	P%	Zpf	Ipf	Ppf
Iron	[30]	0.9183	0.0000	0.0717	0.0000	-0.3600	-0.0100
Mixer	[30]	0.7065	0.0000	0.2835	0.1300	-0.0800	0.1700
PC	[30]	0.3273	0.1251	0.5430	1.2000	-1.1100	-1.0800
TV	[30]	0.1402	0.0187	0.8352	-3.0300	-2.4500	-0.6500
Plasma-Sony TV	[19]	-0.3207	0.4836	0.8371	0.8491	0.9083	-0.9924
Plasma - Sony	[12]	-0.3207	0.4836	0.8371	0.8500	0.9100	-0.9900
LCD	[30]	0.1745	0.0015	0.8146	-3.0500	-3.0200	-0.6600
LCD - Del l 1901FP	[19]	-0.4070	0.4629	0.9441	-0.9712	-0.9779	-0.9717
LCD-Clarity TV	[19]	-0.0383	0.0396	0.9987	0.6079	-0.5374	-0.9998
LCD - Dell	[12]	-0.4070	0.4629	0.9441	-0.9700	-0.9800	-0.9700
LCD - Clarity	[12]	-0.0383	0.0396	0.9987	0.6100	-0.5400	-1.0000
TV-Magnovox CRT	[19]	0.0015	0.8266	0.1719	-0.9872	0.9999	-0.9204
TV-Magnavox CRT	[12]	0.0015	0.8266	0.1719	-0.9900	1.0000	-0.9200

Fan

Table 4.14: Phase angle-based ZIP Coefficients for fans

Component	Ref	Z%	I%	P%	Zpf	Ipf	Ppf
Fan	[30]	0.8457	0.0000	0.1444	0.3600	0.5500	0.7300
Fan	[19]	0.7332	0.2534	0.0135	0.9686	0.9530	-0.9997
Fan and 20W CFL	[19]	0.5518	0.5188	-0.0706	0.9848	-0.9994	-0.9215

Oscillating Fan	[12]	0.7332	0.2534	0.0135	0.9700	0.9500	-1.0000

4.2.2 220V / 50 Hz – International Based Voltage

The following tables are the review of all the ZIP coefficients in the previous researches according to 220V – international based, and categorized into cooling, lighting, equipment, fan, and refrigerators end-use.

Cooling

Table 4.15: ZIP Coefficients for cooling – 220V International based

Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
Air conditioner	[10]	1.550	-2.120	1.570	1.560	-2.140	1.580
Air conditioner	[24]	0.442	0.442	0.116	1.215	0.090	-0.304

Interior/Exterior Lighting

Table 4.16: ZIP Coefficients for interior/exterior lighting – 220V International based

Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
Incandescent light	[10]	0.490	0.590	-0.080	2.200	-1.770	0.570
Incandescent light	[24]	0.796	0.406	-0.202	0.313	0.365	0.322
Fluor lamp	[24]	2.037	-0.795	-0.242	0.638	0.488	-0.125
CFL	[10]	0.110	0.640	0.250	0.000	1.090	-0.090
CFL	[24]	-0.887	2.145	-0.258	-0.500	1.839	-0.339
CFL	[8]	0.100	0.900	0.000	0.270	-1.260	-0.010
CFL	[1]	-0.010	0.960	0.050	0.100	-0.730	-0.370
LFL	[1]	0.000	0.000	1.000	0.000	0.000	0.000
LED light	[10]	0.730	-1.700	1.970	0.520	-1.410	1.890
LED light	[24]	-0.553	0.500	1.053	-0.026	0.909	0.117
LP LED	[8]	0.230	0.850	-0.080	-1.050	0.040	0.010
HP LED	[8]	0.790	0.820	-0.620	4.120	-4.590	1.480
HP LED	[8]	-0.920	1.840	0.090	-0.490	-0.220	1.700

HP LED	[8]	-4.240	9.560	-4.320	-8.480	17.800	-8.310
HP LED	[8]	-0.860	1.820	0.040	0.390	0.140	0.480

Interior/Exterior Equipment

Table 4.17: ZIP Coefficients for interior/equipment – 220V International based

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Battery charger	[24]	2.177	3.378	-4.556	1.215	1.022	-1.237
Bread toaster	[10]	0.940	0.090	-0.030	0.610	0.560	-0.170
Bread toaster	[24]	1.501	0.349	-0.850	-0.500	1.033	0.467
Coffee maker	[10]	1.010	-0.020	0.010	1.030	-0.040	0.010
Computer	[24]	1.425	0.799	-1.224	1.068	1.773	-1.841
Cooler	[24]	0.867	0.354	-0.221	1.980	-0.888	-0.092
Dishwasher	[10]	0.890	0.110	0.000	-2.750	6.290	-2.540
Induction cooktop	[24]	0.034	0.311	0.655	0.500	3.093	-2.593
Iron	[10]	0.990	0.010	0.000	3.920	-4.860	1.940
Iron	[24]	1.550	1.977	-2.527	1.354	0.173	-0.527
Kettle	[10]	0.950	0.070	-0.020	0.290	1.020	-0.310
Laptop charger	[24]	0.895	0.051	0.055	0.381	1.032	-0.412
Microwave	[10]	1.000	0.600	-0.600	0.000	2.020	-1.020
Microwave	[24]	1.516	0.499	-1.015	1.997	1.872	-2.869
Mixer	[24]	1.129	1.006	-1.135	-1.000	2.988	-0.988
Oven	[10]	0.870	0.220	-0.090	0.870	0.220	-0.090
Rice cooker	[24]	1.883	1.331	-2.214	0.969	1.525	-1.494
UPS	[24]	1.925	1.696	-2.621	0.430	0.973	-0.403
Vacuum cleaner	[10]	0.820	0.220	-0.040	5.950	-7.330	2.380
Washing machine	[10]	0.780	0.340	-0.120	-2.290	5.510	-2.220
LCD-TV	[10]	-0.400	0.450	0.950	3.920	-4.860	1.940
Television	[24]	0.571	0.484	-0.055	2.212	1.233	-2.445
PC desktop	[10]	-0.320	1.140	0.180	1.560	-2.130	1.570

PC monitor	[10]	0.480	-0.640	1.160	0.140	0.260	0.600

Fan

Table 4.18: ZIP Coefficients for fans – 220V International based

Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
Fan	[10]	2.740	-2.640	0.090	1.190	-0.020	-0.170
Fan	[24]	0.583	1.277	-0.860	1.688	2.506	-3.195

Refrigerator

Table 4.19: ZIP Coefficients for refrigerators – 220V International based

Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
Refrigerator	[10]	1.040	-1.570	1.530	5.690	-8.560	3.870
Refrigerator	[24]	0.758	-0.297	0.539	1.000	1.412	-1.412

Motor

The ZIP coefficients for motors determined in [1] are included Adjustable Speed Drive (ASD), higher & power directly connected motors, Single-phase Induction Motor (SPIM), Single-phase Adjustable Speed Drive (SASD), and other types.

Table 4.20: ZIP Coefficients for ASD Motor – Discontinuous Mode of Operation

Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
Lower power V/Hz open-loop ASDs – CT	[1]	0.400	-0.890	1.490	1.600	-3.100	2.500
Lower power V/Hz open-loop ASDs – LT	[1]	0.020	0.000	0.980	1.100	-1.910	1.810
Lower power V/Hz open-loop ASDs – QT	[1]	-0.270	0.760	0.510	0.700	-0.980	1.280
Lower power V/Hz open-loop ASDs – CP	[1]	1.080	-2.500	2.420	2.670	-5.490	3.810
Lower power V/Hz closed-loop ASDs - All	[1]	1.080	-2.500	2.420	2.510	-5.960	4.450

Higher power V/Hz open-loop and closed-loop ASDs - All	[1]	0.130	-0.330	1.200	0.550	-1.700	2.150
Lower and higher power V/Hz ASDs w/ advanced control - All	[1]	0.000	0.000	1.000	1.220	0.450	-0.670

Table 4.21: ZIP Coefficients for ASD Motor – continuous Mode of Operation

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Lower power V/Hz open-loop ASDs - CT	[1]	0.450	-1.070	1.620	1.750	-3.550	2.800
Lower power V/Hz open-loop ASDs - LT	[1]	0.020	0.000	0.980	1.180	-2.180	2.000
Lower power V/Hz open-loop ASDs - QT	[1]	-0.270	0.760	0.510	0.660	-0.970	1.310
Lower power V/Hz open-loop ASDs - CP	[1]	1.080	-2.500	2.420	2.640	-5.500	3.900
Lower power V/Hz closed-loop ASDs - All	[1]	1.080	-2.500	2.420	2.640	-5.500	3.900
Higher power V/Hz open-loop and closed-loop ASDs - All	[1]	0.130	-0.330	1.200	1.300	-2.380	2.080
Lower and higher power V/Hz ASDs w/ advanced control - All	[1]	0.000	0.000	1.000	0.990	-1.960	1.970

Table 4.22: ZIP Coefficients for higher power directly connected motors

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Higher power motors	[1]	0.030	-0.060	1.030	1.600	-2.100	1.500

Table 4.23: ZIP Coefficients for lower power directly connected motors

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
CT	[1]	0.270	-0.630	1.360	1.550	-1.700	1.150
LT	[1]	0.020	-0.020	1.000	1.550	-1.700	1.150
QT	[1]	-0.150	0.430	0.720	1.550	-1.700	1.150
CP	[1]	0.640	-1.530	1.890	1.550	-1.700	1.150

Table 4.24: ZIP Coefficients for SPIM

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
RSIR CT	[1]	0.630	-1.200	1.570	1.400	-0.910	0.510
RSIR LT	[1]	0.310	-0.430	1.120	1.400	-0.910	0.510
RSIR QT	[1]	0.100	0.100	0.800	1.400	-0.910	0.510
RSIR CP	[1]	1.160	-2.420	2.260	1.400	-0.910	0.510
RSCR CT	[1]	0.500	-0.610	1.110	1.540	-1.430	0.890
RSCR LT	[1]	0.340	-0.220	0.880	1.540	-1.430	0.890
RSCR QT	[1]	0.220	0.090	0.690	1.540	-1.430	0.890
RSCR CP	[1]	0.730	-1.160	1.430	1.540	-1.430	0.890

Table 4.25: ZIP Coefficients for SASD

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Higher power V/Hz open-loop SASDs - CT	[1]	0.400	-0.890	1.490	1.540	-3.950	3.410
Higher power V/Hz open-loop SASDs - LT	[1]	0.020	0.000	0.980	0.950	-2.600	2.660
Higher power V/Hz open-loop SASDs - QT	[1]	-0.270	0.760	0.510	0.540	-1.650	2.110
Higher power V/Hz open-loop SASDs - CP	[1]	1.080	-2.500	2.420	2.470	-6.040	4.560
Higher power V/Hz closed-loop SASDs - All	[1]	1.080	-2.500	2.420	2.470	-6.040	4.560
Higher power advanced controlled SASDs - All	[1]	0.000	0.000	1.000	1.450	-3.660	3.190
Lower power V/Hz open-loop SASDs - CT	[1]	0.400	-0.890	1.490	-3.320	10.500	-8.180
Lower power V/Hz open-loop SASDs - LT	[1]	0.020	0.000	0.980	-3.650	10.340	-7.690
Lower power V/Hz open-loop SASDs - QT	[1]	-0.270	0.760	0.510	-3.670	10.310	-7.640
Lower power V/Hz open-loop SASDs - CP	[1]	1.080	-2.500	2.420	-3.020	10.620	-8.600

Lower power V/Hz closed-loop SASDs - All	[1]	1.080	-2.500	2.420	-3.020	10.620	-8.600
Lower power advanced controlled SASDs - All	[1]	0.000	0.000	1.000	-3.610	10.390	-7.780

Table 4.26: ZIP Coefficients for EV type battery charger – 220V International based

Component	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
EV Type battery charger - A	[8]	0.010	0.990	0.000	0.127	1.281	-0.402
EV Type battery charger - B	[8]	0.075	0.926	0.000	0.861	0.062	0.084

4.3 Mapping and Visualization

With regard to all previous works that related to ZIP model coefficients determination, and grouping all of them into end-use categories, the visualization of load components based on the ZIP coefficients obtained from the literature review is achieved in this section. The load components are selected among the reviewed ZIP coefficients based on the most commonly used in the residential class. Then, residential load components are grouped into end-use types according to EnergyPlus categorization.

In order to visualize the end-use components, the active and reactive power at different voltage levels for each component needs to be obtained throughout the mathematical equations of the polynomial model shown in the following:

$$P = P_o\left[Z_p\left(\frac{V}{V_o}\right)^2 + I_p\left(\frac{V}{V_o}\right) + P_p\right] \qquad (6)$$

$$Q = Q_o\left[Z_q\left(\frac{V}{V_o}\right)^2 + I_q\left(\frac{V}{V_o}\right) + P_q\right] \qquad (7)$$

Where Zp, Ip, Pp and Zq, Iq, Pq are ZIP model coefficients for the active power and reactive power respectively. ZIP coefficients will be obtained from the literature review of the previous work. P_o

is equal to 1 pu as it is the nominal active power of the load component. V_o equal to 1 pu, and V is the applied voltage that is changed within a specific range of voltage variations starting from 0.80 pu to the 1.10 pu of the nominal voltage. This range of voltage is defined according to the reference [23] based on the American National Standards Institute (ANSI) Standard for Conservation Voltage Reduction (CVR) study purposes . Therefore, ZIP coefficients obtained from the literature review & applied voltage within CVR ranges are substituted into ZIP model equations so the active and reactive power can be calculated at each voltage level.

An example of the implemented calculation is provided in table 4.27 for the compact fluorescent lamp (CFL) in lighting end-use type. The ZIP coefficients for the compact fluorescent lamp Zp, Ip, Pp, Zq, Iq, and Pq are 0.810, -1.030, 1.220, 0.860, -0.820, and 0.960 respectively [23].With respect to ZIP model equations for active and reactive power, ZIP coefficients are substituted for each voltage level to calculate the active and reactive power. At voltage 0.80 pu, the active and reactive power for the compact fluorescent lamp are 0.625 pu and 0.803 pu respectively. By increasing the voltage values, the active and reactive power will be increased. For instance, the active and reactive power for the CFL at voltage 0.85 pu are 0.743 pu and 0.851 pu respectively.

Table 4.27: Calculated active and reactive power for the CFL

V (pu)	Calculated P (pu)	Calculated Q (pu)
0.80	0.914	0.854
0.85	0.930	0.884
0.90	0.949	0.919
0.95	0.973	0.957
1.00	1.000	1.000
1.05	1.032	1.047
1.10	1.067	1.099

The figure 4.2 shows the relationship between voltage and active power for all documented interior/exterior lighting components, where the horizontal axis represents the applied voltage V in pu, which is varied from 0.80 to 1.10, and the vertical axis represents the calculated active power P in pu. Similar work is plotted and shown in figure 4.3 for reactive power Q

