DISSERTATION

EFFICIENCY OF AC VS. DC DISTRIBUTION SYSTEMS IN COMMERCIAL BUILDINGS

Submitted by

Arthur Felício Barbaro dos Santos

Department of Systems Engineering

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Spring 2022

Doctoral Committee:

Advisor: Peter Young
Co-Advisor: Daniel Zimmerle

James Cale
Maggie Clark

ABSTRACT

EFFICIENCY OF AC VS. DC DISTRIBUTION SYSTEMS IN COMMERCIAL BUILDINGS

Decarbonization and modernization of the grid, electrification of transportation, and energy storage are some of the trends pushing towards the significant growth of power electronics in the past few decades. The massive application of such devices has increased the interest in direct current (DC) power distribution as an alternative to the conventional alternating current (AC) distribution systems in residential and commercial buildings. This increase in non-linear loads, however, substantially increases current harmonics, which compromises the lifespan, efficiency, and/or operability of distribution components, such as transformers and protection equipment. Additionally, when comparing the efficiency of AC vs. DC distribution systems, the literature is often based on simulation studies rather than real measured data. In this regard, this study focuses on three major topics: a) Harmonic cancellation within building circuits; b) Endpoint use efficiency comparison for AC and DC in-building distribution systems; and c) A cautionary note on using smart plugs for research data acquisition. The analyses are based on recorded power consumption data from office-based appliances, made by smart plugs, combined with detailed characterization of sampled Miscellaneous Electric Loads (MELs') power converters.

While harmonic cancellation studies often assume that AC converters operate across their rated power range, measured realistic power profiles reported in this work show that MELs operate below 40% of rated power the majority of the time when not in standby mode. This makes the harmonic cancellation significantly lower than that predicted when using full-range power assumptions, which could provide incorrect guidance to building

design engineers. In contrast, increased diversity of MELs increases harmonic cancellation. Blending typical office loads with lighting, for instance, improves the harmonic cancellation to near the levels predicted by traditional methods. Regarding the endpoint efficiency of AC and DC distribution systems, no systematic efficiency advantage was found, when endpoint AC/DC converters were compared to a similar, commercially available, DC/DC converter powering the same load profile. That goes in the opposite direction of prior studies, which estimate converters' efficiency based on datasheet information or the efficiency at rated load.

ACKNOWLEDGEMENTS

I would like to acknowledge many people that, through their guidance and support, made this life-changing experience much more pleasant and fulfilling. First, I'd like to thank my committee members for devoting their time and providing their valuable feedbacks. Dr. Peter Young for being my advisor, for his support, and for providing me assistance when needed. Dr. James Cale for his valuable lessons, for his collaboration, and for advising me on his projects. I also would like to thank Dr. Maggie Clark for her support and for the time she took serving on my committee.

I am especially thankful to Daniel Zimmerle, my co-advisor, for mentoring me through my Master's and Ph.D. research. His immense knowledge, enthusiasm, frankness, and humanity were especially inspirational to me and contributed immensely to my appreciation for research. I am very grateful for having such a bright and exceptional human being guiding me over all the past years. Daniel, thank you for the world of opportunities, for the unconditional support, for all the encouragement, and for caring way more than just research. My gratitude for you is beyond words.

A very special thanks to Christopher Lute, for the guidance and assistance, and his always clever and insightful inputs. To Jerry Duggan for his kindness and mentorship in my early years at CSU; and Avpreet Othee for the good times in the lab. Thank you for your friendship and for cultivating a great and welcoming environment in the Microgrid Lab at the Powerhouse. It was a pleasure to work and learn from you all.

I'd like to express my profound gratitude to my parents who have always encouraged my academic pursuits, no matter the circumstances. Thank you for providing me the best education you could, many times beyond your means, for your incessant work, and for the many sacrifices you made. Life, literally and in all its fullness, was only possible because of you.

I am thankful to all my friends in Brazil and Fort Collins, and all my family, for making this a vivid and joyful journey. Lastly, I thank Roberta for keeping my heart warm in freezing (but lovely) Colorado, for being the incredible woman that she is, and for staying by my side through the good and hard times.

DEDICATION

To Roberta, Bárbara, Rogério and Sandra.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction and Background

The following documents complete the author's work for his Ph.D. research. Chapters 1 through 4 discuss the main body of work, primarily focused on the experimental analysis of DC and AC distributions systems in commercial buildings. Chapter 5 outlines a cautionary note when using smart plugs for research data acquisition. Chapter 6 summarizes the conclusions of this work and highlights future topics of research.

1.1 Study Design and Aims

This research is part of a larger project, *DC Design and Scoping Tool* (hereafter 'DC Design Tool'), funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Building Technologies Office (BTO) under the *Emerging Technologies Program*. Colorado State University (CSU) is a subcontractor for the project, under prime contractor National Renewable Energy Laboratory (NREL), and in conjunction with Lawrence Berkeley National Laboratory (LBNL) and several other entities. The term of the project was 2018-2021.

The overall goal of the project is to equip architects and engineers to make technical and economic evaluations of DC power distribution relative to the typical AC distribution systems utilized in commercial buildings. The primary output of the project is a *DC Design Tool* that will be integrated to OpenStudio or other building energy simulators [1].

The research performed for the author's Ph.D. program completes a specific portion of the DC Design Tool, namely characterization of the efficiency of devices and power distribution networks. The author developed a test laboratory, performed tests, and analyzed data at CSU's Powerhouse Campus, Fort Collins, Colorado, USA.

The objectives of this research can be divided into three specific aims:

1. Characterization of harmonics and harmonic cancellation from AC/DC converters in low voltage power distribution in commercial buildings.

2. Comparing the endpoint-use efficiency for AC and DC appliances typical of commercial buildings.

3. Analyses on the power measurement accuracy of smart plug devices.

Most of the first aim was completed throughout the author's master's degree in electrical and computer engineering. By the time of the completion of this dissertation, the characterization dataset was expanded to 33 AC appliances, 58 AC/DC converters, and 35 DC/DC converters; the data are publicly available at https://hdl.handle.net/10217/207807 [2]. The study analyzed both the efficiency and harmonics of external AC/DC power converters, but only measured the harmonics of appliances with internal AC/DC converters that could not be directly accessed to measure efficiency. Additionally, low-cost 'smart plugs' were utilized to monitor the load level of the appliances over an extended period. These data were used to simulate harmonic cancellation within an AC distribution system of a commercial building using Monte Carlo (MC) methods. Results were published in the author's master's thesis and a journal article, in the *International Journal of Electrical Power & Energy Systems*, entitled "Harmonic cancellation within AC low voltage distribution for a realistic office environment" [3].

Previous studies of harmonic cancellation considered the operational range of the power converters to be uniformly distributed across the full range of the converter's rated power [4–9]. However, the long-term power monitoring data (most appliances were monitored for approximately 2 months), indicated that these converters operate over a restricted load range, usually between 0-40% of their rated power. In effect, many converters are oversized relative to the loads seen when the appliances are in use.

Monte Carlo simulations illustrated that limiting the operational power range significantly decreases harmonic cancellation, especially for higher-order (9th onwards) harmonic components. Additionally, a higher diversity of equipment connected to the same system increases harmonic cancellation, including that of the critical low-frequency components (3rd and 5th).

The second and third aims reflect the content of the author's Ph.D. research, forming the bulk of this document.

Regarding the second aim, almost all appliances will require some form of power conversion between the power distribution system and the internal requirements of the appliance. This is true for both AC and DC power distribution systems. For AC distribution systems (DS), power conversion is typically from 120, 220, or 240V_{AC} to the internal voltage requirement(s) of the appliance – typically 5-24 V. For a DC DS, the conversion is from the DC distribution voltage – typically 24, 48 or 380 V_{DC} – to the same internal voltages. A common hypothesis is that DC/DC power conversion is more efficient than AC/DC power conversion. Therefore, if DC DS is efficiently powered using a central AC/DC converter or a DC source (e.g. photovoltaics or batteries), the hypothesized advantage in DC/DC end-point conversion efficiency will make a DC DS more efficient than a similar AC DS.

To test this hypothesis, additional AC/DC and DC/DC converters were acquired, paired by common power rating and output voltages. The efficiency of the converters was then characterized, and the effective efficiency of the end-point power conversion was developed by weighting measured efficiency by typical power consumption, using the same power recordings as mentioned above. This comparison simulates the result a design engineer might achieve by sourcing and substituting a DC/DC power converter for an AC/DC power converter for any given appliance and thus represents a fair comparison end-point conversion efficiency between an AC DS and a comparable DC DS. Results were published as a journal article, in the special issue *Modeling and Simulation of Power Systems and Power Electronics* from the *Energies* journal, entitled "Endpoint Use Efficiency Comparison for AC and DC Power Distribution in Commercial Buildings" [10].

Finally, a few Belkin WEMO smart plugs were used to collect power profiles from a variety of appliances for aim one and two. Therefore, for the third and final aim, we evaluate the power measurement accuracy for smart plug devices from five major players in this market: TP-Link, Belkin, Emporia, Etekcity, and Sonoff. Previous studies had a strong focus on cybersecurity aspects, but little has been discussed about their accuracy on taking power measurements, especially when monitoring loads with fast variations in power, as observed in office-based appliances, such as laptops and desktops.

1.2 Background on AC vs DC Power Distribution Systems in Commercial Buildings

The rapid increase in on-site electricity generation, battery storage, and electronic loads that utilize DC internally, have increased interest in DC DSs. While AC systems have dominated building power distribution for more than a century, the recent, fast-paced, evolution of power electronics has made DC voltage control and conversion simpler and more efficient, encouraging research to reassess and evaluate new opportunities that a DC distribution might bring.

While AC power distribution utilizes well-established specifications embodied in regional building codes, DC power distribution is less standardized, although there are several efforts underway to develop a small number of standard distribution configurations [11–14]. Multiple parameters define different DC power distribution system topologies, including voltage level, power rating, configuration (bipolar or unipolar), and power quality. This study focuses on DC power distribution at low, touch-safe, voltages ($<60V_{DC}$), which can be routed in buildings without conduits and can often be powered by multi-channel LED lighting supplies.

Solar photovoltaics (PV) has a great potential in the commercial sector, due to the large roof area of commercial buildings [15]. Worldwide, by 2024, renewable generation capacity is expected to grow by 50%, with PV generation the largest source type, and responsible for 60% of this growth, mainly in commercial and industrial applications [16]. According to the US Energy Information Administration's *Annual Energy Outlook 2020*, PV installation costs are projected to decrease quickly by 2030, and the capacity for distributed solar generation to increase 50 GW in the US [17].

The energy storage market in the US is also growing. Storage power output is expected to grow from 1.2 GW in 2020 to 7 GW in 2025. The non-residential sector deployed approximately 70 MWh of storage in Q2 2020 alone [18]. Additionally, climate change has driven the production and adoption of electric vehicles. This change has directly impacted the power system, as utility distribution systems need to accommodate a significant increase in demand to charge vehicles. Vehicles also add the possibility of grid storage if operated in the vehicle to grid mode (V2G) [19–21].

Power consumption by lighting in commercial buildings has decreased as LED lighting replaces incandescent and fluorescent lighting. However, offsetting load growth is projected in office equipment [22], which is expected to grow by 60% by 2050 [23].

Multiple studies [24–29] have proposed that, since most of this load growth operates internally on DC voltages, DC power distribution would improve the efficiency of these loads. Additionally, when a commercial building also has PV generation on-site, using DC power distribution could remove the need to convert PV generation to AC for power distribution and then to DC for use in the devices. Patterson states that, depending on the appliance, the conversion losses from AC to DC can range from 10-25% [30], while Wu et al. reports power conversion losses in a $380V_{DC}$ bus as 8% less than in conventional AC [31] systems. Therefore, assuming DC/DC conversion is more efficient, eliminating AC/DC conversions and selecting efficient DC/DC power conditioning could improve the efficiency of this growing load category.

In the few cases where DC power distribution systems have been implemented at a large scale, they have been found to be more reliable and economic, and to need fewer space [19, 32, 33]. The US Navy, for instance, has opted for DC distribution systems due to its high reliability and the high power quality requirements of certain shipboard loads [34–36]. Data centers have also implemented distribution DC distribution systems, due to high reliability and energy costs savings. However, data centers often rely on uninterruptible power supplies (UPS), and distributing DC power eliminates power conversion inside the data center [13,37–41]. Since typical commercial buildings do not have stringent UPS requirements, similar efficiency gains may not be present.

1.3 Scope

Miscellaneous Electric Loads (MELs) are typical loads in a building that are not related to the building's core functions, such as heating, ventilation, and air conditioning (HVAC), and lighting. MELs include desktop and light process equipment (e.g. laptops, monitors, TVs, phone chargers) and heavier equipment required for commercial operations (e.g. process equipment tools, electric forklifts, etc.). Due to the rapid increase in power electronics, MELs often utilize DC voltages internally and need an AC/DC converter to supply the DC power for their electronic components. As with any power conversion, AC/DC converters have losses and also inject current harmonics that may cause voltage distortion in the distribution system.

When comparing AC and DC distribution systems, the leading argument is that DC/DC conversion is more efficient due to the advances in power electronics, the advancement of DC distributed energy resources (DERs), and the increasing number of MELs operating internally on DC. However two important factors are often disregarded in past studies [19, 42–44]: First, little attention has been given to the actual load on the converters. Since converters' efficiency curves vary non-linearly with changes in load, load levels may have a substantial impact on the net efficiency of the converter. Based on our experiments, MELs converters seldom operate at full load and more often operate at a small fraction of their rated load; conversion efficiency is typically lower at low loads than at full load. Prior studies typically make simplified assumptions about conversion efficiency, such as using a fixed value for conversion efficiency when comparing AC/DC and DC/DC converters. Second, prior studies and simulations typically do not use measured loads for comparisons, but instead assume load levels or utilize data taken from data sheets of converters.

Previous work by the author while analyzing harmonic cancellation in AC low voltage distribution systems indicated that cancellation using realistic load levels differed substantially from cancellation calculated using the loads distributed uniformly over the entire rated power of the converter. Therefore, the hypothesis of this study is that load assumption will also have a significant impact on net (weighted by load) efficiency of end-point power conversion – i.e. power conversion occurring at the MEL. The study will look at losses in end-point conversion to make an endpoint efficiency comparison of AC and DC distribution systems in commercial buildings using experimental data.

Finally, with the advances in the Internet of Things (IoT), smart devices such as smart plugs, are becoming increasingly common in monitoring applications, such as energy management systems. Problems related to cybersecurity are often highlighted in research studies, as smart plugs, like many new IoT devices, are connected to local WiFi networks and/or the Internet while lacking the robust security features of computers. In contrast, little is questioned regarding the quality of measurements performed by such devices. Since the research reported elsewhere in this work utilized appliance load profiles recorded by smart plugs, the author performed a detailed review of the accuracy of one plug brand (WEMO™) which had been used in the study. Results of this 'close look' revealed interesting behaviors, stimulating a more detailed examination of smart plug accuracy, extending to several smart plug models from major players in this market. As with the remainder of the work, this work concentrated on highly variable electronic loads, all powered by switching power supplies, which are common in office-based appliances.

1.4 Document Structure

This dissertation is structured as follows:

Chapter 2 describes the study analyzing harmonic cancellation within an office environment at low voltage AC distribution. Three scenarios are investigated comprising full load range of power converters and realistic load profiles obtained through power monitoring with smart plugs.

Chapter 3 makes an end-point efficiency comparison for AC and DC distribution systems based on AC and DC experimental data collected in laboratory experiments.

Chapter 4 details the appliances and converters characterized for this study, and points out where the characterization data can be freely downloaded.

Chapter 5 analyzes the accuracy of power measurements made by five different brands of smart plugs, focusing on its usage in research data acquisition.

Chapter 6 discusses the conclusions of this research and suggest topics for future work.

Chapter 2

Harmonic Cancellation within AC Low Voltage Distribution for a Realistic Office Environment

This chapter was published in the *International Journal of Electrical Power and Energy Systems*. While preliminary version of this content was included in the author's master's thesis [45], this chapter represent the significantly updated version that resulted from journal submission, review, and revision.

2.1 Introduction

Non-linear loads arise when the impedance of a load changes with the applied voltage. For AC-power devices, these variations in impedance distort the sinusoidal current, creating current harmonics. Most AC/DC converters are switch-mode power supplies that are highly non-linear, and current harmonics vary substantially in both magnitude and phase angle with the load on the supply. High current-harmonic levels increase power losses in transformers, reducing efficiency and causing extra heating that reduces transformer lifespan. Current harmonics can also impact power quality sufficiently to cause either other loads to malfunction, protection failures, or metering errors [46, 47]. More buildings are now using subpanel metering to monitor loads and energy efficiency, and the presence of harmonics may create higher errors in these submetering systems.

Miscellaneous electric loads (MELs), also known as "plug and process" loads, already comprise nearly 50% of electrical load in commercial buildings in the United States, and their load share is anticipated to grow to 60% by 2050 [22, 23]. In the U.S. residential sector, televisions, personal computers, and other MELs (excluding cooking, laundry, and dishwashing) presently account for 37% of load, growing to 42% by 2050 [22]. Such MELs consist primarily of electronic devices with switching power supplies. With the rapid increase of MELs, the use of converters is increasing; today, small power electronics loads are responsible for a substantial part of harmonic generation in commercial buildings.

Wang et al. [48] showed that the 3rd and 5th harmonics are predominant in residential feeders. Because residential service transformers typically are grounded on both sides, harmonics are propagated into the medium-voltage distribution system. Commercial and industrial systems generally use three-phase delta-wye distribution transformers that are able to trap triplen ("triple N") harmonics [49]. Hence, while residential consumers have a higher impact on harmonics at the feeder level, commercial and industrial loads primarily impact the distribution transformers: the utility transformer and/or step-down transformers within the building. Gomez et al. [50] found a quadratic relation between the distribution transformer life reduction and total harmonic current distortion (THDI). Using constant values for THDI in a simulation, they estimated that levels of THDI in the system should be below 30% to keep a reasonable lifespan of the transformer [50]. In cases where the source impedance is high, current harmonics may cause voltage harmonics, and that can also affect the neutral wires on distribution systems. Desmet et al. [51] found that the current in the neutral wire is quite sensitive to high-order harmonics in the power supply voltage, which increases both safety risks and probability of system failure [52]. Harmonics may also induce voltage on poorly shielded data or telecommunication cables.

To deal with this problem and improve the system power quality, several techniques have been applied to cancel or mitigate the harmonics at the system level and at the device itself [53, 54]. Regarding the system-level corrections, one technique is the use of phase shifting transformers, where part of the harmonics generated in the system are shifted 180 degrees, increasing harmonic cancellation [55]. Harmonics may also be reduced using series line reactors and other current-shaping devices [56, 57]. Furthermore, passive and active filters are often utilized to mitigate harmonic content in the power system. A passive filter combines resistors, inductors, and capacitors to capture harmonic currents, while an active filter uses power electronics to inject active power with matching frequencies to the harmonics, but opposite phase angle so that they can be cancelled. Active filters have gained popularity recently due to improvements in their performance and affordability [58–60].

Power factor correction (PFC) is a widely used technique that decreases the harmonic components at the device by increasing the power factor of the power supply. The high pulses of current of short duration are smoothed by passive or active techniques, decreasing current amplitude and increasing power factor. Considering current harmonics, switch-mode supplies can be divided into three groups: no PFC, passive PFC, and active PFC [61]. Passive PFC topologies improve the power supply power factor by using reactive components such as inductors and capacitors to improve the current waveshape. Among the techniques used, one can utilize an inductor in series with the power supply, or one inductor at the output, so that it is connected in series with the load. Alternatively, an active PFC topology will make use of semiconductor switching devices to control the supplied current so that its angle is in phase with the supplied voltage's [62].

Technological advances have impacted current harmonics from some devices. As an example, in the 1990s, electric vehicle chargers had an average THDI of 50%, whereas recent models have a THDI averaging 7.5%, below the limit of 17.3% established by the IEC 61000-3-4 norm [56].

Several harmonic standards have been established to maintain the network voltage distortion at an acceptable level. Some standards establish limits for individual devices and others for the distribution system as a whole.

The European standard IEC 61000-3-2 [63, 64] deals with limitation of harmonics for individual devices with input current equal or below 16 A, rated at 220/380 V, 230/400 V and 240/415 V, 50/60 Hz. However, it does not present any limits for systems with nominal voltage below 220 V. It also does not present limits to lighting equipment with active input power below 25 W. IEC 61000-3-4 [65] extends application of 61000-3-2 for equipment rated above 16 A per phase, rated up to 240 V (single phase) and up to 600 V (three phase), 50/60 Hz [66–68].

On the other hand, other norms transfer the responsibility of harmonic mitigation to the building owner/operator. That is the case of the norms IEC 61000-2-2 [69] and IEC 61000-2-4 [70], applied for low- and medium-voltage systems. Also, in North America, IEEE-519 [71] establishes limits for current and voltage harmonics at the point of common coupling for different bus voltages. The intent is to prevent current harmonics from propagating and affecting other consumers connected to the power system. Norms like EN 50160 [72], D.A.CH.CZ [73], and G5/4 [74] deal specifically with the quality of the distribution system in different countries [75].

A final strategy for harmonic reduction is to rely in part on harmonic cancellation at the load. When estimating harmonic cancellation, it is important to consider two effects: attenuation and diversity. The *attenuation effect* happens when a distorted voltage is applied to a non-linear load, causing a reduction in the current harmonics generated by load, relative to the same load fed by an non-distorted supply voltage. On the other hand, the phase angle of each current-harmonic output from a converter also varies with converter load; this is called the *diversity effect*. Therefore, harmonic cancellation increases when there are multiple devices at different power levels connected to the same circuit [4,76,77]. Variability in both converter construction and in converter loading contribute to harmonic cancellation due to diversity [78, 79]. Diversity is quantified using diversity factor (DF), which is the magnitude of the phasor sum of all harmonic components, divided by the arithmetic sum of those components. A lower DF corresponds to a higher diversity of sources (i.e., more harmonic cancellation).

Most studies of harmonic cancellation focus on the distribution systems, where variations in cancellation play a significant role in the total voltage harmonic distortion in medium- and low-voltage feeders [61,80–82]. In contrast, this study focuses on harmonics on distribution circuits *within* commercial buildings. In this case, the impact of harmonics is primarily on the building's distribution transformers and protection systems. Harmonics can also produce unwanted interference between devices tied to the secondary winding of a distribution transformer. Overestimating or underestimating harmonics may increase costs by requiring additional equipment, such as line reactors or filtering, that would not be necessary if harmonic cancellation was considered. Conversely, underestimating current harmonics can accelerate aging of transformers, filters, cables, and other system components; reduce power factor; and/or cause the system to fail to comply with standards [83, 84]. Therefore, considering harmonic cancellation can help for new and more efficient distribution, avoiding unexpected electrical losses, misoperation, and premature aging of equipment [85].

Past studies of harmonic cancellation typically assumed the power level of the AC/DC converters are randomly but uniformly distributed across their rated power power range (20%–100% is typical) [4–9]. These power ranges are assumed; the studies did not measure the magnitude and frequency distribution of the operational power draw of the converters. Assuming a uniformly distributed power range introduces two errors. First, total power and the diversity in power level is overestimated, relative to what this study measured. Second, the studies assumed that power levels were randomly distributed over the assumed range, while our data indicates that many controllers operate much of the time at discrete power levels. Both assumptions may introduce errors into estimated harmonic cancellation. Our study attempts to bound these errors by simulating multiple converters using realistic power levels taken from long-term recordings, coupled with harmonic profiles collected from complete measurement of the converters.

2.2 Methods

Three methods are required to complete this study: (1) characterization of individual converters across a wide range of loads; (2) characterization of the routine operational loads seen by the converters; and (3) simulation and comparison of harmonic cancellation. Before detailing methods, we define metrics utilized in the study.

Three standard metrics are used in this study: total harmonic distortion (THD), total rated-current distortion (TRD), and diversity factor (DF). THD is a common metric constrained to a single power level, and it can be used either current (THDI) or voltage (THDV), using the standard definition in Eqn. 2.1 for current.

$$THDI = \frac{\sqrt{\sum_{k=2}^{\infty} |I_k|^2}}{|I_1|} \tag{2.1}$$

However, because THD does not scale harmonics by total power, the impact of high harmonics at low load levels overstates the relative fraction of harmonics on a circuit with combined loads. Therefore, instead, TDD is more appropriated when assessing the total distortion caused by a certain number of loads connected to the same circuit (Section 2.3). TDD is calculated similarly to THD, but scales relative to the *rated* 60-Hz component of maximum demand current, as in Eqn. 2.2 defined in IEEE-519. At maximum load, THDI equals TDDI.

$$TDD = \frac{\sqrt{\sum_{k=2}^{\infty} |I_k|^2}}{|I_{D(max)}|} \tag{2.2}$$

IEEE 519 is typically applied at the primary level of distribution transformers, and considers full-rated or the time-averaged full load for the study period. For many buildings, large loads with low harmonics (e.g., directly connected motors) dilute high harmonics from power electronics load and reduce TDD at the distribution transformer.

As the maximum demand current can be hard to estimate, the IEEE 1547 standard recommends Total Rated-Current Distortion (TRD) instead. This metric scales the distortion relative to the *rated* 60-Hz component of the rated current, as shown in Eqn. 2.3.

$$TRD = \frac{\sqrt{\sum_{k=2}^{\infty} |I_k|^2}}{|I_{1(rated)}|} \tag{2.3}$$

However, in this study, the TRD is evaluated for a circuit inside a commercial building. In this application, the numerator of Eqn. 2.3 is defined as the sum of the harmonic components for all devices connected to the circuit, while the rated load in Eqn. 2.3 is the sum of the rated load. For laptops, we considered the rated load to be the current at the converter's rated power (fundamental component), and for monitors the maximum current specified in their name plate.

TRD was calculated at the power levels measured during converter testing. Tested MELs included a subset of laptops and monitors utilized for the load and the simulation, and additional devices available at the laboratory were characterized individually.

Finally, high-order harmonics exhibit more variation in phase angle than lower-order harmonics [49], both with respect to load level and between different power converters. When multiple non-linear loads are connected to the same circuit, phase angle variation increases harmonic cancellation. DF [4,9,61] provides a measure of harmonic cancellation:

$$DF_k = \left| \frac{\sum_{i=1}^{N} I_k^i}{\sum_{i=1}^{N} \left| I_k^i \right|} \right| \tag{2.4}$$

$$I_k^i = \left| I_k^i \right| \angle \theta_k^i \tag{2.5}$$

where k is the current-harmonic order injected by the i^{th} load of N loads. DF_k ranges between 0 and 1; smaller numbers indicate higher harmonic cancellation.

2.2.1 Converter Characterization

This study focuses on appliances typical of those found in an office environment; the environment simulated here is a building distribution circuit (120-V single phase in the United States) supporting a variety of office equipment. Heating, ventilation, and air conditioning (HVAC) and general lighting on separate circuits are not considered. This type of load is commonly classified as a *miscellaneous electric load*, or MEL. Five types of appliances were tested: laptops, monitors, working stations, printers, and network appliances. Table 2.1 shows model identifiers and converters monitored for this study.

Table 2.1: Appliances Monitored

Smart Plug	Appliance	Converter Specification
1	HP Laptop	854056-002, 90W
2	DELL Laptop Inspiron	LA45NM140, 45W
3	HP Laptop	TPN-CA04, 45W
4	Microsoft Laptop	1620, 48W
5	Microsoft Laptop	1749, 90W
6	Microsoft Laptop	1749, 90W
7	HP Laptop	GB4943 1-2011, 65W
8	Microsoft Laptop	1749, 90W
9	ViewSonic Screen	VX2703MH-LED, 36W
10	HP Screen E232	Internal, 35W
11	HP Screen E232	Internal, 35W
12	HP Screen E232	Internal, 35W
13	HP Screen E242	Internal, 38W
14	ACER Screen CB241HYK	Internal, 60W
15	DELL Screen P2415Qp	Internal, 90W
16	HP Screen E232	Internal, 35W
17	HP Screen E273	Internal, 42W
18	HP Screen E273	Internal, 42W
19	Apple Thunderbolt Display	Internal, 250W
20	DELL Screen E2010Ht	Internal, 26W
21	Phillips 4k Screen 288P6L	Internal, 60W
22	HP Z240 Tower Workstation	Internal, 400W
23	HP Z240 Tower Workstation	Internal, 400W
24	HP Printer LaserJet 1022	Internal, 300W
25	HP Printer OfficeJet Pro 9018	Internal, 30W
26	Netgear RND-6C / RN31600	Internal, 200W
27	Netgear WNR2000 v3	LSE0107A1236, 36W

All appliances analyzed in this study had AC/DC converters.

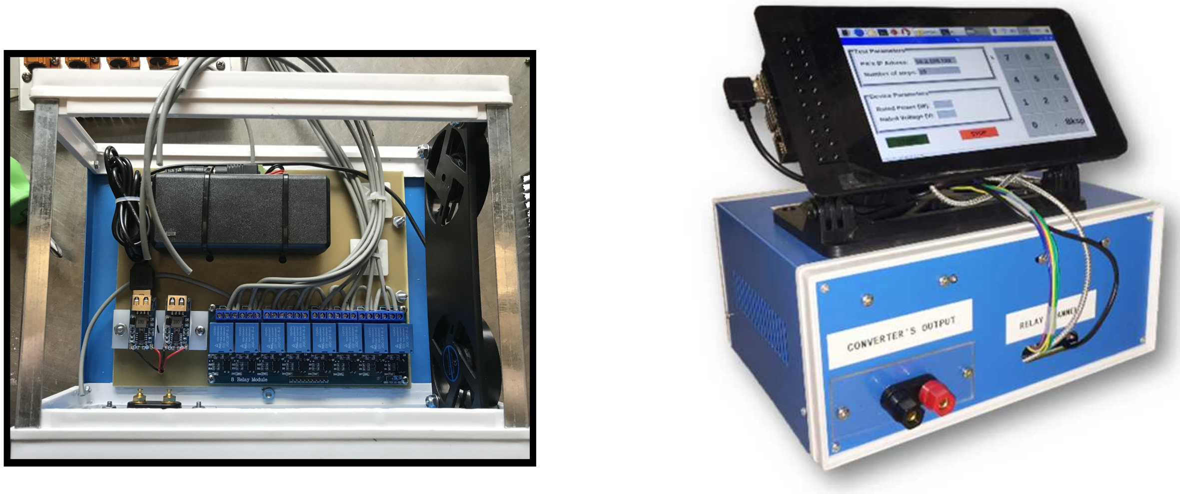
Some of the MELs utilize *external AC/DC converters*, known colloquially as “power bricks”; these MELs include laptop computers, phones, and USB-powered devices. These converters have easily accessible input power connectors (wall plug) and DC output ports that can be readily accessed to load the converter across its full range while collecting input voltage, current, and power data. In contrast, *internal converters* are included inside of appliances, often soldered into complex electronic boards, and are not readily accessible for measurement [86]. Internal converters are common in desktop computers (e.g., work stations) and computer monitors.

For external converters, this study utilizes resistive load banks to vary the load applied to the converter under test. In general, load was applied between no load (0 W) and the rated power of the converter under test in 10 load steps at approximately equal intervals. The load banks used a pattern of parallel resistors that can be individually toggled to produce a conductance between 0 and 0.99 Siemens with 8 binary digits of resolution. The load banks were rated for 400 W at 20 V. The resistors were controlled automatically via an 8-channel relay board to allow for repeated automated testing (see Figure 2.1).

Test data, including waveforms, harmonics, and the TRD for different devices can be found in the supplementary material. There, the reader will find references to more than sixty miscellaneous electric loads characterized in laboratory, supplementary tables and figures regarding this study.

Internal converters could not be externally loaded with a load bank. Loads on these converters were varied by changing the operating state of the appliance. For example, monitors were measured in sleep mode and one or more display configurations. Desktop computers were loaded by changing the programmatic load on the computer. Because load was indirectly controlled, load steps were fewer and, in general, unevenly spaced.

Power was measured using a Keysight PA2203A power analyzer (PA). The PA has 4 channels, each supporting both current (0–50 A) and voltage (0–1,000 V) measurements. The analyzer was used to capture waveforms, AC and DC signal strength, power, power efficiency, and harmonics. Accuracy is 0.05% for voltage and current measurements and 0.1% for power measurements. For current harmonics, these performance characteristics translate to a resolution of ± 25 mA, and most analyses focus on measurements where



(a) Internal structure of load bank

(b) External view of load bank

Figure 2.1: Load banks used for testing external AC/DC converters. Internal structure (a) shows control relays prior to installing resistor board. Screen (b) houses a Raspberry Pi controller, which runs an automated test program. A touch screen allows the user to specify the size and voltage of the converter. Photos: Arthur Santos

total current is ≥125 mA. In practice, PA channels were allocated to one or more devices to allow testing of multiple devices in parallel. Figure 2.2 shows a typical measurement configuration.

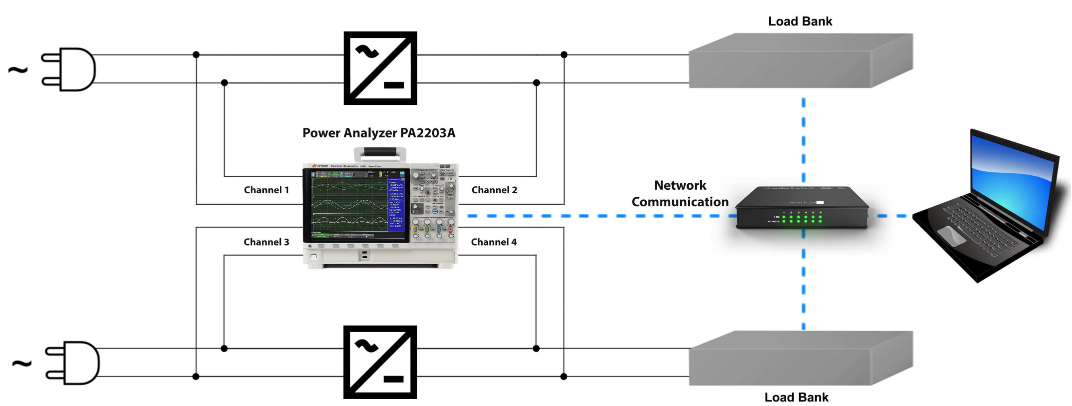


Figure 2.2: Configuration for simultaneously testing two external AC/DC converters using load banks.

All measurements supported analysis to the 128th harmonic (7,680 Hz in the U.S. 60-Hz system), three times the limit (40th harmonic) specified by the norm IEC 61000-3-2. Our team characterized each supply using current and voltage waveforms collected for 1 second, at steady state, at a sample frequency of 15.36 kHz, and used a fast Fourier transform algorithm (Python `numpy` library [87]) to extract magnitude and angle of voltage and current-harmonic components.

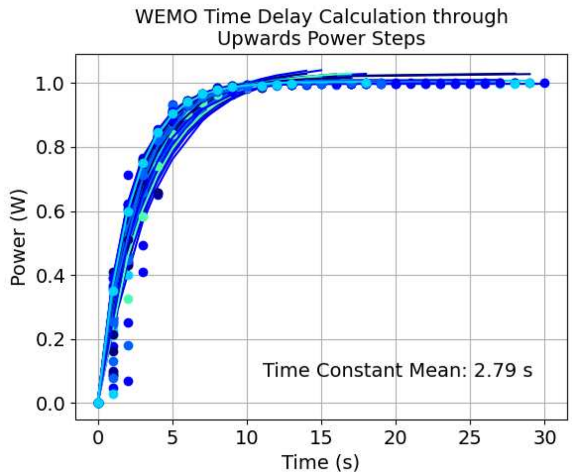
2.2.2 Power Monitoring

To acquire operation loads for appliances, we monitored 27 appliances using smart plugs (WEMO model F7C029V2, rated for 120 VAC and 15 A) for approximately two months. Data was recorded at 1 Hz using custom WiFi recording software.

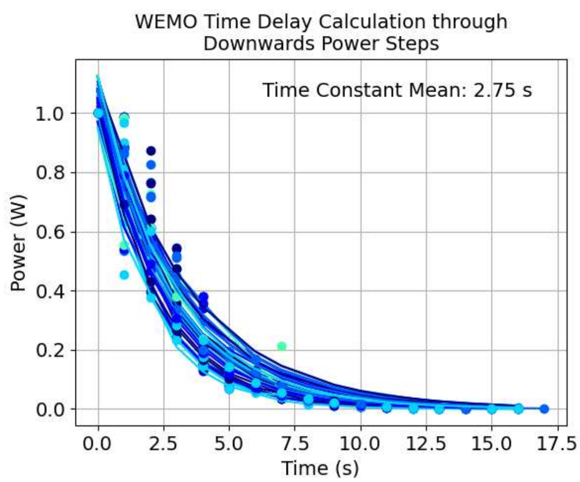
Because the smart plugs are low-cost consumer-grade measurement equipment, and measurements at low power levels are expected to have significantly more uncertainty than measurements at higher power levels, our study evaluated the accuracy of the measurements by loading each smart plug with resistive loads from 0.10 to 4.11 W and comparing the measurements by those made by the PA. The steady-state accuracy of the smart plugs was excellent, with an average error of 0.05 W (1.2%). However, load testing indicated that their measurements exhibited a time-constant-like delay. This measurement delay has little impact on measurement accuracy for steady-state loads, as it impacts only the first few seconds after a change in load. However, many of the converters tested here—particularly laptop converters—changed load level often and quickly. For these devices, the measurement time constant of the smart plug clips peak power levels sufficiently to distort measurements of peak loading and estimates of the time spent at intermediate load levels.

To characterize the observed smart plug time constant (τ), a sample smart plug was step loaded using 8 purely resistive loads from 30–330 W and recorded at 1 Hz. Power decay/rise curves were then normalized and fit to a first-order transfer function ($\frac{1}{\tau * s+1}$)

to characterize the time constant of the unit (Figure 2.3). The estimated value for τ across all data samples is equal to approximately 2.77 s.



(a) Smart plug Upwards Power Steps



(b) Smart Plug Downwards Power Steps

Figure 2.3: Smart Plug Time Constant Calculation (a) Smart Plug Upwards Power Steps; (b) Smart Plug Downwards Power Steps

Each smart plug power recording was then post-processed using MatLab® Simulink® to approximately compensate for time-delay using an approximate inverse transfer function. The impact of the time constant correction varied between MELs. Printers exhibited the least impact. For example, for the HP Printer OfficeJet Pro 9018, recordings for the most frequent operational power was altered by 0.02%, and total power recorded was change by 0.10%. In contrast, power levels for laptops change rapidly, and the impact on their most frequent power was substantially higher. For example, the most frequent power for the DELL Inspiron Laptop (converter model LA45NM140) increased by 7.29%, but total power changed much less (0.22%).

The corrected signal was then binned to 1-W intervals to produce probability distributions for the load for each MEL, considering only periods when the unit was on (i.e., power consumption exceeded 1 W).

2.2.3 Harmonic Cancellation Simulation

The study simulated harmonic cancellation by adding harmonics component-by-component for multiple converters, with each converter's operating characteristic sampled based on the loads recorded during the power monitoring study. Cancellation was simulated by summing the phasor representation of the current for each harmonic and calculating the metrics specified earlier. The simulation utilized Monte Carlo methods. A detailed application of the Monte Carlo methods can be found in the supplementary material, Section A.1. In brief, the algorithm was:

1. Identify a set of MELs for the test case
2. For N Monte Carlo iterations ...
   (a) For each converter, sample a load level from the corresponding probability distribution recorded during the power monitoring work
   (b) Utilize the selected load level based on the nearest characterized load level to identify all current harmonic phasors
   (c) Calculate the metrics described earlier (DF and TRD) using the current harmonics of all active loads
   (d) Accumulate results in the Monte Carlo output.

Monte Carlo simulation investigates harmonic cancellation with differing numbers and types of devices connected in parallel on one circuit. Three scenarios were developed. In each scenario, we analyzed the DF for odd harmonic components 3–13 (3^{rd}, 5^{th}, 7^{th}, 9^{th}, 11^{th}, and 13^{th}) using 1,000 Monte Carlo iterations that randomized power levels. For each iteration, software calculates and records the DF, which is then processed to extract the mean and empirical 95% confidence interval, defined as the 2.5% and 97.5% percentiles of the resulting distribution.

The three scenarios utilized two equipment configurations. Scenarios A and B considered 5–35 laptop converters, in increments of 5, connected to 1 circuit. This scenario reflects an office environment for knowledge workers, each equipped with a computer. Laptops were randomly assigned from the 9 fully characterized laptop converters measured in the study. Therefore, while all devices were laptops, there was some diversity in the *type* of laptop. In Scenario A, harmonic cancellation was computed using the method in Mansoor et al. [4,5], where load was uniformly sampled the *rated* load of the converter when on (10% to 100% loading). Scenario B considers the same hardware, except converter loading is randomly selected from the empirical probability distribution obtained from the long-term monitoring study. Comparing Scenario B with Scenario A illustrates the impact of assuming full-range power versus real power levels. Finally, Scenario C utilizes a more diverse set of loads, and investigates the impact of that increased diversity on harmonic cancellation.

2.3 Results

2.3.1 Converter Operating Power Distribution

Figure 2.4 summarizes the observed power levels for all 27 MELs during the on state (power consumption $\geq$1 W). The y-axis is the percentage of the rated power for each device during regular operation, and the x-axis is the smart plugs that they are connected to.

