Power Factor and Reactive Power in US Residences – Survey and EnergyPlus Modeling

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Abstract – Electric power systems are experiencing a growing number of electronic loads in the residential sector as modern appliance technology progress, and it has become increasingly more important to consider the total power factor (PF) of residential communities. This paper provides a survey based on literature and publicly available information of typical appliance PF values and effects at the residential level as well as a discussion on appliance energy use and corresponding operation schedules. A procedure for the calculation of equivalent PF is proposed and exemplified with minutely experimental data at 15-minute and hourly time intervals, which correspond to smart metering and traditional practices, respectively. The application of the proposed equivalent PF procedure in coordination with building energy modeling, may, in principle, be employed to determine PF for entire communities at an aggregated level. The paper includes a proposal to simulate reactive power through an approach that utilizes EnergyPlus, a building energy modeling software. Such simulation capability could facilitate improved planning for compensation implementation both in electric power distribution networks and in individual residences, which offers significant opportunity for energy savings.

***Keywords*—Appliances, Building Energy Modeling (BEM), Energy Use/Consumption, Heating, Ventilation, and Air-Conditioning (HVAC), Losses, Power Factor (PF), Reactive Power, Schedules, Smart Grids, Smart Home.**

I. INTRODUCTION

In U.S. electric power systems, transmission and distribution losses account for around 5% of total used energy [1]. In 2019 alone, the estimated loss was over 206 TWh [2]. Since losses are proportional to the squared current (I^2) that flows through the resistive elements of transmission and distribution lines, they may be reduced by minimizing the current, which, in turn, is also dependent upon power factor (PF). A load with a higher PF draws less current than that of the same active power with a lower PF. Therefore, improving PF by compensating for these effects can reduce total losses.

Two main causes of reduced PF exist in electric networks: displacement of the phase angle between voltage and current as well as harmonic distortion. The general representations of displacement and harmonic effect in the overall ”true” rms PF of typical residential appliances on building wiring and transmission and distribution lines are illustrated in Fig. 1. Real examples of voltage and current waveforms for a vacuum cleaner and DC power supply illustrating the influence of harmonic distortion on power factor are provided in Fig. 2. Phase displacement occurs when the current of the reactive loads lag (for inductance) or lead (for capacitance) the voltage. As a result of the displacement, higher current needs to be drawn to supply the required power to the load.

Types of loads in residential buildings include resistive, reactive, and non-linear, including those that are electronically supplied or controlled. Resistive loads, such as incandescent lamps and electric water heaters, cause neither displacement nor harmonic impacts, resulting in unity PF. Reactive loads can be either inductive or capacitive with electric motors, pumps, and compressors as examples. Non-linear loads are generally operated by a switched-mode power converter, functioning as a rectifier. Examples include most electronic loads, such as computers, TVs, monitors, and printers. Because of the solid-state converter or rectifier operating with this load type, they may generate high harmonic content. which can be substantial unless PF correction measures are implemented.

Although electronically-controlled loads may reduce PF through harmonic impacts, several technological advancements that utilize such loads have been made to improve overall energy efficiency for residential appliances, such as energy use/consumption forecasting [3] and appliance control and energy monitoring through smart plugs [4].

II. TYPICAL POWER FACTOR VALUES AND EFFECTS

PF management has great potential to increase energy savings both at the residential and community level. Currently, few regulations exist to encourage implementation of PF correction on common electronic devices. California is the only state so far with PF regulation, but, currently, only televisions of 100W and higher are required to have a PF of at least 0.9 [5]. The vast opportunity for increased energy savings from improving PF of other residential electronics and appliances has yet to be fully harnessed.

According to research conducted by EPRI, PF correction of devices and requiring all plug loads above 50W to have a minimum PF of 0.9 at 50 and 100% load, could save 241 GWh per year for California [5]. At a national level, the potential energy savings increases to 15.8 TWh per year [11]. Energy savings can accrue quickly through PF improvements on residential devices. Based on calculations by California's Energy Commission, if a television with a PF of 0.5 is

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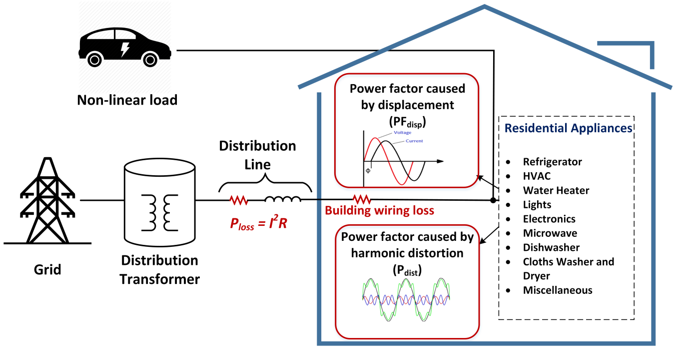


Figure 1. Overview of the system losses (grid level and building level) caused by low PF of the typical residential home appliances. The upstream losses of the distribution transformers are not shown.

