Power management strategy for the electric recreational vehicle

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POWER MANAGEMENT STRATEGY FOR THE ELECTRIC RECREATIONAL VEHICLE

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ABSTRACT

There is a growing trend towards electrification within various sectors, including automotive and residential. The aim of this trend is to increase the utilisation of renewable energy sources (such as solar and wind) and to reduce dependency on fossil fuels which are of high cost, unsustainable, and adverse environmental impact. However, this electrification process leads to higher demands on the current electrical grid. Such demand increases require increased infrastructure investments if not addressed with "smart" solutions.

The recreational vehicle (RV) falls under both sectors of automotive and residential, as it combines both functions of transportation and temporary living. Therefore, the electrification of both driving and living facilities is desirable. The campground facilities within the leisure industry are of restrictive electrical infrastructure capability, and this heavily restricts electrical equipment usage and electric recreational vehicle (ERV) charging. If not addressed via some "smart" solution, this again would require further infrastructural investments. This will potentially lead to an unaffordable and unreliable system, limiting the adoption of the ERV.

The possibility of utilising power management solutions to eliminate the requirement of infrastructural investments was analysed in this thesis for both the electrification of the transportation side of the RV (i.e. the facility to charge an ERV from the campground supply) and the living facility functions (e.g. the appliances) of the ERV. Furthermore, existing power management solutions which can potentially be applied for either ERV functions were reviewed. The requirements analysis and the reviews for both electrification functions then were utilised to propose relevant advanced novel power management solutions for each electrification function which achieved the aim of reduced infrastructural investment requirements in an optimised manner.

Finally, both proposals were combined and further advanced, developing a holistic and novel ERV central controller power management solution. The proposal is smart grid integrated and creates a platform for the future ERV which doesn't require infrastructural upgrades, thus, enhancing and accelerating its adoption.

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NOMENCLATURE

AC	Alternating Current
ACU	Power Managing Unit
BMS	Battery Management System
CAES	Energy Management Unit
CC	Constant Current
CV	Constant Voltage
DC	Direct Current
DOD	Depth of Discharge
EMC	Electromagnetic Compatibility
ERV	Electric Recreational Vehicle
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
HF	High Frequency
HVAC	Heating Ventilation and Air Conditioning
NL	Non-schedulable load
PFC	Power Factor Correction
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaics
RBP	Rechargeable Battery Pack
RCD	Residual Current Device
RV	Recreational Vehicle
SOC	State of Charge
SL	Schedulable Load
TLM	Monitoring Unit

MATMATICAL VARIABLIS AND SYMBOLS

AC_{QUE}	Any AC grid powered time-dependant load placed in the queue for operation
B_v	RBP voltage
B_{ci}	Instant RBP capacity
B_{cn}	Nominal RBP capacity
DC_{QUE}	Any RBP powered time-dependant load placed in the queue for operation
E	Energy
E_{Ds}	Energy required to maintain operation of remaining RBP powered loads
E_{Dt}	Energy requirement for all operating RBP powered time-dependent loads
E_{Dt2}	Energy requirement for all operating RBP powered time-dependent load 2
E_{Dtnr}	Required energy for operating the new RBP powered time-dependant load
E_{Dunr}	Required energy for operating the new RBP powered user-dependant load
E_m	Microwave oven energy
F	Faraday constant
I	Current
ΔI	Load current variation
ΔI_p	Active load current variation
$\mathrm{I}(t_1)$	Current at time of fluctuation occurrence
$\mathrm{I}(t_2)$	Current at the fluctuation end point
$j\Delta I_q$	Reactive load current variation
MW_c	Microwave oven operation RBP energy requirement
n	Number of transferred electrons per molecule

P	Power
P_c	Charging power
P_D	RBP instant discharge power limit
P_{DS}	RBP instant power consumption
$P_{Dt}(t)$	RBP powered time-dependant load operational settings including power and time
$P_{Dtn}(t_{Dtn})$	RBP powered time-dependant load (n) operational settings including power and time
P_{Dtnr}	New RBP powered time-dependant load operational power request
P_{Dt1}	RBP powered time-dependant load 1 operational power setting
$P_{Dt1}(t_{Dt1})$	RBP powered time-dependant load 1 operational settings including power and time
P_{Dt2}	RBP powered time-dependant load 2 operational power setting
P_{Du}	RBP powered user-dependant load operational power
P_{DU1}	RBP powered user-dependant load 1 operational power setting
$P_{Du}(t)$	RBP powered user-dependant load operational settings including power and time
P_g	AC grid supply capability defined by the campground
P_{gs}	Overall AC grid supply power consumption
P_l	AC grid supply limit defined by the management strategy
P_{la}	Available AC grid supply capacity
P_{lanew}	AC grid supply capacity to be made available
P_{lnew}	New AC grid supply limit to be defined by the management strategy
P_{ls}	AC grid powered non-charging loads power consumption

P_{lt}	AC grid powered time-dependant load operational power setting
P_{lt1}	AC grid powered time-dependant load 1 operational power setting
P_{lt2}	AC grid powered time-dependant load 2 operational power setting
P_{lt3}	AC grid powered time-dependant load 3 operational power setting
P_{lt-n}	Alternative AC grid powered time-dependant load operational power setting to that originally requested
P_{lu}	AC grid powered user-dependant load operational power setting
P_{l1}	AC grid powered schedulable load power request
P_{l2}	AC grid powered non-schedulable load power request
P_{l3}	Allowable charging power
P_{l3new}	New allowable charging power to be implemented
P_m	Microwave oven operational power setting request
P_{m-n}	Alternative microwave oven operational power setting to that originally requested
$P_m(t)$	Microwave oven operational settings including power and time
P_{overload}	Overload power
P_R	Required ERV AC supply power consumption reduction
Q	Capacity
Q_o	Nominal Capacity
R	Resistance
t	Duration
T	Duration gap
t_{Dtnr}	RBP powered time-dependant load operating time for the alternative power level proposed

t_{lt-n}	AC powered time-dependant load operating time for the alternative power level proposed
t_m	Microwave oven request operation time
t_{m-n}	Microwave operating time for the alternative power level proposed
t_{max}	Longest operational time remaining out of all RBP powered appliances in-situ and those requesting operation
$T_{P_{c1}}$	Time of last substantial charging power variation occurrence
$T_{P_{c2}}$	Time of new substantial charging power variation occurrence
$\Delta U_{hp}(t)$	Voltage fluctuation
$U_{hp}(t_1)$	Voltage at time of fluctuation occurrence
$U_{hp}(t_2)$	Voltage at the fluctuation end point
U_n	Nominal voltage
V	Voltage
V_o	Electromotive force
x	Number of reactant moles consumed

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Chapter 1 GENERAL INTRODUCTION

1.1 Motivation

Fossil fuels are unsustainable energy sources of adverse environmental impact and increasing costs [1]. There is increasing demand for a shift towards renewable energy sources usage (such as wind and solar) [1]. The United Kingdom renewable energy road map has an aim of achieving renewable energy dependency at 15% of the energy consumption by 2020 and potentially reaching 30% to 45% by 2030 [2].

Various sectors including automotive and residential are undergoing an electrification trend to reduce the usage of fossil fuels and increase utilisation of renewable energy sources [3] [4] [5] [6]. Such electrification trends are resulting in an increased demand on the electrical grid [3] [4] [5]. However, the current electrical grid is dependent on fossil fuels. Therefore, a shift towards non-fossil fuel sources within the power generation sector is a crucial compliment to such electrification trend [7] [6] [8]. To address those demands within the power industry, the current electrical grid is undergoing a transformation towards a smarter electrical system known as the smart grid [6] [7].

The smart grid focuses on the use of renewable energy for electricity generation in a distributed manner [9]. It consists of various technologies and systems which allow the utilisation of renewable energy reliably and efficiently, keeping the utilisation of fossil fuels at minimum level [10]. For this to be achieved it includes the requirement of electrified appliances having smart capability [9].

As part of the electrification trend within the automotive sector, plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) are of increasing interest [11]. These incorporate a rechargeable battery pack (RBP) which supports the vehicle [11] [12].

Recreational vehicles (RVs) facilitate both transportation and temporary living facilities for leisure purposes [13]. To support temporary living, household like appliances such as the microwave oven, boiler, space heater, and refrigerator are found on-board [13] [14]. Following the power generation, automotive, and residential sectors, electrification within the leisure industry (reference to the leisure industry within this thesis covers the use of RVs in campgrounds) in inevitable. Furthermore, this will support the overall aim of fossil fuel reduction in order to address the environmental concerns.

1.2 Aim

This thesis aims to identify and analyse the requirements and challenges of RV electrification and accordingly propose a novel smart solution which would accelerate such development.

1.3 Objectives

- Identify RV electrification challenges through a thorough review of existing literature of relevant topics.
- Analyse the requirements for an electric recreational vehicle (ERV) campground charging power management solution that would optimise the available AC grid supply and avoids the need for infrastructural upgrade.
- Review and analyse literature of proposed charging power management strategies which can be potentially applied in the ERV application.
- Design and develop an advanced and compatible ERV campground charging power management strategy.
- Identify the requirements for RBP powered smart appliances management within an ERV.
- Analyse existing literature on current supply and demand management strategies which are of potential use within the ERV electrical appliances application.
- Design and develop an advanced novel RBP powered smart appliance management strategy which addresses the challenges of RV appliance electrification.
- Design and develop a holistic and novel ERV central power management strategy which forms a platform for the future ERV. The solution should

address the identified challenges of RV electrification, hence, enhancing and accelerating the ERV development and adoption.

1.4 Thesis Organisation

Chapter 2 presents a comprehensive literature review for relevant aspects in the RV electrification proposal including smart grid, EV charging, rechargeable batteries, the leisure industry, and microwave ovens (as a practical example for an electric appliance onboard an RV). The review forms the basis of identifying RV electrification challenges.

Chapter 3 provides a requirement analysis for an ERV campground charging management strategy. It utilises the requirements identified to review and analyse from the literature previously proposed electric vehicle charging management strategies. The chapter then presents and evaluates a novel advanced management strategy that is more suitable to an ERV.

Chapter 4 analyses the requirements for managing RBP powered smart appliances (utilising the microwave oven as an example) within an ERV. Identified requirements are then used for analysing current supply and demand management strategies. Finally, the chapter describes and assesses a novel RBP powered smart appliance management strategy which fulfils the identified requirements and challenges of appliance electrification within the RV.

Chapter 5 presents a holistic and novel ERV central power management strategy which combines both proposals of Chapter 3 and Chapter 4 in an advanced and synergised manner, forming a platform for the future electrified RV.

Chapter 6 presents a general conclusion for the work described within the thesis and highlights potential further work in certain areas which is required for effective commercial implementation of the proposal.

1.5 Contribution to knowledge

This thesis makes the following novel contributions:

- Identified the requirements and challenges for RV electrification.
- Provided an up-to date review of EV charging technologies and developments.
- Presented a thorough review of RBP parameters, capabilities, and its optimum operational conditions for increased lifespan.
- Achieved a critical review of current proposed EV charging management strategies. This includes assessing their suitability within the RV application.
- Critically reviews and analyses present supply and demand appliance management strategies. The evaluation incorporates their capability in fulfilling the ERV application.
- Design, construction, and testing of a novel smart programmable ERV campground charging management strategy.
- Design, construction, and testing of a novel RBP powered smart appliances management strategy.
- Design, simulation development, and testing of a novel smart grid integrated ERV central controller power management strategy which optimises the available power sources and demand in a user convenient manner. Hence, enhancing the adoption and development potential of ERVs without the requirement of electrical infrastructure upgrades. The proposal can be utilised in other applications such as the residential sector.

Chapter 2 LITERATURE REVIEW

2.1 Introduction

This chapter provides a review on different aspects which play a role in the electrification of recreational vehicles (RVs) and the proposal of this thesis. Sections 2.2 provides an introduction to the leisure industry with emphasises on the challenges and limitations of the electrical supply within the leisure industry. Furthermore, Sections 2.2 utilises the microwave oven as an example of an electrical appliance onboard an RV to demonstrate the negative impact of the limited electrical supply in the leisure industry on its capability and usability. The microwave oven operation, performance, and advantages are also described in the section, with focus on their use in RVs.

Section 2.3 highlights and describes the transition in the power generation and transmission sector towards the new electrical system of smart grid. This includes the three key elements of generation, management, and protection.

An overview of electric vehicle (EV) charging is then provided in Section 2.4, where a thorough review is provided including charging technique, type, classification, architecture, infrastructural requirement, technical standard, and topology.

Finally, Section 2.5 then provides a review on rechargeable batteries including their types, characteristics, and operational conditions lifespan reduction impact.

2.2 Recreational vehicles and the leisure industry

In the leisure industry, vehicles utilised for transportation and temporary living for the purpose of recreation and camping are known as RVs. Those are of two categories: caravans and motorhomes [13]. A caravan is a towable RV which exists in different configurations including travel trailer, fifth-wheel trailer, pop-up trailer, and the pickup camper. Meanwhile, the motorhome is a motorised RV which has a driving facility. It is built on an automotive manufacturer van chassis existing in three different types of class A, B, and C [13] [15]. It is estimated that in the United Kingdom there are 205,000 motorhomes, 550,000 caravans, and more than 3000 campsites [15].

RVs are of very restricted dimensions (such as 4.0 m in length and 2.3 m in width). However, they include many household facilities such as kitchen, bathroom, sleeping area, and living space. The RV kitchen facility consists of appliances comprising of nearly all those present in a household. This includes appliances such as cooker (consisting of a hob, grill, and oven functionalities), microwave oven, refrigerator, kettle, extraction hood, and others. The RV also includes equipment serving other facilities. This includes water heating, space heating, lighting, and television [13] [14].

2.2.1 **Challenges and limitations**

Campsites provide mains electricity supply at a low rating ranging between 10 A and 16 A per vehicle at a site in the United Kingdom. However, the electric supply can be as low as 5 A in other countries. Therefore, this limits the number of electrical appliances that can operate at the same time or even at the desired performance/power consumption level. This limited electric supply, in relation to the large number of appliances onboard, created the need for gas or dual fuel (gas and/or electric) powered equipment within the RV. Furthermore, it limits the specification of installed electric equipment (such the microwave oven) to low performance power consumption levels (e.g. 800W maximum cooking power for microwave ovens) [14] [16].

The weight of the recreational vehicle is another challenge within the leisure industry which manufacturers are continuously addressing [15]. This is to ensure that a caravan is capable of being towed by many car types and sizes [17]. Furthermore, drivers within the United Kingdom and other countries require provisions beyond their conventional driver’s license in order to drive RVs which are in excess of 3.5 tonnes [15].

2.2.2 **Microwave Ovens**

The microwave oven was first developed mid – 1940s but production at a commercial scale wasn’t until 1967 [18]. Microwave ovens cook and heat up food by dielectric heating [19] achieved from microwave radiation [20]. This microwave radiation is of 2.45 GHz frequency [21].

The oven cavity is constructed out of metal walls, resulting in a Faraday cage where microwaves fed into it reflect of the walls and are absorbed by the food, thus, cooking it [22]. Due to the nature of a cooking appliance, an opening is required to add and remove food for cooking, therefore, a microwave oven has a special well-engineered door to avoid high levels of microwave leakage which can cause human health hazards [23]. Standards specify the maximum allowable microwave leakage limits in the domestic application [24] [25].

Microwave radiation is generated by the magnetron and guided to the oven cavity via the waveguide [26] [22]. A high voltage power supply drives the magnetron which is cooled down during operation by a fan [26]. To accomplish uniform heating of the food, the microwaves are either stirred by a “stirrer” at the point of entry or the food is turned via a “turn table” [22].

Microwave heating is much faster than conventional heating [27]. It is almost instantaneous due to the previously described microwave heating mechanism of volumetric heat generation [27]. The speed of microwave oven heating and cooking is increased with higher operational power levels [28]. In addition to the speed of cooking, ease of use, convenience, and low maintenance are all additional advantages of the microwave oven [27].

Microwave ovens are typically of 70% efficiency [29]; the common 800W microwave ovens used in RVs consume 1200W and hence are of 66.67% efficiency [30] [31]. Therefore, in accordance to Section 2.2.1, such microwave ovens will not be capable of operating in campsites of 5A supply capability per RV. Furthermore, the operation of such microwave oven will limit the operation of other electrical appliances at the same time. The microwave oven will be utilised throughout the thesis within presented proposals as an example for an electrical appliance onboard an RV.

2.3 Smart grid

The current aim of the electrical grid is to supply end-users with the power demand required at any moment in time, in all locations, in a cost effective manner [6] [7]. However, the ultimate goal of the smart grid is to provide a new electrical supply platform which is sustainable, environmentally friendly, efficient, reliable, and capable of meeting the increased electricity demands in a cost-effective manner [6] [3].

This is achieved by introducing intelligence within the electrical generation and consumption network technologies via various hardware, software, and communications [6] [7] [8]. In turn, this enhances the monitoring and control capability for both the supplier and the consumer. The smart grid composes of three main aspects:

- Generation
- Management
- Protection

The above-mentioned aspects and how they contribute towards the smart grid goal are highlighted, below.

2.3.1 **Smart grid generation**

In the current electrical grid, supply of electricity for all consumers is generated from a small number of large generation plants [32]. Those central generators are remotely located supporting the electric supply to the end-users with long transmission lines as demonstrated in Figure 1 [8] [5].

