INTEGRATION OF LEGACY APPLIANCES INTO THE SMART HOME

by

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Abstract

Reducing greenhouse-gas emissions and improving energy security are two energy related challenges the world faces. Renewable energy such as wind and solar appears to be encouraging in solving these issues due to their clean and environmentally sustainable character. The problem with such renewable energy source is that it is variable in nature and most users expect a continuous supply of electricity. As a result, an advanced and intelligent electricity grid is required that can handle this variable nature in order to satisfy environmental concerns for the continued growth of the renewable energy sources, by changing over to a smart grid. By adjusting or controlling the load via load management process, the smart grid can enhance the growth of renewables as well as maintaining the reliability of the electricity grid.

Due to variable nature of renewables, smart grids requires smart home where the load management coordination can be done by a smart-home controller managing the power consumption of appliances based upon the information from the appliances and the grid. Smart homes considers its appliances to be smart which possess communication and processing capabilities to broadcast information about themselves and despite such advantages of smart appliances, there is nothing to stop someone from “plugging-in” a non-smart legacy appliance into the smart home system having none of these features. This results in a dilemma: the user wants to use the legacy appliance but the smart home controller is unable to control it.

This thesis discusses some of the issues surrounding the integration of legacy appliances into a smart home system and elaborates the requirements and components which are necessary to realize such a design so that legacy appliances operate in a smart home.

List of Abbreviations and Symbols Used

RES	Renewable Energy Source
AC	Alternating Current
DC	Direct Current
SS	Smart Socket
SH	Smart Home
SHC	Smart Home Controller
ADC	Analog to Digital Converter
SG	Smart Grid
WPCOM	Wireless Power Controlled Outlet Module
AREF	Analog Reference Voltage
V_{cc}	Analog Reference Voltage
SD	Secure Digital
MISO	Master In Slave Out
MOSI	Master Out Slave In
SCK	Serial Clock
GND	Ground
CS	Chip Select
SG	Smart Grid
VA	Volt-Ampere
A	Ampere
V	Volt
RMS	Root Mean Square
mA	Milliampere

LA	Legacy Appliance
kW	Kilowatt
W	Watt
kg	Kilogram
CT	Current Transformer
SSR	Solid State relay
k	Kilo
Ω	Ohm
k Ω	Kiloohm
F	Farad
µF	Microfarad
RTP	Real Time Pricing
SLRP	Scheduled Load Reduction Program
PDP	Peak Day Pricing
HEMS	Home Energy Management System
DR	Demand Response

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Chapter 1 Introduction

Electricity meets 41% of residential demand for energy in American homes and home appliances account for 42% of total electricity in households of United States [1, 2]. About 67% of electricity in US is generated by power plants using fossil fuels such as coal, natural gas and petroleum [3, 4], or by other means such as hydro and nuclear [3, 4]. Coal, among all other fossil fuels, accounted for 24% of the US's energy production in 2014 [5], making it one of the main causes of carbon emissions [6]. As a result, in many jurisdictions, there is a direct relation between energy consumption and carbon emissions.

With the world's increasing demand for electricity every year [7, 8], there is also growing concern over the reduction of fossil energy sources and the environmental impact of fossil energy sources. As a result, many countries are looking to alternatives and investing in renewable energy sources (RES) such as wind, hydroelectric and solar for electricity generation [9, 10]. There is also evidence in many countries such as Denmark, the Netherlands, and the United States that indicates that there are technical as well as economic benefits in incorporating renewable energy such as solar and wind technologies into the grid [11]. For example, in 2014, RES accounted for 11% of the US's total energy production [5] of which hydroelectric accounted for 6-9% of U.S. electric generation [12]. Though conventional power plants produce electricity in a process which can be well-controlled and predicted, the behavior of RES are different and are mostly uncontrollable, unpredictable, and variable in nature when compared to classical energy sources [13].

Also the share of variable renewable energy in electricity grid is expanding [11]. Added to that, the existing electricity grid system is under pressure to deliver the growing demand for power, as well as provide a stable and sustainable supply of electricity [14]. To handle the variable nature of renewable energy requires an effective approach to grid management in order to maintain reliability and stability of the electric grid system [11]. A new kind of grid is required that is efficient, hence making electricity less costly than conventional power grids and is autonomous with self-managing capability in order to manage the increasing complexity and needs of electricity – and is therefore, "intelligent" [15]. Added to that a grid is needed that is more resilient with the ability to address emergencies such as severe storms, earthquakes [16]. These complex requirements for a grid are driving the evolution of “smart grids” and its technologies [11].

There is no universal definition of what a smart grid is; however, it is generally understood to incorporate a wide range of communication, information, management and control technologies into every aspect of electricity generation, transmission, and end-use that contributes to lower environmental impact, improved efficiency, reliability and flexibility of an electricity system’s operation [4, 17, 18, 11]. Smart grids are seen as way of improving a jurisdiction’s energy security by improving electricity supply (availability), reducing the cost of electricity (affordability), and addressing environmental concerns (acceptability) [19]. The technologies that are used with the smart grid vary widely in cost, applicability, and market maturity [11]. Advanced electricity pricing is one smart grid program which involves a broad range of approaches and pricing schemes such as Real-Time Pricing. Real-Time Pricing refers to modifying price profile estimation at intervals all through the day [20]. Consumers making a choice for real-time pricing could gain from the features of the smart grid in which prices are announced and smart appliances strive for the supply [21]. The coverage time for a real time pricing (RTP) profile could be from hours to days and are updated frequently (typically from five minutes to an hour) in order to indicate consumer prices that reflect more precisely the actual production costs so that customers can modify consumption toward times when electricity is less expensive [11].

Among many, one of the arguments for the smart grid is that it will mean that electricity will be used more wisely (i.e., smartly) by, for example, producing electricity only when it is needed and increasing the consumption of variable, low-impact renewable-electricity [22, 23]. Also, the smart grid require customers to have an “intelligent building” or “smart home” in order to adjust and control loads autonomously based on pricing signals [11]– which is central to the entire concept of the smart grid [24, 25].

The smart home (SH), like the smart grid, attempts to use electricity only when needed, and, ideally, at the lowest possible price. According to Zipperer et al [24], smart home may be able to reduce demand, decrease the cost of energy use, and transform the role of the occupant to monitor, manage, and conserve electricity. Due to the convergence of low-cost embedded electronics, low-cost wireless communications, and low-cost processing power, consumers now have access to smart appliances, typically, white-goods such as refrigerators, washing machines, and dishwashers

[26]. If a customer wants to take advantage of the features of a smart home, they need smart appliances that can automatically control and make adjustments to their power consumption based on dynamic price signals from the smart grid [27, 28, 29, 11]. Smart appliances are also able to broadcast their power consumption profile, which is the representation of its power consumption [29]. To manage different types of smart appliances and also in order that the various smart devices in a house both benefit the householder and the smart grid, it is necessary to introduce a third component to the smart home – the smart-home controller (SHC) or home-energy management system (HEMS). The smart home controller gathers power consumption information of smart appliances (using on board power measuring unit or from profiles), analyzes it, and from this, produces information based upon which it coordinates power consumption between the smart appliances, where possible, scheduling consumption to take advantage of real-time pricing and reducing peak consumption through load-shifting (typically driven by price) [30, 31].

One of the underlying assumptions of the smart home is that all electrical goods within the home are smart and able to communicate with the smart-home controller [32]. To take advantage of the smart grid, the smart home requires smart appliances. However, not all household appliances are smart – some, referred to as legacy appliances, have no internal processing or communication capabilities, meaning that they are unable to take advantage of all the features offered by a smart home.

Since smart homes were not designed with legacy appliances in mind [33], legacy appliances, when used in a smart home are unable to control and adjust their operation. They are incapable of automatically reducing their energy consumption based on signals from smart home controllers, unlike smart appliances [27, 28, 29]. This results in a dilemma: the resident expects the appliance to respond as it has in the past, while the benefits of the smart system are lost if the smart home controller is unable to meet appliance's unexpected and uncontrollable demand. Unless this unexpected demand can be controlled in some way, the benefits of the smart home, and by extension, the smart grid, can be lost.

Also for the smart grids to achieve success, it needs to ally with smart consumption strategy so that power is used wisely in order to realize its full potential of affordability, reliability, efficiency and sustainability. As a result, insight into the pattern of how appliance consume power is necessary in order to make the most out of the smart grid concept [34]. One feasible solution is to attach sensing systems to legacy appliances in order to track their consumption. Smart sockets and smart plugs supposedly configure such a system of shared nodes sensing, which normally gives access to remotely control the state (on /off) of an appliance [29, 35].

It is unrealistic to assume that households will abandon existing legacy devices for the foreseeable future. As it may be too costly to replace all legacy appliances with new smart appliances, it is inevitable that legacy appliances will be used in smart homes. In order to benefit from the potential of the smart home and smart grid, this thesis describes the method to integrate legacy appliances in a smart home using smart sockets and profiles. Also there is an Appendix that describes the design and implementation of the electrical power measurement tool that captures real power, apparent power, root mean square voltage, root mean square current and power factor for any 110 V appliance connected to it in order to create profile.

1.1 Objective

This thesis examines some of the problems associated with legacy appliances and describes the methods in order to integrate two distinct legacy appliance to a smart home. Also how appliance profiles are built along with the design of the smart sockets and its requirements to operate the two distinct legacy appliances are described. In addition, communication steps between the legacy appliances, smart socket and smart home controller and how power is allocated to the legacy appliances are discussed.

1.2 Organization

The remainder of the thesis is organized as follows.

Chapter 2 discusses smart grids, smart home, its components as well as the legacy appliances and the problems with legacy appliances in a smart home. Also the necessity of appliance power consumption profile and the role of smart socket are discussed.

Chapter 3 introduces the readers to the design of smart sockets, how appliance profile is built to handle two distinct legacy appliances. Also the communication steps for power allocation between the two distinct legacy appliance, smart socket and smart home controller are discussed.

Chapter 4 introduces the readers to the implementation and results of an appliance to create a profile and how the profile is used in a smart home environment. The thesis concludes with Chapter 5 and discusses potential future work.

Chapter 2 Background

The energy industry faces challenges such as growing demand for electricity, reducing its use of fossil energy, increasing its use of variable renewable energy sources, increasing energy costs, and growing environmental concerns [36]. With such a diverse set of problems, it is necessary to select an extensive approach to overcome these obstacle by changing over to a smart grid. By means of integrating electronics and information technologies throughout the electric power grid systems, smart grid delivers real-time electricity prices to consumers and simultaneously send back their power consumption data to the utility and thereby in order to strengthen grid reliability, flexibility, security, safety and efficiency [37]. The smart grid makes incorporation of renewable energy sources such as wind and solar energy easier, resulting in a cleaner and efficient power grid [38]. As a result, the cost of electricity generation decreases since generators running at economy zone exhibits much higher efficiency [2]. Also, a smart grid reduces the rate of greenhouse gas emission by limiting the need for costly and dirty coal-fired plants [38].

One argument for the smart grid is the potential reduction of electricity usage by coordinating the load balance in the system during peak hours when electricity prices are high [37]. Also, customers are able to participate in demand response (DR) programs to reduce peak electricity demand by receiving real time pricing (RTP) information from the electricity supplier [38]. Consumers can adjust their energy use during low electricity price periods and thereby reducing their costs. In some cases, this can even lead to the consumption of more electrical energy, but pay less for it [39].

For example, there are several types of automated demand response program offered by the electricity utility company in California, PG&E such as Peak Day Pricing (PDP) that encourages participants to use less electricity on the event of Peak Day Pricing (PDP) during which the power grid is expected to be in most stress thereby maintaining the reliability and stability of the grid [40]. A discount is given to the program participants on regular summer electricity rates in exchange for higher prices on 9 to 15 event days per year—typically the hottest days of the summer.

Another demand response program offered by PG&E is Scheduled Load Reduction Program (SLRP) that gives the participants of the program an allowance to curtail their electric load during pre-selected time periods which the participants specify beforehand [41]. The participants are able to choose the time period (between 8 a.m. to 8 p.m.) on one or more weekdays and their intended load reduction, which must be at least 15 percent of the participant's average monthly demand or 100 kW, whichever is greater. To receive the allowance, the participants are encouraged to reduce their load by the pre-selected commitment of load reduction during their selected time period on their selected weekdays.

The commercial headquarters of Adobe Systems Incorporated in Calfornia participated in PG&E's automated demand response program. The commercial building saved 23% in energy consumption and reduced their total demand by 39% compared to the demand before participation by means of integrating daily load management through programmed demand-limiting controls and state-of-the art information systems [42].

While much of the focus of the smart-grid discourse has been on the real-time pricing of electricity by means of demand response program, minimization of electricity cost for users and increase in the consumption of variable, low-impact renewable-electricity [43, 44], central to the entire concept of the smart grid is the smart home [45].

2.1 The Smart Home

The smart home introduces the concept of networking devices and equipment in a house [46]. The concept of smart homes, in fact, started gaining ground in the 1980s in the United States as a project of the National Research Center of the National Association of Home Builders (NAHB) with the cooperation of a collection of major industrial partners [47]. A smart home is an intelligent house equipped with various types of heterogeneous smart objects such as smart appliances (SA), smart sockets (SS) and supporting devices like smart-home controller (SHC) [48], that are able to interact with each other using a communication network [49].The overall system architecture for smart home is depicted in Figure 1.

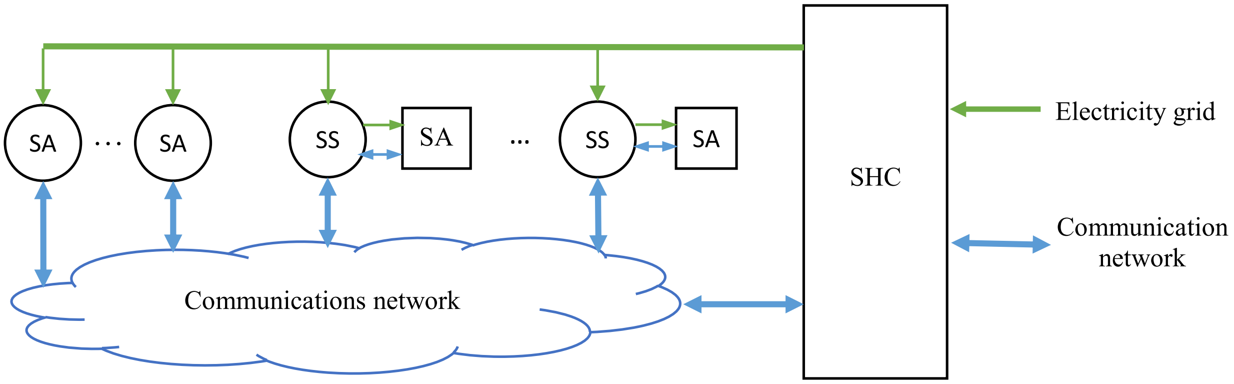

Figure 1: Smart Home

The smart home attempts to use power smartly when needed, ideally, at the lowest possible price. The main component in a smart home is the smart home controller, which is in charge of controlling the allocation of energy based on signal (price/ volume) coming from electricity grid and the information collected from the smart appliances as well as smart sockets that are in turn connected to other appliances in the home [50]. By knowing the expected electricity demand of a smart appliance (either based on built-in power measurement units or maintained by appliance itself in a profile, which is the smart home controller's internal representation of the appliance's power consumption) or via smart plugs, the smart home controller can either negotiate with smart grid for additional electricity or schedule operation of the appliance by changing the operating state of the active appliances by submitting appropriate control primitives so that demand never exceeds a defined maximum (thereby ensuring that the electricity generated meets demand) [51].

Typically the electricity grid starts by sending out notification signals (price/volume) for upcoming time period. This signal is received by a smart home controller. Once a signal is received by the smart home controller, the smart home controller uses power consumption information from smart appliances (either by means of profiles or on board power measurement unit or via smart sockets) and a priority list of pre-selected curtailments of appliances identified by the smart home users in accordance with their own needs to process scheduling of the appliances [51]. Typical curtailments include non-essential lighting and appliances whose operations can be delayed without noticeable disruption such as refrigerator, clothes dryer, washing machine, or water heater [52].

In a smart home, all the devices acts like peers and the smart services provided by a smart home can range from sophisticated monitoring and automated control over a building's function to the simple turning a light ON or OFF automatically [53]. For example, Samsung Electronics in association with a Toronto condominium developer is launching the first of its smart home systems to offer smart services in a building to open in 2017 [54]. By enabling smart TVs, smart home appliances and smart phones to be connected and managed through a single integrated platform that uses a special app, the users will be able to control access to the building, surveillance system, door-lock, temperature, lightning and administer entertainment system, washer-dryer, stoves and other smart appliances [54].

The rest of the section discusses the various components of smart home and the state of art technology available in the market.

2.1.1 The Smart Home Controller (SHC)

A smart home could have multiple appliances and the user wouldn't want to install an individual control device for every appliance. This is where smart-home controller plays its role by helping all the devices communicate with each other. The smart-home controller is central to the automation in a smart home [45], normally undergoing a set of commands. It receives information from one device and uses that to trigger another device into action, exhibiting energy resource optimization and bi-directional communication of smart home information to the service provider [53]. That is it has the ability to (i) gather power consumption information of connected smart appliances in a home [29], (ii) collect information through smart sockets and monitor the electricity supply from service provider [29, 45]. Based upon the gathered data, the smart-home controller uses algorithms which are commands or a set of predefined rules [45], in order to implement strategies to control appliances [30], which simultaneously co-optimize several objectives of the smart home users such as: comfort, convenience, cost to the inhabitant and efficiency in energy consumption [29]. For residential home automation, the most common home controllers are typically a standalone or embedded operating system such as Linux, Windows, or OS-X PC, performing the home control application and duties for the house [46] [45].