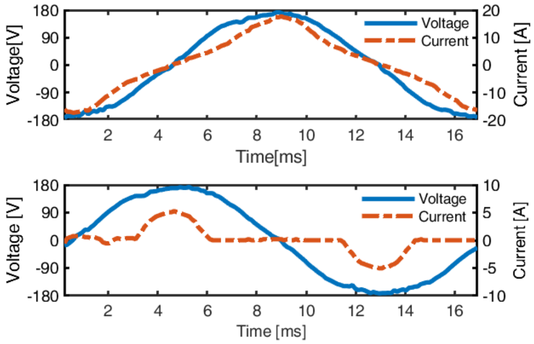


Figure 2. Real examples of voltage and current waveforms for (top) a vacuum cleaner and (bottom) DC power supply illustrating the influence of harmonic distortion on PF.

improved to be 0.95, the load current reduces from 1.7A to 0.9A, reducing building wiring power losses by more than 70% [12]. The HVAC system, a high power appliance and generally the largest energy-user, can offer significant savings but is heavily dependent upon climate. Hot and humid climates may realize more energy savings than more mild regions.

III. APPLIANCE ENERGY USE AND OPERATION SCHEDULES

The residential sector is one of the largest energy-using categories in the U.S. composing of nearly 25% of the total energy [13]. Regardless of the type of building, geographic location, and year of construction, there is a vast number of appliances in U.S. residences. Based on a survey conducted to determine energy consumption by end users, space heating and cooling are the largest energy-using categories [14]. On average, these two appliances combined, which may also be recognized as the HVAC system of the house, are using over 50% of total energy annually [15]. For insight into the energy makeup of a typical residences, the total energy usage of different appliances and end-user consumption share by different house types were analyzed and provided in Fig. 3.

TABLE I
ENERGY AND POWER FACTOR CHARACTERISTICS OF TYPICAL RESIDENTIAL APPLIANCES IN THE U.S.

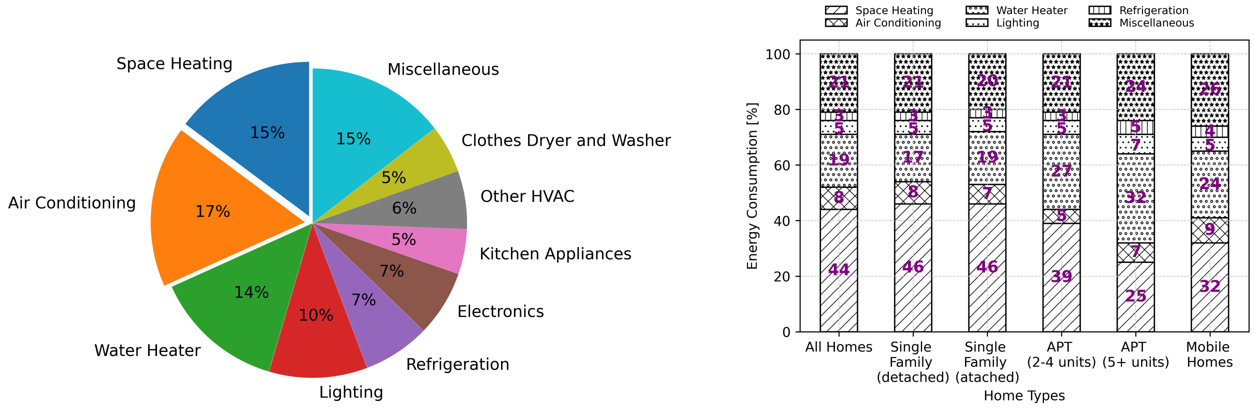
Appliance	**Energy Usage [%]**	**Active Power [W]**	**Power Factor**	**Source**
Refrigerator	7.0	100-145	0.8-0.99	[6], [7], [8], [9]
Clothes dryer	4.5	2500-5700	1.0	[6], [7], [9]
Washing Machine	0.4	500-540	0.55-0.59	[6], [7]
Dishwasher	0.5	1100	1.0	[7]
Water heater	13.6	4500	1.0	[7]
Microwave oven	1.1	1700	0.9	[8], [9], [10]
HVAC	36.1	1840-2340	0.90-0.92	[6], [7]
Pool/hot tub/ sauna pump	1.5	900-2300	0.35-0.8	[11]
Dehumidifiers	1.2	200-750	0.3-0.8	[11]
TV	*a*	49-190	0.53-0.94	[6], [5], [8]
Computers (Desktop)	*a*	95-200	0.63-0.99	[6], [8], [10]
Laptop	*a*	26-130	0.53-0.99	[6], [8]
LED Lamps	*b*	8-10	0.7-0.8	[11]
Fluorescent lamps	*b*	13-16	0.5-0.8	[6], [11]
Incandescent lamps	*b*	96	1.0	[6], [10]
Vacuum	*c*	987-1360	0.96-0.98	[6], [8]