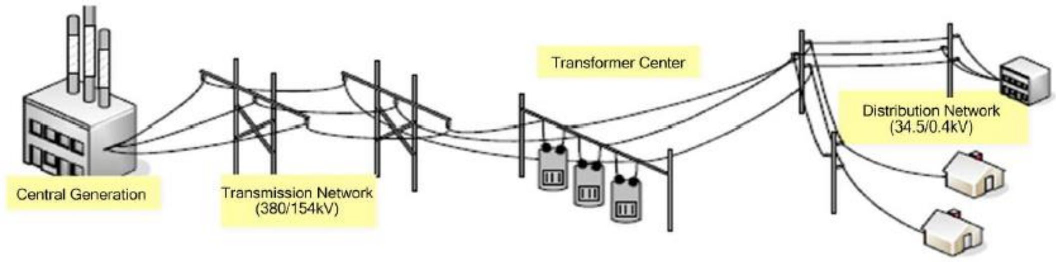

Figure 1 Conventional electric grid generation [5]

Although current central generation and transmission occurs at high voltage, which is then gradually reduced to the suitable level at the consumer, significant losses (up-to 8% of the generated electric supply) are present over the long transmission lines [8] [5] [33]. Furthermore, such reduced efficiency results in increased generation requirements which are currently heavily dependent on fossil fuel sources; hence, producing increased levels of greenhouse gases [8].

The smart grid, represented and shown in Figure 2, addresses those limitations of the current electrical grid by introducing increased number of renewable energy generation plants within the macrogrid and most importantly by the introduction of the microgrid paradigm [32] [34]. Microgrid, also known as distributed generation, is where electricity is generated locally within the low-voltage network of the consumers through renewable resources as shown in Figure 2 (for example, solar panels on the rooftop of the house) [35] [32].

Microgrid generation enhances the utilisation of renewable energy sources, reducing the dependency on fossil fuels and the carbon foot print [32] [35] [36]. The localised generation of the microgrid results in improved transmission efficiency and limited transition losses when compared to current central generation plants [32] [35] [36]. Furthermore, within the smart grid, microgrids can generate and transmit electricity to the macrogrid when in abundance locally as shown in Figure 2. This further reduces the demand on the central generation plant [32] [37]. This is facilitated via the smart grids' capability of two-way electricity generation and transmission, unlike the unidirectional nature of the current grid [32] [7].

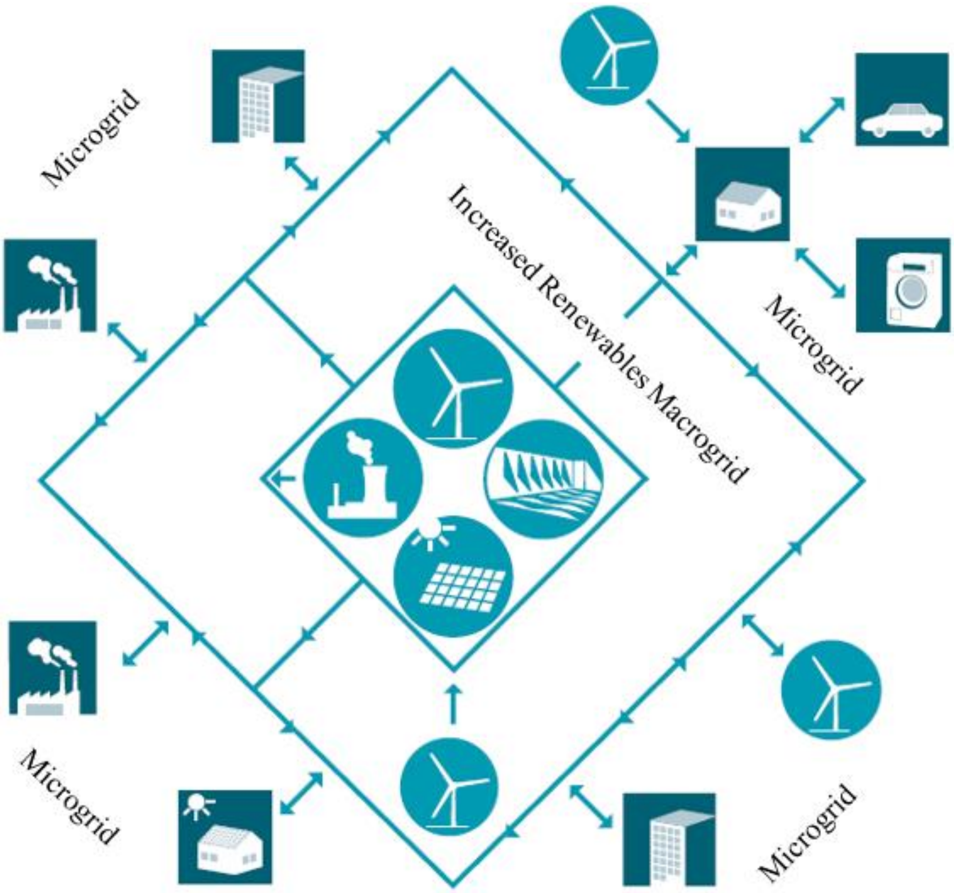

Figure 2 Smart grid generation architecture [34]

Renewable energy sources within the macro/microgrids are intermittent. Energy storage systems are usually present to store unused generated electricity from such renewable sources [1] [6] [33]. The stored energy can then be utilised in presence of increased load demand in the absence of sufficient renewable energy sources [1] [6] [33]. However, this is insufficient to ensure adequate reliability of the smart grid (i.e. avoiding blackouts). Therefore, conventional central generation plants are not eliminated within the macrogrid of the smart grid. They are to be used only when renewable energy electrical supply shortage is present [8]. The combination of additional renewable energy sources, conventional generation plants, and distributed generation results in the composition of the smart grid as shown in Figure 2 [3].

2.3.2 **Smart grid management**

Currently in the power industry, sufficient generation is required to satisfy the instantaneous load demand [3]. Therefore, the generation capacity is continuously following the load demand. This results in peak demand durations within the day due to similarities in user behaviour [34] [32]. For example, people turn on the air conditioning in the afternoon of a hot day yet don't reduce other load usages as shown in Figure 3 [32]. With increased electrical load introductions, such as EVs, this will result in increased amplitudes of peak demands. To accommodate for such increased peak demands with the current electrical grid, this will necessitate increased capital investment [6] [32]. Such increased costs can result in an unaffordable and unreliable electric supply [32]. Furthermore, the load profile with peak demands will minimise the usage of renewable energy sources as they are not necessarily present in the specific peak periods [6].

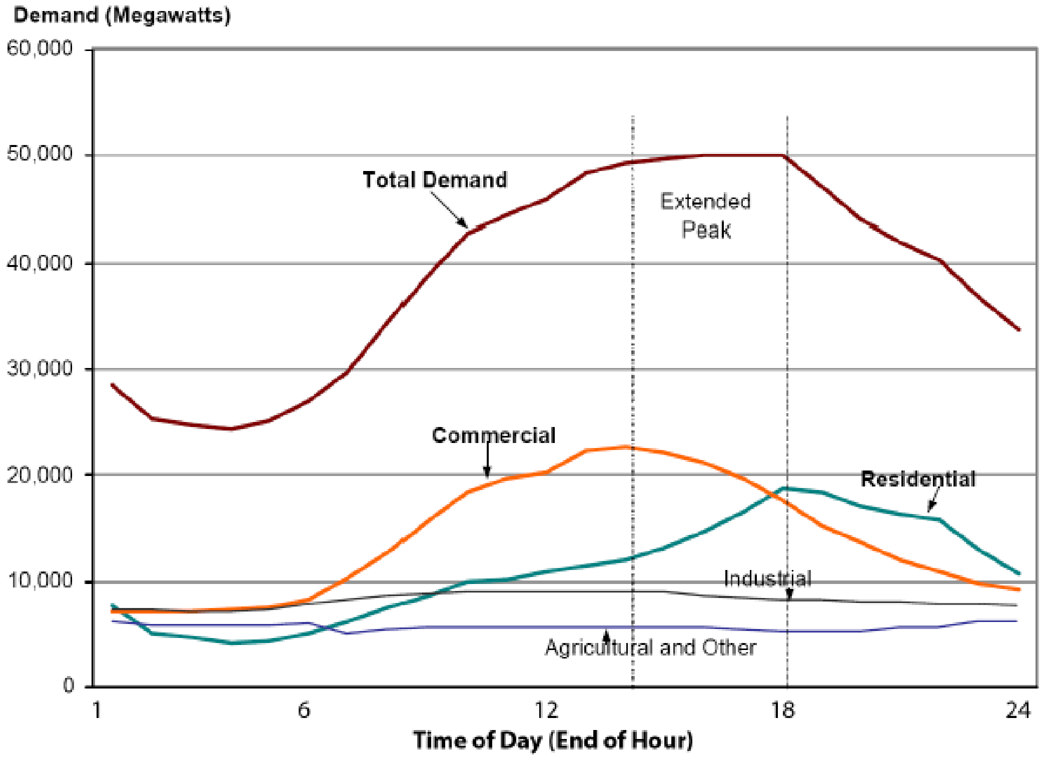

Figure 3 An example of current grid load profile for a hot day in California [32]

The smart grid introduces a supply-demand profile management scheme in order to optimise the usage of renewable energy sources and serve the increased electric loads without the need of increased capital investments [3] [8] [37]. This results in an electrical supply which is affordable and reliable. The principle behind such management is to flatten the load and supply profile by having the load demands follow the supply capability [32] [33]. This is achieved by encouraging the loads to operate in off-peaks times (where overall grid demand is low) and/or when there is increased renewable energy generation [7].

For such management capability to be implemented, clear visibility of real-time consumption is required for both the end-user and the supplier [33]. Furthermore, communication between the grid suppliers and consumers is required to facilitate such capability implementation [7] [38]. Finally, providing visibility of real-time consumption to the end-user can automatically result in increased electric supply usage efficiency, thus further reducing overall grid demands [33].

2.3.3 **Smart grid protection**

The conventional electric grid comprises of various protection capabilities to prevent failures [39]. Failures can either be a reduction in the supply quality or its complete interruption [39]. Current protection facilities are of reactive and manual nature [39]. For the purpose of supply quality reduction failures, the current grid monitors various AC supply aspects including voltage and frequency [3]. Corrective action is taken accordingly as required to ensure the stability of the system, preventing the failure from developing [3] [39]. In the case of a supply interruption failure, manual onsite troubleshooting is required after the incident occurs to restore the supply [40]. Such manual localisation and clearance of an interruption failure is time consuming and can result in extended periods of supply interruption impacting large number of consumers [41] [39].

Protection within the smart grid aims for a more resilient approach towards failures achieved via [39] [32]:

- Prediction and prevention of failures
- Automatic identification and restoration of failures

The first level of protection depends on data collection and advanced software to predict potential failures within the grid. This allows preventative actions to be proactively taken, minimising the occurrence of failures [39]. In the case of the second level of protection, as a failure occurs the smart grid is to be capable of automatically identifying its presence and carry required recovery action, minimising restoration time and efforts through a self-healing capability [40] [32] [38].

In addition to the smart grid resilience improvement with regards to the proactivity and automation in failure protection, further practical changes and expansions to the current protection system are required due to the introduction of microgrids and other features of the smart grid [32] [42]. For example, one of the features of the microgrid is that it is capable of being isolated during an interruption failure on the wider transmission grid [43] [32]. This allows the microgrid to continue its loads using the local generation without being impacted by the interruptive supply failure on the macrogrid [43]. In such a scenario, the fixed high fault current relays currently in use are not going to be adequate for the protection of the isolated microgrid [32] [43]. This is due to the utility grid currents being much greater in relation to that of the microgrid, therefore, overcurrent failures within the isolated microgrid operation will not be picked up by the fixed current relays which are originally designed for operation within the utility grid at higher normal operation current levels [43].

Finally, cyber security is a critical point of additional protection enhancement required within the smart grid due to the increased information collection and dependency on reliable communications for its operation [32].

2.4 EV charging overview

Rechargeable battery pack (RBP) charging is a substantial element of EV technology due to its impact on many aspects including [11] [44] [45]:

- Speed of charging can affect the usability of EVs thus their user acceptance.
- Undesirable charging methods, conditions, and parameters can lead to RBP lifespan and reliability reduction.
- Charging loads of such high-power demand result in infrastructural challenges within the electrical supply and generation sector.
- High cost of charging facilities can result in lack of investment in an adequate charging points network to facilitate EV usage.

2.4.1 Charging profile

Charging of an RBP can be achieved using different profiles [46]. This includes constant current (CC), constant voltage (CV), constant current-constant voltage (CC-CV), and pulse charging [46]. The profile chosen impacts the rate of charge, lifespan of the RBP, and the complexity of charge control required [47]. The suitability of a specific charging profile is dependent mainly on the RBP chemistry [47]. As EVs are usually Lithium-ion based, a CC-CV charging profile is most commonly used [48] [47]. A CC-CV charging profile is based on use of a high constant current rate in the first phase of charging where the RBP state of charge (SOC) is low [49] [48]. When the RBP SOC reaches higher levels, the CC-CV charging profile goes into its second phase where it reduces the charging current gradually through a constant voltage mode [49] [48]. Figure 4 demonstrates the CC-CV charging profile and its relation to the RBP SOC [49].

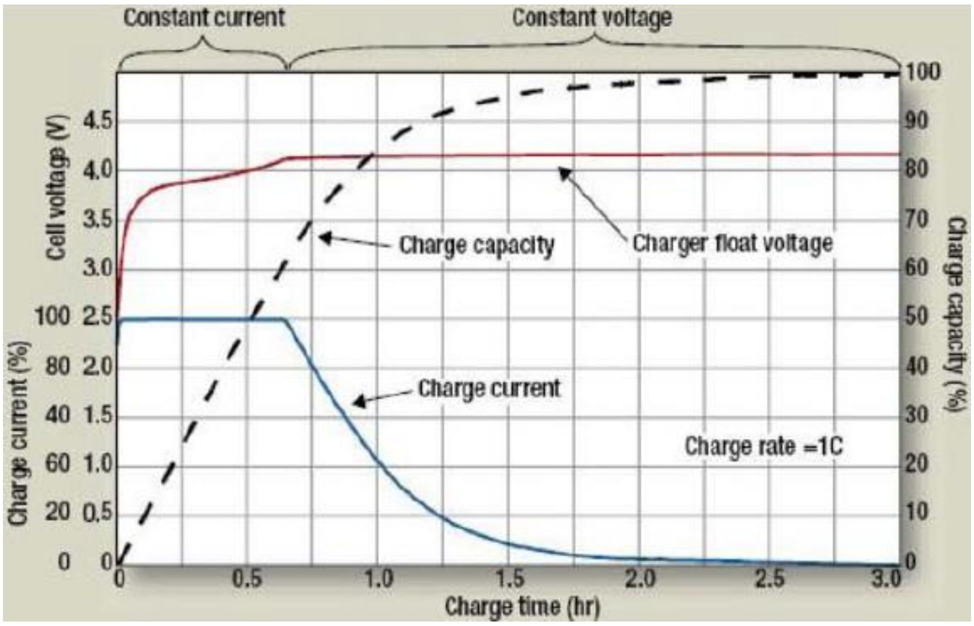

Figure 4 Characteristics of a CC-CV charging profile [49]

2.4.2 **EV charging classifications**

EV charging is categorised into either conductive or inductive/wireless charging methods [49] [50]. This categorisation reflects the nature of energy transfer connection between the supply and the EV [50] [51].

Conductive charging is currently the most common and popular method for EVs [51] [52] [11]. It is based on metal to metal contact for energy transfer between the electric supply and the EV [53]. This is achieved via a power cord direct plug-in connection into the EV [51] [11]. Its advantages include simplicity, low cost, and high efficiency [51] [52]. Meanwhile, its main disadvantage is the safety concerns with regards to accessible live parts potentially causing electrocutions [52] [54]; these concerns are currently addressed and controlled through relevant standards [52].

Figure 5 Conductive charging method [55]

In general, conductive chargers consist of 3 mains function [49] [53] [11]:

- AC-DC rectification
- Power factor correction (PFC)
- DC-DC conversion

The arrangement of those functions is demonstrated in Figure 6, below [56].

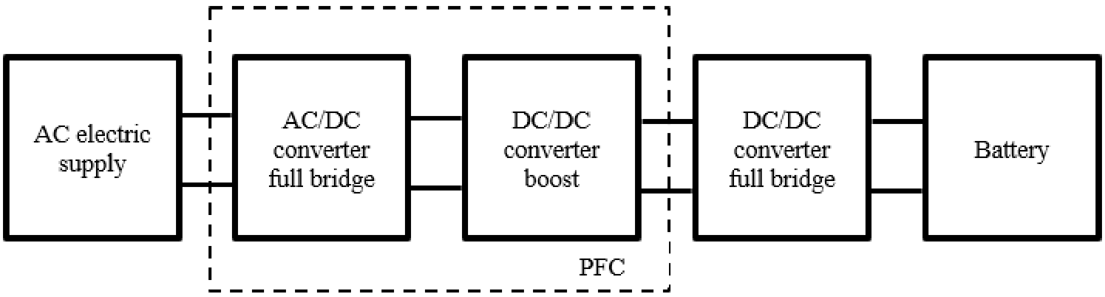

Figure 6 EV RBP conductive charger generic architecture

In Figure 6, AC-DC rectification is needed for the conversion of AC grid supply into a DC form [53]. Meanwhile, the PFC function is needed for phase synchronisation between the grid voltage and input current [11]. This is to ensure standard compliance in relation to reduced grid harmonics injection and maximisation of the real power consumption [11] [57]. Finally, the DC-DC conversion is required to regulate the DC voltage supply (following the PFC) to achieve a suitable level for a specific RBP [49] [53] [57]. The DC-DC converter voltage regulation is determined via a with-in vehicle RBP controller which takes into consideration different RBP specific parameters such as voltage, capacity and electrochemistry [11] [57].

Wireless charging is currently of limited presence but of high potential for future EVs [58] [59] [60] [61]. It is currently an active area of research and development into its various challenges [62]. Wireless charging depends on non-contact power transfer between the ground level electric supply and the EV above it [62] [61]. This can occur in a stationary, quasi-dynamic, and dynamic manner [61]. The idea behind quasi-dynamic wireless charging is to have the electric supply embedded in the roads, allowing the EVs to charge when they come to a stop (for example, at traffic lights) [61]. Meanwhile, dynamic charging can be used to continuously charge EVs while driving above those electric supply embedded roads [61]. Advantages of wireless charging include robustness, safety, user experience, and range anxiety improvement through dynamic charging [62] [59] [60] [63]. Meanwhile, its main disadvantages are infrastructure investment, efficiency, control complexity, and alignment tolerances between the electrical supply and EV [62] [59] [60] [63]. Various programmes of research are currently investigating the development and improvement of those disadvantages [63] [59] [11].