4.3.1 Interior/Exterior Lighting

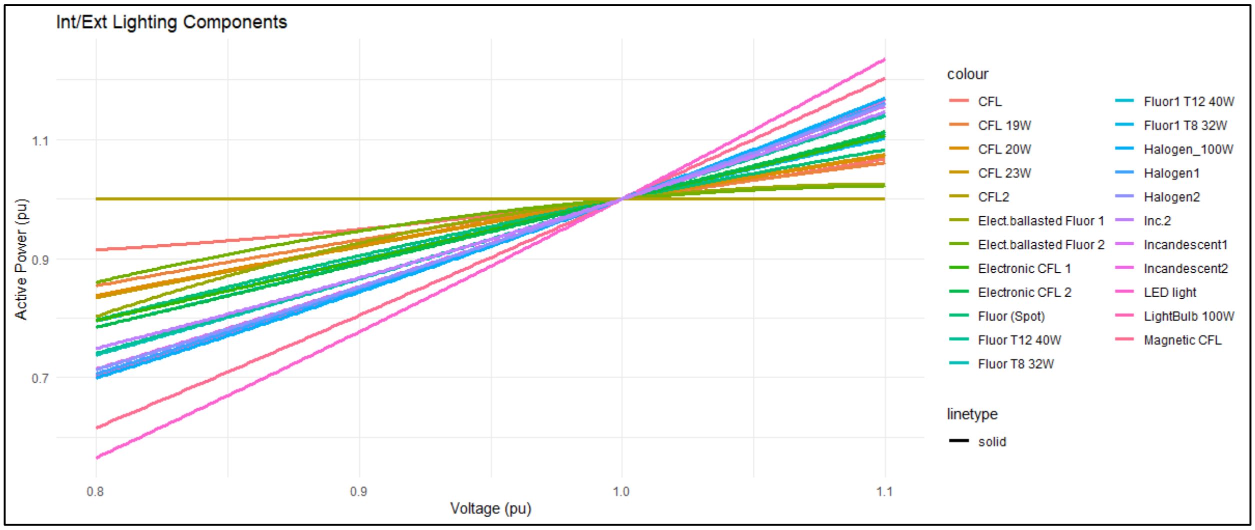

Figure 4.2 V-P for Interior/Exterior Lighting End-Use Components

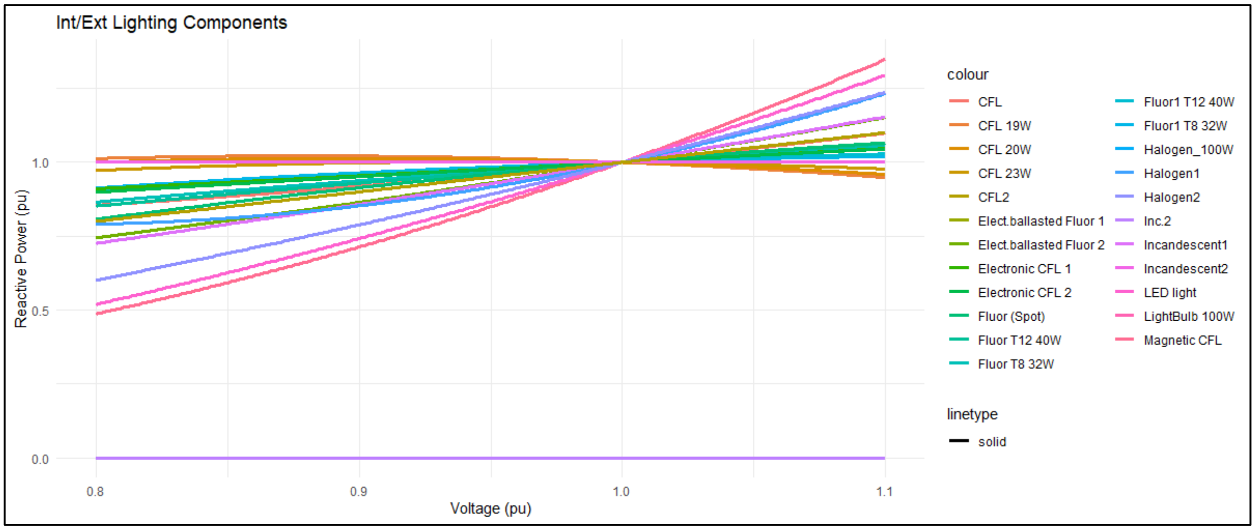

Figure 4.3 V-Q for Interior/Exterior Lighting End-Use Components

4.3.2 Interior/Exterior Equipment

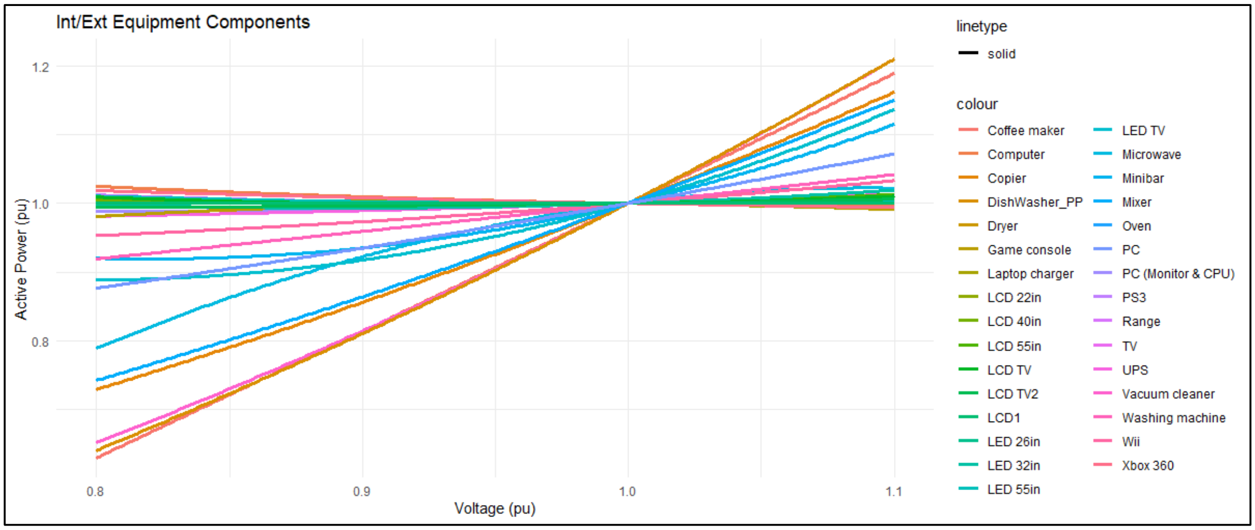

Figure 4.4 V-P for Interior/Exterior Equipment End-Use Components

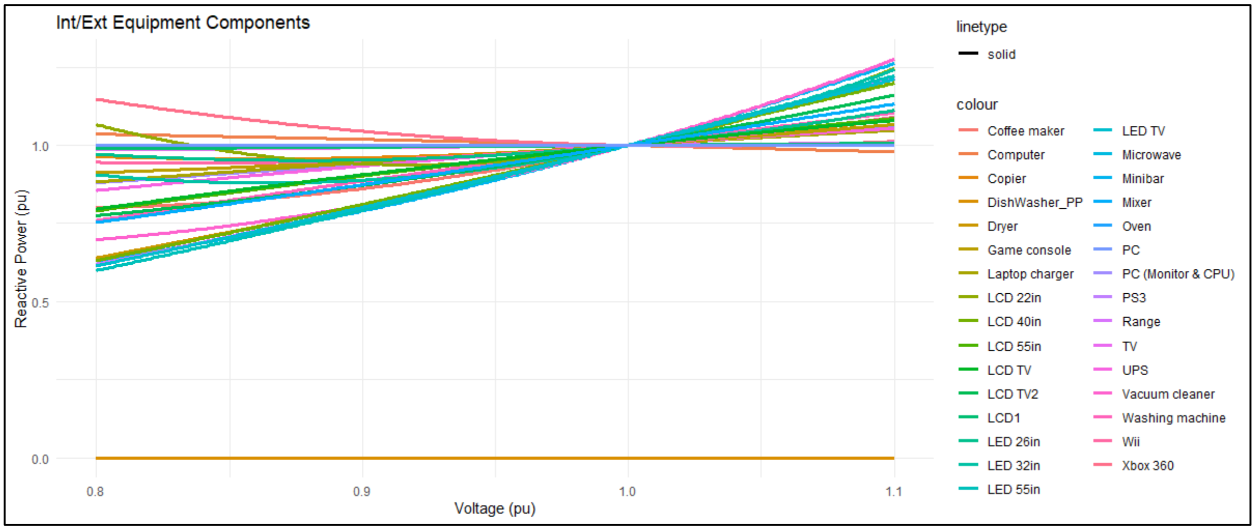

Figure 4.5 V-Q for Interior/Exterior Equipment End-Use Components

4.3.3 Refrigerator

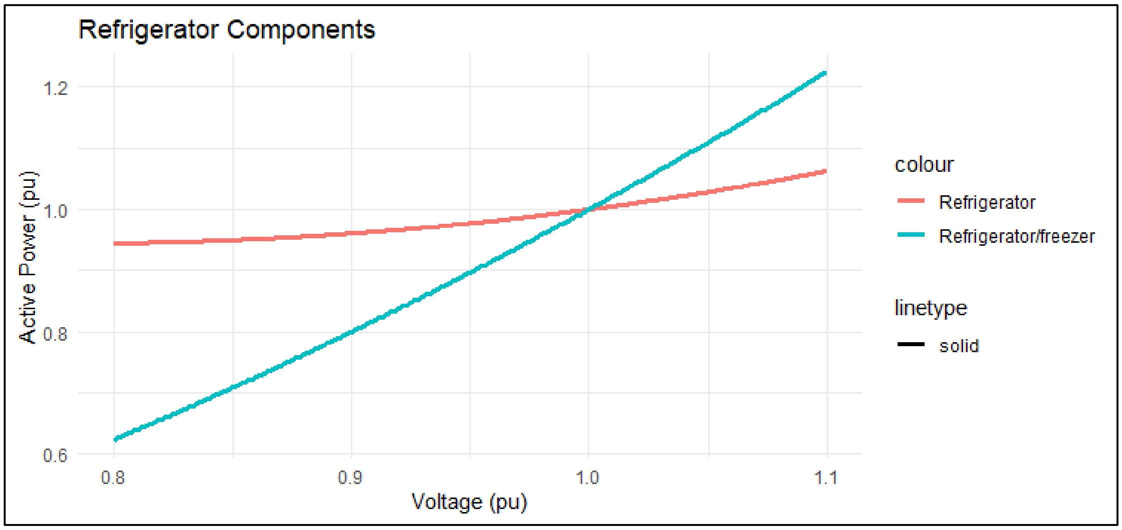

Figure 4.6 V-P for Refrigerators End-Use Components

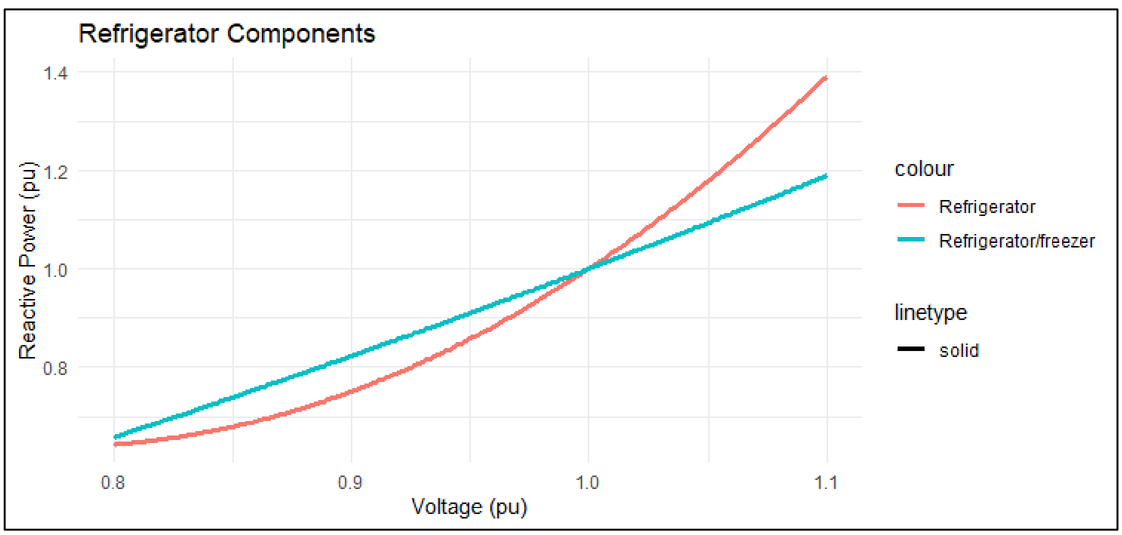

Figure 4.7 V-Q for Refrigerators End-Use Components

4.3.4 Fan

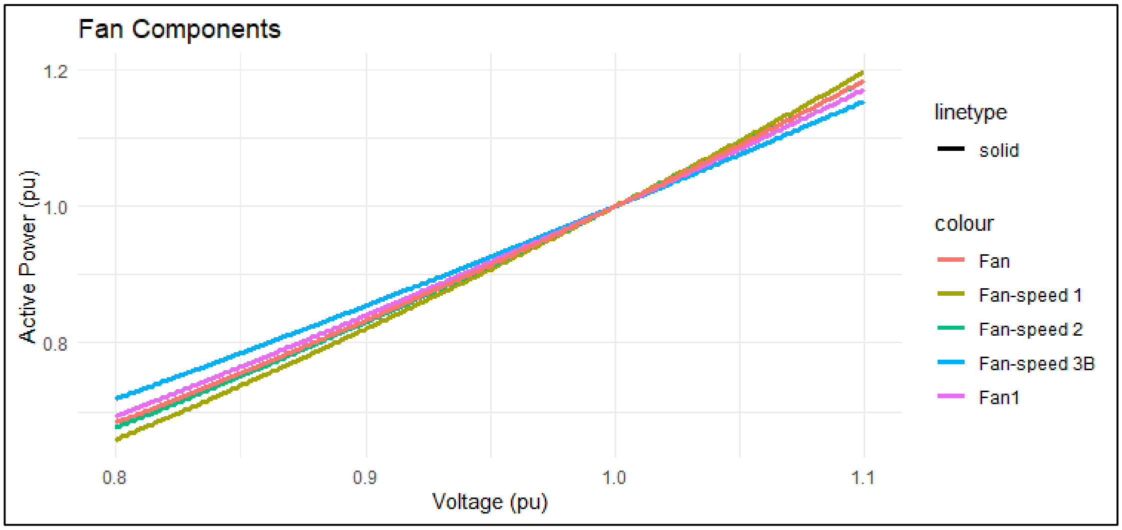

Figure 4.8 V-P for Fans End-Use Components

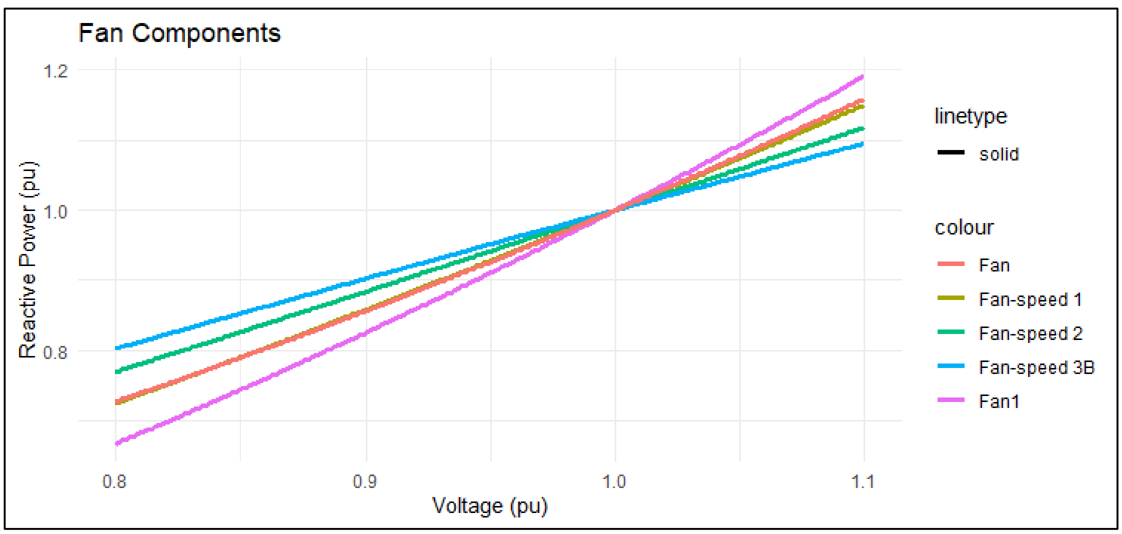

Figure 4.9 V-Q for Fans End-Use Components

4.3.5 Heating

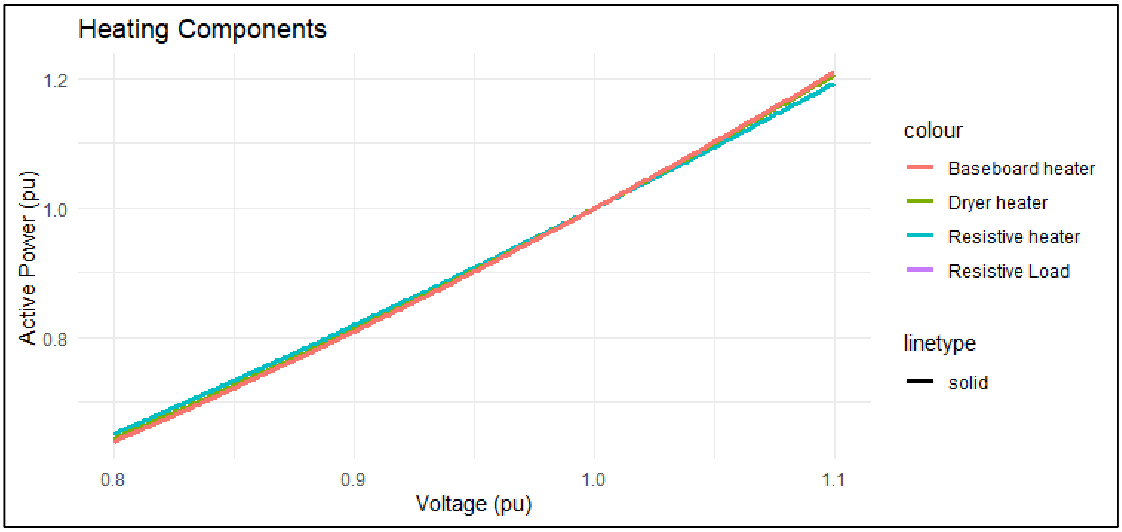

Figure 4.10 V-P for Heating End-Use Components

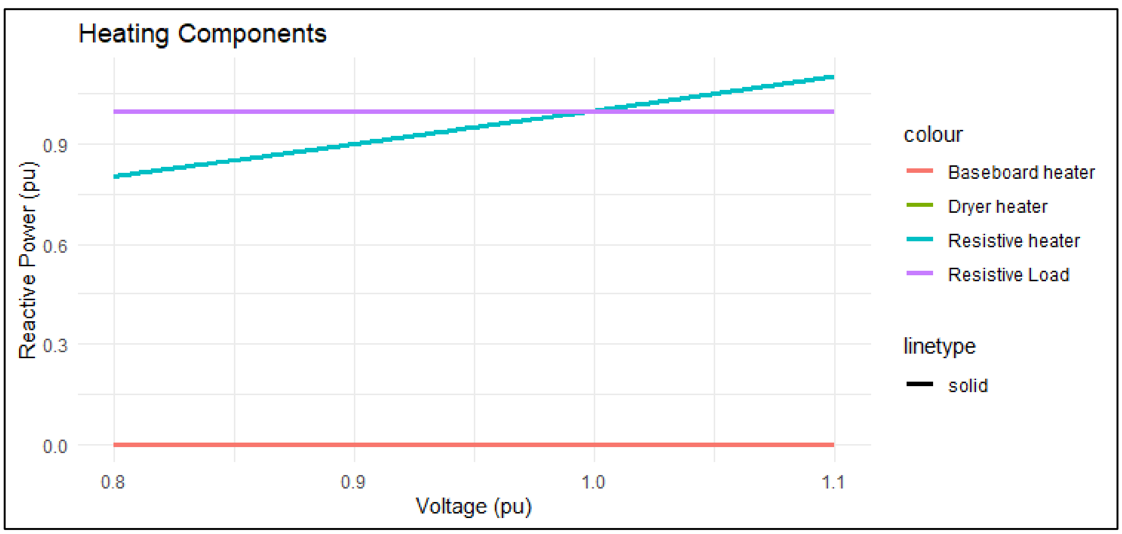

Figure 4.11 V-Q for Heating End-Use Components

4.3.6 Cooling

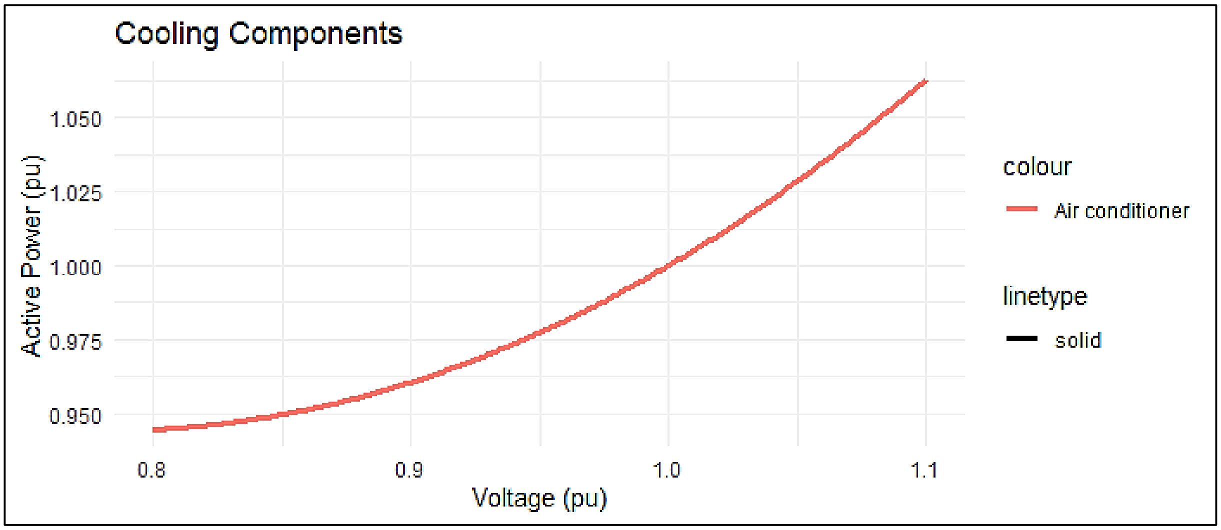

Figure 4.12 V-P for Cooling End-Use Components

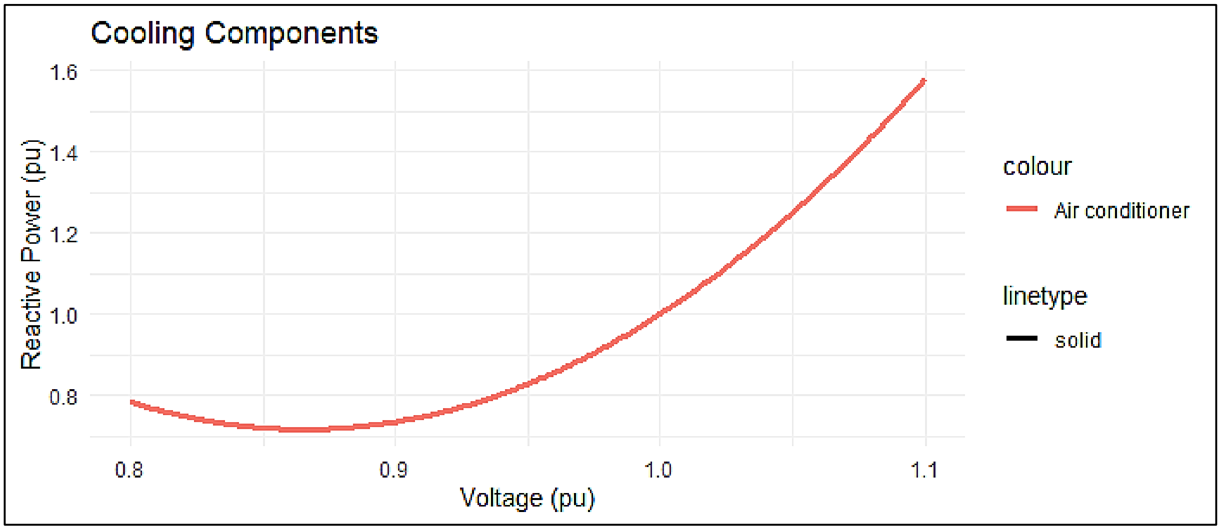

Figure 4.13 V-Q for Cooling End-Use Components

4.3.7 Pump

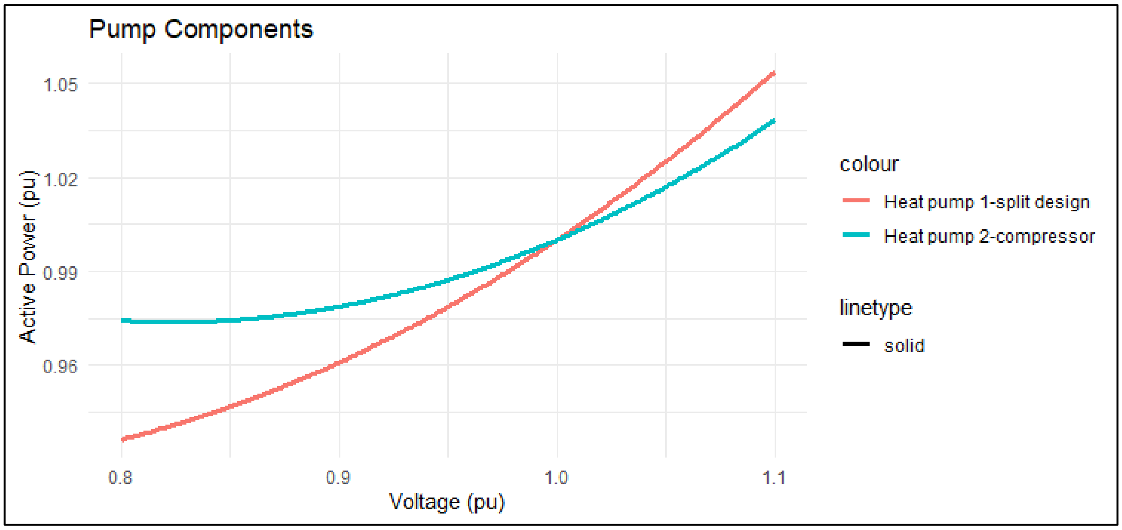

Figure 4.14 V-P for Pumps End-Use Components

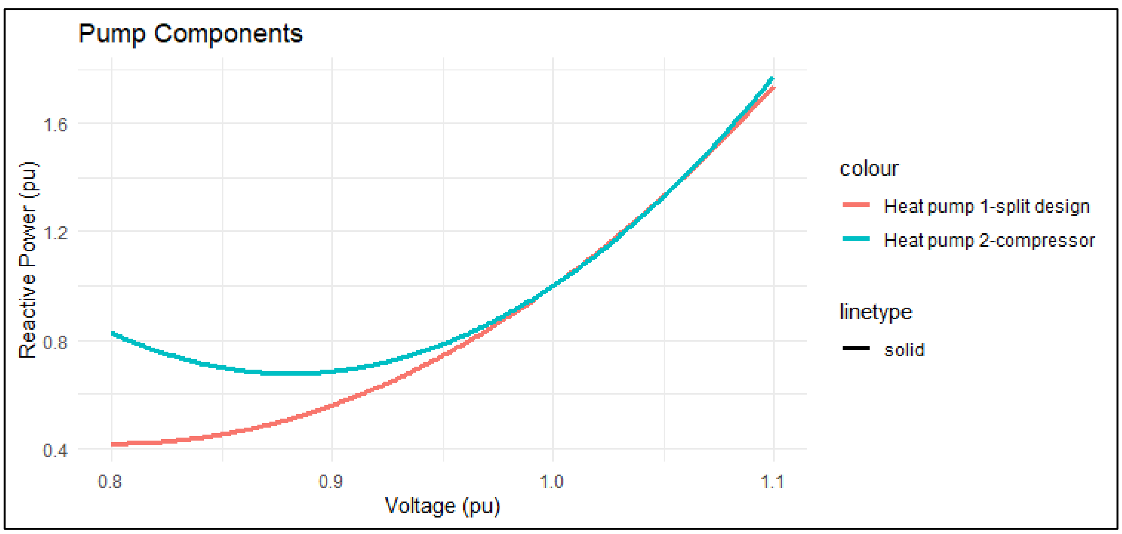

Figure 4.15 V-Q for Pumps End-Use Components

4.4 ZIP Coefficients Identification for End-Use Types

The object of work in this section is to determine the ZIP coefficients for end-use types, which are interior/exterior lighting, interior/exterior equipment, heating, cooling, pump, fan, and refrigerator, relying on the load components documented in the previous section.