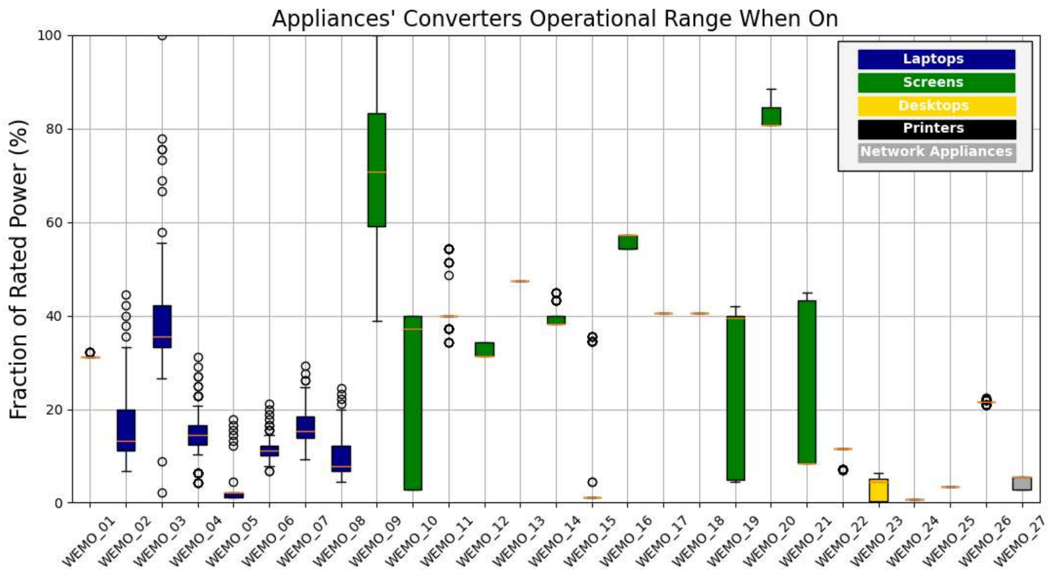


Figure 2.4: Converter operational power consumption. Results summarize approximately two months of 1-Hz power recordings. Frequencies are shown as box-plots with whiskers representing a 95% inner quantile range, and boxes representing the interquartile range (IQR) from the 25th to the 75th percentile. Outliers are shown as circles.

For the laptops in our sample, typical interquartile (IQR) load is between 10% and 42% of each converter's rated power. The maximum observed load power divided by the converter output power rating is defined as the maximum fraction of rated power (MFRP), and for the laptops the highest MFRP was 55.6%. Seven out of eight laptops never used their full rated power; the converters for these seven laptops were oversized by a factor of 3 or more relative to observed load. The converter connected to smart plug 05 has an atypical IQR of only 1.1%–2.2%, because the laptop was often in sleep mode.

The monitors on smart plugs 09 and 20 have the highest MFRP of 100% and 88.5%, respectively, while 60% of the monitors have their MFRP equal or below 42%, indicating that their internal converter's rating are also oversized relative to observed loads. However, it is important to note that the built-in USB hubs in the monitors were not being used to charge USB devices or support peripherals; the additional converter power could be needed if USB devices were in use.

Both desktop computers are rated at 400 W, and as configured their MFRP are 6.3% and 11.5%. These devices are on at least 98.5% of the time, and although they are constantly used to perform simulations, the typical load on their internal converters was an order of magnitude lower than the converters' rating (average factor of 8.7x).

The printers monitored (smart plugs 24 and 25) had similarly low MFRP: one had a typical load of 0.7% of 300-W rated power; the other 3.3% of 30 W. Both printers were on ≈90% of the time, but because they rarely perform printing, the power consumption when printing is always classified as an outlier on the plot. The maximum power for smart plug 25 was 23 W for 0.01% of the time. For smart plug 24, it was 5 W for 1.1×10^{-6}% of the time.

Smart plugs 26 and 27 were connected to a Netgear ReadyNAS RN31600 (network backup drive) and to the router providing network services for the 27 smart plugs. Both were on 100% of the time. The router is connected to an external AC/DC adapter, which was not the original equipment provided by the manufacturer. This type of substitution is not uncommon in commercial offices, where after-market converters may be quickly swapped in for failed power supplies if voltages and plugs match and the available power exceeds that required by the device. The converter was rated for 36 W, substantially above the router's actual power consumption of 3.1 W. The router's typical load range and MFRP were low: 2.8%–5.6% and 5.6%, respectively. The NAS had a MFRP of 21.6%, with the same value for its typical load, indicating the converter could handle approximately 5 times the maximum load recorded.

89% of the tested appliances never operated above 60% of their rated capacity, and three quarters (78%) had IQRs below 42%. Although converters are sized for a theoretical maximum power requirement, most devices did not operate near the rated power of their converter during typical operation. Some portion of this under-utilization is the "as found" configuration of the appliances, which were sampled in a realistic office environment. For example, converters for desktop and monitors will be sized for using all available resources (such as USB ports, card slots, and sound systems), but resources are only partially used in typical applications. Additionally, converters may be oversized by manufacturers who utilize one converter for multiple product offerings, because the converter will be sized for the product with the highest peak load.

These data indicate that harmonic cancellation studies using the assumption that loads operate across their full rated power range do not accurately represent typical usage of MELs in a common office environment. Subsequent sections quantify the impact of this reduced operating range.

2.3.2 Calculated TRD for appliances

IEEE Std 519 recommends that the maximum load current (the denominator in Eqn. 2.2) is the average current of the maximum demand for 12 months at the point of common coupling. However, the analysis in this study focuses on a single circuit, and an analog for the maximum demand current is required. We therefore define the maximum load current as the current rating of the device at maximum power, as suggested by the IEEE 1547 standard; note that this power level did not occur in long-term recordings of the converters powering appliances in an office environment. Figure 2.5 shows the TRD over percentage of rated power for laptop chargers. The plot shows similar behavior for all devices analyzed: a nearly linear increase of TRD as the converters power level increases.

2.3.3 Impact Analysis

Scenario A

In Scenario A, we randomly selected harmonic data from the 9 laptop converters and varied the power level for each laptop in an uniform distribution from 10%–100%. Results are shown in Fig. 2.6.

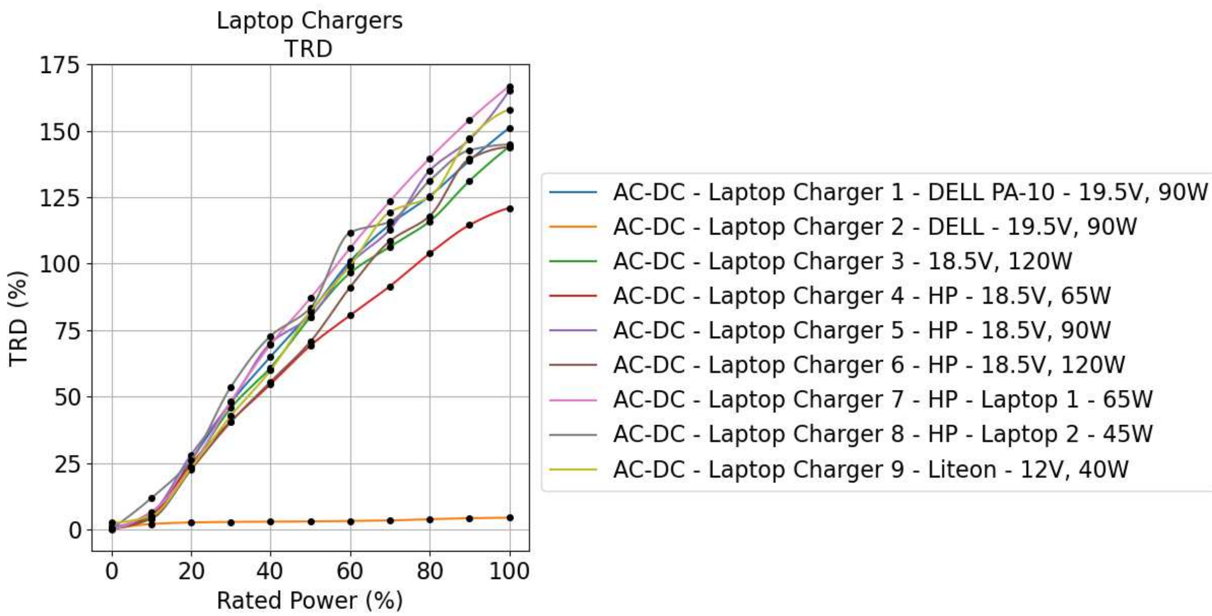


Figure 2.5: TRD vs. percentage of rated power for nine laptop chargers characterized in laboratory. An almost linear increase of TRD is noticed as power increases. The slope of the curve for laptop charger 2 is significantly lower because the device has PFC.

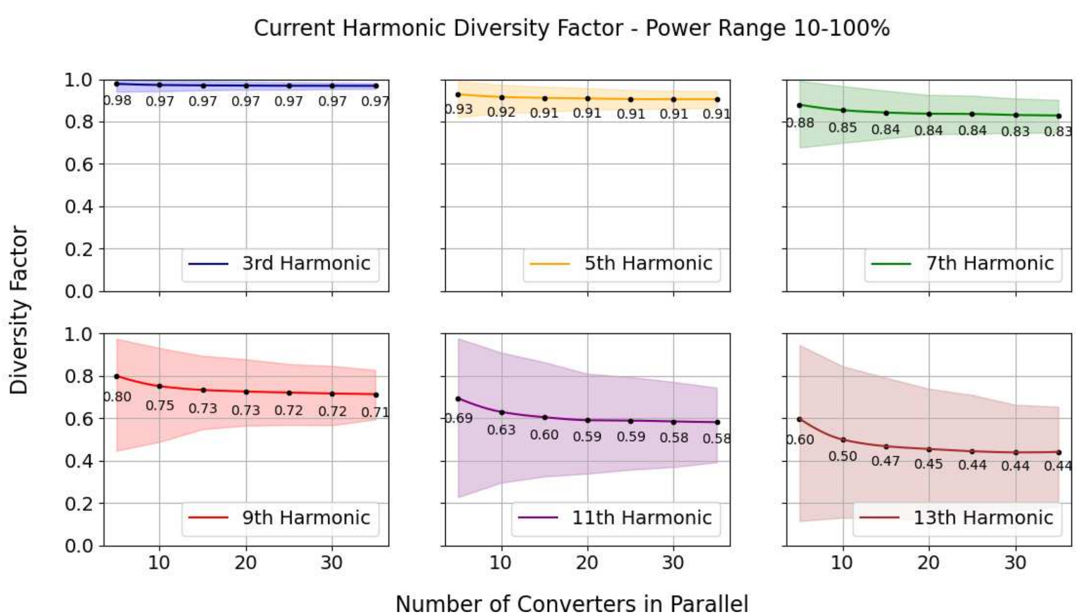


Figure 2.6: Scenario A: DF for 5–35 laptop converters operating at a load range of 10%–100%. Shaded area represents the 95% confidence interval from 1,000 Monte Carlo iterations; the dark line is the mean of all iterations.

The results show that the most substantial harmonic cancellation occurred in the higher harmonics, as expected, because current phase angle varies more with load at higher harmonics. Additionally, as the harmonic order increases, the confidence interval width increases substantially, indicating that harmonic cancellation varies widely with the randomly selected load levels of the converters. In the case of the 13th harmonic (and likely higher harmonics), Monte Carlo iterations inside the 95% confidence interval range from nearly zero cancellation (DF $\approx$1) to almost 90% cancellation (DF $\approx$0.1). These data indicate that, at any given time, cancellation could range from near-zero to near-complete at higher harmonics. Therefore, for planning purposes, a design engineer might assume the worst case—i.e., minimal cancellation—or could take the mean case, with substantial cancellation above the 5th harmonic (e.g., 65% cancellation, DF=0.45, for 13th harmonic).

Additionally, while cancellation increases (decreasing DF) with increased unit count, DF plateaus for all harmonics above 20 devices. These data indicate that maximum cancellation is seen on any circuit with 15 or more units on the circuit. Given practical electrical layouts for commercial office space, coupled with National Electrical Code (NEC) restrictions on the number of outlets per circuit (NEC allocates of 1.5 A per outlet (180 VA for a 120-V circuit), limiting the number of outlets to $\leq$10 for a 15-A circuit), this number of devices may seldom be achieved on typical commercial building circuits. Therefore, estimates with unit counts $\leq$10 units may be more applicable to most in-building circuits.

Scenario B

This scenario utilizes the same hardware setup (5–35 laptops) as Scenario A, but the converters are loaded as observed in long-term monitoring. As noted earlier (see Fig. 2.4), the majority of laptop converters operate at 0%–40% of rated power. This scenario reflects a more realistic loading case, where power level is randomly selected from the distribution of loads for the laptops connected to smart plugs 1–8. Results are shown in Figure 2.7 for Scenario B, and Figure 2.8 compares Scenarios B and A.

DF is normalized to the interval [0,1] such that the DFs represent lower the harmonic cancellation. Since DF is an inverse representation of harmonic cancellation, the harmonic ratio between two scenarios, A & B, in Figure 2.8 is calculated as $\frac{(1-DF_B)}{(1-DF_A)} * 100\%$.

Switching to observed power measurements reduces the harmonic cancellation substantially, and also reduces the uncertainty in the cancellation (smaller background shading in the figure). As in Scenario A, harmonic cancellation is higher for high-order harmonics relative to lower-order harmonics, but the difference is substantially reduced. For this scenario, the common "full-range" loading assumption overestimates harmonic cancellation overall, and overestimates more severely for higher-order harmonics.

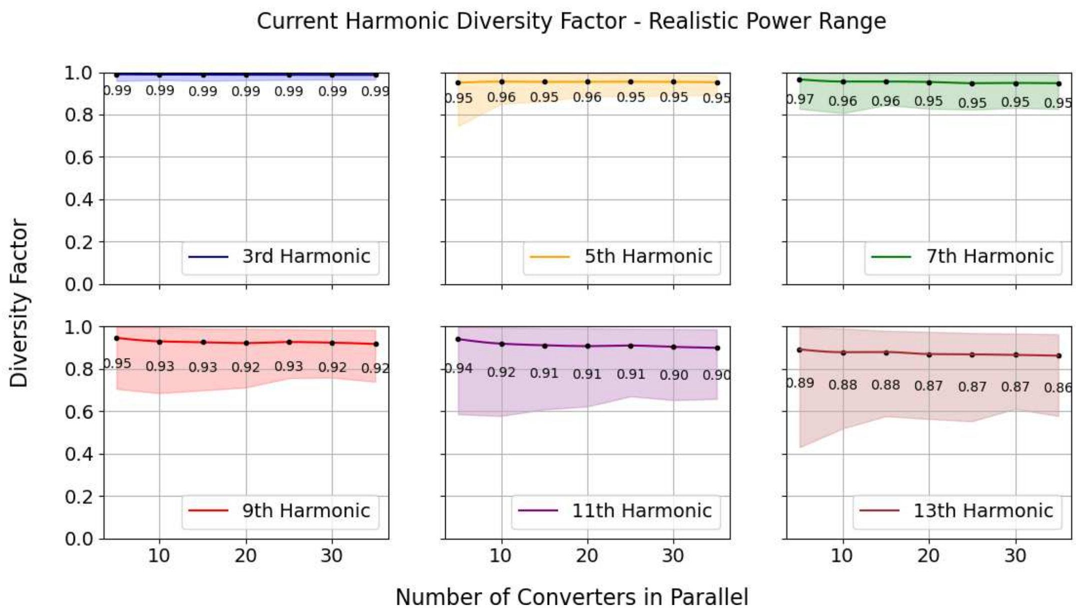


Figure 2.7: Scenario B: DF for 5–35 laptops operating at load levels seen in long-term monitoring, where loads range mainly from 10%–40%. Shaded area represents the 95% confidence interval from 1,000 Monte Carlo iterations; the dark line is the mean of all iterations.

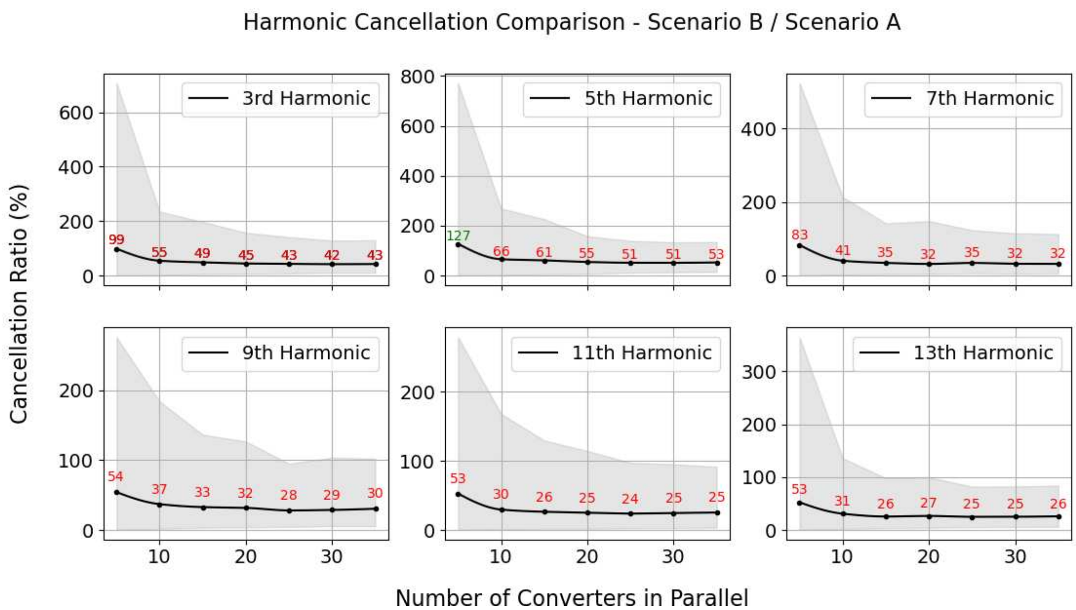


Figure 2.8: Comparison of harmonic cancellation between Scenario B and Scenario A. Comparison was performed by dividing random iterations from Fig. 2.7 to those in Fig. 2.6. Background represents the 95% confidence interval on the subtracted iterations; values coded green for positive change (more cancellation) and red for negative change (less cancellation). The dark line is the mean of all iterations.

Scenario C

In this last scenario, we considered heterogeneous devices operating at realistic load levels, in combinations representative of an office environment. The intent of the simulation is not to investigate all possible combinations of devices, but to understand if diversity in load types has a substantial impact on harmonic cancellation. The simulation considered 4, 10, 14, 20, 24, 30, and 34 devices connected in parallel—half laptops and half monitors. For laptop converters, we randomly selected harmonics data from the 9 converters tested in the lab; the power level distribution is the same used in Scenario B (A.2). For monitors, harmonic data was randomly selected from three different monitors models tested in the lab (HP Model 273, HP EliteDisplay E232, HP EliteDisplay E242), using the three power levels observed when the monitors were on: black screen, white screen, and playing a video. Power levels for each monitor was selected from a uniform distribution comprising these three operation modes.

Figure 2.9 shows the mean and the 95% confidence interval of the current DF.

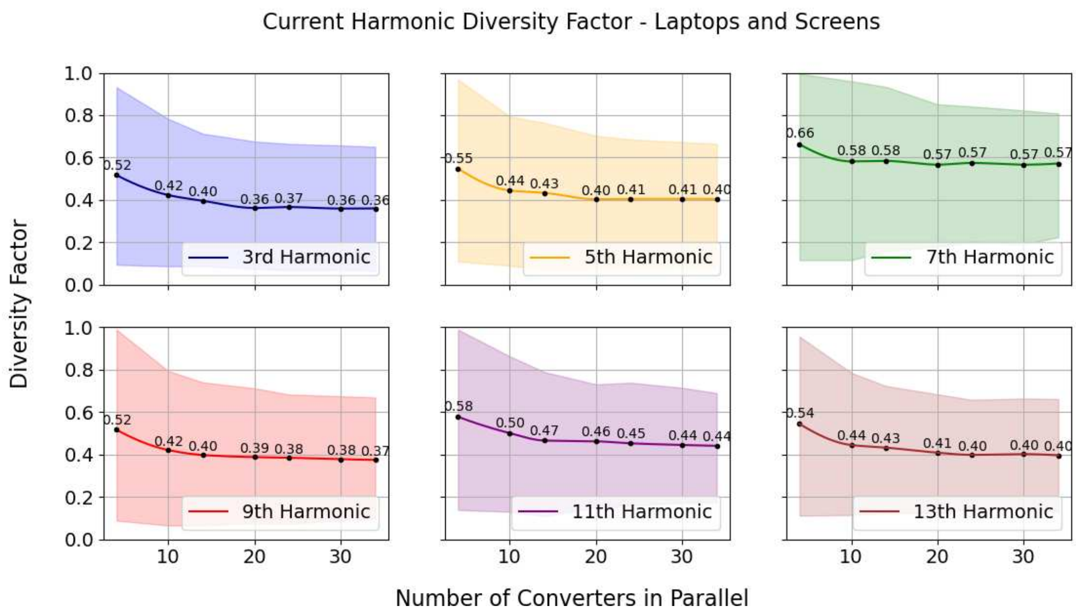


Figure 2.9: Scenario C: Current Harmonic DF—Laptops and Monitors

In Scenarios A and B, the confidence interval was wider for high harmonics. In Scenario C, the confidence interval is also wider for the low harmonics, due to the greater variety of current waveforms, which when added together in the various possible scenarios, present highly variable results. This dispersion, as observed in the other scenarios, tends to decrease with the number of loads connected to the circuit.

For Scenario C, the cancellation was considerably higher when compared to Scenarios A and B, and the DF of the lower order harmonics, such as the 3rd, 5th, and 7th, had a significant drop in comparison to the two previous scenarios. Considering the mean DF for all devices in parallel, 48%–64% of the 3rd harmonic was canceled, compared to 1% in Scenarios A. For the 5th order component, harmonic cancellation was between 45% and 60% in Scenario C, and 4% and 5% in Scenario A.

As noted earlier, data for approximately 10 devices or fewer is typically the most applicable to commercial office space, due to the previously mentioned limitations on outlets per circuit in those environments. These data indicate that in an office environment with diverse load types, supporting more units on one circuit would lead to substantially better harmonic cancellation, and would likely not overload circuit ratings.

Finally, TRD for each scenario is shown in Figure 2.10. As is typical for TRD, in all scenarios the mean and standard deviation of the TRD decreases (i.e., more harmonics cancellation) as the number of loads increases. Scenario A presents the highest TRD because more laptops are operating near their full rated power. As the converters' power ranges start to narrow down (Scenario B), the TRD improves, and as we add more diversity to the circuit, it improves more (Scenario C).

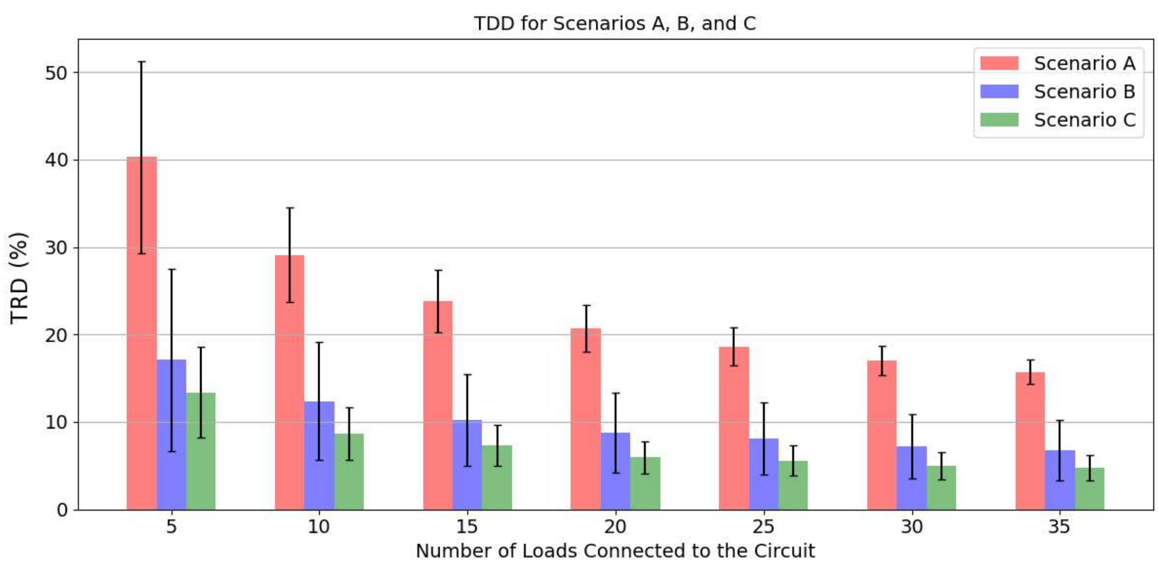


Figure 2.10: TRD for Scenarios A, B, and C calculated for 1,000 Monte Carlo iterations

These data indicate that the common full-load assumption overestimates harmonic cancellation (Scenario A), but also overestimates TRD (Fig. 2.10). In both cases, the estimates may provide incorrect guidance to design engineers.

Building Simulation

Scenarios A-C considered electronic devices typical of office MELs: laptops and monitors. However, commercial buildings include additional load types intermixed with office MELs – although these loads may not share secondary circuits with MELs. Commercial Buildings Energy Consumption Survey (CBECS, U.S. Energy Information Administration [88]) indicates 17% of the commercial building load is lighting, 34% MELs, and 49% HVAC. The two scenarios considered in this section (Scenarios D and E) simulate circuits including combinations of these loads.

For this analysis, we assume lighting has been converted to LEDs, operating at full power, which are connected to secondary circuits shared with MELs – a reasonable assumption for buildings with mixed lighting and MELs circuits on the same distribution transformer. However, it is important to note that, for newer buildings and more recent conversions, lighting systems often use centralized power converters connected directly to building primaries rather than the secondaries shared with MELs. These cases more closely resemble the prior analysis in Scenarios A-C.

Scenario D considers a realistic power levels from laptop power profiles collected by the smart plugs. For the other MELs, following our data that indicates converters primarily operate from 0-40% of their rated power, loads are randomly assigned in the 0-40% load interval. To compare, Scenario E considers all MELs' converters operating, uniformly distributed, over their full rated power. Each Scenario was analyzed through a Monte Carlo simulation, 1000 iterations, focusing on odd harmonics between 3^{rd} and 13^{th}. The quantity and model numbers of the MELs and LED drivers used in this experiment are described in Section A.2 of the supplementary material.

The characterization data was randomly selected for each MEL. Figure A.6 in supplementary material show the waveforms for a few devices considered in this simulation and Figure 2.11 below shows the results.

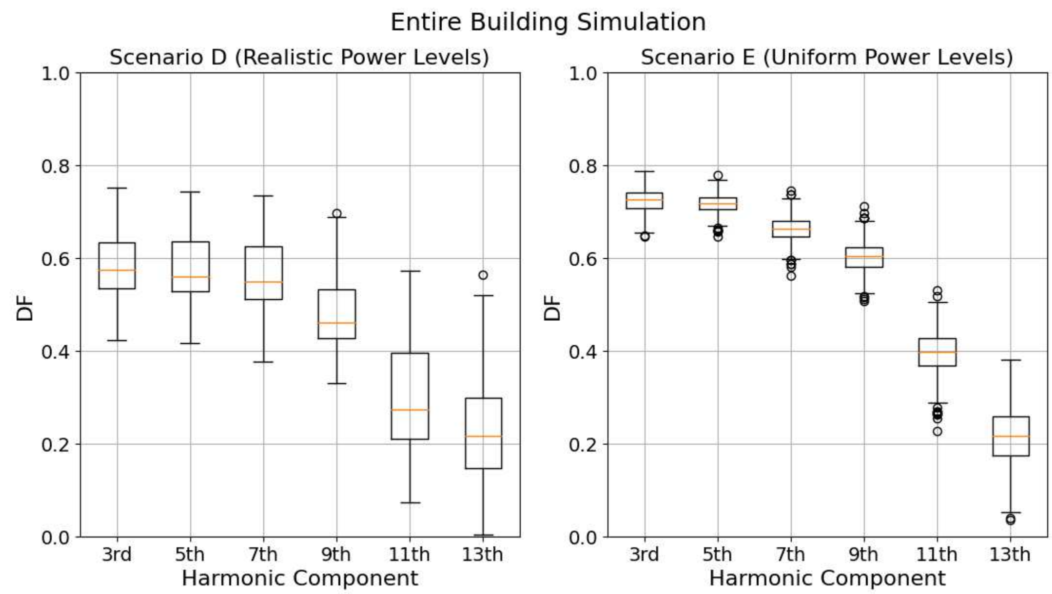


Figure 2.11: The diversity factor (DF) for each harmonic component is represented by a boxplot with 95% confidence interval whiskers, with the boxes representing the interquartile range between the 25th and 75th percentile. Data outside the confidence interval are represented by the circles.

Fig. 2.11 summarizes the results, harmonics and Figure 2.12-(a) shows the variation in DF for the third harmonic component with the LEDs as a percentage of the total load in the building. For all harmonic components, harmonic cancellation was higher with realistic power levels. The results are reversed from prior scenarios, as one would expect that in Scenario E (full load range) the harmonic cancellation would be higher due to more variability in harmonics from MELs converters. However, the TRD for Scenarios D and E for a 95% confidence interval is $2.45\,\% \pm 1.04\,\%$ and $4.10\,\% \pm 0.54\,\%$ respectively. TRD is lower in Scenario D because we have converters often operating in the lower range of their rated power. This reinforces the problem of harmonic overestimation when assuming a uniform power distribution for MELs' converters.

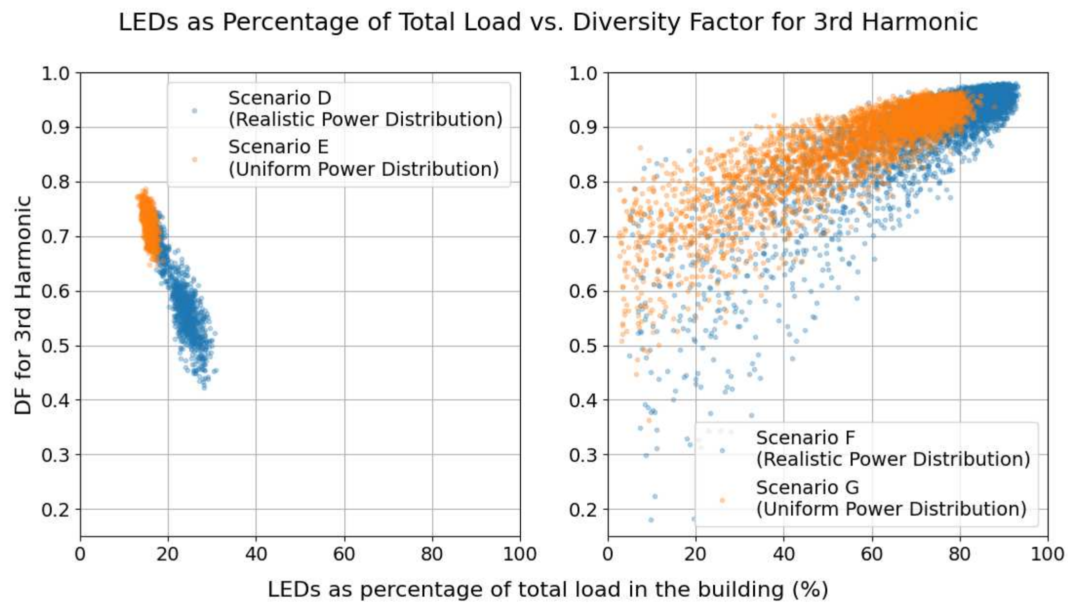


Figure 2.12: (a) On the left, for a constant number of LEDs in the building, the plot shows the variation of the diversity factor (DF) for the third harmonic with the LEDs as a percentage of the total building load for Scenarios D and E; (b) On the right, for a varying number of LEDs in the building, the plot shows the variation of DF for the third harmonic with the LEDs as a percentage of the total building load for Scenarios F and G. There's a narrower variability for DF in Scenario G as it has more MELs converters operating close or at full load, which decreases the harmonic cancellation since LED drivers are also operating at full load.

Since the LED drivers are all the same - a likely case in a lighting upgrade – their harmonic injection is identical across all units; i.e. it adds together. Therefore, intuition would suggest the DF should increase (i.e. harmonic cancellation should decrease) as a set of identical loads (i.e. the LEDs) represent a higher portion of the total load in the building. Simulations, however, indicate the opposite. To illuminate this discrepancy, we performed two additional Monte Carlo Simulations (Senarios F and G), focusing on change in third harmonic cancellation over a wider range of LEDs as a percentage of total load in the building. Both simulations ran 4000 iterations with 3 MELs of each group (e.g. laptops, phone chargers, etc.), and the number of LEDs was randomly generated between 1 and 100. Scenario F considered realistic power profiles for the MELs converters, and

Scenario G a uniform distribution between 10-100% of rated power. For both simulations, the LED drivers operate only at full power. Results in figure 2.12-(b).

As the LEDs become a larger fraction of the load, harmonic cancellation decreases (i.e. higher DF). However, heteroscedasticity is noted for both Scenarios F and G: the DF variability is higher when the LEDs represent a small fraction of the total load in the building. As expected, when LEDs is the predominant load in the building and their drivers are both identical and operating at rated power, there is less cancellation. When the MELs are the predominant loads in the building though, DF varies more because in the simulation their converters have varying load profiles.

Current lighting design practice utilizes larger, centralized, converters which tend to be connected to the primaries of building distribution circuits (480/277V in the USA), particularly for larger commercial buildings. This moves lighting loads, which are typically designed to operate at higher, nearly constant levels, from transformers secondaries mixed with MELs to primary connections unmixed with MELs. As a result, harmonic cancellation on the MELs heavy circuits will be less than predicted by traditional methods, as shown in Scenarios A-C. This problem is mitigated in many scenarios by combining LEDs with MELs circuits.

2.4 Conclusions

Experimental data collected for this study clearly indicates that the actual loads on common office power converters, even when restricted to on periods, differs substantially from common loading assumptions utilized to estimate harmonics in the distribution system. Simulations using observed loads produce substantially different cancellation results that are highly dependent on the mix of office equipment on an individual circuit. However, the levels of TRD are substantially lower, when realistic load profiles are considered. Harmonic levels are further increased by limitations on the number of receptacles on each circuit, leading to TRD levels in excess of 10% for common circuit configurations.

Because much of the electrical infrastructure in commercial buildings is substantially oversized (typical loads on building distribution transformers is often below 20%), harmonics may not create substantial issues within that distribution equipment. However, with efforts to improve the efficiency of in-building electrical distribution, data and simulations presented here indicate that actual harmonic levels must be considered for new and more efficient distribution designs.

Chapter 3

Endpoint Use Efficiency Comparison for AC and DC Power Distribution in Commercial Buildings

This chapter was published in the special issue *Modeling and Simulation of Power Systems and Power Electronics* from the *Energies* journal [10].

3.1 Introduction

Since the "war of the currents" in the 19$^{\text{th}}$ century, alternating current (AC) has been the predominant method for electrical power transmission and distribution due to the ease of voltage conversion using transformers and the practical advantages of three-phase systems in electrical machines [25]. However, advances in power electronics have increased direct current (DC) voltage conversion efficiency and lowered its cost, increasing interest in DC distribution at all scales. In addition, because low-voltage DC power distribution ($\leq$60 V_{DC} in the United States (U.S.)) does not require all cable runs to be in conduit, it can potentially be implemented at a lower cost than AC distribution in commercial buildings.

Commercial buildings consume 35% of all electricity in the U.S. [89]. Commercial building loads include a large number of electronic devices that are classified as "miscellaneous electric loads" (MELs), i.e., loads that are not related to the building's core functions—lighting or heating, ventilation, and air conditioning (HVAC). MELs are also known as plug and process loads (PPLs). In 2017, MELs represented 40% of the electrical load in commercial buildings in the U.S.; this is projected to increase to 49% by 2040 [23].

As the majority of MELs in commercial buildings are electronic, they operate internally on DC. When connected to an AC distribution system (DS), they require an AC/DC converter to provide power at the correct DC voltages. While a DC DS could theoretically avoid a converter between the DC DS and the MEL, in most cases the DC DS operates at a different voltage than the MEL. Therefore, most MELs still require a DC/DC converter when connected to a DC DS. We term this last voltage/power conversion stage, which exists in both systems, as the 'endpoint conversion'. The focus of this study is to characterize the efficiency of commercially available DC/DC endpoint power converters relative to existing, standard, AC/DC converters supplied with most MELs.

Other elements of a building's power system also impact the efficiency of the entire building, including the performance of lighting, HVAC, on-site generation and/or storage when coupled to each type of distribution system; variations in distribution system voltage for nascent DC systems; and losses related to power quality issues in either system [29, 32, 33, 44, 90]. These other loads and systems were not included in this study but could be similarly analyzed.

Although DC loads are not often designed to leverage the unique advantages of DC DS [86], one argument in favor of a DC DS over an equivalent AC DS is that the DC/DC conversion efficiency is typically thought to be higher than AC/DC conversion efficiency [91–93]. AC/DC converters require a rectifier followed by a capacitor to reduce the ripple on the internal DC bus. This bus voltage is then level-shifted using an additional stage of DC/DC conversion for the desired output voltage. In some cases, rectification and DC/DC conversion are combined in a single module. Rectification introduces additional losses relative to DC/DC converters, which do not require rectification, and this is one reason DC/DC converters are often considered to be fundamentally more efficient.

Few DC distributions systems have been built at scale. Therefore studies using varying inputs provide the only comparisons between the two distribution strategies. Some simulation studies indicate that a DC DS can be significantly more efficient than a traditional AC DS [43, 94–96]. For example, in simulations considering U.S. offices [27], DC DS achieved a 9.9–18.5% in efficiency savings for zero net energy buildings serving small and medium-size offices provided the building had ample battery storage.

This simulation, however, assumed that MELs would be designed to connect directly to the DC bus, not requiring endpoint converters; currently few MELs of this type exist. Another simulation ([29]) reported that a residential DC DS, without on-site generation or storage, presented a 1.5–4.7% in efficiency improvement in comparison with a conventional AC DS. The simulation used load-packaged DC/DC converters to replace the AC/DC counterparts but did not report the efficiency for them.

Prior studies have been hampered by a lack of detailed data on the efficiency of converters and statistical data on the power levels of converter loads. For example, a study in Sweden analyzed a low voltage DC DS for offices and commercial facilities using operating voltage levels of 48, 120, 230, and 326 V_{DC} by assuming that all converters operated at the rated power of the appliances [96]. The authors in [43] assumed that AC power converters had an efficiency rating of 90%, while DC converters had 95%, 97%, and 99.5%, based on a survey that considered a constant value for the efficiency of the converters when operating at different power levels. Nevertheless, the authors stated that DC/DC converters seldom achieved 95% efficiency in practice, and therefore concluded that the most relevant factor for improving DC DS efficiency relative to AC DS efficiency is to improve the efficiency of DC/DC converters through technology advancements.

Other studies suggest that DC DS might not exhibit better efficiency than AC DS. An investigation of a small residential DC DS found that when DC converters operate at part load their efficiency is significantly worse than when operating at full load [97]. The lower efficiency at partial load is mainly due to economic factors, including the use of low-quality electronic components [98] and a tendency to prioritize factors other than efficiency, such as size and cost, when manufacturing or procuring power supplies.

Some organizations and programs promote higher efficiency, such as Energy Star [99, 100], Climate Savers [101, 102], DOE level VI efficiency standards for wall adapters [103, 104], and 80 PLUS [105, 106]. The latter, for instance, certifies power supplies that achieve at least 80% efficiency in energy conversion at 20%, 50%, and 100% of rated load [107] and also offers higher tiers of certification (bronze, silver, gold, etc.) for higher efficiency levels. Additionally, although studies such as [108] state that efficiencies are better for high voltage DC (500 V), DC efficiencies at this voltage are similar to those of similar AC voltages, which are typically not used for comparisons in the literature.

For equivalent voltages, wiring conduction losses in building distribution systems have been found to be lower in a DC DS compared to an AC DS [13]. Low voltage DC systems require larger currents for the same power transfer. As copper losses are proportional to the square of the current, this can cause unacceptable losses if the DC voltage selected is too low for the load being served [96]. However, the same is true regarding voltage selection for AC loads. The majority of loads inside buildings do not require high voltage [43] and conduction losses are not generally the primary motivation for selecting a voltage level. Prior research has established that in well-designed systems, conduction losses are mostly negligible when compared to power converter losses [27, 97, 109]; we therefore do not consider wiring losses in the present analysis.

Other research focused on power flow modeling of AC, DC and hybrid distribution systems [110, 111]. To further understand AC and DC distribution choices, this study focused specifically on the efficiency of commercially available AC/DC and DC/DC end-use converters for common MELs, considering common DC DS voltages: 24 and 48 V_{DC}. The majority of the existing literature in this area used loss estimations based upon data sheet information and constant values for converter efficiency [24, 112].

In contrast, this study performs all analyses using (a) time-series load data collected directly from deployed electronic devices commonly found in an office environment [3] and (b) the characterized efficiency for the full load range of each converter. The time series allows the measured converter efficiency to be weighted by actual load, producing more realistic estimations of converter efficiency. This is the key contribution of the present analysis. Section 3.2 explains the methods used in this study; Section 3.3, the results achieved; and Section 3.4 summarizes the lessons learned.