Figure 7 Static wireless charging [59]

Wireless chargers are broken down into sending and receiving sides [62]. In general, the sending side consists of five functions [64]:

- AC-DC rectification
- PFC
- High frequency (HF) DC-AC conversion
- Compensation network
- Sending coil

Meanwhile, the receiving side consists of three or four functions, depending if it is of a stationary or dynamic nature. These are [64] [11]:

- Receiver coil
- Compensation network
- DC-DC converter (if dynamic)
- AC-DC converter

The arrangement of those functions is demonstrated in below Figure 8 [64].

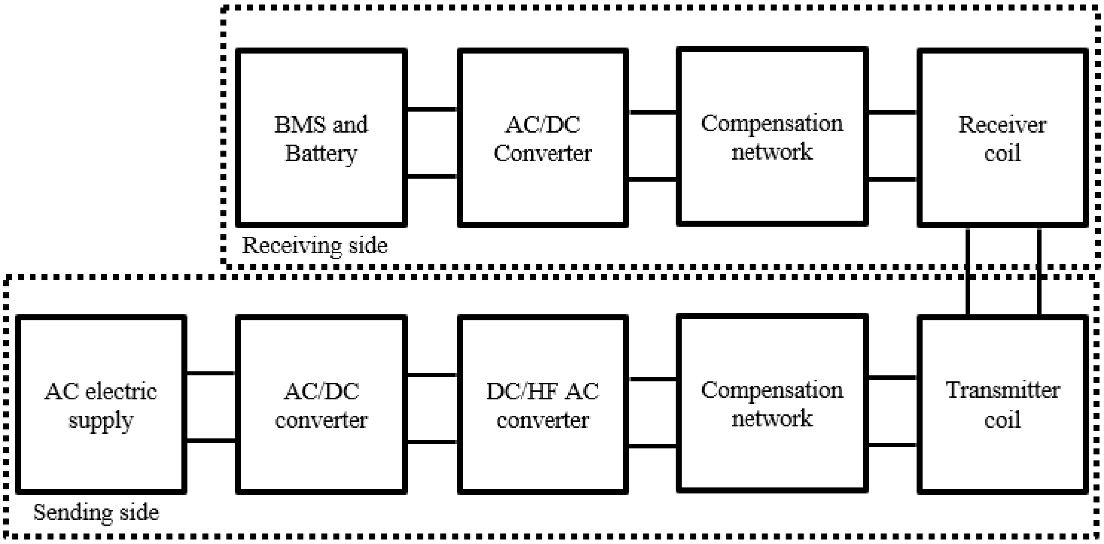

Figure 8 EV RBP wireless charging architecture

On the sending side of Figure 8, in order to convert the AC electric supply into a DC form, AC-DC rectification is used [64]. The PFC function is implemented within the AC-DC rectifier ensuring harmonics and real power utilisation standard compliance [11] [57]. This is achieved through its performance in synchronising the grid voltage and input current [65] [11]. A HF DC-AC converter follows the AC-DC PFC, allowing it to generate a HF AC supply enabling power transfer through the sending coil [64]. A compensation network is present prior to the coil to improve overall efficiency [64].

On the receiving side of Figure 8, a receiver coil converts the magnetically transferred power from the sending coil into HF AC [64]. A compensation network is also present after the receiver coil for efficiency purposes [64]. Then, the received AC is converted into a DC supply for RBP charging [64]. Power level control is achieved by the sending side within a stationary charger (in co-ordination with its receiver), meanwhile, this is preformed within the DC-DC converter of receiving side [65] [11].

Within the conductive and wireless charging categorisation, further classification is possible based on following charger aspects [50]:

- Energy source electrical waveform
- Location
- Charging electrical waveform power level
- Power flow direction
- Topology

The various classifications and their relevance to the inductive and conductive charging categories are highlighted below separately.

2.4.2.1 Energy source electrical waveform

The AC electrical grid is currently the energy source for existing chargers [50] [66]. However, DC energy sources (such as solar panels) can be utilised as an alternative for EV charging [66] [50]. The utilisation of a DC energy source results in elimination of AC-DC rectification and PFC conversion function requirements (highlighted in previous section) of both conductive and wireless charging methods [50] [66]. However, a DC-DC voltage boost function is required [50] [67] [66]. This is because DC energy sources such as solar panels often have low output voltage [50]. Furthermore, with such intermittent DC energy sources, a storage battery must be utilised [67] [66]. The elimination of one of the conversion function of AC-DC rectification results in reduction of power losses that occur through multiple conversions [50]. Examples of DC source based EV charging architectures of conductive and wireless are shown in Figure 9 and Figure 10 respectively [67] [66].

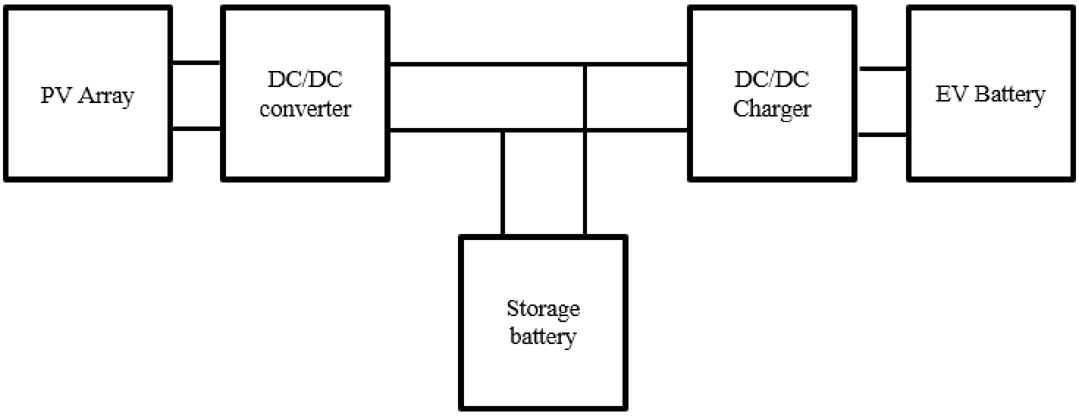

Figure 9 DC energy source EV conductive charging general architecture

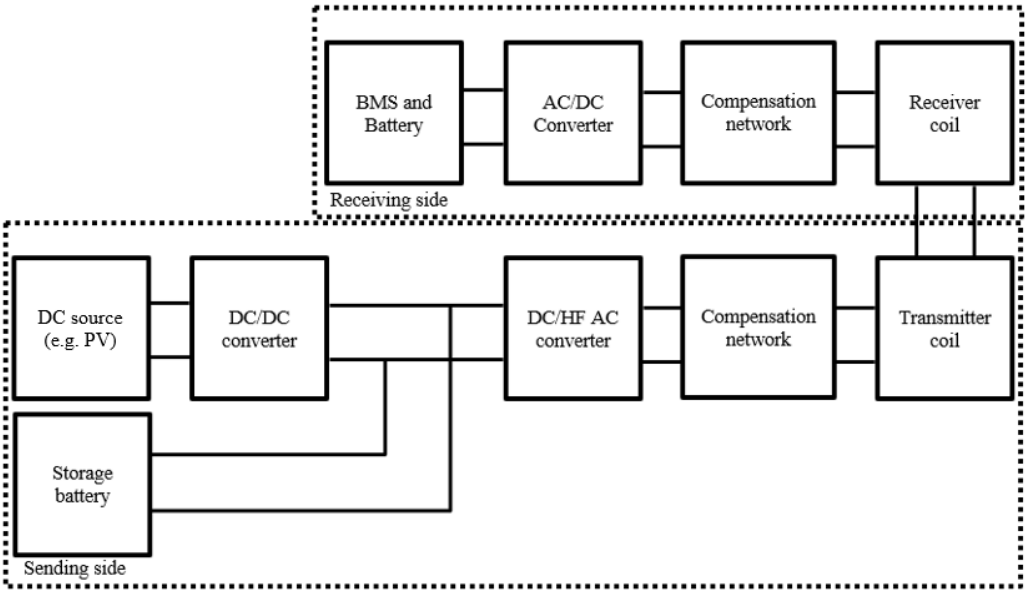

Figure 10 DC energy source EV wireless charging general architecture [66]

2.4.2.2 Charging electrical waveform power level

The electrical waveform supplied to an EV for conductive charging can be of AC or DC nature [68]. Hence, conductive charging is classified based on charging modes including [53] [69]:

- AC charging
- DC charging

There are multiple power levels under which AC or DC charging can occur [53] [69]. In general, those classifications include AC and DC levels of 1 to 3 [53] [69] [48].

Meanwhile, wireless charging is based on an AC electrical waveform supplied to the sending side of the charger [70] [65]. This includes power levels between 1 and 5, with a power level of 5 being for heavy duty vehicles such as buses and trains [70] [65].

The power specification for the various charging levels of both conductive and wireless charging are summarised in Table 1 below with reference to SAE and IEC standards [53] [69] [71] [70] [65].

Table 1 A summary of various power level classifications for EV conductive and wireless charging in SAE and IEC standards [53] [69] [71]

Level	Conductive charging maximum power	Wireless Charging maximum power
SAE		
AC level 1	1.9KW	3.7KW
AC level 2	19.2KW	7.7KW
AC level 3	96KW	11.1KW
AC level 4	NA	22KW
AC level 5	NA	>22KW
DC level 1	80KW	NA
DC level 2	400KW	NA
DC level 3*	TBD	NA
IEC		
AC level 1	7.7KW	3.7KW
AC level 2	15.4KW	7.7KW
AC level 3*	TBD	11.1KW
AC level 4	NA	22KW
AC level 5	NA	>22KW
DC charging	400KW	NA

As seen from Table 1, with the increase in charging level, the maximum power delivery is increased. Therefore, the power level of the charger utilised impacts the speed of the charging process [72] [73]. However, faster charging potentially reduces the EV RBP lifespan [72] [73].

2.4.2.3 Location

This classification is not relevant to wireless charging; hence, this section will focus on the conductive charging category. Conductive charging can be classified with regards to the location of the EV charger control function [74]. Those classifications include [75]:

- On-board charger control
- Off-board charger control

On-board conductive chargers are those that are built-in to the EV [74]. Off-board chargers are those which are external to the EV and are usually part of the electric vehicle supply equipment (EVSE) [53] [49].

EVSE facilitate the energy transfer between the energy source and the EV battery during the charging process [11] [69]. This can include cords, attachment plugs, protective components, charging stations, and control boxes [11] [69]. The EVSE setup required depends on whether the charger is on-board or off-board, along with its power level classification [11] [69].

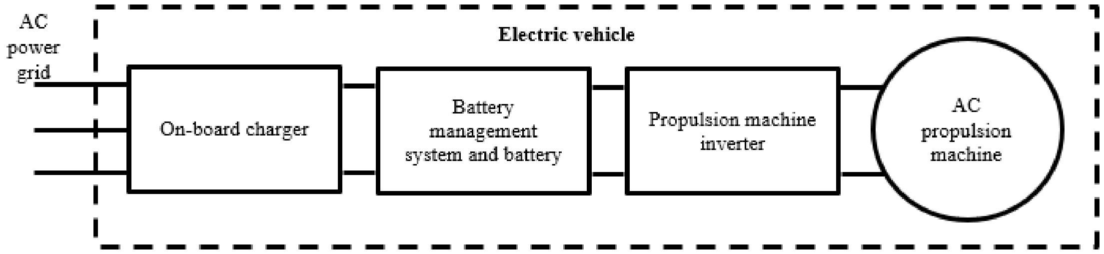

Figure 11 On-board EV charging architecture

As shown in Figure 11, in on-board charging, the AC supply is provided to the EV where the internal charger performs all the control functions [49]. Therefore, on-board chargers can be utilised for AC charging of all power levels [53].

On-board AC power level 1 chargers utilise limited EVSE due to their low charging rate [11] [72] [69]. This includes a cord, vehicle connector, and supply plug [11] [69]. Due to their low charge rates, simplicity of EVSE requirements, and supply voltage rating (being same as domestic supply), they are mostly utilised in households for slow overnight charging by utilising standard outlets directly [11]. In certain countries, a requirement of residual current devices (RCDs) is present for safety purposes [48] [69]. This can be satisfied by being embedded within the cord or as part of household electrical supply set-up [69] [48]. On-board AC power level 1 chargers are of low investment in general (typically $500-$880) [11].

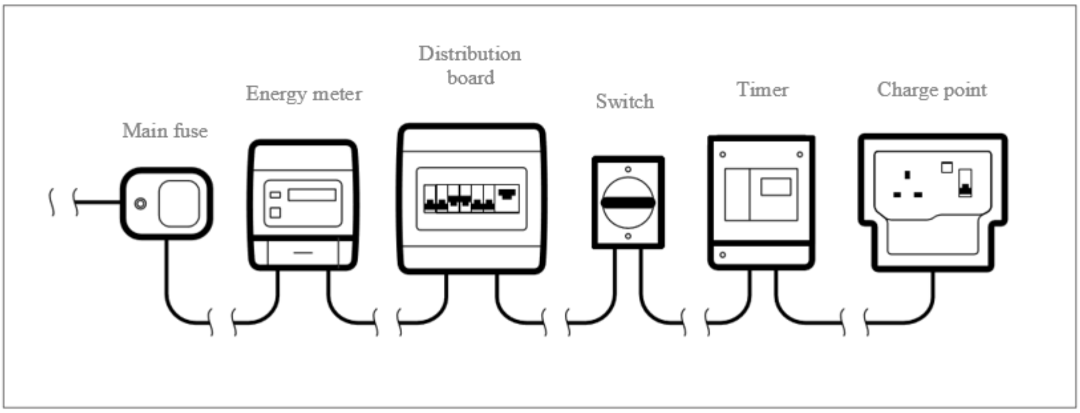

Figure 12 A typical EV on-board AC level 1 charging setup [76]

On-board AC power level 2 chargers require the addition of a control box to the EVSE set-up (a control pilot function is also required in certain countries for this level [69] but will be highlighted in on-board AC power level 3 of Figure 14); this serves as dedicated safety equipment for advanced protection due to the higher charging rate [53] [11] [72] [69]. They remain capable of utilising standard socket outlets as the AC source [53]. Due to their manageable charge rates, acceptable EVSE set-up requirements, and supply voltage rating (being same as domestic and industrial supply), they are utilised for both residential and commercial (such as offices and malls) purposes [11] [57] [73]. On-board AC power level 2 chargers are of higher investment (in general between $1000-$3000) [11].

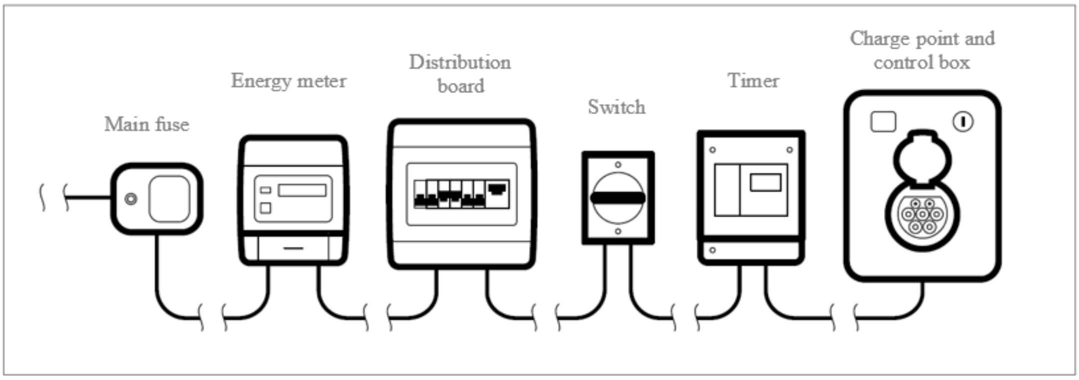

Figure 13 A typical EV on-board AC level 2 domestic charging setup [76]

On-board AC power level 3 chargers require a charging station as part of its EVSE to replace the control box (the charging station includes the safety functions of the control box) as shown in Figure 14 [53] [69] [48]. Furthermore, due to the high charging rate, additional safety functions in EVSE set-up are a compulsory requirement in all countries [53] [69]. Those are preformed within what is known as the control pilot. The additional safety functions performed by the control pilot module include the following [48]:

- Connection between the EVSE and vehicle verification
- Indication of EVSE readiness for energy supply
- EVSE ventilation requirement determination
- Communicating charging station current withdraw capacity and ensuring it is met

The charging stations are directly and permanently connected to the electrical grid to provide the AC electrical source for the on-board level 3 charging [48]. Such fast charge capability being implemented results in infrastructure costs in the $30,000 to $160,000 range [11] [77] [76]. Therefore, they are mainly utilised for commercial purposes (such as fuel stations) and not in residential environments [11].