[a] 6.9% including all other electronics appliances
[b] 10.3% including all other lighting loads
[c] 13% including all other miscellaneous appliances

With the advent of new technology, more efficient HVAC systems are being installed in recently developed buildings [16]. Further improvement is possible through PF correction and reactive power compensation [17]. With a considerable amount of possible energy savings, benefits include reduced electricity cost, higher power quality, and longer equipment life. For example, improved PF can reduce resistive losses that result in heat generation in conductive elements. Avoiding excessive heat preserves utility grid (i.e. transformer) and residential equipment.

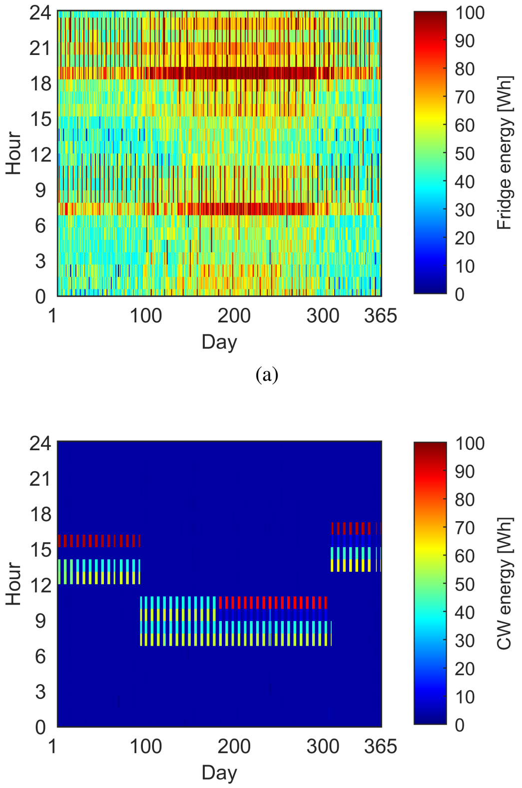
The set of appliances and equipment contained in typical U.S. residences have different energy use behaviors based on both the schedule of occupant use and power requirements during operation. It is important to understand these factors in order to determine the reactive power contributions of appliances. The variability in use schedules at the individual building level is a challenge for building energy modeling. The operation times of such appliances (i. e. refrigerator, dryer) become more predictable at the aggregated level and may be represented by equivalent schedules as exemplified in Fig. 4.

Since the HVAC system is generally the largest energy-



(a) (b)

Figure 3. Residential energy use survey results for 2015 provided by the U.S. Energy Information Administration. Provided are (a) annual energy use by different appliances of a typical residential building in the U.S. and (b) end-user energy use distribution by different types of U.S. homes. Energy use excludes the losses in electricity generation and delivery.



(a)

(b)

Figure 4. Typical operation schedule through energy use for (a) a refrigerator (Ref) and (b) clothes washer (CW) of a 3 bedroom, 2.5 bathroom house based on the Building America house simulation protocols.

using appliance, a focused example case of power requirements during operation is provided in Fig. 5(a). The system's power has much less variability than that of the refrigerator and clothes washer cycles in Fig. 5(b). However, the HVAC system is different from other typical residential appliances in that its operation schedule is significantly climate-based and effects from weather conditions supplant that of the occupant's influence. Therefore, the variability for the HVAC system lies in the scheduling, which may be resolved by considering weather data as input for simulation in addition to the other building parameters in a typical model.