3.2 Methods

This study focused on the efficiency of endpoint power conversion, that is, the last voltage level conversion prior to power delivery to a MEL's internal DC circuitry (see discussion in Section 3.2.5). The methods required for this study are:

1. Characterize the efficiency of endpoint converters across their full load range.

2. Characterize realistic loads observed in office MELs by acquiring time-series load data.

3. Weight the converter efficiency by the observed load levels to create a weighted energy efficiency comparable between AC/DC and DC/DC test converters.

This approach is analogous to the weighted efficiency technique developed for comparing the performance of photovoltaic inverters adopted by the California Energy Commission [113,114]. Additionally, the study characterized a single available central AC/DC converter to understand how its efficiency compared with that of in-building, step-down transformers.

The central challenge in comparing endpoint efficiency is that most MELs are not available in versions that support both AC and DC power systems. Most are available only in an AC version that includes either an internal or external AC/DC converter. DC versions are uncommon, and when available, are often tailored for automotive applications (12 V_{DC}), rather than the distribution voltages commonly utilized in commercial buildings [96]. To address this issue, converter testing for this study was conducted by using matched pairs of converters.

Each pair included a commercially available AC/DC and a DC/DC converter (hereafter test converters) with similar power ratings and the same voltage outputs. The power ratings and voltages were selected to reflect those seen in MELs utilized elsewhere in the study, primarily office equipment, such as laptops, monitors, and network equipment. Table 3.1 summarizes the identification and ratings of all units.

Table 3.1: AC/DC and DC/DC test converters

Converter ID	Brand	Model	Input Voltage	Output Voltage (V_{DC})	Rated Power (W)
Converter 1	Mean Well	IRM-30-24ST	100-240V_{AC}	24	30
Converter 2	Mean Well	RSD-30G-24	9-36V_{DC}	24	30
Converter 3	DELL	DA90PE1-00	100-240V_{AC}	19.5	90
Converter 4	BixPower	BX-DD90X-24V	24V_{DC}	19.5	90
Converter 5	Emaks	A1749	100-240V_{AC}	15	90
Converter 6	BixPower	BX-DD90X-24V	24V_{DC}	15	90
Converter 7	Integrated Power Designs	REL-70-4006 -CHCO	85-264V_{AC}	5/24/12	70
Converter 8	Integrated Power Designs	DC2-70-4006 -CHCO	18-36V_{DC}	5/24/12	70
Converter 9	Integrated Power Designs	DC4-70-4006 -CHCO	36-72V_{DC}	5/24/12	70
Converter 10	Integrated Power Designs	GRN-110-4003 -CHCO	85-264V_{AC}	5/24/12	110
Converter 11	Integrated Power Designs	DC2-110-4006 -CHCO	18-36V_{DC}	5/24/12	110
Converter 12	Integrated Power Designs	DC4-110-4006 -CHCO	36-72V_{DC}	5/24/12	110
Converter 13	Integrated Power Designs	REL-185-4001 -CHCO	85-264V_{AC}	3.3/5/12	185
Converter 14	Integrated Power Designs	DC2-185-4001 -CHCO	18-36V_{DC}	3.3/5/12	185

Each power converter was characterized in laboratory conditions using controlled loads (not the MEL itself), to construct efficiency curves across the full rated power range of the converter, primarily because, as noted in detail below, most MELs do not operate at the full rated load of their power supplies. Long duration appliance load recordings were then used to weigh the efficiency curves by a realistic mix of load levels to calculate the weighted energy efficiency for both AC/DC and DC/DC appliance configurations. The resulting weighted endpoint conversion efficiency can be compared within each pair of converters.

Selecting pairs of converters simulates the likely design process that would be used to convert a MEL from the common AC-input version to a DC-input version for use with a DC DS—i.e., the design engineer would select a DC/DC power converter that (a) accepts the correct input voltage provided by the DC DS, (b) produces the same outputs as the AC/DC converter, and (c) serves the same anticipated load as the AC/DC converter. It is important to note that the paired selections made by the study team do not optimize either the AC/DC or the DC/DC converter efficiency.

Instead, the AC/DC converter is 'given'—i.e., was the exact converter, or a close duplicate of the converter, from a MEL included in the study—while the DC/DC converter was selected from common power supply vendors to have the same rated power and the same output voltages. In actual practice, a design engineer may select a DC/DC converter with higher or lower efficiency than the converter selected for this study. Therefore, for some power ratings, we test more than one matched pair to illustrate how performance may vary when selecting different DC/DC converters to replace an existing AC/DC converter.

The DC market is not yet as mature and well-established as the AC; most of the commercially available DC converters are limited to automotive 12/24 V_{DC} applications. Therefore, the availability of DC converters was significantly lower than those that operate in AC. This market limitation is reflected in the number of manufacturers for our sampled DC converters and is, consequently, a limitation of this work (see Section 3.4.3).

3.2.1 Test Converters Characterization

This study focused on four types of MELs typically found in an office environment: laptops, desktops, monitors, and network appliances (e.g. switches and routers). Table 3.2 shows all monitored appliances together with their matched test converters. Some appliances were not linked to any test converter, as it was not possible to find converters with equivalent or similar power ratings. These appliances were not included in the endpoint efficiency comparison between AC and DC DS; however, their power profiles were considered in the grouped appliances' operational power range analysis (Figure 3.1). The purpose of this analysis is to capture a realistic load range during operation.

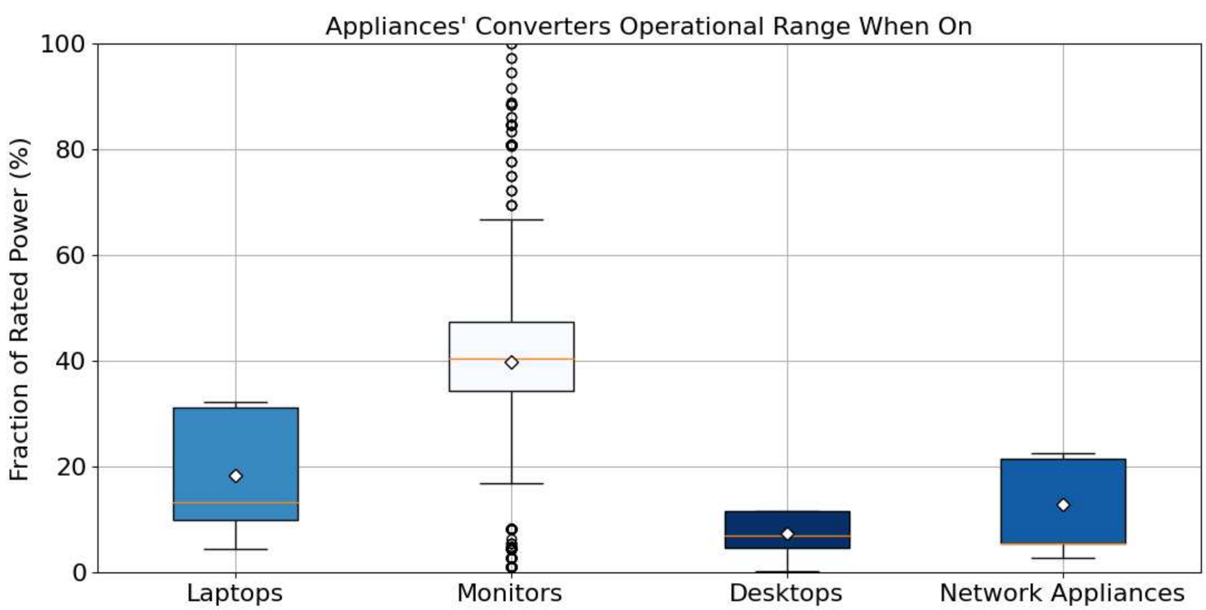


Figure 3.1: Grouped appliances' operational power range when on. Data was collected for approximately 2 months at 1 Hz resolution. Frequencies are represented by boxplots with 95% confidence interval whiskers, with the boxes representing the interquartile range between the 25th and 75th percentile, and the orange lines representing the medians. Data outside the confidence interval are represented by the circles. Table 3.3 provides the whisker and median values.

Table 3.2: Appliances and their respective AC/DC and DC/DC test converters

Smart Plug ID	Device	Output Voltage (V_{DC}) Voltage (V_{DC})	Power (W)	AC/DC Test Converter	DC/DC Test Converter
Smart Plug 1	Netgear WNR2000 v3	12	36	Converter 1	Converter 2
Smart Plug 2	HP Laptop	19.5	90	Converter 3	Converter 4
Smart Plug 3	Microsoft Laptop 1	15	90	Converter 5	Converter 6
Smart Plug 4	Microsoft Laptop 2	15	90		
Smart Plug 5	ViewSonic Monitor	5/12/24	36		
Smart Plug 6	HP Monitor E232	5/12/24	35		
Smart Plug 7	HP Monitor E232	5/12/24	35		
Smart Plug 8	HP Monitor E232	5/12/24	35		
Smart Plug 9	HP Monitor E242	5/12/24	38		
Smart Plug 10	Acer Monitor CB421HYK	5/12/24	60	Converter 7	Converter 8, 9
Smart Plug 11	Dell Monitor P2415Qp	5/12/24	90	Converter 10	Converter 11, 12
Smart Plug 12	HP Monitor E232	5/12/24	35		
Smart Plug 13	HP Monitor E273	5/12/24	42		
Smart Plug 14	HP Monitor E273	5/12/24	42		
Smart Plug 15	Apple Thunderbolt Display	5/12/24	250		
Smart Plug 16	Dell Monitor E2010Ht	5/12/24	26		
Smart Plug 17	Phillips Monitor 288P6L	5/12/24	60	Converter 7	Converter 8, 9
Smart Plug 18	HP Z240 Tower Workstation	3.3/5/12	400		
Smart Plug 19	HP Z240 Tower Workstation	3.3/5/12	400		
Smart Plug 20	Netgear RND-6C / RN31600	3.3/5/12	200	Converter 13	Converter 14

Table 3.3: Appliances' Converter Power Level Distribution (% of rated load)

	Laptops	Monitors	Desktops	Network Appliances
Minimum Value	4.4	16.8	0.2	2.8
Lower Quartile	10	34.3	4.6	5.6
Median	13.3	40.5	7.0	5.6
Mean	18.2	39.8	7.3	12.9
Upper Quartile	31.1	47.4	11.5	21.5
Maximum Value	32.2	66.7	11.5	22.5

3.2.2 Converter Types

In addition to input and output voltage, converters may also be classified by the number or range of acceptable input voltages and the number and capacity of output voltages. Converters generally fall into four classifications by input and output configuration: single or multiple input (SI or MI) and single or multiple output (SO or MO); a single-input, single-output unit is a 'SISO' converter. In practice, multiple input converters are rare but SISO and SIMO types are common. Of the 14 test converters purchased for this study, six were SISO and eight were SIMO converters.

Loads in commercial buildings vary substantially in the power rating and voltages used internally. Computer work stations and monitors, for instance, typically have SIMO internal power converters; common outputs are 3.3/5/12 V_{DC} and 5/12/24 V_{DC}. Laptops typically have SISO converters rated at 18–19.5 V_{DC}; other voltages are created on the computer's motherboard. To match this diversity of loads, the study utilized several configurations of commercially available test converters.

All the AC/DC converters were tested at 120 V_{AC}, 60 Hz, the typical office supply voltage in the U.S., although many accept input voltages over 200 V_{AC}. Most DC/DC test converters were tested at an input voltage of 24 V_{DC}, which is the voltage standard in the Occupied Space Standard proposed by the EMerge Alliance [11]. However, for monitors, the study also included DC test converters rated at 48 V_{DC} (representative of the Power over Ethernet standard [115]), allowing a comparison of endpoint efficiency between 120 V_{AC}, 24 V_{DC}, and 48 V_{DC} for a subset of MELs.

Efficiency for SISO converters was characterized using controllable resistive load banks. Loads varied from no load to the converter's rated power, in 10 load steps of approximately equal size. For SIMO converters, multiple scenarios with specific load levels were applied across the three output ports (scenarios are listed in Section 3.3). Since some SIMO converters had one output rated at 24 V_{DC}, a higher voltage than the available resistive load banks, the study used BK Precision 8614 DC electronic load bank to load the 24 V port. All measurements were made using a Keysight PA2203A power analyzer (PA) for both input and output power on each port. The PA has an accuracy of 0.05% for voltage and current measurements and 0.1% for power measurements.

Efficiency at the i^{th} load level of an AC/DC (η_{AC_i}) or DC/DC (η_{DC_i}) converter was calculated using Equations (3.1) and (3.2), which also define the relevant power terms for subsequent equations:

$$\eta_{\mathrm{AC_i}} = \frac{\mathrm{P_{out(DC)_i}}}{\mathrm{P_{in(AC)_i}}} \tag{3.1}$$

$$\eta_{\mathrm{DC_i}} = \frac{\mathrm{P_{out(DC)_i}}}{\mathrm{P_{in(DC)_i}}} \tag{3.2}$$

3.2.3 Power Monitoring

Load profiles used in the study were measured at 1 Hz on in-use office appliances. Measurements were made for approximately 2 months using WEMO™smart plugs (Model F7C029V2, rated for 120 V_{AC} / 15 A). The smart plug has a steady-state accuracy of 0.05 W; however, its readings exhibit a time-constant-like delay when power levels change rapidly. The time constant was characterized by applying resistive load steps to the smart plugs and fitting the rising and decaying curves to a first-order transfer function ($\frac{1}{\tau * s+1}$); fitting produced $\tau = 2.77$ s.

The load profiles were then corrected by applying an approximate inverse transfer function using Matlab™Simulink™. Once corrected, the loads were binned at 1 W intervals for all periods when the MELs were on (defined as load $\geq$ 1 W) to build load probability distributions for each MEL. Note that this correction substantially recovers the (typically short-duration) peak loads of the MELs that are otherwise attenuated in the smart plug recordings.

3.2.4 Endpoint Efficiency Weighted by Time Series Load Data

The efficiency of a power converter varies with the load, typically with lower efficiency at lower power levels. Therefore, to estimate the operational efficiency of the converter, it is necessary to weigh the converter's efficiency by time series load data to compute the weighted energy efficiency of the converter. In general, there was insufficient access to each MEL's converter to measure the DC output of internal converter(s) while monitoring equipment deployed in a non-laboratory office environment. Therefore, the DC output power was estimated using the conversion efficiency of the AC test converter, as in Equation (3.3).

$$\mathrm{P}_{\mathrm{out(DC)_i}} = \mathrm{P}_{\mathrm{in_i}} \times \eta_{\mathrm{AC_i}} \tag{3.3}$$

where i indicates the i^{th} power bin, $i = 1 \ldots N$, where N is the number of power bins for rated load of the converter.

This step translated the measured AC load from long-duration recordings to an estimate of DC output power consumed by the MEL. It also assured that the AC/DC efficiency was that of the chosen test converter, rather than the converter supplied with the MEL, which, in a few cases, may have higher or lower efficiency than the test converter. To estimate DC input power for DC/DC converters, the process was reversed (Equation (3.4)): The estimated output power calculated for each bin in Equation (3.3) was divided by the corresponding efficiency value of the DC/DC test converter to estimate the DC input power.

$$\mathrm{P}_{\mathrm{in(DC)_i}} = \frac{\mathrm{P}_{\mathrm{out(DC)_i}}}{\eta_{\mathrm{DC_i}}} \tag{3.4}$$

Time series load data provides the fraction of time (γ_i) that a device operates at each load level bin, i, considering only times when the MEL load exceeded 1 W. Equations (3.5) and (3.6) were used to compute the weighted (or *net*) efficiency for the AC/DC and DC/DC test converters—i.e., comparable, weighted, endpoint use efficiency. Note that the binned power interval, i, varies from the lowest 'on' load bin to the converter's rated power. In practice, the center of each load bin was utilized as the load for each bin. For example, γ_1 is the fraction of 1 Hz load samples where 1 W $\leq P_{in} <$ 2 W, and the power value for the bin is $P_{in_1} = 1.5$ W. Similarly, the last bin, which ends with the converter's rated power, has a value of $P_{in_N} =$ Rated Power $- 0.5$ W.

$$\eta_{\mathrm{net(AC)}} = \frac{\sum_{i=1}^{N} P_{\mathrm{out(AC)}_i} \times \gamma_i}{\sum_{i=1}^{N} P_{\mathrm{in(AC)}_i} \times \gamma_i} \tag{3.5}$$

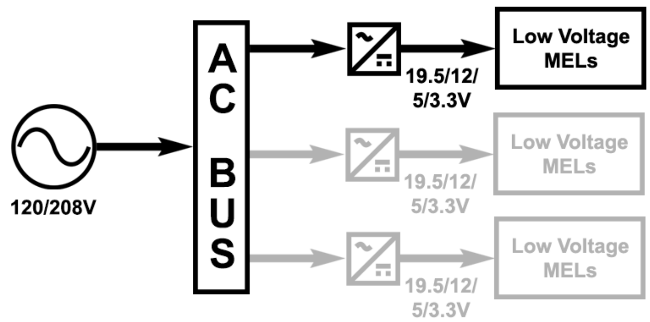
$$\eta_{\mathrm{net(DC)}} = \frac{\sum_{i=1}^{N} P_{\mathrm{out(DC)}_i} \times \gamma_i}{\sum_{i=1}^{N} P_{\mathrm{in(DC)}_i} \times \gamma_i} \tag{3.6}$$

3.2.5 Context Summary

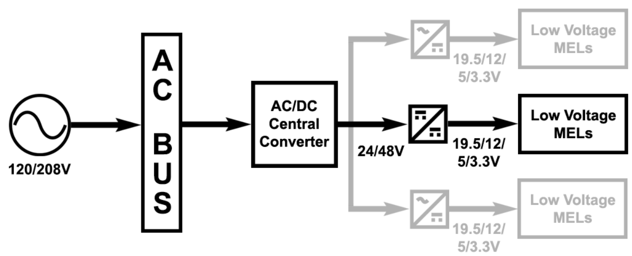
A typical layout for an AC and a DC distribution in commercial buildings is shown in Figure 3.2. In an AC building, on-site energy storage or generation, which are often DC internally, must be converted to AC by inverters. In a DC building, these sources are typically coupled to the DC bus via a DC/DC converter, for example, a maximum peak power tracker for PV or wind generation. This study did not compare the efficiency of coupling storage and generation to either type of distribution system.

Assuming the building is coupled to grid power, an AC DS in commercial buildings often has step-down transformers inside the building while the DC DS requires a central AC/DC converter that converts AC grid power to the DC DS voltage. (There are exceptions where AC systems may not have step-down transformers, or DC systems may require a DC/DC converter to couple the DC DS to a higher voltage DC bus.) Some limited published measurements of efficiency exist for step-down transformers [116,117], which are often substantially underloaded [118]. As the current study did not have access to in-building transformers to characterize, no measurements were performed in this area. In contrast, the study had access to one central AC/DC converter—a class of device for which there are few published measurements. Therefore, the central converter *was* measured, and the results are included below.

Therefore, the AC DS and DC DS architectures most often have analogous components. For grid connected buildings, the step-down transformer in the AC DS case fulfills



(a)



(b)

Figure 3.2: Typical (**a**) AC and (**b**) DC distribution for commercial buildings.

the same purpose as the central AC/DC converter for the DC DS, while inverters coupling local generation and storage to the AC DS fulfill the same purpose as DC/DC converters for the DC DS. The scope of the study did not support measurement of all components of these two architectures, and comparisons do not include the performance of these components.

Rather, this paper focuses on the endpoint conversion efficiency: i.e., comparing the weighted efficiency of the AC/DC converter needed to connect a MEL to the AC DS, to the comparable DC/DC converter necessary to connect the same MEL to a DC DS. As noted earlier, prior studies have concluded that the endpoint conversion efficiency of DC DS exceeds that of an AC DS [91–93]. This study performed pairwise comparisons of commercially available converters to determine if this DC advantage exists *in practice*, and if so, how large the advantage is.

3.3 Results

3.3.1 Power Consumption Monitoring

Figure 3.1 and Table 3.3 summarize the load distribution for the 20 office appliances analyzed when on (i.e., power consumption ≥ 1 W). The data comprised three laptops, 13 monitors, two computer work stations, and two network appliances.

These data illustrate that MELs operate at substantially less than their rated load most of the time. In the measured data, monitors operated below 66.7% of their rated power 90% of the time, while laptops, desktops, and network appliances always operated below 32.3% of their rated power. These data showed that the typical operation is significantly below the rated power of the converter—i.e., the converters were oversized relative to the maximum power recorded while in use. This oversizing may be due to features in the appliances that are seldom utilized, design decisions, or product line requirements to use the same adapter for a range of products. As loads in a typical application are compressed into the lower end of the converter's power rating, the lower 1/3 to 1/2 of the converter's efficiency curve had a determinant impact on the weighted energy efficiency of these converters.

3.3.2 Converter Selection

Test converters were matched to appliances by power rating and output voltage(s), as shown in Table 3.2. In all cases, converters exactly matched the output voltage found in the appliance's original internal or external converter. The match in power rating was less exact, due to poor commercial availability of both AC/DC and DC/DC converters, which precisely matched both the output voltage and output power ratings. The rated power of converters 3–6 matched the rated power of their linked appliances, while the rated power of the others were approximate matches.

Additionally, within each pair of test converters, both the power rating and output voltage(s) matched exactly. These controls assured that the test converters were representative of the converters in the test appliances and, more importantly, pairs of AC/DC and DC/DC converters were closely matched to assure that comparisons of endpoint efficiency were valid.

Single Input Single Output (SISO) Test Converters

Three pairs of test converters were SISO (converter pairs 1–2, 3–4, and 5–6), which were characterized across the full range of power using controllable load banks. Load recordings for these converters were taken from three laptops and one router (Figure 3.3). From Figure 3.1, the sampled MELs seldom operated above 33% of the rated power, and often operated below that level—at median loads of 13.3%, 7.0%, and 5.6% for laptops, desktops, and network appliances, respectively. As the efficiency of DC/DC converters was lower at low load levels, the DC/DC converter in each pair of SISO converters typically had lower weighted energy efficiency than the AC/DC converter.

Table 3.4 summarizes the data in Figure 3.3, focusing on the lower load range, at discrete fractions of rated power. In pair 1–2, the AC/DC converter efficiency exceeded that of the DC/DC converter at all loads. For pair 3–4, the DC/DC converter had lower efficiency below 10% load and higher efficiency above that load. Since the HP laptop load level was above 10% for 99.8% of the time, the DC weighted energy efficiency was better than the AC for this case.

For pair 5–6, the DC/DC converter has lower efficiency below 15% load—a load level that occurred 80.8% of the time to Microsoft laptop 1 and 82.4% for Microsoft laptop 2—and higher efficiency for the remainder of the load range, peaking at 35% load. However, since the laptops were loaded above 35% load for 0.7% and 0.4% of the time, respectively, the weighted energy efficiency of the DC/DC converter is lower than that of the AC/DC converter for these appliances.

Net delta efficiency is defined as the difference between the DC/DC weighted energy efficiency minus the AC/DC weighted energy efficiency. Only the HP laptop had a better performance in DC, contradicting the common argument that DC converters are more

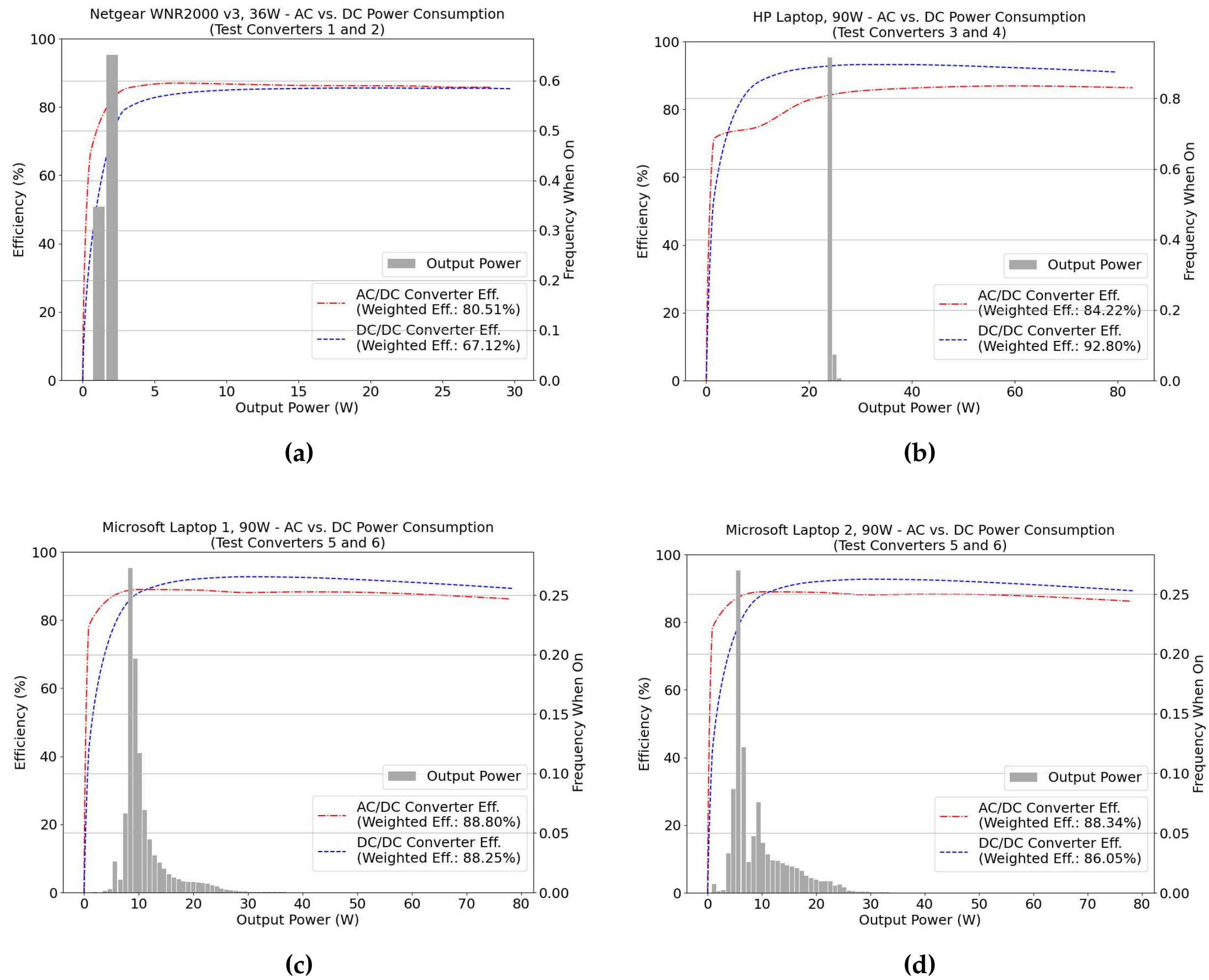


Figure 3.3: Weighted energy efficiency for SISO converters, assuming load profiles for: (**a**) HP Laptop, 90 W (**b**) Microsoft laptop 1, 90 W (**c**) Microsoft laptop 2, 90 W, and (**d**) Netgear WNR2000 v3. Efficiency curves for the test converters are represented by the dotted lines, and probability distribution of load for each MEL is represented by the histogram. Legend provide the weighted energy efficiency for each converter, over the period in which power was monitored (≈2 months).

Table 3.4: Delta Efficiency (DC-AC) for pairs of test converters and AC and DC weighted energy efficiency for each appliance

Device	Rated Power	1%	5%	10%	15%	20%	35%	50%	70%	100%	Weighted Energy Efficiency	
Netgear WNR2000 v3	Eff. Conv. 9 (%)	41.7	77.9	85.2	86.4	86.9	86.8	86.4	86.2	85.8	AC	80.5%
	Eff. Conv. 10 (%)	8.4	51.1	79.1	82.0	83.3	85.0	85.4	85.6	85.5	DC	67.1%
	Delta Eff (%)	**-33.3**	**-26.8**	**-6.1**	**-4.4**	**-3.6**	**-1.8**	**-1.0**	**-0.7**	**-0.3**	**Net Delta**	**-13.4%**
HP Laptop	Eff. Conv. 1 (%)	43.8	73.2	74.1	76.1	79.8	85.2	86.3	86.9	86.5	AC	84.2%
	Eff. Conv. 2 (%)	37.1	71.1	85.1	89.4	91.3	93.2	93.2	92.5	91.0	DC	92.8%
	Delta Eff (%)	**-6.7**	**-2.0**	**11.0**	**13.3**	**11.5**	**8.0**	**6.9**	**5.6**	**4.5**	**Net Delta**	**8.6%**
Microsoft Laptop 1* and 2**	Eff. Conv. 3 (%)	75.6	85.2	88.6	89.0	88.9	88.2	88.3	88.0	86.2	AC	88.8% */ 88.3% **
	Eff. Conv. 4 (%)	40.1	68.8	84.8	89.1	91.0	92.7	92.6	91.6	89.3	DC	88.3% */ 86.1% **
	Delta Eff (%)	**-35.5**	**-16.4**	**-3.8**	**0.2**	**2.0**	**4.5**	**4.3**	**3.6**	**3.1**	**Net Delta**	**-0.6% */ -2.3% ** **

efficient than AC. For the other three devices (Microsoft laptops 1 and 2, and Netgear WNR2000 v3) the AC/DC converter was more efficient for the period analyzed, primarily because these devices had their highest frequency of operation at low power, exactly where the AC/DC test converters exhibited higher efficiency than the DC/DC units.

In contrast, had this analysis utilized only the efficiency at the rated power for all load levels, as is often done in the literature, the converters would yield substantially different results: the DC/DC converter would have higher efficiency than the AC/DC converter for three of the four appliances analyzed. This emphasizes the need to utilize recorded loading data when assessing the weighted energy (i.e., practical) efficiency of converters. It also suggests that more attention must be paid to the operational efficiency of DC/DC converters at realistic load levels.

Single Input Multiple Output (SIMO) Test Converters

Monitors, desktops, and some network appliances make use of SIMO AC/DC converters, typically as internal power supplies, to power different electronic circuits at different voltage levels. This section analyzed eight SIMO test converters rated at 70, 110, and 185 watts, all from the same manufacturer: Integrated Power Designs. The test converters rated at 70 and 110 W were representative of those used in computer monitors. For these power ratings, one AC/DC test converter rated at 120 V_{AC} (input voltage) was paired with two DC/DC converters: one rated for 24 V_{DC} input, the other 48 V_{DC} input—two common DC distribution voltages proposed for commercial buildings [11,96].

The three output ports on each converter operated at 5, 12, and 24 V_{DC}. The 185 W test converters were representative of power supplies for a network-attached storage device (Netgear RND-6C). The AC/DC version was rated for 120 V_{AC} input; the DC/DC for 24 V_{DC}. For this pair, the three output ports operate at 3.3, 5, and 12 V_{DC}.

To perform efficiency tests with these converter models, load levels were defined based on the realistic load levels shown in Figure 3.1. There were five scenarios for each load level, in which each of the three output ports were loaded with different power values such that the sum of the total load in all ports remained the same for all scenarios. The efficiency was compared across these combinations of output load to determine if there was a significant change in the converter's efficiency based on how the ports were loaded. As an example, for test converter 7, at 30% load, measurements for output power in the five scenarios had a mean of 20.2 W and a standard deviation of 0.32 W; for efficiency, the measurements resulted in 64.8% $\pm$ 0.81%.

For test converter 8, at the same load, the measurements for output power and efficiency were 20.3 W $\pm$ 0.29 W and 69.7% $\pm$ 0.80%, respectively. As the variations were below 2% of the mean for all SIMO converters, this indicated that most of the losses occur in the switching components of the power supply. Therefore, the efficiency and the output power for each load level was defined as the mean of the efficiency and the mean of output power, respectively, for the five loading scenarios. This methodology allowed SIMO converters to be analyzed using the same comparisons as those used for SISO converters, where we calculated the weighted energy efficiencies of the test converters based on their single efficiency curves and the matching appliance's time series load data.

The manufacturer specified that a minimum load of 10% on output 1 (5 V_{DC} or 3.3 V_{DC} depending on the model) was required for the power supply to properly regulate the other outputs. To meet this requirement, port 1 was always $\geq$10% of rated power, and if the total load was below 10% of the rated power, only port 1 was loaded.

70 W SIMO Test Converters

To illustrate this loading plan, Table 3.5 shows the test plan for the 70 W test converters. *Max Power (W)* is the maximum load that the resistive load banks could handle at the corresponding testing voltage; when not specified, the port was loaded with the BK Precision controllable load. The resulting efficiency curves for these converters are shown in Figure 3.4; the close grouping of data points indicates that changes in the output loading at one aggregate load level had little impact on the efficiency of the converter.

Table 3.5: Test plan for 70W multi-output converters

Test Converters 7, 8 & 9 Rated Power (W)	70	Max Power (W)	Load (W) Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1%	Out 1 (5V)	24.89	0.7	-	-	-	-
5%	Out 1 (5V)	24.89	3.5	-	-	-	-
15%	Out 1 (5V)	24.89	7.0	7.4	7.4	7.9	8.4
	Out 2 (24V)	-	1.5	1.6	2.1	2.1	1.1
	Out 3 (12V)	143.37	2.0	1.6	1.1	0.5	1.1
30%	Out 1 (5V)	24.89	7.0	10.5	14.7	8.4	7.4
	Out 2 (24V)	-	7.0	5.3	4.2	10.5	3.2
	Out 3 (12V)	143.37	7.0	5.3	2.1	2.1	10.5
40%	Out 1 (5V)	24.89	7.0	14.0	8.4	11.2	9.8
	Out 2 (24V)	-	14.0	7.0	8.4	14.0	4.2
	Out 3 (12V)	143.37	7.0	7.0	11.2	2.8	14.0
70%	Out 1 (5V)	24.89	20.0	14.7	14.7	7.4	9.8
	Out 2 (24V)	-	19.0	17.2	14.7	22.1	29.4
	Out 3 (12V)	143.37	10.0	17.2	19.6	19.6	9.8

Both 70 W DC/DC converters (24 V_{DC} and 48 V_{DC} input) exhibited higher efficiency compared with the comparable AC/DC converter across the entire tested power range. When loaded above 1% of the rated power, the efficiency of the 48 V DC/DC converter exceeded that of the 24 V converter.

In Table 3.6, the delta efficiency peaks near 5% of rated power: +6.8% and +8.1% for 24 V_{DC} and 48 V_{DC} converters, respectively. The difference decreased to 2.0% and 4.7%, respectively, when the converters were loaded at 70% of rated power. Therefore, for these converters, the largest efficiency advantage for DC/DC versions falls at load levels often seen in MELs.

Table 3.6: Delta Efficiency (DC-AC) for SIMO test converters rated at 70W

Rated Power (70W)	0%	1%	5%	15%	30%	40%	70%
AC Eff. Conv. 7, 120V_{AC} (%)	0.0	9.0	31.6	53.6	64.8	68.8	73.7
DC Eff. Conv. 8, 24V_{DC} (%)	0.2	12.5	38.4	58.8	69.7	72.8	75.8
DC Eff. Conv. 9, 48V_{DC} (%)	0.0	12.4	39.7	60.4	71.1	75.5	78.5
Delta Eff. [Conv 8 - 7] (%)	0.2	3.5	6.8	5.1	4.9	4.0	2.0
Delta Eff. [Conv 9 - 7] (%)	0.0	3.4	8.1	6.8	6.3	6.7	4.7

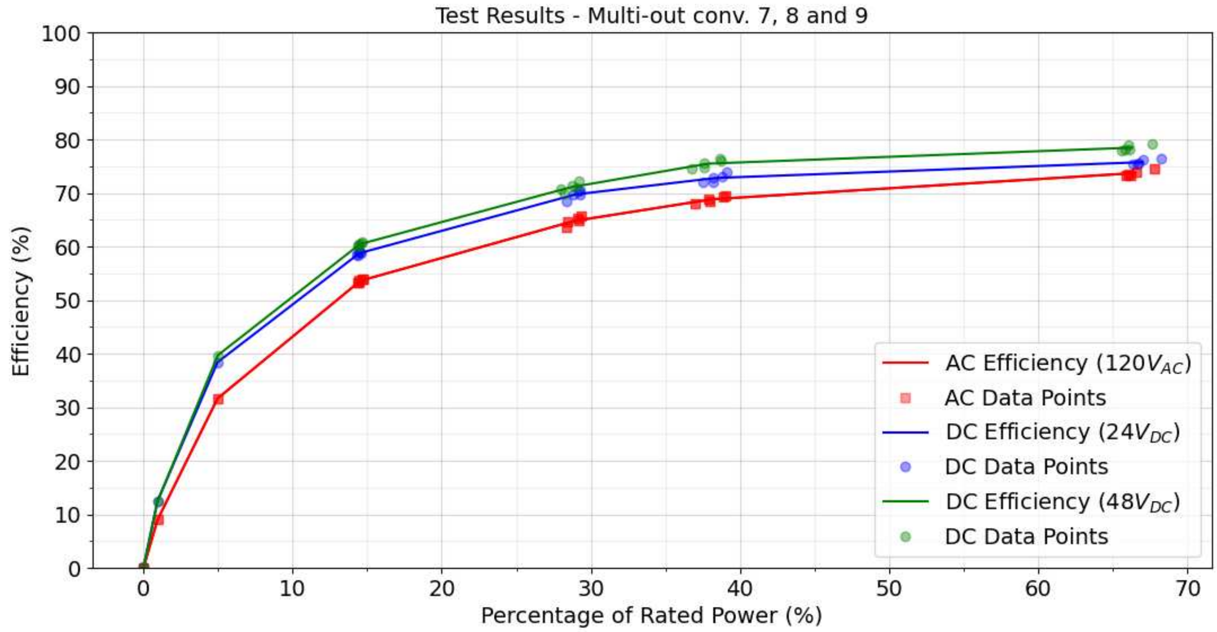


Figure 3.4: AC and DC efficiency comparisons for 70W SIMO power supplies for the test plan in Table 3.5. Converter 7 is the AC/DC converter (red line); the blue line shows converter 8, a DC/DC converter with 24 V_{DC} input; and the green line converter 9 with a 48 V_{DC} input.

The weighted energy efficiency was simulated using time series load data of two computer monitors: an Acer model CB421HYK and a Phillips model 288P6L, both rated at 60 W. Figure 3.5 shows the results for this simulation, and Table 3.7 summarizes the net delta efficiency. Given the higher efficiency of the DC/DC test converters at all power levels, the weighted energy efficiency of the DC/DC converters was higher than that of the AC/DC converter. However, a substantial fraction of the appliance's operating time was at load levels higher than the load levels where the DC/DC converters exhibited the highest efficiency advantage (5–15% of the rated power). The Acer monitor, for instance, operates outside this range 99.8% of the time; the Phillips Monitor, 32.0%.

The full load efficiencies for converters 7, 8, 9 were measured in a separate experiment, and they were equal to 76%, 76.3%, 80%, respectively. These values are close to the efficiency provided by the converters' data sheet, which is estimated at 78% at full power for these three converter models. However, if we consider the weighted energy efficiency for the Acer Monitor, using converters 7, 8, and 9, it was 16.5%, 11.7%, and 14%

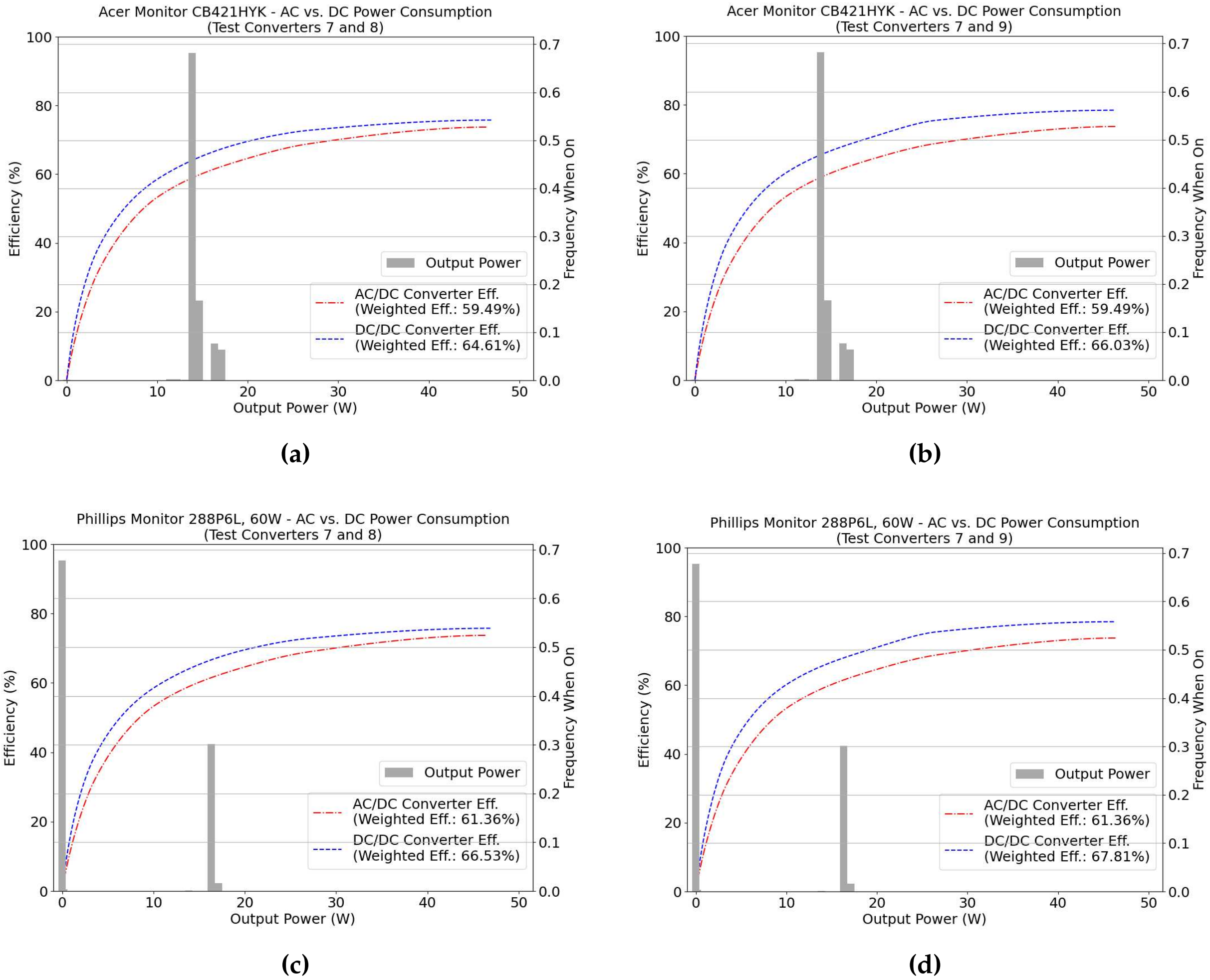


Figure 3.5: AC and DC weighted energy efficiencies for flat panel display screens: Acer CB421HYK (60 W) in (**a**) and (**b**) and for Phillips 288P6L (60 W) in (**c**) and (**d**). Simulations were done with 70 W SIMO test converters. Panels (**a**) and (**c**) show a comparison with DC test converter rated at 24 V_{DC} and panels (**b**) and (**d**) at 48 V_{DC}. Efficiency curves for the test converters are represented by the dotted lines, and the frequency when the appliance is on for each power bin is by the bar chart.