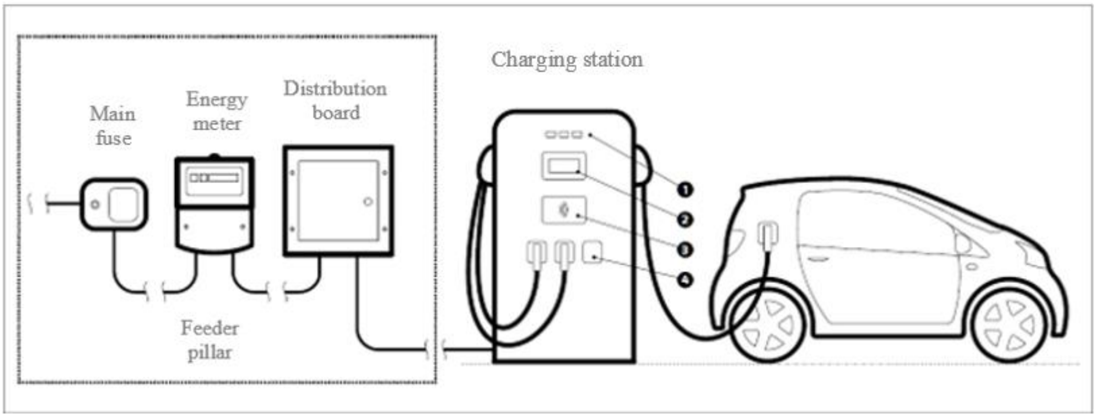

Figure 14 A typical EV on-board AC level 3 charging setup [76]

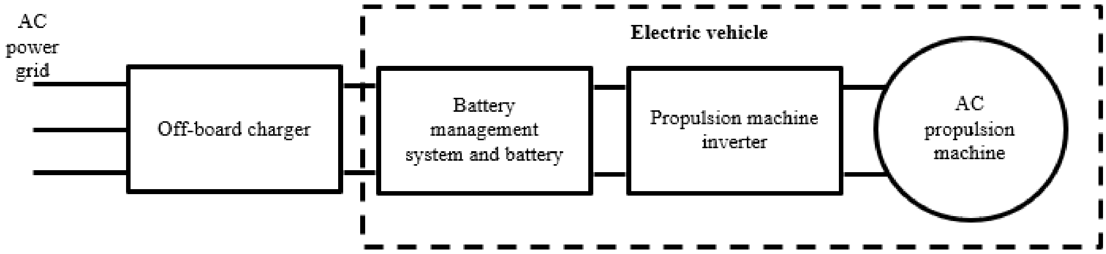

Figure 15 An EV off-board EV charging architecture

As shown in Figure 15, in off-board charging, the AC supply is provided to the charger which is located outside the EV [49]. The off-board charger produces a DC supply which is provided to the EV by directly connecting to its RBP management system for charge control [49] [53] [78]. Therefore, off-board chargers are utilised for DC charging of all power levels [53].

Both defined DC charger levels 1 and 2 are capable of high charging rates [79]. Therefore, both DC charger levels require the same EVSE to that of AC power level 3, including the charging station and its incorporated safety functions (with the charger being located in charging station as mentioned previously for AC chargers) [53] [71]. DC charger EVSE also includes additional communication functionality to that present in AC level 3 charger EVSE [53] [48]. This is mainly focused on understanding charging requirements from the EV based on its RBP specific factors including chemistry, parameters (such as voltage and current), and SOC [53] [71] [48].

In general, DC off-board chargers are utilised mainly in fast charging setups for commercial purposes (such as fuel stations) [80] [81] [82]. This requires direct and permanent connection of the charging station to the grid [48] [80]. Such fast charging capability results in high costs in the $30,000 to $160,000 range [11] [81] [76]. DC level 1 chargers (or low rated DC chargers in those countries that use no power classification in DC charging [48]) can be used with limited maximum power (much less than that actually allowed by standards) for residential or public purposes (such as offices) [53]. Such low power DC charging stations don't require direct and permanent connection to the grid [53] [77]. This option is cheaper than that of fast DC charging as no requirement for grid level supply improvement investment is required [77] [80]. However, this is still of much more significant cost than that of AC power levels 1 and 2 chargers which provide similar charging rates [77] [11]. Average cost of such low power DC charging EVSE is around $10,000 (excluding installation charges) [77]. A typical off-board charging set-up is similar to that shown in Figure 14 for AC level 3 with the difference being that the charger is within the station itself [76].

On-board and off-board charging comparison

On-board charging requires charger presence within the EV which results in limitation of its power level capabilities [83]. This is due to higher levels resulting in increased weight, space claim, and cost within the EV [83]. Therefore, in general on-board chargers are currently slow chargers [84]. Meanwhile, its inclusion within an EV is advantageous as it provides high accessibility for EV charging through direct domestic mains outlet connection [85]. This allows overnight slow charging with low investment costs [84]. If fast on-board charging could be achieved, it would allow AC charging stations of low cost and low installation requirements, due their low complexity, size, and weight (as they don't need to incorporate charger power electronics) [86]. Furthermore, AC charging stations are flexible (easily scalable) in relation to variations of their power capabilities due to the limited components involved [86].

Off-board charging doesn't require the charger to be within the EV which eliminates weight, cost, and charging power limitations [83]. Therefore, in general off-board chargers are currently used as fast chargers [85]. However, off-board chargers cause incapability of charging access in locations where charging stations don't exist (i.e. cannot charge through directly connecting to domestic mains outlet) [86]. Furthermore, off-board charging stations are bulky, heavy, and of high cost due to the additional power electronics required [86]. The size of such stations results in the further disadvantage of urban environment cluttering [84]. Finally, DC charging stations are less flexible than that of AC charging stations in relation to variations of power level capabilities due to the incorporation of the charger [86].

Due to the different advantages and disadvantages of on-board and off-board conductive charging mentioned, the current generation of EVs tend to incorporate on-board and off-board charging facilities within each vehicle [87]. This provides the following advantages which make EVs more appealing [88] [56]:

- Low investment and high access capability for the end-user in domestic charging provided by on-board chargers
- Fast charging capability addressing range anxiety by a gas station equivalent provided by commercial off-board fast charging stations

This situation results in redundant power electronics and increased overall cost due to chargers present in the DC charging stations and the on-board vehicle charging facility [88] [86]. This is being addressed with new on-board charging topologies where chargers are integrated within the existing vehicle power electronics (further discussed in following sections) [87] [89].

2.4.2.4 Power flow direction

Conductive and wireless chargers can be of unidirectional or bidirectional classification [64] [11]. Unidirectional chargers are those which only allow power flow from the grid (or other energy source) to the EV RBP [11]. In contrast, bidirectional chargers additionally allow the power to flow from the EV RBP to the grid [11].

The bidirectional charger feature is facilitating the vehicle to grid concept of a future power grid where parked vehicles provide power to the grid when required, hence, supporting its operation [52]. This concept is of concern with regards to its impact on EV RBP lifecycle due to the increased charging and discharging frequency [11]. Furthermore, the bidirectional capability allows integrated charger capability for conductive on-board chargers, as highlighted in the next section [11].

2.4.2.5 Topologies

This section is only relevant to conductive charging category; hence, wireless charging is excluded.

Conductive on-board chargers can be either dedicated or integrated [50]. Dedicated chargers are those where the different functions such as AC-DC, PFC, and DC-DC all have relevant circuitry with those functions being their sole application [50]. Integrated chargers are those where some or all those functions are integrated with similar circuitry already present within the EV for drivetrain purposes [50].

The advantages of an integrated on-board charger topology include reduction in weight, space, and cost [86]. Those advantages mean that onboard high-power charging is feasible, which in turn eliminates the need for off-board chargers [86]. Integrated on-board charging also eliminates redundant electronics achieving cost-effective EV charging [86]. Integrated on-board chargers are challenging to implement due to control complexity and additional hardware required [11]. A typical completely integrated on-board charger architecture is shown below in Figure 16 [11].

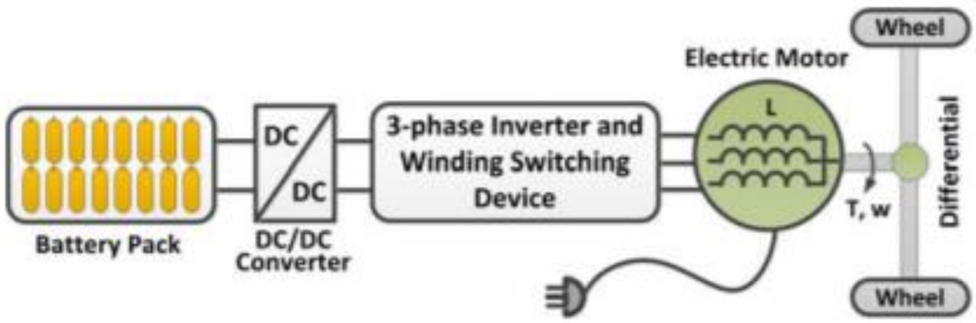

Figure 16 The architecture of a typical integrated on-board EV charger [11]

2.5 Rechargeable batteries

Batteries play a major role within smart grids and EVs [90] [12]. They are energy storage devices which comprises of an anode, a cathode, and an electrolyte [91] [92] [12] [93]. They can provide a load with a DC electric supply via chemical reactions. Such discharge of the battery changes its chemical composition. Zero battery SOC is the resultant of insufficient discharge level i.e. no more energy is stored within the battery for further electricity supply.

Rechargeable batteries are capable of chemical composition restoration after discharge, hence, further storage of energy capability [94] [90] [95] [93]. This is achieved through the reverse process of charging. There are various types of rechargeable batteries including:

- Lithium-ion (Li-ion)
- Lead Acid
- Nickel-Metal Hybrid (Ni-MH)
- Lithium-sulphur

The different rechargeable battery types vary in their capabilities including [94] [95] [12]:

- Energy density
- Power density
- Lifespan

The above-mentioned capabilities of the rechargeable battery are highlighted and discussed below separately.

2.5.1 **Energy density**

A rechargeable battery cell has limited electric supply capacity defined in ampere-hours (Ah). Theoretically, this capacity, Q, is expressed as [93]:

$$Q = x \times n \times F \tag{1}$$

Where x is the number of reactant moles consumed, n is the number of transferred electrons during reaction per molecule, and F is Faraday's constant.

The energy, E, within a rechargeable battery cell is the capacity, Q, it is capable of holding in relation to the voltage, V, at which it is supplied [93]. This is defined in watt-hours (Wh) and given by:

$$E = Q \times V \tag{2}$$

This determines its discharging capability at various rates, for example, an RBP of 24kWh energy capacity would be capable of suppling a load at a discharge rate of 24kW for one hour before it reaches zero SOC [96]. Meanwhile, the capability of a rechargeable battery cell in terms of how much energy it can withhold within a specific weight (Wh / kg) and volume (Wh / L) is described as its energy density [97] [44]. This capability varies from a rechargeable battery type to another as shown in Figure 18 of Section 2.5.2 [94].

The energy capacity of a rechargeable battery cell is an important factor within the design of an RBP as a higher energy capacity results in increased duration of load supply at a specific rate [96]. Meanwhile, energy density is a critical aspect to be considered within the design as reduced energy density and increased energy capacity will result in substantial RBP weight, space claim, and cost. Those characteristics of an RBP will potentially result in failure of commercial and technical feasibility in an automotive application.

2.5.2 **Power density**

The instant charge/discharge power value of a rechargeable battery cell is described in C-rate [96]. This refers to the duration its specific energy capacity requires to be fully discharge/charged at a specific power level. Taking the example mentioned in previous section, a 24kWh RBP discharging at 24kW would last for one hour, such power discharge would be described as 1C-rate.

Rechargeable battery cells don't have infinite discharging/charging C-rate capability due to their internal resistance [98]. With focus on the discharging element for this thesis, the power delivered from a battery is defined through equations (3) - (5).

$$V = V_o - RI \tag{3}$$

Where the voltage (V) at which battery discharges is defined through the voltage losses within its internal resistance (R) at a specific discharge current level (I) in relation to the batteries electromotive force (V_o).

$$P = VI \tag{4}$$

The power discharged from a battery in Equation (4) is determined from the battery delivered current (I) at the specific discharge voltage (V).

$$P = (V_o - RI)I \quad (5)$$

Substituting equation (3) within equation (4) results in calculating the actual battery discharged power through equation (5) accounting for internal resistance losses. It can be seen from Figure 17 that the maximum delivered power is limited in relation to the battery's voltage drop due to internal resistance power losses. This is due to power losses exceeding that delivered to the load with battery power releases beyond the maximum power delivery point. Therefore, delivery power starts to reduce in relation to that lost reaching zero power delivery to the load where all power released from the battery is consumed by its internal resistance rather than delivered to the load.

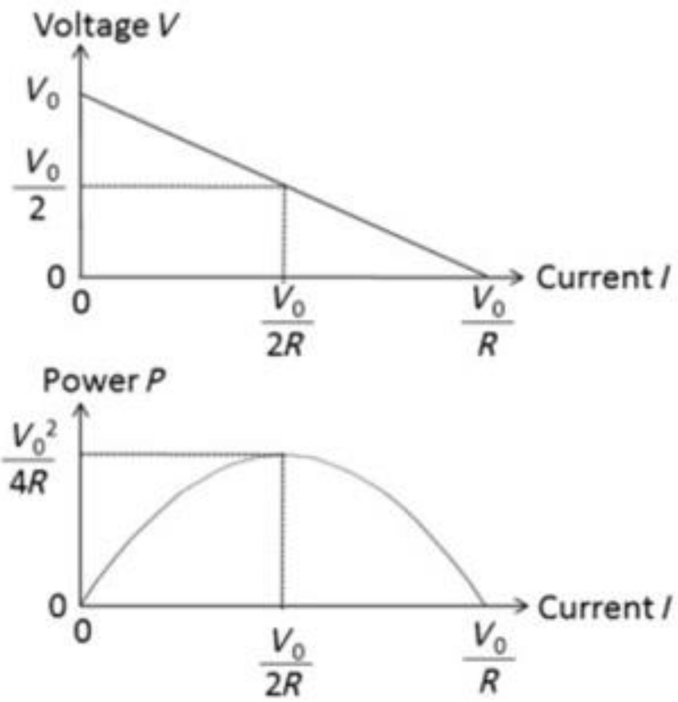

Figure 17 Maximum power delivery from a rechargeable battery cell [98]

The instant power delivery capability of a rechargeable battery cell within a specific weight and volume is referred to as its power density (W/kg and W/L respectively) [93]. Therefore, the RBP size and weight is linked to the maximum power capabilities required and the used battery cell types [94]. The power density of a rechargeable battery is dependent on its type as shown in Figure 18.

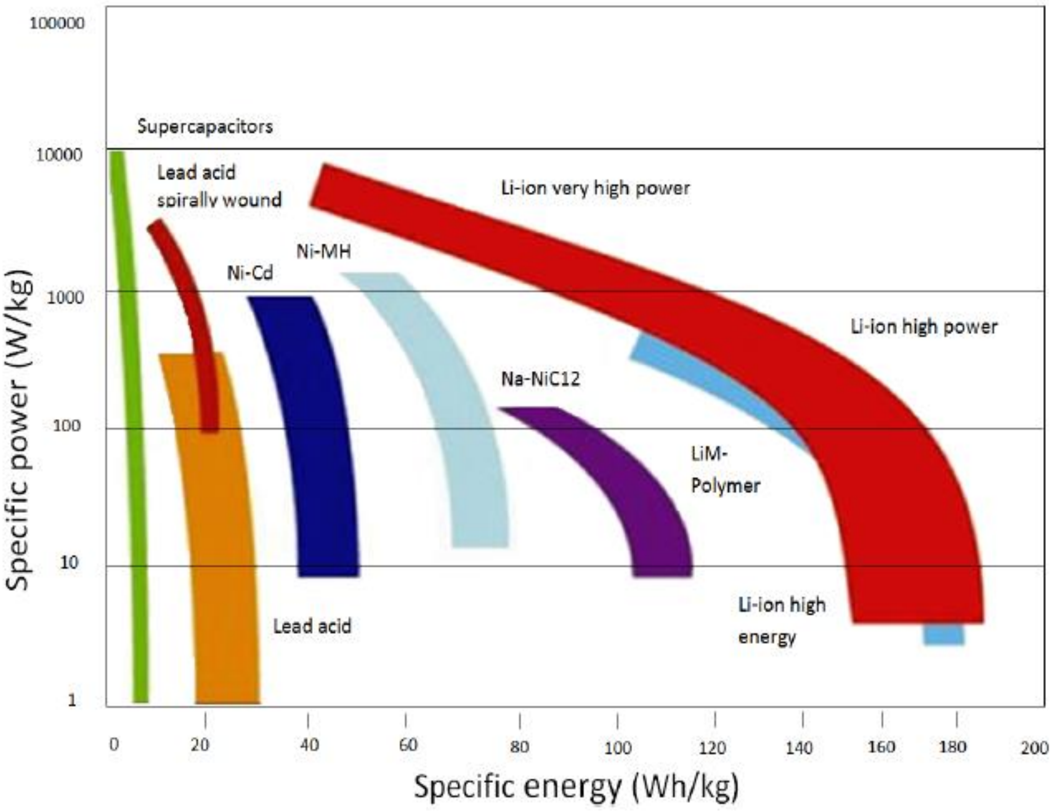

Figure 18 Energy and power densities of different rechargeable battery types [94]

In general, reduced RBP size and increased discharge power rates result in increased power losses due to the internal resistance, hence, limited power delivery capability [99] [100] [96]. This results in increased RBP weight, cost, and space claim with increased power capability requirements which can potentially result in loss of commercial and technical feasibility especially within the automotive applications.

2.5.3 **Lifespan**

A rechargeable battery is capable of undergoing charging and discharging for many cycles [101]. Its effective capacity decreases with the number of cycles it undergoes as shown in Figure 19. This is due to its chemical composition degradation i.e. its full SOC capacity becomes less than that originally specified [101] [102]. The exact number of cycles a rechargeable battery is capable of is known as the lifespan. The specified effective capacity limit at which a rechargeable battery is considered to have reached end of life is 70% of its nominal. This is due to an unacceptable performance reduction beyond that point.

