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Framework to Develop Time- and Voltage-Dependent Building Load Profiles Using Polynomial Load Models

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ABSTRACT The power consumption of buildings over the course of each minute, hour, day and season plays a major role in how this load influences the Electric Power System voltage and frequency, and vice versa. This consumption is based on the building's load component types, efficiencies, and how they consume power and react to changes in real time. Due to this complexity, standard full-building load models are typically voltage-invariant. This paper proposes a novel framework to transform these voltage-invariant building load models into fully time- and voltage-dependent load profiles using available data on the voltage sensitivity of individual load components. While a voltage-dependent building model could theoretically be generated from static load models of every component in a building, this approach faces two challenges: first, load models representing all load components are impractical to develop for all possible load component types; second, building energy consumption is never measured or modeled at the individual component level. The proposed framework compiles available component data in the form of static ZIP load model parameters, and maps them into the end use categories utilized by standard building modeling programs. The voltage sensitivity of each end use category is then bounded by the extrema of the component models within it. This framework is applied to a load profile case study representing the aggregate U.S. residential building stock. In addition to the minimum/ maximum conditions, a load profile based on typical load composition and weighted ZIP parameters is generated for the same building stock. The results show that for a 10% drop in voltage, using the least sensitive ZIP parameters, active power is expected to be 3% to 14% lower than nominal, depending on the season and time of day. Using the most sensitive ZIP parameters, the active power is expected to be 9% to 20% lower than nominal, also depending on the season and time of day.

INDEX TERMS Load model, load component, ZIP parameters, load profile, energy consumption.

I. INTRODUCTION

The built environment is undergoing a major change in how it uses, manages and interacts with energy. This is due to technology advances, energy efficiency efforts, demand response, Distributed Energy Resources (DERs), Grid-Interactive Efficient Buildings (GEB) [1], Advanced metering infrastructure (AMI) is providing detailed load profile data. The building load component types, efficiencies, and responses to varying voltage and frequency in the Electric Power System (EPS) cannot be overlooked when considering a host of distribution system simulations and analyses. As the system voltage and frequency vary, the loads' active and reactive power varies. This variation depends on the type of each load component and its consumption relative to the overall building load profile. To capture the load behavior, load models may be developed for each load component and then used to simulate the building's load behavior. However, how the load

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is modeled in a given analysis and how up to date its parameters are may influence simulation results, especially when considering conservation voltage reduction (CVR) studies.

Load models are defined as the mathematical relationship that represents the change in active power or reactive power demand as a function of the voltage and frequency in the power system [2]. Load models are classified as static, dynamic, and composite load models. Static load models express the load power as a function of the electrical system's voltage and frequency at any instant of time (time-invariant). They respond instantaneously to voltage and frequency changes. They are used in steady state modeling such as power flow analysis [3]. The static load models include constant power, constant current, constant impedance, exponential model, polynomial model (ZIP model), frequency dependent model, and the EPRI LOADSYN model [4]. Dynamic load models express the load power as a function of the current and previous electrical systems' voltage and frequency, i.e., as a function of time (time-variant). They are used in dynamic studies where transient analysis is required [3]. The dynamic load models include: Induction Motor (IM) model and the Exponential Recovery Load Model (ERL) [4]. Composite load models, which mix characteristics of static and dynamic models include: the ZIP+IM model, the complex load model (CLOD) and the Western Electricity Coordination Council (WECC) CLM model [4].

The load model parameters can be determined using the measurement-based method, a top-down approach, or the component-based method, a bottom-up approach. The measurement-based method relies on a given distribution system's measured data using phasor measurement units (PMUs), smart meters, and other devices connected along the system to determine the system load model [4]. The component-based method relies on having load models for each load component in a given building along with its relative consumption, i.e., the amount of power a load component consumes in relation to the full building's load consumption, at every time-step or time resolution. Then, aggregating all the load models with their relative consumption components for each building type (residential, commercial and industrial buildings) connected to a given distribution feeder; then aggregating all building type load models to generate the overall load model for the entire distribution system as shown in Figure 1. ZIP and exponential models are used to describe the electrical characteristics of the buildings' load model with most of the research focusing on residential load characterization.

As can be seen in Figure 1 and the discussion above, the bottom-up approach requires knowledge of each load component and its associated load model parameters. Once all the building's load components are identified, their relative consumption as a function of time is needed in order to develop a complete load model for a given building. However, there is limited information available in the literature due to the lack of a comprehensive inventory of load components in each building type and their associated load composition in relation to the full building consumption. For example, in [5] and [6], the authors discuss the need for time varying characteristics for loads and generation. They use the exponential load model to incorporate the time varying voltage dependent (TVVD) loads in their analysis. They highlight the computational difficulty for obtaining the voltage exponents due to the lack of data.

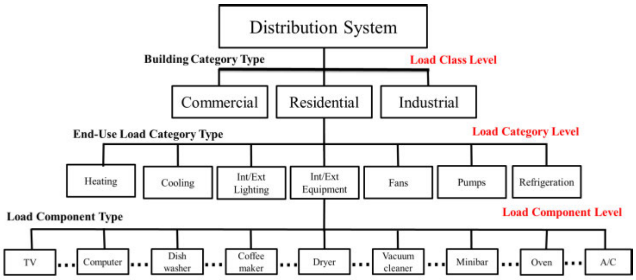

FIGURE 1. Component-based method to determine the load model parameters for a given distribution system.

A survey of current publications found the following references addressing detailed load models, load composition, and relative power consumption. In [7], the authors present an Object-oriented Controllable, High-resolution Residential Energy (OCHRE) model that simulates residential energy systems down to the 1-minute resolution. They use published ZIP model parameters, presented in later sections of this paper including [8], [9] and [10] to model the voltage-power relationship for the load components. They account for heating, cooling, and most typical load components found in a typical residential home. However, for equipment without published ZIP parameters, they assume the load's power consumption is a voltage-invariant relationship. In [11], the authors discuss the use of standard load profiles for load modeling purposes. These profiles are generated using top-down, bottom-up, or hybrid models representing physics-based, data driven, or a combination of the two models. To account for the temporal variations, ZIP model parameters such as the one presented in [8] are used. To provide further flexibility in management and control, the loads are further classified as "shiftable", "curtailable" and "inflexible". This allows for the simulation and management of the proposed functional integration of hybrid renewable energy systems (HERS) in multi-energy buildings.

In [12], the authors discuss the benefits of CVR. However, accurate determination of these benefits depends on accurate load models in the distribution system. The ZIP load model is considered, since it can be used to represent a mix of constant impedance, constant current, and constant power load types. The authors propose a quasi-real-time ZIP model for each timestep using disaggregation of the load into its consumption appliances using tools such as Non-Intrusive Load Monitoring (NILM) and statistical data analysis. The approach is developed for a typical North American residential house. The authors identified typical appliances and their impact factor, where impact factor is the duty cycle of a given appliance in each appliance category. The ZIP model parameters used for each appliance are obtained from published models such as the parameters derived in [8]. They provided a 24-hour consumption load profile with one-hour time-resolution consumption data and equivalent ZIP model parameters. The proposed method is validated on a 33-node distribution feeder where each node was assigned a residential building load profile. In [13], a time varying exponential load model is used to model the percentage of residential, commercial and industrial load models in a given distribution system with the presence of distributed generation. The analysis is conducted for one day using a one-hour time resolution. In [14], the authors propose to use time-varying synthesis load modeling (SLM) as a load modeling approach for distribution system analysis. The SLM model consist of three models, the ZIP model, the IM model and the equivalent impedance model.

To overcome the need for a comprehensive list of load models for every load component in a given building type, and to address the need for real-time ZIP load models for distribution system analysis, this paper proposes a novel framework to develop and generate ZIP load models for the buildings, and demonstrates the framework using a case study of a modeled aggregate U.S. residential building load profile. Specifically, the paper presents a comprehensive literature review and documentation of existing load component ZIP model parameters. Then, it maps the parameters into their end-use load category type and applies the ZIP model voltage/power relationship to visualize the behavior of each load component and determine their impact as a function of system voltage. Instead of determining each load component consumption portion in a building, the proposed framework focuses on bounding conditions. Specifically, minimum and maximum extrema load models for end-use load categories are generated and proposed for applications to determine a building's behavior when it is most or least sensitive to voltage variations. To obtain the consumption composition, the framework utilizes EnergyPlus, a building energy modeling (BEM) software [15], to generate time-series building load profiles at any desired time-resolution. For this framework, an hourly time-resolution is selected and used to generate ZIP models at the same time scale for distribution system analysis. In addition to the two extreme cases, a typical load composition for each end-use load category is calculated using DOE published data [16], then the ZIP load model for the building is determined and analyzed to compare the extreme cases. The results of this approach are limited to buildings with a similar load composition, but the same framework can be applied to generate load models for any type of building when the load composition information is available.

In summary, a typical voltage-invariant building energy load profile model predicts only the nominal power as a function of time, and the typical application of a ZIP model provides the ratio of actual to nominal power as a function of voltage. When combining these two models, the result is a model that is both voltage- and time-dependent, as the references summarized in this paper show. Building on this combined model, this paper presents a novel, visual, end-use load category-based bounded ZIP model. In contrast to the existing methods for generating voltage-dependent load profiles, the novel features of this research are:

1- Developing a visualization framework to identify the ZIP load model parameters that are the least and most sensitive to system voltage variations within each end-use load category.
2- Formulating a mathematical framework to express the full building voltage dependence as a time-dependent function of the ZIP models of end-use load categories (as opposed to individual load components, the focus of previous literature).
3- Enabling full building voltage dependence to vary according to the relative consumption of each end-use load category at every time-step.
4- Demonstrating the impact of bounded load model parameter selection on the time-dependent ZIP model for the full building via a case study of a residential building load profile.