Table 3.7: Delta Efficiency (DC-AC) for simulations with converters rated at 70W

	Acer Monitor (60W)	**Phillips Monitor (60W)**
AC	59.5%	61.4%
DC (24V)	64.6%	66.5%
DC (48V)	66.0%	67.8%
Net Delta (24V)	5.1%	5.2%
Net Delta (48V)	6.5%	6.5%

lower than the efficiency of the converters at full-load, respectively. For the the Phillips Monitor, those values were 14.6%, 9.8%, and 12.2%, respectively.

110 W SIMO Test Converters

The same procedure described for the 70 W SIMO test converters was followed for the 110 W SIMO converters. Figure 3.6 shows the efficiency curves for the test converters 10, 11, and 12. Further details are in the Supplemental Material: Table B.1 shows the test plan, and Table B.2 shows the delta efficiency, following the same methodology as above.

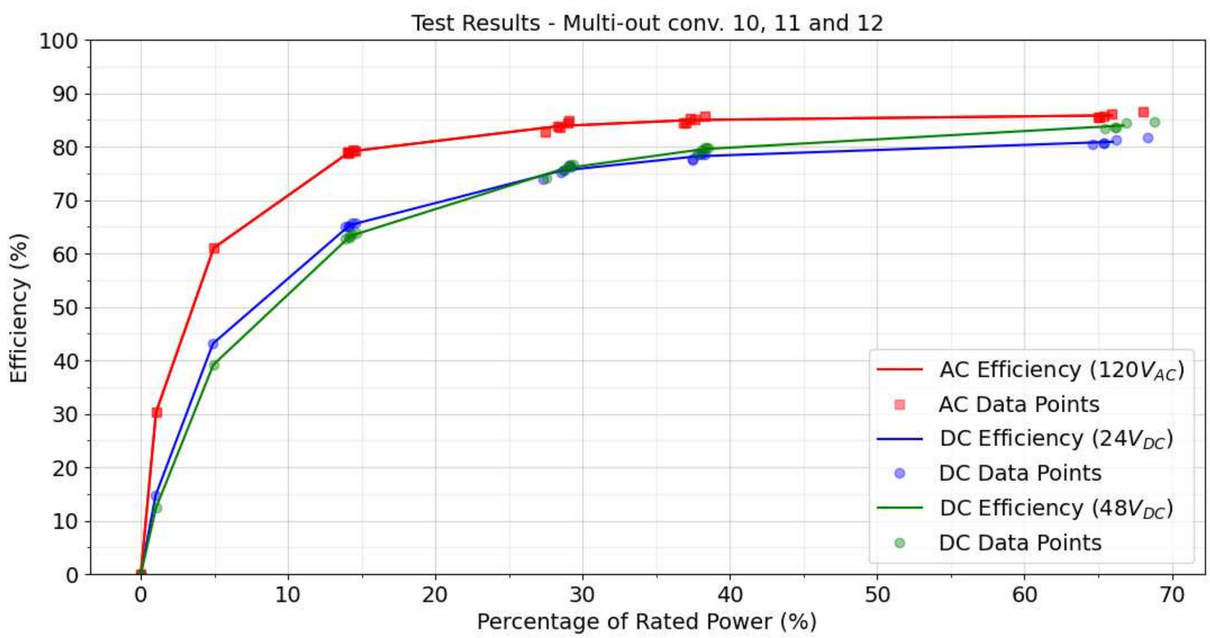
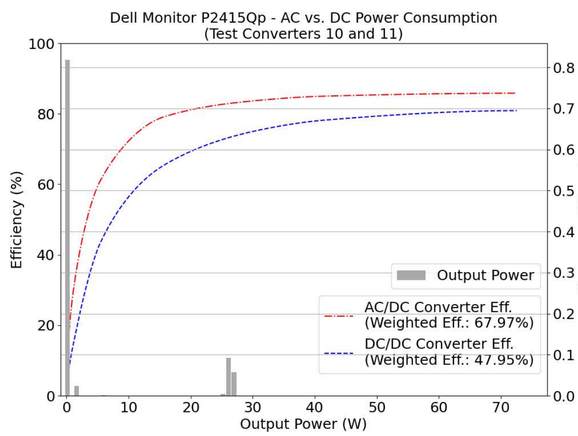


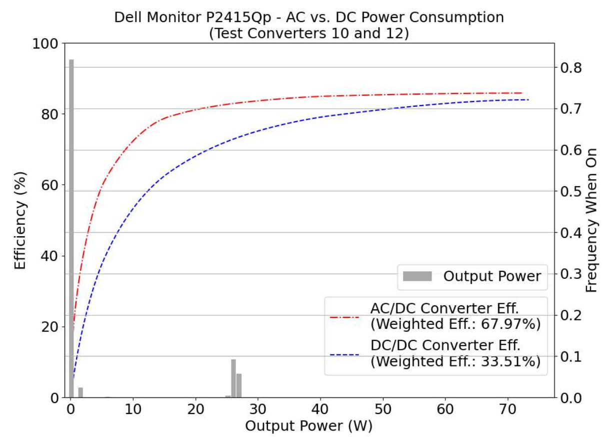
Figure 3.6: AC and DC efficiency comparisons for 110W SIMO power supplies for the test plan in Table B.1. The converter 10 is the AC/DC converter (red line); the blue line shows converter 11, a DC/DC converter with 24 V_{DC} input; and the green line converter 12 with a 48 V_{DC} input.

For the 110 W test converters, contrary to both the 70 W SIMO converters and data published in other studies, both DC/DC converters had significantly worse performance than of the comparable AC/DC converter. The biggest difference in efficiency occurred when loaded at 5% of rated capacity: -17.9% for the 24 V_{DC} version and -21.8% for the 48 V_{DC}. This difference decreased to -4.9% and -1.9% at loads of 70% of rated power.

The weighted energy efficiency simulation used the load data of a Dell monitor, model P2315Qp, rated at 90 W. Figure 3.7 shows the results of the simulation, and Table 3.8 shows the net delta efficiency for both DC input voltages. The weighted energy efficiency was 68.0% in 120 V_{AC}, 48.0% in 24 V_{DC}, and 33.5% in 48 V_{DC}. The AC/DC weighted energy efficiency was significantly better than the DC/DC results, with net delta efficiencies ranging from −20 to −34.5% (see Table 3.8). The 48 V_{DC} converter was less efficient than the 24 V_{DC} at loads below approximately 30% of the rated power, but more efficient above.



(a)



(b)

Figure 3.7: AC/DC and DC/DC weighted energy efficiencies for a load profile from a Dell monitor, model P2415Qp, rated at 90W. Simulations utilized efficiency data from 110W SIMO test converters. Both panels utilize the same AC/DC converter. Panel (a) compares to a DC/DC converter with 24V_{DC} input; panel (b) with 48V_{DC} input. Formatted as in Figure 3.3.

Table 3.8: Delta Efficiency (DC-AC) for simulation with converters rated at 110W

Test Converter	Weighted Energy Efficiency (%)	Net Delta Efficiency (Δ%)
AC	68.0%	
DC (24V)	48.0%	-20.0%
DC (48V)	33.5%	-34.5%

185 W SIMO Test Converters

One pair of converters had a rated load of 185 W: an AC/DC converter at 120 V_{AC} paired with one DC/DC converter with 24 V_{DC} input. The converters' efficiency curves are shown in Figure 3.8. Further testing details are given in Supplementary Material,Table B.3 for the test plan and Table B.4 the weighted energy efficiencies at different load levels. As with the 70 W converters, the DC/DC test converter was more efficient than the AC/DC converter at all load levels. The largest difference (+4.1%) occurred at 5–10% of the rated load. Above 10% of the rated power, the difference in performance started to decrease, dropping to +2.5% when the converters were 25% loaded. This resulted in a positive net delta efficiency of 3.3%, as shown in table 3.9.

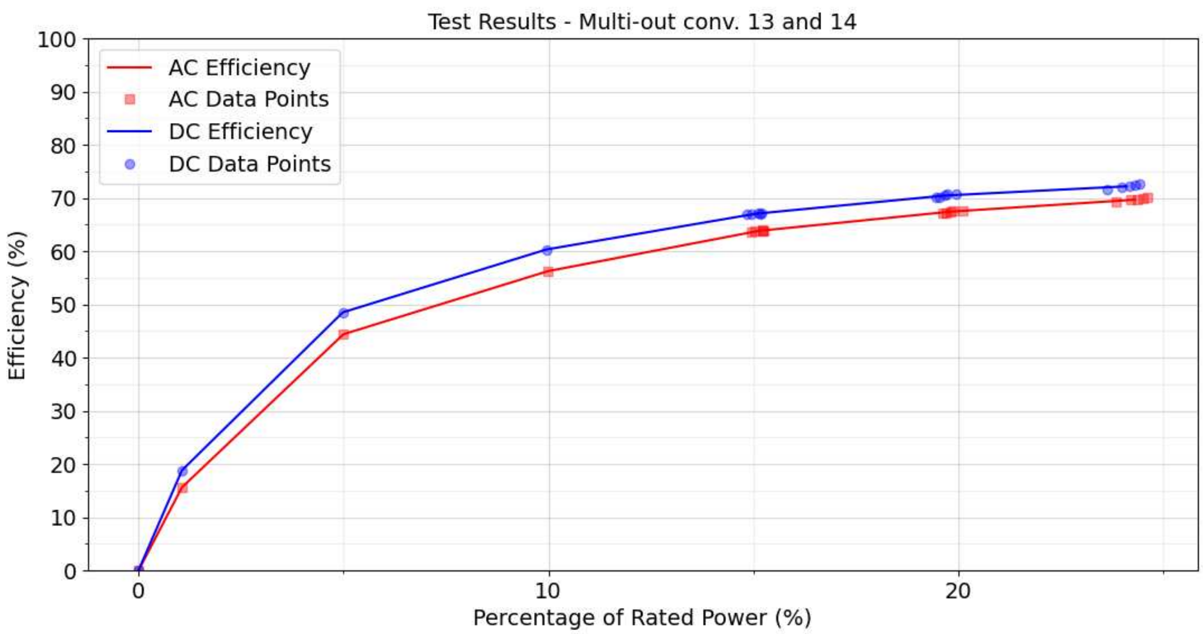


Figure 3.8: Efficiency curves for Converters 13 and 14. Converter 13 is model REL-185-4001-CHCO, 185W. Converter 14 is model DC2-185-4001-CH, 185W, tested at 24VDC.

Weighted energy efficiency was simulated using load profiles from a network storage device, Netgear RND-6C (200 W); Figure 3.9. The DC/DC converter exhibited a weighted energy efficiency of +3.3% relative to the AC/DC converter.

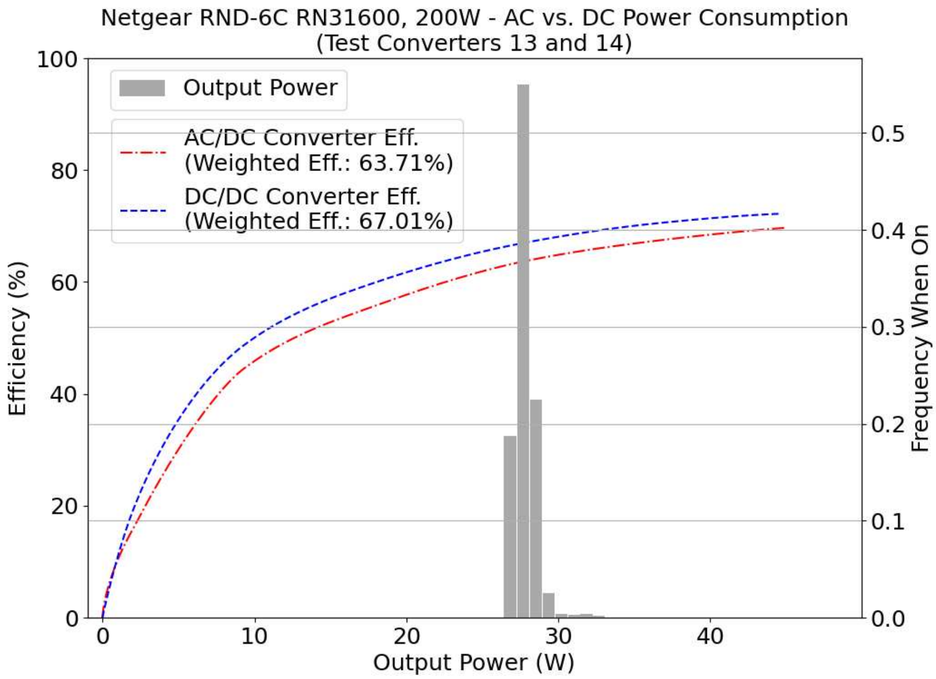


Figure 3.9: AC and DC weighted energy efficiencies for Netgear RND-6C RN31600 (200 W). Simulations were done with 185 W SIMO test converters. The figure shows a comparison with DC test converter rated at 24 V_{DC}. Formatted as in Figure 3.3.

Table 3.9: Delta Efficiency (DC-AC) for simulation with converters rated at 185W

Test Converter	Weighted Energy Efficiency (%)	Net Delta Efficiency (Δ%)
AC	63.7%	
DC (24V)	67.0%	+3.3%

3.3.3 Observations in AC/DC Central Converter Efficiency

As indicated earlier, for many commercial buildings, some or all of the power routed to a DC DS would be provided by a central AC/DC converter (CC). Therefore, the study also analyzed a commercially available power hub often used for this purpose, which has a voltage input range of 90-305$_{AC}$ or 127-431$_{DC}$. This device was tested operating at three supply voltages: 120 V_{AC}, 208 V_{AC}, and 380 V_{DC}. The converter provides DC power via 16 output ports, rated at 100 W and 24 V_{DC} each, and is currently sold primarily for powering LED lighting. The characterization of this device is described in the Supplementary Information, Section B.5.

Figure 3.10 summarizes the efficiency curve for the three voltage input levels, with their respective uncertainties, and Table B.6 in the Supplementary Material summarizes the same data. The CC exhibited the highest efficiency when operating at higher input voltages (208 V_{AC} and 380 V_{DC}), with efficiency typically above 90% for loads above 500 W.

According to the device's data sheet, above 50% of total load (50% $\times$ 1600 W = 800 W), the power hub should have an efficiency above 95% efficiency when operated on a 380 V_{DC} supply. However, the maximum efficiencies observed in this test were 92.6% [92.0% to 93.2%] at 208 V_{AC}, and 93.4% [92.6% to 94.1%], for 380 V_{DC}, both of which are statistically lower than the 95% peak efficiency stated in the data sheet.

The tests performed for the AC/DC central converter showed that the CC's efficiency was comparable to the efficiency of converters in the MELs tested [2], with higher input voltages tested (208 V_{AC} and 380 V_{DC}) exhibiting slightly higher efficiencies than typical MELs converters. These efficiencies are comparable to the stated efficiencies for in-building step-down transformers [118], although test data for this type of transformer is sparse, and, as noted above, in-building transformers are frequently underloaded and operate below their peak efficiency.

The importance of this testing is that it highlights that neither the central nor endpoint power converters show a systematically superior efficiency to their AC DS counterparts. Tests of endpoint converters did not exhibit a consistent advantage for DC/DC endpoint converters over AC/DC endpoint converters *and* the single AC/DC central converter tested here (a) exhibited an efficiency comparable to in-building step-down transformers and (b) did not show a significant efficiency advantage over the endpoint converters.

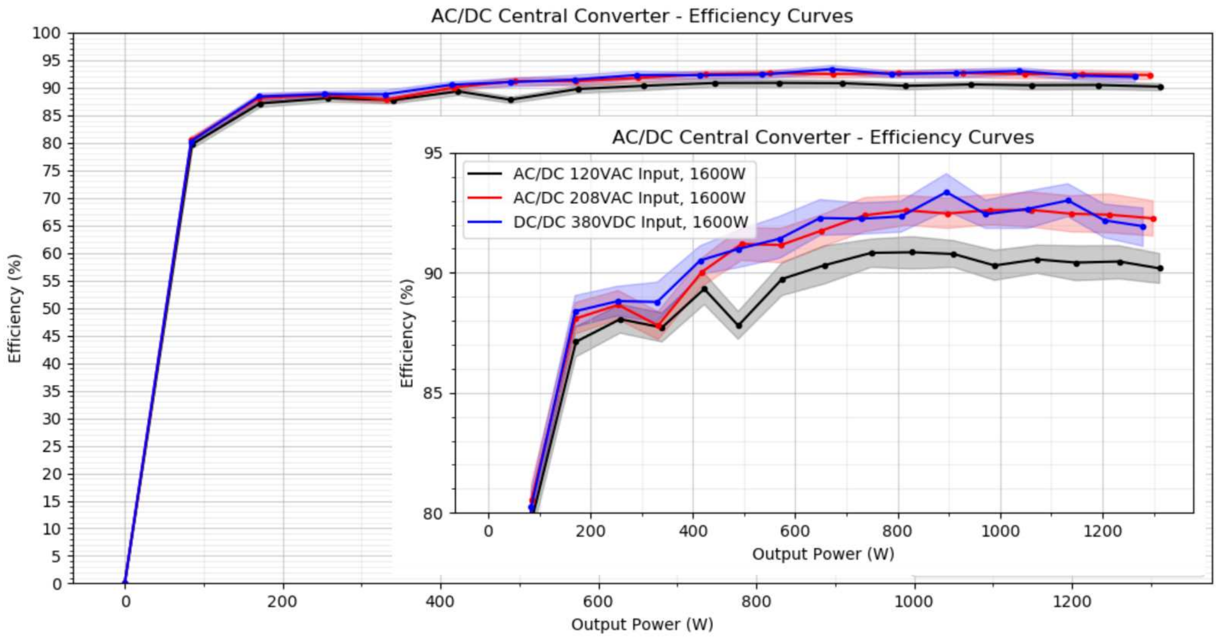


Figure 3.10: CC Efficiency curves at $120V_{AC}$, $208V_{AC}$, and $380V_{DC}$, with respective uncertainties. Outer chart summarizes the full test range. Inset chart focuses on the area with loads of 100W or higher. Note that performance at $208V_{AC}$ and $380V_{DC}$ present similar efficiencies, while efficiency at $120V_{AC}$ is lower.

Therefore, for the devices tested here, the efficiency of CC (versus a step-down transformer) does not provide an efficiency advantage for DC DS versus the traditional AC DS.

3.4 Discussion

3.4.1 Interpretation of Test Converters Results

For the selection of the test converters measured in this study, weighted energy efficiency of DC/DC converters was not consistently superior to that of AC/DC converters, likely due to variations in the design and performance of individual converters. These results differ substantially from the common assumption found in the literature—namely that the efficiency of DC/DC converters is better than that of AC/DC converters. Further, due to the highly variable nature of efficiency curves for seemingly similar converter units, these data also showed that the appliance's load profile is a key determinant of weighted energy efficiency and must be considered when comparing AC and DC distribution solutions.

To compare the endpoint efficiency, we considered four scenarios to analyze converter efficiency: (1) the maximum efficiency detected over the whole efficiency curve (peak efficiency); (2) the efficiency at the converter's rated load; (3) the efficiency provided by the converter's data sheet; and (4) the energy efficiency weighted by load. Scenarios 1, 2, and 3 are often used in literature, while Scenario 4 is the method utilized in this study. Table 3.10 summarizes each scenario for the eight loads simulated in this study.

Data sheets for 2 of the 14 test converters (test converters 3 and 5) were not available, and those efficiencies are omitted from the table. Due to load bank limitations, test converters 10–14 could not be tested over their full range of power, and, consequently, their peak efficiency and efficiency at full load are also missing from the table for these units.

Table 3.10 illustrates that the converters' weighted energy efficiencies were substantially lower than the efficiencies provided by their data sheets. Only test converters 4 and 6, when linked to load profiles from the HP Laptop and Microsoft Laptop 1, respectively, had a performance above that stated in their data sheets. Overall, data sheet information was available for four scenarios for seven test converters. For 57% of these scenarios, the efficiencies provided in the data sheet were higher than the peak efficiency or the efficiency at full load measured here. Therefore, based on this limited sampling, a design engineer selecting a power converter from its data sheet has an approximately 50/50 chance of seeing performance as good as the data sheet's stated efficiency.

If the endpoint efficiency comparison was made using either peak efficiency or efficiency at full load (Scenarios 1 and 2, respectively), five of six appliances would be considered to have a better performance in DC compared to AC. However, if we consider a comparison that uses the weighted energy efficiency (Scenario 4), only four of the eight appliances would be more efficient in DC. Additionally, differences in weighted energy efficiency also changed substantially when comparing Scenario 1 to 4 or Scenario 2 to 4.

For the Acer Monitor, for instance, the AC-input weighted energy efficiency was 59.5%, while the peak and full load efficiency were both 76%.

Additional tests on converters with 12 V_{DC} and similar input voltages were also completed and showed similar efficiency curves. These data are discussed in SI Section B.3. To illustrate the analytic assumptions commonly utilized in the literature, a comparison to other studies is also included in Section 3.4.2.

Taking all data and simulations together, practitioners should be cautious about making broad assumptions regarding converter efficiency based upon power ratings or data sheet values, *or* making the assumption that appliance load profiles are at or near the rated load of converters. The values found for peak efficiency, efficiency at full load, and data sheet efficiency were close to each other for most converters, with variations within 3.5% for the sampled converters.

This indicates that the efficiency provided in the converters' specification documents were measured at, or near, the load where they operate at their best performance. However, as shown here, MELs seldom operate at load levels near the converters' peak efficiency. Therefore, when the endpoint efficiency comparison is made using efficiency data provided by any of these metrics (i.e., data sheet, peak efficiency, or efficiency at the rated load), the results are likely to be misleading.

Finally, combining these data with the efficiency of the single central converter unit tested here provides a cautionary note about whether existing buildings would benefit from providing DC DS circuits to power office MELs: If one considers a CC running at 208 V_{AC}, powered on the secondary of a building distribution transformer, and operating at its peak efficiency (92.6% at 880 W), DC/DC converters powered by the CC's outputs would need efficiencies that were consistently 8 percentage points higher than comparable AC/DC converters for the DC DS to have higher efficiency than the AC DS.

The measurements from this study indicated that this type of efficiency advantage is rare: only one converter—an HP laptop powered by SISO test converters 3 and 4—had a

Smart Plug ID	Appliance	AC/DC Test Conv.	AC/DC Peak Eff. (%)	AC/DC Eff. at Full Load (%)	AC/DC Eff. in Datasheet (%)	AC/DC Wt. E. Eff. (%)	DC/DC Test Conv.	DC/DC Peak Eff. (%)	DC/DC Eff. at Full Load (%)	DC/DC Eff. in Datasheet (%)	DC/DC Wt. E. Eff. (%)	Delta Peak Eff. (%)	Delta Eff. at Full Load (%)	Delta Eff. Data sheet (%)	Delta Net Eff. (%)
Smart Plug 1	Netgear WNR2000 v3	Conv. 1	86.9	85.8	88.5	80.5	Conv. 2	85.6	85.5	89.0	67.1	-1.3	-0.3	0.5	-13.4
Smart Plug 2	HP Laptop	Conv. 3	86.9	86.5	-	84.2	Conv. 4	93.2	91.0	>88.0	92.8	6.3	4.5	-	8.6
Smart Plug 3	Microsoft Laptop 1	Conv. 5	89.0	86.2	-	88.8	Conv. 6	92.7	89.3	>88.0	88.3	3.7	3.1	-	-0.6
Smart Plug 4	Microsoft Laptop 2	Conv. 5	89.0	86.2	-	88.3	Conv. 6	92.7	89.3	>88.0	86.1	3.7	3.1	-	-2.3
Smart Plug 10	Acer Monitor CB421HYK	Conv. 7	76.0	76.0	78.0	59.5	Conv. 8	76.4	76.3	78.0	64.6	0.4	0.3	0.0	5.1
							Conv. 9	80.0	80.0	78.0	66.0	4.0	4.0	0.0	6.5
Smart Plug 11	Dell Monitor P2415Qp	Conv. 10	-	-	85.0	68.0	Conv. 11	-	-	82.0	48.0	-	-	-3.0	-20.0
							Conv. 12	-	-	82.0	33.5	-	-	-3.0	-34.5
Smart Plug 17	Phillips Monitor 288P6L	Conv. 7	76.0	76.0	78.0	61.4	Conv. 8	76.4	76.3	78.0	66.5	0.4	0.3	0.0	5.2
							Conv. 9	80.0	80.0	78.0	67.8	4.0	4.0	0.0	6.5
Smart Plug 20	Netgear RND-6C / RN31600	Conv. 13	-	-	82.0	63.7	Conv. 14	-	-	77.0	67.0	-	-	-5.0	3.3

Table 3.10: AC vs. DC endpoint efficiency comparison

weighted DC/DC efficiency sufficient to offset losses in the CC. Additionally, if the CC is also underloaded—the likely case given common design practice—its efficiency falls below its peak efficiency. When loaded under 25% of its rated power, the CC's conversion efficiency dropped as low as 89.3–90.5% for all three operational voltages (120 V_{AC}, 208 V_{AC}, 380 V_{DC}).

Therefore, while by no means a comprehensive study, the measurements performed for this study indicate that wholesale provision of DC distribution systems in existing commercial buildings is unlikely to provide an efficiency advantage without either (a) substantial improvements in endpoint DC/DC converter efficiencies or (b) significant savings achieved by reducing conversion losses in other distribution equipment not typically present, such as connected PV or energy storage converters.

3.4.2 Example Comparison to Representative Efficiency Studies

As an illustration, we compare our analysis to that of a typical literature analysis of converter efficiency—as shown in Figure 4 of a study provided by Pang et al. [44]. In this analysis, the authors collected efficiency data on a range of power converters at different power ratings.

The data accumulated in this study disagree with the Pang et al. study for the following reasons: first, in Pang's analysis, the efficiency of AC/DC and DC/DC converters tends to increase with the power rating. However, our study shows that the weighted efficiency of the converter depended on the appliance load profile and could vary substantially relative to the efficiency at the rated power. Comparing, for example, the Acer and the Phillips Monitors, both rated at 60 W and using the same AC test converter (Converter 7, rated at 70 W), the weighted efficiencies were 59.5% and 61.4%, respectively.

The Dell monitor (AC test converter 10, rated at 100 W) presented a weighted efficiency of 68.0%, which was significantly lower than the 80.5% presented by a Netgear router rated at 30 W; second, for our sampled test converters, no significant correlation was seen between the power ratings and efficiency at the rated power for the converters utilized in our experiments (30–185 W); and finally, contrary to Pang's results, the study data did not show that the AC/DC and DC/DC converters' efficiencies tended toward similar values as the power rating increased.

Another study [91] analyzed AC adapters operating at different voltage inputs (AC and DC). The operational efficiency was compared at 120 V_{AC} and 240 V_{AC}, with their peak values after the input rectification (169 V_{DC} and 339 V_{DC}, respectively). When operating in DC, the adapters presented better efficiencies. However, these tests were done in the same converter, operating either with AC or a DC input, despite the fact that they were not listed for DC applications. In practice, (a) the DC voltage levels considered are quite uncommon and hardly available in the market; (b) there are no standards supporting these voltages unless the 380 V_{DC} level called by the EMerge Alliance Data/Telecom Center Standard [119]; (c) at commercial voltage levels, based on our sampled converters, this efficiency advantage does not happen often.

3.4.3 Limitations

While realistic, there are several limitations to the experimental work performed here. First, the analysis is limited to the selection of actual converters that we were able to obtain, characterize, and analyze. The study's focus of physical devices limited the breadth of the analysis; purely simulation-based studies and studies using manufacturers' product data can draw on a much wider body of information. However, as discussed in Section 3.4.1, such studies often lack complete information and may yield misleading results. The advantage of our approach is the depth of analysis possible when using full converter characterization data and realistic load levels.

As a wide range of DC/DC converters could not be tested, there exists some possibility that DC/DC converters exist that are higher efficiency than those tested here. We were able to test only a small number of manufacturers. While it is possible that the manufacturers tested are not representative of the current state of the art, other manufacturers' products were not available for general commercial purchase. However, our review of available products suggests that a systematic improvement in DC/DC converter efficiency is unlikely unless regulatory or similar outside pressures eliminate lower-performing converters from the market. Indeed, we found no commercially available units with performance exceeding those purchased for testing.

Conversely, the AC/DC converters shipped with products today may also benefit from improved design. Given that the converters selected here did not have space or heat constraints common for internal SIMO converters, it is also possible that the DC/DC converters tested here were *higher* in efficiency than those that would be built into MELs. We, therefore, contend that the AC-to-DC replacement process simulated here was representative of what would happen under current market forces and product availability constraints. Nevertheless, future studies should analyze a broader selection of converter manufacturers and product lines if or when they become commercially available.

Finally, for nearly all MELs tested here, the loads were substantially below the rated load when operating. The study identified two primary reasons for this under-loading. First, since many MELs are part of larger product families, manufacturers may choose one converter to support a broad product family, and must select that converter for the products with the highest loads; this sizing methodology results in relative under-loading for some products. Second, many MELs have multiple operating modes—e.g. monitors have built-in USB hubs designed to power peripherals—which are seldom used but must be considered when sizing power circuitry.

3.5 Conclusions

This study considered endpoint conversion, which exists in both AC and DC distribution system architectures, using commercially available products for both AC/DC and DC/DC converters. Multiple studies [91–93] have indicted that, in theory, DC/DC converters should have superior efficiency than comparable AC/DC converters. However, the measurements performed here indicated that commercially available DC/DC converters did not exhibit systematically better efficiency that comparable AC/DC converters in practice, and any efficiency advantage was substantially reduced when weighted by realistic load profiles. For the eight appliances analyzed in this work with matching pairs of AC/DC and DC/DC converters, half presented higher weighted energy efficiency using the DC/DC converter, and half using AC/DC. These data suggest that either (a) DC/DC converters are not being designed with the same rigor as AC/DC converters, or with the same focus on maximum efficiency; or (b) prior theoretical evaluations of DC/DC converter architectures have not accounted for all losses inherent in economically viable designs.

For building power systems that include local generation and/or storage, there may be additional advantages to DC distribution that were not characterized in this study. However, considering the measurements performed here, any such advantage cannot rely on endpoint conversion for common low voltage loads to contribute an efficiency advantage—such an advantage is simply not seen in the measured efficiency, particularly when weighted by realistic load levels. We recommend further research to expand the analysis to other categories of load, to incorporate more converter samples (as they become commercially available for purchase), and to inform more comprehensive, simulation-based DC distribution efficiency studies.

Chapter 4

Characterization Dataset for Appliances and Converters

Over the course of the author's Master's degree, a variety of power converters and office-based appliances were tested and characterized in laboratory, at the Powerhouse Campus in Colorado State University. This data is published online, and can be freely downloaded from https://mountainscholar.org/handle/10217/207807. As the research continued during the Ph.D., this dataset was updated with additional characterization data and additional device. In total, 126 devices were measured, divided into:

– 58 AC/DC Converters (Including SISO and SIMO models)

– 35 DC/DC Converters and 5 SIMO (Including SISO and SIMO models)

– 33 AC Appliances

Tables 4.1, 4.2, and 4.3 show in details the devices characterized.

Table 4.1: AC Appliances Characterized

Appliance	Manufacturer	Model	Input Voltage	Power
Box Fan	Lasko	B20201	120VAC	60W
Coffee Maker	Keurig	K10	120VAC	1425W
Dishwasher	Whirlpool	WDT975SAHV	120VAC	972VA
Drill Charger	Snap-on	CTB8172BK	100-240VAC	60W
Drill Charger	DeWalt	DW9118	120VAC	$\sim$120VA
Fridge	Frigidaire	FCRS201RFB6	115VAC	575VA
Fridge	Whirlpool	WRF757SDHZ	115VAC	816VA
Hot Water Machine	Bunn	CWTF15-TC	120VAC	1370W
Microwave	GE	TSSTTVSKBT	120VAC	1300W
Microwave	Whirlpool	WMHA9019HV	120VAC	1800W
Mini Fridge	Magic Chef	HMDR310SE	115VAC	110W
Monitor	HP	E273	100-240VAC	$\sim$100VA
Monitor	HP	EliteDisplay E232	100-240VAC	$\sim$150VA
Monitor	HP	EliteDisplay E242	100-240VAC	$\sim$150VA
Multimeter	Keysight	34461A	100-240VAC	25VA
Portable Fan	Honeywell	HT900V4	120VAC	30VA
Power Strip	ACE	3279056	120VAC	1800W
Power Strip 1	Monster Power	S3A603	120VAC	-
Printer	HP	LaserJet 1022	110VAC	$\sim$440VA
Projector	BENQ	SH910	100-240VAC	$\sim$370VA
Server	HP	ProLiant ML350p Gen8	120-230VAC	460W
Server DL380 - With 1 Power Cable	HP	HPE ProLiant DL380 Gen10	100-240VAC	500W
Server DL380 - With 2 Power Cables	HP	HPE ProLiant DL380 Gen10	100-240VAC	500W
Soldering Iron	Weller	WES51	120VAC	60W
Tea Kettle	Aroma	AWK-108	120VAC	1500W
Toaster	Oster	JES2051SN2SS	120VAC	1650W
TV	Samsung	UN75JU6500FXZA	120VAC	342W
TV	Sharp	LC-60EQ10U	110-240VAC	188W
TV	Vizio	E43u-D2	120VAC	264VA
TV 2	Sharp	LC-60EQ10U	110-240VAC	188W
TV 3	Sharp	LC-60EQ10U	110-240VAC	188W
TV 4	Sharp	LC-60EQ10U	110-240VAC	188W
Water Dispenser	ClearH2O	D7A	120VAC	-

Table 4.2: AC/DC Converters Characterized

Converter	Type	Device Type	Manufacturer	Model	Input Voltage	Output Voltage	Power
AC-DC	SISO	Fan Converter	ShenZhen SOY Technology	SUN-0900070	100-240VAC	9VDC	6.3W
AC-DC	SISO	Label Printer	EDACPOWER ELEC.	EA1024F2-090	100-240VAC	9VDC	27W
AC-DC	SISO	Laptop Charger	Zmoon	A1749	100-240VAC	15VDC	90W
AC-DC	SISO	Laptop Charger	DELL	DA90PE1-00	100-240VAC	19.5VDC	90W
AC-DC	SISO	Laptop Charger	DELL	-	100-240VAC	19.5VDC	90W
AC-DC	SISO	Laptop Charger	Liteon	PA-1400-02	100-240VAC	12VDC	40W
AC-DC	SISO	Laptop Charger	Sibusa	391174-001	100-240VAC	18.5VDC	120W
AC-DC	SISO	Laptop Charger	HP	Series PPP014L	100-240VAC	18.5VDC	90W
AC-DC	SISO	Laptop Charger	HP	Series PPP017L	110-240VAC	18.5VDC	120W
AC-DC	SISO	Laptop Charger	HP	Series PPP009L-E	100-240VAC	19.5VDC	65W
AC-DC	SISO	Laptop Charger	HP	Series PPP013C-5	100-240VAC	19.5VDC	90W
AC-DC	SISO	Laptop Charger	HP	Series PPP012H-5	100-240VAC	19VDC	90W
AC-DC	SISO	Laptop Charger	HP	Series PPP009L-E	100-240VAC	19.5VDC	65W
AC-DC	SISO	Laptop Charger	HP	740015-002	100-240VAC	19.5VDC	45W
AC-DC	SISO	Monitor HP Pavilion 25xw Power Supply	TPV Electronics	ADPC1945	100-240VAC	19VDC	45W
AC-DC	SISO	iPhone Charger	Apple	A1385	100-240VAC	5VDC	5W
AC-DC	SISO	Phone Charger	Nokia	AC-20U	100-240VAC	5VDC	3.75W
AC-DC	SISO	Phone Charger	Samsung	ETA0U10JBE	100-240VAC	5VDC	3.5W
AC-DC	SISO	Phone Charger	Samsung	ETA0U10JBE	100-240VAC	5VDC	3.5W
AC-DC	SISO	Phone Charger	LG	STA-U17WS	100-240VAC	5.1VDC	3.57W
AC-DC	SISO	Phone Charger	LG	STA-U34WVI	100-240VAC	5.1VDC	3.57W
AC-DC	SISO	Phone Charger	LG	STA-U34WVI	100-240VAC	5.1VDC	3.57W
AC-DC	SISO	LED Driver	Mean Well	APV-25-24	90-264VAC	24VDC	25.2W
AC-DC	SISO	LED Driver	Osram	Oti48	120-277VAC	10-55VDC	48W
AC-DC	SISO	Switch Converter	Netgear	SAL012F1	100-120VAC	12VDC	12W
AC-DC	SISO	DC Power Supply	Tekpower	TP6005E	110VAC	60VDC	300W
AC-DC	SISO	DC Power Supply	Wanptek	KPS3010DF	110-220VAC	30VDC	300W
AC-DC	SISO	Power Supply	Delta Electronics	PMC-12V100W1AA	100-240VAC	12VDC	100W
AC-DC	SISO	Power Supply	Delta Electronics	PMC-24V100W1AA	100-240VAC	24VDC	100W
AC-DC	SISO	Power Supply	Omron	S8VM-03024 CD	100-240VAC	24VDC	30W
AC-DC	SISO	Power Supply	Mean Well	IRM-30-24ST	100-240VAC	24VDC	30W
AC-DC	SISO	Power Supply	Mean Well	IRM-30-12ST	100-240VAC	12VDC	30W
AC-DC	SISO	Power Supply	Mean Well	RSP-1000-48	100-240VAC	48VDC	1000W
AC-DC	SISO	Power Supply	Mean Well	SE-1000-48	100-240VAC	48VDC	1000W
AC-DC	SISO	Power Supply	Xunbuma	T-1000-48	110VAC	48VDC	1000W
AC-DC	SISO	Credit Card Machine Converter	Verizon	Au-790Mu	100-240VAC	6VDC	13.5W
AC-DC	SIMO	Power Supply	Seasonic	SSR-550PX	100-240VAC	3.3VDC	66W
AC-DC	SIMO	Power Supply	Seasonic	SSR-550PX	100-240VAC	5VDC	100W
AC-DC	SIMO	Power Supply	Seasonic	SSR-550PX	100-240VAC	12VDC	348W
AC-DC	SIMO	Power Supply	Seasonic (Fan ON)	SSR-550PX	100-240VAC	3.3VDC	66W
AC-DC	SIMO	Power Supply	Seasonic (Fan ON)	SSR-550PX	100-240VAC	5VDC	100W
AC-DC	SIMO	Power Supply	Seasonic (Fan ON)	SSR-550PX	100-240VAC	12VDC	348W
AC-DC	SIMO	Socket with USB output	Charging Essentials	LA-5A-4	125VAC	5VDC	4.2W
AC-DC	SIMO	USB plug 2 ports	No Brand	US2018	100-240VAC	5VDC	10.2W
AC-DC	SIMO	Power Hub Driver	Nextek	PHD16-ACDC-DIM-P-24-6	120VAC	16 x 24VDC	1600W
AC-DC	SIMO	Power Hub Driver	Nextek	PHD16-ACDC-DIM-P-24-6	208VAC	16 x 24VDC	1600W
AC-DC	SIMO	Power Hub Driver Blade	Nextek	PHD-Blade-S9	120VAC	12 x 24VDC	1200W
AC-DC	SIMO	Power Hub Driver Blade	Nextek	PHD-Blade-S9	208VAC	12 x 24VDC	1200W
AC-DC	SIMO	Power Supply	Integrated Power Designs	REL-70-4006-CHCO	85-264VAC	5V-24V-12V	70W
AC-DC	SIMO	Power Supply	Integrated Power Designs	GRN-110-4003-CHCO	85-264VAC	5V-24V-12V	110W
AC-DC	SIMO	Power Supply	Integrated Power Designs	REL-185-4001-CHCO	85-264VAC	3.3V-5V-12V	185W

Table 4.3: DC/DC Converters Characterized

Converter	Type	Device Type	Manufacturer	Model	Input Voltage	Output Voltage	Power
DC-DC	SISO	Cigarette Lighter	Gearmo	GM-UCPDCARB	12VDC	5VDC	15W
DC-DC	SISO	Cigarette Lighter	Gearmo	GM-UCPDCARB	24VDC	5VDC	15W
DC-DC	SISO	Laptop Charger	HP	F1455A	12VDC	19VDC	75W
DC-DC	SISO	Laptop Charger	Powseed	PA-3900-Z3	12VDC	19VDC	90W
DC-DC	SISO	Laptop Charger	Outtag	PA-4900-OT	12VDC	19VDC	90W
DC-DC	SISO	Laptop Charger	Bixpower	BX-DD90X	24VDC	18.5VDC	90W
DC-DC	SISO	Laptop Charger	Bixpower	BX-DD90X	24VDC	18.5VDC	90W
DC-DC	SISO	Laptop Charger	Bixpower	BX-DD90X	24VDC	18.5VDC	90W
DC-DC	SISO	Laptop Charger	Bixpower	BX-DD90X	24VDC	15VDC	90W
DC-DC	SISO	Cig. Car Adapter	RoHS	CRA-HLY-PD65W	12VDC	5VDC	15W
DC-DC	SISO	Cig. Car Adapter	RoHS	CRA-HLY-PD65W	24VDC	5VDC	15W
DC-DC	SISO	Laptop Charger, 12V to 19V	Bixpower	BX-DD90X	12VDC	19.5VDC	90W
DC-DC	SISO	Power Supply	Mean Well	RSD-30G-12	12VDC	12VDC	30W
DC-DC	SISO	Power Supply	Mean Well	RSD-30G-12	24VDC	12VDC	30W
DC-DC	SISO	Power Supply	Mean Well	RSD-30G-24	12VDC	24VDC	30W
DC-DC	SISO	Power Supply	Mean Well	RSD-30G-24	24VDC	24VDC	30W
DC-DC	SISO	Power Supply	Mean Well	SD-100A-24	9.5-18VDC	24VDC	100W
DC-DC	SISO	Power Supply	Mean Well	SD-100B-12	19-36VDC	12VDC	100W
DC-DC	SIMO	Power Supply	Integrated Power Designs	DC2-70-4006-CHCO	18-36VDC	5V-24V-12V	70W
DC-DC	SIMO	Power Supply	Integrated Power Designs	DC4-70-4006-CHCO	36-72VDC	5V-24V-12V	70W
DC-DC	SIMO	Power Supply	Integrated Power Designs	DC2-110-4006-CHCO	18-36VDC	5V-24V-12V	110W
DC-DC	SIMO	Power Supply	Integrated Power Designs	DC4-110-4006-CHCO	36-72VDC	5V-24V-12V	110W
DC-DC	SIMO	Power Supply	Integrated Power Designs	DC2-185-4001-CH	18-36VDC	3.3V-5V-12V	185W
DC-DC	SIMO	Power Hub Driver	Nextek	PHD16-ACDC-DIM-P-24-6	380VDC	16 x 24VDC	1600W
DC-DC	SIMO	Power Hub Driver Blade	Nextek	PHD-Blade-S9	380VDC	12 x 24VDC	1200W
DC-DC	SIMO	Cig. L. Purdue - L. port	Herrick Labs Purdue	-	12VDC	5VDC	10.5W
DC-DC	SIMO	Cig. L. Purdue - L. port	Herrick Labs Purdue	-	24VDC	5VDC	10.5W
DC-DC	SIMO	Cig. L. Purdue - U. port	Herrick Labs Purdue	-	12VDC	5VDC	10.5W
DC-DC	SIMO	Cig. L. Purdue - U. port	Herrick Labs Purdue	-	24VDC	5VDC	10.5W
DC-DC	SIMO	Cig. L. Verizon - MiniUSB	Verizon	MIC34DUALVPC-F2	12VDC	5VDC	17W
DC-DC	SIMO	Cig. L. Verizon - MiniUSB	Verizon	MIC34DUALVPC-F2	24VDC	5VDC	17W
DC-DC	SIMO	Cig. L. Verizon - USB	Verizon	MIC34DUALVPC-F2	12VDC	5VDC	17W
DC-DC	SIMO	Cig. L. Verizon - USB	Verizon	MIC34DUALVPC-F2	24VDC	5VDC	17W
DC-DC	SIMO	Power Hub Driver	Nextek	1600-C2-Z-380	380VDC	16 x 24VDC	1600W
DC-DC	SIMO	Desktop Power Supply	IEI Technology	ACE-4520C	24VDC	12VDC	120W

To perform the characterization tests, a testbed capable of emulating an AC or DC distribution was built. For an AC distribution, a 3kVA Delta-Wye transformer connected to the utility mains converts from $480V_{AC}$ to $208/120V_{AC}$ into a load center. From the 100A main circuit breaker of the load center, there are six branches, each protected with a 10A circuit breaker: 4x $120V_{AC}$, 1x two-phase $208V_{AC}$, and 1x three-phase $208V_{AC}$. Each branch has measurement boxes installed, which provide access to current and voltage probes. For a DC distribution, a Nextek power hub is connected to either $120V_{AC}$ or $208V_{AC}$, providing 16 DC outputs, each rated at 24V and 100W. Figure 4.1 shows a diagram of the testbed described and Figure 4.2 is a real picture of the system.