Based upon the devices needed to be controlled and the number of home automation protocols to be run, various types of smart-home controllers are commercially available in market as follows:

1. The SmartThings Hub is a home controller that features three different types of wireless communication technology namely ZigBee, Z-Wave and WiFi and is compatible with any other devices featuring either of the communication technology. The controller requires to be

plugged into the router via an Ethernet cable in order to control it using apps in a smartphone that is connected to the same network [55].

2. SmartLinc is an example of another commercially available smart controller that integrates Insteon technology with any web-enabled devices allowing user to control home appliances remotely. Insteon technology is a networking topology based on mesh network that utilizes AC-power lines and radio-frequency for communication with peer Insteon devices [56]. The SmartLinc has the ability to control light bulbs, wall switches, lamps and other peer Insteon devices [57].
3. VeraEdge is another commercially available smart-home controller that can manage up to 220 devices compatible with Z-Wave and WiFi communication protocol. It is equipped with Vera UI7 app by means of which a user can remote view and control their system from anywhere in the world by means of internet using computers, tablet and smartphones. Custom automation scene can also be set by the user where one device triggers another. For example a user can mention the time of sunrise/sunset that triggers to control lights, door locks, thermostats, etc. VeraEdge also features occupancy sensing. For example the triggering of smoke detector. It also features Geofencing, by means of which the system defines geographical boundaries in order to locate the user based on their cell phone location. For example, when a user drives close to home, the thermostat can be made active along with several other features [55, 58].

While much of the focus of the smart-home discourse has been on the various heterogeneous devices such as smart home controller, it is necessary to introduce another component – the smart appliances.

2.1.2 Smart Appliances

At present, there is no single, accepted definition for a smart appliance [59]. This is because some manufacturers address an appliance with touch controls, digital displays and wide range of settings than its competitor to be smart device [59]. Appliances with some sort of information sharing via communication technology are also considered as smart device by many manufacturers [59]. Therefore, the capabilities associated with an appliance to be smart are as follows [59]:

1. The ability to share its information so that a user or an external device (such as the SHC) has the ability to access its functions and monitor as well as control its status and settings remotely

2. The ability to automatically adjust and optimise its operation based on deliberately made signal from a user or an external device such as smart home controller, or both.

Hence smart appliances in a smart home are devices that use electricity for its main power source and have the capability to identify itself as well as receive, interpret, and act on a signal received from a utility via home energy management device or smart home controller and automatically make adjustment to its operation depending on both the signal's contents and settings from the consumer [60, 61]. Additionally, smart appliances are also able to control and reduce their energy consumption to a significant amount by modifying their behaviour based on signals from smart home controller [29], or in other words they can be told to modify their behaviour by the smart home controller.

For example, a washing machine that has more than one mode to choose from. Each mode is a sequence of cycles for washing, rinsing and spinning with varied times, speeds and water temperatures. A washing machine is considered smart that is able to identify itself as well as provide its power consumption forecast related to each mode and cycle along with its duration [50].

The Nest thermostat is a commercial example of smart appliance comprising to smart home technology that is recognized for its smart functionality and benefits to users. Nest has the ability to learn from the behavioral pattern of its user [49] . The thermostat has a built-in sensor to check user presence and access to Wi-Fi connectivity to check local weather forecasts in order to automatically adjust temperature to the desired comfortable setting according to the presence of its user as well as depending on the weather forecast [62]. The smart thermostat can also be controlled by its user with a smart phone [63]. The Nest thermostat is addressed smart because it can be operated based on what it learns and how and when it is being used due to possession of communication technology [62].

To achieve success, it is necessary to have end-use energy information of how power is consumed by appliances to realize full potential of smart grid [64]. As a result, insight into individual appliance energy use is necessary in order to make the most out of the smart home, by extension smart grid concept [65]. According to Elmenreich et al [66], some smart appliances have a measurement unit in which the current, voltage and other electrical values are measured and computed to indicate the power consumption for the corresponding operating state of an appliance as well as a communication unit for information sharing. Some smart appliance also have their own power consumption recorded in their memory as profile to represent its power consumption features [29]. Hence in order to establish the relationship between the operating state of an appliance and the power and current it draws in real time during the operation, another variable called profile is required in the smart home equation [65].

2.1.3 Profile

An appliance profile can be defined as a time-series data of measureable parameters such as real power, current of a load that gives information about the nature and operating characteristic of an appliance [65]. The logging information could be where, when and how during an appliance's operation causes power consumption and what activities are causing the power consumption. Having a realistic electricity load profile of an appliance allows external entities such as a smart home controller to understand and monitor the pattern of energy consumption and how much energy different appliances are consuming. The smart home controller can also obtain appliance-specific energy consumption statistics from the electricity load profile of appliances which in turn can be used to devise load-scheduling strategies for optimal energy utilization [67].

According to literature review, there is no fixed content of a profile nor is there is fixed standard. According to [29], an appliance profile consist of:

- **Appliance type**: indicates whether an appliance is used for heating, lightning, entertainment, laundry, cleaning, kitchen or cooling.
- **Physical Service**: specifies the activity of a device for a particular task, for example a certain washing cycle for a washing machine.
- **Signature**: describes the energy demand for the appliance.
- **Current Status**: indicates whether the corresponding appliance is switched ON, OFF or Paused along with Start Time and Elapsed Duration.
- **State**: indicates parameters namely peak active power, tolerance to power variations, duration and two distress factors: i) a delay sensitivity (in seconds) that describes the responsiveness of an appliance and ii) an interruption sensitivity (in seconds) that determines the tolerance to state interruption. For example, the beginning of a coffee machine should not be delayed once it is initialized due to extremely low delay sensitivity, while its state of water heating state should not be postponed due to low interruption sensitivity

In order for smart home to realize the full potential and benefits of smart grid, appliances in a smart home must have processing features along with the ability to broadcast those features to other smart devices [68], as well as act on signals received from those device [59]. Features as such can be exhibited by smart appliances having or board measurement unit or built- in profile along with a communication unit, while without any internal processing or communication capabilities, legacy appliances are not designed to be incorporated into the smart home [48].

2.1.4 Legacy Appliances

Legacy appliances are non-intelligent, non-smart electrical or mechanical household devices such as toasters, microwave ovens or consumer electronics such as TV that accomplish household functions such as cooking, washing and entertainment. Legacy appliances don't have embedded intelligence, nor do they support the smart services in a smart home unlike smart appliances that have the ability to identify itself, broadcast their features as well as receive, interpret and act on a signal received from other devices. Legacy appliances are also not able to provide power consumption forecast for each mode or cycle. As a result, legacy appliances cannot self-control and self-adjust their operation and are thereby incapable of automatically reducing their energy consumption based on those signals unlike smart appliances [27, 29, 28].

One main problem with legacy appliances are, neither their power requirements nor their duration of use are known when it begins drawing power. According to the literature review, a deterministic appliance is one whose length of operation is known where as a non-deterministic appliance's length of operation is unknown. Similarly a single mode appliance has only one operating state, that is it will either on or off where as a multiple mode appliance has more than one operating state and settings when they are operating. The overall characteristics of legacy appliances are summarized in Table 1.

Table 1: Characteristic of Legacy Appliances

	Non-deterministic	Deterministic
Single mode	• Length of operation is unknown (time) • Power demand is known (max) • Example: Light-bulb, Laptop adaptor	• Length of operation is known • Power demand is known
Multiple mode	• Length of operation is unknown (time) • Max power demand for each mode is known • Example: Microwave, Variable speed fan, Toaster	• Length of each cycles in the mode is known • Max power demand for each cycle is known • Example: Washing machine

- Non-deterministic Single mode: A non-deterministic single mode legacy appliance is one that has only one operating mode and whose corresponding power consumption is known (rated power mentioned in the body). But the length of time the appliance can run is unknown. That is, the length of operation is not known for this type of legacy appliance.
- Deterministic Single mode: A deterministic single mode legacy appliance is one that has only one operating mode and whose corresponding power is known (rated power mentioned in the body) along with its length of operation.
- Non-deterministic multiple mode: A non-deterministic multiple mode legacy appliance is one that has more than one operating mode and the power consumption for each corresponding mode can be known. But for how long the appliance would be running is unknown. That is length of operation is not known for this type of legacy appliance.
- Deterministic multiple mode: A deterministic multiple mode legacy appliance is one that has more than one operating mode and whose power consumption for each corresponding mode can be known along with the length of operation for each mode.

Legacy appliances are everywhere and one just can’t expect to replace the legacy appliances with smart appliance as it will incur additional cost to the user [49]. Furthermore, there is nothing to stop someone in a smart-home from “plugging-in” a non-smart or legacy appliance into the smart-home system where devices needs information about other devices. Plugging the legacy appliance will result in a dilemma: the resident expects the appliance to respond as it has in the past, while the benefits of the smart system are lost as the smart home controller is unable to schedule the legacy appliance. It is also unrealistic to assume that households will abandon existing legacy devices. Because legacy appliances lack the extended functions of smart appliances, another device called smart sockets are used that acts as proxy for legacy appliance adding some intelligence to it [29], for example turning on and off any device from smartphone [69].

2.1.5 Smart Socket

According to Giorgio et al [50], smart sockets are devices that sit in between any appliance and the AC outlet and is able to measure the power consumption and send that information over communication technology to a receiver along with the capability to receive, interpret, and act on a signal received from a transmitter. To some manufacturers, if the power being supplied to a plug can be controlled or restricted by means of communication technology such as Wi-Fi using smart phone then that plug can be considered as smart socket [69]. Also sockets with the ability to measure and control how much energy an appliance is consuming are also referred as smart socket [70].

Alertme is a commercially available internet accessible smart socket that indicates how much energy an appliance is consuming to users. Users can also control the power being supplied to the appliance online or by using their smart phone [70]. Similar to Alertme, Meter Plug smart socket sits in between any appliance and the AC outlet. It measures the connected appliance's consumption and sends that information over Bluetooth to a user's smart phone, where the app displays the real cost to run the appliance [70].

Another commercially available smart socket is the Digi XBee smart socket, that has the ability to measure and control appliances connected to it. This smart socket integrates communication technology such as ConnectPort® X to unify input from heterogeneous Digi XBee smart socket into a smart home. Power consumption information from the appliances attached to it can be transferred to external entities for monitoring and along with the ability to control supply of power to the connected appliance [70].

Along with the commercial smart sockets available, research is also being conducted on smart sockets.

A paper by Shekarabi presented a smart socket that provides features to measure energy consumption and identifies the type of electrical device connected to the smart plug by means of magnetic tags [71]. The proposed smart plug constitutes of four subsystems as follows:

- **Recognition subsystem**: This subsystem contains magnetic sensors that senses magnetic label attached to the appliance's plug in order to obtain the type of connected appliance.
- **Switching subsystem**: This subsystem is used to supply or restrict supply of power to the connected appliance using a power triac.
- **Measurement subsystem**: This subsystem contains a current transformer where samples of current flowing into the appliance is measured and processed to calculate the energy consumption and power factor.
- **Communication subsystem**: This subsystem relays the recognition information and power measurement information to other devices using RS-485 communication technology.

A paper by Lin proposed a wireless power controlled outlet module (WPCOM) for home power management [72]. The system integrates a microcontroller into a power outlet in order to measure the electrical power consumption of plugged home appliance and when necessary switch the power of the appliance using solid state relays (SSR) to turn its state into on or off. The remote monitoring and control of electrical home appliances was provided using six scalable modules which together provided an indoor wireless and outdoor remote control and monitor of electrical appliances as follows:

- **Power measurement module**: The power measurement module indicates the real time power measuring status of the appliance connected to WPCOM. The module consists of four parts: current transformer (CT), electrical power detector, multiplexer and a power load micro-processor. Therefore when an appliance is switched ON and as the load current changes, the output of the CT, which is a voltage signal, is transmitted to the power measuring module where the electrical power detector transforms the voltage signal as digitized data. This digitized data is fed to a multiplexer that selects one of several digital input signals and forwards the selected input to the power load micro-processor that then processes power measurements of the appliance connected.
- **Bluetooth module**: Using this module, users can send commands to the WPCOM system using the Bluetooth network of their PDA phone to control the state of the appliance connected to WPCOM

- **GSM module**: Using this module, users could send text messages to the WPCOM system in order to turn the electric home appliance on/off connected to WPCOM and receive latest measurement information.
- **Ethernet module**: This module allows user to change settings and monitor the power measurement of connected appliance to WPCOM over the internet.
- **SD card module and Essential control module**: This module executes the basic functions of the system such as processing command from the other modules, controlling the state of SSR, monitoring the power measurement and status for the connected appliance as well as storing the recorded data into the SD card module.

Guangming describes a wireless-controllable power outlet system that realizes remote control of various home appliances [73]. The outlet computes power measurement using a power transformer and uses a low-cost micro-controller unit as main board to implement the control logics to drive the relay to control the supply of power. The system also has a radio that uses ZigBee wireless communication to share the power measurements with other Zigbee compliant devices in range.

Shajahan and Anand developed a smart socket that provides real-time energy consumption information of the appliance connected to the socket based on Arduino-Android platform. The socket uses a microcontroller board by Arduino and a current transformer sensor of non-invasive type to process and store the power consumption information to a server using Ethernet connection. The information in the server can be accessed by means of the device's user interface developed using Android platform. [74].

2.2 Summary

The chapter discussed the concept of smart grids and how it plays an important role in saving energy by including smart homes. Also the constituents of smart homes and how different objects such as smart appliance, smart home controller and smart socket in a smart home coordinate with each other using real time power consumption information or profiles are discussed. Additionally, legacy appliances and their characteristics as well as their problems are discussed in details.

Chapter 3 Design

In the literature review, it was shown that neither the power requirements nor the duration of use for a legacy appliance is known when it begins drawing power. Also, legacy appliances don't have any identification, processing and communication capabilities to identify themselves in a smart home nor are they able to respond to signals from smart home controller. Unlike smart appliances, legacy appliances are unable to tell the smart home controller about their power consumption. This chapter introduces a method of integrating legacy appliances using smart sockets into a smart home, where legacy appliances can be either (i) Unidentified Legacy Appliances (appliances that are unidentified in a smart home with unknown power requirements) or (ii) Identified Legacy Appliances (appliances that can be identified with known power requirements by means of profiles). The chapter also describes how appliances are identified, the steps and parameters considered for building appliance profiles, the design and requirements of the smart socket to handle both unidentified and identified legacy appliances. Finally, the communications between the legacy appliance (unidentified and identified), smart socket and smart home controller are discussed upon the activation of either legacy appliance in a smart home.

3.1 Identifying Appliances

Identifying an appliance means establishing or indicating who or what an appliance is. Smart appliances are able to identify themselves while features as such aren't available with legacy appliances. Hence a label or tag which indicates an ID, must be attached to the legacy appliance plug for the purpose of identification or to indicate what appliance it is. The tag is attached to the appliance plug and is read by a system called tag reader located in the proposed smart socket design.

A legacy appliance can be unidentified or identified:

1. The plug of the unidentified legacy appliance doesn't have any tag that can be read by a tag reader for identification of the appliance. Its length of operation and the corresponding power demand is unknown.
2. The identified legacy appliance's plug is associated with a tag that can be read by a tag reader for identification making it identifiable. Identifiable legacy appliance's power requirements

are known by the smart home using appliance profile, meaning that its length of operation and the corresponding power demand is known by the smart home.

3.2 Profile

In the literature review, it was shown that smart appliances provide power consumption forecast related to each mode and cycle along with its duration whereas legacy appliance don't have such features. Also some smart appliances have their own power consumption recorded in their memory as profile to represent the relationship between the operating state and the power it draws in real time during the operation. Smart appliances report their power consumption to smart home controllers using profiles in order to coordinate their operation. Legacy appliance have no such characteristic. As such, to integrate legacy appliances in a smart home requires their power consumption profile to be recorded beforehand so that it can be interpreted by the smart home controller. As such, in the design, the thesis considers a profile to contain power consumption at regular intervals for identified appliances in order to make the power consumption known.

In order to create a profile, the power consumption of an appliance can be measured using a power measurement tool. The electrical power measurement tool sits in between AC mains voltage and the appliance plug as shown in Figure 2 and captures the electrical parameters of an appliance such as real power, apparent power, root means square voltage, root mean square current and power factor.

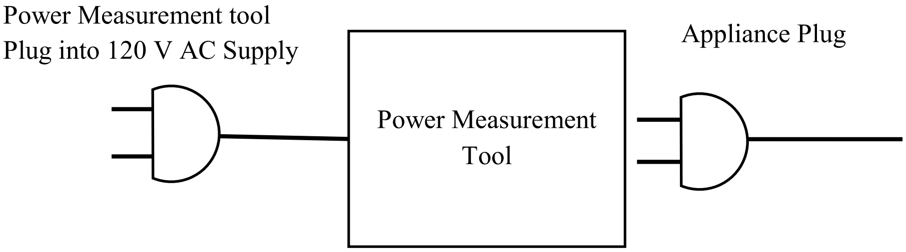

Figure 2: Electrical Power Measurement Tool Layout

The tool consists of a current sensing circuit and a voltage sensing circuit. Therefore when an appliance plug is inserted into the receptacle of the tool box, the corresponding voltage signal and current signal are recorded and processed using a micro-controller to extract as well as record the aforementioned electrical parameters for the connected appliance. The full details of the tool is described in appendix of the thesis.