The paper is organized as follows: section II provides a brief description of existing static load models; Section III provides detailed description of the proposed framework; Section IV provides analysis of the proposed framework using an aggregate U.S. residential building load profile; finally, Section V provides summary and conclusions.

II. LOAD MODELING DESCRIPTION

Since the focus of the paper is on static load models, this section provides a brief description of common static load models found in the literature and commonly applied in distribution system analysis. The most common static load models are the constant power, constant current and constant impedance models. In the constant power load model, the load's power consumption remains constant regardless of the bus voltage variation. As the bus voltage increases, the load current decreases and vice versa. With an assigned power factor, a constant reactive power is determined. This model is also referred to as the constant PQ model in the literature and is represented by $P = P_0$; where P_0 is the nominal/rated or initial active power consumption of the load at the nominal/rated system voltage (V_0), and P is the actual power at each given timestep (time-resolution). Examples of loads that exhibit constant power behavior include power electronics such as switch mode power supplies (SMPS) and light emitting diode (LED) lighting fixtures [17]. In the constant current model, the load's current is represented as a constant regardless of the bus voltage variation. As the bus voltage varies, the power consumption varies linearly via, $P = P_0\left(\frac{V}{V_0}\right)$; where V is the actual voltage at the load at a given timestep. Examples of loads that match the constant current model include motor loads and fluorescent and compact fluorescent lighting (CFL) fixtures [17]. In the constant impedance model, the load's impedance remains constant regardless of the bus voltage variation. As the bus voltage varies, the power consumption varies as a function of the square of the system voltage via, $P = P_0\left(\frac{V}{V_0}\right)^2$. Examples of loads that exhibit constant impedance model include resistive loads such as toasters, ovens, and space heaters [17].

Building upon the static models described above, in the exponential load model, an exponential equation is used to represent the relationship between the system voltage and frequency and the power consumption of the load. This relationship is shown in Equation 1 for the real power and Equation 2 for the reactive power.

$$P = P_0\left(\frac{V}{V_0}\right)^{K_{pv}}\left(\frac{f}{f_0}\right)^{K_{pf}} \tag{1}$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{K_{pf}}\left(\frac{f}{f_0}\right)^{K_{qf}} \tag{2}$$

where Q_0 is the nominal or initial reactive power consumption of the load at V_0, f_0 is the nominal system frequency, f is the actual frequency, K_{pv}, K_{pf}, K_{pf} and K_{qf} are the model parameters, also known as the sensitivity factors or coefficients [17]. If the frequency portion is neglected, since changes in the frequency are typically very small and controlled, the relationship becomes as shown in Equations 3 and 4.

$$P = P_0\left(\frac{V}{V_0}\right)^{K_{pv}} \tag{3}$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{K_{qv}} \tag{4}$$

It can be seen that if the parameter $K_{pv} = 2$, the model becomes the constant impedance model; if $K_{pv} = 1$, the model becomes the constant current model and if $K_{pv} = 0$, the model becomes the constant power model. The same is true for the K_{qv} parameter [17].

In the polynomial model (ZIP model), the constant impedance (Z) model, the constant current (I) model and the constant power (P) model are combined in a polynomial equation to represent the ZIP model, an equation used to represent the relationship between the system voltage and frequency and the power consumption of the load. The ZIP model is shown in Equation 5 for the real power and Equation 6 for the reactive power.

$$P = P_0\,[z_p\left(\frac{V}{V_0}\right)^2 + i_p\left(\frac{V}{V_0}\right) + p_p](1 + K_{pf}\,\Delta \mathrm{f}) \tag{5}$$

$$Q = Q_0\,[z_q\left(\frac{V}{V_0}\right)^2 + i_q\left(\frac{V}{V_0}\right) + p_q](1 + K_{qf}\,\Delta \mathrm{f}) \tag{6}$$

where z_p, i_P, p_P, and z_q, i_q, p_q represent the percentages of each model parameter type for the real and reactive power, each adding to one or 100%, and $(1+K_{pf}\,\Delta\mathrm{f})$ and $(1+K_{qf}\,\Delta\mathrm{f})$ represent the frequency component. Removing the frequency component [17], the ZIP models become as shown in 7 and 8.

$$P = P_0\,[z_p\left(\frac{V}{V_0}\right)^2 + i_p\left(\frac{V}{V_0}\right) + p_p] \tag{7}$$

$$Q = Q_0\,[z_q\left(\frac{V}{V_0}\right)^2 + i_q\left(\frac{V}{V_0}\right) + p_q] \tag{8}$$

Furthermore, the parameters exist in a bounded [0, 1] or unbounded fashion, where the latter is more accurate, but the former is intuitive following percentages of each type [17].

III. FRAMEWORK TO DEVELOP TIME- AND VOLTAGE-VARIANT BUILDING LOAD PROFILES

To develop a ZIP model for a complex system such as a full building, it is assumed that each load component has its own ZIP model in the form of Equations 7 and 8. For simplicity of notation only the active power is considered below, but the form of the reactive power is identical. By summing the active power P_n of each of N load components, the equation for the active power of the full building is given by Equation 9,

$$\begin{aligned}P_{building} = \sum\nolimits_N P_n\left(\sum\nolimits_N P_{0,n}z_n\right)\left(\frac{V}{V_0}\right)^2 \\ + \left(\sum\nolimits_N P_{0,n}i_n\right)\left(\frac{V}{V_0}\right) + \left(\sum\nolimits_N P_{0,n}p_n\right)\end{aligned} \tag{9}$$

This can be converted to the form of a ZIP model for power per unit by dividing both sides by the nominal power of the full building resulting in Equation 10,

$$\begin{aligned}\frac{P_{building}}{P_{0,building}} &= \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}}z_n\right)\left(\frac{V}{V_0}\right)^2 \\ &+ \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}}i_n\right)\left(\frac{V}{V_0}\right) \\ &+ \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}}p_n\right)\end{aligned} \tag{10}$$

Or simplifying Equation 10 into Equation 11,

$$\frac{P_{building}}{P_{0,building}} = z_{building}\left(\frac{V}{V_0}\right)^2 + i_{building}\left(\frac{V}{V_0}\right) + p_{building} \tag{11}$$

where

$$z_{building} = \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}}z_n\right)$$

$$i_{building} = \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}}i_n\right)$$

$$p_{building} = \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}}p_n\right)$$

The parameters z_n, i_n, and p_n are the ZIP parameters for each load component in the building. The factor $\frac{P_{0,n}}{P_{0,building}}$ is the relative power consumption of each load component. While knowing these two pieces of information for every load component in a building would provide a complete ZIP model for the building, this is highly impractical. Instead, the following framework simplifies the problem by grouping end-use load components with similar function (i.e. lighting, cooling, heating, equipment, etc. …) into various end-use load category types. The above equation is valid for both N load components and for N categories of end-uses loads. The appropriate choices for z, i, and p for each end-uses load category are considered and combined with relative consumption estimates for each load category type to obtain the full building model.

The framework to obtain a voltage variant load profile consists of six stages as shown in Figure 2. The first stage consists of documenting existing component-based ZIP load model coefficients found in the literature. The second stage consists of mapping each load component into an associated end-use load category type. The third stage consists of visualizing the voltage-power relationship of each ZIP model within a given end-use load category type to identify their load behavior and response to voltage variations. The fourth stage consists of identifying and selecting representative ZIP load model coefficients for each end-use load category type. Specifically, multiple ZIP load models are identified in this stage, namely, ZIP load models that are most sensitive to voltage variations and ZIP load models that are least sensitive to voltage variations. The fifth stage involves the selection and application of time-series, end-use load category building load profiles, using the nominal relative consumption to scale the ZIP parameters for each end use category. The final result is a full building load profile that is a function not only of time, but of voltage and ZIP parameter selection. The following subsections provide more detailed information on each stage.

A. STAGE I. INVENTORY EXISTING ZIP LOAD MODEL PARAMETERS

A comprehensive literature review is carried out to document exiting static ZIP model parameters for residential, commercial and industrial loads from 1998 through 2019. The results are separated into ZIP model parameters for loads in the U.S. where the single-phase voltage is 120V or 277V with 60 HZ frequency and loads in Europe and Asia where the single-phase voltage is 220 & 230V with 50 HZ frequency. This paper focuses on ZIP load models for the U.S. load components and their associated ZIP parameters, but the approach is valid for other systems. In addition, the parameters are further categorized according to the method used in the determination process, i.e. based on PQ or S and phase angle (power factor). For the entire list of all documented U.S. and international parameters see [18]. The following paragraphs provide a review and a brief description of each paper containing parameters used in stage II and in the proposed framework.

In [4], the authors provide a comprehensive review of load models and their implication on the distribution system analysis. They recognize the need to understand the characteristics of modern loads used in the built environment (residential, commercial and industrial buildings) and the lack of current and updated detailed load component/device model parameters, to accurately investigate the impact of DER on the distribution system analysis studies. They define load modeling as the development of a mathematical relationship that describes the behavior of the load component's power consumption as a function of the electrical systems' bus voltage and frequency it is connected to. They provide an overview of static, dynamic load models along with discussion on recent research combining both types to provide composite load models and the use of neural network to provide ANN-based load modeling.