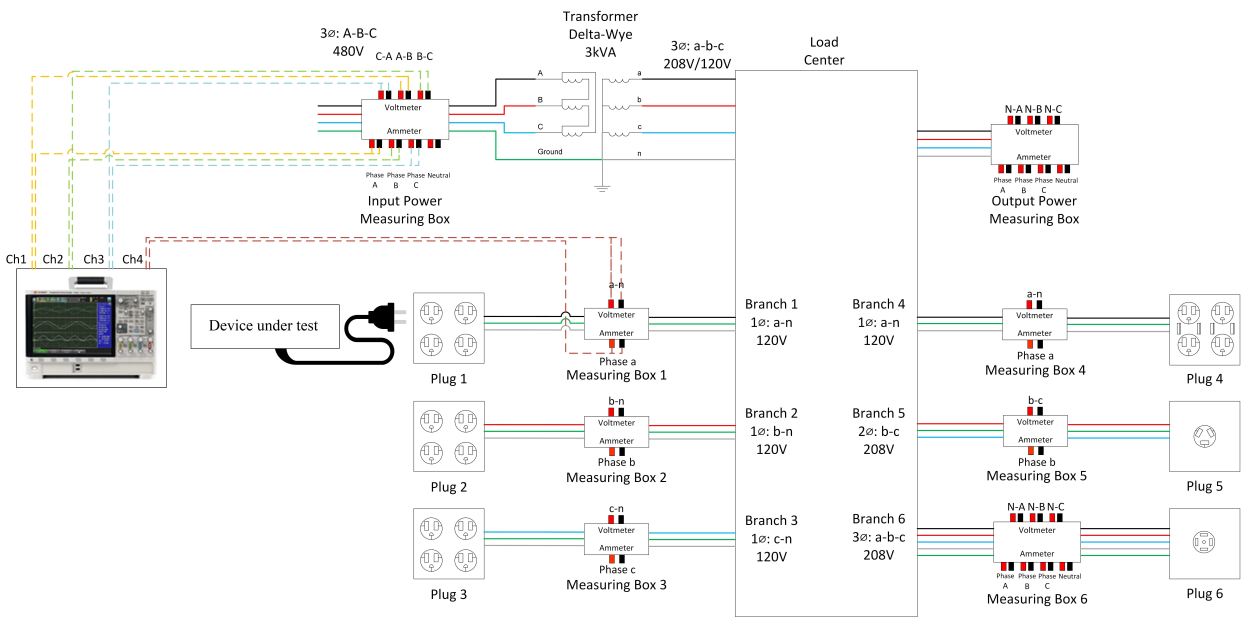


Figure 4.1: Testbed diagram for AC distribution configuration.

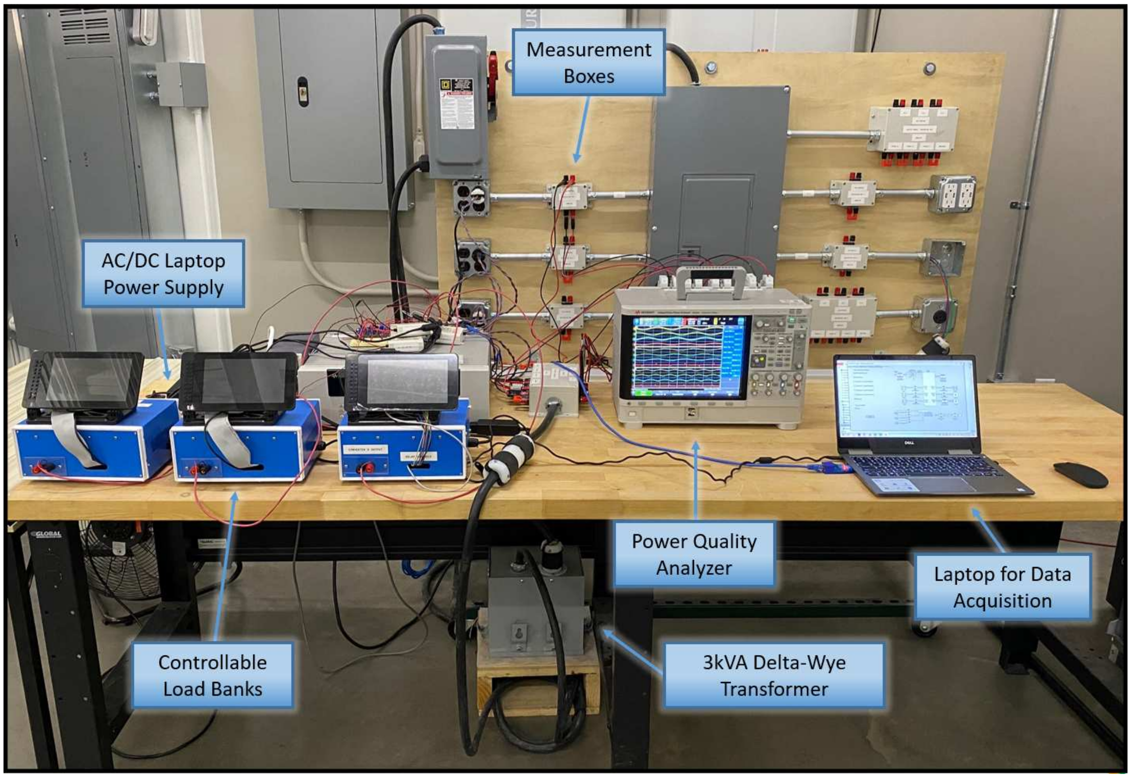


Figure 4.2: Test setup built to run characterization tests

Chapter 5

A Cautionary Note on Using Smart-Plugs for Research Data Acquisition

This chapter was submitted to *Energies* journal and is under review [120].

5.1 Introduction

Smart plugs have increased in popularity with the growth of home automation and internet of things (IoT) applications. The smart plug market has grown from an estimated $0.71 billion in 2016 to $2.59 billion in 2021 [121]. North America leads this market due to its high acceptance of new technologies and consumers' disposable income [122]. Smart plugs are one class of 'smart' IoT devices that communicate via local or internet networking, allow connected loads to be switched on and off remotely, and often include monitoring functions for on/off times, power consumption, and usage patterns. With the modernization of the power grid, newer home appliances increasingly build these capabilities into the appliance's control circuitry. In contrast, the add-on smart plugs studied here can be used to add on/off control and monitoring to legacy appliances without built-in capabilities. For example, several smart plugs manufacturers offer an 'away' mode, in which controlled loads switch on/off randomly to give the appearance that the user is home.

The most basic function of a smart plug is to programmatically connect or disconnect loads remotely via Wi-fi or cellular phone networking. Technologies such as Bluetooth Low Energy (BLE), Sigfox, and ZigBee are also being studied and used as alternatives [122, 123]. In a typical implementation, households can control their smart plug through specific apps from manufacturers, or through an application programming interface (API) using common programming languages. More advanced versions, particularly the energy monitoring smart plugs, include low-cost circuits that measure power and energy consumption. Hence, the device can not only be controlled remotely, but, depending on the model, it can also exchange voltage, current, and/or power consumption data via external communication [124].

Local power measurement is particularly useful for energy management systems, such as demand response systems, to balance demand and supply in the electric system [125]. A simulation showed that using smart plugs to defer shiftable loads from peak hours reduced peak demand of a household by up to 33% [126]. Smart plugs can eliminate appliances' energy consumption when in standby mode by simply disconnecting them from the wall plug; multiple studies indicate these losses are not negligible and must be taken into consideration to improve grid efficiency [123, 127]. If people monitor energy usage, they not only become aware of their energy use behavior but may also change the way they consume energy [128, 129]. In an observational study in South Korea, when the power consumption of 125 households was monitored by smart plugs [130] the households used 5% less energy than comparable households. The savings increased when more appliances were monitored and were more prominent when smart plugs were used for cooling and heating appliances, and video and audio devices.

While IoT devices in residential, industrial, and commercial buildings are essential for this type of monitoring and control, their presence on communications networks also raises privacy and security concerns [131–134]. For example, energy usage information can indicate periods when residents are not at home and what their habits are [135] – a potential security concern. A study exposed a vulnerability of Kasa HS100 and the Belkin Wemo Mini smart plugs when operating in 'away' mode. Although the smart plugs system can simulate human usage, it is statistically different from real usage patterns and could easily be detected by an attacker either by observing acoustic and visual cues or by wi-fi sniffing [136]. Another study analyzed security problems with the Edimax SP-2101W smart plug [137]. They were able to launch four attacks on different fronts: device scanning, brute force, spoofing, and firmware. Through the attacks, they acquired the user's authentication credentials, allowing for malicious remote operation and malware installation into the plug. Likewise, a variety of studies have analyzed the threats and vulnerabilities associated with a wide range of similar IoT devices that likely occur in smart plugs as well [138–143].

Additional applications are being built on smart plugs. As the home automation market grows, manufacturers are tapping machine learning to perform advanced functions such as behavior diagnosis and classification [124, 136]. Environment awareness smart plugs (EnAPlugs) were proposed, integrating artificial intelligence and multiple sensors in one device [144]. This would make it possible to understand the context of the load being controlled, and also share this information. At the time of this study, none of these advanced uses was available commercially.

Across all studies surveyed by the authors, there was a conspicuous acceptance that power and energy usage reported by the plugs is accurate; no study validated the accuracy of the devices used for measurement or control. In contrast, the authors' recent studies [3, 10, 45], noted substantial errors in power measurements from the smart plugs used in the study, raising questions about the accuracy of this class of device for research work, demand management, or other applications where accurate power measurements are assumed. Therefore, this paper analyzes the accuracy of five commercially available energy monitoring smart plugs from major market players Belkin, TP-Link, Etekcity, Emporia, and Sonoff. Live smart plug data were recorded and compared to measurements made by a high-accuracy laboratory instrument. Section 5.2 explains the methods used in this study; Section 5.3 presents results and discussion; and Section 5.4 summarizes lessons learned.

5.2 Methods

This study measures and analyzes the accuracy of power and energy measurements from five smart plug models. When smart plugs are used to capture load data for research, the monitored loads often exhibit fast variations in power consumption. Our prior experience [3,10,45] indicates that these variations impact the measurements made by the smart plugs. Therefore, the testing performed for this study considered not only steady-state loads but also loads that vary at a range of frequencies. The methods required for this study are:

1. Analyze the power measurement error.
2. Calculate and analyze the energy measurement error.
3. Estimate measurement delays

The study also did a qualitative analysis of differences between datasheet specifications and laboratory tests.

Table 5.1 summarizes all five energy monitoring smart plugs analyzed in this study, the technology used for communication, their prices, and the integration they offer. The Emporia and the Sonoff devices did not offer the 'away' mode, although it was available for all remaining models. Table 5.2 provides data sheet specifications for key electrical parameters. Since this study focused on the U.S. market, all devices were tested at 120VAC, 60Hz. *Specified power consumption* indicates the data sheet's indication of the internal power consumption of the smart plug itself. Functionally, four of the 5 units were compact enough to fit into one space on a duplex receptacle; the Belkin WEMO has a larger body and blocks the other space.

Figure 5.1 illustrates the test setup. Power measurements reported by the smart plugs were collected using python scripts developed by the study team. These scripts request measurement data from the device under test via Wi-Fi at a frequency of 1Hz. Data were

Table 5.1: Smart Plugs - Models and features

Manufacturer	Model	Technology	Price	Integration	Away Mode
Belkin	FC029V2	Wi-Fi	$47.95	WEMO app, Alexa, Google Assistant, and Apple HomeKit	Yes
TP-Link	KP115	Wi-Fi	$22.99	Kasa app, Alexa, Google Assistant, and Samsung SmartThings	Yes
Etekcity	ESW15-USA	Wi-Fi	$10.99	VeSync app, Alexa, Google Assistant	Yes
Emporia	EMS02	Wi-Fi	$8.50	Emporia app, Alexa, and Google Assistant	No
Sonoff	S31	Wi-Fi	$16.95	eWeLink app, Alexa, and Google Assistant	No

Table 5.2: Smart Plugs - Electrical specifications

Manufacturer	Model	Voltage	Maximum Current	Frequency	Specified Power Consumption
Belkin	FC029V2	$120V_{AC}$	15A	60Hz	<3W
TP-Link	KP115	$100\text{-}120V_{AC}$	15A	60Hz	not stated
Etekcity	ESW15-USA	$120V_{AC}$	15A	60Hz	0.7 - 1.2W
Emporia	EMS02	$100\text{-}240V_{AC}$	15A (1hr/day); 10A continuous	50-60Hz	<3W
Sonoff	S31	$120V_{AC}$	15A	60Hz	not stated

time-stamped when received by the script. The reference instrument (Keysight Power Analyzer (PA) model PA2203A, power measurement accuracy of 0.1%) was connected to the two measurement boxes in Figure 5.1, immediately before and after the smart plug in the circuit, allowing the power analyzer to measure both the smart plug's power consumption as well as the load on the smart plug.

For each smart plug, tests were run for 15-minutes. One of the two resistors was used to load the smart plug at any time. For each test, the resistor was switched on and off by a solid-state relay (SSR) controlled by a microcontroller (Raspberry Pi, Model 3). Loads were switched on and off (full cycle) at the following frequencies (time step): 0Hz (i.e. steady-state), 0.01Hz (100s), 0.02Hz (50 s), 0.05Hz (20 s), 0.1Hz (10 s), 0.2Hz (5 s), 0.5Hz (2 s), 1Hz (1 s), and 2Hz (0.5 s). With two resistors, 24Ω (600 W) and 240Ω (60W), and 9 switching frequencies, a total of 18 tests were performed for each smart plug.

Once the data was recorded, measurements from the smart plugs were synchronized and compared with measurements from the power analyzer. Power error was calculated using:

$$\epsilon_{P,i} = |P_{s,i} - P_{a,i}|, i = 1...N \tag{5.1}$$

where ϵ is the calculated error, P is one reported power value with the subscripts s and a indicating the smart plug and the power analyzer, respectively, i indicates the i^{th} time

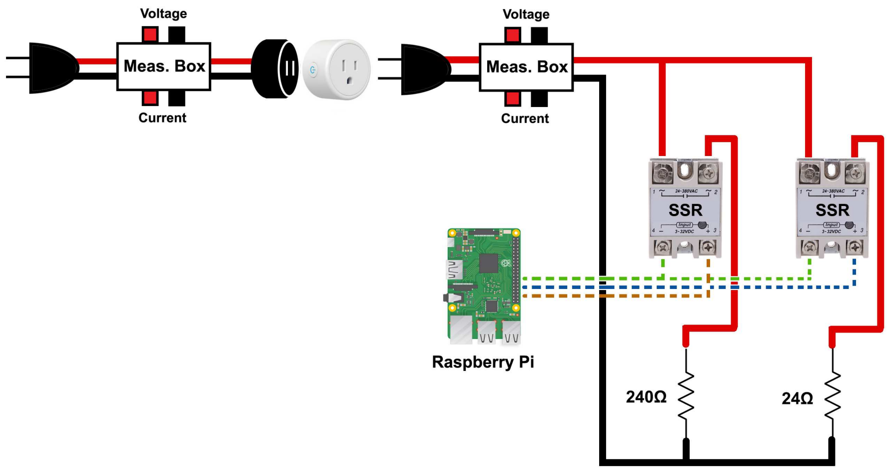


Figure 5.1: Test Setup. The Raspberry Pi switches the solid state relays by generating PWM pulses using one General Purpose Input/Outputs (GPIOs) pin. The reference instrument was connected to the indicated measurement boxes for both voltage and current probes.

step, and N is the number of samples being compared. Measured or reported energy is calculated as

$$E_x = \Delta t \cdot \sum_{i=1}^{N} P_{x,i} \tag{5.2}$$

where the x may be s and a to indicate the smart plug and the power analyzer values. The time step, Δt, is 1 second for this study. Finally, energy error for a test is:

$$\epsilon_{\mathrm{E}} = \frac{|E_a - E_p|}{E_p} \tag{5.3}$$

As noted below, the smart plugs are typically controlled or queried using a software app of some type, which may also provide summaries of measured power data. Unless otherwise noted, the app was available on the App Store® for iPhone™ and on Google Play™ for the Android™. However, for this study, as for most research use, we utilized a device-specific API to retrieve and store measured data. Four of the 5 devices offered a python API to record measured data, the 5th required the use of a 'Home Assistant' tool. The connectivity method for each unit is described below:

5.2.1 Belkin WEMO

This study used the `ouimeaux` [145] python API, a library that provides simple commands to detect the smart plug on the WiFi network and to request power consumption information from it. The user also sets a power threshold (in the control app or the code), above which the device starts to report measurement data; for this study, the threshold was set to the minimum value, 0W. The app controls the smart plug, tracks electricity usage over time, and can export data directly to the user's e-mail.

5.2.2 TP-Link KP115

This study used the `pyHS100` [146] library, which can also be used for other TP-Link smart devices, such as power strips, wall switches, and light bulbs. The*Kasa Smart* phone app allows users to control and monitor the device.

5.2.3 Etekcity ESW15-USA

This study used the `pyvesync` [147] library, which is also compatible with other *VeSync smart home* devices, such as humidifiers, smart lights, etc.

5.2.4 Emporia EMS02

This study used the `PyEmVue` [148] library. The Emporia device stores measurements remotely in the cloud; there is no option to directly query the smart plug. Additionally, due to the significant data traffic on Emporia's servers, the manufacturer limited the number of requests that can be made for data. Therefore, the study made a single server request, after each test, for the last N seconds of data, at 1 second time step.

5.2.5 Sonoff S31

The Sonoff unit also required additional and indirect methods to query data from the device. First, the smart plug required *Home Assistant*, open-source software for home automation which is able to communicate with a range of smart devices (currently integrates with more than 1000 devices) and performs a variety of home automation commands [149]. Home Assistant was installed on a Raspberry Pi microcontroller to create a local server. To directly access voltage, current, and power information provided by the smart plug, the data collection software utilized the *Home Assistant Community Store (HACS)*, which allows users to build their own libraries and add-ons, and *eWeLink* [150], a recently developed add-on for HACS for Sonoff products. Using the python utility `AppDaemon`, the data acquisition software queried power measurements from the smart plug and inserted data into Google Sheets™, using the `gspread` [151] library. Due to the complexity of this data access method, measurements could not be received consistently at rates faster than every 3 seconds. The reader should note that *Home Assistant* and associated libraries are undergoing rapid growth and frequent change, and the method utilized here may be obsolete by the time of publication.

5.3 Results

5.3.1 Errors in Energy Measurements

For many research or control applications, the primary quantity of interest is energy - either as a control input or as the dependent variable of an experiment. Energy measurement errors were calculated for all test units as per Eqn. 5.3, and are shown in Figures 5.2-5.4 as a function of the load switching frequency.

Energy errors follow the same pattern for all models. For steady state loads (0Hz), the energy error is small. As the load becomes more variable (0.01-1 Hz), energy error increases, indicating that the smart plugs are not able to accurately follow the changes in power consumption. When the switching speed increases above 1 Hz, the smart plugs see the load as a PWM-equivalent resistance and current, and the on/off cycling is integrated within the power measurement, causing the energy measurement error to decrease. Similar behavior was seen for both 24Ω and 240Ω loads, indicating that the energy measurement error depends more on the variability of the load than the size of the load. While

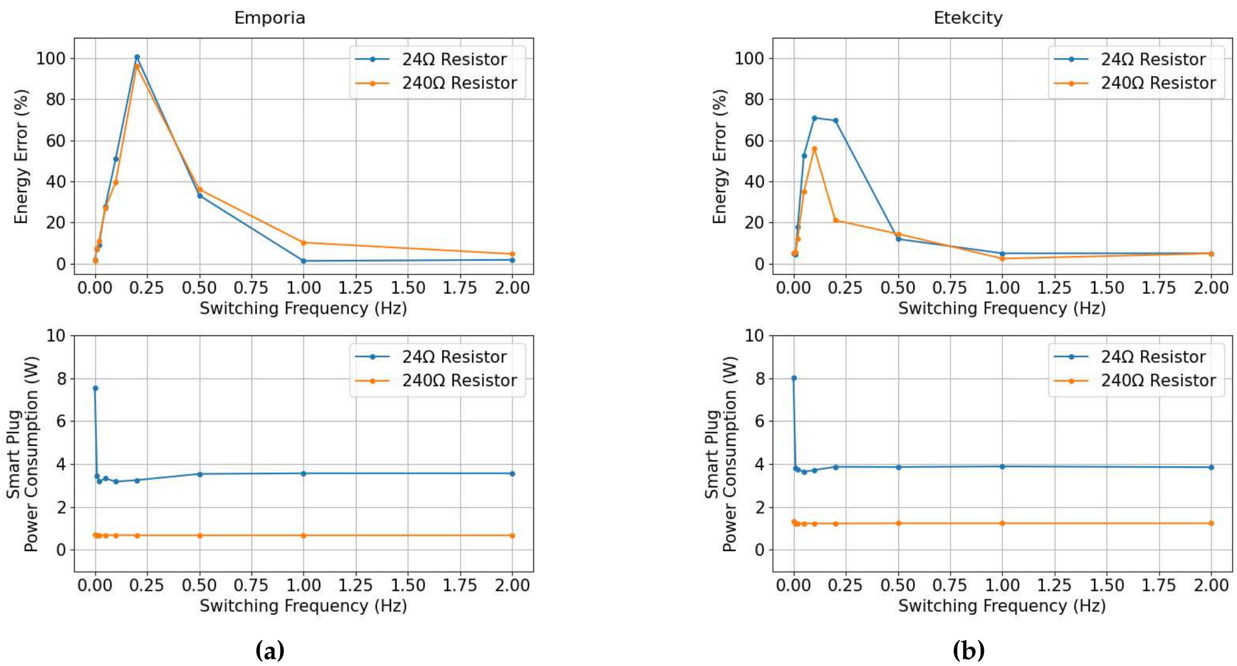


Figure 5.2: Frequency response of energy error on smart plugs: (a) Emporia and (b) Etekcity.

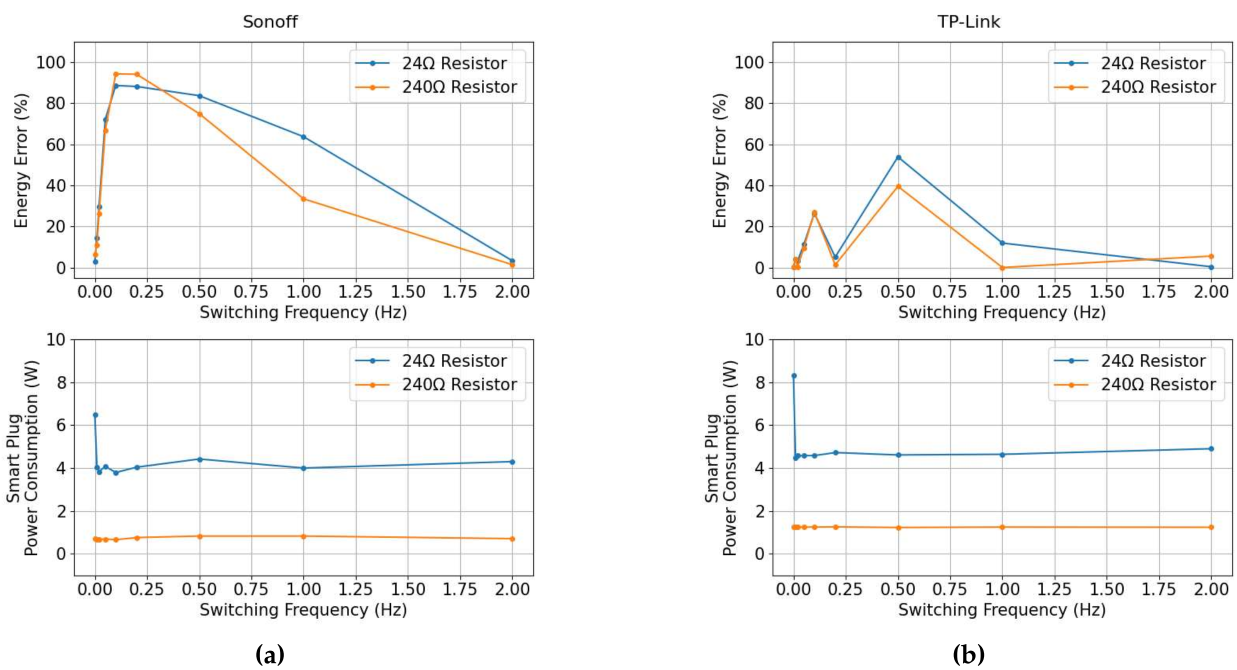
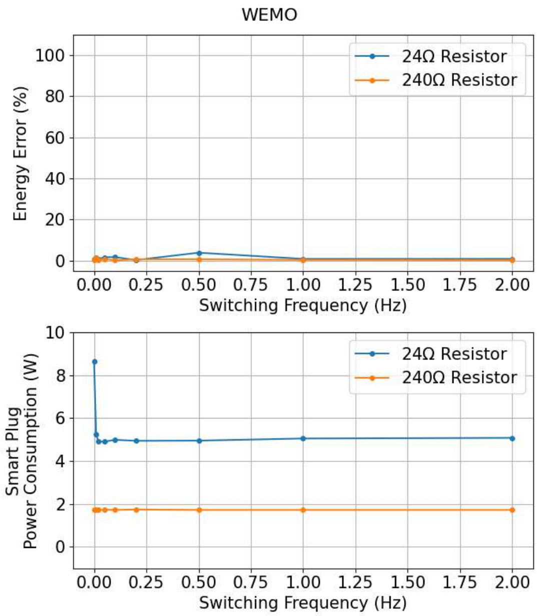


Figure 5.3: Frequency response of energy error on smart plugs: (a) Sonoff and (b) TP-Link.



(a)

Figure 5.4: Frequency response of energy error on WEMO smart plug.

similar for all units, errors were largest in the Emporia and Sonoff models, with maximum errors of 101% and 94%, respectively, and somewhat smaller for the Etekcity and TP-Link models (71%, and 54% respectively). The Belkin WEMO had the smallest error, never exceeding 1.7%. These results indicate that, for all models but the WEMO smart plug, there are substantial errors in measured energy if the smart plugs are used to measure electronic loads with a high variation on power consumption.

Unfortunately, this type of highly variable load is common in residential or office environments. To illustrate this point, it is useful to look at the load behavior for electronic loads, such as laptops, desktops, and monitors [45]. Figure 5.5 shows the variation in power consumption for an HP ProBook 440 G7 Laptop, converter model L25298-002, 65W, during regular operation. The plot on the left shows the power consumption variation for an interval of 10 seconds; the plot on the right shows data for the same test focusing on the interval from 6.5 to 7.0 seconds.

The instantaneous active load is defined as *voltage* $\times$ *current* at any instant [152], 21 kHz in this example. However, for most instruments average power depends on the integrating time of the instrument. When integrating over a short interval, such as one 60 Hz cycle (16.67 ms, light red curve in Figure 5.5), the reported power captures the fast variations in load produced by power electronic loads, which have current waveforms generally synchronized with voltage. However, if power is averaged over a longer time window – e.g. 250 ms – reported power will average these variations across the integrating period of the instrument (red curve in Figure 5.5). Therefore, individual power measurements may deviate from instantaneous power due to the sampling period of the meter, but, in all cases, an accurate instrument should integrate power accurately over an extended period – i.e. it should produce an accurate *energy* measurement. This is clearly not the case with 4 of the 5 smart plugs tested here.

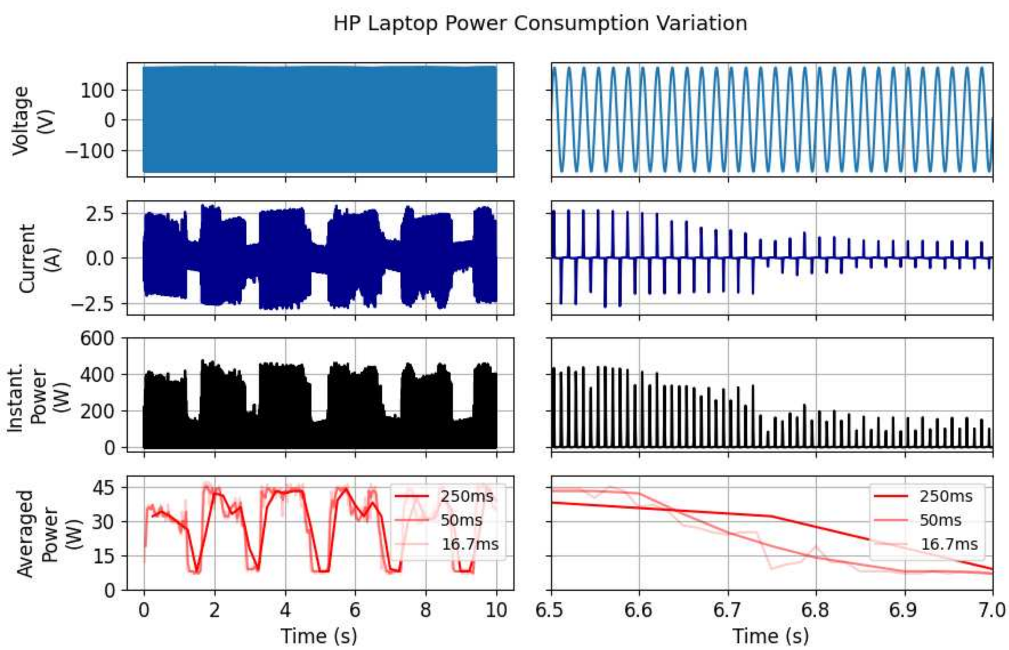


Figure 5.5: Variations in power consumption for an HP ProBook 440 G7 Laptop during regular operation. The plots on the left show the results for a 10 seconds time window (21000 sample points); the plots on the right zoom in into the interval between 6.5 and 7 seconds.

5.3.2 Errors in Power Measurements

Figure 5.6 shows the power measurement error for all energy monitoring devices, from 0-2Hz, based upon reported and measured power for all switching frequencies, included in the Supplementary Material. The error for each load switching frequency is represented by a box plot, as indicated in the caption. Each smart plug is represented by one group of four charts, where left are errors for frequencies below the Nyquist cutoff of the load switching frequency, right is above, upper is 600W load, lower 60W.

For all models, the power measurement error is low at constant load, and substantial when loads are switching, even when the switching period is 20s or longer. For switching frequencies below 0.5 Hz (or 0.17Hz for the Sonoff model), below the Nyquist cutoff of the smart plug's reporting rate, change in the load is sufficiently slow that a power measurement instrument should reflect the on/off switching of the load. This frequency range also represents the common frequency range for variable power electronic loads, as noted above. None of the smart plugs reports power accurately under these conditions; this is reflected in the both wide box plots and number of outlier observations.

For a load switching frequency of 2 Hz, and likely above, load variability is faster than the internal measurement process, and gravitates toward the average power reading – i.e. $\frac{1}{2}$ peak power. However, these readings are typically unstable, and the smart plugs report highly variable readings that frequently stray from average power. While this is unsurprising, given the type of measurement device, it is clear that none of the units contain filtering for high-frequency load changes, and therefore produce a substantial number of near-random power readings that do not reflect the actual load. Figure 5.7 shows a time series for this behavior, which is representative of all models tested.

For other frequencies, each smart plug exhibited a unique set of measurement anomalies. Figure 5.8 shows the power measurements with a 240Ω load switched at 0.01Hz (50s on / 50s off). When the load was switched off, the Emporia model measured an offset power value of 20-25W several times, while Etekcity and Sonoff had a significant offset

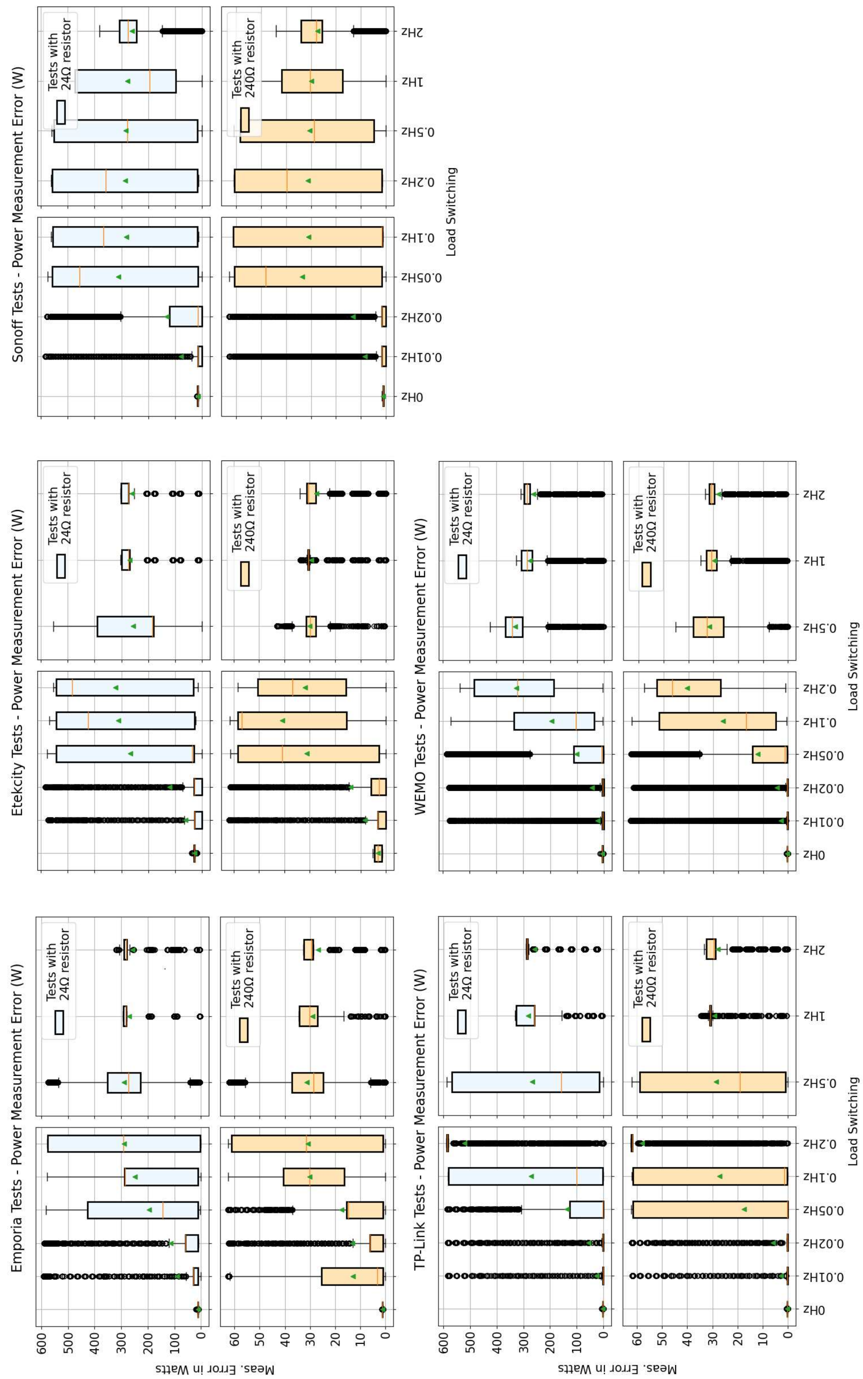


Figure 5.6: Power measurement errors. Each group of plots presents results from one smart plug. Box plots on the left in each group are for frequencies below the Nyquist cutoff of the sample frequency (0.17Hz for the Sonoff model and 0.5 Hz for the remaining); plots on the right are for frequencies above. Upper plot in each group is for 600W load, lower for 60W load. Lines in boxes are medians, triangles are means, whiskers represent the upper and lower quartiles and points are outliers.