With the electrical parameters captured using the tool, a complete appliance profile can be created. Appliances can have only one mode with one continuous cycle such as a refrigerator. Appliances can also have multiple modes where each mode consists of one or more cycles. For example, a washing machine with more than one mode to choose from where each mode consists of a sequence of cycles for washing, rinsing and spinning with varied times, speeds and water temperatures. Also each mode of a washing machine with variable loads weight can have slightly different instantaneous power values and also there is no guarantee that any random runs of the same mode are going to be identical.

In the proposed design to create a profile, at first multiple real power data for several runs of a washing machine undergoing a particular mode with variable load weights are recorded using the power measurement tool. Then for every point of all the washes for a particular mode, a maximum power value for each point from the all sets of data is chosen. Hence a maximum real power value for each point of the washing machine, operating in a particular mode with all types of load weight is retrieved, where each point is the maximum value of power from the all sets of data for that point. For example, the blue plot in Figure 3 shows the maximum real power consumption for the last eight minutes of a multi-mode, multi-cycle washing machine exhibiting a particular mode, where each point is the maximum power value selected from several sets of data of the corresponding point.

The washing machine consumed about 27 watt of power for the first 125 seconds after which several sudden spikes are recorded until 470 seconds as depicted in Figure 3. In this several spikes time period, the power level of the washing machine oscillated between 26 and 480 watt before ending to consuming no power. Then a profile is created for that mode where power is selected "by block" and each block specifies a maximum wattage and its starting time. In this particular mode and cycle of the washing machine, the proposed profile design divides the appliance's maximum real power consumption into multiple intervals of 120 seconds each, called "block", with each block been assigned its own maximum power.

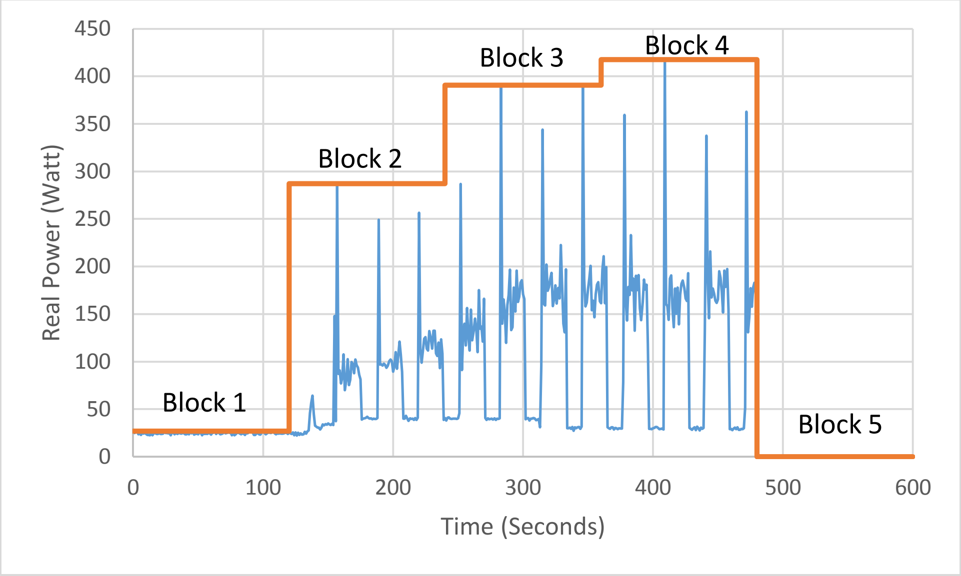

Figure 3: Washing Machine Maximum Real Power Consumption for Last 8 minutes

The maximum power for each corresponding interval is the "power demand" for that block. Similarly, the time when a block starts is considered the "starting time" for the corresponding block. For example, in Figure 3, the orange plot depicts that maximum power demand for each block. Here the washing machine consists of total five blocks where the first block's power demand is 27 watt with a starting time of 0 seconds. The second block starts at 120 second and has a maximum power demand of 288 watt and third block starts at 360 second with a corresponding maximum power demand of 391 watts and subsequent blocks also specify starting times and their associated demands. If the final starting-time demand is zero, the design considers the appliance to be stopped (Block 5).

So, for every appliance, each mode is associated with one or more blocks and each block has a starting time and demand. Also each appliance is associated with a "maximum profile power" which is the maximum demand recorded in any operating mode and stage. The appliance whose profile is to be created is also associated with a tag. The ID of the tag is considered as the identifier in the profile of the corresponding appliance. Also, a smart home controller needs to know the priority for an appliance for scheduling and hence each appliance is given a priority by the smart home user. Therefore, in the proposed design an appliance profile consists of:

- An identifier or ID of the tag which uniquely identifies the appliance.
- The priority assigned to the appliance

- The number of modes.
- The number of blocks in each mode
- Each block’s starting time and demand.
- The appliance’s maximum power

Figure 4 is the proposed structure of an appliance profile.

	Identifier (ID # 1,2,….Z)		
	Priority (1,2,3….T)		
	Total number of modes (1..M)		
	Maximum Profile Power		
Mode 1	Total number of blocks (1..N)		
	Start Time	Demand	Block 1
	…		
	Start Time	Demand	Block N
…	…	…	…
Mode M	Total number of blocks (1..N)		
	Start Time	Demand	Block 1
	…		
	Start Time	Demand	Block N

Figure 4: An Appliance Profile

A multi-mode identified appliance has multiple blocks. The first block specifies its starting time and demand. Subsequent blocks also specify starting times and their associated demands with the last block’s starting time specifies a demand of zero. Similarly a single-mode identifiable appliance actually has two blocks. The first block specifies the starting time and the demand, while the second block’s starting time specifies a demand of zero (i.e., the time the appliance is to stop). For appliances that are not associate with an “off” time, the “off” time is considered infinite as the stopping time of the appliance is unknown as the appliance can only be stopped by issuing an explicit “off”.

This information must be available to the smart socket to allow it to identify an identified appliance and the corresponding power consumption.

3.3 The Smart Socket

The smart socket must be designed so that it can handle both identified and unidentified legacy appliances. The proposed smart socket is a terminal node of smart home. Figure 5 shows the hardware block of the smart socket.

The socket consists of the following units:

- Tag reading unit – This unit is a tag reader that reads the ID of the tag mounted on the appliance plug in order to identify an appliance.
- Electrical power measurement unit – This unit measures instantaneous power consumption. The unit senses the incoming current and voltage signal using a current and voltage sensor in order to process the electrical power consumption using the processing unit.
- Switching unit - The socket controls the supply of power to the connected appliance by means of switching unit such as relay.
- Communication unit – Using this unit, the socket is able to transmit instantaneous power measurements to a smart home controller and control the supply of power to the connected appliance based upon signal from the controller
- Light unit- This unit of three colored lights (amber, green and red) indicates the current operating situation of the smart socket; green indicates power supplied to the connected appliance, amber indicates attempting to get power, and red indicates that no power is available.
- Memory unit-The memory unit stores the profiles bearing power consumption information at regular intervals of the identified appliances and also reproduces the information when needed by smart socket.
- Processing unit - The processing unit manages other units and processes the required parameters and send signals to the required unit. For example, the processing unit takes the incoming voltage and current signals as the basis of the electrical parameters calculation to measure electrical parameters such as voltage, current, power. Also, when the communication unit receives signals from the smart home controller, the processing unit send signals to activate or deactivate switching unit (relay) to restrict the supply of power to the appliance.

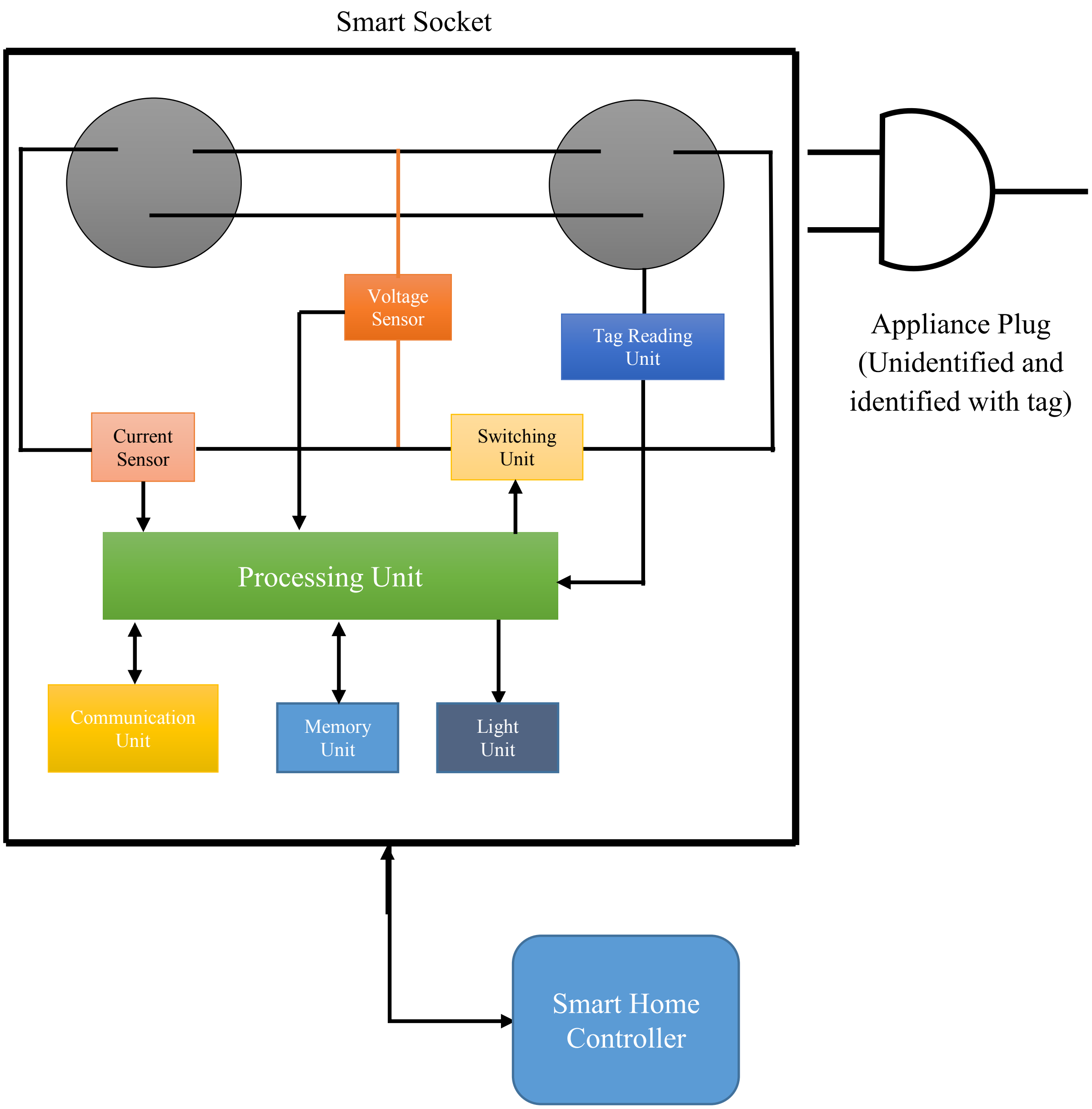

Figure 5: Smart Socket Block

3.3.1 Steps for Handling Legacy Appliances in a Smart Home

When a legacy appliance is plugged into a smart socket to draw power, the socket is able to distinguish between an unidentified and identified appliance using the tag reader. If a tag is read on the appliance plug by the reader of the socket, the smart socket knows that is an identified appliance, whereas, the lack of a tag indicates an unidentified one. Hence the communication steps for handling both approach of legacy appliance (unidentified and identified) by the smart socket in a smart home, are discussed separately below.

3.3.1.1 Power Allocation for Unidentified Appliance

If the smart socket detects an unidentified appliance, it then restricts the supply of power to the appliance by enabling the relay and turns the light amber. Since the socket doesn't know anything about the power consumption of the plugged-in unidentified appliance and the demand of the unidentified appliance could be anything, the smart socket requests the maximum available power for the smart home from the smart home controller in order to meet the instantaneous demand of the connected unidentified appliance (at Step 0) as shown in Figure 6.

Assuming that there is power available with the smart home controller for the smart home, the smart home controller then allocates the maximum available power to the smart socket (at Step 1). Once the smart socket has the available power, it disables the relay so that the legacy appliance can draw power; the colour of its light is changed to green (at Step 2). Once the legacy appliance starts drawing power, the socket then monitors the power consumption of the appliance every second by means of its power measuring circuit as long as the appliance is connected to the smart socket. The socket then determines the maximum power of first three seconds and informs that maximum power demand to the smart home controller in order to decrease the power supply for the smart socket to the current instantaneous maximum (at Step 3). The longer the monitoring period, better the chance of finding a higher maximum power value for the appliance, but then if an appliance is faulty and demands infinite amount of power that exceeds the allocated maximum available power in between the monitoring period might cause the smart home system to trip and cause power outage. Hence, neither too long nor too short monitoring period of three seconds is chosen. The smart home controller then reduces the maximum power allocated for the unidentified appliance and determines new available power for the connected appliance based upon the maximum power demand for every three seconds of the appliance from the socket (at Step 4).

Step	Appliance	Smart Socket		Smart Home Controller
0	Turned On	- Appliance sensed - If there isn't a tag? -Enable relay -Light=Amber -Request Maximum Available Power	⇨	
1			⇦	- Allocates requested power - Inform socket of available power
2		- If relay enabled? -Disable relay -Light=Green		
3	Draws Power	- Monitor power demand - Inform smart home controller of current maximum power demand	⇨	
4				- Determine new available power

Figure 6: Initial Power Allocation to Unidentified Appliance by a Smart Socket

Once the new determined power is allocated to the unidentified appliance as shown in Figure 6, the smart socket allows the appliance to draw the new determined or allocated power (at Step 5) as shown in Figure 7. The smart socket then monitors the power consumption of the appliance every second and compares the instantaneous power value with the determined or allocated power value. As long as any instantaneous power value is below the allocated power value, the socket allows the appliance to operate without any interference. If any instantaneous power value exceeds the allocated power value, then socket momentarily enables its relay to restrict power to the unidentified appliance causing the socket light to turn amber and at the same time requests the smart home controller to allocate an additional 20% more power of the previously allocated power (at Step 5) as shown in Figure 7. Allotting any infinite instantaneous power value to the unidentified appliance that exceeds the allocated power value can imbalance the system. The benefit of the 20 % increase in power is, that the smart socket then serves the power requirement to the unidentified appliance in a step-up and more controlled manner, offering a little more, in this case 20%, from the previous allocated power and thus reaching near to the required power. The smart socket then allocates the newly requested power to the smart socket (at Step 6). The socket then disables its relay allowing the unidentified appliance to consume the allocated power and changing the light to green (at Step 7). The socket then repeats the action of monitoring and comparing every instantaneous power value with the immediate last allocated power in order to enable or disable the relay (at Step 8) which in turn causes the socket light to change colour accordingly as shown in Figure 7.

Step	Appliance	Smart Socket		Smart Home Controller
0	Turned On	• Appliance sensed • If there isn’t a tag? -Enable relay -Light=Amber -Request Maximum Available Power	→	
. .		• •		• •
4				• Determine new available power
5	Draws Power	• Monitor power demand • Power Exceeds Allocated Power? -Enable relay -Light=Amber -Inform smart home controller to allocate 10% more of previously allocated power	→	
6				• Determine new available power
7		• If relay enabled? -Disable relay -Light=Green		
8	Draws Power	• Monitor power demand • If Power Exceeds Allocated Power? -Enable relay -Light=Amber - Inform smart home controller to allocate 10% more of previously allocated power Else -Disable Relay -Light=Green	→	

Figure 7: Subsequest Power Allocation to Unidentified Appliance by a Smart Socket

3.3.1.2 Power Allocation for Identified Appliance

If the tag reader detects a tag mounted on the appliance plug, the sockets knows that an identified appliance is plugged to it. The socket then restricts the supply of power to the identified appliance by enabling the relay and changing the socket-light to amber as shown in Figure 9.

The smart socket then compares the ID from the tag with the list of IDs it has associated for appliances in its memory as profile to identify which appliance is connected to the socket as shown Figure 8.

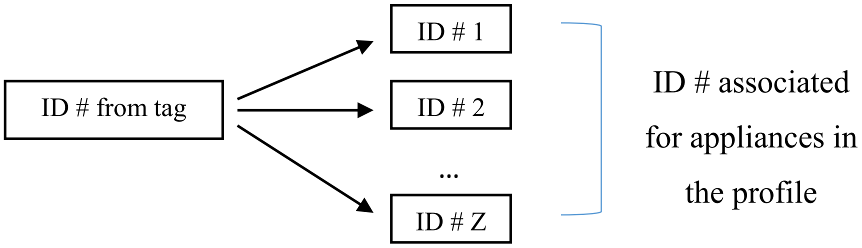

Figure 8: Comparing ID from the Tag with ID in the Profile

Using the ID associated for appliances in the profile that matches with the tag ID, the smart socket then identifies the associated power profile for the connected appliance. From the associated profile, the socket determines the maximum profile power for the appliance in order to meet the instantaneous demand of the connected identified appliance. The socket then requests this maximum profile power associated for the appliance in the profile from the smart home controller (at Step 0) as shown in Figure 9. Assuming that smart home controller is able to meet the requested power, the smart home controller then allocates the requested power to the smart socket (at Step 1). The smart socket disables its relay allowing the identified appliance to draw power and changes the light colour to green (at Step 2). Since the power profile demand for the identified appliance are built based on 120 second interval, the socket then monitors the power consumption of the appliance every second by means of its power measuring circuit to determine the maximum power of the appliance's first 120 seconds. The socket then compares this maximum power value with all the demands in the profile of the appliance having the same ID as the tag in order to determine the current operating block and the corresponding mode of the appliance.