It should also be noted that an example case for a water heater, typically the second largest energy user, was not provided due to the entirely resistive nature of electric water heaters, which are the most prevalent type. No reactive power is contributed by this appliance and the PF remains at unity. Should a water heater be of the heat pump type, the reactive power would need considered, especially if the compressor were to be electronically controlled, which can reduce PF substantially.

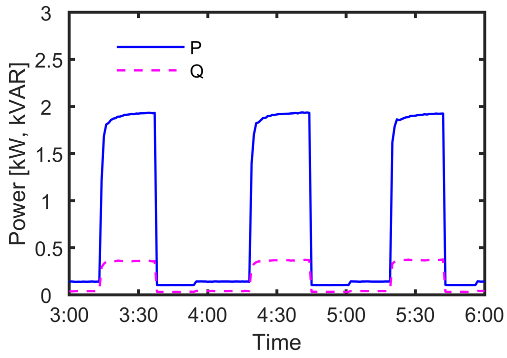
TABLE II
EXAMPLE LIST OF COMMON RESIDENTIAL APPLIANCES WITH AVERAGE ENERGY USE

Appliance	Model	Ratings	Avg. Energy
Refrigerator	Amana 12828158	92.4V/16.2A 1.5kW	150kWh/month
Clothes dryer	Samsung DV4006	122.6V/45.8A 5.6kW	2.5-4 kWh/load
Cooking range	Frigidaire CMEF212ES3	122.9V/31.7A 3.9kW	3.8 kWh/hour
Interior lights	*a*	*a*	*b*
Heat pump	American standard 4A6116036B1000AA	36.4V/101.5A 3.7kW	*c*
Furnace fan & thermostat	Broan QTRE090C	101.9V/5.7A 0.6kW	*c*

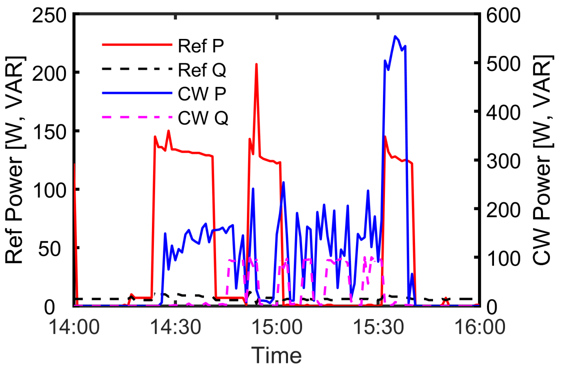
[a] Miscellaneous models included
[b] Average usage is 4.6 kWh/day per resident based on [18] (table 4.1)
[c] Climate-based

IV. EQUIVALENT POWER FACTOR CALCULATION AND REACTIVE POWER ESTIMATION

As reactive power contributions in the utility grid become more prevalent among residential buildings due to the pro-



(a)



(b)

Figure 5. Real and reactive power during example operation cycles of (a) a typical HVAC system as well as (b) a refrigerator and a clothes washer based on experimental data.

gression of modern appliance technology that may employ power electronics converters, it is increasingly important to incorporate reactive power effects in building energy modeling. Software, such as EnergyPlus, typically employs schedules of use and weather data as input for simulation [19]. As discussed in section III, both the schedule of use and corresponding power ratings are important for equivalent PF calculation.

Reactive power may be determined in post processing of BEM simulation to accommodate for building energy modeling software that may not inherently consider it. Equivalent PFs are calculated by averaging the corresponding real and reactive power based on specified time scales and interpolating the average as a constant value to the original time scale. Example equivalent PF calculation is provided in Fig. 6 based on the same minutely data utilized in Fig. 5 for a clothes washer, a refrigerator, and an HVAC system at 15-minute and hourly time intervals, which correspond to smart metering and traditional building modeling practices.

In the provided example, it may be observed that the equivalent PF may vary greatly between time scales (Fig. 6). In aggregation, the calculation of equivalent PF through the proposed procedure may be utilized, in principle, for the determination of reactive power of entire communities by averaging from the house level.

V. ENERGYPLUS^{TM} SOFTWARE FOR BUILDING ENERGY MODELING

EnergyPlus is a widely used open-source building energy simulation tool that models energy consumption for most commonly used electrical loads (i.e. HVAC, lighting, and plug and process loads) and water use in buildings [19]. The first version of the software was published in 2001 and has continually been updated on a bi-annual basis since.