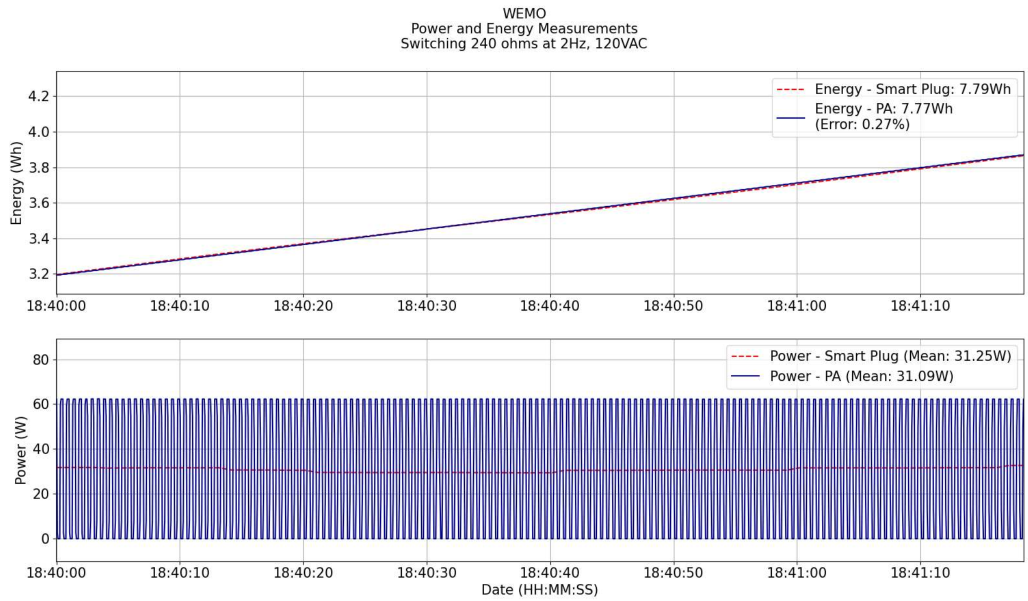
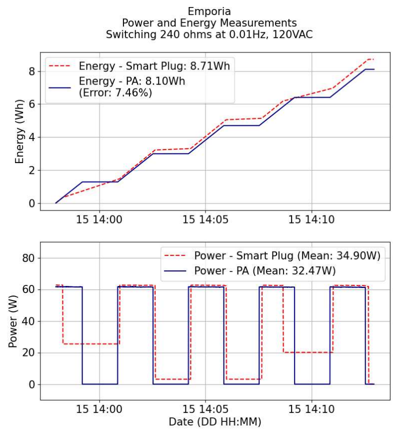


Figure 5.7: One-second power readings from the Belkin WEMO, compared to the power analyzer readings. The ≈60W load was switching at 2 Hz, and the WEMO power reading reflects the average power of approximately ≈30 W, as expected.

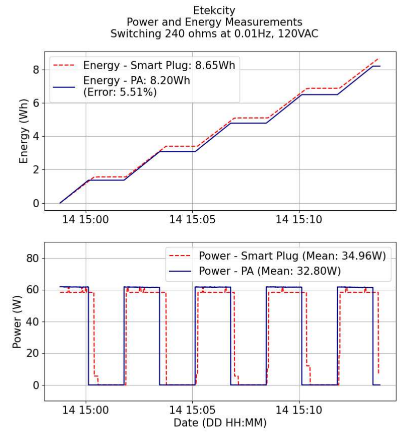
delay on their measurements. TP-Link had a smaller offset delay following the variations in load, while the Belkin exhibited the fastest reaction to load changes. These delays and offsets produce many of the large errors or outliers in Figure 5.6.

To identify reporting delays and measure their variability, a set of 5 replicate tests were completed with each smart plug loaded with a 24Ω load switching at 0.02Hz for 15 minutes. Delays were computed at 50% of output power (≈ 300W), to avoid 'stuck' outputs as in Figure 5.8a. Results represent a measure of the time required for the smart plug to react to a substantial change in load. Table 5.3 shows the average time delay and standard deviation in the delay over the 5 replicate tests. *Off* and *on* delays are similar for units other than the Etekcity and Sonoff units, which exhibited substantially longer delays sensing a load had switched off.

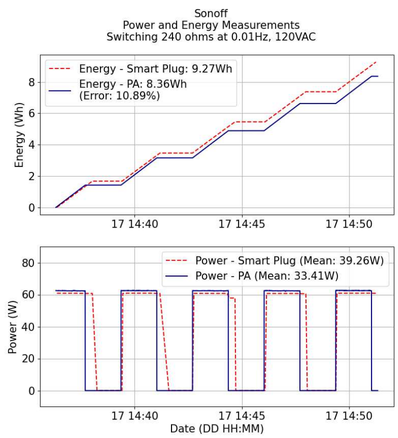
In contrast to the other units, the measurement delay of the Belkin WEMO exhibits a behavior similar to that of a first-order transfer function – a reaction time constant – rather than a delay. Most of the errors shown in Figure 5.6 for the WEMO are due to this



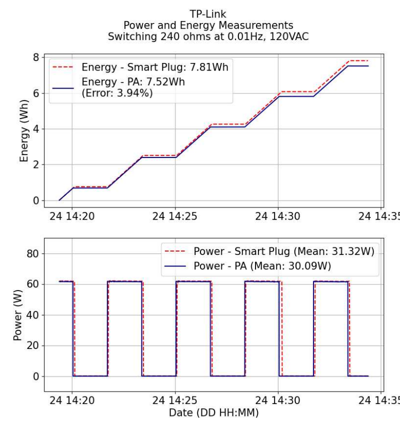
(a)



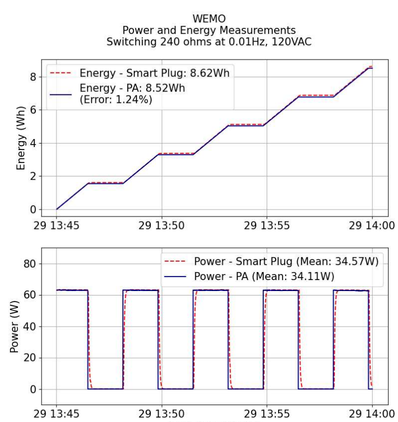
(b)



(c)



(d)



(e)

Figure 5.8: Power and energy measurements, with a load of 240Ω being switched at 0.01Hz. Top panel energy, bottom power, measurements. While all unit showed reaction delays, some also failed to return to low power readings and/or exhibited highly variable delays.

source, and as a result, the mean power for the WEMO is more accurate than the other units, and energy exhibits little measurement error. For all units, the reporting delays - typically 3-6 times the sample frequency - would make it difficult to combine loads made by multiple smart plugs measuring simultaneously, as is often desired for research or control purposes.

Table 5.3: Time Delay for detecting load switching states

Model	Average Time Delay - On (s)	Average Time Delay - Off (s)
Emporia	6.53 ± 1.50	6.56 ± 1.44
Etekcity	4.33 ± 1.11	16.06 ± 3.16
Sonoff	3.29 ± 1.22	20.44 ± 1.29
TP-Link	5.19 ± 0.55	5.37 ± 0.62
WEMO	3.23 ± 0.45	3.06 ± 0.39

The accuracy analysis can be further subdivided into 2 additional analyses: First, ϵ_{On}, the accuracy when the load was on, as a fraction:

$$\epsilon_{On} = \frac{\sum_i |P_{a,i} - P_{s,i}|}{\sum_i P_{a,i}} \; for\ i \in \; P_{a,i} > 0.85 \cdot 600W \tag{5.4}$$

and second, ϵ_{Off}, the measurement offset error reported by the smart plug when the load was off, reported as a power error in Watts:

$$\epsilon_{Off} = \frac{\sum_i |P_{a,i} - P_{s,i}|}{N}, \; for\ i \in P_{a,i} < 0.15 \cdot 600W \tag{5.5}$$

Results are shown in Table 5.4 for the same data set as 5.3.

TP-Link was the more accurate device reporting the power measurements when the load was on, and also the model with the lowest offset when the load was off. As previously noted, errors when the load is off, are particularly significant for the Emporia model. The accuracy and offset measurement for the WEMO smart plug are affected by

Table 5.4: Accuracy when load is on, and offset measurement when load is off

Model	Accuracy When On (%)	Offset Meas. When Off (W)
Emporia	1.97 ± 0.10	57.44 ± 1.44 W
Etekcity	4.88 ± 0.09	3.01 ± 1.61
Sonoff	2.49 ± 0.03	1.02 ± 0.26
TP-Link	0.53 ± 0.04	0.26 ± 0.05
WEMO	1.14 ± 0.03	4.28 ± 0.05

the time-constant delay behavior that it presents, since this device has a fast reaction to a load change, but takes a considerable time to reach the steady-state value.

5.3.3 Belkin WEMO Time-Constant

The Belkin WEMO represents a special case for power measurement errors, which is also amendable to correction post-measurement. Assuming the response of the WEMO is represented by a first-order transfer function ($\frac{1}{\tau * s+1}$), where τ is the time constant, a set of tests described in [3] were performed to characterize this time constant value, resulting in $\tau \approx 2.77s$. Using this time constant, an inverse transfer function can be used to at least approximately correct the distortion in the reported power measurements. Since the exact inverse function (τ * s + 1) requires differentiation and is therefore improper, an approximate inverse transfer function is necessary:

$$\frac{\tau * s + 1}{T * s + 1} \tag{5.6}$$

Provided $T << \tau$, this transfer function is implementable.

5.3.4 Parasitic Load

Results in Figures 5.2-5.4 show that all the smart plugs had internal power consumption that was strongly dependent on the load connected to the plug. For small loads (e.g. 240Ω / 60 W) power consumption was within manufacturer specifications. However, for large loads (e.g. 24Ω resistor / 600W), internal power consumption exceeded 3W, substantially higher than manufacturer's specifications (Table 5.2). For the 600 W load, internal power consumption was as high as 6.5-8.5W for steady-state loads, or over 1% of the load. Given that the smart plugs were all rated for 15A (1800W), these data suggest that the devices' power consumption may often substantially exceed that listed in datasheets.

5.4 Conclusions

Data collected for this study indicate that smart plugs exhibit substantial measurement errors for all but long-duration, steady-state, loads. For highly variable power electronic loads, which are common on residential and office circuits, errors include inaccurate and noisy power measurements, systemic energy errors from most units, and substantial, and often variable, reporting delays. Further, both errors and reporting delays are dependent upon the variability in loads, peaking at frequencies where common loads, such as office equipment, often operate.

A common assumption for low-cost measurement devices used in research studies is that, while these devices exhibit errors in short-term measurements, the errors 'average out', minimizing error when averaged over extended periods. Underlying this assumption are two subsidiary assumptions: (1) individual measurements are unbiased in the mean, and (2) errors are not dependent on the variability in measured quantity. Results from this study support neither the main nor subsidiary assumptions. Considering the most common long-term power measurement – i.e. 'energy consumption' – experiments show substantial bias in the mean that is dependent upon load variability (Figures 5.2-5.4 and 5.8). Similarly, our data also show that smart plugs struggle to accurately report current power values in most cases, and these errors are also dependent upon load variability (Figure 5.6). As a result, these data indicate that the use of smart plugs for power research and control applications should be viewed with caution, and practitioners should validate smart plug performance before committing to use of these devices in studies, as control system inputs, in penalty or billing systems, or for similar activities.

Chapter 6

Conclusion

The results presented in the course of this work are based on measured data extracted from tests performed in the laboratory. In contrast, much of the literature focused on in-building power systems based on simulation, which in turn is driven by data extracted from vendors' data sheets or theoretical studies of power converter performance or appliance behavior, rather than measurements of commercial supplies or appliances. The research performed here illustrates that these assumptions can lead to significant errors, and further, that these errors cascade through topics as diverse as in-building harmonic cancellation assumptions, AC versus DC power distribution, and measurement devices utilized by researchers to capture end-point load measurements.

- *Harmonic cancellation:* In AC distribution systems, harmonic cancellation is often overestimated due to faulty assumptions of the load on converters. The outcome changes significantly when actual loads on power converts are recorded.
- *AC/DC versus DC/DC endpoint conversion:* Based largely upon theoretical studies, literature in this area concluded that DC/DC conversion is substantially (2.5 to 15%) [19, 43, 93, 153, 154] more efficient that AC/DC conversion. In contrast, research performed here indicated a significant difference between the results, based upon observations only accessible in measurements:
  - Office-based appliances' power converters are generally oversized for appliances' load in most operating conditions, which concentrates their operation in the lower part of the power converters operational performance curves.
  - Converters efficiency curves at lower operating loads are more variable in efficiency, efficiency is lower, and efficiency drops off quickly and non-linearly near zero load.

  - The combination of errors in load assumptions (uniformly distributed over the power converter's rated load) and errors in characterizing efficiency of converters (DC/DC converters are more efficient that AC/DC converters over the entire load range) compound to create errors in comparisons of these two distribution systems.
  - This study, despite being based on a limited sample of commercially available converters, shows that only half of the analyzed DC/DC converters presented superior efficiency than AC/DC converters in the same application. The relative improvement of that half times the best efficiency found for the central converter often falls below the conclusion of prior studies [19, 43, 95, 96, 154].

- *Smart plugs:* This is a case where a casual-use, informal product, has become increasingly popular as a basis for research, primarily due to low cost, ease of use, and integrated safety suitable for a study environment. Use in this environment imbues these devices with an assumed accuracy that exceeds their actual performance. Indeed, work performed here indicates that the performance of these devices may not even be suitable for less accuracy-intensive applications, such as building automation or energy auditing. The performance becomes even worse when they are used to monitor devices with fast variations in power consumption, as is often the case of home and office loads. When monitoring such loads, the sampled smart plugs presented substantial and variable delays reporting power measurements, depending on the load variability. Results also change significantly depending on the smart plug model, indicating that a validation of the monitoring device to be used is necessary prior to its utilization in research studies.

Much recent work [27,29,43,94–96] has concluded that DC distribution systems would be substantially, if not significantly, more efficient than the current AC distribution systems used in buildings. A substantial portion of this conclusion rests on the performance analyses of devices in each architecture, much of it from theoretical studies of devices – i.e. what *should* be possible with appropriate design – rather than on measurements of actual devices – i.e. what is *actually designed* when economic and commercial considerations come into play.

For example, there is limited the demand for DC/DC converters, which is currently driven by the automotive market (trucks and recreational vehicles) based upon legacy 12 and 24 V systems with a premium on low cost over efficiency. This lower demand and the non-maturity of this segment does not push the competition as strongly as in the AC power converter market, where power converters are manufactured with an economy of scale that enables using higher quality components at a lower cost, more design investment, and more testing. Additionally, the AC/DC market has been subjected to aggressive regulatory and voluntary efficiency standards, such as EnergyStar™ [99] or 80 PLUS™ [105]. These factors promote superior efficiency of these AC/DC devices relative to DC/DC devices. Furthermore, the lack of standards and regulations in DC distribution, impede scaling of the DC market, reducing uptake of these devices and the necessary economies of scale for suppliers to invest in efficiency improvement.

Therefore, *while in theory* DC distribution for commercial buildings has the potential to achieve greater efficiency than the current AC distribution system, measurement results indicate that 'real world' performance may lag theoretical assumptions. While this study does not include all parts of the distribution system, the sharp contrast between measured and simulated results in the study areas indicate that the simulated results for the remaining components of the distribution systems should be treated with caution, as similar economies of scale may impact other components, such as DER power conversion, variable frequency drives, and centralized lighting supplies.

As future topics of research there are a few that could bring relevant contributions to the adoption and maturity of the DC market. One is regarding one of the main findings of this work, which is the need for improvement on efficiency, quality, and cost of commercial DC-DC converters. A second area concerns the definition of regulatory standards for DC distribution systems. If governments are interested in the adoption of renewables, there have to be wide incentives for their penetration, including their integration with the DC market, and standardization is a basic and urgently needed requirement. Not having a standard code establishing the correct plug or receptacle for DC devices is a major obstacle to the manufacture and sale of DC devices. In terms of regulatory standards yet, there is also the need in finding an optimal or appropriate voltage level for residential and commercial in-building DC distribution systems, both in terms of safety and efficiency. A third field, would be an investigation on efficiency of devices upstream of the endpoint conversion, such as in-buildings distribution transformers, central AC/DC converters, and MPPTs.

Bibliography

[1] D. of Energy of the United States, "Energy design and scoping tool for dc distribution systems." https://www.energy.gov/eere/buildings/downloads/energy-design-and-scoping-tool-dc-distribution-systems, 2017. Accessed: 2020-04-23.

[2] A. F. B. d. Santos, *Device characterization on energy design and scoping tool for DC distribution systems and a study on harmonics in AC/DC converters in low voltage distribution*. PhD thesis, Colorado State University, 2020.

[3] A. Santos, G. P. Duggan, P. Young, S. Frank, A. Hughes, and D. Zimmerle, "Harmonic cancellation within ac low voltage distribution for a realistic office environment," *International Journal of Electrical Power & Energy Systems*, vol. 134, p. 107325, 2022.

[4] A. Mansoor, W. Grady, A. Chowdhury, and M. Samotyi, "An investigation of harmonics attenuation and diversity among distributed single-phase power electronic loads," in *Proceedings of IEEE/PES Transmission and Distribution Conference*, pp. 110–116, IEEE, 1994.

[5] A. Mansoor, W. Grady, P. Staats, R. Thallam, M. Doyle, and M. Samotyj, "Predicting the net harmonic currents produced by large numbers of distributed single-phase computer loads," *IEEE Transactions on Power Delivery*, vol. 10, no. 4, pp. 2001–2006, 1995.

[6] W. M. Grady, A. Mansoor, E. F. Fuchs, P. Verde, and M. Doyle, "Estimating the net harmonic currents produced by selected distributed single-phase loads: computers, televisions, and incandescent light dimmers," in *2002 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 02CH37309)*, vol. 2, pp. 1090–1094, IEEE, 2002.

[7] A. Mansoor and W. Grady, "Analysis of compensation factors influencing the net harmonic current produced by single-phase nonlinear loads," in *8th International Conference on Harmonics and Quality of Power. Proceedings (Cat. No. 98EX227)*, vol. 2, pp. 883–889, IEEE, 1998.

[8] Y. Hegazy and M. Salama, "Calculations of diversified harmonic currents in multiple converter systems," in *2000 Power Engineering Society Summer Meeting (Cat. No. 00CH37134)*, vol. 2, pp. 727–731, IEEE, 2000.

[9] A. J. Collin, C. E. Cresswell, and S. Ž. Djokic, "Harmonic cancellation of modern switch-mode power supply load," in *Proceedings of 14th International Conference on Harmonics and Quality of Power-ICHQP 2010*, pp. 1–9, IEEE, 2010.

[10] A. Santos, G. Duggan, S. Frank, D. Gerber, and D. Zimmerle, "Endpoint use efficiency comparison for ac and dc power distribution in commercial buildings," *Energies*, vol. 14, no. 18, p. 5863, 2021.

[11] "Emerge alliance occupied space standard faqs." https://www.emergealliance.org/standards/occupied-space-2/standard-faqs/, 2021. Accessed: 2020-11-25.

[12] J. Staples, J. Martin, and S. Rajan, "Standards for the introduction of accessible dc power in buildings," in *2019 IEEE Symposium on Product Compliance Engineering (SPCE Austin)*, pp. 1–6, IEEE, 2019.

[13] D. J. Becker and B. Sonnenberg, "Dc microgrids in buildings and data centers," in *2011 IEEE 33rd International Telecommunications Energy Conference (INTELEC)*, pp. 1–7, IEEE, 2011.

[14] M. J. Stewart, J. M. Counsell, and A. Al Kaykhan, "Design and specification of building integrated dc electricity networks," in *2016 Future Technologies Conference (FTC)*, pp. 1237–1240, IEEE, 2016.

[15] C. Davidson, P. Gagnon, P. Denholm, and R. Margolis, “Nationwide analysis of us commercial building solar photovoltaic (pv) breakeven conditions,” tech. rep., National Renewable Energy Lab.(NREL), Golden, CO (United States), 2015.

[16] *Renewables 2019*. OECD, 2019.

[17] “Annual energy outlook 2020.” https://www.eia.gov/outlooks/aeo/pdf/AEO2020%20Buildings.pdf, 2020. Accessed: 2020-11-01.

[18] W. M. Power and R. E. S. Association, “Us energy storage monitor: Q2 2020 executive summary,” tech. rep., September 2020.

[19] D. J. Hammerstrom, “Ac versus dc distribution systemsdid we get it right?,” in *2007 IEEE Power Engineering Society General Meeting*, pp. 1–5, IEEE, 2007.

[20] M. Yilmaz and P. T. Krein, “Review of the impact of vehicle-to-grid technologies on distribution systems and utility interfaces,” *IEEE Transactions on power electronics*, vol. 28, no. 12, pp. 5673–5689, 2012.

[21] R. H. Ashique, Z. Salam, M. J. B. A. Aziz, and A. R. Bhatti, “Integrated photovoltaic-grid dc fast charging system for electric vehicle: A review of the architecture and control,” *Renewable and Sustainable Energy Reviews*, vol. 69, pp. 1243–1257, 2017.

[22] Office of Energy Analysis, “Annual energy outlook 2020 with projections to 2050,” tech. rep., U.S. Energy Information Administration, Washington, D.C., 2020.

[23] R. Langner and K. Trenbath, “Integrating smart plug and process load controls into energy management information system platforms: A landscaping study,” Technical Report NREL/TP-5500-74080, National Renewable Energy Laboratory, Golden, CO, USA, 2019.

[24] N. N. Opiyo, "A comparison of dc-versus ac-based minigrids for cost-effective electrification of rural developing communities," *Energy Reports*, vol. 5, pp. 398–408, 2019.

[25] K. Siraj and H. A. Khan, "Dc distribution for residential power networks—a framework to analyze the impact of voltage levels on energy efficiency," *Energy Reports*, vol. 6, pp. 944–951, 2020.

[26] G. Arunkumar, D. Elangovan, P. Sanjeevikumar, J. B. H. Nielsen, Z. Leonowicz, and P. K. Joseph, "Dc grid for domestic electrification," *Energies*, vol. 12, no. 11, p. 2157, 2019.

[27] D. L. Gerber, V. Vossos, W. Feng, C. Marnay, B. Nordman, and R. Brown, "A simulation-based efficiency comparison of ac and dc power distribution networks in commercial buildings," *Applied Energy*, vol. 210, pp. 1167–1187, 2018.

[28] F. Dastgeer and A. Kalam, "Efficiency comparison of dc and ac distribution systems for distributed generation," in *2009 Australasian Universities Power Engineering Conference*, pp. 1–5, IEEE, 2009.

[29] G.-S. Seo, J. Baek, K. Choi, H. Bae, and B. Cho, "Modeling and analysis of dc distribution systems," in *8th International Conference on Power Electronics-ECCE Asia*, pp. 223–227, IEEE, 2011.

[30] B. T. Patterson, "Dc, come home: Dc microgrids and the birth of the" enernet"," *IEEE Power and Energy Magazine*, vol. 10, no. 6, pp. 60–69, 2012.

[31] T.-F. Wu, C.-H. Chang, L.-C. Lin, G.-R. Yu, and Y.-R. Chang, "Dc-bus voltage control with a three-phase bidirectional inverter for dc distribution systems," *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 1890–1899, 2012.

[32] L. Mackay, N. H. v. d. Blij, L. Ramirez-Elizondo, and P. Bauer, "Toward the universal dc distribution system," *Electric Power Components and Systems*, vol. 45, no. 10, pp. 1032–1042, 2017.

[33] A. Pratt, P. Kumar, and T. V. Aldridge, "Evaluation of 400v dc distribution in telco and data centers to improve energy efficiency," in *INTELEC 07-29th International Telecommunications Energy Conference*, pp. 32–39, IEEE, 2007.

[34] M. E. Baran and N. R. Mahajan, "Dc distribution for industrial systems: opportunities and challenges," *IEEE transactions on industry applications*, vol. 39, no. 6, pp. 1596–1601, 2003.

[35] S. Sudhoff, S. Pekarek, R. Swanson, V. Duppalli, D. Horvath, A. Kasha, R. Lin, B. Marquet, P. O'Regan, H. Suryanarayana, *et al.*, "A reduced scale naval dc microgrid to support electric ship research and development," in *2015 IEEE Electric Ship Technologies Symposium (ESTS)*, pp. 464–471, IEEE, 2015.

[36] M. M. Mardani, M. H. Khooban, A. Masoudian, and T. Dragičević, "Model predictive control of dc–dc converters to mitigate the effects of pulsed power loads in naval dc microgrids," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 7, pp. 5676–5685, 2018.

[37] A. T. Elsayed, A. A. Mohamed, and O. A. Mohammed, "Dc microgrids and distribution systems: An overview," *Electric power systems research*, vol. 119, pp. 407–417, 2015.

[38] P. Gross and K. L. Godrich, "Total dc integrated data centers," in *INTELEC 05-Twenty-Seventh International Telecommunications Conference*, pp. 125–130, IEEE, 2005.

[39] G. AlLee and W. Tschudi, "Edison redux: 380 vdc brings reliability and efficiency to sustainable data centers," *IEEE Power and Energy Magazine*, vol. 10, no. 6, pp. 50–59, 2012.

[40] K. Hirose, “Dc powered data center with 200 kw pv panels,” in *2018 International Power Electronics Conference (IPEC-Niigata 2018-ECCE Asia)*, pp. 822–825, IEEE, 2018.

[41] B. R. Shrestha, U. Tamrakar, T. M. Hansen, B. P. Bhattarai, S. James, and R. Tonkoski, “Efficiency and reliability analyses of ac and 380 v dc distribution in data centers,” *IEEE Access*, vol. 6, pp. 63305–63315, 2018.

[42] A. Sannino, G. Postiglione, and M. H. Bollen, “Feasibility of a dc network for commercial facilities,” in *Conference Record of the 2002 IEEE Industry Applications Conference. 37th IAS Annual Meeting (Cat. No. 02CH37344)*, vol. 3, pp. 1710–1717, IEEE, 2002.

[43] M. Starke, L. M. Tolbert, and B. Ozpineci, “Ac vs. dc distribution: A loss comparison,” in *2008 IEEE/PES Transmission and Distribution Conference and Exposition*, pp. 1–7, IEEE, 2008.

[44] H. Pang, E. Lo, and B. Pong, “Dc electrical distribution systems in buildings,” in *2006 2nd International Conference on Power Electronics Systems and Applications*, pp. 115–119, IEEE, 2006.

[45] A. F. B. dos Santos, *Device Characterization on Energy Design and Scoping Tool for DC Distribution Systems and a Study on Harmonics in AC/DC Converters in Low Voltage Distribution*. PhD thesis, Colorado State University, 2020.

[46] A. Elmoudi, M. Lehtonen, and H. Nordman, “Effect of harmonics on transformers loss of life,” in *Conference Record of the 2006 IEEE International Symposium on Electrical Insulation*, pp. 408–411, IEEE, 2006.

[47] M. J. Ghorbani and H. Mokhtari, “Impact of harmonics on power quality and losses in power distribution systems,” *International Journal of Electrical & Computer Engineering (2088-8708)*, vol. 5, no. 1, 2015.

[48] Y. Wang, J. Yong, Y. Sun, W. Xu, and D. Wong, "Characteristics of harmonic distortions in residential distribution systems," *IEEE Transactions on Power Delivery*, vol. 32, no. 3, pp. 1495–1504, 2016.

[49] A. Mansoor, "Lower order harmonic cancellation: impact of low-voltage network topology," in *IEEE Power Engineering Society. 1999 Winter Meeting (Cat. No. 99CH36233)*, vol. 2, pp. 1106–1109, IEEE, 1999.

[50] J. C. Gómez and M. M. Morcos, "Impact of ev battery chargers on the power quality of distribution systems," *IEEE transactions on power delivery*, vol. 18, no. 3, pp. 975–981, 2003.

[51] J. J. Desmet, I. Sweertvaegher, G. Vanalme, K. Stockman, and R. J. Belmans, "Analysis of the neutral conductor current in a three-phase supplied network with nonlinear single-phase loads," *IEEE Transactions on Industry Applications*, vol. 39, no. 3, pp. 587–593, 2003.

[52] N. Gupta, A. Swarnkar, and K. Niazi, "A novel method for simultaneous phase balancing and mitigation of neutral current harmonics in secondary distribution systems," *International Journal of Electrical Power & Energy Systems*, vol. 55, pp. 645–656, 2014.

[53] E. El-Saadany and M. Salama, "Reduction of the net harmonic current produced by single-phase non-linear loads due to attenuation and diversity effects," *International Journal of Electrical Power & Energy Systems*, vol. 20, no. 4, pp. 259–268, 1998.

[54] A. Marzoughi, H. Imaneini, and A. Moeini, "An optimal selective harmonic mitigation technique for high power converters," *International Journal of Electrical Power & Energy Systems*, vol. 49, pp. 34–39, 2013.

[55] M. Davudi, S. Torabzad, and B. Ojaghi, "Analysis of harmonics and harmonic mitigation methods in distribution systems," *Australian Journal of Basic and Applied Sciences*, vol. 5, no. 11, pp. 996–1005, 2011.

[56] L. Kütt, E. Saarijärvi, M. Lehtonen, H. Mõlder, and J. Niitsoo, "A review of the harmonic and unbalance effects in electrical distribution networks due to ev charging," in *2013 12th International Conference on Environment and Electrical Engineering*, pp. 556–561, IEEE, 2013.

[57] R. N. Rao, "Harmonic analysis of small scale industrial loads and harmonic mitigation techniques in industrial distribution system," *International Journal of Engineering Research and Applications*, vol. 3, no. 4, pp. 1511–1540, 2013.

[58] L. Motta and N. Faúndes, "Active/passive harmonic filters: Applications, challenges & trends," in *2016 17th International Conference on Harmonics and Quality of Power (ICHQP)*, pp. 657–662, IEEE, 2016.

[59] S. H. Qazi and M. W. Mustafa, "Review on active filters and its performance with grid connected fixed and variable speed wind turbine generator," *Renewable and Sustainable Energy Reviews*, vol. 57, pp. 420–438, 2016.

[60] J. Aswal and Y. Pal, "Passive and active filter for harmonic mitigation in a 3-phase, 3-wire system," in *2018 2nd International Conference on Inventive Systems and Control (ICISC)*, pp. 668–672, IEEE, 2018.

[61] S. Z. Djokic and A. J. Collin, "Cancellation and attenuation of harmonics in low voltage networks," in *2014 16th International Conference on Harmonics and Quality of Power (ICHQP)*, pp. 137–141, IEEE, 2014.

[62] M. Rashad, D. M. Minhas, M. Ashraf, and S. Hussain, "Pfc topologies for ac to dc converters in dc micro-grid," in *2016 18th Mediterranean Electrotechnical Conference (MELECON)*, pp. 1–6, IEEE, 2016.

[63] I. Standard, "61000-3-2: 2004, limits for harmonic current emissions," *International Electromechanical Commission. Geneva*, 2004.

[64] M. N. Z. Abidin, "Iec 61000-3-2 harmonics standards overview," *Schaffner EMC Inc., Edsion, NJ, USA*, 2006.

[65] I. E. Commission *et al.*, "Electromagnetic compatibility (emc)–part 3-4: Limits–limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 a," *IEC*, vol. 61000, pp. 3–4, 1998.

[66] G. Spiazzi, "Electromagnetic compatibility (emc) low-frequency standards," 2020.

[67] S. Khalid and B. Dwivedi, "Power quality issues, problems, standards & their effects in industry with corrective means," *International Journal of Advances in Engineering & Technology*, vol. 1, no. 2, p. 1, 2011.

[68] V. Ćuk, J. Cobben, P. Ribeiro, and W. Kling, "A review of international limits for harmonic voltages and currents in public networks," in *2014 16th International Conference on Harmonics and Quality of Power (ICHQP)*, pp. 621–625, IEEE, 2014.

[69] I. Standard, "61000-2-2: Electromagnetic compatibility (emc)-part 2-2: Environment-compatibility levels for low-frequency conducted disturbances and signalling in public low-voltage power supply systems," *International Electrotechnical Commission*, 2002.

[70] I. Standard, "61000-2-4," *Electromagnetic Compatibility (EMC), Part*, vol. 2, 2002.

[71] T. M. Blooming and D. J. Carnovale, "Application of ieee std 519-1992 harmonic limits," in *Conference Record of 2006 Annual Pulp and Paper Industry Technical Conference*, pp. 1–9, IEEE, 2006.

[72] C. Masetti, "Revision of european standard en 50160 on power quality: Reasons and solutions," in *Proceedings of 14th International Conference on Harmonics and Quality of Power-ICHQP 2010*, pp. 1–7, IEEE, 2010.

[73] V. d. N. DA-CH-CZ, "Vdn ev et al.(2007) kompendium technische regeln zur beurteilung von netzrückwirkungen," 2013.

[74] E. Association *et al.*, *Planning levels for harmonic voltage distortion and the connection of non-linear equipment to transmission systems and distribution networks in the United Kingdom*. Electricity Association, 2001.

[75] A. Kamenka, "Six tough topics about harmonic distortion and power quality indices in electric power systems," *The Schaffner Group, Luterbach*, 2014.

[76] M. Rylander, W. M. Grady, and M. Narendorf, "Experimental apparatus, testing results, and interpretation of the impact of voltage distortion on the current distortion of typical single-phase loads," *IEEE transactions on power delivery*, vol. 24, no. 2, pp. 844–851, 2009.

[77] V. Ćuk, J. Cobben, W. Kling, and R. Timens, "An analysis of diversity factors applied to harmonic emission limits for energy saving lamps," in *Proceedings of 14th International Conference on Harmonics and Quality of Power-ICHQP 2010*, pp. 1–6, IEEE, 2010.

[78] P. F. Ribeiro, *Time-varying waveform distortions in power systems*, vol. 6. John Wiley & Sons, 2009.

[79] P. Ribeiro, *Investigations of harmonic penetration in transmission systems*. PhD thesis, 1985.

[80] J. P. Trovão, P. G. Pereirinha, L. Trovão, and H. M. Jorge, "Electric vehicles chargers characterization: Load demand and harmonic distortion," in *11th International Conference on Electrical Power Quality and Utilisation*, pp. 1–7, IEEE, 2011.

[81] A. Mansoor, W. Grady, R. Thallam, M. Doyle, S. Krein, and M. Samotyj, "Effect of supply voltage harmonics on the input current of single-phase diode bridge rectifier loads," *IEEE Transactions on Power Delivery*, vol. 10, no. 3, pp. 1416–1422, 1995.

[82] H. A. Attia, M. El-Metwally, and O. M. Fahmy, "Harmonic distortion effects and mitigation in distribution systems," *Journal of American Science*, vol. 6, no. 10, pp. 173–183, 2010.

[83] A. Cavallini, M. Loggini, and G. C. Montanari, "Comparison of approximate methods for estimate harmonic currents injected by ac/dc converters," *IEEE Transactions on Industrial Electronics*, vol. 41, no. 2, pp. 256–262, 1994.

[84] E. E. Ahmed, W. Xu, and G. Zhang, "Analyzing systems with distributed harmonic sources including the attenuation and diversity effects," *IEEE Transactions on Power Delivery*, pp. 2602–2612, 2018.

[85] P. Caramia and P. Verde, "Cost-related harmonic limits," in *2000 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No. 00CH37077)*, vol. 4, pp. 2846–2851, IEEE, 2000.

[86] D. L. Gerber, R. Liou, and R. Brown, "Energy-saving opportunities of direct-dc loads in buildings," *Applied Energy*, vol. 248, pp. 274–287, 2019.

[87] "NumPy, Numerical Computing Library," 2020. https://numpy.org/.

[88] U. E. I. Administration, "Commercial buildings energy consumption survey," 2020.

[89] "Estimated u.s. energy consumption in 2020: 92.9 quads." https://flowcharts.llnl.gov/content/assets/docs/2020_United-States_Energy.pdf, 2020. Accessed: 2021-05-20.

[90] V. A. Prabhala, B. P. Baddipadiga, P. Fajri, and M. Ferdowsi, "An overview of direct current distribution system architectures & benefits," *Energies*, vol. 11, no. 9, p. 2463, 2018.

[91] D. D.-C. Lu and V. G. Agelidis, "Photovoltaic-battery-powered dc bus system for common portable electronic devices," *IEEE Transactions on Power Electronics*, vol. 24, no. 3, pp. 849–855, 2009.

[92] A. Rasheed, S. Khan, H. E. Gelani, and F. Dastgeer, "Ac vs. dc home: An efficiency comparison," in *2019 International Symposium on Recent Advances in Electrical Engineering (RAEE)*, vol. 4, pp. 1–6, IEEE, 2019.

[93] V. Vossos, K. Garbesi, and H. Shen, "Energy savings from direct-dc in us residential buildings," *Energy and Buildings*, vol. 68, pp. 223–231, 2014.

[94] H. Azazi, E. El-Kholy, S. Mahmoud, and S. Shokralla, "Review of passive and active circuits for power factor correction in single phase, low power ac-dc converters," in *Proceedings of the 14th International Middle East Power Systems Conference (MEPCON'10)*, p. 217, 2010.

[95] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, and D. P. Kothari, "A review of single-phase improved power quality ac-dc converters," *IEEE Transactions on industrial electronics*, vol. 50, no. 5, pp. 962–981, 2003.

[96] A. Sannino, G. Postiglione, and M. H. J. Bollen, "Feasibility of a DC Network for Commercial Facilities," vol. 39, no. 5, pp. 1499–1507, 2003.

[97] K. Engelen, E. L. Shun, P. Vermeyen, I. Pardon, R. D'hulst, J. Driesen, and R. Belmans, "The feasibility of small-scale residential dc distribution systems," in *IECON 2006-32nd Annual Conference on IEEE Industrial Electronics*, pp. 2618–2623, IEEE, 2006.

[98] C. Calwell and A. Mansoor, "Ac-dc server power supplies: Making the leap to higher efficiency," in *Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005. APEC 2005.*, vol. 1, pp. 155–158, IEEE, 2005.

[99] "What is energy star." https://www.energystar.gov/about?s=footer&s=footer, 2021. Accessed: 2021-05-22.

[100] O. I. Asensio and M. A. Delmas, "The effectiveness of us energy efficiency building labels," *Nature Energy*, vol. 2, no. 4, pp. 1–9, 2017.

[101] "Working with global businesses to drive the transition to a net-zero economy." https://wwf.panda.org/discover/our_focus/climate_and_energy_practice/what_we_do/climatebusiness/climate_business_network/?, 2021. Accessed: 2021-05-22.

[102] A. Trifilova, J. Bessant, F. Jia, and J. Gosling, "Sustainability-driven innovation and the climate savers' programme: experience of international companies in china," *Corporate Governance*, 2013.

[103] "Energy efficiency requirements by levels." https://slpower.com/data/collateral/PW153KB_DS.pdf, 2021. Accessed: 2021-05-22.

[104] "Energy conservation program: Energy conservation standards for external power supplies." https://www.energy.gov/sites/prod/files/2014/02/f7/eps_ecs_final_rule.pdf, 2014. Accessed: 2021-05-22.

[105] "What is 80 plus certified?," 2021. Accessed: 2021-05-22.

[106] F. H. Khan, T. D. Geist, B. Vairamohan, B. D. Fortenbery, and E. Hubbard, "Challenges and solutions in measuring computer power supply efficiency for 80 plus® certification," in *2009 Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition*, pp. 2079–2085, IEEE, 2009.

[107] Q. Li, F. C. Lee, M. Xu, and C. Wang, "Light load efficiency improvement for pfc," in *2009 IEEE Energy Conversion Congress and Exposition*, pp. 3755–3760, IEEE, 2009.

[108] N. Rasmussen, "Ac vs. dc power distribution for data centers," *American Power Conversion, Tech. Rep*, vol. 63, 2007.

[109] V. Evans, "Why low voltage direct current grids?," 2013.

[110] K. Murari and N. P. Padhy, "A network-topology-based approach for the load-flow solution of ac–dc distribution system with distributed generations," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 3, pp. 1508–1520, 2018.

[111] H. M. Ahmed, A. B. Eltantawy, and M. Salama, "A generalized approach to the load flow analysis of ac–dc hybrid distribution systems," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 2117–2127, 2017.

[112] Z. Liu and M. Li, "Research on energy efficiency of dc distribution system," *AASRI procedia*, vol. 7, pp. 68–74, 2014.

[113] J. Newmiller, W. Erdman, J. S. Stein, and S. Gonzalez, "Sandia inverter performance test protocol efficiency weighting alternatives," in *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)*, pp. 0897–0900, 2014.

[114] W. Bower, C. Whitaker, W. Erdman, M. Behnke, and M. Fitzgerald, "Performance test protocol for evaluating inverters used in grid-connected photovoltaic systems," *Sandia National Laboratories*, 2004.

[115] G. Mendelson, "All you need to know about power over ethernet (poe) and the ieee 802.3 af standard," *Internet Citation,[Online] Jun*, 2004.

[116] D. Said and K. Nor, "Effects of harmonics on distribution transformers," in *2008 Australasian Universities Power Engineering Conference*, pp. 1–5, IEEE, 2008.

[117] M. Shareghi, B. Phung, M. Naderi, T. Blackburn, and E. Ambikairajah, "Effects of current and voltage harmonics on distribution transformer losses," in *2012 IEEE International Conference on Condition Monitoring and Diagnosis*, pp. 633–636, IEEE, 2012.

[118] D. Korn, A. Hinge, F. Dagher, and C. Partridge, "Transformers efficiency: Unwinding the technical potential," in *2000 ACEEE Summer Study on Energy Efficiency in Buildings*, vol. 1, pp. 149–162, American Council for an Energy Efficient Economy, 2000.

[119] "Emerge alliance data/telecom center standard." https://www.emergealliance.org/standards/data-telecom/, 2021. Accessed: 2021-9-8.

[120] A. Santos, G. Duggan, J. Davis, and D. Zimmerle, "A cautionary note on using smart-plugs for research data acquisition," *Energies*, no. In review, In review.

[121] "Global smart plug market - drivers and forecast from technavio." https://www.businesswire.com/news/home/20170228005699/en/Global-Smart-Plug-Market---Drivers-Forecast, 2021. Accessed: 2021-10-01.