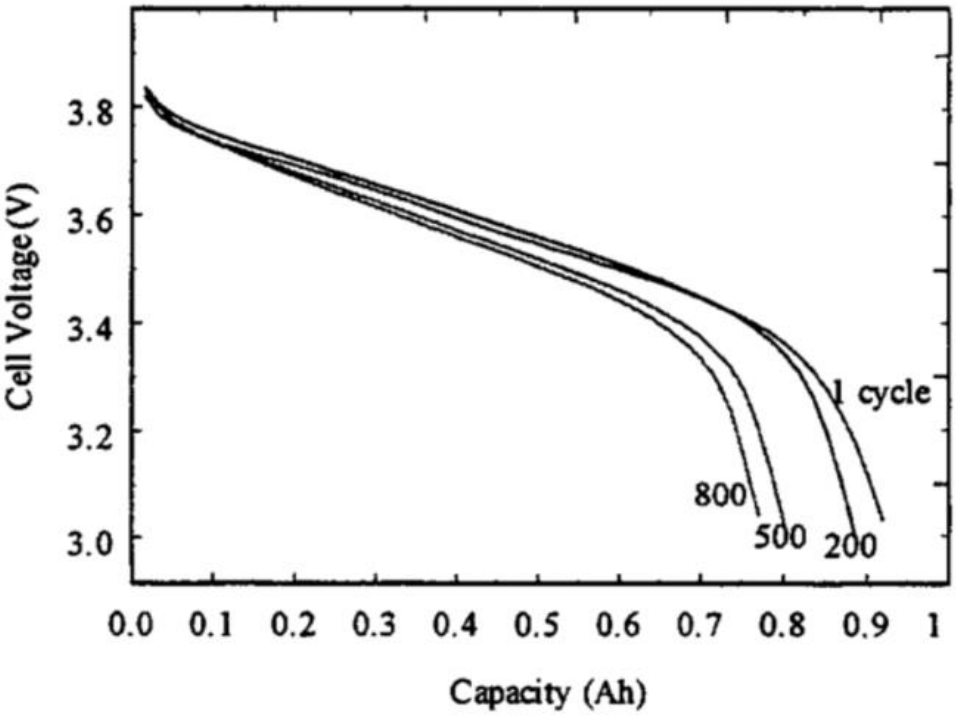

Figure 19 Battery effective capacity degradation with charging discharging cycles [102]

The theoretical lifespan of an RBP is dependant its type [94]. In practice, the achievement of the theoretical life cycle is dependent on the operational conditions [92] [103] [102] [104]. The reduction of a battery's life cycle in practice compared to that in theory results in its reliability reduction within the application. Operational conditions which reduce an RBP lifespan from that theoretically defined include:

- High discharge power rates
- Extreme temperatures
- Excessive depth of discharge
- Overcharging

The above operational conditions and parameters that are factors which determine the lifespan and performance of a rechargeable battery will be explained in terms of how they affect the life span of a rechargeable battery separately below.

2.5.3.1 High discharge power rates

Power losses are present in the battery during discharge due to its internal resistance. Those losses increase with higher discharge rates [98] [105]. Such losses are in the form of dissipated heat. Increased heat generation from power losses within the battery result in substantial temperature rise of the rechargeable battery as shown in Figure 20 [106].

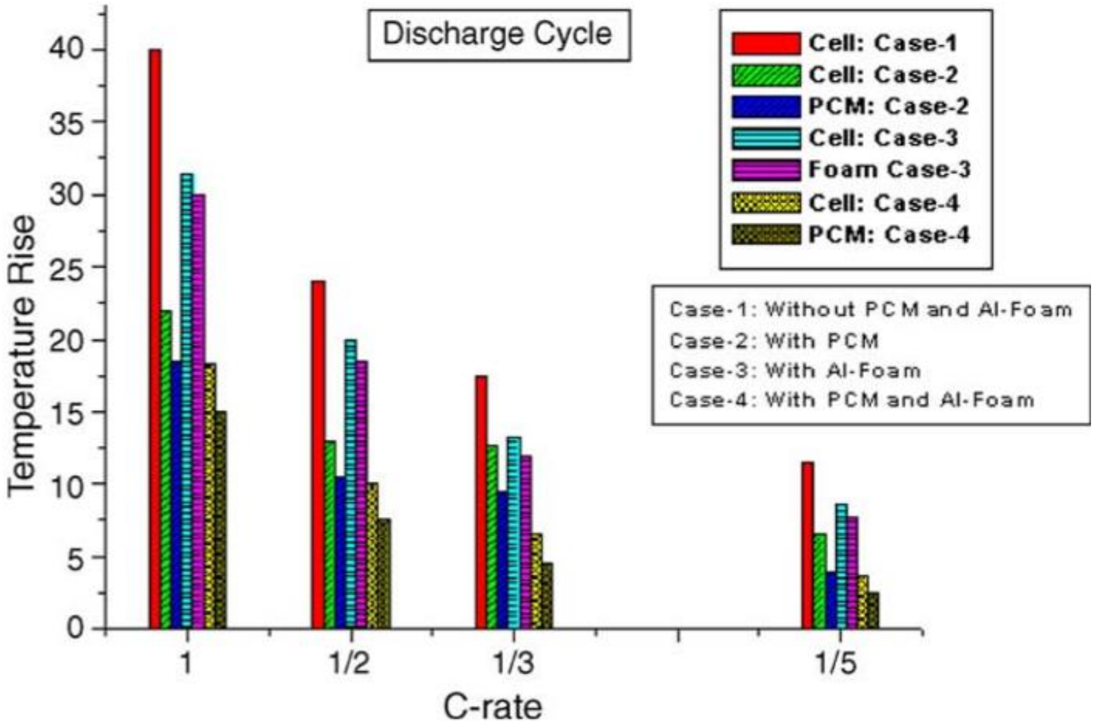

Figure 20 Rechargeable battery temperature rise at different discharge rates and heat dissipation mechanisms [106]

It can be seen from Figure 20 that higher discharge rates result in increasing rechargeable battery temperature rise across all experimented heat dissipation mechanisms [106]. Such battery temperature rises result in higher irreversible battery chemical decomposition rate thus enhanced capacity fade and lifespan reduction [98] [105]. Therefore, management of the discharge rate of an RBP is critical within its application for high reliability and cost effectiveness [100] [99].

2.5.3.2 Extreme temperatures

The actual lifespan of an RBP depends on its storage and operational temperatures [107]. Extremely high ambient storage or operational temperatures for a rechargeable battery result in lifespan reduction [108]. At high temperatures, the rechargeable battery undergoes enhanced chemical reactions resulting in faster chemical content degradation, hence, reduced lifespan. Meanwhile, at very low temperatures, the chemical reactions are slower, but the battery's chemical content is at risk of freezing causing loss of effective capacity, hence, shorter lifespan.

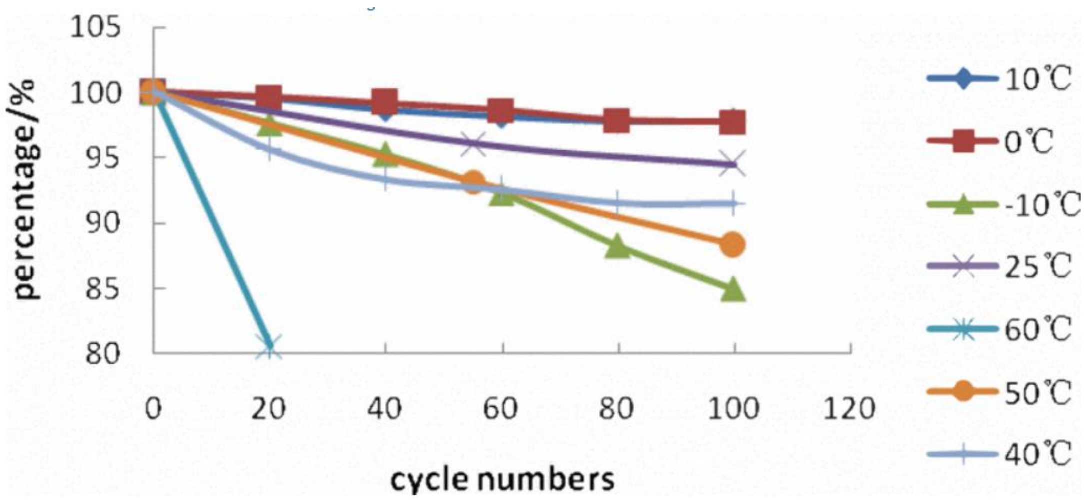

Figure 21 Reduction of rechargeable battery effective capacity over operational cycles at different ambient temperatures [109]

As seen from Figure 21, the effective capacity of a rechargeable battery reduces in an accelerated manner at extremely low and high temperatures, therefore, managing the ambient temperature in the RBP application is vital for its reliability [109] [110].

2.5.3.3 Excessive depth of discharge

Depth of discharge (DOD) is a percentage measure of how much from the RBP's nominal capacity discharges in one cycle [111]. For example, if an RBP of 100Ah is discharged until it reaches a capacity of 30Ah, then this would be considered as 70% DOD. This is determined from below equation (6) where Q_o is the RBP's nominal capacity (Ah), I is the discharged current, and t is the duration for which the discharge has taken place.

$$DOD = \frac{1}{Q_o} \int I(t)dt \tag{6}$$

The actual lifespan of an RBP in its application is impacted by the DOD level at which is being cycled [112]. Figure 22 below demonstrates the relationship between the DOD and the lifespan of an RBP [113].

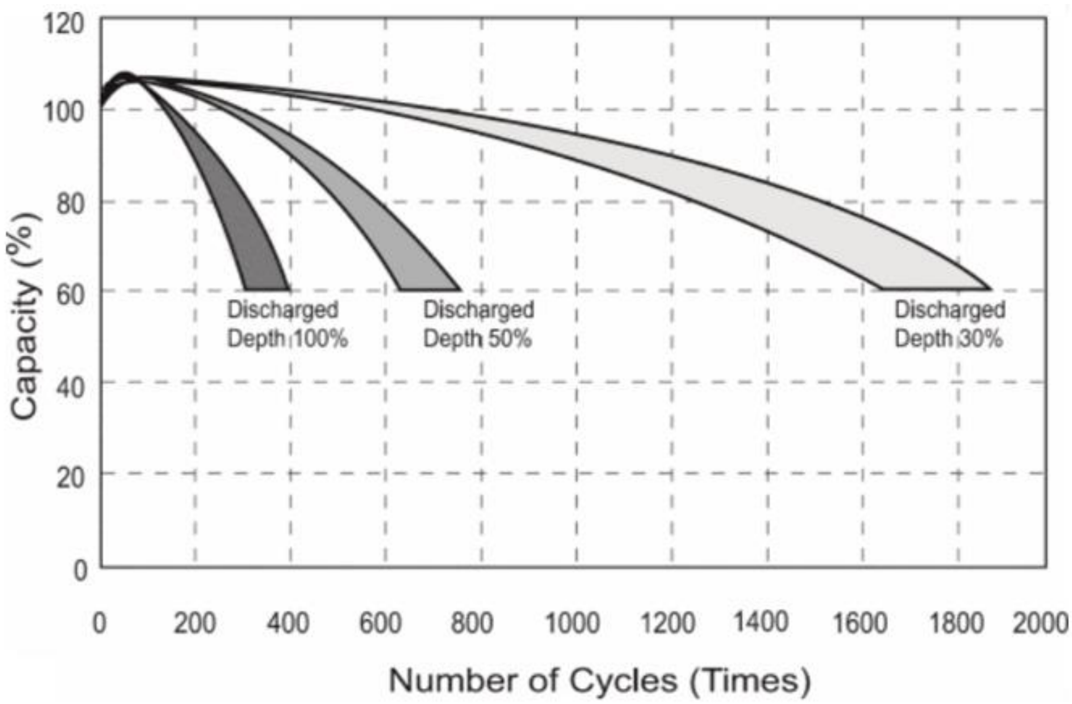

Figure 22 Relationship between DOD and RBP lifespan [113]

As seen from above Figure 22, increased DOD level cycling results in shorter rechargeable battery lifespan [113]. This is due to enhanced battery irreversible chemical decomposition at deeper discharge levels [110]. Therefore, controlling the DOD of a rechargeable battery within its application is critical to its lifespan, hence, commercial feasibility [114].

2.5.3.4 Overcharging

The charging parameters influence the actual lifespan of a rechargeable battery [115] [116]. A rechargeable battery is fully charged once it regains its nominal capacity. Continuing to recharge it beyond that point causes it to generate heat. Such heat generation raises its temperature resulting in enhanced degradation of its chemical composition, hence, reduced lifespan. Therefore, managing the triggering and termination of the charging process is an important capability of the RBP charger.

2.6 Summary

This chapter aimed to provide a strong understanding of different RV electrification aspects in order to identify potential challenges for such transition. The main identified challenges from the review carried in this chapter include:

- Current electrical supply capability within the leisure industry is inconsistent and low.
- Electrification of the RV appliances would result in their reduced performance and usability levels if no electrical infrastructural investments within the leisure industry are implemented.
- RV drivetrain electrification will further amplify the limitation within leisure industry current electrical supply capabilities as it’s an additional high demand load which would require further leisure industry electrical infrastructure investments.
- Electrification of additional sectors result in increased electrical grid demands on the electrical grid, hence, raising the required grid level investments for the required infrastructural upgrades especially if those sectors are not smart grid integrated.
- Maintaining the operation of RBPs within specified parameters is essential for its lifespan and reliability enhancement.

The identified challenges have resulted in discovering opportunities for smart solutions which would aid the RV electrification without the requirement of electrical infrastructural upgrades. Relevant literature of those opportunities will be reviewed in-depth within Chapter 3 and Chapter 4 where relevant advanced proposals were also presented. Chapter 3 addresses the challenges accompanying the inconsistent and low leisure industry electrical supply capability and the additional loading created by RBP charging. Chapter 4 focuses on the challenge of facilitating increased performance and usability of ERV appliances. Furthermore, it addresses the RBP operational requirements to maintain optimised lifespan and reliability. Finally, Chapter 5 then builds on the proposals of both those chapters, creating a holistic smart grid integrated proposal which addresses all the identified challenges.

Chapter 3 ERV CAMPGROUND CHARGING

3.1 Introduction

Batteries are of limited capacity and therefore electric vehicles (EVs) require periodic recharging [49]. Charging infrastructure and charging time are two of the main limiting factors for the adoption of fully electric and hybrid plug-in electric vehicles [11].

Electrification of recreational vehicles (RVs) on a drivetrain and/or equipment level will result in presence of large rechargeable battery packs (RBPs) onboard which will require charging throughout the duration of camping ground. Such large RBPs will act as substantial additional loads to the RV pitch electric supply. Meanwhile, as highlighted in Chapter 2, the RV pitch supply is of low electric supply capability. Introducing electric recreational vehicle (ERV) charging to such locations with the energy supply capability determined on pre-existing non-charging loads will result in overloading and tripping of the RV pitch supply. In such situations, as seen from Chapter 2, an upgrade to the supply capability of the overall campground and RV pitch supply is required. This could be a substantial investment requirement for campsites and therefore likely to be slow to occur. This, therefore, limits ERV adoption. A power management strategy implemented within the ERV can be an alternative solution which eliminates this investment requirement, hence, enhancing its adoption [53].

This chapter will present a novel power management strategy proposal for implementing ERV charging without any investment requirement, hence, accelerating electrification adoption in the leisure industry. Prior to the proposal of the power management strategy, this chapter will provide an overall analysis for required power management features in the ERV application and a review on existing power management strategies proposed for implementing EV charging alongside pre-existing non-charging loads.

3.2 Power management strategy requirements analysis

As seen in Chapter 2, the EV charging requirement at its lowest levels equals or exceeds the RV pitch supply capabilities. In order to avoid the requirement of substantial infrastructure investments within camping grounds, novel ERV charging power management strategy is required. This section analyses various aspects relating to ERV charging and the current campsites situation from which a set of power management strategy feature requirements are deduced.

The lowest EV charging level identified from literature is at a rate of 1.9kW. Simultaneously, the campsites vary in their electrical supply capability to each RV ranging between 0.69kW to 3.45kW. This means in the case of ERV adoption, end-users will not have a charging facility in several campsites, which have a supply capability below 1.9kW. Furthermore, at camping grounds with supply capabilities 1.9kW and beyond, overloading and tripping of the electrical supply can occur. For example, in a campsite of 3.45kW supply capability, if charging is being performed at 1.9kW and other electrical loads are switched on requiring 3kW, this would result in an overload of 1.45kW calculated using the following equation.

$$\mathrm{P}_{\mathrm{overload}} = P_{gs} - \mathrm{P}_{l} \qquad (7)$$

In equation (7), $\mathrm{P}_{\mathrm{overload}}$ is the overload power, P_{gs} is the consumed power from various loads, and P_{l} is the supply capability power. An overload power of 1.45kW equates to 6.3A at 230V. This Ampere value is used to determine the electrical supply tripping possibility through different 16A circuit breakers. The current-time characteristics retrieved from Trimble Protect software are shown in Figure 23 to Figure 26.