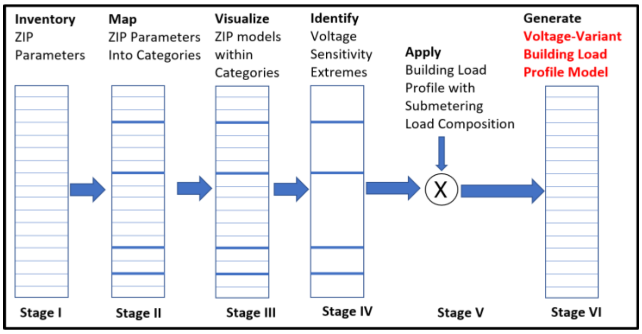

FIGURE 2. **Framework to generate voltage-dependent load profile models.**

In [17], the author states that the loads are the most challenging component of the EPS to model due to their complexity and diversity. Furthermore, since the model parameters determine the model performance, accurate and modern parameters are essential for distribution system study analysis. To model the loads, a load model type is first selected, then its parameters are determined using component based or measurement-based approaches. While the measurement-based approach is straight forward, it is limited to representing the characteristics of the building stock that was measured. The component-based approach has the disadvantage that the end use load categories and their constituent loads are hard to identify. A case study is performed on an actual system in which ZIP model parameters are derived using both approaches and compared with parameters in which the utility company used parameters they have identified based on their knowledge of the system load type. The identified parameters for each case depend on if the parameters are constrained to the interval [0,1] or not bounded, providing no physical significance. The component-based approach provides reactive parameters with no physical representation whereas the active power parameters were constrained to the [0,1]. The measurement-based approach was bound in the active and reactive power because of the initial constraints on the solution. The author asserts that bound ZIP models are used by utilities since the parameters provide physical significance to the percentage of the Z, I or P in the system.

In [9], the authors highlight the distribution system voltage stability and the factors impacting it including loads and their characteristics that change with voltage and time. To model the loads, two options are available: measurements of small step disturbances on feeders or large step disturbances on actual loads in a laboratory setting. Thirteen loads are tested individually or in parallel to produce one composite load. The loads are typical loads found in residential, commercial and industrial buildings such as washing machines, dryers, adjustable frequency drives, lighting fixtures, microwave oven and so forth. The loads were subjected to large voltage changes ranging from −25% to −75% of the nominal system voltage. As the voltage increased or decreased in steps, the associated current is measured. Then the active and reactive power is calculated at each step for each load. This data is then used to extract the ZIP or exponential model parameters using fitting techniques. One of the requirements is that the ZIP parameters add to one (100%). The load model results are then presented for each measured load for the ZIP and the exponential model. In order to conduct a study to utilize the developed models, a percentage of end-use category is assumed for each building type.

In [19], the authors conducted surveys to determine the loads used in residential and commercial buildings and grouped them into 17 separate categories. Laboratory experiments are then conducted to determine the load model and parameters for each type by varying the voltage between 50% and 110% of the nominal system voltage. If testing was not feasible, data from other sources such as the data in [9] are used. ZIP models for the 17 categories are then developed. Examples of how these ZIP models based on percentages of use in a small and large residential and commercial building are conducted using a MATLAB program.

In [10], the authors recognize the complexity of load modeling due to many factors including the difficulty in estimating the load composition and the large number of available appliance and equipment loads. Yet, they highlight the need to understand the load characteristic in order to develop load models at the transmission and distribution system. In evaluating existing information on load models, they justify the need to update the existing load models, because existing models do not reflect new loads or the fact that for the same loads, they now behave differently under voltage and frequency disturbances due to improvements and changes in their electronic/component makeup. In their study, they develop ZIP load model parameters for residential appliances and office building equipment. In their results, if the reactive power of a device under test is less than 0.1 per unit, then the ZIP parameters for reactive power calculations are set to zero. The authors introduced a constant factor in the ZIP equation to ensure that the coefficients add to one. Based on their testing and application of voltage signals that contain sags, oscillation and ramping, they observed that fans, ovens, dishwashers and dryers behave as constant impedance loads, power source conversion types of equipment such as computers, monitors and power supplies behave as a constant power loads, and that motor loads with stalling issues will require different models.

In [20], the authors identify three areas that need to be modeled accurately in order to perform adequate analysis of the EPS, namely: the power generation source(s), the transmission and/or distribution medium to transport the generated power, and the end use loads. Loads are categorized as simple or complex loads, where simple loads have no thermal cycles (time-invariant model), whereas complex loads contain thermal cycles (time variant). The simple loads are characterized by the ZIP model where the model parameters are developed for typical residential loads. In the development of the model parameters, the ZIP model is presented as a function of the apparent power, where a power factor for each ZIP parameter is also derived. The complex model is derived using an equivalent thermal parameter (ETP) model for the HVAC system. The developed models are used in the IEEE 8500 node test feeder to study loads with thermal cycles and their behavior in a demand response environment as well as the effect of implementing energy efficiency measures. The simulation results show the effect on the power consumption as the temperature settings are adjusted and the insulation of the house is changed.

In [21], the authors develop static ZIP load model parameters for LCD and LED Television set as well as the Xbox 360, PS3 and Wii gaming consoles. Since the gaming consoles operate with the TV, combinations of TV and gaming console ZIP parameters are developed. Building on this work, ZIP model parameters for different sizes of flat panel TVs are developed in [22].

In [8], the authors investigate the behavior of typical building loads under varying voltage to determine the impact of Conservation Voltage reduction (CVR) techniques. They conducted experiments to obtain updated ZIP model parameters for residential, commercial and industrial loads in 2014. They started by conducting on-site surveys in New York City to identify loads used in each building type. As part of the survey, they collected load nameplate data for equipment used and the number of times, or usage period for each device in each day. Then they identified the load composition in each building type and conducted experiments on individual and composite loads by varying the voltage from zero volts to 1.1 Per unit. Finally, they developed the ZIP parameters using curve fitting techniques. The paper further investigates building type load composition. They group the building types into three classes, residential, commercial and industrial. They aggregate similar loads into load component categories such as motor loads, heating, power-electronics loads and so forth. From the survey results they identified the following categories: lighting equipment, elevators, pumps, compressors, household appliances and power-electronic devices. Finally, they aggregate different percentages of each load component to determine the overall load for each class. To create an accurate load model for each class, the loads were classified based on running loads as a function of annual loads. Furthermore, to account for the different seasons, they developed models for three seasons: winter, spring/fall and summer, and they correlated the load component category for each customer/class with duty cycles. The developed hourly data was validated by comparing it with measured utility data for each customer. To build an accurate load model for each class, they used the component-based approach, the ZIP model. The ZIP parameters are obtained from their experiments for the surveyed equipment/loads. Their published data regarding class types, equipment duty cycle and ZIP parameters is very comprehensive, detailed, and cited by most research papers in this field, since their publication in 2014.

In [23], the authors discuss the impact of load models on the distribution system when implementing CVR for energy conservation. Using the exponential load model, constant PQ and constant impedance (Z) models are considered. A case study involving 600 nodes is carried out with and without DER penetration. The results show that CVR resulted in increased losses with the constant PQ load model when compared with the Z load model. Furthermore, the results show that with the PQ load model, consumption remains the same, i.e., no effect as a result of decreasing the system voltage. However, with the Z load model, as the voltage decreased, the consumption decreased. This highlights the importance of accurate load models in a given distribution system analysis.

B. STAGE II–GROUP ZIP LOAD MODEL PARAMETERS INTO END-USE LOAD CATEGORY TYPES

The previous section documented existing research into ZIP model parameters for load components found in commercial and residential buildings. However, there does not exist a library of representative load model parameters for all existing load components. This is because it is unreasonable to document and model every existing load component in use. Furthermore, the load composition continues to expand, be modified, updated or replaced to reflect continued utilization of newer load component technology and advancement in energy efficiency among other factors. For this reason, developing designated end-use load category types and a methodology to assign representative ZIP load model parameters will aid in developing analysis using limited available information.

The determination of the end-use load category types is based on sub-metered data for the end-use categories or on modeled data from building energy modeling (BEM) tools that provide detailed time-series load profiles of building energy consumption by end-use load category type. In this research, EnergyPlus, an open-source source program commonly used by engineers, designers, and researchers, is used to generate the load profile for the case study. EnergyPlus consists of a group of modules that are integrated together to calculate the energy consumption for the total building. The calculation is achieved by an integrated simulation of building and associated energy systems under different conditions of operation. In addition, the generated building energy consumption load profile can be disaggregated into several time-series end-use load category load profiles. EnergyPlus can provide the following end-use load categories: Cooling, Central System, Extra Refrigerator, Freezer, Refrigerator, Hot tub Heater, Pumps Heating, Central, System Pumps Heating, Pool pump, Hot tub pump, Well pump, Fans Heating, Fans Cooling, Water Systems, Cooking Range, Dishwasher, House Fan, Rang Fan, Bath Fan, Ceiling Fan, Clothes Washer, Clothes Dryer, Heating, Central System Heating, Pool Heater, Interior Light, Exterior Light, Electricity PV, Plug Loads, Electricity Gap [15]. For the proposed framework in this project, the exact categorization of end-uses is highly flexible, and the tightest bounds are obtained when equipment with similar static load models are grouped together. For the purposes of simplicity in documentation, and incorporation into the residential case study in Section IV, the EnergyPlus end-use load categories are further aggregated into the following main end-use load categories: heating; cooling; interior/exterior lighting; interior/exterior equipment; fans; pumps; refrigeration; water systems. Tables 1-7 show all the documented ZIP load model parameters for all end-use load category types.

1) HEATING AND WATER SYSTEMS

The heating end-use category includes the devices used for heating purposes such as resistive and baseboard heaters. In addition, water systems are assumed to exhibit similar behavior to the heating systems listed here, due to a lack of water system static load models in literature. Heat pumps have been deliberately excluded from this category, as their voltage sensitivity and consumption behavior is very different than other heating components, and are less common than the other types of electric heating equipment. Table 1 shows the ZIP coefficients for load components in the heating end-use, with references to the studies from which the data was obtained. In the following table and all subsequent tables in this section, the superscript $^{(1)}$ is used for ZIP coefficients with 100 V cutoff voltage, and superscript $^{(2)}$ is used for ZIP coefficients of the same piece of equipment with a variable cutoff voltage, which is the shut off voltage. Because the ZIP coefficients correspond to a best polynomial fit of the experimentally observed power-voltage relationship, the coefficients can be different when a wider range of voltages are considered, whereas the 100 V coefficients will be more accurate at voltages above 100 V.