[122] "Smart plug market - growth, trends, covid-19 impact, and forecasts (2021 - 2026)." https://www.mordorintelligence.com/industry-reports/smart-plug-market, 2015. Accessed: 2021-09-30.

[123] N. K. Suryadevara and G. R. Biswal, "Smart plugs: Paradigms and applications in the smart city-and-smart grid," *Energies*, vol. 12, no. 10, p. 1957, 2019.

[124] M. Aftab and C.-K. Chau, "Smart power plugs for efficient online classification and tracking of appliance behavior," in *Proceedings of the 8th Asia-Pacific Workshop on Systems*, pp. 1–7, 2017.

[125] "Demand response." https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/demand-response, 2021. Accessed: 2021-09-30.

[126] O. Ayan and B. E. Turkay, "Smart home energy management technologies based on demand side management and a review of smart plugs with smart thermostats," in *2017 10th International Conference on Electrical and Electronics Engineering (ELECO)*, pp. 1247–1252, IEEE, 2017.

[127] G. Galioto, N. Galioto, C. Giaconia, L. Giarré, G. Neglia, and I. Tinnirello, "Smart plugs: A low cost solution for programmable control of domestic loads," in *2014 AEIT Annual Conference-From Research to Industry: The Need for a More Effective Technology Transfer (AEIT)*, pp. 1–6, IEEE, 2014.

[128] R. C. C. Castro, M. A. R. Lunaria, M. C. Leyesa, N. E. G. Silao, J. G. Jaudian, E. J. Morsiquillo, *et al.*, "Intelliplugs: Iot-based smart plug for energy monitoring and control through wifi and gsm," in *2020 IEEE 12th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM)*, pp. 1–4, IEEE, 2020.

[129] A. Srinivasan, K. Baskaran, and G. Yann, "Iot based smart plug-load energy conservation and management system," in *2019 IEEE 2nd International Conference on Power and Energy Applications (ICPEA)*, pp. 155–158, IEEE, 2019.

[130] J. Oh, "Iot-based smart plug for residential energy conservation: An empirical study based on 15 months' monitoring," *Energies*, vol. 13, no. 15, p. 4035, 2020.

[131] "Insecurity in the internet of things." https://docs.broadcom.com/doc/insecurity-in-the-internet-of-things-en, 2015. Accessed: 2021-09-30.

[132] A. Jacobsson, M. Boldt, and B. Carlsson, "A risk analysis of a smart home automation system," *Future Generation Computer Systems*, vol. 56, pp. 719–733, 2016.

[133] B. Ali and A. I. Awad, "Cyber and physical security vulnerability assessment for iot-based smart homes," *sensors*, vol. 18, no. 3, p. 817, 2018.

[134] D. Geneiatakis, I. Kounelis, R. Neisse, I. Nai-Fovino, G. Steri, and G. Baldini, "Security and privacy issues for an iot based smart home," in *2017 40th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO)*, pp. 1292–1297, IEEE, 2017.

[135] K. Basu, L. Hawarah, N. Arghira, H. Joumaa, and S. Ploix, "A prediction system for home appliance usage," *Energy and Buildings*, vol. 67, pp. 668–679, 2013.

[136] S.-H. Lee and C.-S. Yang, "An intelligent power monitoring and analysis system for distributed smart plugs sensor networks," *International Journal of Distributed Sensor Networks*, vol. 13, no. 7, p. 1550147717718462, 2017.

[137] Z. Ling, J. Luo, Y. Xu, C. Gao, K. Wu, and X. Fu, "Security vulnerabilities of internet of things: A case study of the smart plug system," *IEEE Internet of Things Journal*, vol. 4, no. 6, pp. 1899–1909, 2017.

[138] A. Iqbal, J. Olegård, R. Ghimire, S. Jamshir, and A. Shalaginov, "Smart home forensics: An exploratory study on smart plug forensic analysis," in *2020 IEEE International Conference on Big Data (Big Data)*, pp. 2283–2290, IEEE, 2020.

[139] A. Halterman, "Storming the kasa? security analysis of tp-link kasa smart home devices," 2019.

[140] K. Sha, W. Wei, T. A. Yang, Z. Wang, and W. Shi, "On security challenges and open issues in internet of things," *Future Generation Computer Systems*, vol. 83, pp. 326–337, 2018.

[141] H. Habibzadeh, B. H. Nussbaum, F. Anjomshoa, B. Kantarci, and T. Soyata, "A survey on cybersecurity, data privacy, and policy issues in cyber-physical system deployments in smart cities," *Sustainable Cities and Society*, vol. 50, p. 101660, 2019.

[142] H. Alasmary, A. Khormali, A. Anwar, J. Park, J. Choi, A. Abusnaina, A. Awad, D. Nyang, and A. Mohaisen, "Analyzing and detecting emerging internet of things malware: A graph-based approach," *IEEE Internet of Things Journal*, vol. 6, no. 5, pp. 8977–8988, 2019.

[143] W. Zhou, Y. Jia, Y. Yao, L. Zhu, L. Guan, Y. Mao, P. Liu, and Y. Zhang, "Discovering and understanding the security hazards in the interactions between iot devices, mobile apps, and clouds on smart home platforms," in *28th {USENIX} Security Symposium ({USENIX} Security 19)*, pp. 1133–1150, 2019.

[144] L. Gomes, F. Sousa, T. Pinto, and Z. Vale, "A residential house comparative case study using market available smart plugs and enaplugs with shared knowledge," *Energies*, vol. 12, no. 9, p. 1647, 2019.

[145] "Ouimeaux python api." https://ouimeaux.readthedocs.io/en/latest/api.html, 2021. Accessed: 2021-10-05.

[146] "pyhs100 python api." https://github.com/GadgetReactor/pyHS100, 2021. Accessed: 2021-10-05.

[147] "pyvesync python api." https://pypi.org/project/pyvesync/, 2021. Accessed: 2021-10-05.

[148] "Pyemvue python api." https://pypi.org/project/pyemvue/, 2021. Accessed: 2021-10-05.

[149] "Home assistant." https://www.home-assistant.io/, 2021. Accessed: 2021-10-05.

[150] "ewelink smart home center." https://www.ewelink.cc/en/, 2021. Accessed: 2021-10-05.

[151] "gspread python api for google sheets." https://docs.gspread.org/en/latest/, 2021. Accessed: 2021-10-05.

[152] J. J. Grainger, *Power system analysis*. McGraw-Hill, 1999.

[153] R. Weiss, L. Ott, and U. Boeke, "Energy efficient low-voltage dc-grids for commercial buildings," in *2015 IEEE First International Conference on DC Microgrids (ICDCM)*, pp. 154–158, IEEE, 2015.

[154] M. Gjelaj, C. Træholt, S. Hashemi, and P. B. Andersen, "Optimal design of dc fast-charging stations for evs in low voltage grids," in *2017 IEEE Transportation Electrification Conference and Expo (ITEC)*, pp. 684–689, IEEE, 2017.

Appendix A

Supplementary Material for Harmonic Cancellation Within AC Low Voltage Distribution for a Realistic Office Environment

This is supplementary material for Chapter 2. The laptop converters and screens utilized in this study as well as a few other miscellaneous electric loads were characterized in a laboratory, and their harmonic data are available at: https://hdl.handle.net/10217/207807.

Table A.1 summarizes the impact of correcting the smart plugs power logs for their time-constant-like behavior. The impact assessment focuses on two key metrics. The column *Change in Most Frequent Power* summarizes the change in the statistical mode of the distribution, while *Change in Total Power* indicates the change in total power consumption of the device.

Table A.1: Accounting for smart plug Time Constant

Category	Smart Plug	Change in *Most Frequent Power* (%)	Change in Total Power (%)
Laptops	01	0.20	0.03
	02	7.29	0.22
	03	0.42	0.10
	04	2.77	0.25
	05	7.15	0.76
	06	1.05	0.00
	07	1.73	0.02
	08	6.78	0.06
Screens	09	5.32	0.85
	10	0.22	0.00
	11	0.16	0.01
	12	0.13	0.01
	13	0.01	0.01
	14	0.12	0.01
	15	0.03	0.02
	16	0.46	0.01
	17	0.01	0.01
	18	0.03	0.01
	19	1.07	0.01
	20	0.22	0.02
	21	0.04	0.01
Desktops	22	0.00	0.01
	23	4.08	0.10
Printers	24	0.52	0.26
	25	0.02	0.10
Network Appliances	26	10.96	0.31
	27	19.00	7.50

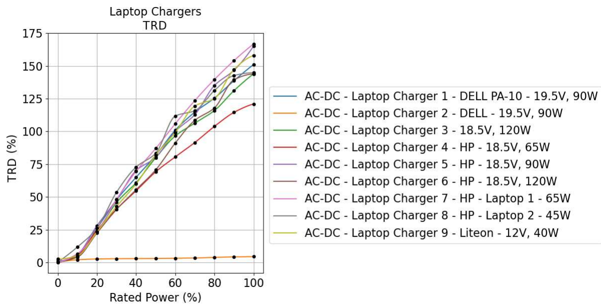
Table A.2: Laptops' Realistic Power Level Distribution

	Load Level									
	10%	**20%**	**30%**	**40%**	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
Smart Plug 1	0.20%	0.05%	0.06%	99.68%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%
Smart Plug 2	3.41%	58.70%	16.49%	9.74%	4.62%	3.13%	2.12%	1.15%	0.41%	0.24%
Smart Plug 3	1.64%	3.95%	3.20%	48.35%	19.58%	8.00%	4.48%	7.71%	1.85%	1.24%
Smart Plug 4	18.69%	56.08%	19.77%	3.51%	1.11%	0.71%	0.12%	0.00%	0.00%	0.00%
Smart Plug 5	83.09%	8.82%	4.60%	1.54%	1.31%	0.48%	0.15%	0.01%	0.00%	0.00%
Smart Plug 6	10.77%	79.17%	8.00%	1.69%	0.27%	0.07%	0.03%	0.01%	0.00%	0.00%
Smart Plug 7	0.26%	74.30%	19.15%	4.57%	0.81%	0.33%	0.30%	0.26%	0.01%	0.00%
Smart Plug 8	54.75%	32.11%	11.11%	1.87%	0.14%	0.02%	0.00%	0.00%	0.00%	0.00%

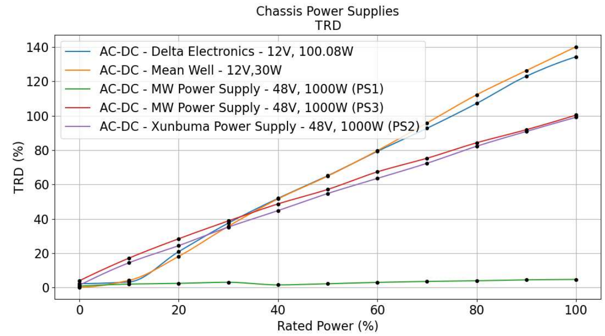
Table A.3 shows a comparison for each harmonic component for Scenarios A, B, and C.

Table A.3: Comparison of Harmonic Cancellation for Scenarios A, B, and C

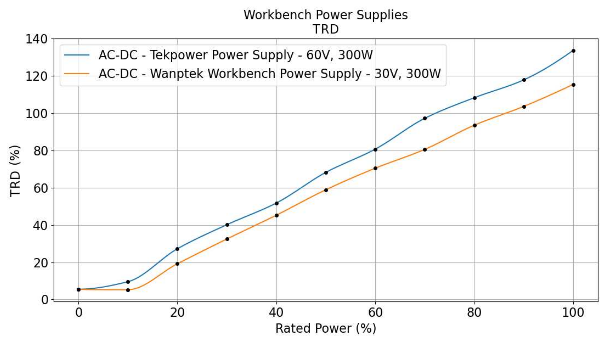
Harmonic Component	**Harmonic Cancellation Ratio Scenario B / A (%)**	**Harmonic Cancellation Ratio Scenario C / A (%)**	**Harmonic Cancellation Ratio Scenario C / B (%)**
3	42 to 99	2135 to 4587	7167 to 94044
5	51 to 127	659 to 1172	1675 to 27828
7	32 to 83	265 to 747	1449 to 6532
9	28 to 54	230 to 500	1315 to 8784
11	24 to 53	140 to 363	1167 to 4747
13	25 to 53	113 to 214	692 to 3904



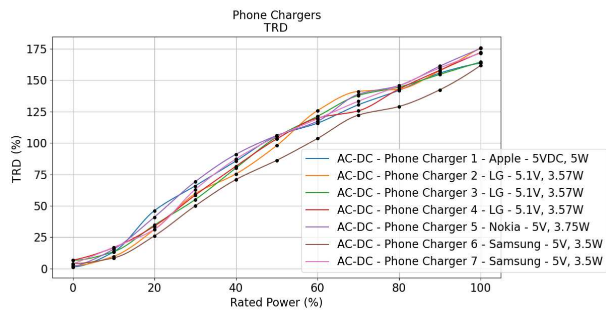
(a) Laptop Chargers



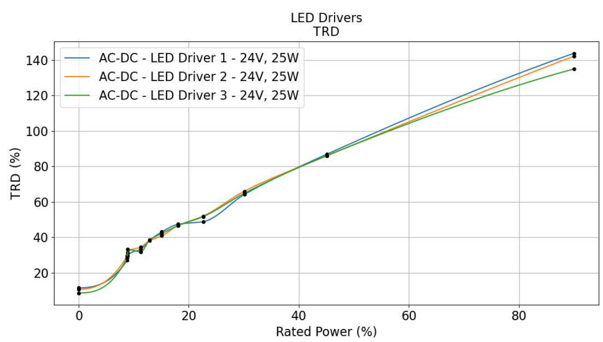
(b) Chassis Power Supplies



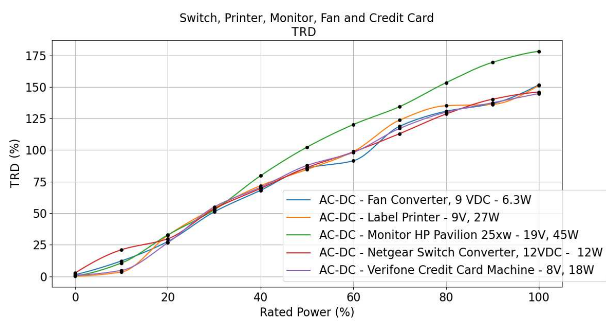
(c) Workbench Power Supplies



(d) Phone Chargers



(e) LED Drivers



(f) Switch, Printer, Monitor, Fan and Credit Card Machine

Figure A.1: TRD over percentage of rated power for different types of appliances' converters

Figure A.2 compares harmonic cancellation between Scenarios C and A (Figure A.3 in the supplementary material shows the comparison for Scenarios C and B). Green numbers indicate increased cancellation. These results indicate that commonly used assumptions underestimate the potential harmonic cancellation. In contrast to Scenario A, when converters operate in observed power ranges, harmonic cancellation increases for low-order harmonics due to timing variations between current flow in different converters (see Fig. A.4 for an example).

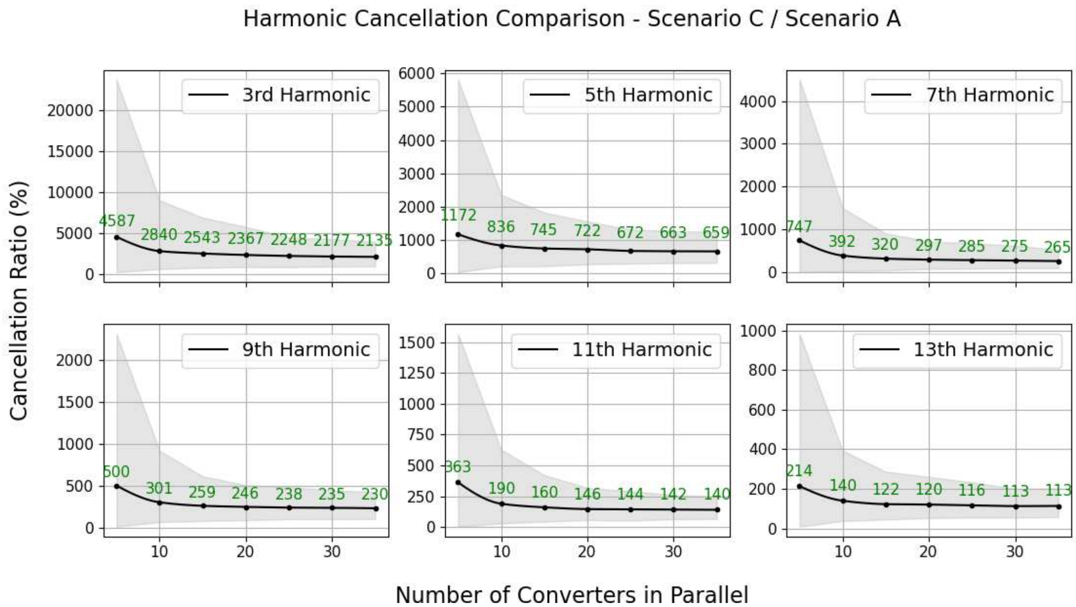


Figure A.2: Comparison of harmonic cancellation between Scenario C and Scenario A. Comparison was performed by dividing random iterations from Scenario C to those in Scenario A. Background represents the 95% confidence interval on the subtracted iterations, values coded green for positive change (more cancellation) and red for negative change (less cancellation). The dark line is the mean of all iterations.

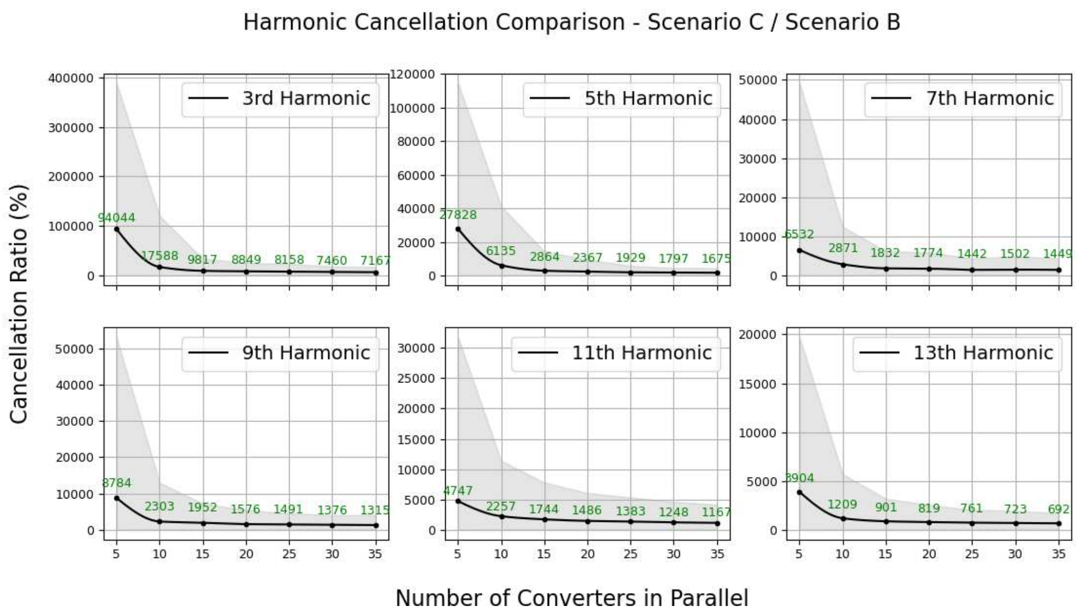


Figure A.3: Harmonic Cancellation Improvement—Scenario C vs Scenario B

Figure A.4 shows the current waveforms of a laptop charger 20% loaded and of an HP monitor. Figure A.5 shows the differences of laptop chargers rated at 90W, loaded at 100% but with different distortions.

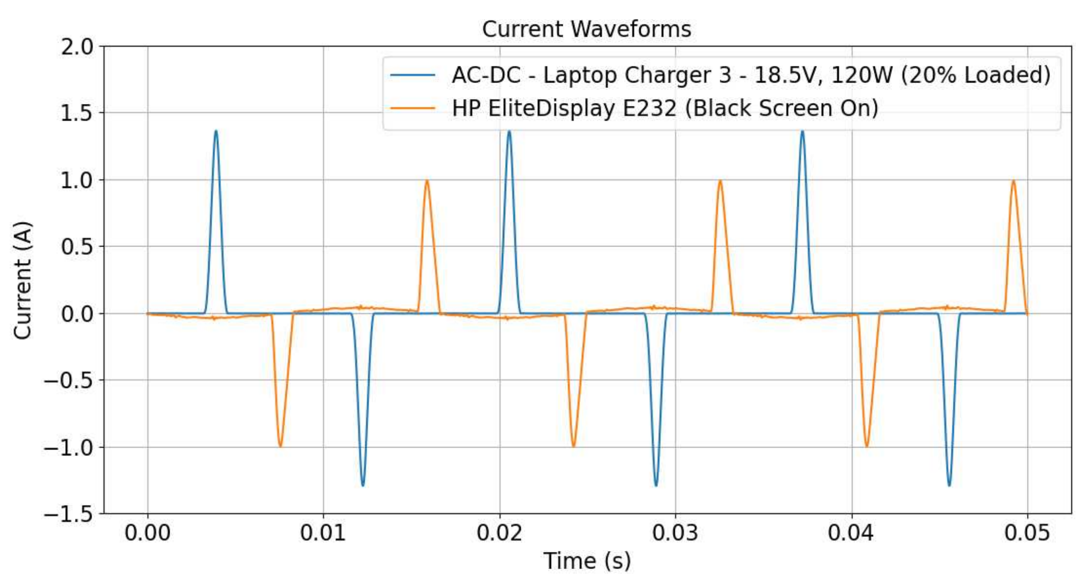


Figure A.4: Timing variations between current flow in two different converters

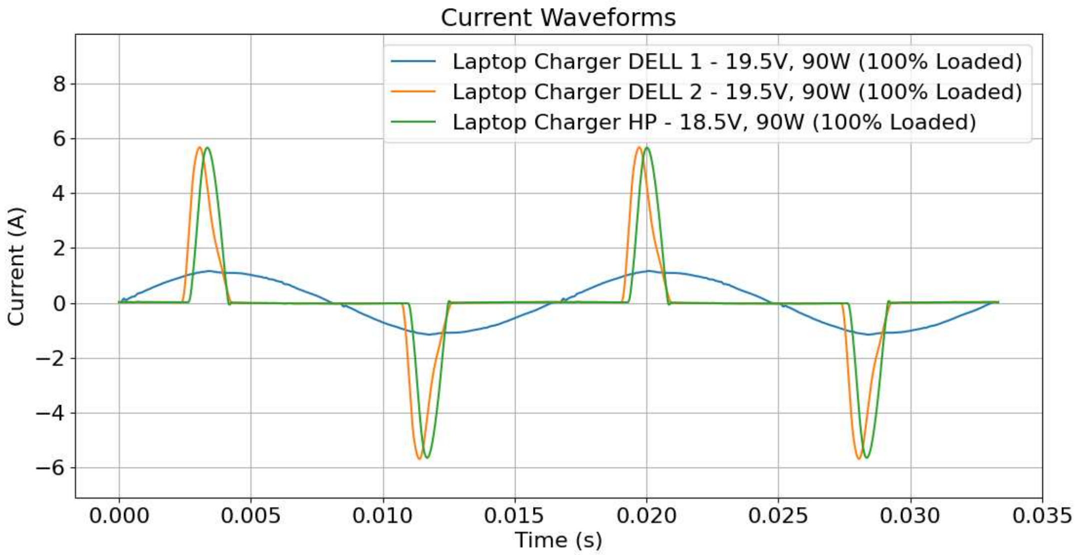


Figure A.5: Difference in current distortion for three different laptop chargers

Figure A.6 below shows the current waveforms for a few other devices used in the simulations.

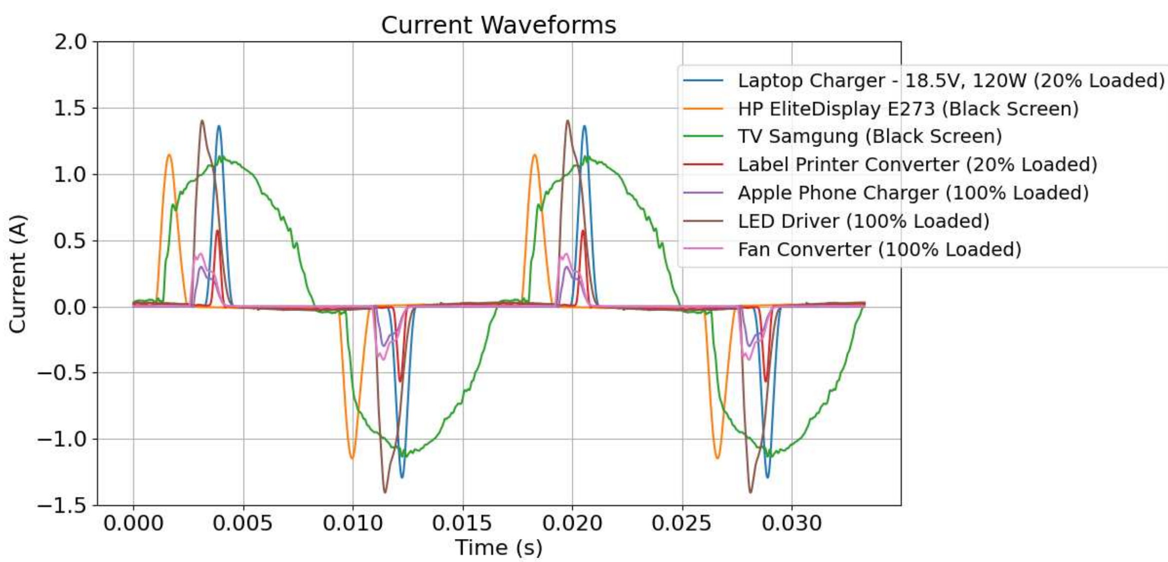


Figure A.6: Current waveforms for a few devices used in the simulations.

A.1 Monte Carlo Method

The harmonic cancellation simulation used the Monte Carlo method, using harmonic experimental data for each converter, at different load steps. Each converter was characterized from 0 to 100% of its rated power, in steps of 10% load. For each of the N Monte Carlo iterations, we had several converters connected in parallel, each one at a specific load level. Depending on the Scenario, the load level is defined by one of the following probability distributions: (a) uniform distribution from 10-100%; or (b) a realistic probability based on the smart plug recordings. The harmonic cancellation was simulated by summing the current harmonic phasors of each converter connected to the circuit. At the end of the iteration, we calculated the diversity factor and total rated-current distortion. After all the iterations were done, we plotted the DF average from the 3^{rd} to the 13^{th} harmonic and their 95% confidence interval. In scenario B, for instance, we run a Monte Carlo simulation with 1000 iterations using characterization data of 8 laptops. This data is randomly associated with 5-35 laptops connected in parallel, with converters loaded at 0-40% of their rated power (realistic probability).

A.2 Devices used in Building Simulation

The models for the MELs and LED drivers used in this experiment are the following:

- 8 Laptop Chargers: same used in previous simulations.
- 3 Screens: same used in previous simulations.
- 3 Phone Chargers: Apple 5W model A1385, LG 3.57W model STA-U17WS, Nokia 3.75W model AC-20U.
- 1 Portable Fan: AC converter 6.3W model SUN-0900070.
- 1 Label Printer Chargers: AC converter 27W model EA1024F2-090.

- 3 TVs: TV Samsung model UN75JU6500, TV Sharp model LC-60EQ10U, TV Vizio model E43u-D2.
- 1 LED Driver: Mean Well 25W model APV-25-24.

The quantity of each device considered in this experiment is specified below.

- 40 Laptop Chargers
- 35 Screens
- 25 Phone Chargers
- 15 Portable Fans
- 10 Label Printer Chargers
- 15 TVs
- 70 LED Drivers

Appendix B

Supplementary Material for Endpoint Use Efficiency Comparison for AC and DC Power Distribution in Commercial Buildings

This is a supplementary material for Chapter 3.

B.1 110W SIMO Converters - Tables

Table B.1: Test plan for 110W multi-output converters

Testing Conv. 10, 11, 12		Max	Load (W)				
Rated Power (W)	110	Power (W)	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1%	Out 1 (5V)	24.89	1.1	-	-	-	-
5%	Out 1 (5V)	24.89	5.5	-	-	-	-
15%	Out 1 (5V)	24.89	11.0	11.6	11.6	12.4	13.2
	Out 2 (24V)	-	2.5	2.5	3.3	3.3	1.7
	Out 3 (12V)	143.37	3.0	2.5	1.7	0.8	1.7
30%	Out 1 (5V)	24.89	11.0	16.5	23.1	13.2	11.6
	Out 2 (24V)	-	11.0	8.3	6.6	16.5	5.0
	Out 3 (12V)	143.37	11.0	8.3	3.3	3.3	16.5
40%	Out 1 (5V)	24.89	14.6	21.9	13.2	17.6	15.4
	Out 2 (24V)	-	14.6	11.0	13.2	21.9	6.6
	Out 3 (12V)	143.37	14.6	11.0	17.6	4.4	21.9
70%	Out 1 (5V)	24.89	24.0	23.0	23.0	11.5	15.4
	Out 2 (24V)	-	27.2	26.9	23.0	34.6	46.1
	Out 3 (12V)	143.37	25.6	26.9	30.7	30.7	15.4

Table B.2: Delta Efficiency (DC-AC) for SIMO test converters rated at 110W

Rated Power (110W)	0%	1%	5%	15%	30%	40%	70%
AC Eff. Conv. 10, 120VAC (%)	0.0	30.3	61.0	79.1	83.9	85.0	85.8
DC Eff. Conv. 11, 24VDC (%)	0.0	14.8	43.2	65.3	75.5	78.2	80.9
DC Eff. Conv. 12, 48VDC (%)	0.0	12.4	39.2	63.3	75.9	79.5	83.9
Delta Eff. Conv [11 - 10] (%)	0.0	-15.6	-17.9	-13.8	-8.3	-6.8	-4.9
Delta Eff. Conv [12 - 10] (%)	0.0	-18.0	-21.8	-15.8	-7.9	-5.5	-1.9

B.2 185W SIMO Converters - Tables

Table B.3: Test plan for 185W multi-output converters

Testing Conv. 13 and 14		Max Power (W)	Power (W)				
Rated Power (W)	185		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
1%	Out 1 (3.3V)	BK	1.9	-	-	-	-
5%	Out 1 (3.3V)	BK	9.3	-	-	-	-
10%	Out 1 (3.3V)	BK	18.5	-	-	-	-
15%	Out 1 (3.3V)	BK	18.5	19.4	19.0	19.2	18.7
	Out 2 (5V)	24.89	4.6	4.2	3.3	6.9	2.8
	Out 3 (12V)	143.37	4.6	4.2	5.5	1.7	6.3
20%	Out 1 (3.3V)	BK	18.5	18.5	19.0	19.4	18.7
	Out 2 (5V)	24.89	9.3	4.0	12.5	7.2	12.7
	Out 3 (12V)	143.37	9.3	14.5	5.5	10.4	5.6
25%	Out 1 (3.3V)	BK	18.5	19.0	18.8	19.2	19.0
	Out 2 (5V)	24.89	18.5	15.8	11.5	17.8	20.8
	Out 3 (12V)	143.37	9.3	11.5	16.0	9.3	6.5

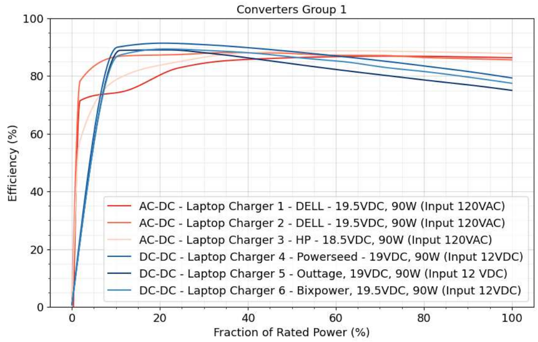
Table B.4: Delta Efficiency (DC-AC) for SIMO test converters rated at 185W

Rated Power (185W)	0%	1%	5%	10%	15%	20%	25%
AC Eff. Conv. 13, 120VAC (%)	0.0	15.6	44.4	56.2	63.8	67.4	69.7
DC Eff. Conv. 14, 24VDC (%)	0.0	18.8	48.5	60.3	67.0	70.5	72.2
Delta Eff. [Conv 14 - 13] (%)	0.0	3.2	4.1	4.1	3.2	3.0	2.5

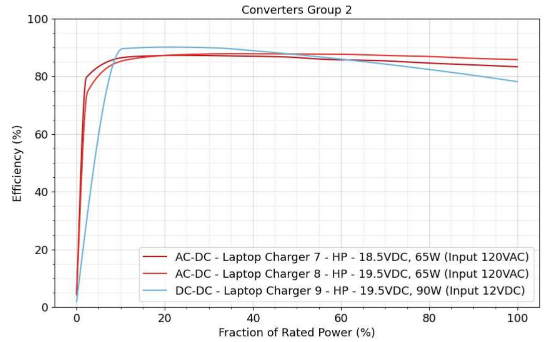
B.3 Additional Tests on Power Converters

The DC input voltages analyzed in the main paper include test converters operating at 24VDC, and 48VDC inputs. Test converters with 12V and other input voltage ranges were also tested, with a primary emphasis on those with 12VDC input voltages. These tests illustrate if there are any substantial difference in converter efficiency between these lower input voltages and the higher voltages discussed in the main paper. Table B.5 shows how these converters were grouped and their respective specifications.

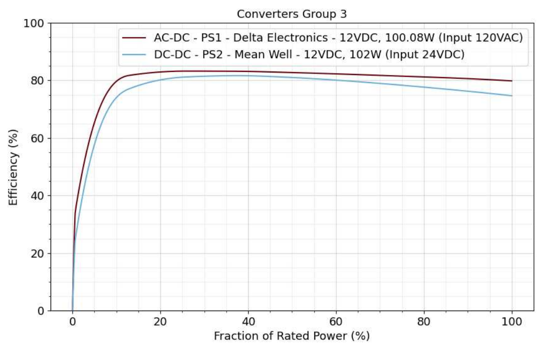
The plots shown in Figure B.1 illustrate a similar efficiency pattern: Results were highly variable with some peculiarities at low load levels. For groups 3, 4, and 5, for example, the AC/DC converter had the better performance than its DC/DC comparable at all load levels, while for group 6, results are the opposite. Groups 1 and 2 show the same pattern discussed in the main paper, where AC/DC converters were more efficient than DC/DC for low load levels (below 10% of the converter's rated power), DC/DC was more efficient for loads of 10% - 50% of the rated load, and AC/DC is more efficient at loads above 50%.



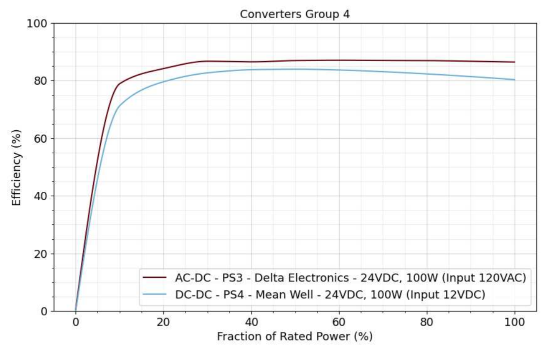
(a)



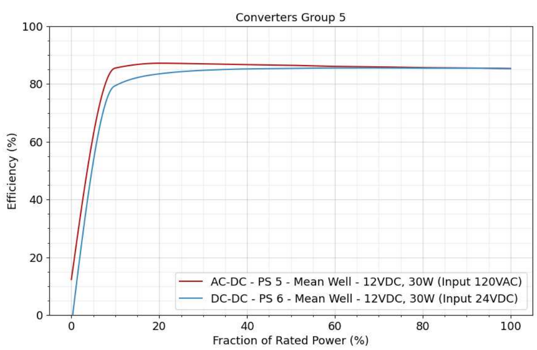
(b)



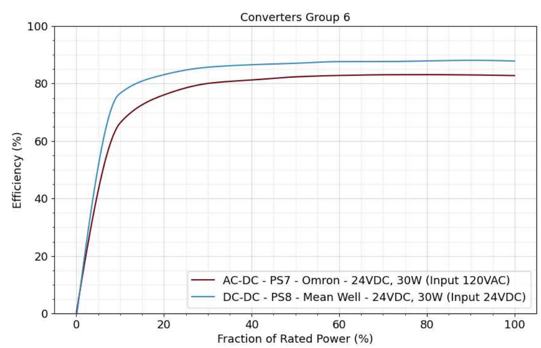
(c)



(d)



(e)



(f)

Figure B.1: Efficiency curves for additional AC/DC and DC/DC converters with similar power rating and output voltage. Converters are divided in six groups, according to their rated power and output voltage. Groups 1, 2, 3, 4, 5, and 6 are represented by (a), (b), (c), (d), (e), and (f), respectively

Table B.5: Groups of Additional Converters Tested

Group	Converter	Type	Manufacturer	Model	Input Voltage	Output Voltage	Rated Power
Group 1	AC-DC	Laptop Charger 1	DELL	DA90PE1-00	100-240VAC	19.5VDC	90W
	AC-DC	Laptop Charger 2	DELL	PA-10	100-240VAC	19.5VDC	90W
	AC-DC	Laptop Charger 3	HP	Series PPP014L	100-240VAC	18.5VDC	90W
	DC-DC	Laptop Charger 4	Powseed	PA-3900-Z3	12VDC	19VDC	90W
	DC-DC	Laptop Charger 5	Outtage	PA-4900-OT	12VDC	19VDC	90W
	DC-DC	Laptop Charger 6	Bixpower	BX-DD90X	12VDC	19.5VDC	90W
Group 2	AC-DC	Laptop Charger 7	HP	Series PPP009L-E	100-240VAC	18.5VDC	65W
	AC-DC	Laptop Charger 8	HP	PA-1650-32HJ	100-240VAC	19.5VDC	65W
	DC-DC	Laptop Charger 9	HP	F1455A	12VDC	19VDC	75W
Group 3	AC-DC	Power Supply 1	Delta Electronics	PMC-12V100W1AA	100-240VAC	12VDC	100W
	DC-DC	Power Supply 2	Mean Well	SD-100B-12	19-36VDC	12VDC	100W
Group 4	AC-DC	Power Supply 3	Delta Electronics	PMC-24V100W1AA	100-240VAC	24VDC	100W
	DC-DC	Power Supply 4	Mean Well	SD-100A-24	9.5-18VDC	24VDC	100W
Group 5	AC-DC	Power Supply 5	Mean Well	IRM-30-12ST	100-240VAC	12VDC	30W
	DC-DC	Power Supply 6	Mean Well	RSD-30G-12	24VDC	12VDC	30W
Group 6	AC-DC	Power Supply 7	Omron	S8VM-03024 CD	100-240VAC	24VDC	30W
	DC-DC	Power Supply 8	Mean Well	RSD-30G-24	24VDC	24VDC	30W

B.4 AC/DC central converter efficiencies operating at different voltage levels

Table B.6 shows the efficiency at different voltage and power levels for the AC/DC converter characterized in this study.

Table B.6: Efficiency values for CC operating at $120V_{AC}$, $208V_{AC}$, and $380V_{DC}$

Input: $120V_{AC}$		Input: $208V_{AC}$		Input: $380V_{DC}$	
Rated Power (%)	**Efficiency**	**Rated Power (%)**	**Efficiency**	**Rated Power (%)**	**Efficiency**
0.0%	0.0% [0.0% to 0.0%]	0.0%	0.0% [0.0% to 0.0%]	0.0%	0.0% [0.0% to 0.0%]
5.3%	79.7% [79.0% to 80.4%]	5.3%	80.5% [79.8% to 81.2%]	5.2%	80.2% [79.5% to 80.9%]
10.7%	87.1% [86.5% to 87.7%]	10.6%	88.1% [87.4% to 88.7%]	10.6%	88.4% [87.7% to 89.0%]
16.1%	88.1% [87.5% to 88.7%]	15.9%	88.7% [88.0% to 89.3%]	15.8%	88.8% [88.2% to 89.4%]
21.2%	87.7% [87.1% to 88.3%]	20.7%	87.8% [87.2% to 88.4%]	20.6%	88.8% [88.0% to 89.6%]
26.4%	89.3% [88.6% to 90.0%]	26.1%	90.0% [89.4% to 90.7%]	25.9%	90.5% [89.9% to 91.1%]
30.5%	87.8% [87.2% to 88.3%]	30.9%	91.2% [90.5% to 91.9%]	30.5%	91.0% [90.2% to 91.8%]
35.9%	89.7% [89.1% to 90.4%]	35.8%	91.2% [90.4% to 91.8%]	35.6%	91.4% [90.6% to 92.4%]
41.1%	90.3% [89.5% to 91.1%]	40.7%	91.7% [91.1% to 92.4%]	40.5%	92.3% [91.6% to 93.1%]
46.8%	90.8% [90.2% to 91.4%]	46.0%	92.4% [91.7% to 93.1%]	45.6%	92.2% [91.6% to 92.9%]
51.8%	90.9% [90.2% to 91.5%]	51.1%	92.6% [92.0% to 93.3%]	50.4%	92.4% [91.7% to 93.0%]
56.8%	90.8% [90.2% to 91.3%]	56.1%	92.5% [91.8% to 93.1%]	55.9%	93.4% [92.6% to 94.1%]
61.8%	90.3% [89.7% to 90.9%]	61.2%	92.6% [92.0% to 93.2%]	60.7%	92.4% [91.9% to 93.0%]
67.0%	90.5% [90.0% to 91.1%]	66.4%	92.6% [91.9% to 93.3%]	65.8%	92.7% [91.9% to 93.4%]
71.8%	90.4% [89.7% to 91.1%]	71.2%	92.5% [91.7% to 93.2%]	70.8%	93.0% [92.3% to 93.7%]
77.0%	90.5% [89.7% to 91.1%]	75.8%	92.4% [91.7% to 93.3%]	75.2%	92.2% [91.5% to 92.9%]
82.0%	90.2% [89.6% to 90.8%]	81.2%	92.3% [91.5% to 93.0%]	80.0%	91.9% [91.1% to 92.7%]

B.5 Characterization of the Central Converter

The commercially available power hub characterized for this study can operate at three supply voltages: $120V_{AC}$, $208V_{AC}$, and $380V_{DC}$. The converter has 16 output ports, rated at 100 W and 24 V_{DC} each.