Once the mode and the operating block and the corresponding demand for the appliance is known, the smart socket then informs the smart home controller of the current demand for the operating block along with subsequent power requirements and their specific starting times of the upcoming blocks of the appliance (at Step 3). The smart home controller then reduces the maximum profile power level to a new power level based upon the information on current power requirements provided by the smart socket (at Step 4) as shown in Figure 9.

Step	Appliance	Smart Socket		Smart Home Controller
0	Turned On	- Appliance sensed - If there is a tag? -Enable relay -Light=Amber -Request Maximum Profile Power	→	
1			←	- Allocates requested power - Inform socket of available power
2		- If relay enabled? -Disable relay -Light= Green		
3	Draws Power	- Monitor power demand - Compare the maximum power of 120 seconds with the profile demand data to identify the mode and subsequent power requirements. - Inform smart home controller of current and subsequent power requirements and starting time	→	
4				- Determine new available power

Figure 9: Initial Power Allocation to Identified Appliance by Smart Socket

Once a new power level is allocated to the identified appliance as shown in Figure 9, the smart socket allows the appliance to draw the newly allocated power (at Step 5) as shown in Figure 11. The smart socket then monitors the instantaneous power consumption of the identified appliance and compares this value with the corresponding power demand of the operating block indicating the associated mode of the appliance from the profile (at Step 5). As long as any instantaneous power value is equal or below the power demand of the operating block indicating the associated mode of the appliance from the profile, the socket allows the appliance to operate without any interference and smart home controller allocates the subsequent power demand of the next block to the smart socket at the respective starting time to meet the identified appliance's demand.

But the power consumption pattern between the appliance instantaneous power consumption and the power demand of the operating block indicating the associated mode of the appliance from the profile can be incoherent or not in phase. For example, as shown in Figure 10, at any stage during its operation, an appliance can start consuming higher power before it is supposed to consume that high power according to its profile demand (Start Early) or an appliance can continue to consume high power and move to next block where it is supposed to consume lower level of power according to its profile demand (Late Finish). If any of the two incoherent or not in phase situations or events takes place (either Start Early and/or Late Finish) then the smart socket enables its relay momentarily to restrict power to the identified appliance causing the socket light to turn amber in color (at Step 5) as shown in Figure 11.

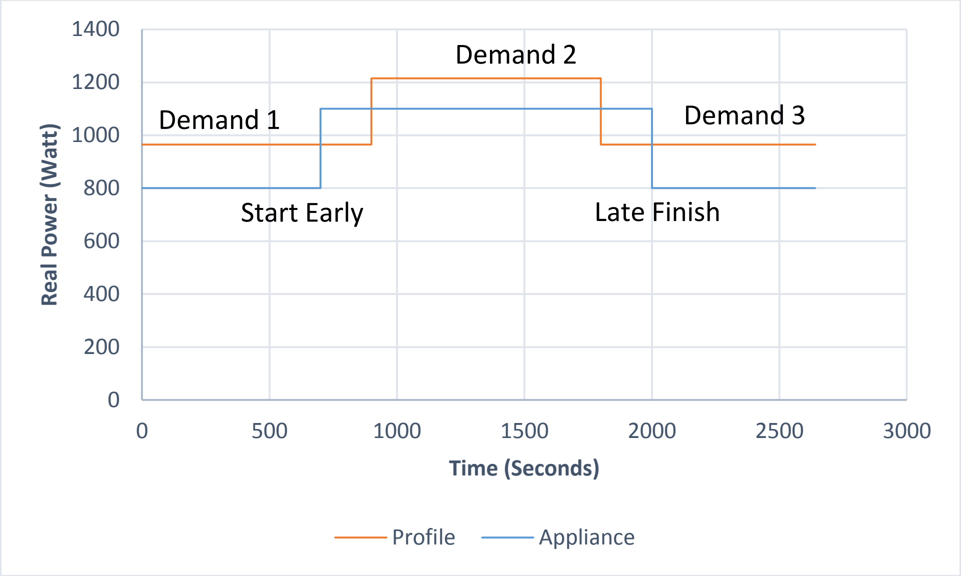

Figure 10: Appliance Instantaneous Power Consumption Comparison with Profile Demand.

The socket then requests the smart home controller to allocate next higher block demand for the associate mode of the identified appliance from the profile (at Step 5) for “Start Early” situation. If the situation is “Late Finish”, the smart socket requests the smart home controller to continue with the immediate last block demand for the associate mode of the identified appliance from the profile (at Step 5). For example as can be seen in Figure 10, if the socket senses “Start Early” at the “Demand 1” block then the socket requests “Demand 2” from the smart home controller and if the socket senses “Late Finish” at the “Demand 3” block then the socket requests “Demand 2” from the smart home controller. The smart home controller then allocates the newly requested power to the smart socket (at Step 6). The socket then disables its relay allowing the identified appliance to consume the allocated power and causing its light to turn green in color (at Step 7) as shown in Figure 11. The socket then repeats the action of monitoring the instantaneous power consumption, comparing the instantaneous power value with the demand of the operating block indicating the associated mode of the appliance from the profile (at Step 8) in order to enable or disable the relay as shown in Figure 11

Step	Appliance	Smart Socket		Smart Home Controller
0	Turned On	• Appliance sensed • If there is a tag? -Enable relay -Light=Amber -Request Maximum Profile Power	→	
. .		• •		• •
4				• Determine new available power
5	Draws Power	• Monitor power demand • Instantaneous Power Exceeds Profile Demand? -Enable relay -Light=Amber -Inform smart home controller to allocate new block demand of the appliance from profile.	→	
6				• Determine new available power
7		• If relay enabled? -Disable relay -Light=Green		
8	Draws Power	• Monitor power demand • Instantaneous Power Exceeds Profile Demand? -Enable relay -Light=Amber - Inform smart home controller to allocate new block demand of the appliance from profile. Else -Disable Relay -Light=Green	→	

Figure 11: Subsequest Power Allocation to Identified Appliance by a Smart Socket

3.3.1.3 Power allocation for both unidentified and identified appliance if power is not available to meet their demand

If by any chance the smart home controller has insufficient available power to meet the maximum power requests from the smart socket for identified or unidentified appliance (at Step 1) corresponding to Figure 6 and Figure 9, the controller then informs the smart socket about the unavailability of power. As such the smart socket keeps its relay enabled and changes its light color to red. The smart home controller then starts switching off other active appliances in the house, one at a time in the home based on their priority identified by the smart home user as shown in Table 2. Priority here means the order of preference for the appliance in accordance with the user's own needs to process switching or restricting power to the appliances. The Table 2 shows a list of appliances with their corresponding priority. In the list each appliance is associated with its rated maximum profile power and a priority.

Table 2: List of Appliances with Their Corresponding Priority

Appliance	Maximum Profile Power (Watt)	Priority
A	10	1
B	20	2
.	.	.
.	.	.
Z	***	T

An appliance with priority "T" is of least importance while appliance with priority "1" is of most importance. For example, an appliance "Z" with priority "T" will be signalled to switch or restrict power first by the smart home controller, if necessary to maintain a balance between the demand and supply of power, before switching OFF the appliance "A" and "B" with priority 1, 2 or any appliance having priority greater than T. The smart controller will keep turning off one appliance at a time, switching off the immediate next high priority appliance from the previous switched off appliance until the demand for the connected appliance is met. The smart home controller will have a maximum allowable limit for switching off appliances based on a user's preference. Once a maximum allowable switching off limit for appliances is reached and even after that if there remains unmet demand from the socket, then the smart home controller requests the grid to allocate more power to the smart house system. Once the power is allocated by the grid, the grid then informs smart home controller about the new available power which is then informed to the smart socket to meet the demand of the connected identified or unidentified appliance. If an appliance is faulty and demands an infinite amount of power even after power being allocated from the grid, then the smart home controller completely stops allocation of power to the socket to which the faulty appliance is plugged into.

3.4 Summary

This chapter introduced the design requirements in order to handle legacy appliances (unidentified and identified) in a smart home. Also how profile is generated and used by the smart socket in order to handle the identifiable legacy appliance in a smart home is discussed. The two legacy appliance approach, unidentified and identified appliance, their corresponding communication steps with the smart socket and how initial and subsequent power is allocated to them within the smart home are discussed.

The implementation of profiles along with the results are discussed in the next chapter.

Chapter 4 Implementation, Testing and Results

In this chapter, the profile generating method for an appliance developed in chapter 3 is implemented using outputs from a power measurement tool comprising of current sensor, voltage sensor and a micro-controller as main processor. The tool captures power consumption information (Real Power, Apparent Power, RMS Voltage, RMS Current and Power Factor) of any 110 V appliances connected to it using which profile is built. Also discussed is how this profile data could be used by smart socket and the smart home controller in a smart home in order to operate legacy appliances.

4.1 Electrical Parameters Recorded by the Power Measurement Tool to Create Profile

To create a profile, information on how an appliance consumes power and its corresponding duration is required. The following section describes how the five parameters of the power measurement tool are captured.

a. Root Mean Square Voltage (V_{RMS})

The analog signal of the voltage sensor is converted into digital signal. These digital signals are squared and averaged to find the mean squared voltage. Then the root mean square voltage (V_{RMS}) is calculated by applying square root of the mean squared voltage value and thereby giving the instantaneous root mean square voltage (V_{RMS}) at the supply mains shown as follows and measured in Volt (V):

```
$for\ (n = 0; n < Total_{NumofSamples}; n++)$
    {
        $\boldsymbol{Squared_{Voltage} = Instantaneous_{Voltage} \times Instantaneous_{Voltage}}$ ;
        $Sum_{SquaredVoltage} += Squared_{Voltage}$ ;
    }
        $Mean_{SquaredVoltage} = \frac{Sum_{SquaredVoltage}}{Total_{NumberofSamples}}$ ;
        $Voltage_{RMS} = \sqrt{}(Mean_{SquaredVoltage})$ ;
```

b. Root Mean Square Current (I_{RMS})

Similarly, the digital samples of the analog current signal from the current sensor are squared and averaged to find mean squared current. Then the root mean square current (I_{RMS}) is calculated by applying square root of the mean squared current value giving the instantaneous root mean square current flowing through the phase line of the appliance shown as follows and is measured in Ampere (A):

```
$for\ (n = 0; n < Total_{NumofSamples}; n++)$
        {
                $Squared_{Current} = Instantaneous_{Current} \times Instantaneous_{Current}$ ;
                $Sum_{SquaredCurrent} += Squared_{Current}$ ;
        }
                $Mean_{SquaredCurrent} = \frac{Sum_{SquaredCurrent}}{Total_{NumberofSamples}}$ ;
                $Current_{RMS} = \sqrt{}(Mean_{SquaredCurrent})$ ;
```

These two values, RMS voltage and RMS current, are basic and important for the extraction of other electrical parameters. The sampled values are stored in a memory array of micro-controller for processing other electrical parameters such as real power, apparent power and power factor.

c. Real Power

The instantaneous power is a measure of the power being absorbed at a particular moment. The instantaneous power is obtained by multiplying instantaneous digital voltage samples with the corresponding instantaneous digital current sample and stored in another array. The instantaneous power values stored in this array are added and averaged to obtain the real power consumption shown as follows which is measured in Watt (W):

```
$for\ (n = 0; n < Total_{NumofSamples}; n++)$
        {
                $Power_{Instantaneous} = Voltage_{Instantaneous} \times Current_{Instantaneous}$;
                $Sum_{InstantaneousPower} += Power_{Instantaneous}$ ;
```

}

$$Real\ Power = \frac{Sum_{InstantaneousPower}}{Total_{NumberofSamples}};$$

d. Apparent Power

The apparent power is the measure of alternating current power in VA (Volt-Ampere) and is derived by taking into account the product of root mean square voltage and root mean square current as shown by equation below:

$$Apparent\ Power = Current_{RMS} \times Voltage_{RMS}$$

e. Power Factor

Power factor is the ratio of the real power flowing to the appliance to the apparent power as shown by equation below. It indicates the phase difference between the voltage and current signals.

$$Power\ Factor = \frac{Real\ Power}{Apparent\ Power}$$

These captured five output electrical parameters of the power measurement tool can be viewed using an excel work sheet as shown in Table 3. For example the excel table data is for a washing machine operating for the first five seconds constituting of five parameters namely real power, apparent power, root mean square voltage (RMS voltage), root mean square current (RMS current) and power factor.

Table 3: Captured Electrical Parameters

A	B	C	D	E	F
Time (Seconds)	**Real Power (Watt)**	**Apparent Power (VA)**	**RMS Voltage (V)**	**RMS Current (A)**	**Power Factor**
1	79.4	103.12	121.32	0.85	0.77
2	18.6	50.27	122.68	0.38	0.37
3	21.28	48.11	122.51	0.4	0.44
4	17.92	49.52	122.44	0.38	0.36
5	18.91	47.45	122.1	0.38	0.4

The power measurement tool records the real power along with other electrical parameters, mentioned earlier for an appliance, over a period of time. Figure 12 is an example of the real power consumption data for a washing machine operating measurements over 2639 readings or 2639 seconds, that is, sampling was done every second.

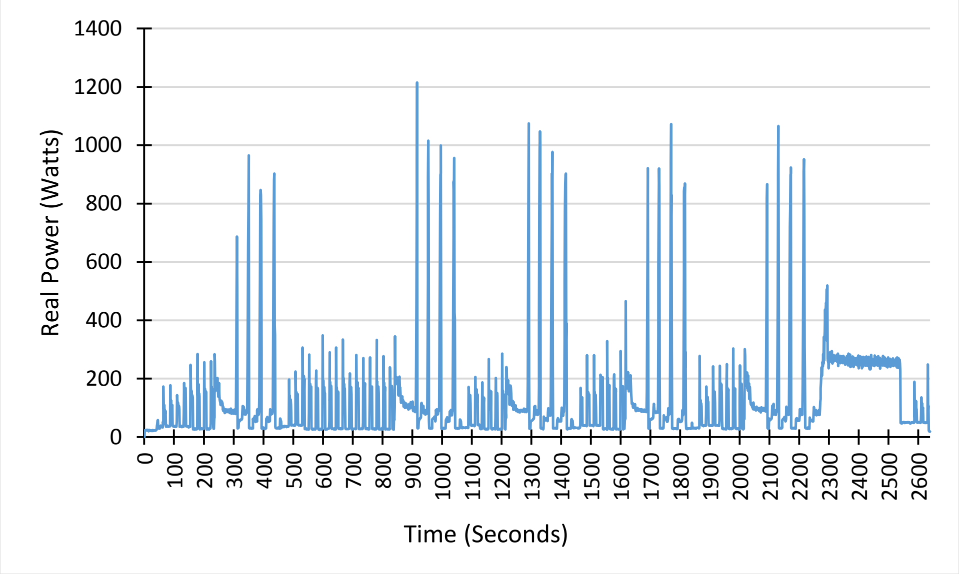

Figure 12: Washing Machine Data (For 2639 seconds)

As the data for real power consumption for every second of the washing machine is too coarse in Figure 11, a finer (i.e., less coarse) presentation is in Figure 13, showing the first 75 seconds of the washing machine's operation.

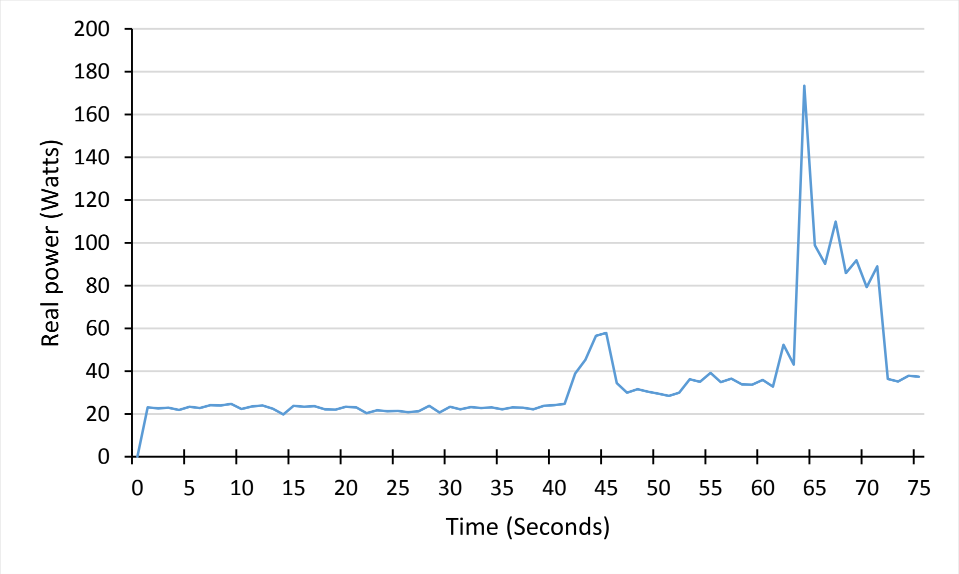

Figure 13: Washing Machine Data (First 75 seconds)

As observed from Figure 12 and Figure 13, the real power consumption of the washing machine spikes at least once in every 120 seconds exhibiting a significant difference from other power values in that 120 seconds. For example, as can be seen from Figure 12 and Figure 13, the washing machine spiked to 174 Watts at 65th second and up till 120 seconds this power remained the maximum power value recorded. Hence a 120 second interval is chosen to create profile with an interval resolution of 2 minutes (120 seconds) as shown in Figure 14, taking into consideration the maximum real power for each corresponding 120 second interval. A 120 second interval and the corresponding maximum demand acts as a good estimate and covers all the power values given in that distribution of samples. For example, as can be seen in Figure 14, the plot in blue depicts the washing machine's real power consumption while the plot in orange represents the maximum power for every 120 seconds interval in order to create profile. Thus each 120 seconds interval is the block and the maximum real power for every 120 seconds interval constitutes to demand for the corresponding block to form a profile for washing machine.