2) COOLING

Cooling end-use includes the systems used in the residential class to cool the building, such as air conditioners. Table 2 shows the ZIP coefficients for cooling components.

3) 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. Table 3 shows the ZIP coefficients for Interior/Exterior Lighting components.

TABLE 1. ZIP load model parameters for all load components within the heating end-use load category.

Load Component	Ref	z_p	i_p	p_p	z_q	i_q	p_q
Resistive heater (1)	[8]	0.640	0.590	-0.230	0.130	0.750	0.120
Resistive heater (2)	[8]	0.920	0.100	-0.020	0.150	0.860	-0.010
Resistive Load	[19]	1.000	0.000	0.000	0.000	0.000	1.000
Dryer heater	[9]	0.960	0.050	-0.010	0.000	0.000	0.000
Industrial heater/ blower	[9]	0.980	0.020	0.000	0.690	0.250	0.060
Baseboard heater	[9]	1.000	0.000	0.000	0.000	0.000	0.000

TABLE 2. ZIP load model parameters for all load components within the cooling end-use load category.

Load Component	Ref	z_p	i_p	p_p	z_q	i_q	p_q
Air conditioner (1)	[8]	1.170	-1.830	1.660	15.680	-27.150	12.470
Air conditioner (2)	[8]	1.600	-2.690	2.090	12.530	-21.110	9.580

4) INTERIOR/EXTERIOR EQUIPMENT

Interior/exterior equipment includes several sorts of electrical appliances used in the residential house for different functionalities such as cooking, cleaning, and entertainment. Table 4a shows ZIP coefficients for common appliances obtained from the literature review. Tables 4b and 4c list the ZIP coefficients for video game consoles and TVs, respectively.

In Table 4b, 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 $z_P + i_P + p_P = 1$, and LCD $22''^{(5)}$ is the ZIP coefficients with two constraints: coefficients bounded to [0,1] and $z_P + i_P + p_P = 1$

5) FANS

Fan end-use covers the fans used in residential buildings, with the ZIP coefficients shown in Table 5.

6) PUMPS

The pump end-use category includes water pumps used in the residential class, as shown in Table 6 below.

7) REFRIGERATOR

The refrigerator end-use contains the loads used for food preservation such as refrigerator and freezer. Table 7 shows the ZIP coefficients for the components reviewed in the literature review.

C. STAGE III–VISUALIZE ZIP LOAD MODEL PARAMETERS WITHIN END-USE LOAD CATEGORY TYPES

In this stage, the load models represented by the various documented ZIP parameters for each load component are visualized. In order to visualize the voltage dependence of end-use

TABLE 3. ZIP load model parameters for all load components within the interior/exterior lighting end-use load category.

	Ref	z_p	i_p	p_p	z_q	i_q	p_q
Fluor lamp (U-shape)	[19]	-0.300	1.270	0.040	-9.230	16.640	-6.400
Fluor lamp (Spot)	[19]	-0.640	2.170	-0.530	-1.020	2.800	-0.780
Fluor lamp (Magnetic)	[19]	-5.240	10.710	-4.470	-5.680	12.270	-5.590
Fluor lamp (Electronic)	[19]	-7.420	13.970	-5.550	7.420	-10.590	4.180
Fluor lamp T8_32W - Instant-on electronic ballast	[10]	0.350	0.720	-0.040	0.280	-0.900	0.030
Fluor lamp T12_40W - Instant-on electronic ballast	[10]	0.340	0.710	-0.030	0.200	-0.760	0.020
Fluor lamp T8_32W- Instant-on no flicker electronic ballast	[10]	-0.030	1.100	-0.050	0.320	-0.750	0.030
Fluor lamp T12_40W- Instant-on no flicker electronic ballast	[10]	0.060	0.970	-0.030	0.240	-0.600	0.020
Electronically ballasted Fluor 1- (composite load)	[9]	-2.480	5.460	-1.970	0.000	0.000	0.000
Electronically ballasted Fluor 2- (composite load)	[9]	-1.600	3.580	-0.980	0.790	-0.160	0.360
CFL(1)	[8]	0.810	-1.030	1.220	0.860	-0.820	0.960
CFL(2)	[8]	-0.630	1.660	-0.030	-0.340	1.400	-0.060
Electronic CFL 1	[9]	0.140	0.770	0.090	-0.060	-0.340	-0.600
Electronic CFL 2	[9]	0.160	0.790	0.050	0.180	-0.830	-0.350
Magnetic CFL	[9]	0.340	1.310	-0.650	3.030	-2.890	0.860
CFL 19W	[10]	-0.420	1.500	-0.060	0.660	-1.160	0.060
CFL 23W	[10]	-0.280	1.350	-0.050	0.580	-1.110	0.050
CFL 20W	[10]	-0.300	1.360	-0.050	0.600	-1.080	0.040
External Fluor dimmer	[9]	-0.480	1.890	-0.410	12.210	-18.380	7.160
Incandescent light(1)	[8]	0.470	0.630	-0.100	0.550	0.380	0.070
Incandescent light(2)	[8]	0.540	0.500	-0.040	0.460	0.510	0.030
Incandescent	[24]	0.690	0.000	0.300	0.000	0.000	0.000
Light Bulb 100W	[10]	0.640	0.400	0.000	0.000	0.000	0.000
Incandescent light	[19]	0.430	0.640	-0.080	0.000	0.000	1.000
LED light(1)	[8]	0.580	1.130	-0.710	1.780	-0.800	0.020
LED light(2)	[8]	0.690	0.920	-0.610	1.840	-0.910	0.070

TABLE 3. ***(Continued.)*** **ZIP load model parameters for all load components within the interior/exterior lighting end-use load category.**

High pressure sodium HID(1)	[8]	0.090	0.700	0.210	16.600	-28.770	13.170
High pressure sodium HID(2)	[8]	-0.160	1.200	-0.040	3.260	-4.110	1.850
High pressure sodium lamps	[9]	0.980	-0.030	0.060	29.840	-45.260	14.410
Mercury vapor HID light(1)	[8]	0.520	1.020	-0.540	-1.330	2.400	-0.070
Mercury vapor HID light(2)	[8]	-0.160	2.330	-1.170	0.420	-1.010	1.590
Halogen(1)	[8]	0.460	0.640	-0.100	4.260	-6.620	3.360
Halogen(2)	[8]	0.510	0.550	-0.050	0.430	0.520	0.050
Halogen_100W	[10]	0.660	0.390	0.000	0.000	0.000	0.000
Halogen	[19]	0.480	0.570	-0.050	-3.570	0.690	0.000
Induction light(1)	[8]	2.960	-6.040	4.080	1.480	-1.290	0.810
Induction light(2)	[8]	0.180	-0.750	1.570	7.510	-12.350	5.840
Tungsten light(1)	[8]	0.430	0.700	-0.130	-0.110	0.660	0.450
Tungsten light(2)	[8]	0.450	0.660	-0.110	0.210	0.110	0.680
Electronic ballast(1)	[8]	0.220	-0.500	1.280	9.640	-21.590	12.950
Metal halide HID electronic ballast(1)	[8]	1.000	-2.020	2.020	8.800	-18.640	10.840
Electronic ballast(2)	[8]	-0.070	0.080	0.990	9.320	-20.960	12.640
Metal halide HID electronic ballast(2)	[8]	-0.030	-0.060	1.090	11.400	-23.500	13.100
Electronic dimming ballast	[9]	-0.160	1.770	-0.620	0.000	0.000	0.000
Magnetic ballast (1)	[8]	-1.580	3.790	-1.210	36.180	-67.780	32.600
Metal halide HID magnetic ballast (1)	[8]	0.860	-0.660	0.800	32.540	-59.830	28.290
Magnetic ballast (2)	[8]	-3.160	6.850	-2.690	34.260	-64.040	30.780
Metal halide HID magnetic ballast (2)	[8]	-0.200	1.350	-0.150	1.370	-0.630	0.260

components, the published ZIP parameters presented in the previous section are applied to the ZIP model (Equation 7). Voltage per unit is considered in the range of 0.80 pu to 1.10 pu. This range of voltage is defined according to the American National Standards Institute (ANSI) Standard for Conservation Voltage Reduction (CVR) study purposes [8].