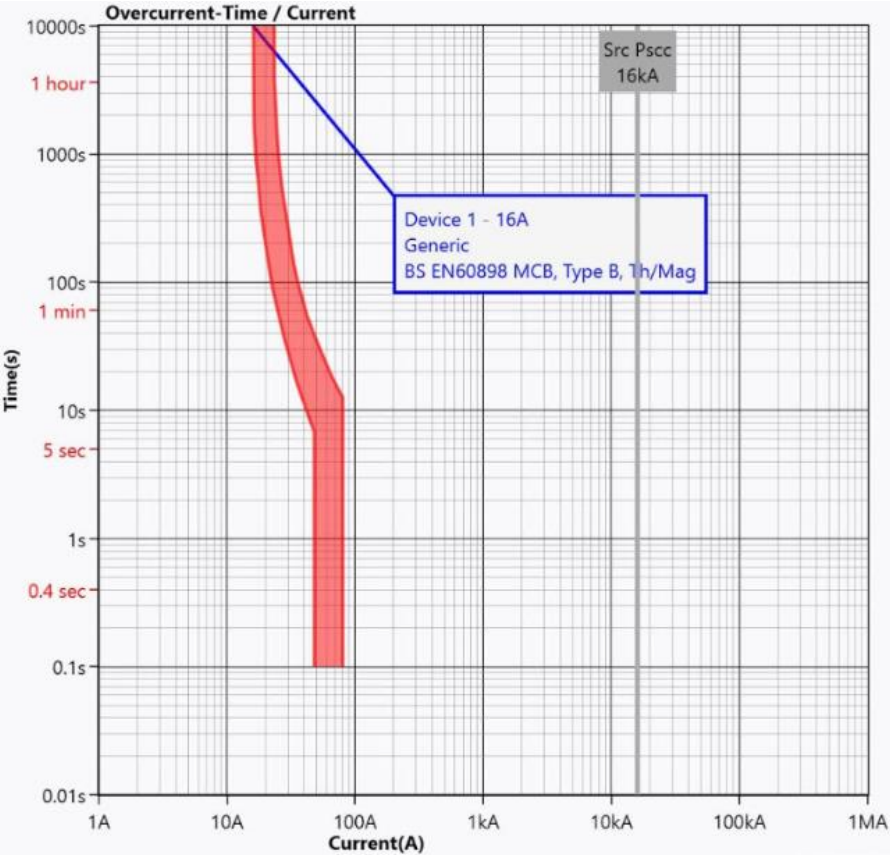

Figure 23 Generic BS EN60898 MCB, Type B 16A

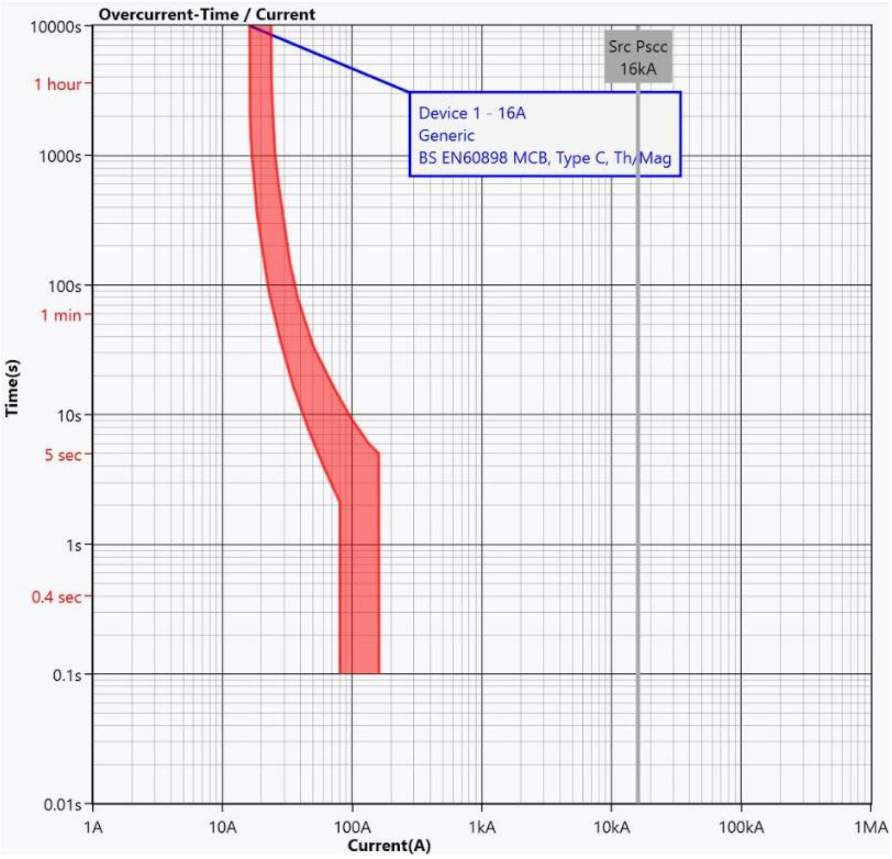

Figure 24 Generic BS EN60898 MCB, Type C 16A

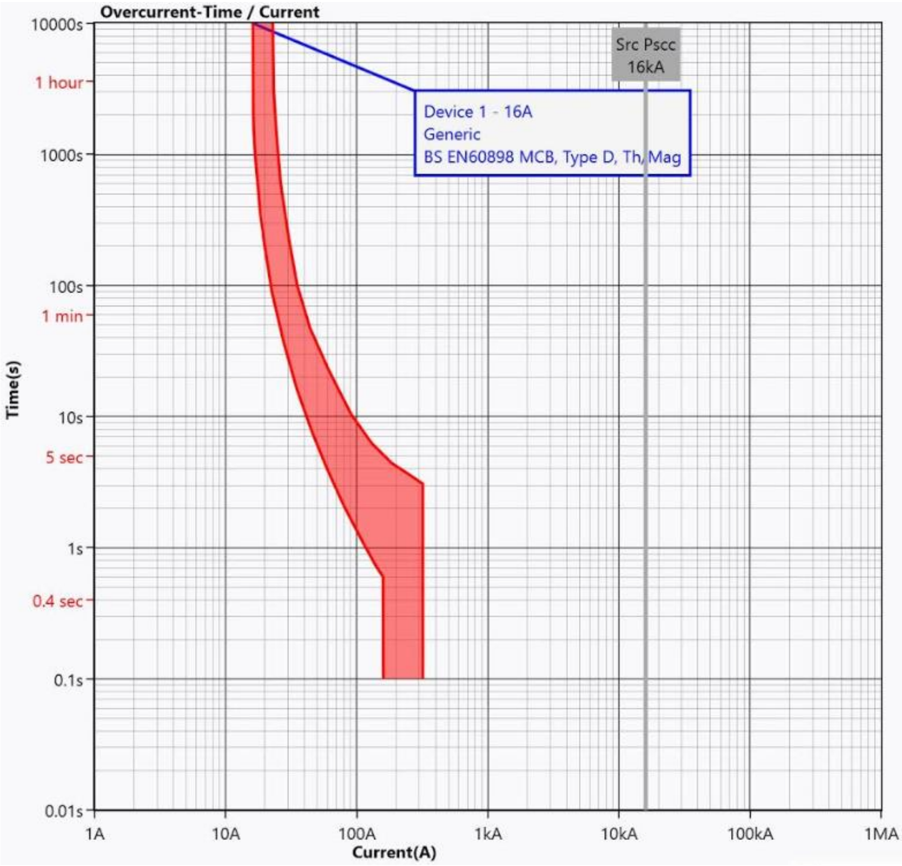

Figure 25 Generic BS EN60898 MCB, Type D 16A

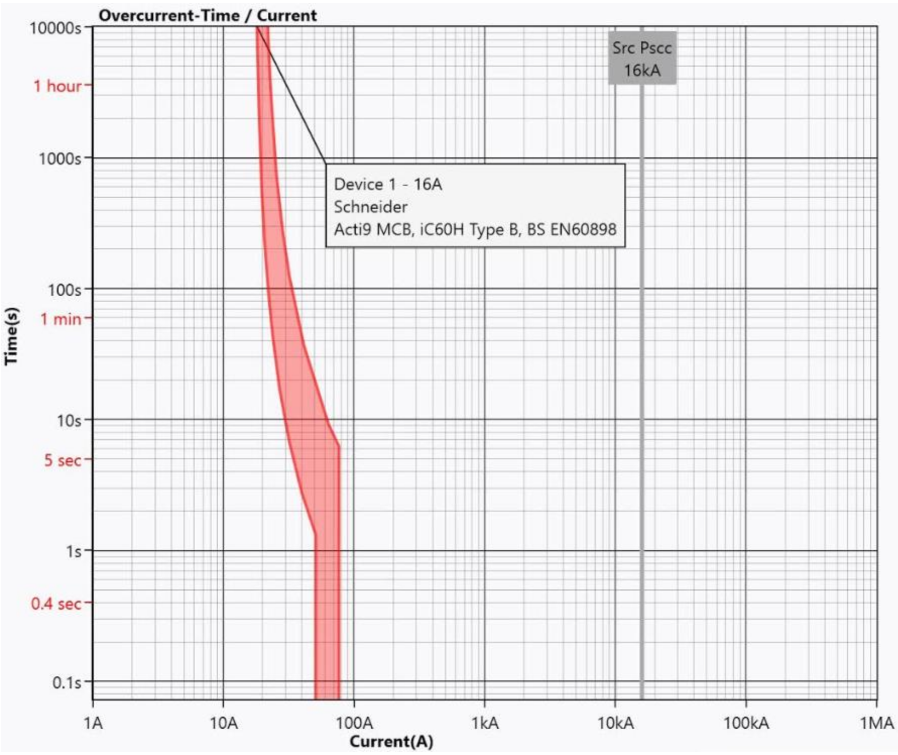

Figure 26 Schneider Anti9 MCB, iC60H Type B 16A, BS EN60898

Figure 23, Figure 24, and Figure 25 reflect the minimum characteristics of which a 16A circuit breaker of relevant type is required to have for compliance with the appropriate European Standard. Meanwhile, Figure 26 demonstrates an example for the actual characteristics of a commercially available Type B 16A circuit breaker. As highlighted in Figure 27, the commercial circuit breaker is of tighter current-time limits than that of the standard minimum requirements.

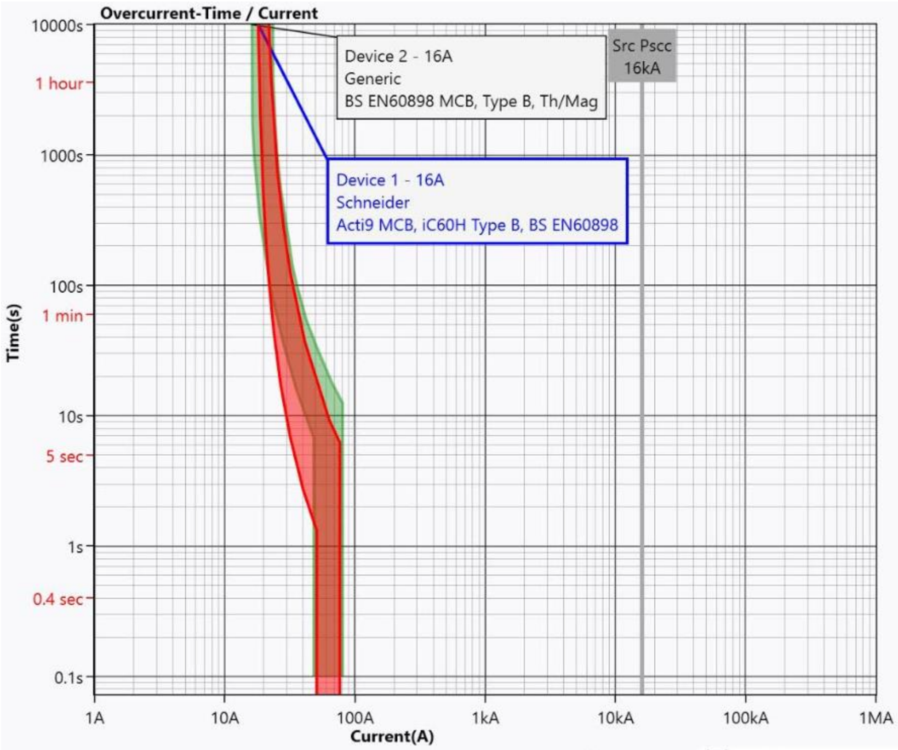

Figure 27 Comparison between generic BS EN60898 MCB, Type B 16A and Schneider Anti9 MCB, iC60H Type B 16A, BS EN60898

In the scenario of a 6.3A overload as per given example (21.3A total consumption on a 15A capable supply), this will result in a circuit breaker of characteristics such as that in Figure 26 to trip within around 100 seconds. Frequent ERV supply tripping can be inconvenient to the end-user. However, overloading impact shouldn't be limited to the user convenience of tripping the circuit breaker but also from a grid quality point of view. The additional load of EV charging is already a major concern for network operators if high EV market adoption is achieved [117] [118].

Non-charging loads operated in the ERV are usually not permanently in situ. In occasions where the end-user is on a camping ground with a supply capability of 3.45kW and no non-charging loads are operating. The ERV charging speed is not optimised in relation to the available power if only preforming charging at 1.9kW.

It can be deduced from above analysis that with ERV adoption, the following disadvantages would face the end-user and the electrical grid:

- Overloading (electrical grid)
- Supply tripping (end-user)
- Limited number of campsites at which charging can be performed (end-user)
- Slow ERV charging regardless of campsite supply capabilities (end-user)

The listed disadvantages can be eliminated if a novel ERV charging power management strategy with the capability of infinitely varying its charging power in relation to that available is implemented. This capability should be tailored to incorporate flexibility in the supply limit parameter due to the nature of the leisure industry where supply capabilities vary from one campsite to another. Furthermore, for complete elimination of supply tripping and overloading possibilities, the power variation capability should be proactive in order to avoid any overloading transients due to lags between ERV charging power variation and non-charging loads starting.

However, electrical loads varying their power consumption including their connection and disconnection results in grid supply voltage fluctuation at other loads [119]. Voltage fluctuation is the difference between two successive phase-to-neutral voltage values determined through equation (8) [120].

$$\Delta U_{hp}(t) = U_{hp}(t_1) - U_{hp}(t_2) \quad (8)$$

Where $\Delta U_{hp}(t)$ is the voltage fluctuation, $U_{hp}(t_1)$ is the voltage at time of voltage fluctuation occurrence, and $U_{hp}(t_2)$ is the voltage at the fluctuation end point. This fluctuation occurs due to variation in voltage drop across the supply impedance resulting from the variation in the loads input current [120]. The load current variation is given by [120]:

$$\Delta I = \Delta I_p - j\Delta I_q = \mathrm{I}(t_1) - \mathrm{I}(t_2) \quad (9)$$

Where the active and reactive aspects of load current variation ΔI are I_p and I_q respectively. From equations (8) and (9), the voltage fluctuation across a reference impedance due to current fluctuation can be determined by [120]:

$$\Delta U_{hp}(t) = |\Delta I_p R + j\Delta I_q X| = \mathrm{I}(t_1) - \mathrm{I}(t_2) \quad (10)$$

The voltage fluctuation can be expressed in relation to the supply's nominal voltage as per below equation [120]:

$$\mathrm{d} = \Delta U_{hp}/\mathrm{U_n} \quad (11)$$

According to the European electromagnetic compatibility (EMC) standard [120], loads such as the EV charger have to adhere to a limit of 6% voltage fluctuation [120]. The reference impedance to be utilised for calculating the voltage fluctuation is 0.4 + j0.25 ohm [121]. In an operational scenario where current to be varied by 15A, assuming the charger is of power factor 1, this results in a voltage fluctuation of 6V i.e. 2.6% of the nominal which is compliant to the standard.

Such fluctuation percentage is only allowed every 60 seconds if it was a step change [120]. If the fluctuation is to occur in a ramp manner, the frequency of such change is increased with certain limitations and conditions depending on the duration of which the ramp change occurs [120]. The varying frequency in relation to the change nature is determined through Figure 28 and Figure 29 [120].

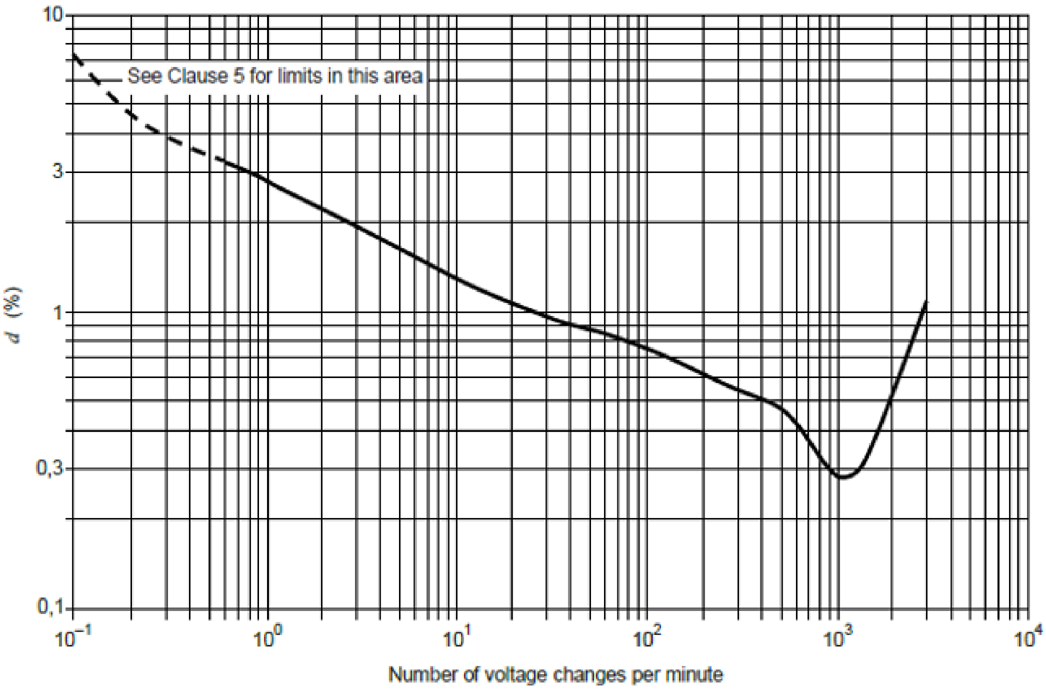

Figure 28 Number of allowed charging rate step variations at different resultant supply voltage fluctuations [112]

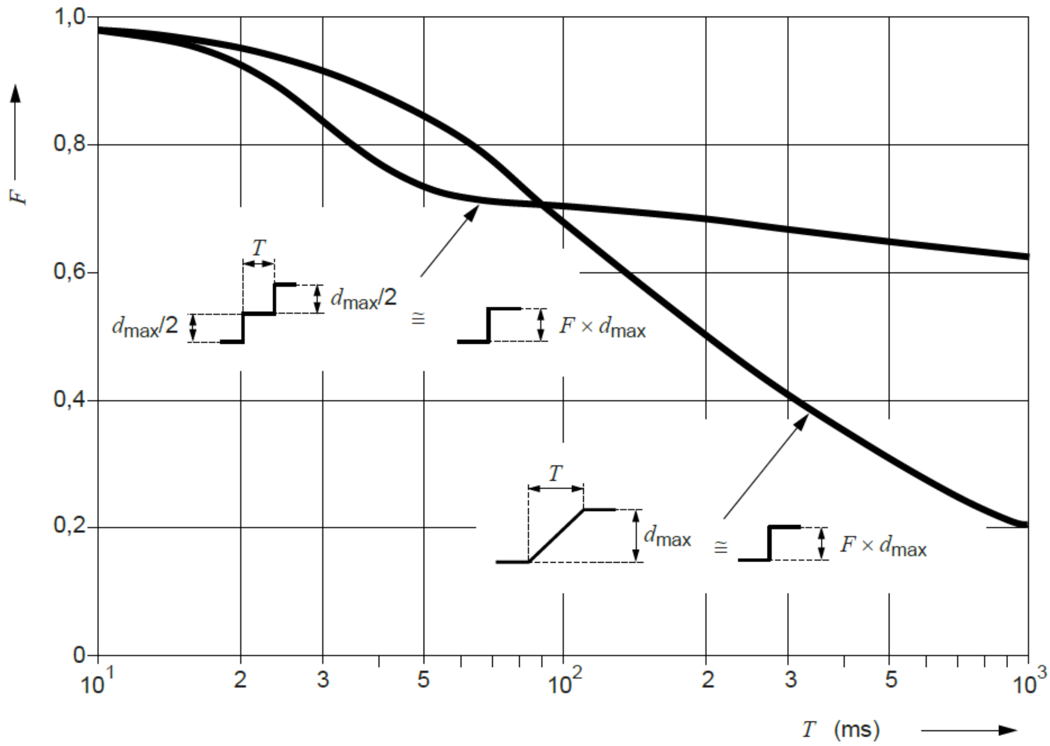

Figure 29 Frequency factor of step changes in the case of load variation of ramp form [112]

The minimum charge rate step variation level to be considered as substantial; hence, requiring the threshold time delay to be implemented in between such two consecutive variations is that resulting in a fluctuation exceeding 0.27% according to Figure 29 which equates to 1.55A at 230V.