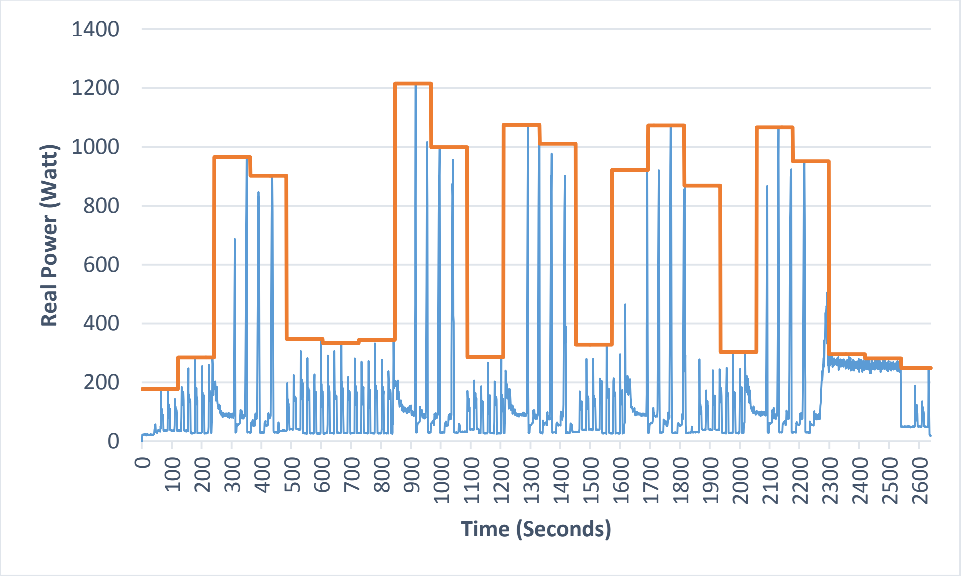

Figure 14: Washing Machine Data with Corresponding Profile Based on 120 second Interval

The real power consumption information for the washing machine consists of 23 blocks with a corresponding demand for each block. Assuming the washing machine has only one mode with a user assigned priority of 7 and tag of 22, the washing machine profile for Figure 14 is shown in Figure 15.

Identifier	22	
Priority	7	
Number of modes	1	
Number of cycles (mode 1)	87	
Block 1	0	178
Block 2	120	285
Block 3	240	965
Block 4	360	903
Block 5	480	349
………..	……..	……..
Block 21	2520	282
Block 22	2640	249
Block 23	2760	0

Figure 15: Washing Machine Profile

The Figure 15 shows the profile for a washing machine with one single mode. In similar manner, the profile for the subsequent mode is built.

4.2 Testing

This section illustrates testing of real power consumptions captured in one-second intervals for a washing machine and shows its corresponding profile.

A front load washing machine from Huebsch was selected for testing to show the results of the profiles for different modes of the machine. The washing machine is rated 120 V 60 Hz 9.8 A [80]. In order to complete a washing process, the washing machine offers the user three choices:

(i) Wash: It is used to select specific washing stage, one of Normal, Permanent Press, and Delicates/Bulky.

(ii) Temperature: It is used to select the temperature of the water used for the wash fill, one of Cold, Warm and Hot.

(iii) Soil Level: It is used to select wash modifier options, one of Light, Medium, and Heavy. If either the MEDIUM or HEAVY option is chosen, the washer can be programmed to handle for additional extra features including an added prewash, extra wash time, an added extra rinse, and a warm rinse temperature.

Several testing were carried out on the aforementioned washing machine, operating in different combination of settings for wash, temperature, and soil level. The following three different combination of settings were used for testing three different loads (0 kg, 3 kg and 6 kg):

a. Test 1: Delicate/Bulky, Warm, Heavy (Mode A)
b. Test 2: Normal, Hot, Medium (Mode B)
c. Test 3: Permanent Press, Cold, Light (Mode C).

These three combination of settings were chosen for testing to put on all load types (Light, Medium, and Heavy) as well as to touch all temperatures of the water (Hot, Cold, Warm) for washing and rinsing cycles. The three combination of settings also meant to cover all types of machine agitation (Normal, Permanent Press, and Delicates/Bulky). The expectation from these test was to find difference in power consumption level at different combination of settings and thereby allow different profile power for different modes or test of the washing machine.

4.3 Results

This section describes the results of capturing the power consumption of the Huebsch washing machine undergoing the aforementioned tests and their resulting profiles.

The results of the three test combination of settings for the washing machine are encoded as follows to indicate the mode (A,B,C), the weight of the wash (0, 3, 6 kg), and the test number (1,2,3). For example, A32 would be the real power data for the second 3kg wash operating at Delicate/Bulky, Warm, Heavy settings (Mode A)

4.3.1 Results for Test 1

The Figure 16 shows three sets of real power consumption of the front load washing machine Huebsch when operating with 0 Kgs of load in Delicate/Bulky, Warm, Heavy (Mode A) settings. The machine completed its three cycles of operation (Wash, rinse, and spin) in 2545 seconds or in about 43 minutes.

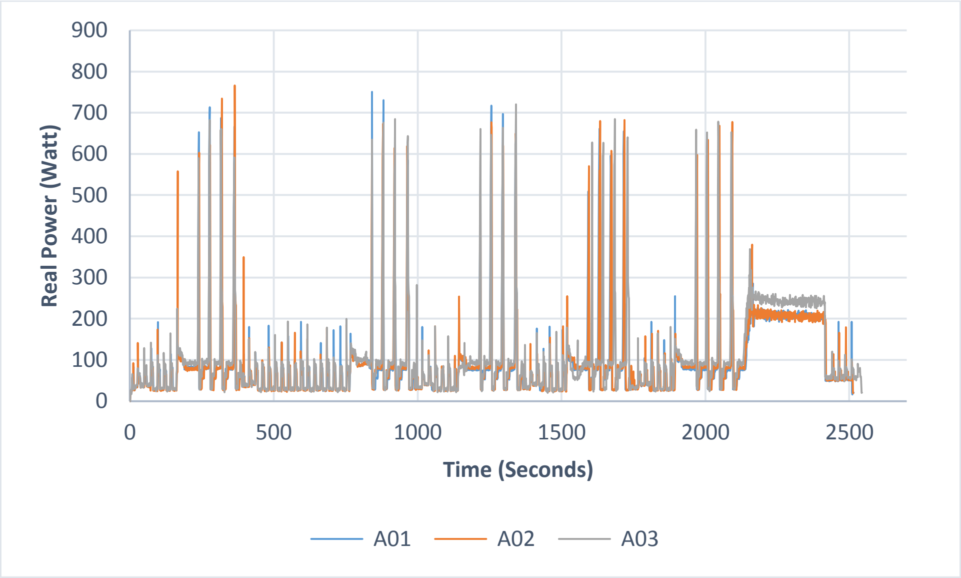

Figure 16: Real Power Consumption for Mode A with 0 kg Load

The washing machine starts its wash cycle by filling in the water for the first 90 seconds. The washing machine consumes 24 to 112 watts of power during the water fill times. Discrete washing speeds are noticed during a washing cycle consuming a maximum of 767 Watts for the second reading. Followed by the wash cycle, the rinse cycle consumes a maximum of 731 watts for the first reading. During this cycle, various rinsing speeds are observed as well. Then, the last cycle is the spin cycle. The maximum power consumption during the spin cycle is noticed to be 683 Watt for the second reading.

The Figure 17 shows three sets of real power consumption of the washing machine when operating with 3 kg of load in Delicate/Bulky, Warm, Heavy (Mode A). With the 3 kg of load, the machine completed the washing process in 2585 seconds or about 43 minutes. The maximum power, the machine consumes with 3 kg of load during the wash cycle is 942 watts for the first reading. For the spin cycle followed by the rinse cycle, the machine consumes a maximum of 926 watts and 1085 watts of power for first reading.

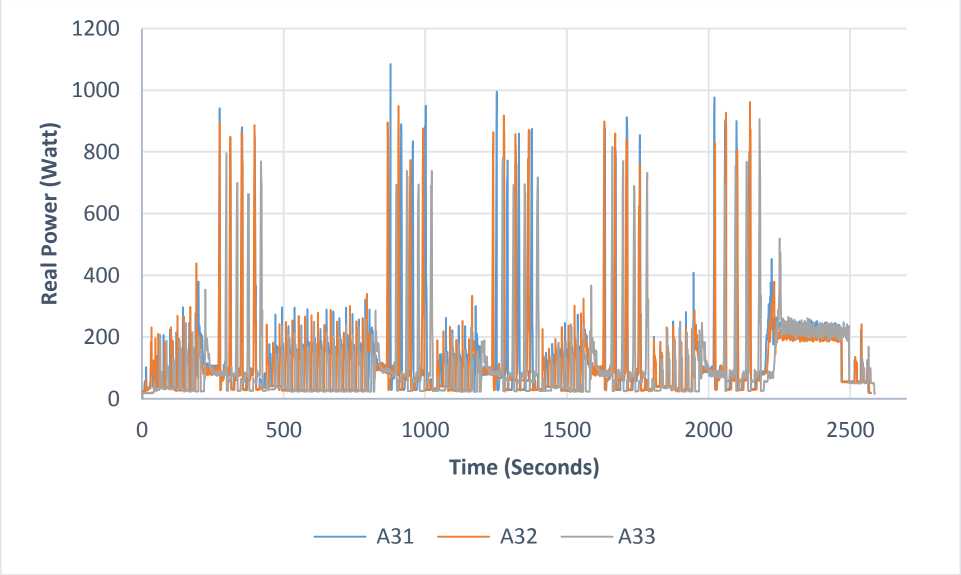

Figure 17: Real Power Consumption for Mode A with 3 kg Load

Similarly the Figure 18 shows three sets of real power consumption when operating with 6 kg of load in Delicate/Bulky, Warm, Heavy (Mode A). The total length of the washing process is recorded to be 2591 seconds or about 43 minutes. The maximum power recorded with 6 kg of load during the wash, rinse and spin cycles is 948 watt, 1113 watt and 936 watt for the third reading.

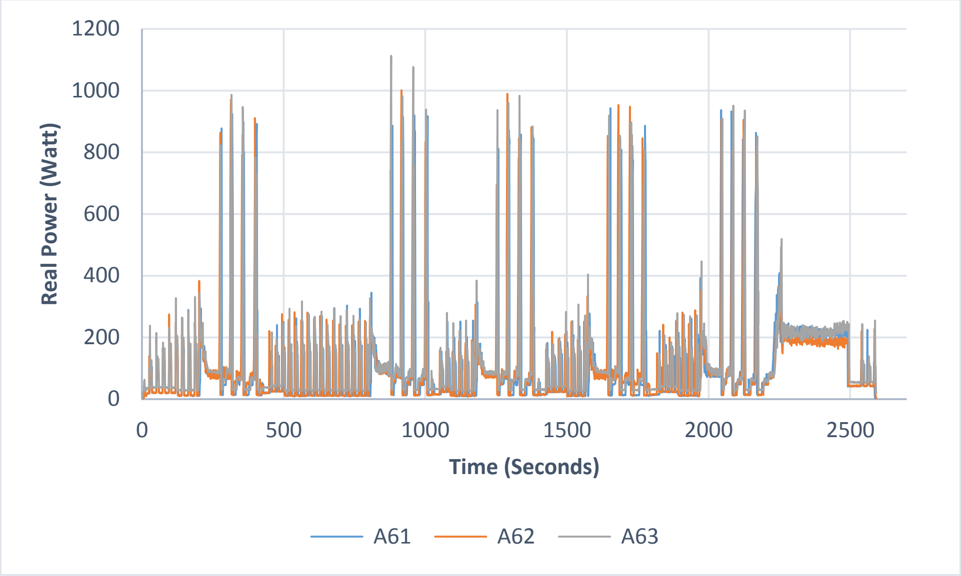

Figure 18: Real Power Consumption for Mode A with 6 kg Load

The Figure 19 shows the real power consumption of all the Mode A tests for the three different load weights.

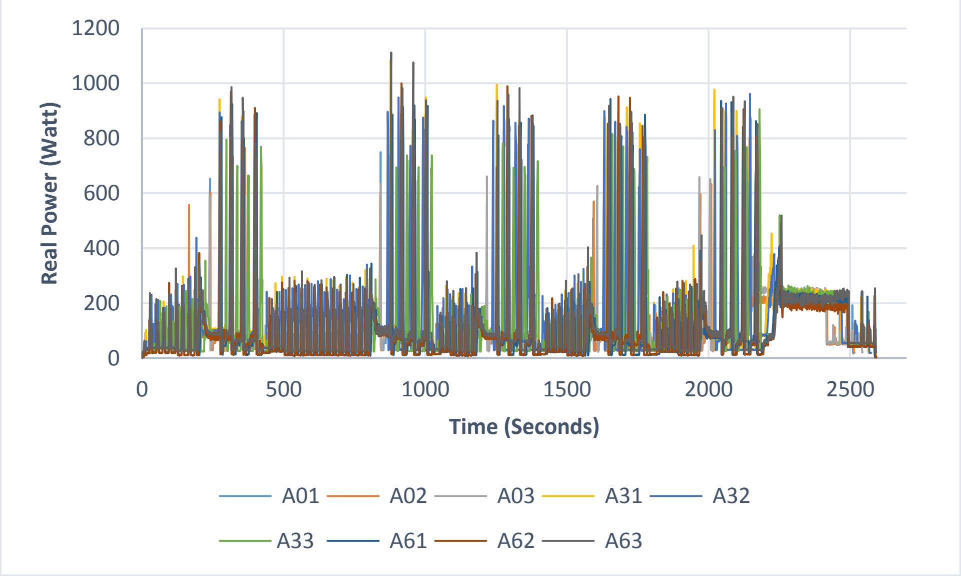

Figure 19: Real Power Consumption for Mode A with 0, 3, 6 kg Load

From the visual observation, each mode of a washing machine with variable loads weight can have different instantaneous power values and also there is no guarantee that any random runs of the same mode are going to be identical. Therefore the "Profile" line in Figure 20 shows total 23 blocks of 120 seconds interval each with a corresponding maximum demand for the washing machine operating in Mode A. The demand is selected considering the maximum real power value of every 120 seconds from the nine data sets.

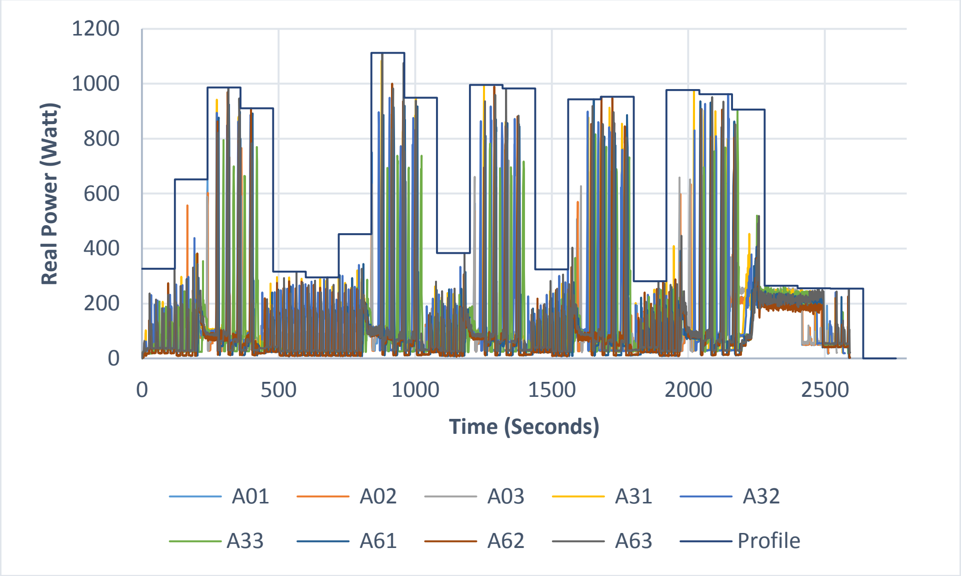

Figure 20: Washing Machine Profile for Mode A with 0, 3, 6 kg Load.

4.3.2 Results for Test 2

The Figure 21 shows the real power consumption of the washing operating in Mode B with three different loads; 0 kg, 3 kg and 6 kg.