Three cases of ZIP coefficients for each end-use category are considered in this study: the minimum case, maximum case, and typical cases. ZIP coefficients of two cases, which are min & max, are extracted by the load components plots for each end-use type by identifying the most and least sensitive component with respect to the relationship between power and voltage. The third case, which is the typical ZIP coefficients, is achieved by the determination of ZIP coefficients for end-use types in one residential house based on two main factors, which are the most commonly used load components in the residential sector, and the participation factor for each load. Participation factor represents the share of electricity consumption for each component.

The investigation of ZIP coefficients determination for end-use types is covered in two sections: section 4.4.1 demonstrates ZIP coefficients boundaries by identifying the minimum and maximum case of the coefficients for each end-use. Section 4.4.2 illustrates the methodology applied to determine the typical ZIP model coefficients for a residential house. And section 4.4.3 provides a summary of three cases of ZIP coefficients resulted in 4.4.1 and 4.4.2 sections.

4.4.1 Min & Max Cases for ZIP Coefficients Boundaries

The method of ZIP coefficients determination implemented here is primarily dependent on the visualization of load components adopted in section 4.3 mapping and visualization. According to the observation of plotted load components, two main cases are extracted for each end-use types: minimum and maximum ZIP coefficients. The minimum case of the ZIP coefficients for a certain end-use type refers that the relationship between power and voltage is equal to the least sensitive load component at each end-use category, to arrive at final ZIP coefficients, and the maximum case of ZIP coefficients means that the relationship between active power and voltage is equal to the most sensitive component in each end-use category, to arrive at final ZIP coefficients.

The min & max ZIP coefficients for the interior/exterior lighting end-use is an instance of the observation adopted in this study. Figure 4.16 shown below represents the load components of the interior/exterior lighting end-use, and Table 4.28 lists the ZIP coefficients for lighting end-use. This group of lighting fixtures is collected from the documented review adopted in the previous section and it consists of several types of the most frequently used lighting fixtures in the residential class such as incandescent, Compact Fluorescent Lamp (CFL), Halogen, and Light Emitting Diode (LED).

Table 4.28: Load components for interior/exterior Lighting End-Use

No.	**Components**	**Ref**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
1	CFL	[23]	0.81	-1.03	1.22	0.86	-0.82	0.96
2	CFL 19W	[3]	-0.42	1.50	-0.06	0.66	-1.16	0.06
3	CFL 23W	[3]	-0.28	1.35	-0.05	0.58	-1.11	0.05
4	CFL 20W	[3]	-0.30	1.36	-0.05	0.60	-1.08	0.04
5	Fluor lamp T8_32W	[3]	0.35	0.72	-0.04	0.28	-0.90	0.03
6	Fluor lamp T12_40W	[3]	0.34	0.71	-0.03	0.20	-0.76	0.02
7	Fluor lamp T8_32W	[3]	-0.03	1.10	-0.05	0.32	-0.75	0.03
8	Fluor lamp T12_40W	[3]	0.06	0.97	-0.03	0.24	-0.60	0.02
9	Fluor lamp (Spot)	[22]	-0.64	2.17	-0.53	-1.02	2.80	-0.78
10	Electronic CFL 1	[6]	0.14	0.77	0.09	-0.06	-0.34	-0.60
11	Electronic CFL 2	[6]	0.16	0.79	0.05	0.18	-0.83	-0.35
12	Magnetic CFL	[6]	0.34	1.31	-0.65	3.03	-2.89	0.86
13	Electronically ballasted Fluor 1	[6]	-2.48	5.46	-1.97	0.00	0.00	0.00
14	Electronically ballasted Fluor 2	[6]	-1.60	3.58	-0.98	0.79	-0.16	0.36
15	Incandescent light	[23]	0.47	0.63	-0.10	0.55	0.38	0.07
16	LightBulb 100W	[3]	0.64	0.40	0.00	0.00	0.00	0.00
17	Incandescent light	[22]	0.43	0.64	-0.08	0.00	0.00	1.00
18	LED light	[23]	0.58	1.13	-0.71	1.78	-0.80	0.02

19	Halogen	[23]	0.46	0.64	-0.10	4.26	-6.62	3.36
20	Halogen_100W	[3]	0.66	0.39	0.00	0.00	0.00	0.00
21	Halogen	[22]	0.48	0.57	-0.05	-3.57	0.69	0.00
22	CFL	[30]	0.00	0.00	1.00	0.00	0.99	0.00
23	Incandescent light	[30]	0.69	0.00	0.30	0.00	0.00	0.00

According to lighting fixtures plot shown in the figure 4.16, it is noticed that the CFL and LED light, obtained from [23], are drawing the boundaries for the voltage-power relationship of 23 lighting fixtures displayed in the interior/exterior lighting end-use, where LED and CFL lights to represent the minimum and maximum boundaries respectively. Consequently, the min ZIP coefficients for the lighting end-use type are determined by LED light, and similarly, the max ZIP coefficients are determined by CFL.

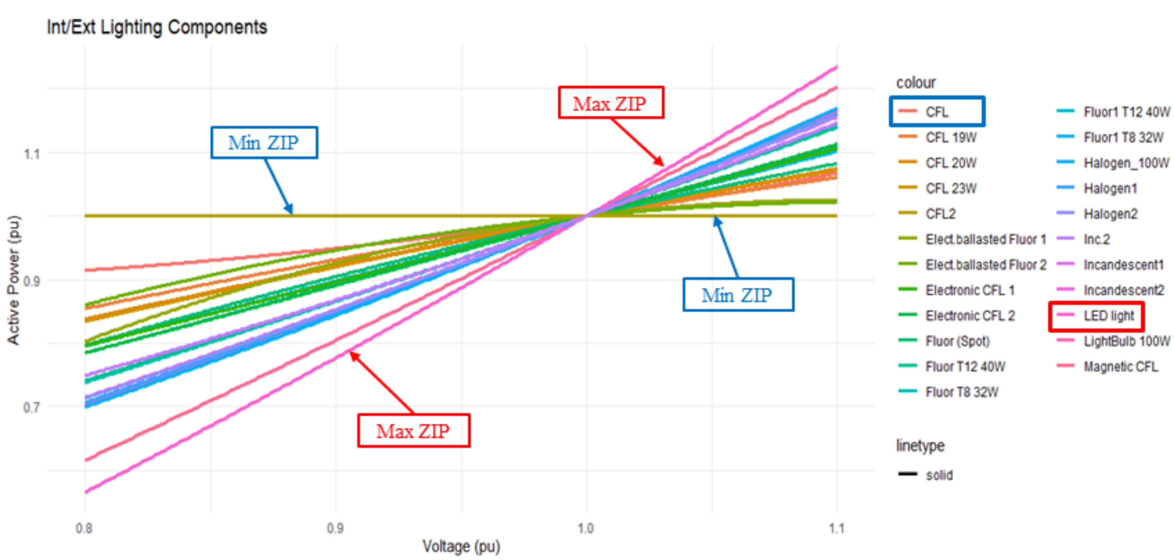

Figure 4.16: Min/Max ZIP Coefficients for interior/exterior Lighting End-use

Table 4.29 below displays the summary of the min & max case of the ZIP coefficients boundaries for the end-use types.

Table 4.29: Min & Max Case of ZIP Coefficients Boundaries for End-Use Types

#	End-Use		Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
1	Heating	Min	Baseboard heater	[6]	1.00	0.00	0.00	0.00	0.00	0.00
		Max	Resistive heater	[23]	0.64	0.59	-0.23	0.13	0.75	0.12
2	Cooling	Min	Air conditioner	[23]	1.17	-1.83	1.66	15.68	-27.15	12.47
		Max	Air conditioner	[23]	1.17	-1.83	1.66	15.68	-27.15	12.47
3	Int/Ext Lighting	Min	CFL	[30]	0.00	0.00	1.00	0.00	0.99	0.00
		Max	LED light	[23]	0.58	1.13	-0.71	1.78	-0.80	0.02
4	Int/Ext Equipment	Min	DishWasher_PP	[3]	1.00	0.00	0.00	0.00	0.00	0.00
		Max	Computer	[22]	0.27	-0.61	1.34	-0.11	0.02	1.08
5	Fan	Min	Fan - speed 1	[3]	0.87	0.14	-0.01	0.11	0.16	-0.01
		Max	Fan - speed 3B	[3]	0.45	0.57	-0.04	-0.03	0.34	-0.02
6	Pumps	Min	Heat pump 1 (split design)	[6]	0.72	-0.98	1.25	14.78	-23.72	9.93
		Max	Heat pump 2 compressor	[6]	0.85	-1.40	1.56	22.92	-40.39	18.47
7	Refrigerators	Min	Refrigerator	[23]	1.17	-1.83	1.66	7.07	-10.94	4.87
		Max	Refrigerator/freezer	[6]	1.19	-0.26	0.07	0.59	0.65	-0.24

4.4.2 Typical ZIP Model Coefficients for One Residential House

This section describes the methodology of applying the component-based ZIP model for a typical residential house to determine the ZIP coefficients for each end-use category. Figure 4.17 shows the general methodology adopted for this study. The object of this study is to determine the typical ZIP coefficients for each end-use type based on load components obtained from the documented work, and load composition represented by the share of electricity for each load. The typical case of ZIP coefficients for a residential house assumes a given load composition based on weighted component coefficients in each end-use category, to arrive at final ZIP coefficients.

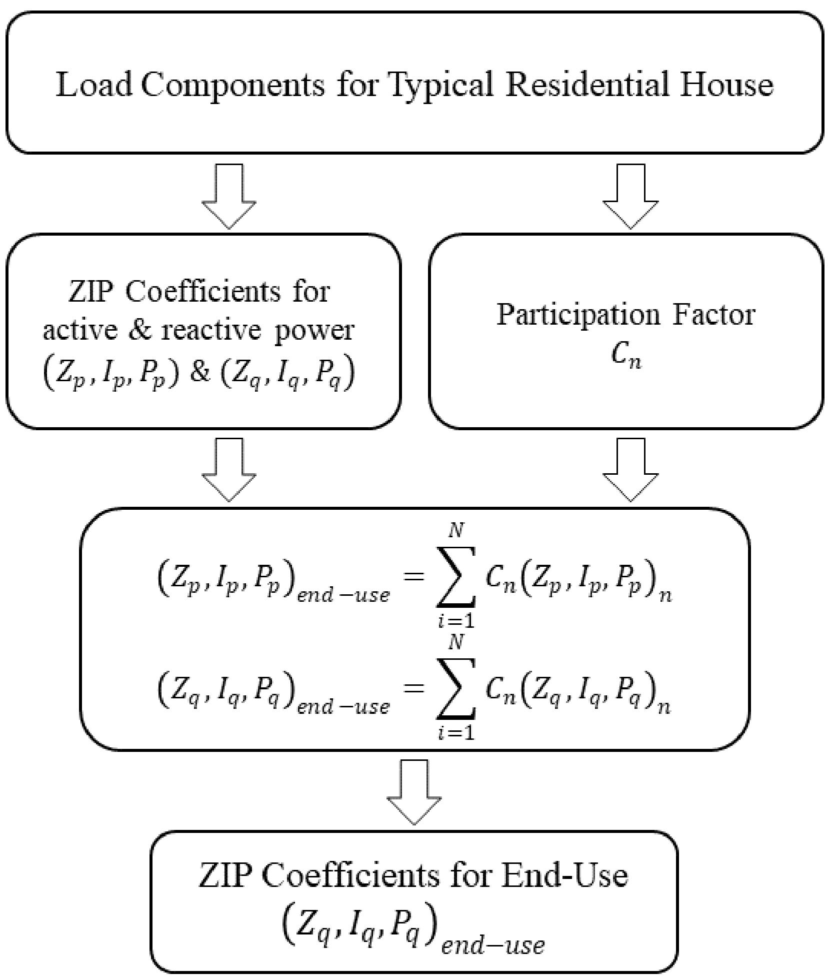

Figure 4.17: Methodology of identifying the ZIP Coefficients for End-Use Category

The first step is to determine the most frequently used components in a residential house such as lighting fixtures, interior equipment, and heating components. The components can be obtained and listed from the review adopted in the previous section. The second step is to list the ZIP coefficients and the participation factor for load components. The participation factor is the relative contribution of each component into the electrical system and mainly represents the share of electricity consumption for each component. Then, the final step is to apply the equations to calculate the ZIP coefficients of the end-use types for both active and reactive power according to the ZIP coefficients and participation factor of each load component.

In order to implement the component-based ZIP modeling for the end-use types, the data about the load inventory at the residential house in the US should be collected, i.e. the type of loads that usually existed in the residential house, and the share of electricity for each load component so the percentage of participation can be obtained. Therefore, this information is drawn from the Building Energy Data Book [46]. This document is developed by the Department of Energy (DOE) and designed for internal use in the United States to provide an accurate set of inclusive data related to buildings energy consumption in different classes, residential, commercial, and industrial. Table 4.30 shows the energy consumption and percentage of Electricity Use for the residential house.

Table 4.30: Energy Consumption & Percentage of Electricity Use for Residential Loads

No.	End Use	Components	Annual kWh	Ref	Electricity Use
1	Heating	Resistive heater	314	[23]	6%
		water heater	4770	[47]	94%
2	Cooling	Air conditioner	1041	[23]	100%
3	Int/Ext Lighting	Incandescent light 75W	40	[19]	7%
		Incandescent light 100W	70	[23]	12%
		Compact Fluorescent	20	[23]	4%
		Halogen	440	[23]	77%

4	Int/Ext Equipment	Range	70	[3]	3%
		Dishwasher (Pot&Pan)	120	[3]	5%
		Dryer	1000	[3]	40%
		Microwave	131	[23]	5%
		Oven	126	[3]	5%
		Coffee maker	58	[23]	2%
		Vacuum cleaner	55	[23]	2%
		Washing machine	110	[6]	4%
		Video game console	41	[23]	2%
		TV - LED 55"	455	[5]	18%
		PC (Monitor & CPU)	322	[23]	13%
5	Fan	Fan	81	[23]	100%
6	Pumps	Pump	725	[22]	100%
7	Refrigeration	Refrigerator	660	[23]	100%

Figure 4.18 below is a demonstration of load composition in the residential class, where it is shown the comprehensive end-use types consumption in the residential house. The participation factor of the interior/exterior equipment, presented by the yellow color, is a 23% of the total consumption, whereas the pie chart on the left side represents the participation percentage for each load component in the interior/exterior equipment end-use, which is derived from the total end-use of the residential house.

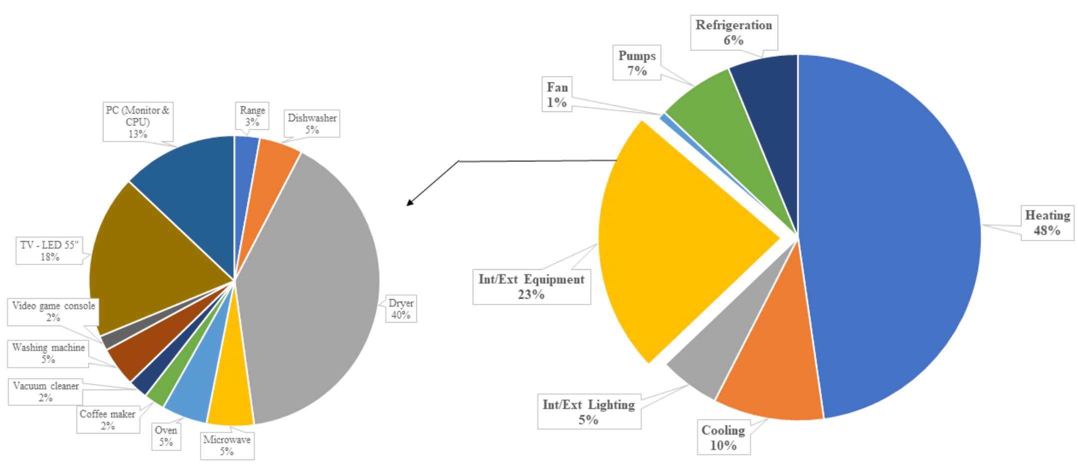

Figure 4.18: Load composition in the residential class

As mentioned in the literature review, the component-based ZIP model starts from the load components which comprise the end-use types for the residential class represented by the typical house in this case. Therefore, The ZIP coefficients of these load components are obtained from the ZIP model-related works reviewed and documented in the previous section. Table 4.31 shows the documented ZIP coefficients for our case study of the typical residential house.

Table 4.31: ZIP Coefficients for Residential Loads

No.	**Components**	**Ref**	**Zp**	**Ip**	**Pp**	**Kp**	**Zq**	**Iq**	**Pq**	**Kq**
1	Resistive heater	[23]	0.64	0.59	-0.23	1.00	0.13	0.75	0.12	1.00
2	water heater	[47]	0.92	0.10	-0.02	1.00	0.15	0.86	-0.01	1.00
3	Air conditioner	[23]	1.17	-1.83	1.66	1.00	15.68	-27.15	12.47	1.00
4	Incandescent light 75W	[19]	0.57	0.43	0.00	1.00	1.00	-1.00	1.00	1.00
5	Incandescent light	[23]	0.47	0.63	-0.10	1.00	0.55	0.38	0.07	1.00
6	Compact Fluorescent	[23]	0.81	-1.03	1.22	1.00	0.86	-0.82	0.96	1.00
7	Halogen	[23]	0.46	0.64	-0.10	1.00	4.26	-6.62	3.36	1.00
8	Range	[3]	0.97	0.00	0.00	1.03	0.00	0.00	0.00	1.00
9	Dishwasher (Pot & Pan)	[3]	1.00	0.00	0.00	1.00	0.00	0.00	0.00	1.00
10	Dryer	[3]	1.02	0.00	0.00	0.98	1.00	0.00	0.00	1.00
11	Microwave	[23]	1.39	-1.96	1.57	1.00	50.07	-93.55	44.48	1.00
12	Oven	[3]	0.99	0.00	0.00	1.01	0.00	0.00	0.00	1.00
13	Coffee maker	[23]	0.13	1.62	-0.75	1.00	3.89	-6.00	3.11	1.00
14	Vacuum cleaner	[23]	1.18	-0.38	0.20	1.00	4.10	-5.87	2.77	1.00
15	Washing machine	[6]	0.05	0.31	0.63	1.01	-0.56	2.20	-0.65	1.01
16	Video game console	[23]	-0.63	1.23	0.40	1.00	0.76	-0.93	1.17	1.00
17	TV - LED 55"	[5]	0.27	-0.54	1.27	1.00	0.73	0.70	-0.42	1.00
18	PC (Monitor & CPU)	[23]	0.20	-0.30	1.10	1.00	0.00	0.60	0.40	1.00
19	Fan	[23]	-0.47	1.71	-0.24	1.00	2.34	-3.12	1.78	1.00
20	Pump	[22]	5.51	-11.30	6.82	0.97	11.77	-24.28	13.51	1.00
21	Refrigerator	[23]	1.17	-1.83	1.66	1.00	7.07	-10.94	4.87	1.00

The determination of ZIP coefficients can be achieved through the following equations (15-16), where each load component is weighted with the percentage of participation for each load, which can be obtained from the annual consumption for each. Therefore, this calculation can be implemented through equations (15) and (16) for active and reactive power respectively.

$$(Z_p, I_p, P_p)_{end-use} = \sum_{i=1}^{N} C_n (Z_p, I_p, P_p)_n \quad (15)$$

$$(Z_q, I_q, P_q)_{end-use} = \sum_{i=1}^{N} C_n (Z_q, I_q, P_q)_n \quad (16)$$

Where $(Z_p, I_p, P_p)_{end-use}$ are the ZIP coefficients for the end-use type, C_n is the participation percentage for the load component, N is the number of load components, and $(Z_p, I_p, P_p)_n$ is the ZIP coefficients for a certain load.