Figure 3 shows the relationship between voltage and active power for all documented heating load components, where the horizontal axis represents the applied voltage V per unit, which is varied from 0.80 to 1.10, and the vertical axis represents the calculated active power P per unit. Reactive power is not shown, but can be plotted in an identical fashion. Similar Figures (Figures 4- 9) show visualizations for the remaining end-use load category types. Note that in this figure and the figures that follow, figure legends are not provided as it is impractical for many of the load categories. Furthermore, the primary takeaway from these figures is the variety of power-voltage behavior that exists within each end-use load category type, and not the specific load model for any individual load component

TABLE 4. **a. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category. b. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category - video game console. c. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category–TVs.**

Load Component	Ref	z_p	i_p	p_p	z_q	i_q	p_q
Battery charger	[9]	3.510	-3.940	1.430	5.800	-7.260	2.460
Coffee maker(1)	[8]	0.130	1.620	-0.750	3.890	-6.000	3.110
Coffee maker(2)	[8]	0.980	0.030	-0.010	0.840	-0.300	0.460
PC (Monitor & CPU)(1)	[8]	0.200	-0.300	1.100	0.000	0.600	0.400
PC (Monitor & CPU)(2)	[8]	0.180	-0.260	1.080	-0.190	0.960	0.230
PC	[24]	0.340	0.000	0.650	0.000	0.000	0.990
Computer	[19]	0.270	-0.610	1.340	-0.110	0.020	1.080
Copier(1)	[8]	0.870	-0.210	0.340	2.140	-3.670	2.530
Copier(2)	[8]	0.520	0.450	0.030	0.390	-0.250	0.860
DishWasher_HD	[10]	0.950	0.000	0.000	0.000	0.000	0.000
DishWasher_NW	[10]	0.990	0.000	0.000	0.000	0.000	0.000
DishWasher_PP	[10]	1.000	0.000	0.000	0.000	0.000	0.000
Dryer	[10]	1.020	0.000	0.000	1.000	0.000	0.000
Laptop charger(1)	[8]	-0.280	0.500	0.780	-0.370	1.270	0.130
Laptop charger(2)	[8]	0.250	-0.480	1.230	0.140	0.320	0.540
Microwave(1)	[8]	1.390	-1.960	1.570	50.070	-93.550	44.480
Microwave(2)	[8]	-0.270	1.160	0.110	15.640	-27.740	13.100
Microwave	[19]	0.550	1.860	-1.400	19.740	-31.300	12.560
Microwave	[9]	-2.780	6.060	-2.280	0.000	0.000	0.000
Minibar(1)	[8]	2.500	-4.100	2.600	2.560	-2.760	1.200
Minibar(2)	[8]	3.950	-6.460	3.510	4.840	-6.640	2.800
Office equipment 1	[9]	0.340	-0.320	0.980	0.000	0.000	0.000
Office equipment 2	[9]	0.080	0.070	0.850	0.000	0.000	0.000
Oven	[10]	0.990	0.000	0.000	0.000	0.000	0.000
Projector(1)	[8]	0.230	-0.520	1.290	0.240	-0.170	0.930
Projector(2)	[8]	0.190	-0.450	1.260	10.180	-18.010	8.830
Range	[10]	0.970	0.000	0.000	0.000	0.000	0.000
TV, Printers, Fax	[19]	1.000	0.000	0.000	0.000	0.000	1.000
Vacuum cleaner(1)	[8]	1.180	-0.380	0.200	4.100	-5.870	2.770
Vacuum cleaner(2)	[8]	0.920	0.070	0.010	0.910	-0.020	0.110
Washing machine	[9]	0.050	0.310	0.630	-0.560	2.200	-0.650
Iron	[24]	0.920	0.000	0.070	0.800	0.160	0.040
Mixer	[24]	0.710	0.000	0.280	0.290	0.700	0.000

D. STAGE IV–CHARACTERIZATION AND SELECTION OF ZIP PARAMETERS WITHIN END USE CATEGORIES

As seen in the previous section and illustrated in the figures (see Figure 6 for example), within each end use category there may be a wide variety of ZIP parameters, representing load components with varying sensitivity to changes in voltage. Additionally, different literature may present different approximations for the ZIP parameters of each type of load

TABLE 4. ***(Continued.)*** **a. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category. b. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category - video game console. c. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category–TVs.**

Load Component	Ref	z_p	i_p	p_p	z_q	i_q	p_q
Game console (1)	[8]	-0.630	1.230	0.400	0.760	-0.930	1.170
Game console (2)	[8]	0.360	-0.580	1.220	0.340	-0.120	0.780
Xbox 360	[21]	0.115	-0.301	1.186	2.875	-5.912	4.037
Xbox 360 & LCD TV	[21]	0.384	-0.733	1.349	1.890	-3.371	2.481
Xbox 360 & LCD TV ss	[21]	0.307	-0.630	1.323	1.282	-1.857	1.575
Xbox 360 & LED TV	[21]	-0.033	-0.104	1.137	2.304	-4.303	2.998
Xbox 360 & LED TV ss	[21]	0.249	-0.516	1.266	2.104	-3.635	2.531
Wii	[21]	0.318	-0.338	1.019	2.078	-3.468	2.390
Wii & LCD TV	[21]	0.416	-0.798	1.382	-0.377	1.643	-0.266
Wii & LCD TV 50% v	[21]	0.438	-0.795	1.357	-0.344	1.595	-0.251
Wii & LED TV ss	[21]	0.314	-0.568	1.254	0.763	0.156	0.081
Wii & LED TV	[21]	0.789	-1.204	1.415	0.816	0.076	0.108
PS3	[21]	0.376	-0.738	1.362	0.831	0.409	-0.240
PS3 ss	[21]	0.167	-0.269	1.102	0.627	0.719	-0.346
PS3 & LCD TV ss	[21]	0.196	-0.416	1.220	-0.084	1.513	-0.429
PS3 & LCD TV 50% v	[21]	0.232	-0.501	1.268	-0.048	1.477	-0.429
PS3 & LED TV	[21]	0.202	-0.374	1.172	0.490	1.070	-0.560
PS3 & LED TV ss	[21]	0.178	-0.357	1.179	0.615	0.844	-0.459

component, in part due to potentially significant technological changes in the load component. Furthermore, the range of voltages over which the ZIP parameters are tested varies in the literature, as well as whether the ZIP parameters are constrained by boundary conditions. The choice of the appropriate set of ZIP parameters to represent an end-use category largely depends on the building being modeled, but presented here are two straightforward approaches to summarize the documented parameters within an end-use load category.

As discussed in the derivation of Equation 9, the most accurate calculation of the effective ZIP parameters for an entire end-use load category requires weighting the ZIP parameters of each equipment type by its relative consumption. If sufficient information is known about the building being modeled, this may be feasible for some end-use load categories, as will be shown in a case study in Section 4. Realistically, however, this level of detailed information is often not available, and some simplifying assumptions must be made to develop a model for each end-use load category.

Figure 10 again presents the relationship between power and voltage for the documented load components ZIP models within the equipment end-use load category. Here, all ZIP parameters have been constrained so that the active power per unit is 1 at the nominal voltage. It is highlighted that the observed behavior of all load components falls between two extremes: a ‘‘Maximum ZIP parameter’’ case where the equipment is most sensitive to voltage changes, and a ‘‘Minimum ZIP parameter’’ case where the equipment is least sensitive to voltage changes (or if applicable, exhibits the strongest inverse relationship between power and voltage).

TABLE 4. ***(Continued.)*** **a. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category. b. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category - video game console. c. ZIP load model parameters for all load components within the interior/exterior equipment end-use load category–TVs.**

Load Component	Ref	z_p	i_p	p_p	z_q	i_q	p_q
LCD Television (1)	[8]	0.110	-0.170	1.060	1.580	-1.720	1.140
LCD Television (2)	[8]	0.330	-0.570	1.240	19.000	-33.220	15.220
LCD 22 " (3)	[22]	0.473	-0.898	1.427	9.035	-16.732	8.658
LCD 22 " (4)	[22]	0.465	-0.889	1.425	9.225	-16.934	8.709
LCD 22 " (5)	[22]	0.000	0.000	1.000	0.000	0.000	1.000
LCD 40 " (3)	[22]	0.163	-0.325	1.161	0.464	1.000	-0.465
LCD 40 " (4)	[22]	0.170	-0.333	1.164	0.479	0.981	-0.460
LCD 40 " (5)	[22]	0.000	0.000	1.000	1.000	0.000	0.000
LCD 55 " (3)	[22]	0.546	-1.051	1.499	-0.646	2.204	-0.560
LCD 55 " (4)	[22]	0.580	-1.088	1.509	-0.637	2.194	-0.557
LCD 55 " (5)	[22]	0.000	0.000	1.000	0.247	0.753	0.000
LCD	[24]	0.000	0.000	1.000	0.030	0.000	0.960
LCD TV	[21]	0.497	-0.941	1.444	-0.766	2.398	-0.632
LCD TV - black sc	[21]	0.447	-0.848	1.401	-0.795	2.436	-0.641
LCD TV - black sc 1080	[21]	0.580	-0.976	1.396	-0.636	2.218	-0.582
LCD TV - white sc	[21]	0.540	-0.977	1.437	-0.793	2.452	-0.659
LCD TV - white sc 1080	[21]	0.496	-0.941	1.445	-0.819	2.483	-0.664
LCD	[10]	0.000	0.000	1.000	0.000	0.000	0.150
LED 26 " (3)	[22]	0.285	-0.563	1.278	3.127	-5.580	3.428
LED 26 " (4)	[22]	0.286	-0.564	1.279	3.260	-5.726	3.466
LED 26 " (5)	[22]	0.000	0.000	1.000	0.000	0.000	1.000
LED 32 " (3)	[22]	0.551	-1.026	1.464	6.396	-11.078	5.673
LED 32 " (4)	[22]	0.613	-1.096	1.483	6.453	-11.143	5.690
LED 32 " (5)	[22]	0.000	0.000	1.000	0.000	0.000	1.000
LED 55 " (3)	[22]	0.276	-0.546	1.271	0.546	0.909	-0.482
LED 55 " (4)	[22]	0.271	-0.540	1.269	0.726	0.697	-0.423
LED 55 " (5)	[22]	0.000	0.000	1.000	1.000	0.000	0.000
LED TV	[21]	2.694	-4.291	2.597	0.590	0.866	-0.456
LED TV - BL0	[21]	0.258	-0.334	1.077	0.546	0.680	-0.226
LED TV - BL14	[21]	0.394	-0.690	1.296	0.389	1.193	-0.582
LED TV - BL20	[21]	0.410	-0.721	1.311	0.176	1.664	-0.840
CRT	[10]	0.000	0.000	1.000	0.000	0.000	0.150
TV	[24]	0.000	0.000	0.990	0.040	0.000	0.950

By making separate models for both of these extreme values to represent each end-use category, the resulting full-building model can be used to estimate the extreme outcomes, even in the absence of detailed information about the exact load components in a particular building. By developing a separate full-building ZIP model corresponding to each

TABLE 5. ZIP load model parameters for all load components within the fans end-use load category.