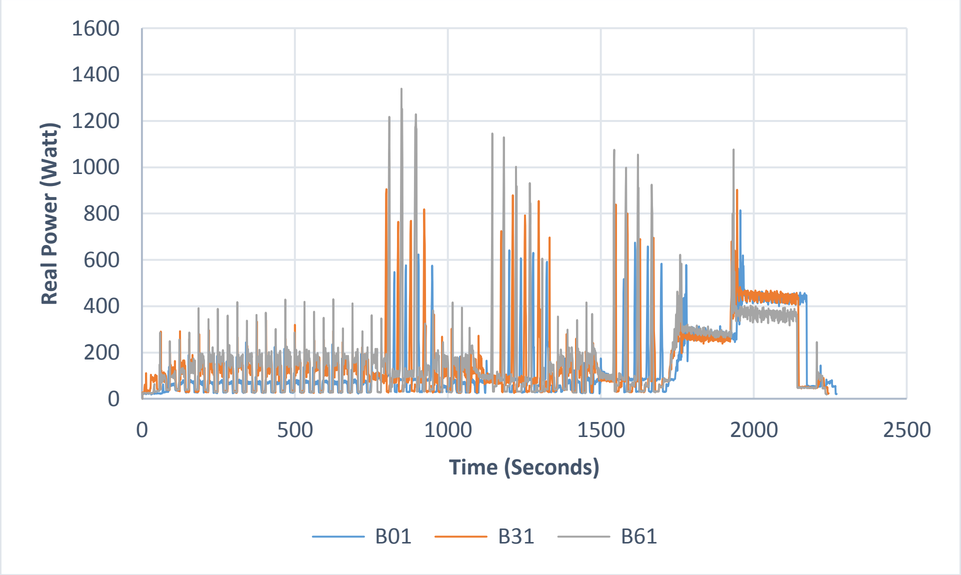

Figure 21: Real Power Consumption for Mode B with 0, 3, 6 kg Load

The machined completed its three cycles of operation (Wash, rinse, and spin) for all the three loads in 2269 seconds or in about 38 minutes. The machine consumes a maximum power of 429 watts during washing cycle between all three loads for 6 kg of load. During the rinsing cycle, the machine consumes (between all three loads) a maximum power of 1340 watts for 6 kg of load. For spinning cycle the maximum power consumed by the machine is 1078 watts for 6 kg of load.

Hence the "Profile" line in Figure 22 shows 20 blocks of 120 seconds interval each with a corresponding maximum demand for the washing machine operating in Mode B. The demand is selected considering the maximum value of every 120 seconds of the three real power consumption data.

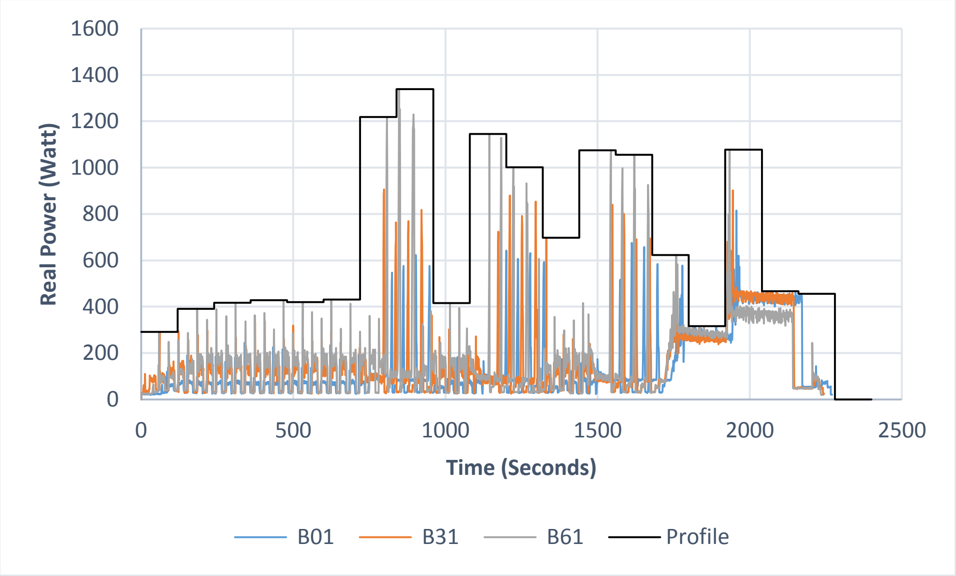

Figure 22: Washing Machine Profile for Mode B with 0, 3, 6 kg Load.

4.3.3 Results for Test 3

The Figure 23 shows the real power consumption of the washing operating in Mode C with three different loads; 0 kg, 3 kg and 6 kg. The machine completed its three cycles of operation (Wash, rinse, and spin) for all the three loads in 2108 seconds or in about 36 minutes. The machine consumes a maximum power of 453 watts during washing cycle with 6 kg load. During the rinsing cycle, the machine consumes a maximum power of 1116 watts for 6 kg of load. For spinning cycle the maximum power consumed by the machine is 1045 watts for 6 kg of load.

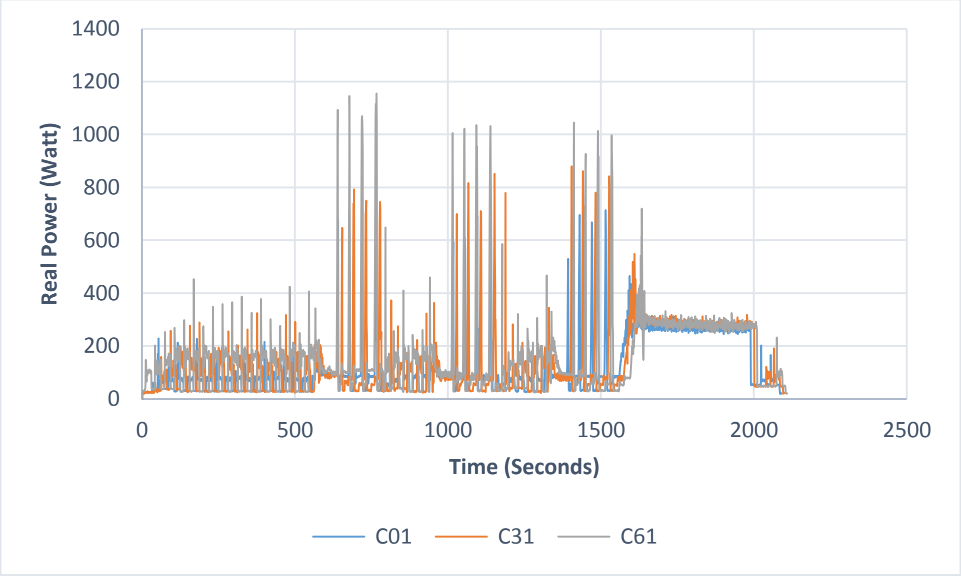

Figure 23: Real Power Consumption for Mode C with 0, 3 , 6 kg Load

Similarly the "Profile" line in Figure 24 has 19 blocks of 120 seconds interval each with a corresponding maximum demand for the washing machine operating in Mode C. The demand is selected considering the maximum value of every 120 seconds of the 3 real power consumption data.

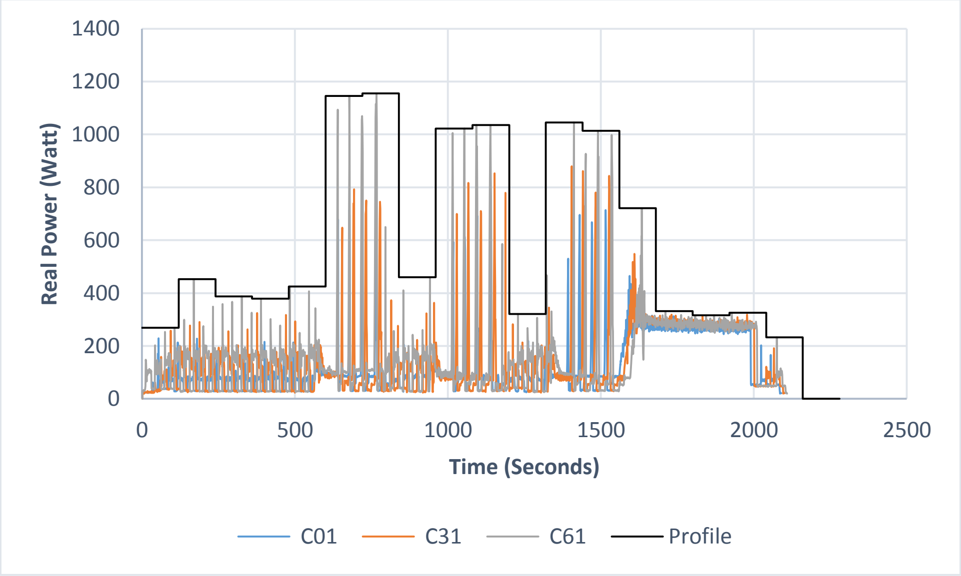

Figure 24: Washing Machine Profile for Mode C with 0, 3, 6 kg Load.

From all above three profile plots, the maximum profile power is observed to be about 1340 Watts corresponding to mode B. Therefore, the complete profile for the Huebsch washing machine for the tested three modes with a user given priority of X and assigned tag ID “Y” is shown in Figure 25.

	Identifier (ID # Y)		
	Priority (X)		
	Total number of modes (3)		
	Maximum Profile Power (1340)		
Mode A	Total number of blocks (23)		
	Start 0	328	Block 1
	Start 120	653	Block 2
	Start 240	987	Block 3
	…		
	Start 2640	0	Block 23
Mode B	Total number of blocks (20)		
	Start 0	391	Block 1
	Start 120	391	Block 2
	Start 240	418	Block 3
	…		
	Start 2280	0	Block 20
Mode C	Total number of blocks (19)		
	Start 0	270	Block 1
	Start 120	453	Block 2
	Start 240	388	Block 3
	…		
	Start 2160	0	Block 19

Figure 25: Huebsch Washing Machine Profile

This profile for the three modes of the Huebsch washing machine is made available to the smart socket.

4.3.4 How is the Profile Used

Considering the appliance plug of the Huebsch washing machine has a tag with ID “Y” and the washing machine is set to operate at Mode C. When the Huebsch washing machine is plugged into the smart socket, the ID of the tag (Y) mounted on the appliance plug is read by the tag reading unit of smart socket. The socket then disconnects the washing machine from the network by enabling the in-built relay and the light color of socket changes to amber. The smart socket then compares the ID of the tag (Y) at the washing machine plug with all the IDs it has in its memory where it has the profile for the Huebsch washing machine with identifier ID “Y”. The smart socket then selects the power consumption profile of the appliance (washing machine) with identifier ID

“Y” from its memory which matches with the tag ID (Y). Therefore now the smart socket knows the power consumption profile of the Huebsch washing machine but the socket doesn’t know in which mode and block the washing machine is running. Using the profile for the Huensch washing machine, the smart socket selects the corresponding maximum profile power (1340 Watt) and requests this power from the smart home controller in order to meet the power requirement of the washing machine. Once the smart home controller allocates the requested power (1340 Watt), the smart socket then reconnects the washing machine to the network allowing it to draw the allocated power by disabling the relay. The color of light on the smart socket turns green and the socket then starts monitoring the power consumption of the washing machine every second using its power measurement unit and determines the maximum power value for the first 120 seconds. Since profiles are created based on 120 seconds interval, a maximum power value for the 120 seconds allows to compare and find a possible match in the profile. Assuming that the smart socket records a maximum power value of 270 W for the first 120 seconds, this maximum power value of the first 120 second (270 W) is then compared with all the block demands corresponding to all modes of the Huebsch washing machine profile to determine the operating mode of the washing machine and the current running block. Hence the socket finds a matching for 270 W in the first block of the Mode C from the power consumption profile of the washing machine. The socket then informs the smart home controller about the current power demand of the running block (270 W) along with the power requirements of the next subsequent future blocks and their corresponding starting times (Block 2 = 453 W, Start time = 120; Block 3 = 388 W, Start time = 240 and so on). The smart home controller then reduces the allocated power for the smart socket from 1340 watt to 270 watt and allocates the subsequent power at respective starting times based on information from the smart socket. The socket then starts drawing the new allocated power and also monitors the instantaneous power consumption of the washing machine. As long as any instantaneous power value is below or equal to the allocated power for the smart socket by the smart home controller, the operation of the washing machine remains uninterrupted. If the socket senses any abnormality in power consumption at any stage, for example a “Start Early” event at Block 1 stage then the socket disconnects the washing machine from the network and requests the smart home controller for the power demand corresponding to Block 2 of Mode C (453 W) for “Start Early” event at Block 1 stage. If the abnormality sensed by the socket is a “Late Finish” event at Block 3 stage, then the socket requests the smart home controller for the power demand corresponding to Block

2 of Mode C (453 W) for “Late Finish” event at Block 3 stage. And in similar manner, the other modes of the washing machine is determined by the smart socket.

Chapter 5 Conclusions

The penetration of renewable energy sources onto the grid is increasing in order to meet environmental and energy-security issues. As such, the integration of renewable energy promises to provide benefit to electricity end-users in order to meet consumer energy demands at lower budgetary and environmental costs. Hence, to support the integration of variable renewable energies into the grid requires a smart grid which has the ability to adjust or control the power consumption via load management processes, thereby enhancing the growth of renewables and maintaining the reliability of the electricity grid, often by offering time-of-day or real time pricing which requires smart home.

At the smart home level, the power management coordination and the response to time of day or real time pricing is done by a smart-home controller, managing the power consumption of appliances in a smart home. Smart homes are intended to work with smart home controllers, smart appliances using information and communications technologies so that the home owner can take advantage of time-of-day pricing and real time pricing. As such, smart homes were not designed with legacy appliances in mind which have neither information nor communication features.

Since replacing a home's legacy appliances with new smart appliances might be expensive for the homeowner, it is impractical to expect that households will withdraw from using existing legacy appliances. If legacy appliances are to be integrated into the smart home, there needs to be a change in the way they are presently being used.

5.1 Motivation

A legacy appliance presents the smart home controller with a dilemma. On one hand, if the appliance operates as it would normally, the controller would be unable to supply power efficiently as the appliance's demand would be changing every second. On the other, if the smart home controlled allocated the maximum possible supply for the duration of the appliance's operation, there would be a considerable waste of power.

Unlike legacy appliances, smart appliances can determine their expected power demand for a given period of time and communicate this information with the smart home controller.

Addressing the problem of the inability of legacy appliances to communicate their power requirements to the smart home controller and to allow their operation to be controlled by it was the motivation for this thesis. This thesis examined some of the issues regarding legacy appliances and the efficiency use of power. The thesis has developed a method of creating demand profiles for legacy appliances. These profiles are intended to allow a smart socket to communicate the appliance's demand to a smart home controller.

5.2 Observations and Findings

In the proposed method of integrating legacy appliances into the smart home, it was shown how the limitations of legacy appliances can be masked, thereby making them appear as smart appliances by means of a smart socket.

Appliances that are not registered with smart home are unidentified appliance with smart home having no information about their power consumption. The unidentified appliance approach requires smart socket with the use of mainly power measurement unit and communication unit only. When the legacy appliance is plugged into the smart socket, rather than simply meeting the demand, the socket determines the appliance's power requirements. This information is conveyed by the socket to the controller which treats the legacy appliance (through its proxy, the smart socket) as it would any other smart device. However, the smart home controller is still required to meet the demand immediately but instead of meeting the unknown power demand, the socket momentarily denies the appliance's immediate power requirement until it can be met by the smart home controller. The limitation with this approach is that the unidentified appliance's power requirement pattern nor the length of operation is not known to the smart home.

The identified appliance approach meant assigning the appliance an identity (some form of tag) and recording its various power requirements for subsequent use with a smart socket with a tag reader and a memory holding the appliance's power consumption. As observed from the results, there are legacy appliances such as washing machines that have different modes and power demands as well as the operating time length corresponding to washing, rinsing and spinning cycle throughout a mode is not same.

The findings also showed that repeated runs of the same mode doesn't have same instantaneous power consumption as a result the repeated runs of the same mode doesn't produce same profile. As such a single profile for allowing an appliance's mode to be identified by the smart socket is needed to be produced. Hence a profile needs to be formed by considering the maximum instantaneous power consumption for each corresponding point from several repeated runs of a mode. The resulting maximum power consumption obtained from combining the maximum power for each point should then be divided into blocks which indicate the maximum power for a fixed interval. That is, the organized profile consists of different “blocks” which reflect the maximum power for a set period of time.

The legacy appliance is then associated with a unique appliance-identifier which can be read by a smart socket. The appliance’s power consumption in intervals as profile, priority and identification is uploaded to the smart socket for subsequent use which requires the power consumption of the identified appliance to be measured beforehand. The power measurement tool described in the thesis provides the leverage to record the power consumption of any 110 V appliance, create the corresponding appliance profile using the power consumption data and thereby allows the smart socket to request specific power levels from the smart home controller for a particular appliance using profile via its communication unit, potentially reducing the demand, as any smart appliance would do.

Using this power consumption information, the smart home controller is able to schedule the appliance and send signal to the smart socket to act on. Based upon the signal from the smart home controller, the smart socket enables or disables its relay in order to change the power consumption behaviour of the appliance connected to it. The advantage of the method presented allows shorter blocks that reduce the volume of power lost and can still be handled by the smart home controller.

5.3 Thesis Contributions

The thesis has the following contributions:

- The thesis contributes to the area of smart homes. Specifically, it offers innovative thinking and techniques in the field of smart homes and smart socket systems research in order to integrate legacy appliances to an intelligent home.
- The thesis showed how to make a legacy appliance act like a smart appliance by means of a smart socket using a profile.

- The thesis also showed the design and implementation of an appliance power measurement tool and how the power consumption information from the tool is used to create profile that consists of different blocks which reflect the maximum power for a set period of time.
- The thesis also contributes to show how the socket uses the stored profiles to request specific power levels from the smart home controller, potentially reducing the demand.
- The thesis pointed that there are two extreme cases: one-second power requests that do not allow the smart home controller to schedule efficiently; and a single block covers the entire mode, forcing the smart home controller to request the maximum, potentially wasting large volumes of power.