An example of identifying the typical ZIP coefficients for heating end-use in the residential house is provided here for clarification. As shown in table 4.32, the percentage of electricity use for the resistive heater and water heater in the heating end-use is 6% and 94% respectively.

Table 4.32: Percentage of electricity use for end-use type

End-Use	Components	Zp	Ip	Pp	Zq	Iq	Pq	Annual kWh	% of Electricity Use
Heating	Resistive heater	0.64	0.59	-0.23	0.13	0.75	0.12	314	6%
	Water heater	0.92	0.10	-0.02	0.15	0.86	-0.01	4,770	94%

In order to calculate the ZIP coefficients for heating end-use, ZIP coefficients of load components and the percentage of electricity use, demonstrated in the table 4.32 above, are substituted in equation (15). The active power ZIP coefficients, Z_p, I_p, P_p, for resistive heater are 0.64, 0.59, and -0.23, and for water heater are 0.92, 0.10, -0.02 will be substituted in the equation, and share of electricity represented in $\mathrm{C_n}$ are substituted with 6% and 94% for resistive heater and water heater respectively.

$$\left(\mathrm{Z_p, I_p, P_p}\right)_{\text{end use}} = \textstyle\sum_{i=1}^{N=2} \mathrm{C_n}\left(\mathrm{Z_p, I_p, P_p}\right)_n = 6\%\ (\mathrm{ZIP}_{\text{Resistive Heater}}) + 94\%(\mathrm{ZIP}_{\text{Water Heater}})$$

$$\left(\mathrm{Z_p, I_p, P_p}\right)_{\text{end use}} = \sum_{i=1}^{N=2} \mathrm{C_n}\left(\mathrm{Z_p, I_p, P_p}\right)_n = 6\%\ (0.64, 0.59, -0.23) + 94\%(0.92, 0.10, -0.02)$$

$$\left(\mathrm{Z_p, I_p, P_p}\right)_{\text{end use}} = (0.90, 0.13, -0.03)_{\text{end use}}$$

Where N is the number of loads in the heating end-use, and $\mathrm{C_n}$ is the percentage of electricity use for each load component. Thus, Table 4.33 shows the calculated ZIP coefficients, energy consumption and percentage of electricity use for end-use types.

Table 4.33: ZIP Coefficients, Energy Consumption and Percentage of Electricity Use for End-Use Types

No.	**End-Use Type**	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**	**Annual KWh**	**%**
1	Heating	0.90	0.13	-0.03	0.15	0.85	0.00	5084	48%
2	Cooling	1.17	-1.83	1.66	15.68	-27.15	12.47	1041	10%
3	Int/Ext Lighting	0.48	0.57	-0.05	3.46	-5.16	2.71	570	5%
4	Int/Ext Equipment	0.70	-0.18	0.48	3.34	-4.91	2.44	2488	23%
5	Fans	-0.47	1.71	-0.24	2.34	-3.12	1.78	81	1%
6	Pumps	5.35	-10.97	6.62	11.77	-24.28	13.51	725	7%
7	Refrigeration	1.17	-1.83	1.66	7.07	-10.94	4.87	660	6%

4.4.3 Summary Table of ZIP Coefficients for End-Use Types

This section provides a summary of three cases of ZIP coefficients for each end-use category that are investigated in this stage: minimum, maximum, and typical case. Two of these cases, which are min & max, of ZIP coefficients are extracted by the load components plots for each end-use type by identifying the most and least sensitive component with respect to the relationship between power and voltage. The third case, which is the typical ZIP coefficients, is achieved by the determination of ZIP coefficients for each end-use type in one residential house based on the documented load components and load composition represented by the share of electricity for each load.

Table 4.34: Summary of Min, Max, and Typical Cases of ZIP Coefficients for End-Use Types

#	End-Use	Case	Component	Ref	Zp	Ip	Pp	Zq	Iq	Pq
		Min	Baseboard heater	[6]	1.00	0.00	0.00	0.00	0.00	0.00
1	Heating	Max	Resistive heater	[23]	0.64	0.59	-0.23	0.13	0.75	0.12
		Typical			0.90	0.13	-0.03	0.15	0.85	0.00
		Min	Air conditioner	[23]	1.17	-1.83	1.66	15.68	-27.15	12.47
2	Cooling	Max	Air conditioner	[23]	1.17	-1.83	1.66	15.68	-27.15	12.47
		Typical			1.17	-1.83	1.66	15.68	-27.15	12.47
		Min	LED light	[23]	0.58	1.13	-0.71	1.78	-0.80	0.02
3	Int/Ext Lighting	Max	CFL	[30]	0.00	0.00	1.00	0.00	0.99	0.00
		Typical			0.48	0.57	-0.05	3.46	-5.16	2.71
		Min	DishWasher_PP	[3]	1.00	0.00	0.00	0.00	0.00	0.00
4	Int/Ext Equipment	Max	Computer	[22]	0.27	-0.61	1.34	-0.11	0.02	1.08
		Typical			0.70	-0.18	0.48	3.34	-4.91	2.44
		Min	Fan - speed 1	[3]	0.87	0.14	-0.01	0.11	0.16	-0.01
5	Fan	Max	Fan - speed 3B	[3]	0.45	0.57	-0.04	-0.03	0.34	-0.02
		Typical			-0.47	1.71	-0.24	2.34	-3.12	1.78
		Min	Heat pump 1 (split design)	[6]	0.72	-0.98	1.25	14.78	-23.72	9.93
6	Pumps	Max	Heat pump 2 compressor	[6]	0.85	-1.40	1.56	22.92	-40.39	18.47
		Typical			5.35	-10.97	6.62	11.77	-24.28	13.51
		Min	Refrigerator	[23]	1.17	-1.83	1.66	7.07	-10.94	4.87
7	Refrigerators	Max	Refrigerator/freezer	[6]	1.19	-0.26	0.07	0.59	0.65	-0.24
		Typical			1.17	-1.83	1.66	7.07	-10.94	4.87

CHAPTER 5

ZIP MODEL DEVELOPMENT FOR LED LIGHTS

5.1 Light-emitting diodes (LEDs)

5.1.1 General Background

Light-emitting diodes (LEDs) are recognized to be one of the semiconductor devices which have the current flows in only one direction (unidirectional) and this polarization results in direct light emission. Nowadays, the LEDs are superior to many other lighting sources such as fluorescent and incandescent due to the LED high efficacy and long life [48].

Compact Fluorescent Lamps (CFL) are superior to the incandescent lights as it has a better performance of energy consumption reduction and efficiency. Therefore, due to the low efficacy of incandescent lights, many countries have been eliminating it and replace it with CFL although of the widespread use of incandescent lights in all class sector [48]. On the other hand, semiconductor lights (LEDs) were improved and considered to be a light source for the sake of efficiency higher than other light sources (CFL and incandescent). Many of the companies and researchers were pulled by the advantages of this technology like the high efficiency and the small size and led them to develop the lighting by utilizing the semiconductor. While this technology is used to be employed for electronic purposes and controlling system, now semiconductor is being able to replace other light sources in different utilization [49].

Light Emitting Diodes (LEDs) is a solid-state lighting source currently being employed in different areas such as transportation equipment lighting (e.g., backlights, and brake lights of the vehicle), communications, medical services, and as a light source of many applications, e.g., backlighting of flat TV, mobile phones, and general lighting.

LEDs have been evolved over time to play a more essential role with respect to energy saving and power environmental pollution reduction, and the LED future is anticipated to be more involved into many different applications such as general lighting (e.g., LED light bulb, LED projector), communication lighting (visible light communication), and other critical application in system control (e.g. biomedical sensors). General lighting applications can be classified into indoor lighting (such as LED lighting bulbs and desk lighting), outdoor lighting (e.g., bridge lighting and stadium lighting), and special lighting (e.g., TV lightings) [50].

5.1.2 LEDs Development

Over the decades, LED has improved and had a better performance of brightness, color variation, and many of its aspects have been developed such as flexibility and efficiency. So, LED can be divided into three generations, and each generation has its own characteristics regarding the development of phosphor material, fabrication technology, and heat dissipation packaging technologies. In the first generation, from the 1960s to the 1980s, the first LED product was released in the 1960s. Additionally, high-brightness LED (300 mcd1) was the first commercially successful LED that was developed by the Fairchild company in the 1980s.

The second generation, which is considered to be the period between the 1990s to the present, high-brightness LEDs became well-known and was implemented in many different applications, e.g., vehicle LED lighting, TV LED backlighting, LED flashers, and cellphones. And finally, the third generation is now arriving in the business [50].

5.1.3 Advantages

LEDs are superior to traditional lighting in terms of the mechanical impact resistance. LEDs have low health influence because of the low radiation of Ultraviolet and are deemed to be environmentally friendly lightings with no mercury [50]. From the perspective of efficiency, LEDs that have a single color are beyond ten times efficient compared to incandescent lamps [51]. The usage of LEDs in general lighting has been growing so fast and has diverse lighting applications; for instance, street lighting, commercial lighting, and residential lightings [50].

5.1.4 Disadvantages

LED has some issues that make the spreading of the LED in the market more challenging. These issues can be defined as the cost and lack of information in regard to reliability [50]. Over the last years, LEDs prices are considered to be too expensive for the lighting applications and the prices of the conventional lighting are much cheaper comparing to the LED lights although its prices are declining rapidly. However, LEDs are superior to incandescent light according to life cycle costs, where the life cycle cost of LED lighting is less than for an incandescent [52]. Lighting costs consist of the initial price, electricity, and replacement costs. However, as the life cycle savings are not ensured in the lighting, the larger initial costs are still an impediment for growing the LED lights in the market [50].

One way to solve the cost issue of LED lights and to grow the market share is to decrease the manufacturing cost and selling price taking into consideration that LED lights still have the same reliability. dependent on the research done by Samsung, it was revealed that the white LED lights can be more competitive with fluorescent lights over the next five years on condition that the selling price of LED lights was reduced by 50% [52].

5.2 ZIP Load Model for LED Lights

5.2.1 LED Load Model

Load model is very essential for network design and analysis, hence the ZIP load model should be updated over time for many reasons, such as the rapid advancement in technology and the involvement of modern loads into the market. Therefore, the updated load model will be able to precisely represent the load characteristics and the evolution of load behavior in the power system.

LED lights is an example of these modern loads as it has been growing rapidly it different customer classes, residential, commercial, and industrial, where the LED lights have diverse lighting applications; for instance, street lighting, commercial lighting, and residential lightings [50]. Several works were adopted to develop the ZIP load model for the LED light in order to understand the load behavior and its impact on the power system. Table 5.1 shows the list of LED lights ZIP coefficients determined by the previous works.

Work in [8] updated the load modeling for the residential and commercial classes in the UK. The authors in this research developed the ZIP model for LED light for different wattages: 4, 5, 7, and 9W, and found that the active power demand characteristics vary from constant power to constant current to constant impedance. [23] also determined the ZIP coefficients for the residential loads and updated the load model for the most common loads used in the lighting end-use back in 2013 such as incandescent, compact fluorescent lamp, halogen, and LED lights. ZIP model was developed according to two different ranges of voltage changes: The Conservation Voltage Reduction (CVR) range that falls between 0.83 – 1.10 pu of the rated voltage, and shut off voltage range, which is between the Voff – 1.10 pu of the rated voltage, where the Voff is the voltage when the load is completely shut off and not operated anymore.

[24] tended to develop the home grid system and update the ZIP model in the residential class to present the behavior of residential loads. ZIP coefficients of LED light were identified for that purpose. [10] identified the load model for smart home appliances and update the ZIP model for a single LED light within the range Voff – 1.10 pu of rated voltage. It was revealed that LED light has a good agreement with the active power ZIP model but it is not compatible with the measurement at certain voltage levels. However, ZIP model does not precisely represent the reactive power measurements of the LED light.

Table 5.1: Previous work of ZIP coefficients determination for LED lights

No.	Name	Ref	Year	Vo	Zp	Ip	Pp	Zq	Iq	Pq
1	Low power LED light	[8]	2013	230	0.23	0.85	-0.08	-1.05	0.04	0.01
2	High power LED light 4W	[8]	2013	230	0.79	0.82	-0.62	4.12	-4.59	1.48
3	High power LED light 5W	[8]	2013	230	-0.92	1.84	0.09	-0.49	-0.22	1.7
4	High power LED light 7W	[8]	2013	230	-4.24	9.56	-4.32	-8.48	17.8	-8.31
5	High power LED light 9W	[8]	2013	230	-0.86	1.82	0.04	0.39	0.14	0.48
6	LED light	[23]	2014	120	0.58	1.13	-0.71	1.78	-0.8	0.02
7	LED light	[23]	2014	120	0.69	0.92	-0.61	1.84	-0.91	0.07
8	LED light	[24]	2015	220	-0.55	0.5	1.05	-0.03	0.91	0.12
9	LED light	[10]	2020	220	0.73	-1.7	1.97	0.52	-1.41	1.89

As seen in the previous review, multiple works in developing the ZIP model for LED light were adopted by researchers in order to update the evolution of load behavior. Most of these ZIP model development works were implemented in 2013 and 2014 without considering the evolution of LED lights design over the recent years, hence LED light has not deeply investigated although the rapid growth in recent years as most focuses were only oriented toward other lighting types that were common, such as incandescent, compact fluorescent lamps, and Halogen. Thus, these lighting types are not used anymore with the spread of LED light.

In this work, ZIP load models for LED Lights are developed and model coefficients is determined to update the ZIP model of the recently produced LED lighting and have a better representation of the load behavior and power consumption when the load exposed to the conservation voltage reduction (CVR). In order to achieve that, a laboratory experiment is conducted to measure the active power and reactive power response to the voltage variations within the CVR range. Then, the measured data is exposed to the ZIP model to determine the coefficients. LED lights are chosen based on the most frequently LED lights used in the residential class. Table 5.2 shows the list of light fixtures that are tested in the laboratory.

Table 5.2: List of tested LED light fixtures in the lab

No.	Type	Brand	Soft White /Daylight	Dimmability	Power rated	Power replc
1	Bulb	EcoSmart	Daylight	Non-dimmable	5.5	40
2	Bulb	GE	Soft White	Dimmable	9	60
3	Bulb	EcoSmart	Daylight	Non-dimmable	9	60
4	Bulb	EcoSmart	Soft White	Non-dimmable	9	60
5	Bulb	Great Value	Soft White	Non-dimmable	9	60
6	Bulb	EcoSmart	Daylight	Dimmable	9.5	60
7	Bulb	Cree	Daylight	Dimmable	10	60
8	Bulb	Great value	Daylight	Non-dimmable	12.5	75
9	Bulb	GE	Soft White	Dimmable	13	100
10	Bulb	EcoSmart	Daylight	Non-dimmable	13	100
11	bulb	Sylvania	Daylight	Non-dimmable	14	100
12	Bulb	Great Value	Daylight	Non-dimmable	14	100
13	bulb	Feit Electric	Daylight	Non-dimmable	15	100
14	Bulb	EcoSmart	Daylight	Dimmable	15.5	100
15	bulb	Feit Electric	Daylight	Dimmable	17.5	100
16	bulb	Sylvania	Soft White	Non-dimmable	22	200
17	bulb	Feit Electric	Daylight	Dimmable	28	150
18	Candle	Yansun	Daylight	Non-dimmable	5	40
19	Candle	Yansun	Daylight	Non-dimmable	6	60
20	Tube	toggled	Daylight	Non-dimmable	8	20
21	Tube	toggled	Daylight	Non-dimmable	16	40

5.2.2 Experimental Setup

To develop the static load model, the laboratory test of the lighting fixtures is conducted in a controlled environment. The power is acquired by the grid, and the range of voltage variation in a slow ramp is implemented by an adjustable AC power supply. Standard instrumentation is used in these tests, and these instrumentations consist of a programmable AC power supply, power analyzer, and computer software. The required instruments for this experiment are adjustable AC Power Supply: California instruments model 1251rp, power logger: AMEC PEL 103, PC Software: PEL software for reading & recording monitored quantities.

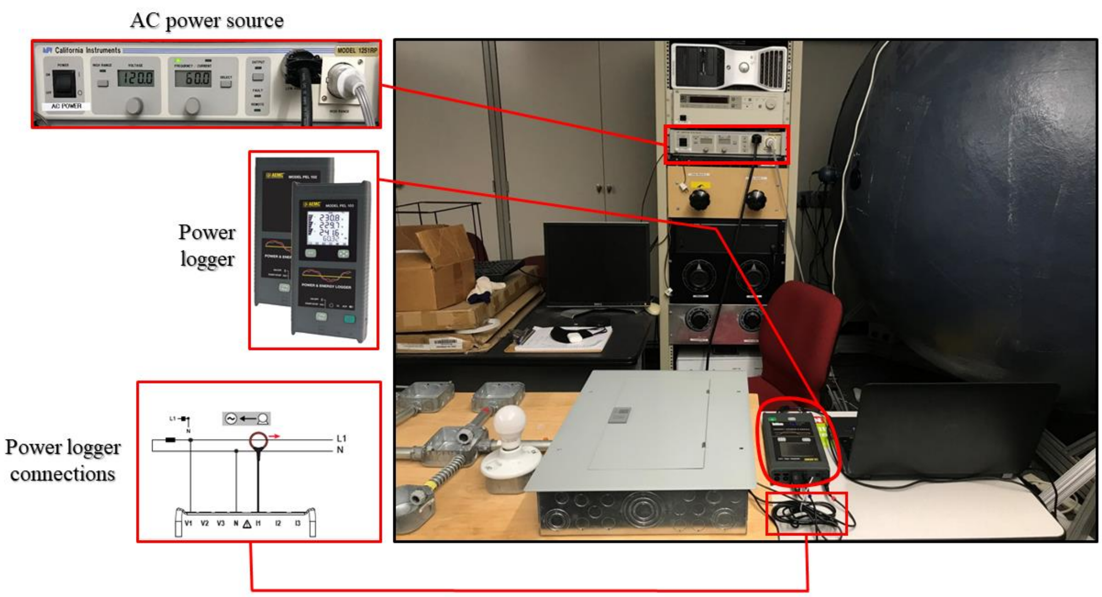

Figure 5.1: Experiment setup

5.2.3 Test Procedure

Before each test, lighting fixtures are operated under a rated voltage 120V for 30 minutes before start conducting the test. This settling down period is to avoid the transient stability of the cold start, and to assure that fixtures are operated and tested under steady-state. A range of voltage variations is applied to each lighting fixture, and the lighting behavior is recorded. Starting at the rated value 120V, the voltage is decreased from 120V in the step of 3V and kept for 1 minutes at each step to avoid any transient undesired transient. The voltage is kept lowering until the light fixture reaches Voff, which is called shut down voltage. Voff is the voltage where the lighting fixture shut down and stop functioning.

This voltage level should be taking into account when lowering the applied voltage. Then, voltage is manually increased to 110% of its rated voltage, in a slow ramp of 3V voltage step. Therefore, the laboratory test is implemented for different voltage levels. The recorded data will be transferred to a usable form to derive the ZIP model coefficients. Step test is performed according to [17].

5.2.4 Data Handling

The monitored quantities, which are voltage, current, active power, reactive power, and power factor, are measured and recorded at each voltage step. This measured data needs to be collected in digital form for analysis purposes. The measured data will be in a row format. Since the research focus is to study the impact of Conservation Voltage Reduction (CVR) on the LED lighting fixture, part of this data, which is between 83% below and 110% above the rated voltage [23], will be specified and selected as a valid data to be analyzed. After measuring both active power and reactive power of each lighting fixture for each different level, the ZIP model for each LED lighting fixture can be developed. The recorded data is processed with R Studio to derive the ZIP coefficients.