Taking into consideration the commercial feasibility of the novel ERV charging power management strategy, it should control the frequency of power variations required due to changes within the status of different non-charging loading throughout the usage of an ERV.

3.3 Power managed EV charging

There are various existing power management strategies proposed today for EV charging implementations in pre-defined supply capability locations alongside non-charging loads. Those are categorised into different types and highlighted separately below where they are discussed and analysed. The assessment is focused on their suitability for potential use in ERV charging implementations within campgrounds without the need of any significant infrastructure investments as per the requirements identified in Section 3.2.

3.3.1 Price forecast strategy

Varying the grid supply prices across the day depending on its loading is proposed as the basis for a power managed EV charging strategy in previous work including [122] [123] [124] [125] [126] [127]. This can be used to schedule the EV charging in low price forecasted time slots in relation to the expected duration for the vehicle to be parked [126] [125], or for a fixed duration in a fixed contracted time of the day [127]. In return, this spreads the loading on the grid across the day alongside other non-charging loads [124]. This can be further advanced by limiting the EV charging level depending on the forecasted parking duration of the vehicle in relation to the required charging for 100% state of charge (SOC) to be achieved [122] [123].

This strategy is beneficial for the grid in terms of controlling its loading. Furthermore, it reduces the cost of EV charging for the end-user. However, this form of power managed EV charging strategy doesn’t address the key concern in ERV charging of overloading the individual low capability supply when EV charging is implemented alongside other non-charging loads. Furthermore, it doesn’t optimise the maximum possible loading level for the fastest possible charging to be achieved as it is only focused on reducing cost for charging over a long period of time when the vehicle is not in use. The charging rate variation is also not continuously and infinitely changing but rather utilises predefined levels which are determined based on forecasted supply costs and charging duration in relation to vehicle parking time. Finally, the charging power variation is not constrained with required EMC compliance frequency parameter.

3.3.2 **Price and local renewable energy sources forecast strategy**

Utilisation of renewable energy sources present within a building/home such as a photovoltaic system (PV) for EV charging management is proposed in [128] [129] [130] [131]. It aims to achieve cost-effective EV charging for the end-user through proactively scheduling its operation in certain times at specific charging levels [128]. It achieves this by utilising user preference constraints (e.g. minimum RBP SOC by a defined time of the day) and forecasted information regarding the weather, PV output, grid supply prices, and other system load [129]. This power management strategy is demonstrated below in Figure 30.

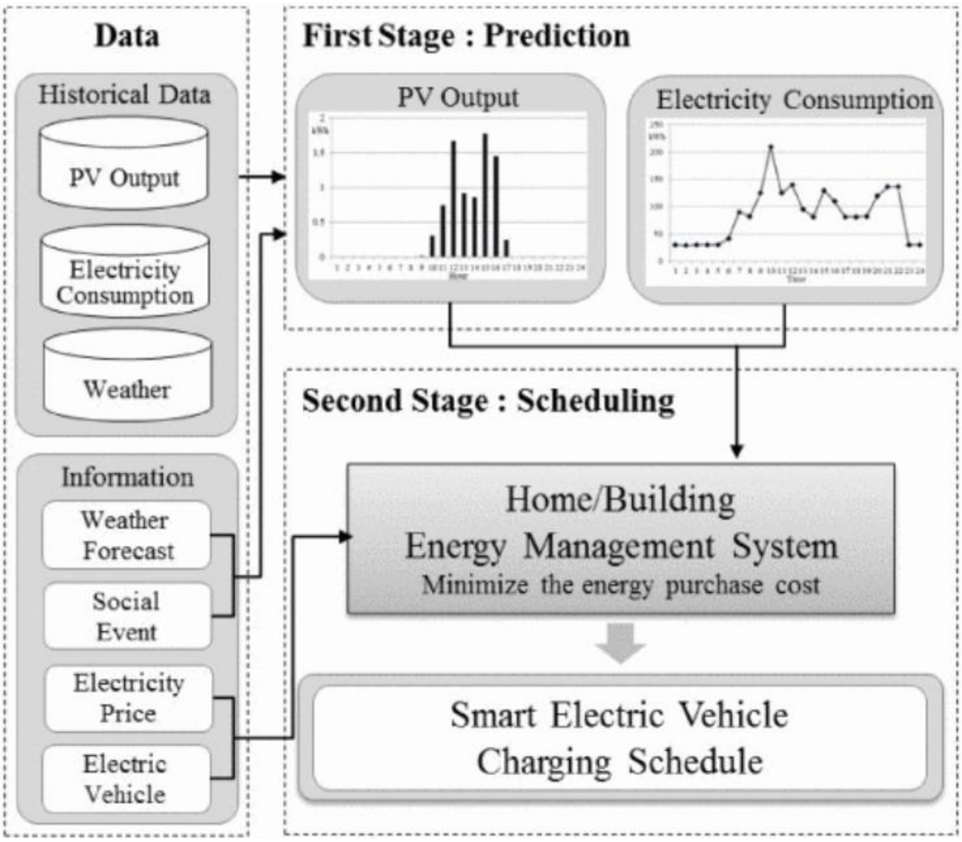

Figure 30 A price and energy sources based EV power managed charging strategy [129]

Such a power management strategy is advantageous for the overall loading of the grid as it considers off-peak times and availability of local PV output to schedule the EV charging operation. It is also beneficial to the end-user in relation to the EV charging costs being optimised by using PV output and cheaper grid supply durations. Except for the proposal in [130], most proposed strategies don't consider the overall loading on a building/home level in relation to its supply capability which is required for the ERV charging implementation. The proposal in [130] includes in its strategy the maximum contracted supply capability in determining the charging rate of the EV, but only is capable of varying it in four steps including a minimum and maximum level which doesn't optimise the maximum possible loading level for fastest possible charging to be achieved. Furthermore, [130] varies the charging rate through a forecast derived from predicted operation of heating, ventilation, and air conditioning (HVAC) loads and reactively reduces the charging rate in an overload event which can result in intermittent transient overloading situations. Finally, the constraint of minimum duration gap between consecutive charging power variations is not considered within this proposal.

3.3.3 **Grid supply monitoring strategy**

Several EV charging power management strategies are based on monitoring one or more grid supply conditions including voltage, frequency, and loading in relation to generation capability including [132] [133] [134] [135]. The various strategies are aimed at mitigating home/building EV charging overloading impact on the grid supply [133] [134] [135]. This is achieved through varying the charging level [133] or scheduling the charging session in a lower grid supply demand time [134]. Some strategies further aim to avoid overloading the distribution transformer in relation to its rating capability [132] [133] [134]. An example of a power management strategy which varies charging level based on generation overloading and distribution transformer stress avoidance is demonstrated below in Figure 31.

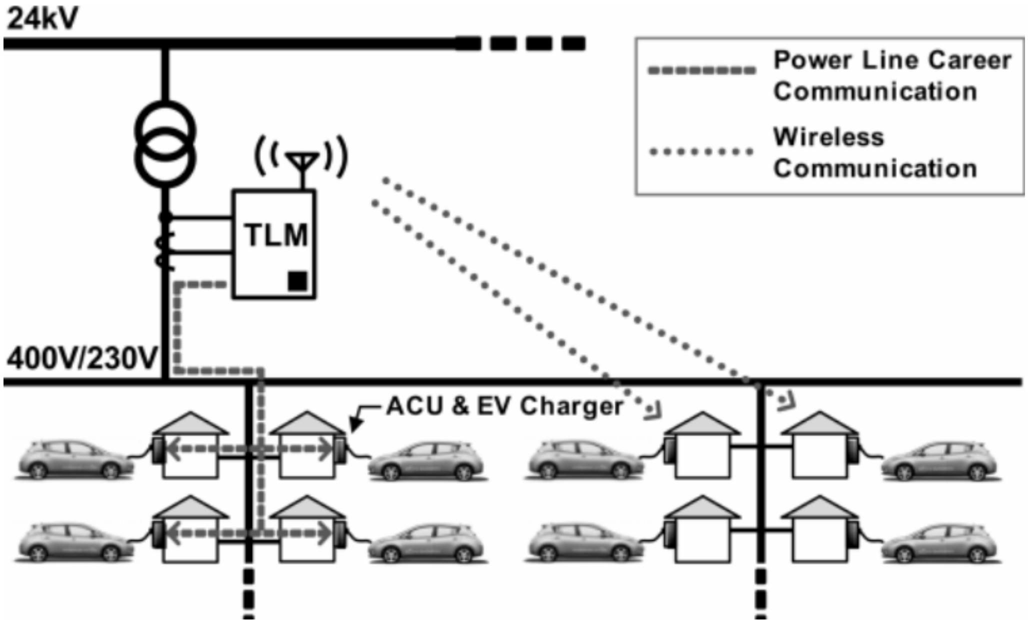

Figure 31 A grid overloading and frequency based EV power managed charging strategy [133]

The power managed EV charging shown in Figure 31 is achieved through a monitoring unit (TLM) sending information (including distribution transformer rating, power loading on the distribution transformer, and the AC frequency) to the EV charger power managing unit (ACU) every five minutes [133]. The ACU then utilises the information to decrease its charging rate from maximum to one of the other four lower charging rates [133]. The charging rate is chosen based on predefined conditions identified from the information sent by the TLM [133].

This power managed EV charging strategy is of benefit to the grid but doesn't address the concern of ERV charging overloading the individual low capability supply when EV charging is implemented alongside other non-charging loads. The strategy is of a reactive nature, where the charging rate is not continuously and proactively adapted. This can potentially result in intermittent transient overloading of the contracted supply. Where possible, most of the proposed strategies vary the charging rates in predefined levels, rather than in infinite steps, which results in a non-optimised charging rate. Furthermore, the proposed strategies don't consider EMC compliance of power variation frequency. Finally, in those strategies which vary charging level to mitigate grid impact, they are of decentralised nature where each EV charger receives relevant information from the grid and decides on its own charging rate. With high EV penetration and no control over non-charging loads, overloading on the grid can still potentially occur, and further be a non-fair distribution of EV charging rates at different homes/buildings locations.

3.3.4 **Grid non-EV charging loads demand forecast strategy**

The strategy proposed in [136] where it is dependent on allocating various EV residential charging operations in different time slots within the day depending on the forecasted non-EV charging loads of the overall area. It aims to flatten out the overall grid demand by increasing the number of vehicles being charged in low demand periods. The strategy utilises the nature of EV charging being of high power at the start and low power towards the end to aid its scheduling sequence.

A strategy of such capabilities is not suitable for implementation in the ERV charging application as it doesn't manage the charging overloading on various campsite supply capabilities with the presence of non-charging loads. It is purely based on forecasted information and doesn't include any means of monitoring, which can potentially result in intermittent overloading. Furthermore, the strategy doesn't include the capability of varying charge levels to optimise the maximum possible EV charge rate. Finally, such a strategy can be of inconvenience for the end-user in relation to when their vehicle can be charged.

3.3.5 **Dynamic power control strategy**

A dynamic power control strategy was proposed for implementing EV charging in homes without needing any supply capability upgrade [137]. This proposal depends on the EV charger monitoring the overall home supply loading which it is sharing at the electrical switchboard with non-charging loads. The EV charger continuously adapts its charging level based on available supply, which varies with time depending on the operation of the non-charging loads in relation to the fixed home supply capability. The power management strategy is shown below in Figure 32.

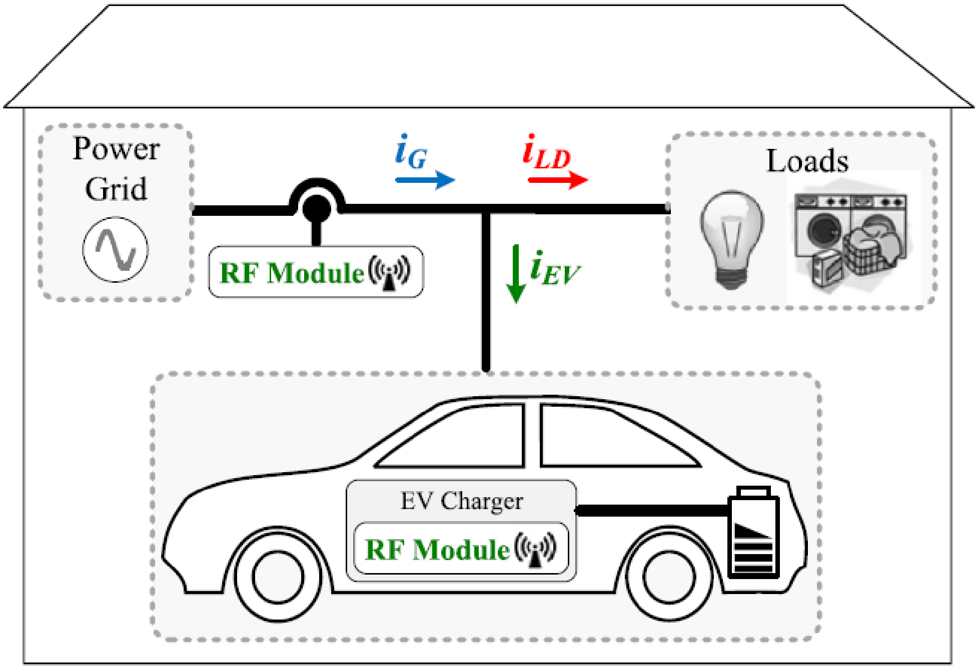

Figure 32 A power management strategy for EV charging implementation on pre-existing supply shared with non-charging loads based on remaining supply capability utilisation [137]

This proposed strategy addresses directly the concern of implementing ERV charging in a low supply capability location where non-charging loads exist. It varies the charging rate based on available power from the supply capability to ensure its not exceeded. It achieves this with an optimised charge rate where the full capacity of the home supply capability is utilised. However, this strategy doesn't cater for a variable supply capability which is required in the leisure industry due to the variation in the supply capability from one campground to another. The strategy also lacks the capability of controlling its charging power variation frequencies for EMC compliance.

Furthermore, like other highlighted strategies previously, it is of reactive nature, and varies the charging rate in reaction to the monitored home loading. Thus, intermittent overloading of the contracted supply can occur. This was highlighted as part of the proposal analysis, where in one charger power variation scenario, a 7A transient overload occurred for around two seconds. This is due to lag between the occurrence of additional home loading and the charger's reaction to accommodate for it. In the proposal this intermittent transient overloading was considered as acceptable as it is for a short duration which the circuit breaker can handle without tripping. The analysis from which this statement was derived is not sufficient as it lacks consideration for the commercial requirement of EMC compliance.

The charging current is varied in a ramp manner across around 30ms for a 7A change within the proposal. This can be utilised to estimate a ramp duration of 60ms in the case of 15A change within such a proposal. According to the equations listed in Section 3.2, such change would be allowed it to happen every 42 seconds if it is to be compliant with the EMC standard. Therefore, if an operational scenario where two consecutive 15A variations are required with a duration gap of 10 seconds, this would result in an overload of 15A (total loading of 30A) for 32 seconds within such a proposal. According to the circuit breaker characteristics of Figure 26, this will result in the supply to trip prior to allowing the second charging power variation. Finally, if this proposal is utilised, its transient overloading disadvantage can potentially lead to intermittent grid overloading with enhanced ERV adoption.

3.4 Proposed novel ERV charging power management strategy

In order to accelerate the adoption of ERVs in the leisure industry, a novel power management strategy is proposed. Its ultimate goal is to facilitate the operation of the additional substantial load of ERV charging. Thus, eliminating the requirement for camping ground infrastructure investment. The power management strategy achieves this by incorporating three features:

- Avoidance of campground ERV pitch varying supply overloading.
- Achieving optimum charging rate in relation to a varying supply capability.
- Charging power control is implemented in a compliant manner with the commercial EMC standard requirements of power variation frequency.