5.4 Future Work

This thesis can be extended with the following future work:

- The proposed smart socket will need to be designed and implemented to handle appliance recognition, power monitoring, and communications.
- An algorithm is needed to identify an appliance's mode and block when it starts partway through a mode. This is necessary because when a washing machine starts its operation other than at the start of the initial block, the instantaneous power recorded by the smart socket will not match the profile's initial power requirements. Without this, the smart socket is unable to inform the smart home controller of the appliance's power demand for the operating block and subsequent blocks.
- The algorithms described in this thesis for recording an appliance's power consumption should be part of the smart socket to allow the socket to learn power profiles of unidentified legacy appliances.
- The simulation of communication steps can be done and from the results of the simulations it would appear that the proposed communication steps are justified.

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Appendix The Power Measurement Tool

This section discusses the design and implementation of the electrical power measurement tool that captures real power, apparent power, root mean square voltage, root mean square current and power factor for any 110 V appliance connected to it. The tool is developed using information from open-source community project named “OpenEnergyMonitor” [76].

1 Design of the Power Measurement Tool

The electrical power capturing tool tool sits in between AC mains voltage and the appliance plug as shown in Figure 26 and captures the electrical parameters of an appliance such as real power, apparent power, root means square voltage, root mean square current and power factor. The tool consists of a current sensing circuit and a voltage sensing circuit. Therefore when an appliance plug is inserted into the receptacle of the tool box, the corresponding voltage signal and current signal are recorded and processed using a micro-controller to extract as well as record the aforementioned electrical parameters for the connected appliance.

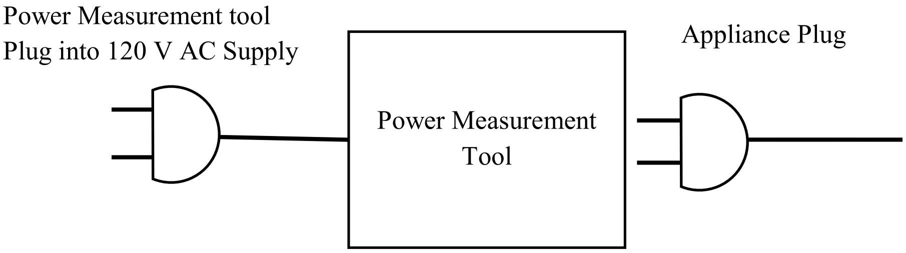

Figure 26: Electrical Power Capturing Tool Layout

Figure 27 shows the internals of the power measurement tool. The tool is incorporated with a data acquisition module which is a micro-controller that is processes the recording of voltage and current signal for an appliance connected to the tool. Therefore the system consists of three parts: main unit, power consumption measurement unit and a memory unit. The main unit is a micro-controller that reads signal that samples and processes raw signals from voltage and current sensor of power measurement unit in order to formulate the electrical parameters. The power consumption measurement unit extracts raw voltage and current signal using a current and voltage sensing circuit comprising of amplification and biasing circuit. The memory unit is a secure digital (SD) non-volatile memory shield that stores all the recorded constituents into a SD card.

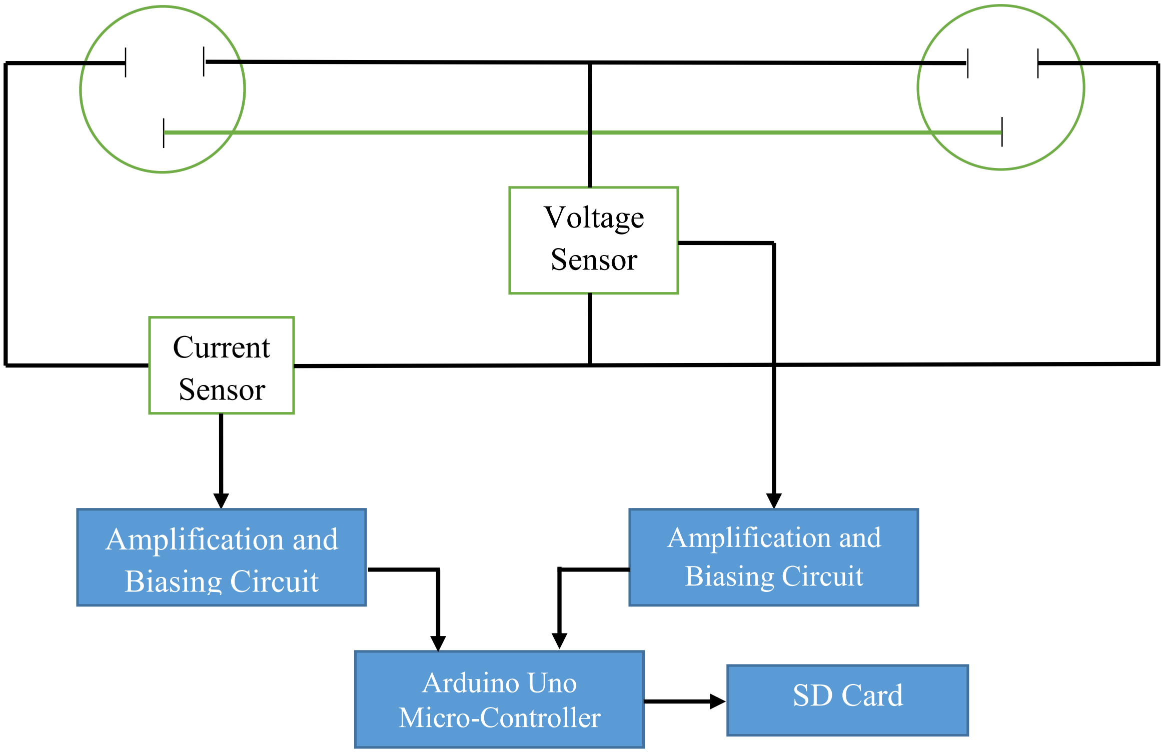

Figure 27: Internals of Power Measurement Tool

2 Hardware and Implementation of the Power Measurement Tool

This section describes the hardware used for main unit, power measurement unit and memory unit along with their schematic connection diagram.

2.1 Main Unit

The main unit is an Arduino Uno micro-controller as shown in Figure 28 that acts as a data acquisition module. It samples the signals received from current sensor and the voltage sensor in order to measure and process the constituents of power consumption profile namely Real Power, Apparent Power, Root Mean Square Current, Root Mean Square Voltage and Power Factor of an appliance and stores all the aforementioned information in the SD card memory. The Uno is based on ATmega328 micro-controller with fourteen digital input/out pins along with six analog input pins and operates at 5V DC which can be supplied either using an external adaptor or powered via a USB connection and can be programmed using its own software named Arduino IDE [77].

Figure 28: Arduino Uno [77]

One of the benefits of using Arduino Uno micro-controller is that it plugs straight into a computer's USB port and is simple to setup its application in order to use it (compared to other development boards). The Arduino board's chip connects straight into a USB port and catalogues itself on a computer as a virtual serial port. This allows the Arduino user to interface it as through it were a serial device. The advantage of this setup is that, serial communication is an intensely easy (and time-tested) step, and USB allows users ease of convenience connecting Arduino to computers. Another benefit of Arduino is its open source design. As a result it has a large community of thousands of people using and troubleshooting it. This makes it easy to find Arduino enthusiasts who have shared their work to help debug a project. Arduino enthusiasts who have worked out how to do more complex things have shared their work by creating contributed libraries. Also the Arduino microcontroller also has a 16 Mhz clock. This makes it not the fastest microcontroller around, but speedy enough for our prototype application.

2.2 Power Consumption Measurement Unit

In Canada, the line to neutral voltage rating in domestic home is 120 V working at 60 Hertz (Hz) frequency [81] and hence this unit comprises of voltage sensing circuit and current sensing circuit that records instantaneous voltage and current required by the appliance connected to the power measurement tool. It is important to choose a good voltage and current sensor for capturing raw signals as it would help understand the consumption pattern of the connected appliances in a more accurate manner.

2.2.1 Current Sensing Circuit

The current sensor model no. SCT-013-000 used in the system is split type non-invasive core AC current transformer (CT) made by Beijing YaoHuadechang Electronic Co., Ltd as shown in Figure 29. It has 100 A RMS rating meaning the input current can range between 0 A to 100 A. The output of the current sensor is between 0 mA to 50 mA [78].

Figure 29: Current Sensor SCT-013-000 [79]

One advantage of using this current sensor is, it can be clipped straight on to the wire coming into the appliance and hence doesn't require any work at high voltage making it ideal for safety issues.

The Figure 30 shows the schematic of the current sensing circuit in order to interface with the Arduino and the choice of design is described as follows.

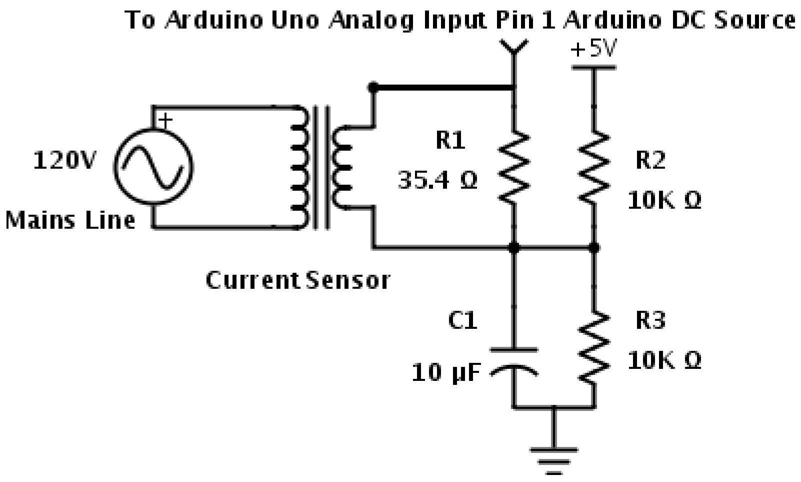

Figure 30: Current Sensing Circuit Schematic

The current sensor (SCT 013-000) has an output which is current and hence the signal needs to be converted to a voltage signal with a burden resistor (R1) in order to meet the Arduino Uno's analog pin 1 input requirement, which is +5 V as shown in Figure 30. Also the output of the current sensor needs to be scaled down to a waveform which contains no negative component.

Therefore peak current in the primary winding of the current sensor is given by Eq (1) as follows:

$$Peak - Current, Primary = RMS\ current \times \sqrt{2} = 100\ A\ \times 1.414 = 141.4\ A \tag{1}$$

The current sensor has 2000 turns in its primary winding according to its data sheet and so the secondary peak current is given by Eq (2):

$$Peak - Current, Secondary = \frac{Peak{-}Current, Primary}{Number\ of\ Turns} = \frac{141.4\ A}{2000} = 0.0707\ A \tag{2}$$

The Arduino's reference voltage (AREF) is 5 V and should be divided by 2 to enhance the measurement resolution in order to increase the precision by adding biasing. Since the Arduino is operating at 5V therefore the division of AREF with 2 will be 2.5 V and so the burden resistance (R1) is calculated using Eq (3) as follows:

$$Burder\ Resistnace\ (R1) = \frac{AREF/2}{Peak{-}Current, Secondary} = \frac{2.5\ V}{0.0707\ A} = 35.36\ \Omega \tag{3}$$

The output of the current sensor is rated 50 mA (RMS), therefore peak output of the current sensor is given by Eq (4):

$$\boldsymbol{Current\ Sensor\ Output, Peak = 50mA\ \times \sqrt{2} = 70.7\ mA} \tag{4}$$

So the peak to peak output of the current sensor is given by Eq (5):

$$Current\ Sensor\ Output, Peak - Peak\ = 2 \times 70.7\ mA = 141.4\ mA \tag{5}$$

Hence the current sensor generates an output voltage which is given by Eq (6):

$$Current\ Sensor\ Output = 141.4\ mA\ \times 35.4\ \Omega = 5.0005\ V \tag{6}$$

The Arduino Uno's analog input pin can handle a maximum of 5V peak to peak voltage and which must be positive. Now if one end of the burden resistor is directly grounded and the other end is measured with respect to ground then the signal fluctuates between positive and negative voltage which doesn't meet the input requirement of the Arduino analog input pins. As a result the resistors R1 and R2 in Figure 30 are used to make up a voltage divider that provides a 2.5 V level in order to add DC bias and hence make the output of the current sensor meet the input requirement of the Arduino analog pins. By connecting the end to a 2.5 V level of the DC bias instead of directly grounding it, the signal shall fluctuate between 5V and most importantly remain positive. The value of resistors R1 and R2 are chosen high (10 K Ω) to lower power consumption in a state or period of inactivity or dormancy. The capacitor C1 (10 μF) provides a low impedance path to ground for the alternating current signal. The analog output from the burden resistor R1 is fed into the analog pin number 1 (A1) of the Arduino Uno micro-controller which has a built-in analog to digital converter (ADC) to transform the analog signal into a digital signal.

2.2.1.1 Calibration for Reading Current Sensor

The current sensor has a current output. This output current is very small and is converted into a voltage using a burden resistor of value 35.36Ω according to the implementation. The voltage across this burden resistor is then measured by the analog input pin 1 of the Arduino Uno. The analog input pins of the Arduino Uno has a built-in analog to digital converter (ADC) and possesses an input range of 0 V to $V_{cc,}$ which is 5 V. That is in the digital domain, the input signal will fluctuate to a minimum value of 0 and a maximum value of 1023. Also in the hardware implementation, the output of the current sensor is biased at $V_{cc}/2$ which is 2.5 V. As a result this causes to an offset incurring in the digital domain at 512. Hence the voltage measured relative to the processor supply voltage (5 V), is used as reference and scaled so that the reference would give the maximum count of 1024 (2^{10}).

The software begins by calculating current flowing through the secondary coil of the current sensor using Eq (7):

$$Current_{Secondary} = \frac{Current_{Primary}}{Number\ of\ Turns} = \frac{Current_{Primary}}{2000} \tag{7}$$

Then the input pin voltage which is the voltage converted from output of current sensor is measured across the burden resistor and is processed according to Eq (8):

$$Input\ Pin\ Voltage = Current_{Secondary} \times Burden\ resistor \tag{8}$$

The value from Eq (8) is applied on Eq (9) to calculate the parameter Counts corresponding to current sensor, which is the digital number seen by the Arduino processor:

$$Counts_{Current} = \frac{Input\ Pin\ Voltage}{V_{cc}} \times 1024 = \frac{input\ Pin\ 1\ Voltage}{5} \times 1024 \tag{9}$$

The software also extracts a parameter named current constant which is extracted using Eq (10):

$$Current\ Constant = \frac{Primary_{Maximum_{Current}} / Secondary_{Maximum_{Current}}}{Burden\ Resistor} \tag{10}$$

$$= \frac{100\ A / 0.050A}{35.36\Omega} = 60$$

Calibration constant which is the output value of the current sensor in digital form is extracted from Eq (11) and is extracted as follows:

$$Calibration\ Constant_{Current} = Current\ Constant\ \times \frac{V_{CC} / 1000}{1024} \tag{11}$$

The root mean square current (I_{rms}) is then computed in software by applying Eqs (9) and (11) to Eq (12).

$$I_{rms} = Counts_{Current} \times Calibration\ Contant_{Current} \tag{12}$$

2.2.2 Voltage Sensing Circuit

The 120 V to 9V AC to AC adaptor used in the system acts as a voltage sensor to measure the line AC voltage in order to calculate real power, apparent power and power factor. The 9V output AC adaptor is manufactured in China by Guangdong HSK Electronics Technology Co., Ltd and has a rated input of 120V AC 60Hz with an output of 9V AC, 200 mA. The isolation between the high and low AC voltage is provided by the built-in transformer in the adapter and hence doesn’t require any work at high voltage making it ideal for safety issues.

The Figure 31 shows the schematic of the voltage sensing circuit in order to interface with the Arduino and the choice of design is described as follows.

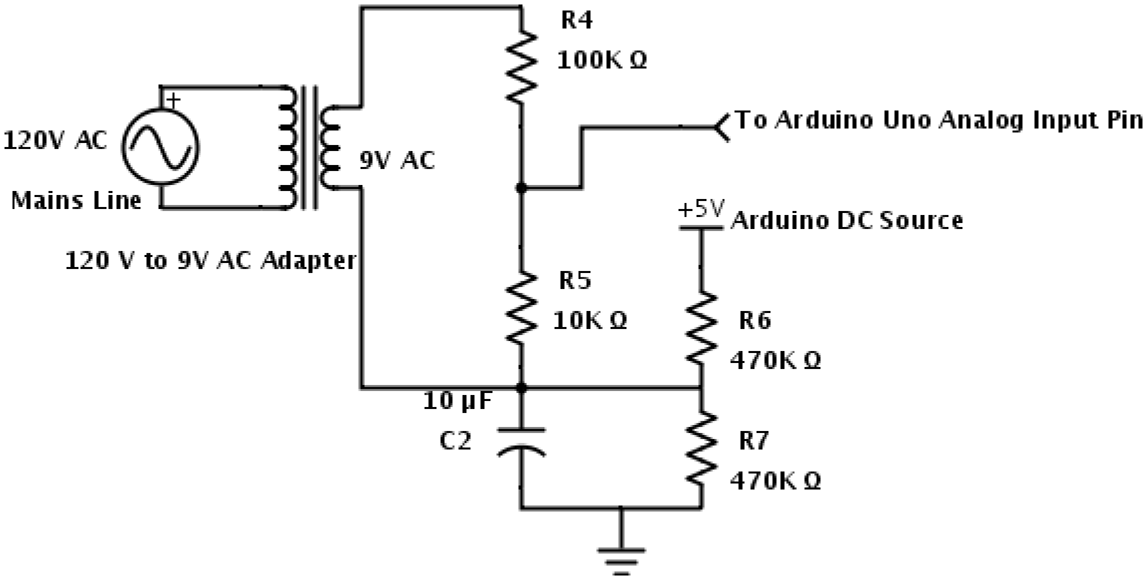

Figure 31: Voltage Sensing Circuit Schematic

For the analog input pins of Arduino, the input voltage should swing between exactly 0 V and the analog reference voltage (AREF), which is 5 V. In order to meet this requirement, the following assumptions and conditions are taken into account for implementation:

- ✓ The AC mains voltage rating might not always be 120 V. The voltage may fluctuate up to 10% on either side of the base value. For safety, the highest possible value for voltage is considered in order to do calculations.
- ✓ The 120 V to 9V AC to AC voltage transformer might not be working at full load. Since the voltage at no load is unknown so for the type of adapter normally used, it is advised to add 20% to base voltage.
- ✓ The Arduino Uno's reference voltage (AREF) might not be exactly at 5 V. The voltage output may dwell or rest between 4.8 V and 5.2 V. Taking into account 4.8 V as AREF, which is the worst case, we consider the calculations.