Sixteen chassis-mount resistors (6.8 ohms, 100W) were used to load the CC, which defines one load level (≈85 W) for each port when that port is loaded. All measurements were made with the power analyzer. Load was recorded starting with no ports loaded and increasing until all 16 ports were loaded. Since the power analyzer can measure only 4 channels at one time, tests were repeated when more than 3 output ports were loaded. For instance, with 4 ports loaded, two test runs were completed: Run 4.1 utilized Channel 1 (Ch1) for input power and channels 2-4 for output ports 1-3, followed by Run 4.2, where channel 1 again measured the input power, and channel 2 measured the output of port 4. Output power is:

$$P_{out} = \sum_{k=1}^{N_{ch}} P_{ch-k} \tag{B.1}$$

where $P_{ch,k}$ is the output power of channel k, for a test with N_{ch} channels loaded. Input power, P_{in}, is measured directly. However, when tests were split into multiple runs, input power varies slightly between test runs. For N_P test runs, we have P_r, $r = 1, 2, ...N_P$, individual power measurements. In this case, we utilize a bootstrap estimate of input power drawn from the set of all measurements of the input power:

$$P = \{P_r, r = 1, 2, ..., N_P\} \tag{B.2}$$

We further assume all power measurements are normally distributed around the mean – i.e. the stated instrument accuracy of the PA was assumed to represent 90% confidence interval on normally distributed noise (z = 1.645). The uncertainty in the measurement was then calculated empirically assuming a normal distribution with parameters (μ, σ) where:

$$\sigma = \frac{\epsilon_r \cdot \mu}{1.645} \tag{B.3}$$

where σ is the instrument measurement and ϵ_r the instrument accuracy (0.05%). For each measurement of input or output power 5000 samples were drawn from the normal distribution for each power measurement. A set of efficiency estimates was then calculated by bootstrapping the above equations:

$$\eta_i = \frac{\sum_{k=1}^{N_{ch}} \{P_{ch,k}\}_i}{\{P_r\}_i}, i = 1, 2, ..., 5000 \tag{B.4}$$

where *i* is a random draw from each of the measurement distributions, or sets of distributions. Mean efficiency is calculated as the mean of the bootstrapped distribution. Confidence intervals, below, are calculated as the 0.025 and 0.975 fractiles of the resulting distribution, for a 95% confidence interval on the efficiency.

Appendix C

Supplementary Material for A Cautionary Note on Using Smart-Plugs for Research Data Acquisition

This is a supplementary material for chapter 5.

C.1 Emporia Smart Plug Tests

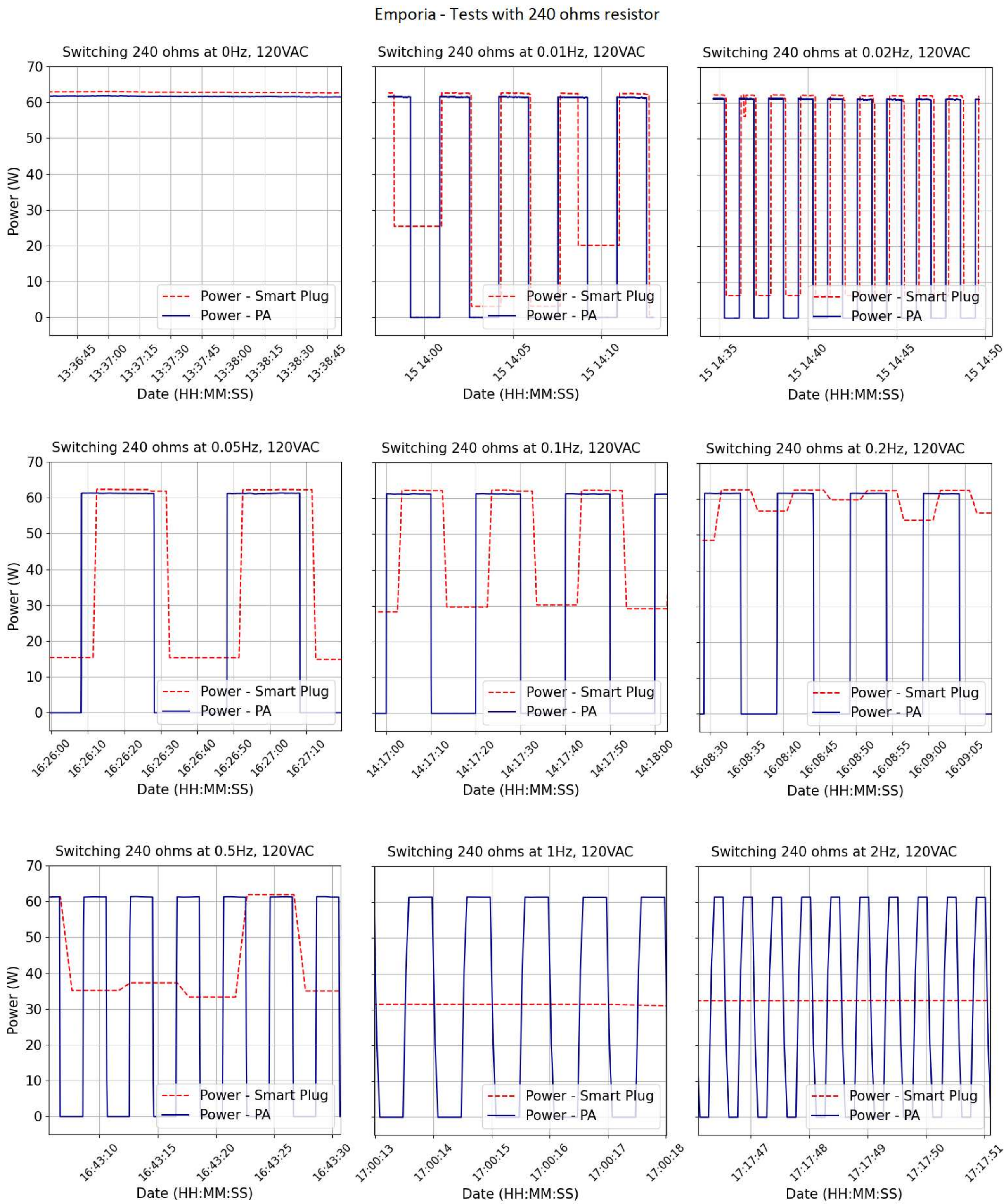


Figure C.1: Emporia - Tests with 240Ω resistor

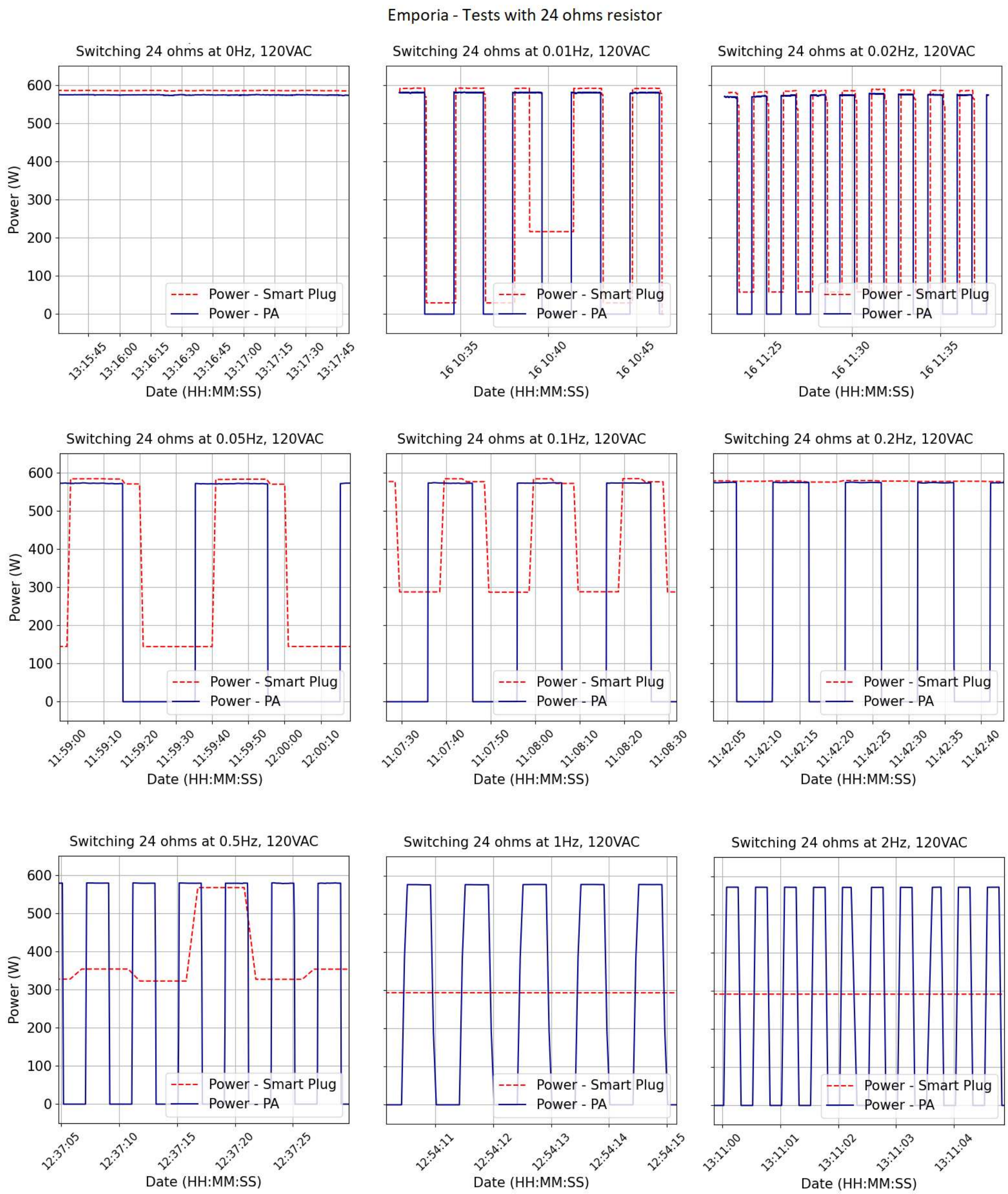


Figure C.2: Emporia - Tests with 24Ω resistor

C.2 Etekcity Smart Plug Tests

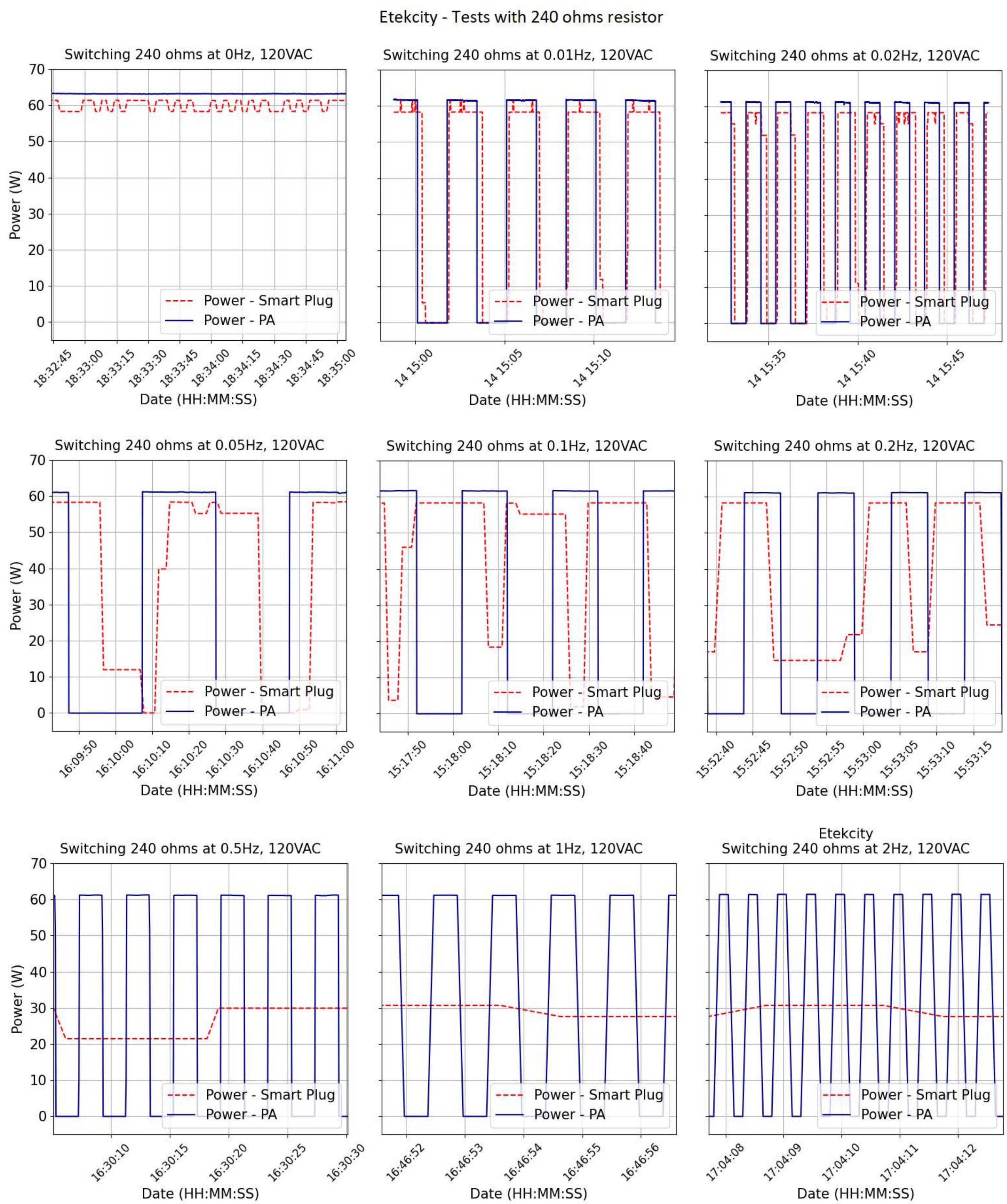


Figure C.3: Etekcity - Tests with 240Ω resistor

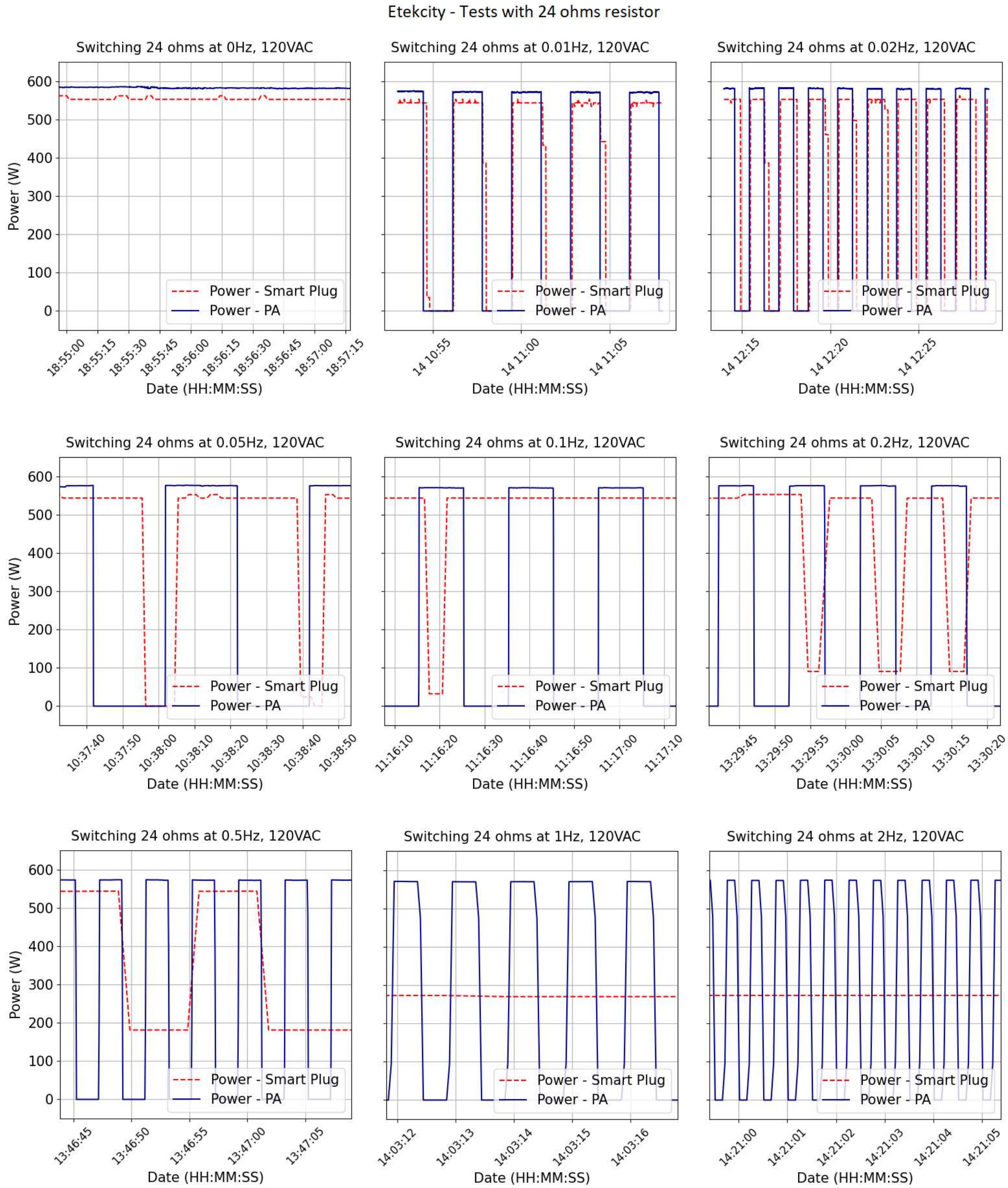


Figure C.4: Etekcity - Tests with 24Ω resistor

C.3 Sonoff Smart Plug Tests

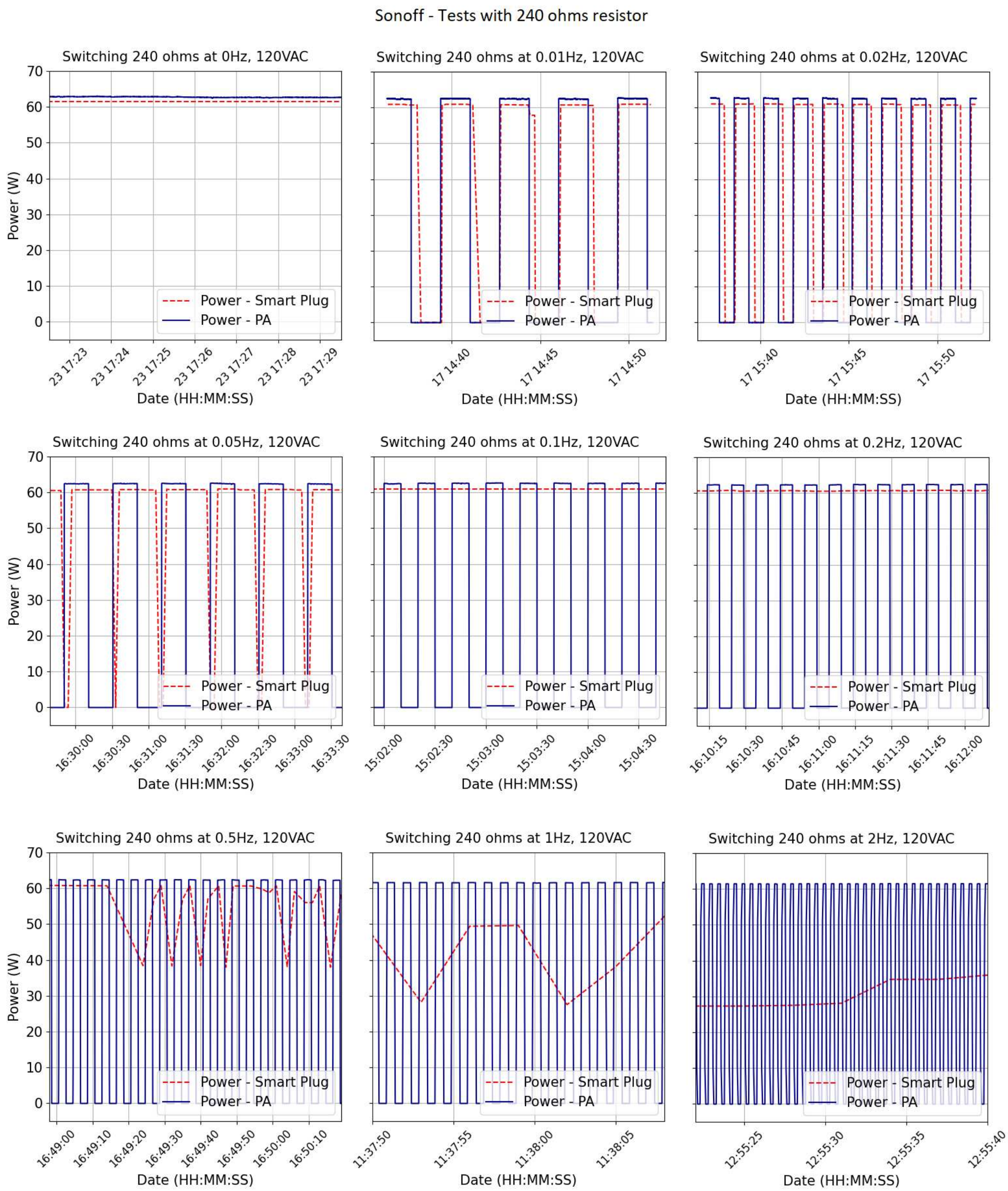


Figure C.5: Sonoff - Tests with 240Ω resistor

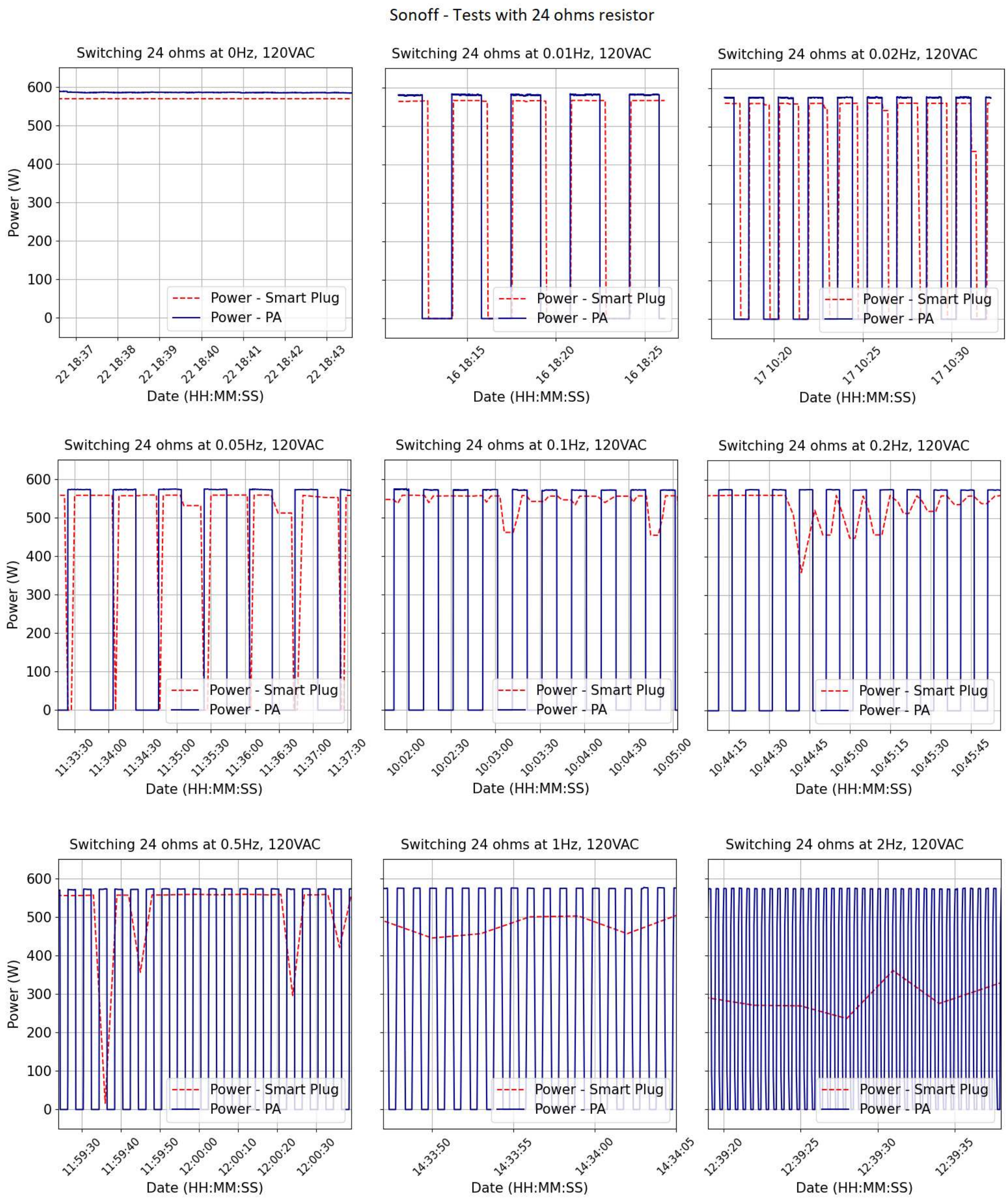


Figure C.6: Sonoff - Tests with 24Ω resistor

C.4 TP-Link Smart Plug Tests

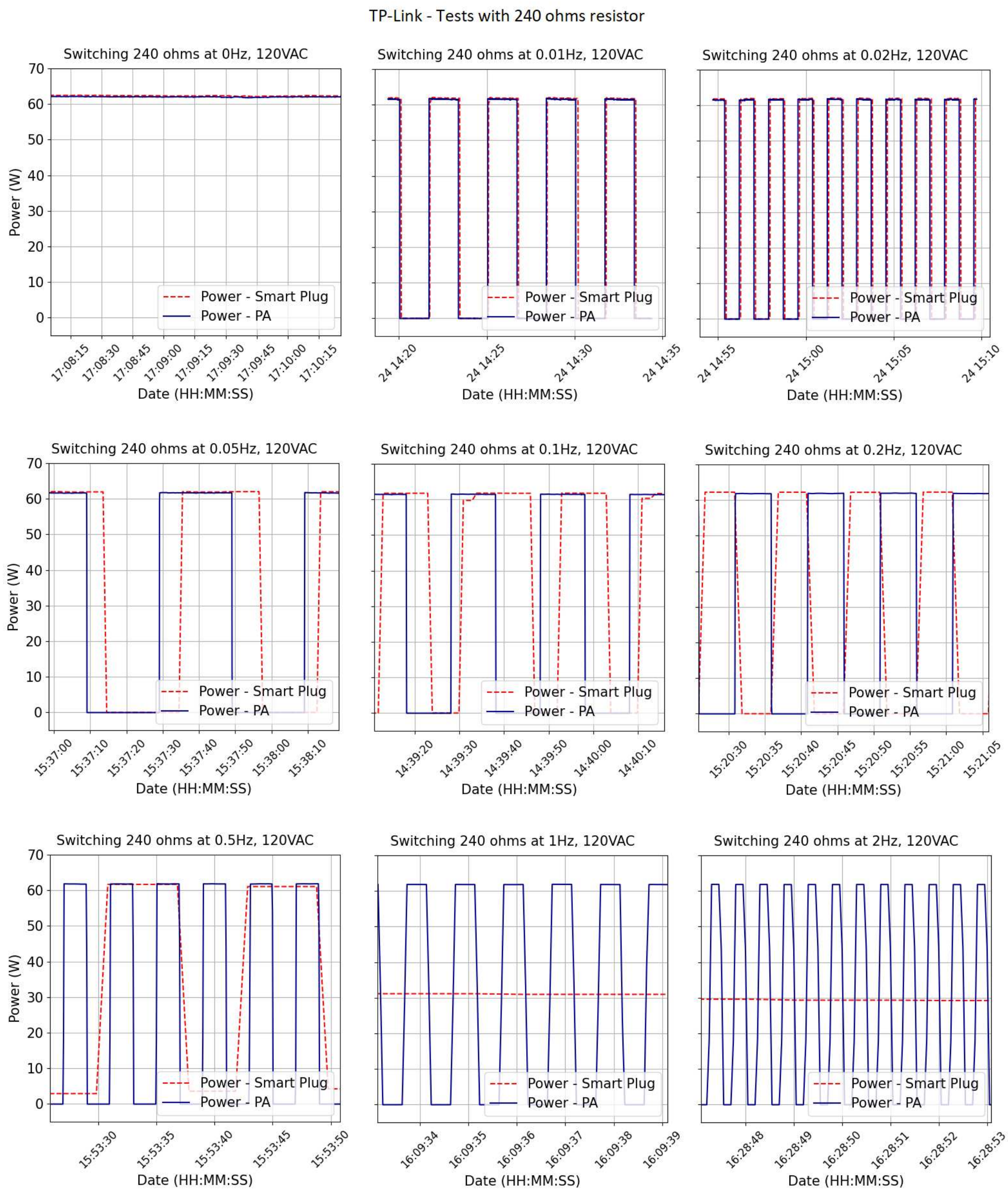


Figure C.7: TP-Link - Tests with 240Ω resistor

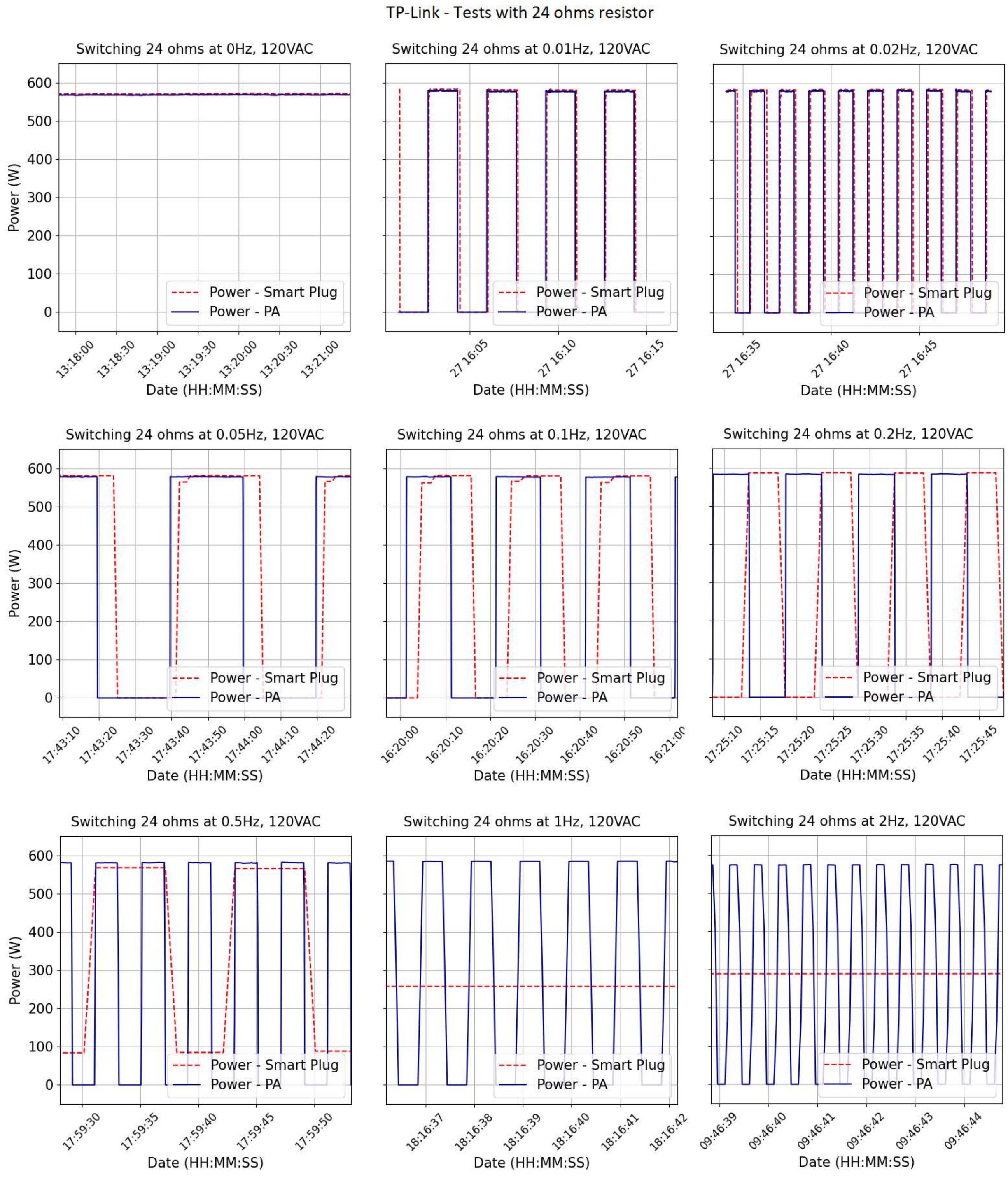


Figure C.8: TP-Link - Tests with 24Ω resistor

C.5 WEMO Smart Plug Tests

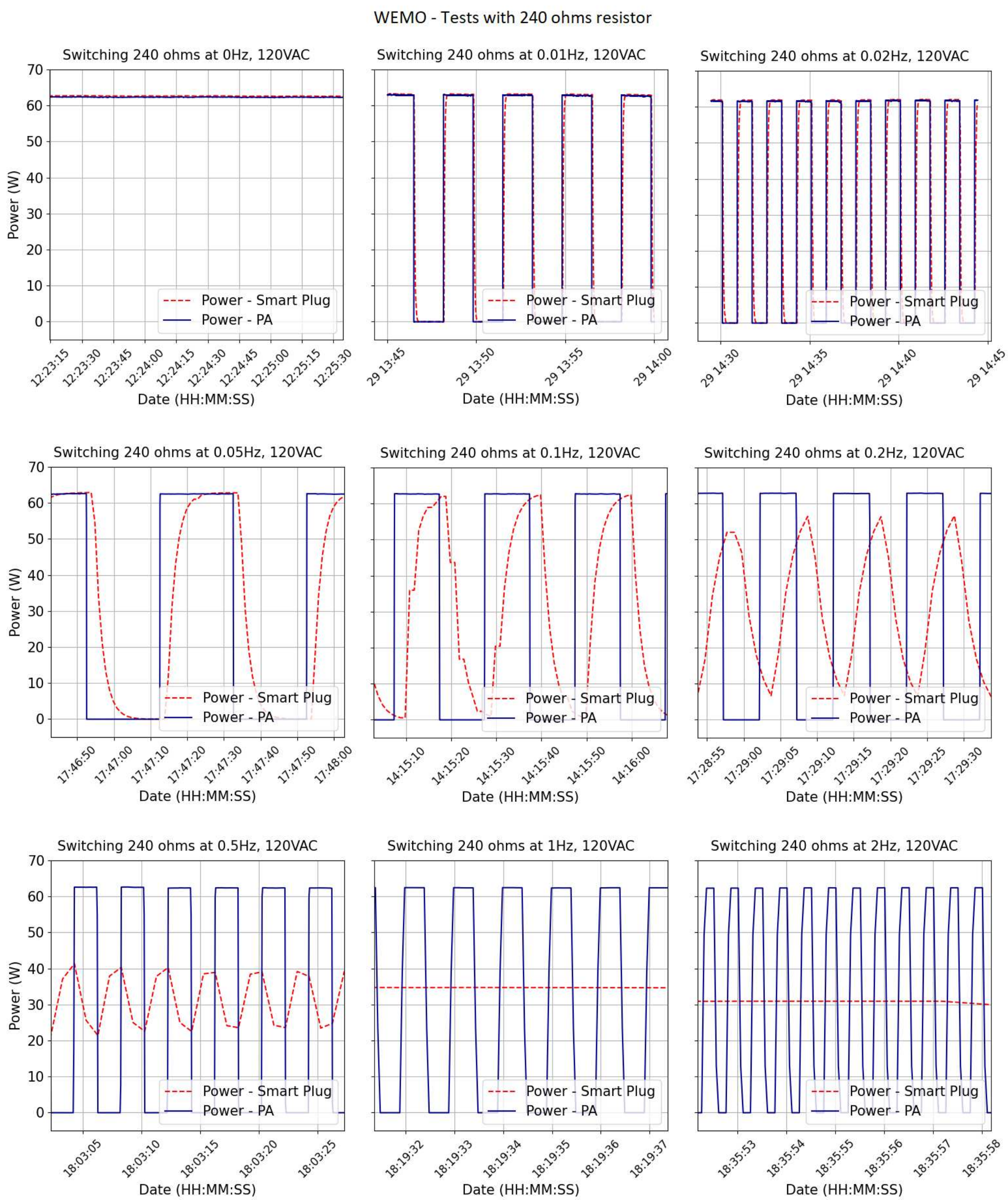


Figure C.9: WEMO - Tests with 240Ω resistor

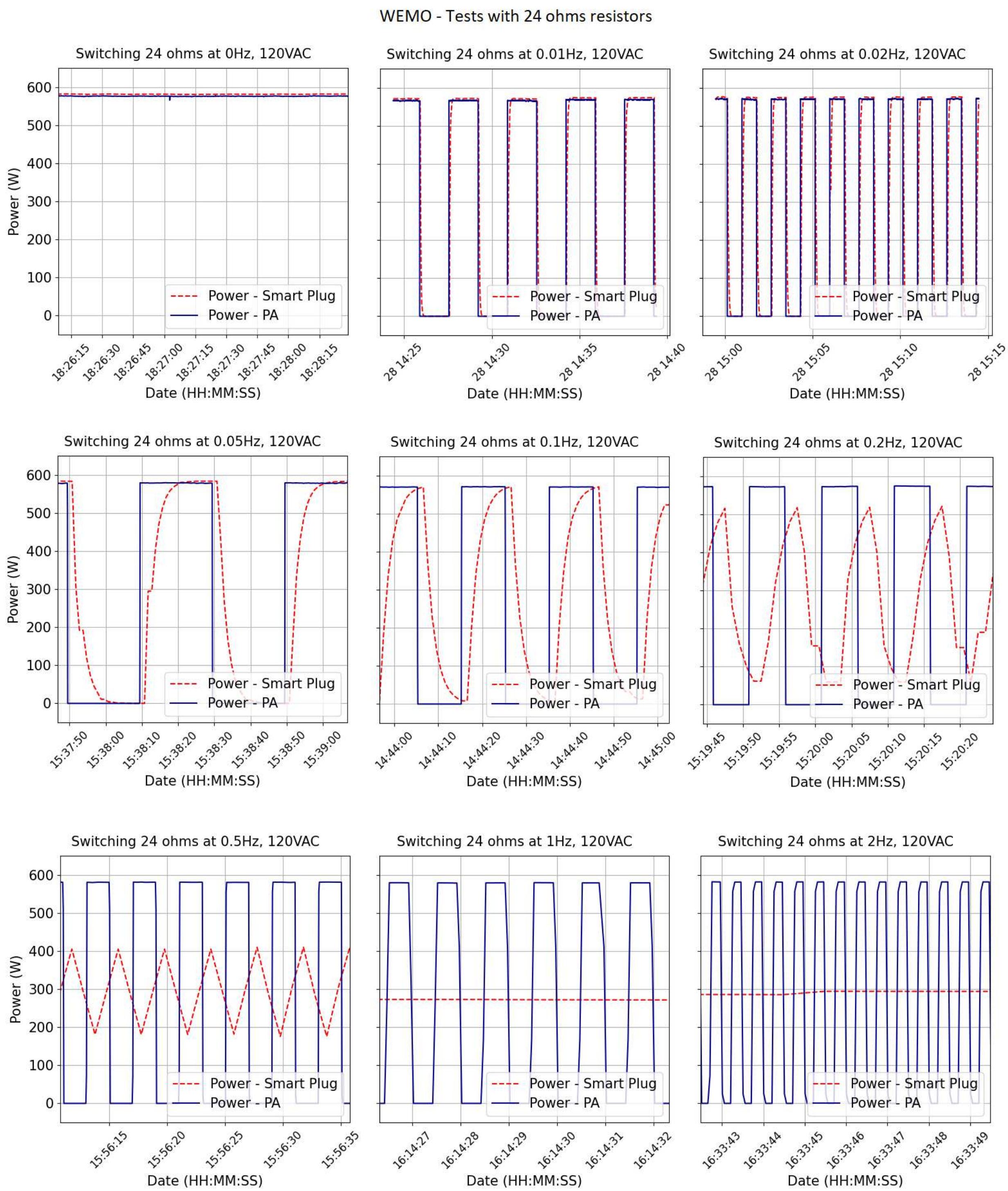


Figure C.10: WEMO - Tests with 24Ω resistor