	Ref	z_p	i_p	p_p	z_q	i_q	p_q
Fan (1)	[8]	-0.470	1.710	-0.240	2.340	-3.120	1.780
Fan (2)	[8]	0.260	0.900	-0.160	0.500	0.620	-0.120
Fan	[24]	0.870	0.000	0.120	0.750	0.000	0.240
Fan1	[19]	0.610	0.420	-0.040	0.830	0.170	0.000
Fan2 (VSD)	[19]	-0.960	3.050	-1.090	-8.210	14.270	-5.060
Fan - speed 1	[10]	0.870	0.140	-0.010	0.110	0.160	-0.010
Fan - speed 2	[10]	0.740	0.270	-0.020	0.030	0.280	-0.020
Fan - speed 3	[10]	0.390	0.660	-0.050	-0.100	0.460	-0.030
Fan - speed 3B	[10]	0.450	0.570	-0.040	-0.030	0.340	-0.020

TABLE 6. ZIP load model parameters for all load components within the pumps end-Use load category.

Component	Ref	z_p	i_p	p_p	z_q	i_q	p_q
Pump 1	[19]	5.510	-11.300	6.820	11.770	-24.280	13.510
Pump 2 (VSD)	[19]	-35.500	75.710	-39.250	19.230	-40.250	22.020

TABLE 7. ZIP load model parameters for all load components within the refrigerator end-use load category.

Component	Ref	z_p	i_p	p_p	z_q	i_q	p_q
Refrigerator (1)	[8]	1.170	-1.830	1.660	7.070	-10.940	4.870
Refrigerator (2)	[8]	5.030	-8.480	4.450	17.440	-28.620	12.180
Refrigerator/freezer	[9]	1.190	-0.260	0.070	0.590	0.650	-0.240

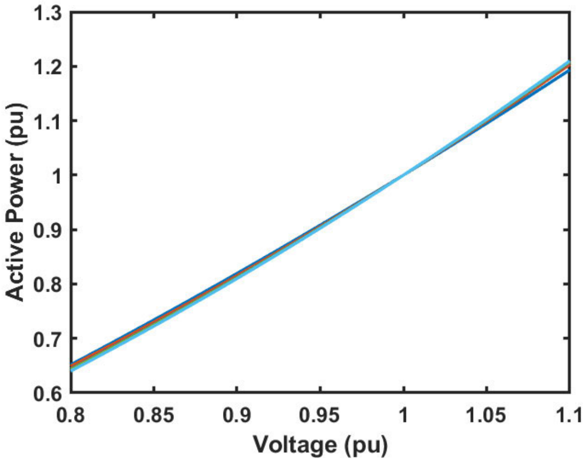

FIGURE 3. The relationship between voltage and active power for all documented ZIP load models for the heating end-use load category.

extreme case, the voltage dependence of the building can be effectively bounded.

Table 8 presents the calculated Minimum and Maximum ZIP parameters for each end-use load category type, after making certain assumptions and simplifications. First, all ZIP parameters are constrained to sum to one (so that the active power is equal to the nominal power at the nominal voltage), but otherwise each coefficient is unbounded. Furthermore, when multiple estimations of these parameters are available, the coefficients best corresponding to the 0.8-1.1 voltage per unit range are chosen, based on expected voltage variations in a typical building. In addition, parameters that exhibit unrealistic behavior over the full range of voltages considered are excluded. Finally, as the case study in Section 4 focuses on modern residential buildings, only load components present in such buildings are considered. The type of load component corresponding to each extreme is noted, along with the source of the experimental data.

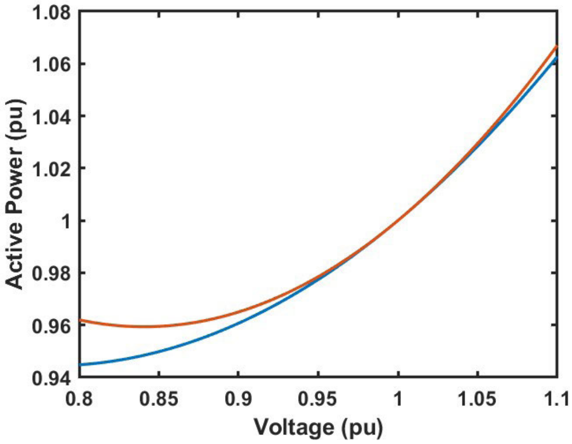

FIGURE 4. The relationship between voltage and active power for all documented ZIP load models for the cooling end-use load category.

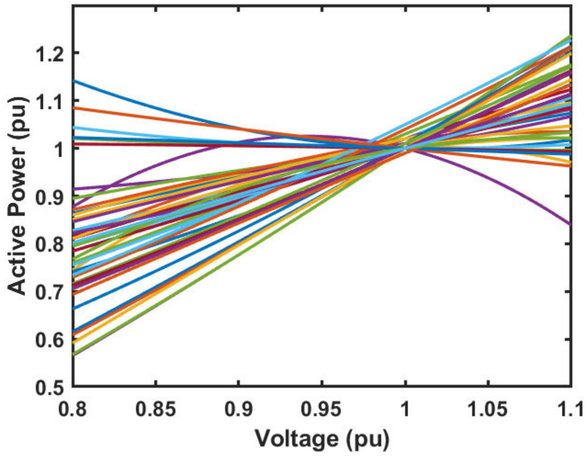

FIGURE 5. The relationship between voltage and active power for all documented ZIP load models for the interior/exterior lighting end-use load category.

For emphasis, selecting the "Max" ZIP parameters for each end-use load category type will result in a full-building ZIP model that predicts the greatest expected positive change in power for a given increase in voltage, while the "Min" ZIP parameters will provide the lowest expected positive change in power. Thus, the expected response of a building to changes in voltage can be bounded, even in the absence of detailed information about building equipment and the load component level. Figure 11 and Figure 12 show the resulting power vs. voltage relationship for each end use category, using both the Minimum and Maximum parameters.

TABLE 8. Summary of 'minimum' and 'maximum' ZIP coefficients for each end-use load category type.

#	End-Use	Case	Component	Ref	z_p	i_p	p_p	z_q	i_q	p_q
1	Heating	Min	Resistive heater	[8]	0.64	0.59	-0.23	0.13	0.75	0.12
		Max	Baseboard heater	[9]	1.00	0.00	0.00	0.00	0.00	0.00
2	Cooling	Min	Air conditioner	[8]	1.17	-1.83	1.66	15.68	-27.15	12.47
		Max	Air conditioner	[8]	1.17	-1.83	1.66	15.68	-27.15	12.47
3	Int/Ext Lighting	Min	CFL	[24]	0.00	0.00	1.00	0.00	0.99	0.00
		Max	LED light	[8]	0.58	1.13	-0.71	1.78	-0.80	0.02
4	Int/Ext Equipment	Min	Computer	[19]	0.27	-0.61	1.34	-0.11	0.02	1.08
		Max	DishWasher_PP	[10]	1.00	0.00	0.00	0.00	0.00	0.00
5	Fan	Min	Fan - speed 3B	[10]	0.45	0.57	-0.04	-0.03	0.34	-0.02
		Max	Fan - speed 1	[10]	0.87	0.14	-0.01	0.11	0.16	-0.01
6	Pumps	Min	Pump	[19]	5.51	-11.3	6.82	11.77	-24.28	13.51
		Max	Pump	[19]	5.51	-11.3	6.82	11.77	-24.28	13.51
7	Refrigerators	Min	Refrigerator	[8]	1.17	-1.83	1.66	7.07	-10.94	4.87
		Max	Refrigerator/freezer	[9]	1.19	-0.26	0.07	0.59	0.65	-0.24

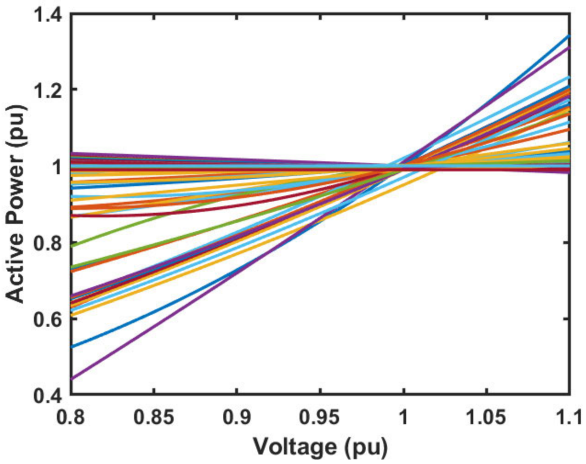

FIGURE 6. The relationship between voltage and active power for all documented ZIP load models for the equipment (interior/exterior equipment, TVs, consoles etc.) end-use load category.

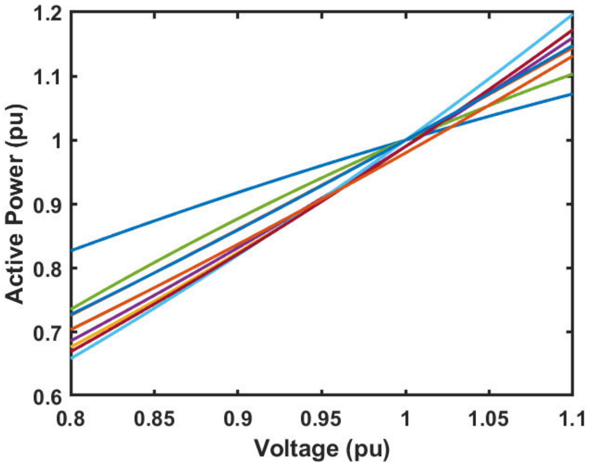

FIGURE 7. The relationship between voltage and active power for all documented ZIP load models for the fans end-use load category.