- ✓ The value of bias chain resistors may not be identical. Their resistive values may be mistaken by 1%. Considering the worst case of both the resistors being mistaken in opposite directions will cause the midpoint to be inaccurate by 1 %.
- ✓ The value of divider chain resistors may also not be identical. Their resistive values may be mistaken by 1%. Considering the worst case when R4 is low and R5 is high will cause the divided voltage value to be inaccurate by 2 % because of significant difference in value between the two resistors.

The highest Canadian mains voltage is given by Eq (13):

$$Highest\ Canadian\ Mains\ Voltage = 120\ V + (10\ \%\ of\ 120\ V) = 132\ V \tag{13}$$

The voltage transformer is labelled "Input: 120 V, Output: 9 V", so the highest possible output AC voltage is given by Eq (14):

$$Highest\ Possible\ AC\ Output\ Voltage = \frac{9\ V \times 132\ V}{120\ V} = 9.9\ V \tag{14}$$

Considering the voltage transformer to be working at no load, the maximum root mean square (RMS) output voltage at no load is given by Eq (15):

$$Maximum\ RMS\ Output\ Voltage\ at\ No\ Load = 9.9\ V + (20\ \%\ of\ 9.9\ V) = 11.88\ V \tag{15}$$

The peak output voltage at no load is given by Eq (16):

$$Peak\ Output\ Voltage\ at\ no\ load = 11.88\ V \times \sqrt{2} = 16.80V \tag{16}$$

The peak-to-peak alternating voltage we consider at the micro-controller's input is 4.8 V and in order to do that we need the bias to be exactly at the midpoint of 2.4 V. The lower meniscus midpoint value due to 1 % difference is given by Eq (17):

$$Lower\ Meniscus\ Midpoint\ Value = 2.4\ V - (1\%\ of\ 2.4\ V) = 2.376\ V \tag{17}$$

While the upper meniscus midpoint value due to the same 1 % difference is given by Eq (18):

$$Upper\ Meniscus\ Midpoint\ Value = 2.4\ V + (1\ \%\ of\ 2.4\ V) = 2.424\ V \tag{18}$$

Therefore considering the worst case scenario in implementation, peak alternating voltage is defined to 2.376 V. Also the value of R5 in Figure 31 is chosen as 10 kΩ. It is considered to be inaccurate by 1 % high causing the actual value given by Eq (19)

$$R5, Actual\ Value = 10\ k\Omega + (1\%\ of\ 10\ k\Omega) = 10.1\ k\Omega \tag{19}$$

Therefore the peak current flowing through R5 is given by Eq (20)

$$Peak\ Current\ through\ R5 = \frac{2.376\ V}{10\ k\Omega} = 0.235\ mA \tag{20}$$

The voltage across the resistor R4 is given by Eq (21):

$$Voltage\ across\ R4 = 16.80\ V - 2.376\ V = 14.424\ V \tag{21}$$

Also the current passing through R5 and R4 is same as both the resistors are in series. So the current passing through R4 is 0.235 mA and therefore the value for R4 is given by Eq (22):

$$Value\ of\ R4 = \frac{14.424\ V}{0.235\ mA} = 61.378\ k\Omega \tag{22}$$

Assuming the resistor value to be inaccurate and low by 1 %, so the fitting resistor for R4 is given by Eq (23):

$$Fitting\ Value\ for\ R4 = 61.378\ k\Omega + (1\%\ of\ 61.318 k\Omega) = 61.99\ k\Omega \tag{23}$$

Hence a 62 kΩ resistor could be used for R4. The 9V AC voltage transformer which is a root mean square (RMS) rating gives an output signal which is a sinusoidal waveform meaning that the output signal has a maximum positive RMS value of +9 V and a maximum negative RMS value of -9 V. Therefore the positive peak value for the output is be given by Eq (24):

$$Peak\ Output\ Value, Positive = \sqrt{2} \times +9V = +12.72\ V \tag{24}$$

Similarly the negative peak value for the output is given by Eq (25):

$$Peak\ Output\ Value, Negative = \sqrt{2} \times -9V = -12.72\ V \tag{25}$$

But if the voltage transformer is considered to be working at no load then the possible RMS output voltage is often between 10 V to 12 V due to poor regulation. As a result the increased peak output value could be anywhere between 14.14 V and 16.97 V which is given by Eqs (26) and (27):

$$Peak\ Output\ Value\ at\ 10\ V\ RMS, No\ Load = \sqrt{2} \times 10\ V = 14.14\ V \tag{26}$$

$$Peak\ Output\ Value\ at\ 12\ V\ RMS, No\ Load = \sqrt{2} \times 12\ V = 16.97\ V \tag{27}$$

While according to our assumption, the possible RMS output voltage at no load is 11.88 V according to Eq (15), giving a peak output voltage of 16.80 V at no load according to Eq (16).

Since the output of the 9V AC transformer has a direct and relative connection with its AC input, it is necessary to transform the voltage transformer output to an accepted value that meets the input condition of the Arduino Uno micro-controller's analog pins (5 V) along with the negative peak being above 0 V. Hence scaling down the output signal of the 9 V AC transformer along with adding of a DC bias circuit is necessary in order to eliminate negative component.

The output signal of the 9V AC voltage transformer is compressed using resistors R4 and R5 coupled, that forms a voltage divider circuit across the transformer terminals as depicted in Figure 31 and also DC biasing (offset) is added in order to refrain negative component to chip in by applying a voltage connection established by another voltage divider using resistors R6 and R7 banded together across the reference voltage of the Arduino Uno micro-controller. The Capacitor C2 (10 uF) ensures a low impedance path to ground for the alternating current signal.

The resistors R4 and R5 are selected such that the peak output voltage must be around 1V. For our selected 120V to 9 V AC-AC transformer with an output of AC 9V RMS, a resistor combination of 100 k for R4 and 10k for R5 would give a convenient output of around 1 V given by Eq (28) as follows:

$$Peak\ Output\ Voltage = \frac{R5}{(R4+R5)} \times Peak\ Input\ Voltage \tag{28}$$

$$= \frac{10\ K\Omega}{10K\Omega + 100\ K\Omega} \times 12.72\ V = 1.15\ V$$

The biasing voltage provided by the resistors R6 and R7 should be half of the Arduino Uno micro-controller's supply voltage (5 V) and so R6 and R7 have to be equal and higher in value (470 KΩ) in order to lower power consumption in a state or period of inactivity or dormancy. Since the Arduino Uno micro-controller operates at 5 V, the resultant signal of the circuit has a positive peak of 3.65 V given by equation and negative peak of 1.35V given by Eq (29) and (30) as follows:

$$Positive\ Peak\ Analog\ Input\ Voltage = 2.5\ V + 1.15\ V = 3.65\ V \tag{29}$$

$$Negative\ Peak\ Analog\ Input\ Voltage = 2.5\ V - 1.15\ V = 1.35\ V \tag{30}$$

Hence the resultant signal meets the micro-controller's analog input pin voltage requirements maintaining sufficient clearance so that there is no possibility of over or under voltage. The analog output resistor R5 is fed into the analog pin number 2 (A2) of the Arduino Uno micro-controller which has a built-in analog to digital converter (ADC) to transform the analog signal into a digital signal.

2.2.2.1 Calibration for Reading Voltage Sensor

The voltage across the appliance connected to the power measurement tool is measured using a voltage transformer, the 9V output of which is scaled down using a voltage divider circuit. The voltage across one of the resistor of the voltage divider circuit is then measured by the analog input pin 2 of the Arduino Uno. As mentioned earlier, the output for the 120 V AC to AC transformer used for voltage sensing is 9 V, considering the transformer is operating at full load. Therefore for no load, as assumption, 20% of 120 V is added as show in Eq (31):

$$RMS\ Output\ Voltage\ at\ No\ Load = 9\,V + (20\,\%\ of\ 9\,V) = 10.80\,V \tag{31}$$

The ratio of the resistors for the voltage divider circuit (R4:R5) across the 9 V output of the voltage transformer is given by Eq (32):

$$Resistor\ Ratio_{VoltageDividerCircuit} = \frac{R4}{R5} = \frac{100\,K\Omega}{10K\Omega} = 10 \tag{32}$$

The software extracts a parameter named voltage constant which is extracted using Eq (33):

$$Voltage\ Constant = \frac{Rated\ Voltage_{RMS} \times \text{Resistor } Ratio_{VoltageDividerCircuit}}{RMS\ Output\ Voltage\ at\ No\ Load} \tag{33}$$

$$= \frac{120\,V \times 10}{10.80\,V} = 111.11\,V$$

Calibration constant which is the output value of the voltage transformer in digital form is extracted from Eq (34):

$$Calibration\ Constant_{Voltage} = Voltage\ Constant \times \frac{{}^{V_{CC}}/_{1000}}{1024} \tag{34}$$

To calculate the parameter Counts corresponding to the voltage transformer, which is the digital number seen by the Arduino processor, Eq (35) is used:

$$Counts_{Voltage} = \frac{Input\ Pin\ Voltage}{V_{cc}} \times 1024 = \frac{input\ Pin\ 2\ Voltage}{5} \times 1024 \tag{35}$$

The root mean square voltage (V_{rms}) is computed in software by applying Eqs (34) and (35) to (36):

$$V_{rms} = Counts_{Voltage} \times Calibration\ Contant_{Voltage} \tag{36}$$

2.2.3 Processing of Electrical Parameters

a. Root Mean Square Voltage (V_{RMS})

The transformed instantaneous digital samples of the analog voltage signal are squared and averaged to find mean squared voltage. Then the root mean square voltage (V_{RMS}) is calculated by applying square root of the mean squared voltage value and thereby giving the instantaneous root mean square voltage (V_{RMS}) at the supply mains shown as follows and measured in Volt (V):

```
$for\ (\ n = 0; n < Total_{NumofSamples}; n++)$
    {
        $Squared_{Voltage} = Instantaneous_{Voltage} \times Instantaneous_{Voltage}$ ;          (37)
        $Sum_{SquaredVoltage} += Squared_{Voltage}$ ;                                           (38)
    }
        $Mean_{SquaredVoltage} = \frac{Sum_{SquaredVoltage}}{Total_{NumberofSamples}}$ ;         (39)
        $Voltage_{RMS} = \sqrt{(Mean_{SquaredVoltage})}$ ;                                      (40)
```

b. Root Mean Square Current (I_{RMS})

Similarly the transformed digital samples of the analog current signal are squared and averaged to find mean squared current. Then the root mean square current (I_{RMS}) is calculated by applying square root of the mean squared current value giving the instantaneous root mean square current flowing through the phase line of the appliance shown as follows and is measured in Ampere (A):

```
$for\ (\ n = 0; n < Total_{NumofSamples}; n++)$
    {
        $Squared_{Current} = Instantaneous_{Current} \times Instantaneous_{Current}$ ;          (41)
        $Sum_{SquaredCurrent} += Squared_{Current}$ ;                                           (42)
```

```
    }
        $Mean_{SquaredCurrent} = \frac{Sum_{SquaredCurrent}}{Total_{NumberofSamples}}$;    (43)
        $Current_{RMS} = \sqrt{(Mean_{SquaredCurrent})}$;    (44)
```

These two values, RMS voltage and RMS current, are basic and important for the extraction of other electrical parameters. The sampled values are stored in a memory array of micro-controller for processing other electrical parameters such as real power, apparent power and power factor.

c. Real Power

The instantaneous power is a measure of the power being absorbed at a particular moment. The instantaneous power is obtained by multiplying instantaneous digital voltage samples with the corresponding instantaneous digital current and stored in another array. The instantaneous power values stored in this array are added and averaged to obtain the real power consumption shown as follows and the unit of which is watt (W):

```
$for\ (n = 0; n < Total_{NumofSamples}; n++)$
    {
        $Power_{Instantaneous} = Voltage_{Instantaneous} \times Current_{Instantaneous}$;    (45)
        $Sum_{InstantaneousPower} += Power_{Instantaneous}$;    (46)
    }
        $Real\ Power = \frac{Sum_{InstantaneousPower}}{Total_{NumberofSamples}}$;    (47)
```

d. Apparent Power

The apparent power is the measure of alternating current power in VA (Volt-Ampere) and is derived by taking into account the product of root mean square voltage and root mean square current as shown by Eq (48):

$$Apparent\ Power = Current_{RMS} \times Voltage_{RMS} \tag{48}$$

e. Power Factor

Power factor is the ratio of the real power flowing to the appliance to the apparent power as shown by Eq (49). It indicates the phase difference between the voltage and current signals.

$$Power\ Factor = \frac{Real\ Power}{Apparent\ Power} \tag{49}$$

2.3 Memory Unit

The memory unit is a SD card shield as shown in Figure 32. The shield stores the electrical parameters processed by the system into the SD card disk which can be read by any plotting, spread sheet or analysis program. The pin connection diagram for interfacing the SD shield with Arduino Uno is shown in Figure 32.

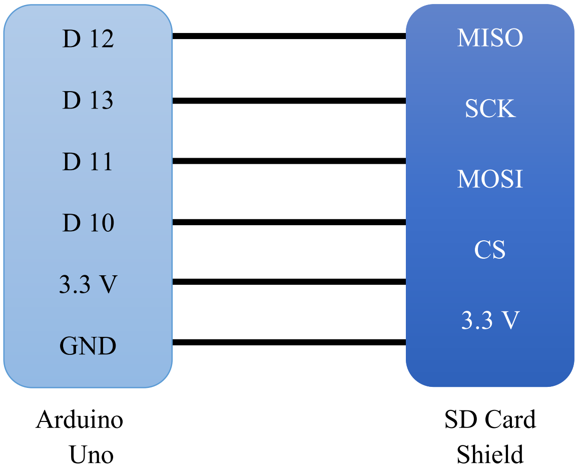

Figure 32: Connection Diagram between SD Card Shield and Arduino Uno

The Master In Slave Out (MISO), Serial Clock (SCK), Master Out Slave In (MOSI), Chip Select (CS), 3.3 V and Ground (GND) pins of the SD card shield is connected respectively to the digital pins D 12, D 13, D 11, D 10, 3.3V and ground pins of the Arduino Uno board.

3 Software Implementation of the Power Measurement Tool

This section describes the software used to write program in order to interface current sensor and voltage sensor (power measurement unit) with the Arduino Uno micro-controller (main unit) to store the corresponding parameters into the SD card (memory unit).

3.1 Arduino Integrated Development Environment (IDE)

The Arduino integrated development environment (IDE) is the software platform written in Java and is used to implement the whole software for the power measurement to create the programs called sketches. The programs composed on Arduino IDE platform are written in C or C++ and adopts a modified C language compiler to compose, convert and relay the code called sketch which is uploaded to the Arduino Uno micro-controller to be executed by the Arduino hardware. The IDE also allows scope to add other coded functions called libraries. Libraries widens the capability to give commands which are not available in the core Arduino language. In essence, a library enhances the user to execute noticeably complicated functions using a small set of commands. For example, the proposed system focuses on reading the current and voltage sensor values, processing the required electrical parameters and storing them in the SD card. Hence, the coded library (.h files and .cpp) such as ProfileGenerator and SD were written using Microsoft Visual C++ and are included within the sketch to make the program simple.

4 Power Measurement Tool Output Sample

In this section the operation of the power measurement tool is described along with the illustration of the results for a laptop connected to it. The operation of the tool is done to show how the data is captured to better understand the working of the system. The example shown below is for a laptop connected to the tool. When the laptop plug is inserted into the receptacle of the tool, the system records electrical parameters for the connected appliance into its memory which could be opened using any spread sheet processing software like Excel as shown in Table 4.

Table 4: Laptop Electrical Parameter Capturing

A	B	C	D	E	F
Time (Seconds)	**Apparent Power (VA)**	**Real Power (Watt)**	**RMS Voltage (V)**	**RMS Current (A)**	**Power Factor**
1	52.16	62.39	119.11	0.52	0.84
2	50.06	60.58	119.10	0.51	0.83
3	49.31	60.12	119.13	0.50	0.82
4	51.28	62.06	119.09	0.52	0.83
5	52.92	62.88	119.03	0.53	0.84

When the appliance is plugged, the laptop started drawing 0.52 A of RMS current which was extracted using Eq (12) and the voltage across the laptop was recorded 119.11 V using Eq (36). Using these two parameters (V_{RMS} and I_{RMS}), apparent power and power factor is calculated using Eqs (48) and (49). The real power is calculated using Eq (40).