The current version of the software has an extensive set of features, including integrated simultaneous solution, heat balance-based solution, user definable time step, component-based HVAC, a large number of built-in HVAC and lighting control strategies, import and export for co-simulation with other engines, and many other capabilities.

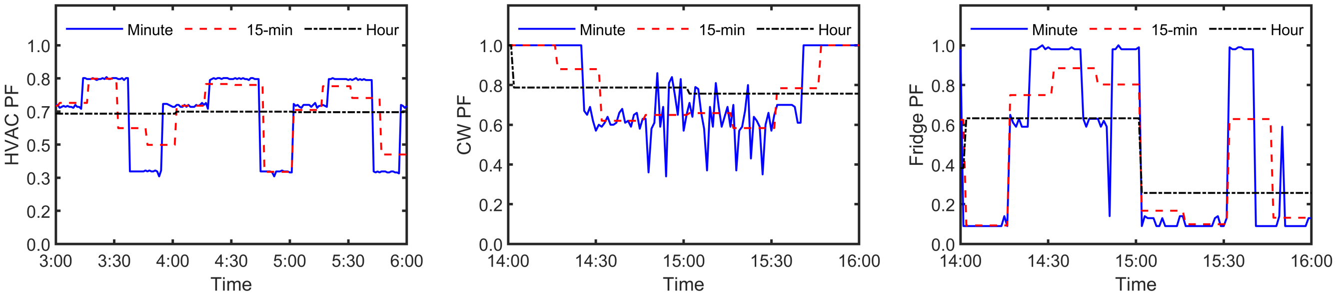
The overall system architecture of the EnergyPlus software is illustrated in Fig. 7. The building descriptions (space, HVAC, etc.) are provided through a user interface. All input files are written in a flat ASCII file that is fully readable and editable. The IDD file consists of objects and specifications of data that is used by the "InputProcessor" to interpret each line of the IDF file to be processed. EnergyPlus executes the simulation process based on the specifications of the IDF file. The desired outputs are also generated by output processing in a predefined manner of which the user has full control.

EnergyPlus can produce energy use of the total building as well as for individual appliances. The software may also interface with Python through third-party libraries and software, such as the Building Controls Virtual Testbed (BCVTB). Upon simulation completion, reactive power may be calculated in post-processing within the Python environment by analyzing the provided energy results and applying an equivalent power factor.

VI. CONCLUSION

Modern electric loads may include power electronics converters and are non-linear in respect to displacement and/or harmonic impacts. The PF, therefore, is a very important component to consider for improved reactive power analysis in building loads. This paper provides a literature survey on typical residential appliance PF values and energy characteristics as well as a proposed approach for equivalent PF calculation, which may be employed in aggregated community level studies on residential reactive power contributions.

The utilization of equivalent PF calculation and reactive power estimation with building energy modeling at the aggregated level may facilitate the installation of compensation technology that can promote further energy savings in residential communities. As an example, a set of high resolution residential data is analysed and utilized to calculate average PF of different appliances for 15-minute and hourly resolutions, which correspond to typical smart metering and building modeling practices, respectively. Also proposed is a method in which the equivalent PF may be applied to the EnergyPlus building energy modeling software to determine reactive power contributions from simulated loads.



(a)

(b)

(c)

Figure 6. Experimental minutely PF and calculated equivalent PF for 15-minute interval, which corresponds to typical smart metering, and the traditional hourly interval for (a) an HVAC system, (b) a refrigerator, and (c) a clothes washer (CW).

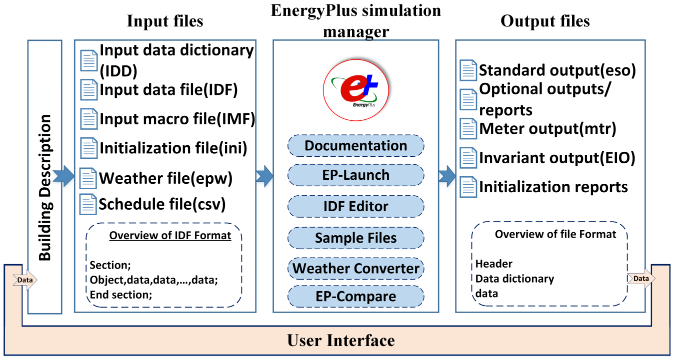


Figure 7. The overall system architecture of EnergyPlus, an open source whole building energy simulation program that models energy use for both HVAC system and plug and process loads.

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