E. STAGE V–GENERATING BUILDING LOAD PROFILE WITH LOAD COMPOSITION UTILIZING A MODELED BUILDING LOAD PROFILE

Having derived the effective ZIP parameters for each end-use load category, the only information missing from Equation 11 for the full building ZIP model is load composition, i.e. the relative consumption of each end-use load category. To reiterate, this relative consumption is an important scaling factor to derive the effective ZIP parameters for the full building given by Equation 11:

$$z_{building} = \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}} z_n\right),$$
$$i_{building} = \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}} i_n\right),$$
$$p_{building} = \left(\sum\nolimits_N \frac{P_{0,n}}{P_{0,building}} p_n\right)$$

This information will be different for every building being modeled, but is already available for actual building types with submetering capabilities, or derived as part of the full-building modeling process when using software such as EnergyPlus. It is important to note that the relative consumption of each end-use category varies over time - both throughout the day, and seasonally. This means that, according to Equation 11 above, the effective ZIP parameters for a building vary greatly over time, unlike the documented ZIP parameters for individual load components, which are assumed to be effectively constant. The building ZIP parameters must therefore be calculated at every timestep of a building load profile model.

F. STAGE VI–GENERATING TIME- AND VOLTAGE-DEPENDENT LOAD PROFILES

Having selected, or modeled, all of the required information in the previous steps, the final time-dependent ZIP load model

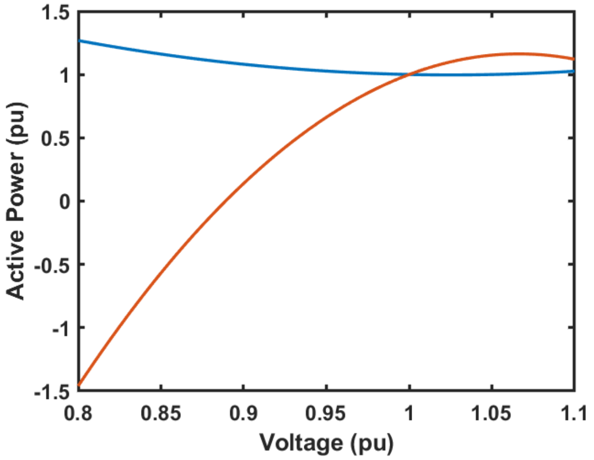

FIGURE 8. The relationship between voltage and active power for all documented ZIP load models for the pumps end-use load category.

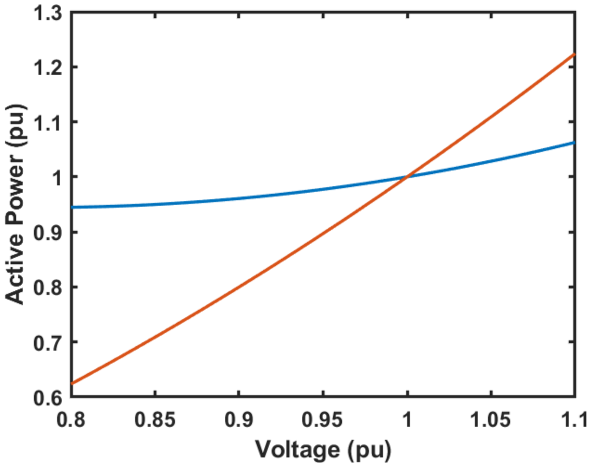

FIGURE 9. The relationship between voltage and active power for all documented ZIP load models for the refrigeration end-use load category.

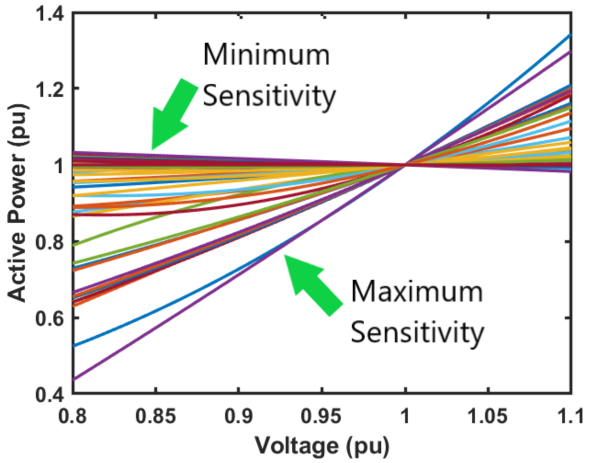

FIGURE 10. The normalized equipment end-use load category showing the load components with the minimum and maximum sensitivity to voltage changes.

for a building is obtained from Equation 11, by calculating the effective building ZIP parameters at every timestep. Because

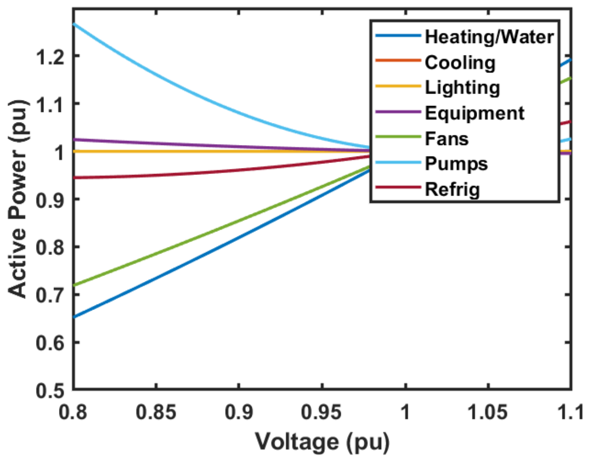

FIGURE 11. Active power vs. voltage using the 'Minimum' ZIP parameters for each end-use load category type.

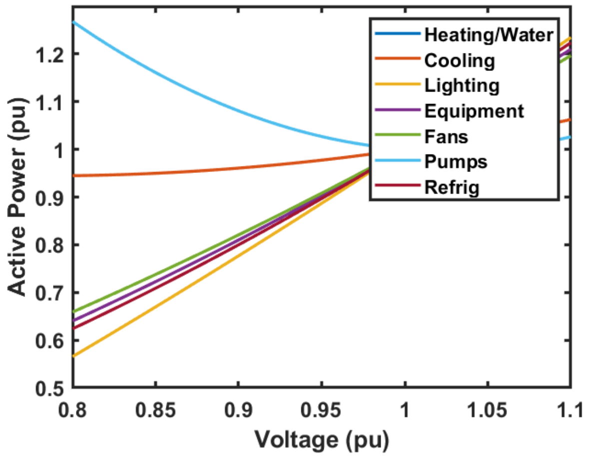

FIGURE 12. Active power vs. voltage using the 'Maximum' ZIP parameters for each end-use load category type.

a standard building energy model predicts only the nominal power (not a function of voltage), and the ZIP model provides the ratio of power to nominal power as a function of voltage, the building ZIP model can be considered a voltage- and time-dependent multiplier M on the nominal power, given by Equation 12:

$$\begin{aligned} \frac{P(V,t)}{P_0(t)} &= z(t)\left(\frac{V}{V_0}\right)^2 + i(t)\left(\frac{V}{V_0}\right) + p(t) = M(V,t) \\ P(V,t) &= M(V,t)\,P_0(t) \end{aligned} \tag{12}$$

Thus, after calculating the parameters in this multiplier from the effective building zip model, the final active or reactive power can be calculated at any voltage and time. The framework is summarized in Algorithm 1.

IV. FRAMEWORK APPLICATION FOR A RESIDENTIAL BUILDING LOAD PROFILE

The proposed framework uses documented ZIP parameters for various end-use load components to convert a standard voltage-independent building load profile model into

Algorithm 1 : Generating a Time- and Voltage-Dependent Load Profile

```
Given a constant P-Q modeled building profile $P_0(t)$, composed of N end-use category load profiles $P_n(t)$: $P_0(t) = \sum_N P_n(t)$
Select the ZIP values $z_n, i_n, p_n$ for each end-use load category (using Minimum, Maximum, or a weighted average of published values)
for t = 1: T
    Calculate the effective building ZIP parameters at each timestep
        $z(t) = \sum_N \frac{P_n(t)}{P_0(t)} z_n,$
        $i(t) = \sum_N \frac{P_n(t)}{P_0(t)} i_n,$
        $p(t) = \sum_N \frac{P_n(t)}{P_0(t)} p_n$
end for
Apply z, i, and p to the final time- and voltage-dependent ZIP model for the building
$P(V,t) = P_0(t)\left[z(t)\left(\frac{V}{V_0}\right)^2 + i(t)\left(\frac{V}{V_0}\right) + p(t)\right]$
```

a voltage-dependent model for active or reactive power. As illustrated above, the two factors influencing the voltage dependence of a building at every timestep are the ZIP parameters of each end-use load category, and the relative consumption. The following application of this framework to a case study illustrates the utility of such a model, as well as the implications of each of the aforementioned factors.

The model used in this case study is developed using EnergyPlus, and is intended to simulate the behavior of a typical U.S. home in 2012 based on aggregated data [25]. The constant P-Q model predicts the load of both the full building, and the eight end-use load categories described in section II, on an hourly basis.

Three separate time-dependent building ZIP models are developed, corresponding to three different selections of ZIP parameters for each end-use load category type.

1. Maximum:
   The ZIP parameters for each end-use load category type are assumed to be equal to those of the load component most sensitive to voltage changes in the available literature, from Table 8.
2. Minimum:
   The ZIP parameters for each end use category are assumed to be equal to those of the load component least sensitive to voltage changes in the available literature, from Table 8.
3. Weighted:
   The ZIP parameters for each end use category are calculated by weighting the published ZIP parameters of each equipment type by the relative prevalence of that equipment in U.S. homes, according to data from the DOE [16]. To derive the weighted ZIP parameters, the relative consumption of various types of Heating, Lighting, and Equipment was estimated from a published survey of U.S. residential electrical consumption, the results of which are shown in Table 9. Using Equation 11, the effective ZIP parameters for these categories were derived by combining this relative consumption with the published ZIP parameters in the previous table. For the remaining end use categories, the ZIP parameters corresponding to the most recently published studies were selected.