5.2.5 Determination of ZIP Coefficients

The ZIP model represents the relationship between the applied voltage and the characteristic of the load power in a polynomial equation as the sum of Constant Impedance (Z_P), Constant Current (I_p), and Constant Power (P_P) to identify the real power (active power). In a similar way, the reactive power is defined by the following equations (6-7) using the coefficients: Constant Impedance (Z_q), Constant Current (I_q), and Constant Power (P_q). algebraically, the ZIP model is represented by the two equations (6-7) shown below [1]:

$$P = P_o\left[Z_p\left(\frac{V}{V_o}\right)^2 + I_p\left(\frac{V}{V_o}\right) + P_p\right] \qquad (6)$$

$$Q = Q_o\left[Z_q\left(\frac{V}{V_o}\right)^2 + I_q\left(\frac{V}{V_o}\right) + P_q\right] \qquad (7)$$

Where $Z_p, I_p, P_p, Z_q, I_q, P_q$: ZIP load model coefficients for active and reactive power. These ZIP Model coefficients can be determined by using numerical methods. For this work, the ZIP coefficients of the LED lighting fixtures are calculated by using Polynomial Regression as curve fitting approach, which is also called Least-Square Regression. The function can be described as the difference between measured and calculated values of active and reactive power. This function is shown in the following equation:

$$L = \sum_{i=1}^{n} L_i^2 = \sum_{i=1}^{n}(f(V_i) - f_i)^2 \qquad (17)$$

Where: $f(V_i) = Z_p\left(\frac{V_i}{V_o}\right)^2 + I_p\left(\frac{V_i}{V_o}\right) + P_p$ (18), $f_i = \frac{P_i}{P_o}$ (19)

$$L = \sum_{i=1}^{n}\left[Z_p\left(\frac{V_i}{V_0}\right)^2 + I_p\left(\frac{V_i}{V_0}\right) + P_p - \frac{P_i}{P_0}\right]^2$$

Limited with: $Z_p + I_p + P_p = 1$ (20)

$$L = \sum_{i=1}^{n}\left[Z_q\left(\frac{V_i}{V_0}\right)^2 + I_q\left(\frac{V_i}{V_0}\right) + P_q - \frac{Q_i}{Q_0}\right]^2$$

Limited with: $Z_q + I_q + P_q = 1$

Where L is the error to be minimized, V_i and P_i is the input values in p.u., V_i/V_o and P_i/P_o are correspond to its per-unit values and they can be called only as V_i and P_i. n is the number of measured quantities at each voltage level, where the measured quantities are voltage, active power, and reactive power. Therefore, the ZIP coefficients of active power (Z_P, I_P, P_P) can be determined through the partial derivation of L in respect of each coefficient, and the resulted equation will be equal to zero, as given in the following:

$$\frac{dL}{dZ_p} = \sum_{i=1}^{n} 2\left(\frac{V_i}{V_0}\right)^2 + \left(Z_p\left(\frac{V_i}{V_0}\right)^2 + I_p\left(\frac{V_i}{V_0}\right) + P_p - \frac{P_i}{P_o}\right) = 0 \qquad (21)$$

$$\frac{dL}{dI_p} = \sum_{i=1}^{n} 2\frac{V_i}{V_0} + \left(Z_p\left(\frac{V_i}{V_0}\right)^2 + I_p\left(\frac{V_i}{V_0}\right) + P_p - \frac{P_i}{P_o}\right) = 0$$

$$\frac{dL}{dP_p} = \sum_{i=1}^{n} 2\left(Z_p\left(\frac{V_i}{V_0}\right)^2 + I_p\left(\frac{V_i}{V_0}\right) + P_p - \frac{P_i}{P_o}\right) = 0$$

The three equations can be re-written in a matrix form as shown in equation (22):

$$\begin{bmatrix} \sum_{j=1}^{n} V_j^4 & \sum_{j=1}^{n} V_j^3 & \sum_{j=1}^{n} V_j^2 \\ \sum_{j=1}^{n} V_j^3 & \sum_{j=1}^{n} V_j^2 & \sum_{j=1}^{n} V_j \\ \sum_{j=1}^{n} V_j^2 & \sum_{j=1}^{n} V_j & n \end{bmatrix} \begin{bmatrix} Z_p \\ I_p \\ P_p \end{bmatrix} = \begin{bmatrix} \sum_{j=1}^{n} P_j\, V_j^2 \\ \sum_{j=1}^{n} P_j\, V_j \\ \sum_{j=1}^{n} P_j \end{bmatrix} \qquad (22)$$

Thus, the three ZIP coefficients for active power can be obtained from the matrix equation. The exact procedure is achieved to calculate the ZIP coefficients for reactive power.

5.2.6 Results and Discussions

5.2.6.1 ZIP Model Coefficients for LED Lights

Laboratory experiment is conducted of LED light fixtures for different wattages to measure the active and reactive power values with the voltage variations. After identifying the rated value of active power P_o, it should be pointed out that P_o values are larger than the rated wattages stated on the nameplate for each light fixture. The comparison is shown in table 5.3 between rated wattages on the nameplates and the P_o, which is described as the active power consumption for LED light at the rated voltage V_o. Table 5.3 also shown the monitored quantities for LED lights tested in the lab, which are, rated voltage V_o, Frequency F, shutoff voltage V_{off}, current I_o, active power P_o, reactive power Q_o, and apparent power S_o.

Table 5.3: Monitored quantities for LED lights tested in the lab

No.	Type	Brand	Soft White /Daylight	Dimmability	Power rated	Power replc	Vo (V)	Voff (V)	F (Hz)	Io (A)	Po (W)	Qo (VAR)	So (VA)
1	Bulb	EcoSmart	Daylight	Non-dimmable	5.5	40	120	47	60	0.103	7	10	12
2	Bulb	GE	Soft White	Dimmable	9	60	120	100	60	0.106	10	8	13
3	Bulb	EcoSmart	Daylight	Non-dimmable	9	60	120	89	60	0.15	11	14	18
4	Bulb	EcoSmart	Soft White	Non-dimmable	9	60	120	94	60	0.152	11	14	18
5	Bulb	Great Value	Soft White	Non-dimmable	9	60	120	102	60	0.142	11	13	16
6	Bulb	EcoSmart	Daylight	Dimmable	9.5	60	120	93	60	0.128	11	10	15
7	Bulb	Cree	Daylight	Dimmable	10	60	120	67	60	0.099	11	5	12
8	Bulb	Great value	Daylight	Non-dimmable	12.5	75	120	94	60	0.186	13	18	23
9	Bulb	GE	Soft White	Dimmable	13	100	120	46	60	0.126	15	5	16
10	Bulb	EcoSmart	Daylight	Non-dimmable	13	100	120	96	60	0.232	13	23	28
11	Bulb	Sylvania	Daylight	Non-dimmable	14	100	120	67	60	0.204	13	21	25
12	Bulb	Great Value	Daylight	Non-dimmable	14	100	120	50	60	0.226	16	22	27
13	Bulb	Feit Electric	Daylight	Non-dimmable	15	100	120	96	60	0.242	13	26	29
14	Bulb	EcoSmart	Daylight	Dimmable	15.5	100	120	91	60	0.187	17	14	22
15	Bulb	Feit Electric	Daylight	Dimmable	17.5	100	120	31	60	0.128	14	5	15
16	Bulb	Sylvania	Soft White	Non-dimmable	22	200	120	63	60	0.390	23	42	48
17	Bulb	Feit Electric	Daylight	Dimmable	28	150	120	30	60	0.220	25	6	26
18	Candle	Yansun	Daylight	Non-dimmable	5	40	120	47	60	0.068	5	6	8
19	Candle	Yansun	Daylight	Non-dimmable	6	60	120	102	60	0.06	6	4	7
20	Tube	toggled	Daylight	Non-dimmable	8	20	120	81	60	0.095	10	4	11

21	Tube	toggled	Daylight	Non-dimmable	16	40	120	87	60	0.155	18	5	19

ZIP model is employed to estimate the load profile for LED lights, represented by active and reactive power, taking into account the voltage variations within the CVR range from 0.83 – 1.10 pu, and ZIP model coefficients are determined for each light fixture. Therefore, ZIP models and data obtained from the experiment for active and reactive measurements are plotted together to show the agreement comparison between model and measurement.

ZIP model is fitted to the measured data taking into account two cases of constrains [5]:

1. No constraints: This is called the accurate load model.
2. One constraint: sum of the ZIP coefficients should be equal to one: $Z_P + I_P + P_P = 1$

Therefore, ZIP coefficients can be derived from the load model in two ways: constrained coefficients and accurate coefficients. The constrained load model is the most widely known to the system operators and system planners as it describes the situation in the field better. The constrained coefficients are found as a fit to the measured data with the constraint that the sum of the ZIP coefficients Z_P, I_P, and P_P should be equal to one [22]. The main purpose of this constrain is to ensure that the load consumes the correct power at the nominal voltage [19], [5].

On the other hand, accurate load model, known as non-constrained model, is employed for the measured data with no constraints. Table 5.4 and 5.5 shows the ZIP Model coefficients extracted from the experiments for LED light fixtures for non-constrained and constrained ZIP model respectively.

Adjustment factor K is used to extract the constrained ZIP coefficients and employ the fact that the load consumes the correct power at the rated voltage (power is 1 pu when voltage is 1 pu) [3].

This can be achieved by multiplying K_P and K_q by ZIP coefficients for P and Q.where K_P and K_q are the adjustment factor for active power and reactive power respectively.

$$Kp = \frac{1}{Z_P + I_P + P_P} \qquad (23)$$

$$Kq = \frac{1}{Zq + Iq + Pq} \qquad (24)$$

$$\mathrm{P} = \mathrm{P_o}\left[\mathrm{K_P}.\mathrm{Z_P}\left(\frac{\mathrm{V}}{\mathrm{V_o}}\right)^2 + \mathrm{K_P}.\mathrm{I_P}\left(\frac{\mathrm{V}}{\mathrm{V_o}}\right) + \mathrm{K_P}.\mathrm{P_P}\right] \qquad (25)$$

$$\mathrm{Q} = \mathrm{Q_o}\left[\mathrm{K_q}.\mathrm{Z}_q\left(\frac{\mathrm{V}}{\mathrm{V}_o}\right)^2 + \mathrm{K}_q.\mathrm{I}_q\left(\frac{\mathrm{V}}{\mathrm{V_o}}\right) + \mathrm{K}_q.\mathrm{P}_q\right] \qquad (26)$$

Where:

$$K_P.Z_P + K_P.I_P + K_P.P_P = 1 \qquad (27)$$

$$K_q.Z_q + K_q.I_q + K_q.P_q = 1 \qquad (28)$$

Table 5.4: ZIP model coefficients for LED lights – non constrained model

No.	Type	Brand	Soft White /Daylight	Dimmability	Power rated	Power replc	Zp	Ip	Pp	Zq	Iq	Pq
1	Bulb	EcoSmart	Daylight	Non-dimmable	5.5	40	-1.43	3.90	-1.11	0.74	-1.96	0.25
2	Bulb	GE	Soft White	Dimmable	9	60	-22.51	45.82	-22.26	23.25	-47.48	22.95
3	Bulb	EcoSmart	Daylight	Non-dimmable	9	60	-6.81	16.27	-8.26	5.24	-12.84	6.54
4	Bulb	EcoSmart	Soft White	Non-dimmable	9	60	-9.11	20.71	-10.55	10.30	-23.21	11.86
5	Bulb	Great Value	Soft White	Non-dimmable	9	60	-5.65	14.46	-7.96	0.38	-4.43	3.10
6	Bulb	EcoSmart	Daylight	Dimmable	9.5	60	-8.36	18.43	-9.03	8.95	-18.42	8.35
7	Bulb	Cree	Daylight	Dimmable	10	60	2.33	-4.07	2.68	-9.46	16.61	-8.28
8	Bulb	Great value	Daylight	Non-dimmable	12.5	75	-5.85	15.47	-8.38	2.66	-8.83	5.15
9	Bulb	GE	Soft White	Dimmable	13	100	-1.47	3.27	-0.81	0.27	-2.21	0.87
10	Bulb	EcoSmart	Daylight	Non-dimmable	13	100	-13.92	29.35	-14.44	12.28	-26.38	13.03
11	Bulb	Sylvania	Daylight	Non-dimmable	14	100	0.00	0.00	1.00	0.00	-0.39	-0.56
12	Bulb	Great Value	Daylight	Non-dimmable	14	100	0.00	0.00	0.94	-1.25	2.05	-1.79
13	Bulb	Feit Electric	Daylight	Non-dimmable	15	100	-10.92	24.84	-12.93	8.74	-20.09	10.42
14	Bulb	EcoSmart	Daylight	Dimmable	15.5	100	-10.21	22.05	-10.81	10.45	-21.11	9.57
15	Bulb	Feit Electric	Daylight	Dimmable	17.5	100	0.00	0.00	1.00	1.60	-4.36	1.84
16	Bulb	Sylvania	Soft White	Non-dimmable	22	200	-1.11	1.95	0.11	0.52	-1.38	-0.05
17	Bulb	Feit Electric	Daylight	Dimmable	28	150	0.00	0.00	1.00	12.72	-26.94	13.20

18	Candle	Yansun	Daylight	Non-dimmable	5	40	0.19	1.12	-0.06	-2.53	3.99	-2.51
19	Candle	Yansun	Daylight	Non-dimmable	6	60	-17.88	38.75	-19.68	-2.54	4.01	-1.60
20	Tube	toggled	Daylight	Non-dimmable	8	20	-1.79	3.98	-1.21	0.70	-2.69	0.81
21	Tube	toggled	Daylight	Non-dimmable	16	40	-0.04	0.35	0.67	2.33	-4.83	1.23

Table 5.5: ZIP model coefficients for LED lights – constrained model

No.	Type	Brand	Soft White /Daylight	Dimmability	Power rated	Power replc	Zp	Ip	Pp	Zq	Iq	Pq
1	Bulb	EcoSmart	Daylight	Non-dimmable	5.5	40	-1.06	2.87	-0.81	-0.76	2.02	-0.26
2	Bulb	GE	Soft White	Dimmable	9	60	-21.44	43.64	-21.20	-18.12	37.01	-17.89
3	Bulb	EcoSmart	Daylight	Non-dimmable	9	60	-5.72	13.66	-6.94	-4.99	12.22	-6.23
4	Bulb	EcoSmart	Soft White	Non-dimmable	9	60	-8.74	19.86	-10.12	-9.87	22.23	-11.36
5	Bulb	Great Value	Soft White	Non-dimmable	9	60	-6.55	16.78	-9.23	-0.40	4.66	-3.26
6	Bulb	EcoSmart	Daylight	Dimmable	9.5	60	-7.97	17.57	-8.61	-8.04	16.54	-7.50
7	Bulb	Cree	Daylight	Dimmable	10	60	2.47	-4.32	2.85	8.42	-14.79	7.37
8	Bulb	Great value	Daylight	Non-dimmable	12.5	75	-4.71	12.45	-6.74	-2.59	8.61	-5.02
9	Bulb	GE	Soft White	Dimmable	13	100	-1.49	3.31	-0.82	-0.25	2.07	-0.82
10	Bulb	EcoSmart	Daylight	Non-dimmable	13	100	-14.21	29.95	-14.74	-11.47	24.65	-12.17
11	Bulb	Sylvania	Daylight	Non-dimmable	14	100	0.00	0.00	1.00	0.00	0.41	0.59
12	Bulb	Great Value	Daylight	Non-dimmable	14	100	0.00	0.00	1.00	1.26	-2.07	1.81
13	Bulb	Feit Electric	Daylight	Non-dimmable	15	100	-11.12	25.29	-13.17	-9.30	21.40	-11.09
14	Bulb	EcoSmart	Daylight	Dimmable	15.5	100	-9.85	21.28	-10.43	-9.55	19.29	-8.75
15	Bulb	Feit Electric	Daylight	Dimmable	17.5	100	0.00	0.00	1.00	-1.73	4.72	-1.99
16	Bulb	Sylvania	Soft White	Non-dimmable	22	200	-1.18	2.07	0.11	-0.58	1.52	0.06
17	Bulb	Feit Electric	Daylight	Dimmable	28	150	0.00	0.00	1.00	-12.52	26.51	-12.99
18	Candle	Yansun	Daylight	Non-dimmable	5	40	0.15	0.90	-0.05	2.40	-3.79	2.39
19	Candle	Yansun	Daylight	Non-dimmable	6	60	-14.99	32.48	-16.49	19.55	-30.87	12.32
20	Tube	toggled	Daylight	Non-dimmable	8	20	-1.81	4.04	-1.22	-0.60	2.28	-0.69
21	Tube	toggled	Daylight	Non-dimmable	16	40	-0.04	0.36	0.68	-1.83	3.80	-0.97

R-squared (R^2) and Root Mean Square Error ($RMSE$) are calculated in this study as a means to evaluate the ZIP model performance, where R-squared is a statistical measure of how close the measured data is to the fitted model, and $RMSE$ is another method to measure the error of the ZIP model in predicting the measurement data. Table 5.6 summarizes the calculated R^2 and $RMSE$ for each active and reactive power ZIP model.

Table 5.6: R^2 & $RMSE$ values for active & reactive power ZIP model

No.	**Type**	**Brand**	**Soft White /Daylight**	**Dimmability**	**Power rated**	**Power replc**	R_P^2	R_Q^2	$RMSE_P$	$RMSE_Q$
1	Bulb	EcoSmart	Daylight	Non-dimmable	5.5	40	87.6%	55.6%	0.0373	0.0415
2	Bulb	GE	Soft White	Dimmable	9	60	83.7%	77.3%	0.1021	0.1354
3	Bulb	EcoSmart	Daylight	Non-dimmable	9	60	99.4%	98.8%	0.0206	0.0273
4	Bulb	EcoSmart	Soft White	Non-dimmable	9	60	97.8%	97.9%	0.0406	0.0428
5	Bulb	Great Value	Soft White	Non-dimmable	9	60	98.4%	100.0%	0.0350	0.0045
6	Bulb	EcoSmart	Daylight	Dimmable	9.5	60	98.8%	97.0%	0.0243	0.0221
7	Bulb	Cree	Daylight	Dimmable	10	60	77.7%	91.2%	0.0198	0.0443
8	Bulb	Great value	Daylight	Non-dimmable	12.5	75	99.6%	99.3%	0.0234	0.0268
9	Bulb	GE	Soft White	Dimmable	13	100	83.0%	87.0%	0.0223	0.0573
10	Bulb	EcoSmart	Daylight	Non-dimmable	13	100	99.4%	98.9%	0.0196	0.0279
11	Bulb	Sylvania	Daylight	Non-dimmable	14	100	-	84.0%	0.0000	0.0145
12	Bulb	Great Value	Daylight	Non-dimmable	14	100	-	90.7%	0.0000	0.0107
13	Bulb	Feit Electric	Daylight	Non-dimmable	15	100	99.2%	99.7%	0.0309	0.0163
14	Bulb	EcoSmart	Daylight	Dimmable	15.5	100	98.0%	84.3%	0.0300	0.0450
15	Bulb	Feit Electric	Daylight	Dimmable	17.5	100	-	80.0%	0.0000	0.0558
16	Bulb	Sylvania	Soft White	Non-dimmable	22	200	79.9%	95.1%	0.0092	0.0073
17	Bulb	Feit Electric	Daylight	Dimmable	28	150	-	57.3%	0.0000	0.1961
18	Candle	Yansun	Daylight	Non-dimmable	5	40	82.5%	64.1%	0.0568	0.0575
19	Candle	Yansun	Daylight	Non-dimmable	6	60	98.0%	22.0%	0.0468	0.1401
20	Tube	toggled	Daylight	Non-dimmable	8	20	75.9%	74.1%	0.0239	0.0634
21	Tube	toggled	Daylight	Non-dimmable	16	40	75.5%	19.9%	0.0137	0.0735

5.2.6.2 ZIP Model vs. Measurement Data Comparison

LED light – Bulb Type

The bulb type-LED light fixtures were tested for different wattages. Table 5.7 shows ZIP coefficients for the LED lights with bulb type for different characteristics. A comparison between ZIP model and measured data of active & reactive power for LED lights – bulb type within the CVR range, from 0.80 – 1.10 pu, are shown from figure 5.2 to figure 5.18. With respect to the comparison, it should be pointed out that the ZIP model has a good compatibility with the measured data for each active and reactive power obtained from the experiment for LED light, bulb type, at the rated wattages: 5.5W, 9W, 9.5W, 10W, 12.5W, 13W, 14W, 15W, 15.5W, 17.5W, 22W, and 28W. This can be confirmed by the calculated R^2 for LED lights shown in table 5.6.

An example of R^2 is provided for LED light bulb, daylight, non-dimmable, rated wattage 9W. R^2 for active power and reactive power for this light bulb are 99.4% and 98.8% respectively, and the figure 5.4 shows how ZIP model has a good agreement with the measured data for each active and reactive power. Table 5.6 shows the calculated R^2 for bulb type-LED lights.

However, ZIP model for “LED EcoSmart Bulb Daylight Non-dimmable 5.5W” is shown in figure 5.2. With reference to the reactive power, the ZIP model of this light fixture is only compatible with the reactive power measurements at certain voltage levels such as 0.87 and 1.08 pu, hence ZIP model does not have a good accuracy to present the reactive power demand as the accuracy of the active power, where the calculated R^2 values for active power and reactive power are 87.6% and 55.6% respectively.

Table 5.7: ZIP coefficients for bulb type LED lights

No.	Type	Brand	Soft White /Daylight	Dimmability	Power rated	Power replc	Zp	Ip	Pp	Zq	Iq	Pq
1	Bulb	EcoSmart	Daylight	Non-dimmable	5.5	40	-1.06	2.87	-0.81	-0.76	2.02	-0.26
2	Bulb	GE	Soft White	Dimmable	9	60	-21.44	43.64	-21.20	-18.12	37.01	-17.89
3	Bulb	EcoSmart	Daylight	Non-dimmable	9	60	-5.72	13.66	-6.94	-4.99	12.22	-6.23
4	Bulb	EcoSmart	Soft White	Non-dimmable	9	60	-8.74	19.86	-10.12	-9.87	22.23	-11.36
5	Bulb	Great Value	Soft White	Non-dimmable	9	60	-6.55	16.78	-9.23	-0.40	4.66	-3.26
6	Bulb	EcoSmart	Daylight	Dimmable	9.5	60	-7.97	17.57	-8.61	-8.04	16.54	-7.50
7	Bulb	Cree	Daylight	Dimmable	10	60	2.47	-4.32	2.85	8.42	-14.79	7.37
8	Bulb	Great value	Daylight	Non-dimmable	12.5	75	-4.71	12.45	-6.74	-2.59	8.61	-5.02
9	Bulb	GE	Soft White	Dimmable	13	100	-1.49	3.31	-0.82	-0.25	2.07	-0.82
10	Bulb	EcoSmart	Daylight	Non-dimmable	13	100	-14.21	29.95	-14.74	-11.47	24.65	-12.17
11	Bulb	Sylvania	Daylight	Non-dimmable	14	100	0.00	0.00	1.00	0.00	0.41	0.59
12	Bulb	Great Value	Daylight	Non-dimmable	14	100	0.00	0.00	1.00	1.26	-2.07	1.81
13	Bulb	Feit Electric	Daylight	Non-dimmable	15	100	-11.12	25.29	-13.17	-9.30	21.40	-11.09
14	Bulb	EcoSmart	Daylight	Dimmable	15.5	100	-9.85	21.28	-10.43	-9.55	19.29	-8.75
15	Bulb	Feit Electric	Daylight	Dimmable	17.5	100	0.00	0.00	1.00	-1.73	4.72	-1.99
16	Bulb	Sylvania	Soft White	Non-dimmable	22	200	-1.18	2.07	0.11	-0.58	1.52	0.06
17	Bulb	Feit Electric	Daylight	Dimmable	28	150	0.00	0.00	1.00	-12.52	26.51	-12.99