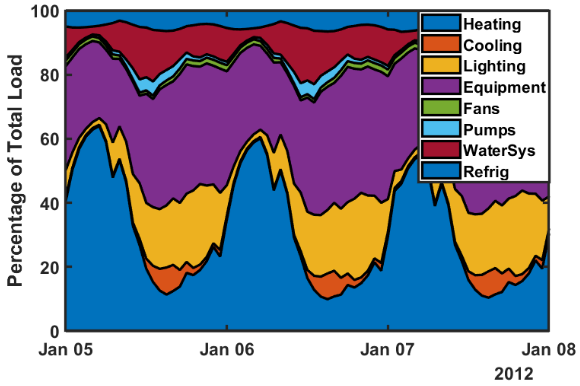

FIGURE 13. Relative consumption of various end use categories in the modeled U.S. housing stock, for 3 days in January 2012.

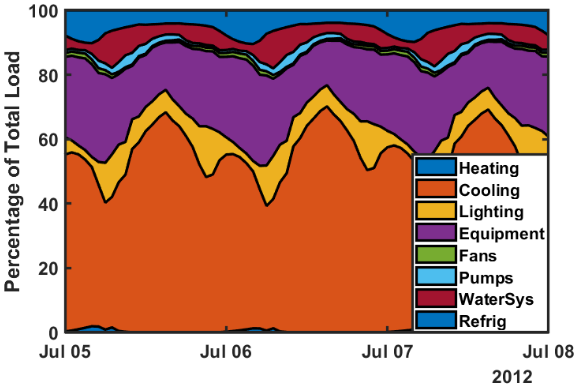

FIGURE 14. Relative consumption of various end use categories in the modeled U.S. housing stock, for 3 days in July 2012.

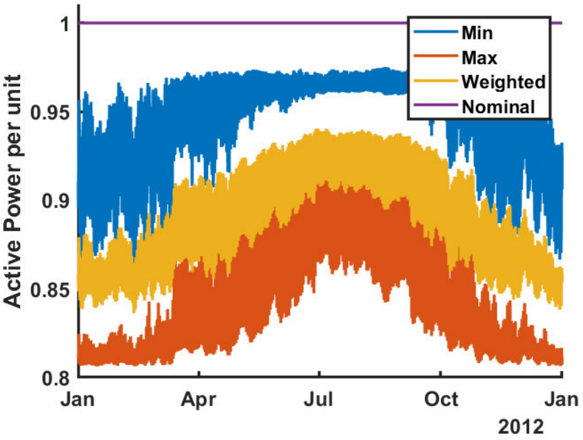

FIGURE 15. Active power per unit over a full year, at 0.90 volts per unit, for 3 different selections of ZIP parameters.

The relative consumption of each end use category, the second component necessary for calculating the building ZIP

TABLE 9. Energy consumption & percentage of electricity use for residential loads.

No.	End-Use Load Category Type	Load Components in Each Load Category	Annual kWh	Ref	Electricity Use Within Each Load Category
1	Heating	Resistive heater	314	[8]	6%
		water heater	4770	[12]	94%
2	Cooling	Air conditioner	1041	[8]	100%
3	Int/Ext Lighting	Incandescent light 75W	40	[20]	7%
		Incandescent light 100W	70	[8]	12%
		Compact Fluorescent	20	[8]	4%
		Halogen	440	[8]	77%
4	Int/Ext Equipment	Range	70	[10]	3%
		Dishwasher (Pot&Pan)	120	[10]	5%
		Dryer	1000	[10]	40%
		Microwave	131	[8]	5%
		Oven	126	[10]	5%
		Coffee maker	58	[8]	2%
		Vacuum cleaner	55	[8]	2%
		Washing machine	110	[9]	4%
		Video game console	41	[8]	2%
		TV - LED 55"	455	[22]	18%
		PC (Monitor & CPU)	322	[8]	13%
5	Fan	Fan	81	[8]	100%
6	Pumps	Pump	725	[19]	100%
7	Refrigeration	Refrigerator	660	[8]	100%

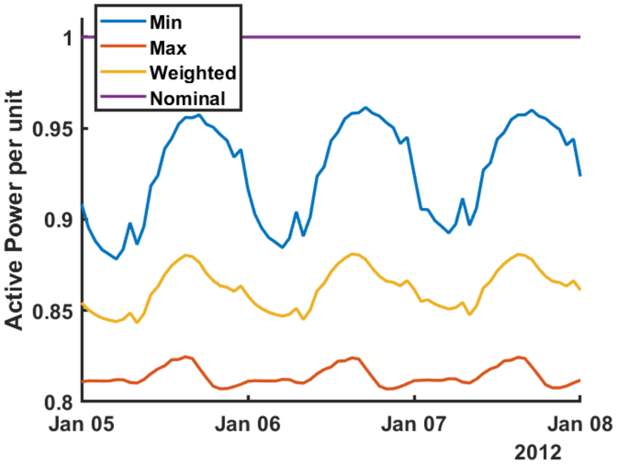

FIGURE 16. Active power per-unit over three days in January 2012, at 0.90 volts per-unit, for 3 different selections of ZIP parameters.

parameters, is illustrated in Figure 13 and Figure 14 for 3 days in both winter and summer.

It is evident from the above figures that for this set of buildings, the relative consumption of different end-use load category types varies significantly throughout each day, and even more significantly across multiple seasons. From Equation 11, this means that the building ZIP parameters can vary significantly as well over these time frames.

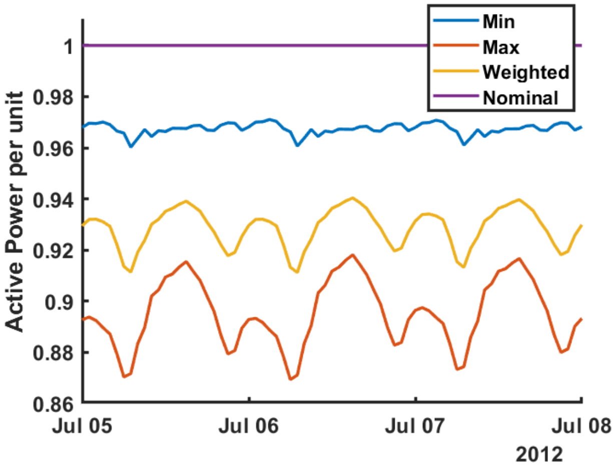

FIGURE 17. Active power per-unit over three days in July 2012, at 0.90 volts per-unit, for 3 different selections of ZIP parameters.

By combining the selected ZIP parameters for all three cases with the relative consumption of each end use category, three distinct models are generated for the full building, providing predictions of active or reactive power at any voltage and time.

Figure 15 presents the active power per unit predicted in all three cases for the full year, at a voltage of 0.90 per unit.

Also shown for reference is the nominal power at 1.0 per unit, which is the prediction given by a constant P-Q model ignoring voltage.

For a 10% drop in voltage, using the minimum ZIP parameters predicts between a 3% and 14% drop in active power, depending on the season and time of day. Using the maximum ZIP parameters, the active power is between 90% and 20% lower than the nominal power. Finally, the 'best estimate' represented by the selection of the weighted parameters falls between these two extremes, predicting 6% lower power in the summer and 16% lower in the winter.

Figure 16 and figure 17 highlight portions of this data for the same three days in January and July as Figure 14 and Figure 15.

The time dependence of the active power per unit is due entirely to the time dependence of the relative consumption of each end use category (from Figure 16 and Figure 17). It is apparent that over the course of a single day, there can be large changes in the active power per unit, even at a constant voltage. The magnitude of these differences depends not only on the relative power consumption changes, but on the sensitivity of each end use category to voltage changes.

In this example building ZIP model, both the ZIP parameters selected for each end use category and the time-dependent relative consumption of each category have a significant impact on the predicted active power. In addition, all three cases predict a significant error in the constant power model, up to 16% even in the minimum case, and up to 25% in the maximum case, for a 10% voltage drop.

V. SUMMARY, CONCLUSION, AND FUTURE WORK

A framework to analyze building load model sensitivity to variations in voltage is presented. A variation on the bottom-up, component-based approach is proposed, to incorporate the documented data on voltage sensitivity for various types of load components. By grouping components into end-use categories, and modeling the extremes of behavior within each category, meaningful bounds for full-building behavior are obtained, even in the absence of detailed information on building load composition. The resulting framework allows for the capture of the time dependent relationship between voltage and power at every time-step, allowing the building power consumption to become significantly more or less sensitive to changes in voltage as the end-use load category consumption varies overtime. Because this framework assumes a static load model, this time dependence of the voltage/power relationship is not due to transient behavior of the system. Accurately modeling the transient effects of sudden load and voltage changes would require a similar framework using a dynamic model.

The resulting bounds for full-building voltage-dependent load profiles are as accurate as the underlying available ZIP parameters. As continued research into the voltage dependence of new and existing load components provides updated or more accurate ZIP parameters, this framework will provide more accurate bounds for full-building load profiles.

A residential case study illustrates the importance of both voltage and time dependence in building load models. As the load composition of a building can change significantly over the course of hours, or between seasons, the voltage dependence can vary greatly over time. The presented model for U.S. homes illustrates that even when voltage is held constant for a full year, at 10% below the nominal voltage, the active power consumption can vary between 80% and 97% of nominal power, depending on the time of day, season, and type of equipment in each building.

This work is part of a large project that is taking place at NREL to analyze the impact of load models on load profiles. Future work will focus on a more comprehensive analysis of the impacts of this framework on building load profiles at various voltages. Specifically, this framework can be applied to predict the effects of CVR on a full building load profile model, in relation to the electric power system.

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