1. EcoSmart Bulb Daylight Non-dimmable 5.5W

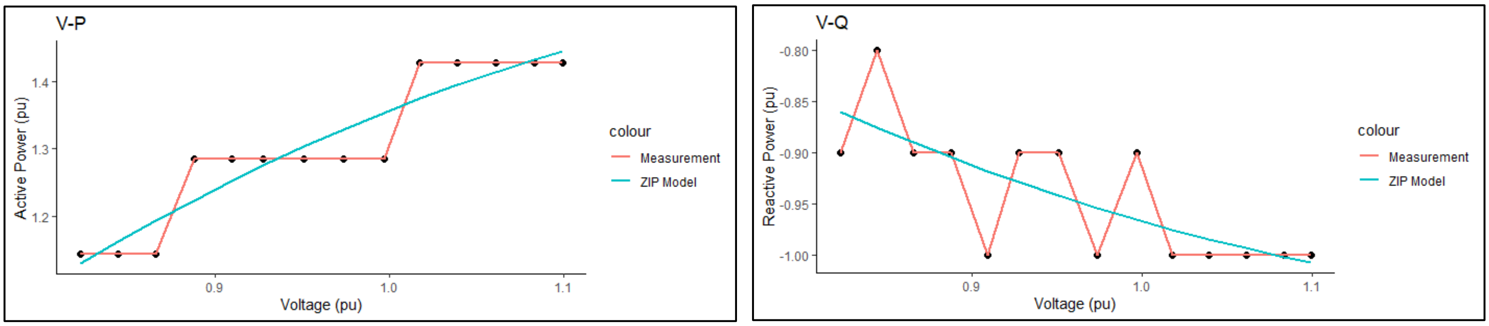

Figure 5.2: P & Q comparison - Bulb Daylight Non-dimmable 5.5W

2. GE Bulb Soft White Dimmable 9W

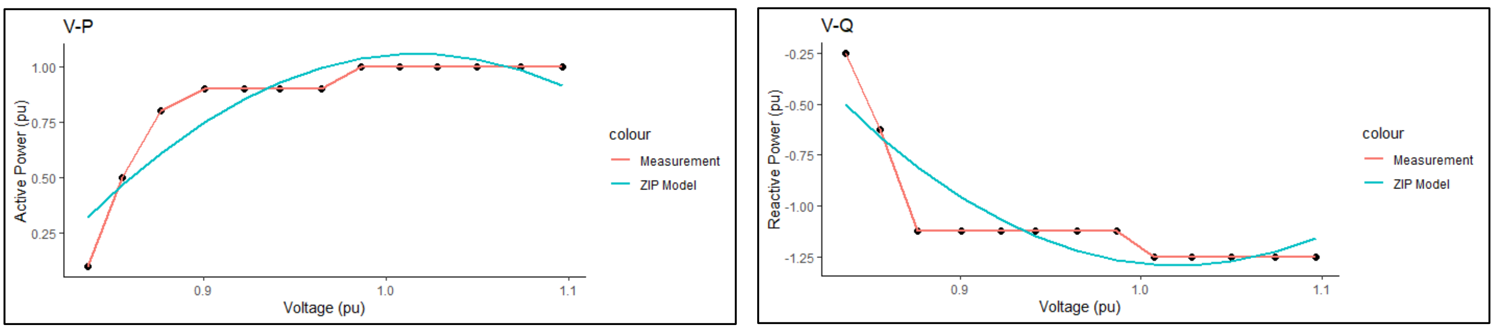

Figure 5.3: P & Q comparison - Bulb Soft White Dimmable 9W

3. EcoSmart Bulb Daylight Non-dimmable 9W

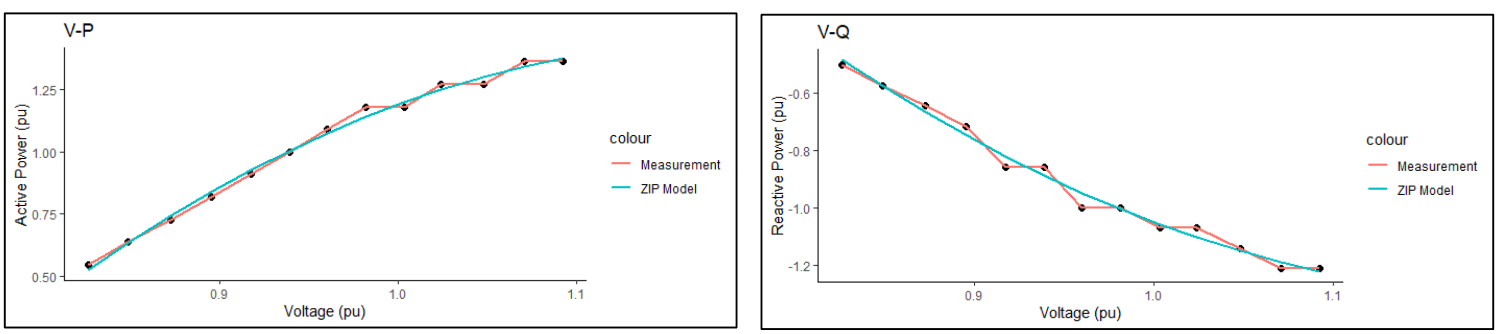

Figure 5.4: P & Q comparison - Bulb Daylight Non-dimmable 9W

4. EcoSmart Bulb Soft White Non-dimmable 9W

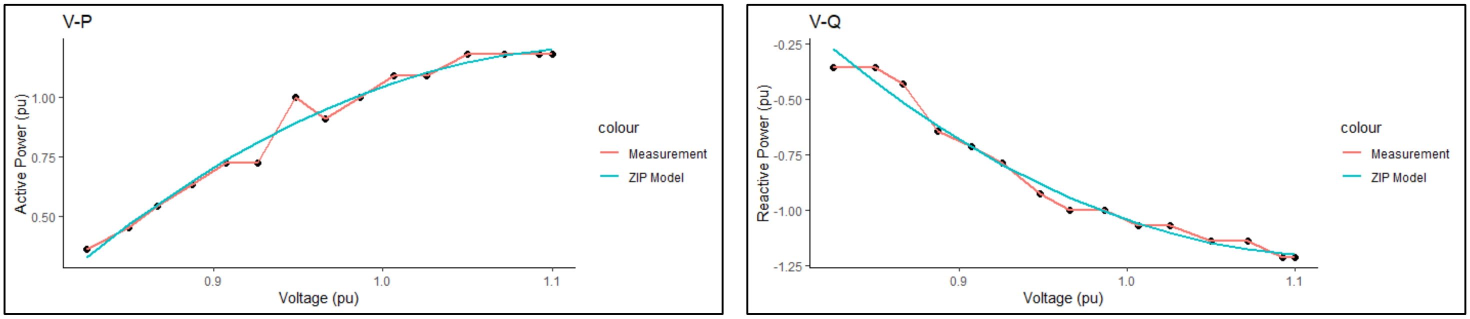

Figure 5.5: P & Q comparison - Bulb Soft White Non-dimmable 9W

5. Great Value Bulb Soft White Non-dimmable 9W

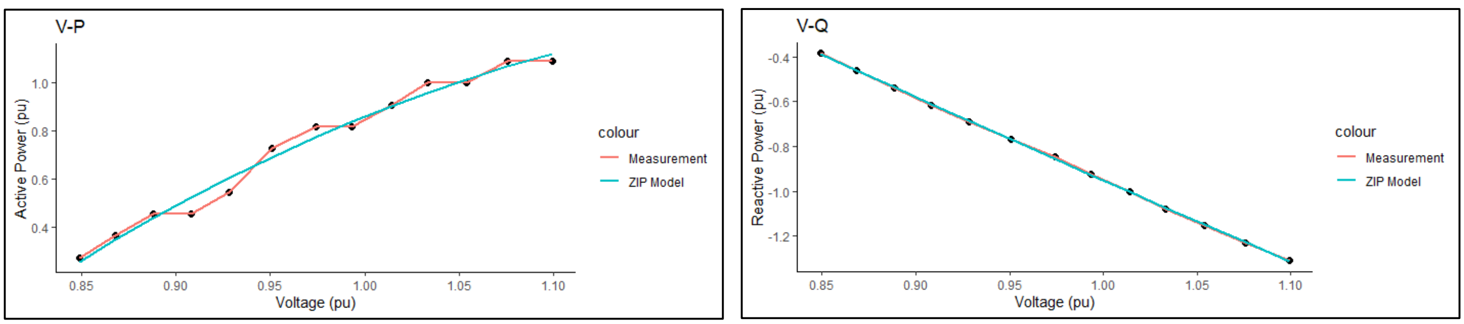

Figure 5.6: P & Q comparison - Bulb Soft White Non-dimmable 9W

6. EcoSmart Bulb Daylight Dimmable 9.5W

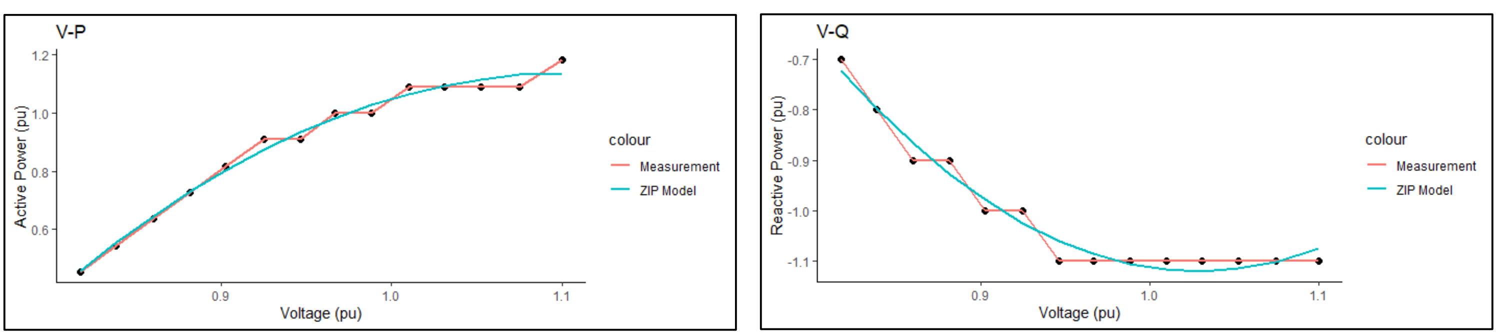

Figure 5.7: P & Q comparison - Bulb Daylight Dimmable 9.5W

7. Cree Bulb Daylight Dimmable 10W

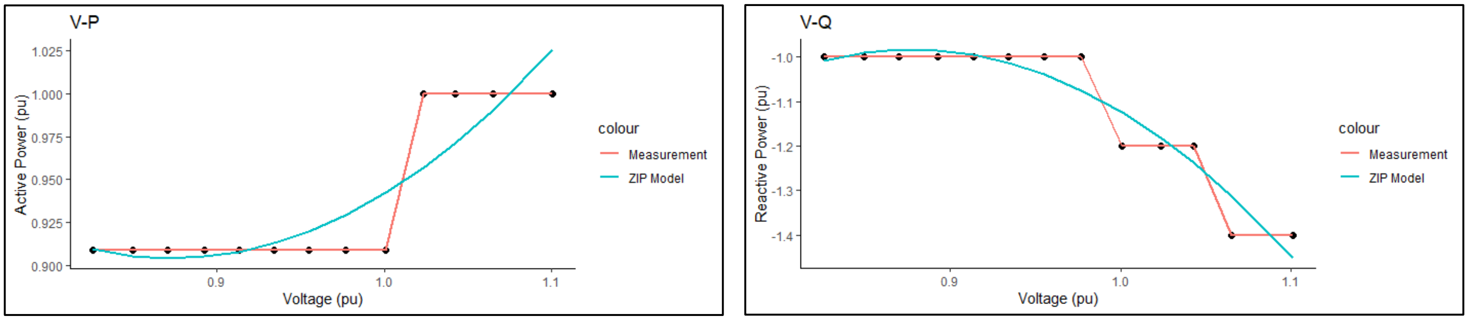

Figure 5.8: P & Q comparison - Bulb Daylight Dimmable 10W

8. Great value Bulb Daylight Non-dimmable 12.5W

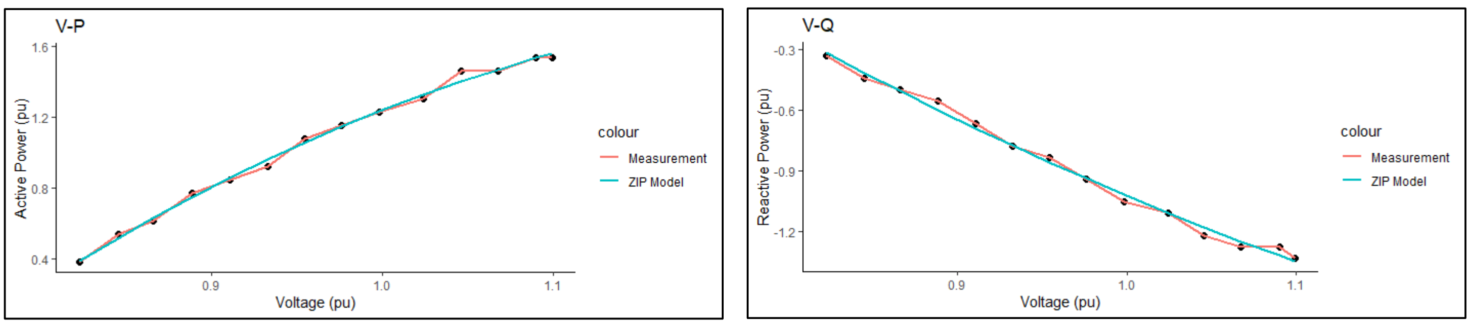

Figure 5.9: P & Q comparison - Bulb Daylight Non-dimmable 12.5W

9. GE Bulb Soft White Dimmable 13W

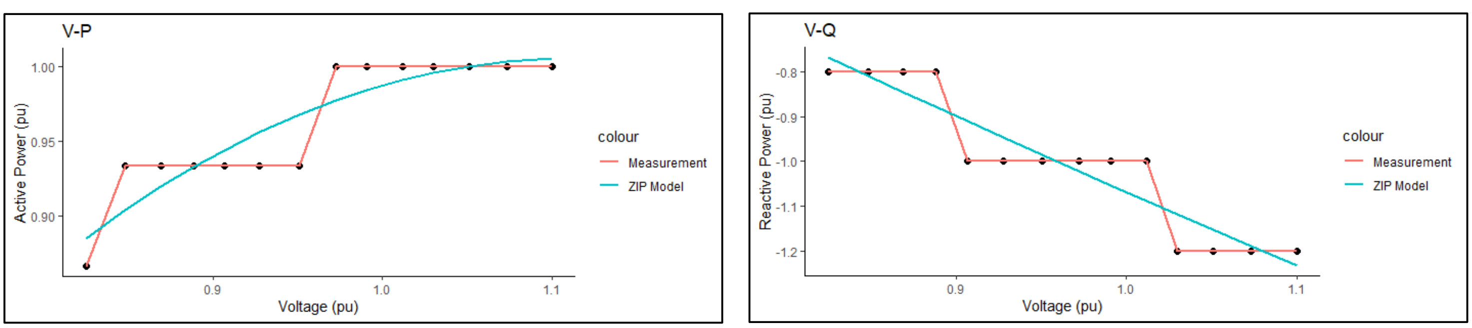

Figure 5.10: P & Q comparison - Bulb Soft White Dimmable 13W

10. EcoSmart Bulb Daylight Non-dimmable 13W

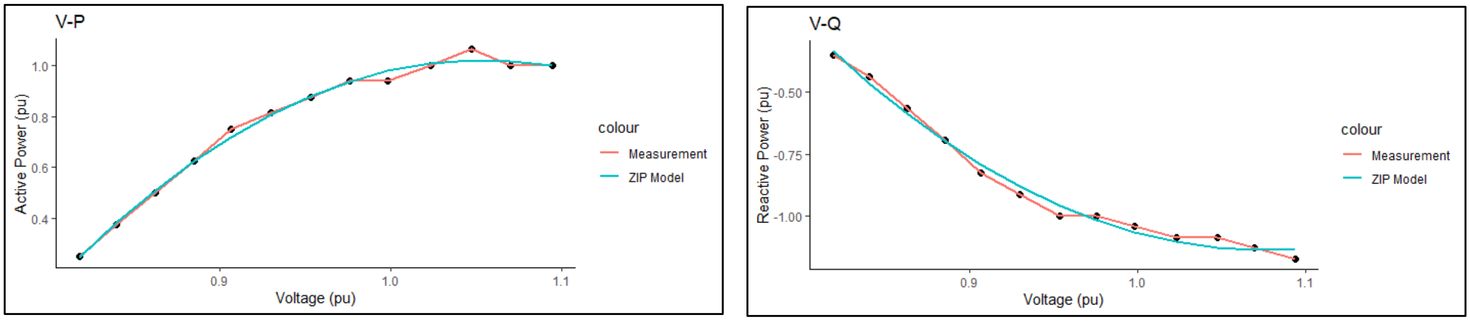

Figure 5.11: P & Q comparison - Bulb Daylight Non-dimmable 13W

11. Sylvania Bulb Daylight Non-dimmable 14W

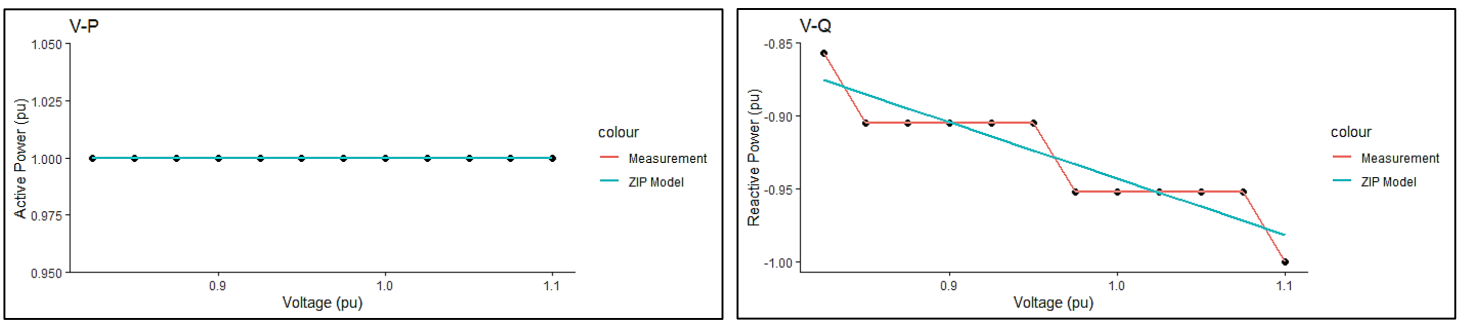

Figure 5.12: P & Q comparison - Sylvania Bulb Daylight Non-dimmable 14W

12. Great Value Bulb Daylight Non-dimmable 14W

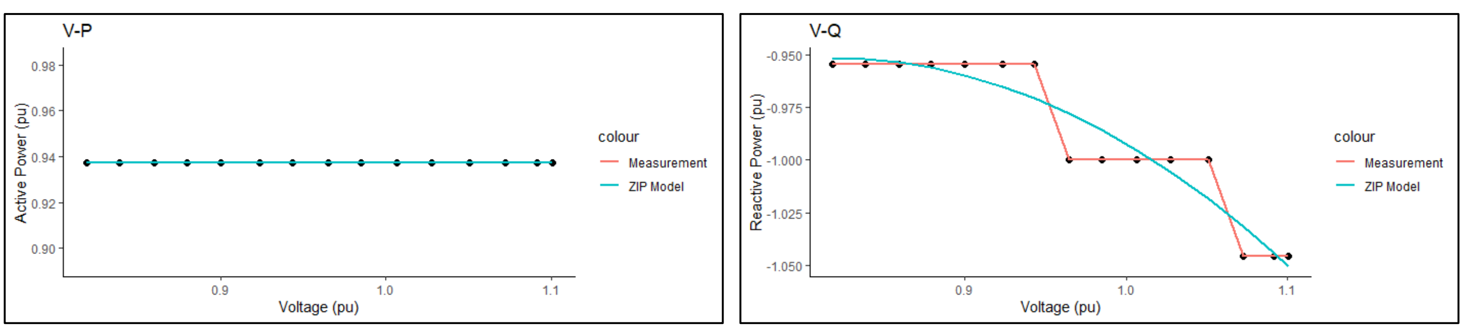

Figure 5.13: P & Q comparison - Great Value Bulb Daylight Non-dimmable 14W

13. Feit Electric Bulb Daylight Non-dimmable 15W

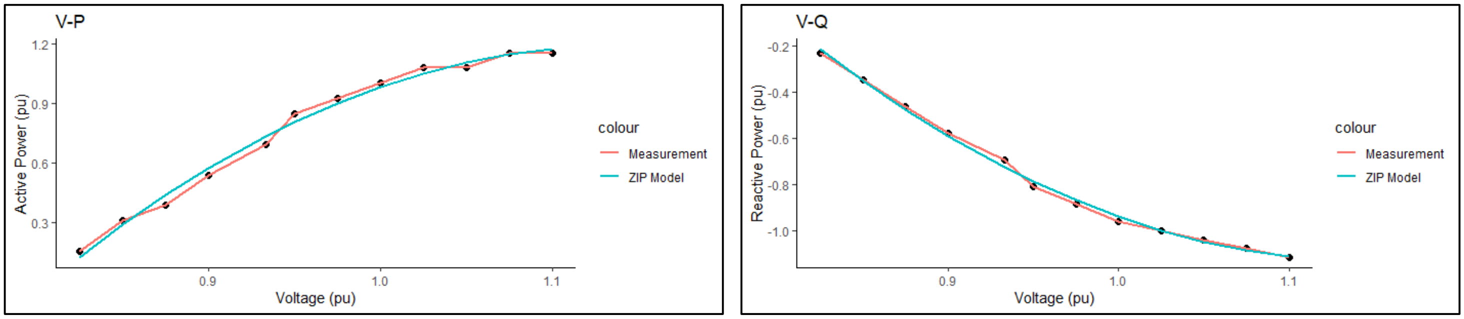

Figure 5.14: P & Q comparison - Feit Electric Bulb Daylight Non-dimmable 15W

14. EcoSmart Bulb Daylight Dimmable 15.5W

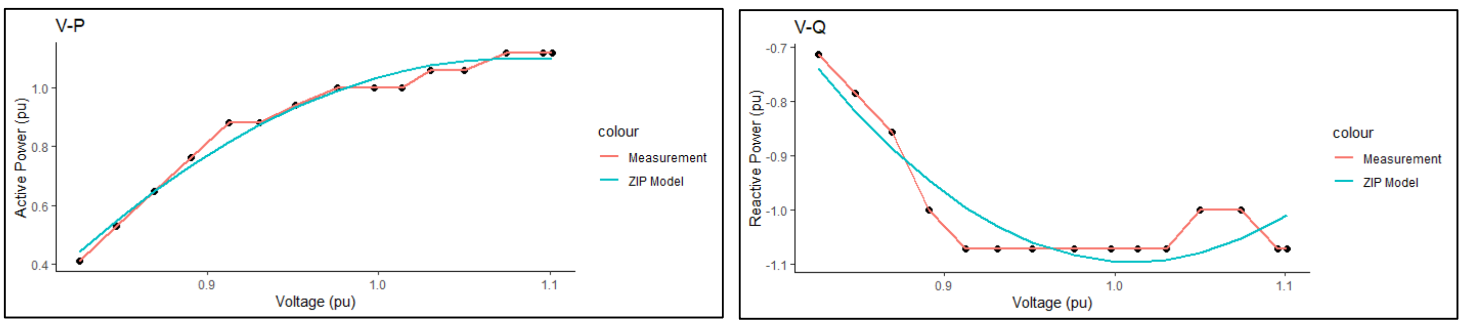

Figure 5.15: P & Q comparison - Bulb Daylight Dimmable 15.5W

15. Feit Electric Bulb Daylight Dimmable 17.5W

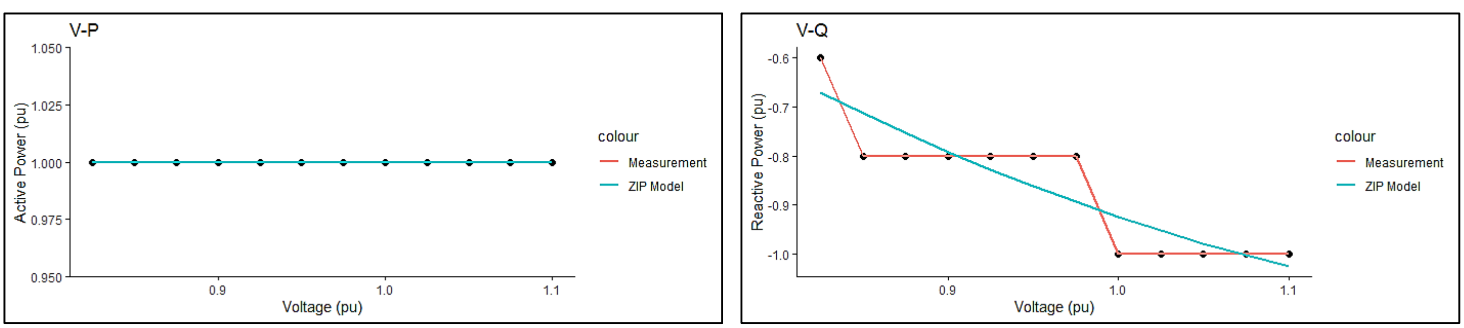

Figure 5.16: P & Q comparison - Feit Electric Bulb Daylight Dimmable 17.5W

16. Sylvania Bulb Soft White Non-dimmable 22W

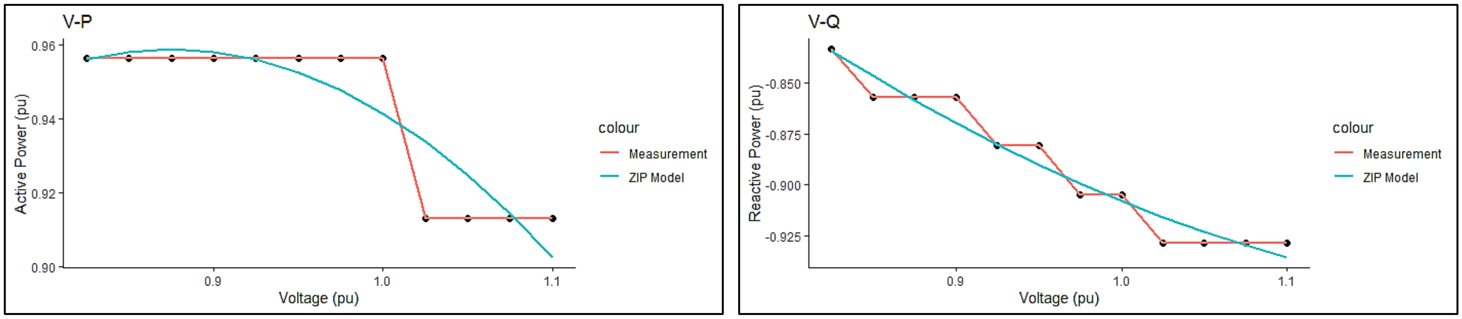

Figure 5.17: P & Q comparison - Sylvania Bulb Soft White Non-dimmable 22W

17. Feit Electric Bulb Daylight Dimmable 28W

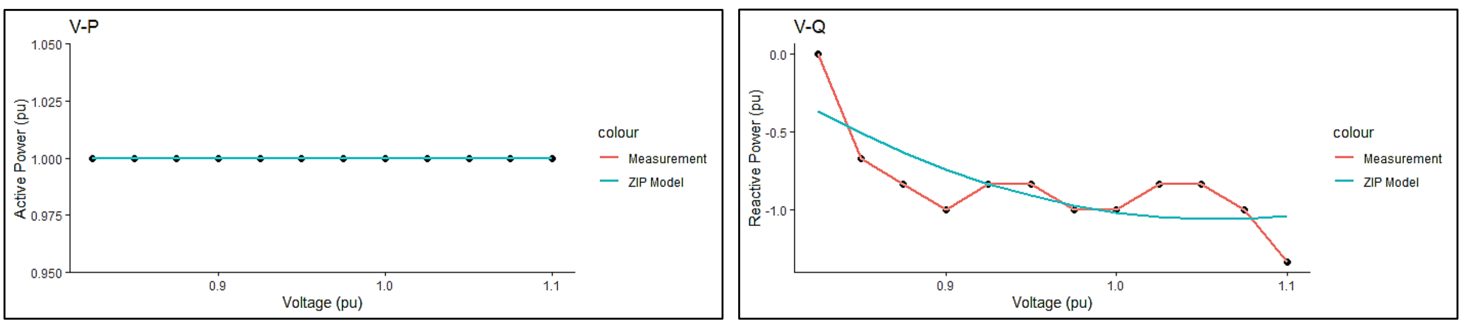

Figure 5.18: P & Q comparison - Feit Electric Bulb Daylight Dimmable 28W

LED light – Linear & Candle Type

The candle type-LED light fixtures were tested for daylight, non-dimmable, 40W and 60W power replacement, and 5W and 6W of power rated. Table 5.8 shows ZIP coefficients for the LED lights with candle type. It is obvious from the figures 5.19 and 5.20 that ZIP model can be used to determine the active power consumption within the conservation voltage reduction (CVR) range as the calculated R^2 for the active power ZIP model of 5W and 6W LED lights are 82.5% and 98.0% respectively. Therefore, the active power ZIP model for 6W LED light is more accurate than the ZIP model for 5W.

On the other hand, ZIP model does not have a good precision of predicting the reactive power, where R^2 values are 64.1% and 22.0% for 5W and 6W LED lights. Thus, the reactive power ZIP model is not as accurate as ZIP model for active power measurements.

With respect to LED light – Tube, table 5.8 also shows ZIP coefficients for the LED lights with tube type. The developed ZIP model for active power in the tube type-LED light is not able to represent the load behavior as it does for the bulb and candle type, where R values for 8W and 16W LED lights are 75.9% and 75.5% respectively. Similar cases are clearly observed for reactive power measurements; it is shown by the figures 5.15 and 5.19 that ZIP model does not have an agreement with the reactive power consumption for the tube LED lights.

Table 5.8: ZIP coefficients for linear & candle type LED lights

No.	Type	Brand	Soft White /Daylight	Dimmability	Power rated	Power replc	Zp	Ip	Pp	Zq	Iq	Pq
1	Candle	Yansun	Daylight	Non-dimmable	5	40	0.15	0.90	-0.05	2.40	-3.79	2.39
2	Candle	Yansun	Daylight	Non-dimmable	6	60	-14.99	32.48	-16.49	19.55	-30.87	12.32
3	Tube	toggled	Daylight	Non-dimmable	8	20	-1.81	4.04	-1.22	-0.60	2.28	-0.69
4	Tube	toggled	Daylight	Non-dimmable	16	40	-0.04	0.36	0.68	-1.83	3.80	-0.97

1. Yansun Candle Daylight Non-dimmable 5W

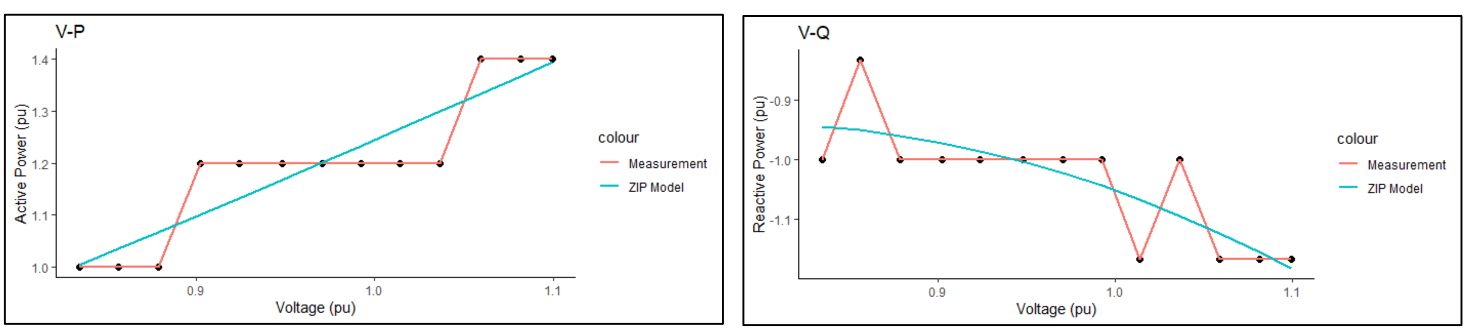

Figure 5.19: P & Q comparison - Candle Daylight Non-dimmable 5W

2. Yansun Candle Daylight Non-dimmable 6W

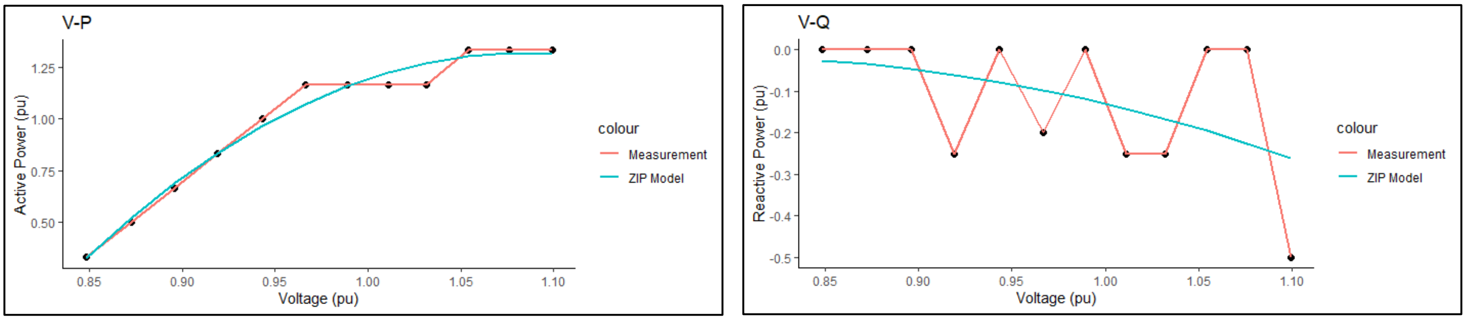

Figure 5.20: P & Q comparison - Candle Daylight Non-dimmable 6W

3. toggled Tube Daylight Non-dimmable 8W

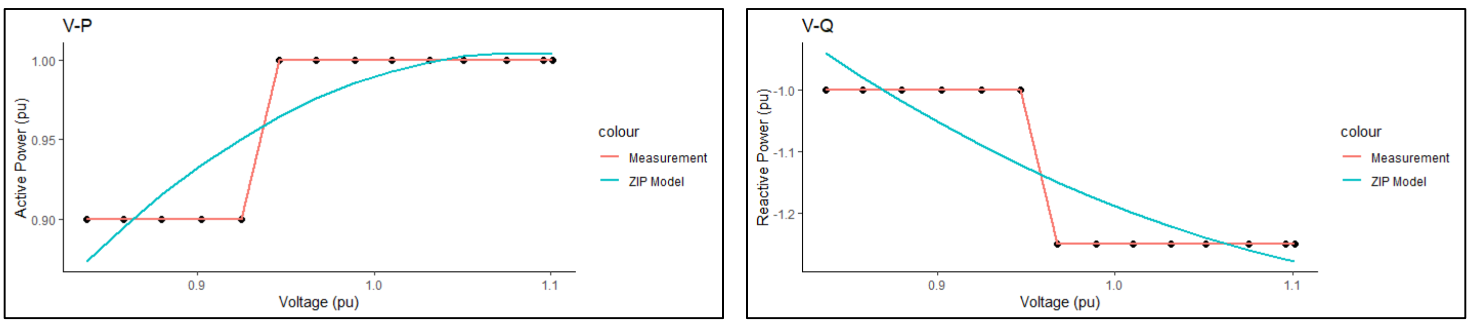

Figure 5.21: P & Q comparison - Tube Daylight Non-dimmable 8W

4. toggled Tube Daylight Non-dimmable 16W

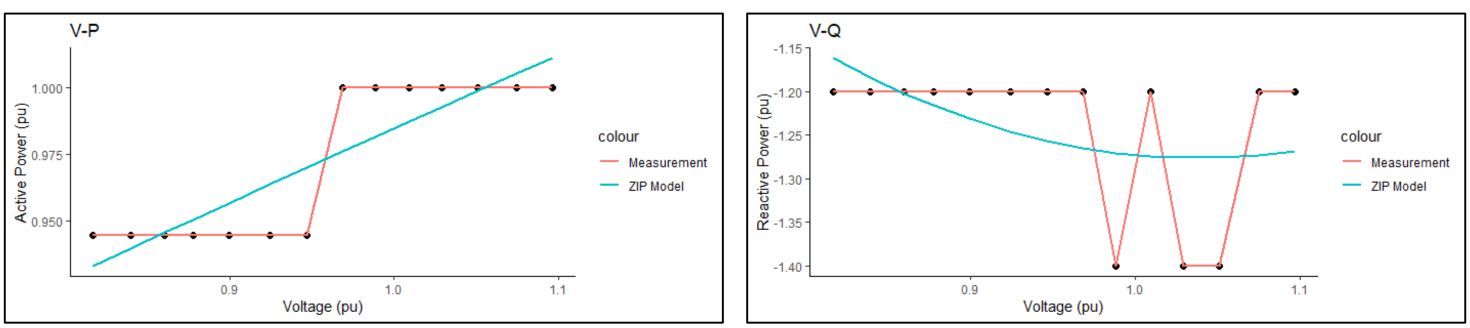

Figure 5.22: P & Q comparison - Tube Daylight Non-dimmable 16W

5.2.6.3 CVR impact on LED Lights

As discussed in chapter 3, the conservation voltage reduction (CVR) method is one of the power-conserve applications used in the utilities. This technique implies that the load consumes less power when the applied voltage is reduced less than its rated value. Therefore, our goal in this study is to identify the impact of CVR on the LED lights, and how the light fixtures perform when it is exposed to voltage reduction. In our experiment, the lights here were subjected to the voltage range from 83% – 110% of the rated voltage 120V [23].

The conservation voltage reduction CVR has an effective impact on most LED lights, where it enables the lights to consume less power with the same performance at the rated voltage. An example of that is demonstrated for 9W LED bulb. Figure 5.4 shows that the light consumed 0.56 pu of its rated active power when CVR is implemented. Also, a very good compatibility between ZIP model and the measurement data of active power within the CVR range is noticed for this light.

LED Lights – Tube Type

With respect to the tube type of LED lights for 8W and 16W, it was clearly observed that CVR technique does not greatly impact the performance of the linear type. This is shown by figures 5.17 and 5.18 of the active power measurements for LED light – tube type, the minimum power required for this type is around 0.90 and 0.95 pu of its rated active power for LED 8W and 16W respectively. Additionally, the light does not perform well and start flickering when the applied voltage goes under the CVR range, hence there is no high power reduction achieved when applying the CVR technique for the LED light – tube type.

Constant power P_p LED lights

CVR has no impact on some high wattages LED lights with 14W, 17W, and 28W of LED – bulb types, which is demonstrated in the figures 5.12, 5.13, 5.16, and 5.18, where the active power consumption is constant during the CVR range. This is also proved by the ZIP load modeling, where the ZIP coefficients for active power Z_P, I_P and P_P are 0, 0, and 1 respectively, hence the ZIP model represents the LED light as a constant power P_P. Table 5.9 lists all the LED lights with high wattages. Consequently, there is no power – conserve achieved when CVR is performed for most of the high wattages of LED light – bulb type.

Table 5.9: ZIP coefficients for constant power – LED lights

No.	Type	Brand	Soft White /Daylight	Dimmability	Power rated	Power replc	Zp	Ip	Pp	Zq	Iq	Pq
1	Bulb	Sylvania	Daylight	Non-dimmable	14	100	0.00	0.00	1.00	0.00	0.41	0.59
2	Bulb	Great Value	Daylight	Non-dimmable	14	100	0.00	0.00	1.00	1.26	-2.07	1.81
3	Bulb	Feit Electric	Daylight	Dimmable	17.5	100	0.00	0.00	1.00	-1.73	4.72	-1.99
4	Bulb	Feit Electric	Daylight	Dimmable	28	150	0.00	0.00	1.00	-12.52	26.51	-12.99

5.2.6.4 Power Consumption Estimation Based on ZIP Coefficients

Conservation voltage reduction (CVR) was applied to LED lights in order to study the effectiveness of CVR on the light components, and ZIP model coefficients were determined according to the CVR accomplished in the experiment. Therefore, the impact of CVR can be mathematically assessed by the CVR f-actor, which is described as the ratio of the change in power consumed by the load to the voltage variations. Thus, the power reduction resulted from CVR needs to be estimated as well.

In this section, the power consumption for LED lights is estimated based on the ZIP model coefficients for each light component. Then, this estimated power consumption is validated against the actual recordings of power consumption achieved under CVR technique. Figure 5.23 shows the validation methodology of power consumption estimation based on ZIP model Coefficients.

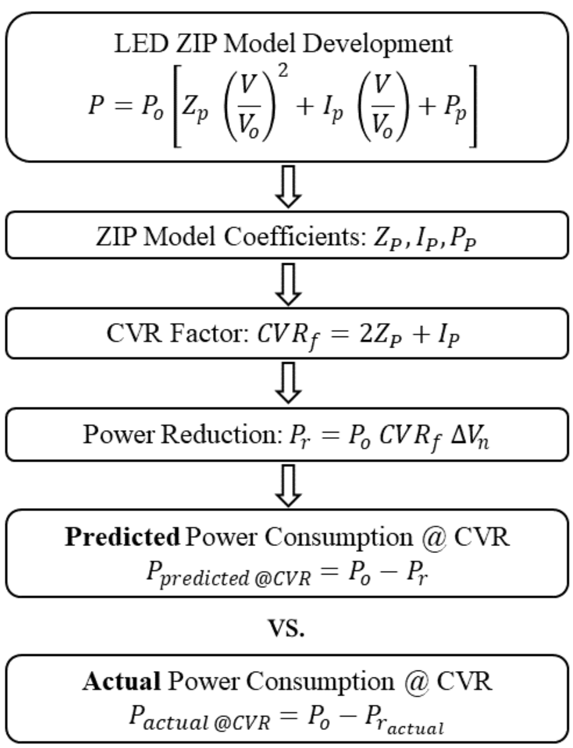

Figure 5.23: Validation methodology of power consumption estimation based on ZIP model

Conservation voltage reduction factor CVR_f for LED lights can be extracted based on the ZIP coefficients determined in the previous section. This can be implemented by the derivation of active power in equation (29)[53].

$$P = P_o \left[Z_P \left(\frac{V}{V_o}\right)^2 + I_P \left(\frac{V}{V_o}\right) + P_P \right] \qquad (29)$$

Per unit (p.u.) is the unit used for active power and rated voltage values in the ZIP model equation. This can be achieved by substituting $P_n = \frac{P}{P_o}$ and $V_n = \frac{V}{V_o}$, where P_n is the active power in per unit, and V_n is the rated voltage in per unit. Equation (30) will be derived for the rated voltage in per unit V_n, as shown in the following:

$$P_n = Z_P\, V_n^2 + I_p\, V_n + P_P \qquad (30)$$

$$\frac{\partial P_n}{\partial V_n} = 2\, Z_P\, V_n + I_P$$

Voltage variations ∂V_n , which presents $\partial V_n = \frac{V - V_o}{V_o} = V_n - 1 \ \rightarrow V_n = \partial V_n + 1$, will be replaced as shown in equation (31), hence the derived active power equation will be expressed as follows:

$$\partial P_n = [2Z_P(\partial V_n + 1) + I_P]\, \partial V_n \qquad (31)$$

$$\partial P_n = [2Z_P\, \partial V_n^2 + 2Z_P\, \partial V_n + I_P\, \partial V_n]$$

$$\partial P_n = (2Z_P + I_P)\, \partial V_n + 2Z_P\, \partial V_n^2$$

$$\frac{\partial P_n}{\partial V_n} = 2Z_P + I_P$$

∂V_n^2 is negligible and can be ignored for simplicity. Therefore, conservation voltage reduction factor CVR_f can be calculated based on ZIP model coefficients, which are constant impedance Z_P and constant current I_P, as shown in equation (32).

$$CVR_f = 2Z_P + I_P \qquad (32)$$

Thus, the power reduction executed by CVR technique can be estimated by equation (33), where P_r is the amount of power reduction, P_o is the rated active power for LED light, CVR_f is the calculated CVR factor based on ZIP model coefficients, and ΔV_n is the voltage reduction.

$$P_r = P_o \, CVR_f \, \Delta V_n \qquad (33)$$

$$\Delta V_n = \frac{V_o - V_{reduction}}{V_0} = \frac{120V - 100V}{120V} = 0.16 \qquad (34)$$

Since the CVR range in our study is from the 0.83 – 1.10 pu of the rated voltage, the applied voltage reduction is equal to 100V. Consequently, ΔV_n is calculated by equation (34), where V_o is the rated voltage 120V, and $V_{reduction}$ is the applied voltage reduction during the CVR application and equal to 100V. Table 5.10 demonstrates the calculated CVR_f and estimated power reduction P_r values for LED lights.

Table 5.10: Calculated CVR_f and Power reduction P_r values for LED lights

No.	Type	Brand	Soft White /Daylight	Dimmability	Power rated	Power replc	Po (W)	CVR_f	ΔV_n	P_r
1	Bulb	EcoSmart	Daylight	Non-dimmable	5.5	40	7.0	0.8	0.16	0.85
2	Bulb	GE	Soft White	Dimmable	9	60	10.0	0.8	0.16	1.21
3	Bulb	EcoSmart	Daylight	Non-dimmable	9	60	11.0	2.2	0.16	3.90
4	Bulb	EcoSmart	Soft White	Non-dimmable	9	60	11.0	2.4	0.16	4.19
5	Bulb	Great Value	Soft White	Non-dimmable	9	60	11.0	3.7	0.16	6.48
6	Bulb	EcoSmart	Daylight	Dimmable	9.5	60	11.0	1.6	0.16	2.88
7	Bulb	Cree	Daylight	Dimmable	10	60	11.0	0.6	0.16	1.11
8	Bulb	Great value	Daylight	Non-dimmable	12.5	75	13.0	3.0	0.16	6.31
9	Bulb	GE	Soft White	Dimmable	13	100	15.0	0.3	0.16	0.79
10	Bulb	EcoSmart	Daylight	Non-dimmable	13	100	13.0	1.5	0.16	3.18
11	Bulb	Sylvania	Daylight	Non-dimmable	14	100	13.0	0.0	0.16	0.00
12	Bulb	Great Value	Daylight	Non-dimmable	14	100	16.0	0.0	0.16	0.00
13	Bulb	Feit Electric	Daylight	Non-dimmable	15	100	15.0	3.0	0.16	7.31
14	Bulb	EcoSmart	Daylight	Dimmable	15.5	100	17.0	1.6	0.16	4.29
15	Bulb	Feit Electric	Daylight	Dimmable	17.5	100	14.0	0.0	0.16	0.00
16	Bulb	Sylvania	Soft White	Non-dimmable	22	200	23.0	-0.3	0.16	-1.09
17	Bulb	Feit Electric	Daylight	Dimmable	28	150	25.0	0.0	0.16	0.00
18	Candle	Yansun	Daylight	Non-dimmable	5	40	5.0	1.2	0.16	0.96
19	Candle	Yansun	Daylight	Non-dimmable	6	60	6.0	2.5	0.16	2.41
20	Tube	toggled	Daylight	Non-dimmable	8	20	10.0	0.4	0.16	0.66

21	Tube	toggled	Daylight	Non-dimmable	16	40	18.0	0.3	0.16	0.81

The predicted power consumption at certain voltage level of CVR, which is 100V in our study, can be estimated according to equation (35), where P_o is the rated active power for LED light, and P_r is the power reduction.

$$P_{predicted\ @CVR} = P_{predicted\ @100V} = P_o - P_r \qquad (35)$$

Consequently, the predicted power consumption at 100V of the applied voltage is calculated for each LED light and compared with the actual measurements of power consumption at 100V to validate the estimation of power consumption based on ZIP model. Table 5.11 shows a comparison between predicted & actual power consumption at 100V for LED lights.

Table 5.11: Comparison between predicted & actual power consumption at 100V for LED lights

No.	**Type**	**Brand**	**Soft White /Daylight**	**Dimmability**	**Po**	**Predicted P @100V**	**Actual P @100V**	**Percentage Change**
1	Bulb	EcoSmart	Daylight	Non-dimmable	7	6	8	-25%
2	Candle	Yansun	Daylight	Non-dimmable	5	4	5	-20%
3	Bulb	Feit Electric	Daylight	Dimmable	14	14	15	-7%
4	Bulb	Cree	Daylight	Dimmable	11	10	10	0%
5	Bulb	Great value	Daylight	Non-dimmable	13	7	7	0%
6	Bulb	Sylvania	Daylight	Non-dimmable	13	13	13	0%
7	Bulb	Feit Electric	Daylight	Dimmable	25	25	25	0%
8	Candle	Yansun	Daylight	Non-dimmable	6	3	3	0%
9	Tube	toggled	Daylight	Non-dimmable	10	9	9	0%
10	Tube	toggled	Daylight	Non-dimmable	18	17	17	0%
11	Bulb	Great Value	Daylight	Non-dimmable	16	16	15	6%
12	Bulb	GE	Soft White	Dimmable	15	14	13	7%
13	Bulb	Sylvania	Soft White	Non-dimmable	23	24	22	8%
14	Bulb	EcoSmart	Soft White	Non-dimmable	11	6	5	17%
15	Bulb	EcoSmart	Daylight	Non-dimmable	13	10	8	20%
16	Bulb	Great Value	Soft White	Non-dimmable	11	4	3	25%
17	Bulb	EcoSmart	Daylight	Dimmable	11	8	6	25%
18	Bulb	EcoSmart	Daylight	Dimmable	17	12	9	25%
19	Bulb	EcoSmart	Daylight	Non-dimmable	11	7	5	29%
20	Bulb	GE	Soft White	Dimmable	10	8	5	38%
21	Bulb	Feit Electric	Daylight	Non-dimmable	15	7	4	43%

With the comparison between the predicted power consumption, based on ZIP model, and the actual power consumption, obtained from the actual measurement, it should be pointed out that the values of predicted power consumption based on the ZIP model has a good agreement with the actual measurements of power consumption at 100V of the applied voltage for LED lights. Figure 5.24 shows the comparison between predicted & actual power consumption for LED lights.

The error between the predicted and actual consumption is calculated to evaluate the ZIP model as shown in table 5.11, it should be pointed out that the average error is 9.1%. Consequently, ZIP load model is considered to be a significant means to assess the conservation voltage reduction (CVR) effectiveness in the network system, and can be employed for the modern lights such as LED, where it precisely represents the behavior of lighting components that are subjected to CVR technique.

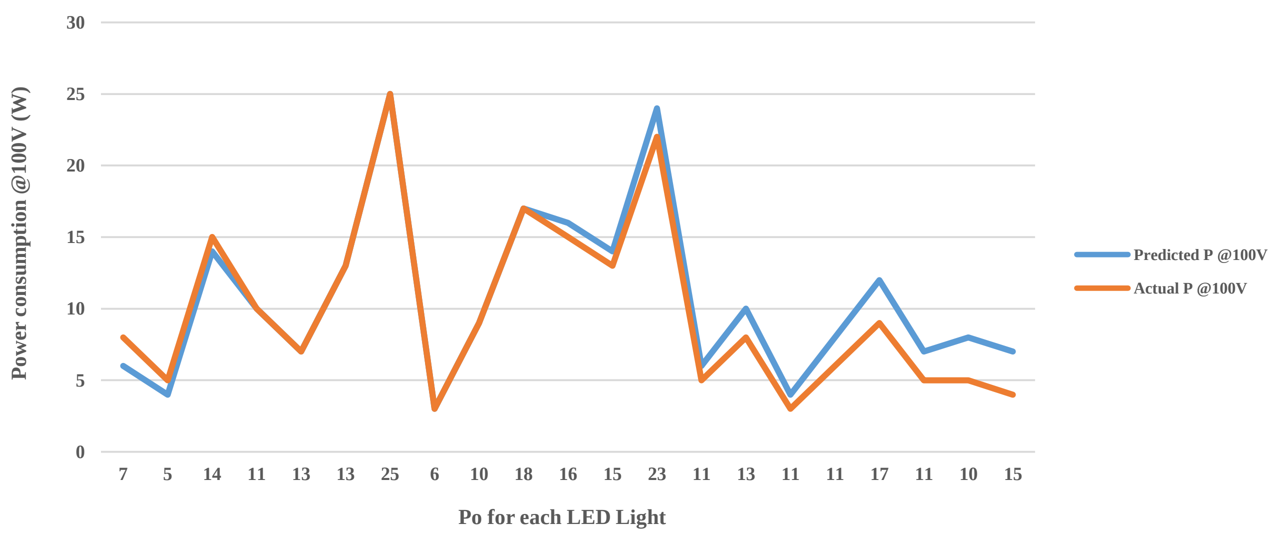

Figure 5.24: Comparison between predicted & actual power consumption for LED lights

5.2.6.5 LED Boundaries Based on ZIP Model

ZIP coefficient boundaries for tested LED lights have been developed and plotted in figure 5.25 in order to extract the minimum and maximum boundaries of LED lights. It should be mentioned that bulb LED light at the wattage 9W represent the maximum boundary, which is the most sensitive to voltage variations. Therefore, CVR is most effective at this wattage level. However, constant power P_P LED lights is the least sensitive to CVR as the load draws constant power under CVR as shown in table 5.12.

Table 5.12: Constant power P_P LED lights

	Name	**Zp**	**Ip**	**Pp**	**Zq**	**Iq**	**Pq**
Min ZIP	Bulb 14W Daylight Non-dimmable - Sylvania	0.00	0.00	1.00	0.00	0.41	0.59
	Bulb 14W Daylight Non-dimmable - Great Value	0.00	0.00	1.00	1.26	-2.07	1.81
	Bulb 17.5W Daylight Dimmable - Feit Electric	0.00	0.00	1.00	-1.73	4.72	-1.99
	Bulb 28W Daylight Dimmable - Feit Electric	0.00	0.00	1.00	-12.52	26.51	-12.99
Max ZIP	Bulb 9W Soft white Non-dimmable - Great Value	-6.55	16.78	-9.23	-0.40	4.66	-3.26

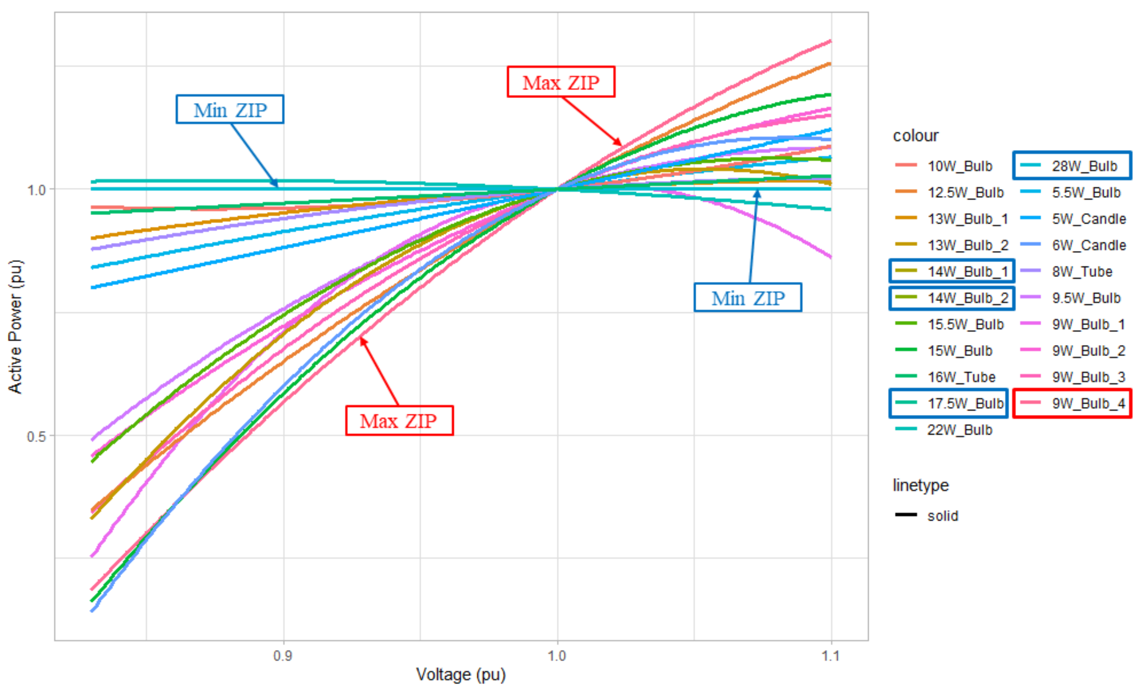

Figure 5.25: LED ZIP coefficients boundaries

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Thesis Summary

The main objective of this thesis was to develop the ZIP load model for LED lights with different wattages and types. The purpose of this modeling is to update the load model for the modern LED lights, which have not deeply discussed before, and to have a better representation of load behavior under the conservation voltage reduction (CVR) technique. Next, the CVR impact on LED lights was investigated in this thesis, and CVR factor and power reduction were calculated based on ZIP model coefficients for each lighting component. Additionally, power consumption estimation for LED lights under CVR was validated against the measurement data obtained from the experiment. Finally, ZIP coefficients boundaries for the tested LED lights was developed, and the minimum and maximum cases of lighting components was determined.

Also, this thesis offered a comprehensive literature review for the existing work of the component-based ZIP model and documented the ZIP coefficients for load components determined by previous works. Then, the ZIP coefficients of these load components were grouped into end-use categories and employed to identify the ZIP model coefficients for end-use types according to three potential cases.

6.2 Conclusions

ZIP load model was developed, and the experimental determination of ZIP model coefficients for LED lights was adopted for each light fixture in this thesis. It was revealed that ZIP load model is a good representative for modern load components, such as LED lights, as it has a good agreement with the behavior of load components that are exposed to conservation voltage reduction (CVR).

Furthermore, ZIP model is an essential approach that should be taken into account for the evaluation of conservation voltage reduction technique and how CVR impacts the LED lights. This was confirmed by validating the power consumption estimation based on ZIP model coefficients for lighting components and comparing it with the actual recordings obtained from the experiment. It was proved that power consumption calculated based on ZIP model has a good agreement with the actual measurement of power consumption of light components.

6.3 Future Work

Most research works on load modeling were done before 2014, hence An extension to this work can be done by developing the ZIP load model for the other equipment that is rapidly involved with the market and have not modeled yet.

With respect to the literature review conducted in this thesis, it was obviously noticed that load model investigations for commercial loads are very limited, and most of the works are focused on residential equipment. Therefore, future research should be more oriented to the commercial sector. Also, the three potential cases of ZIP model coefficients were identified for each end-use type based on the individual ZIP coefficients for load components obtained from the review. Therefore, a real-time ZIP load model should be developed for every timestamp.

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