The above-mentioned features are resultant from various functional capabilities integrated within the proposed novel ERV charging power management strategy. In the camping ground ERV pitch supply overloading avoidance feature, the following capabilities are present:

- The power management strategy is implemented within the ERV via a central microcomputer which proactively controls all charging and non-charging loads initiation

- Maximum overall ERV allowable loading parameter is varied based on the flexibly specified pitch supply capability
- ERV charging rate is continuously altered based on the monitored overall pitch supply loading (due to non-charging loads operation)

Optimum charging rate feature is resultant from the capabilities below:

- Maximum charging rate allocation is determined based on ERV pitch supply maximum supply capability
- Infinite steps of variation in the maximum charging power allocation allowing the remaining ERV pitch supply capability (not required by non-charging loads) at any point to be completely utilised in ERV charging

The feature charging control EMC standard compliance is achieved with the following capability:

- A delay in changing the ERV charging rate is present where required in situations where two consecutive rate changes are to occur. Therefore, avoiding high frequency supply voltage fluctuations

Following this introduction on the features and their relevant capabilities of the proposed ERV charging power management strategy, Section 3.4.1 presents the architecture and algorithm of the proposed strategy providing detailed description on its operation. Further sections follow including experimental setup utilised to trial the proposed strategy, results collected from carried trials, analysis and discussion of the experimentation results, conclusion drawn regarding proposal, and identified further work required on the proposed ERV power management charging strategy.

3.4.1 **Architecture and algorithm**

In the proposed novel ERV charging power management strategy, a central ERV microcomputer continuously gathers relevant data which is processed to determine control actions within different situations. Figure 33 presents the architecture of the proposed ERV charging power management strategy.

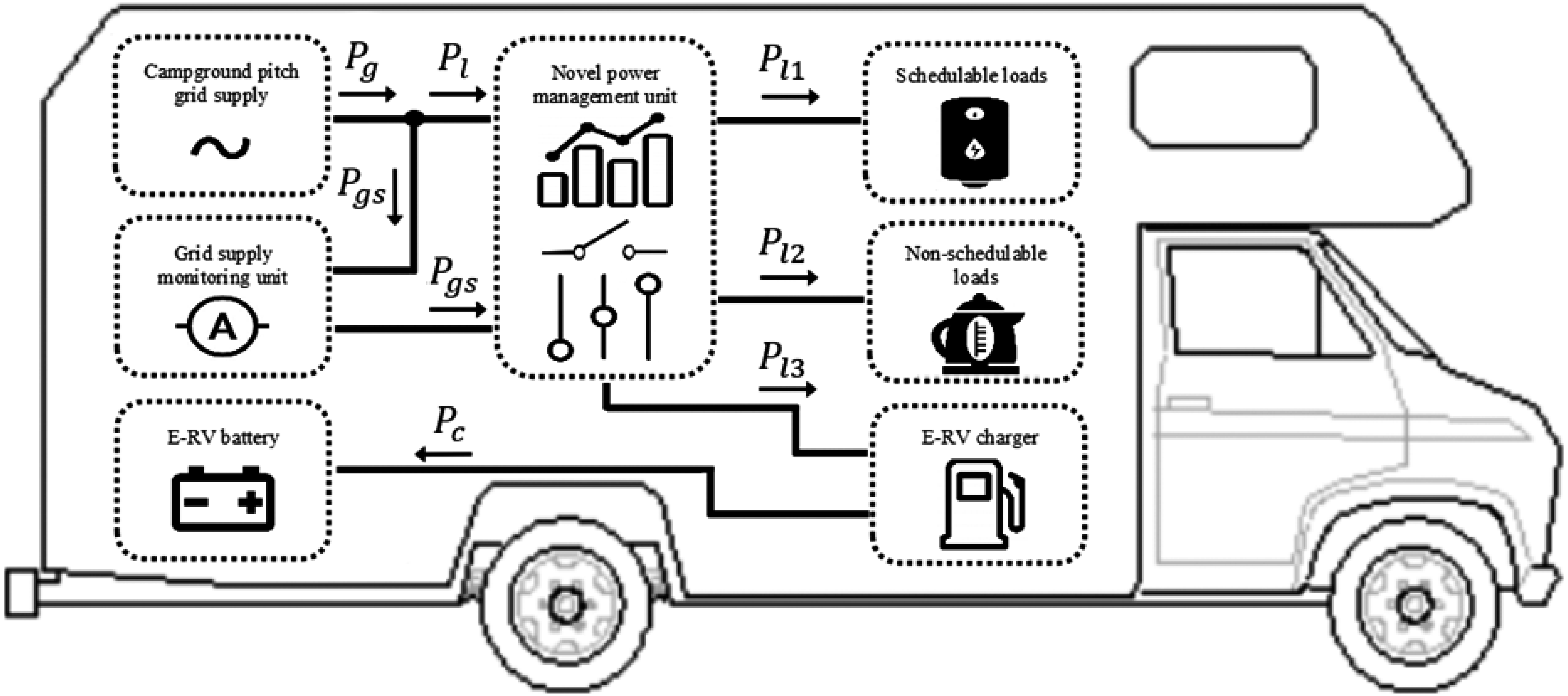

Figure 33 Proposed novel power management strategy architecture

In Figure 33, the central unit of proposed power management strategy monitors the following parameters:

- Maximum supply capability of the specific camping ground supply P_l
- Overall supply loading P_{gs}
- Operational power request P_{l1} generated from schedulable loads through direct communications embedded at the point of ERV manufacture
- Non-schedulable load power consumption requirement P_{l2}, entered by the end-user
- ERV charging power P_c

The proposed power management strategy proactively controls all the loads based on the processed information. This entails the starting and stopping of schedulable, non-schedulable, and ERV charging loads. Furthermore, the power management provides instruction to the ERV charger regarding the maximum allowable charging rate P_{l3} at any one point.

At the initiation of the novel power management unit, the campground pitch supply capacity specification P_l is identified and set in its database as per algorithm in Figure 34.

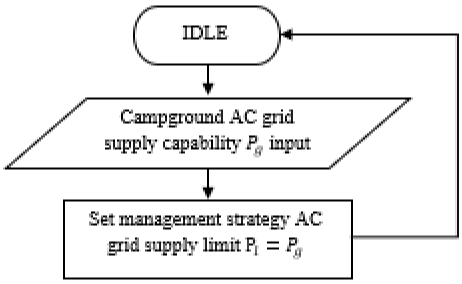

Figure 34 Algorithm for integrating the campground supply capability in the power management unit

The identification of the pitch supply capability shown in Figure 34 is achieved through below equation. This results in the capability of the novel power management unit to control various loads based on a variable supply capability condition. Thus, avoiding overloading at different campgrounds of varying pitch supply capabilities.

$$\mathrm{P}_l = P_g \tag{12}$$

The start-up of ERV charging is controlled through the power management strategy algorithm shown in Figure 35.

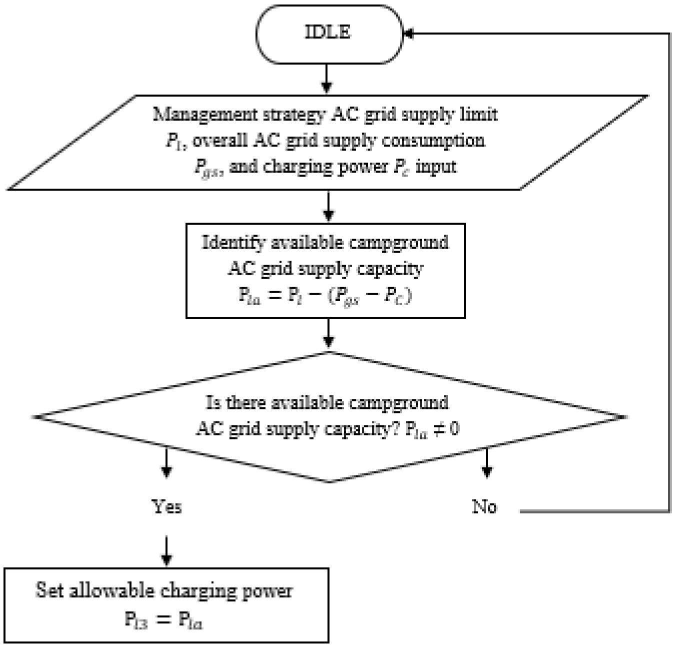

Figure 35 ERV charging start-up algorithm

Figure 35 shows that the control conditions of the ERV charging start-up are determined by the novel power management strategy initially checking if there is available campground supply capacity. This is achieved through:

$$\mathrm{P}_{la} > \mathrm{P}_l - (P_{gs} - P_C) \tag{13}$$

If there is available campground supply capacity, the ERV charging operation is allocated with a maximum charging rate determined via:

$$\mathrm{P}_{l3} = \mathrm{P}_{la} \tag{14}$$

In the case of non-charger loading absence, the allowable maximum charging power is allocated to equal to the maximum camping ground supply capability achieving optimum charging speed as per equation (15).

$$\mathrm{P}_{l3} = \mathrm{P}_l \tag{15}$$

Figure 36 demonstrates the algorithm implemented in the power management strategy responsible for starting a schedulable load.

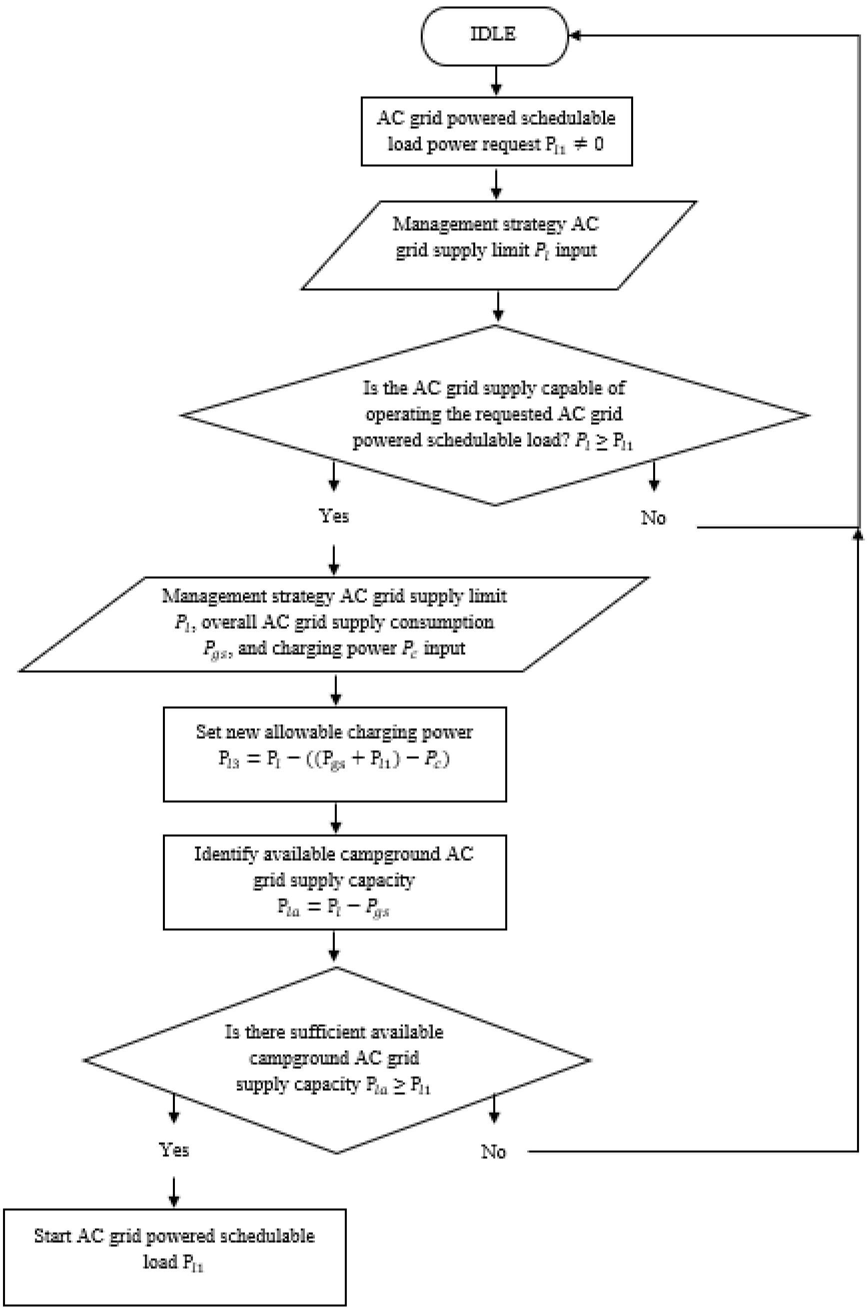

Figure 36 Starting a schedulable load algorithm

Throughout the period of camping, schedulable loads (such as space heaters and air conditioner) often vary in their operational status. Therefore, it is critical for the power management strategy to continuously monitor and control their operation along with the ERV charging power. Figure 36 shows that the power management strategy achieves this by receiving a request signal with the power requirement from a schedulable load (as they are implemented within the RV from point of manufacture and have communication means established with the ERV power management facility) when it is required to operate. The power management strategy utilises this to determine if the schedulable load can operate at the specific power level by initially checking if the campground pitch supply capability is sufficient. This is achieved by:

$$\mathrm{P}_{l} \geq \mathrm{P}_{l1} \tag{16}$$

Then a check is carried on the available supply capacity (P_{la}) in relation to other load operations through equation (17) is performed.

$$\mathrm{P}_{la} = \mathrm{P}_{l} - \mathrm{P}_{\mathrm{gs}} \geq \mathrm{P}_{l1} \tag{17}$$

In both cases of sufficient supply capacity presence or absence, the power management unit updates the allocated maximum power for the ERV charger using equation (18). This new power allocation results in infinite charging rate variation allowing optimum charging speed.

$$\mathrm{P}_{l3} = \mathrm{P}_{l} - ((\mathrm{P}_{\mathrm{gs}} + \mathrm{P}_{l1}) - P_{c}) \tag{18}$$

The management strategy awaits the ERV charger to reduce its charging power accordingly if there is insufficient available capacity. Finally, the supply availability check is carried again using equation (17) and if there is sufficient capacity, the schedulable load is allowed to start its operation.

The algorithm utilised in the novel power management strategy to start a non-schedulable load is shown in Figure 37.

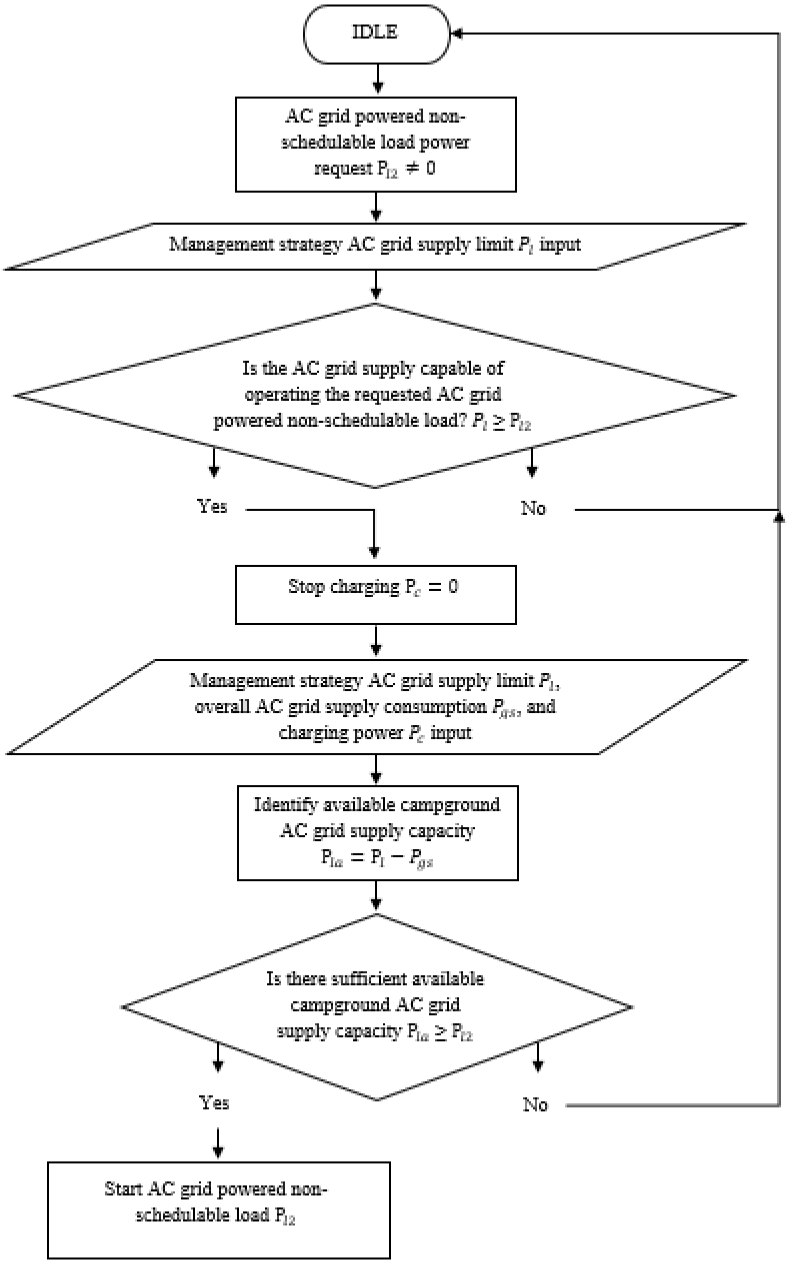

Figure 37 Algorithm for starting a non-schedulable load

As per Figure 37, a request is made by the end-user for the operation of a non-schedulable load entering its maximum power specification. This is because non-schedulable loads are often those brought on-board by the end-user (e.g. kettle, laptop charger, and toaster) and therefore they are not necessarily able to connect to the power management for direct communication. The decision to allow the non-schedulable load to start when requested is achieved by initially checking if the campsite supply is capable of providing the specific required power consumption level via equation (19).

$$P_l \geq P_{l2} \tag{19}$$

If the camping ground supply capability matches that required by the non-schedulable load, the ERV charging is requested to stop. This action is taken as a redundancy to the user's entry of power consumption level required. The non-schedulable load is then permitted to begin its operation. The ERV charging then goes through another start up procedure as per Figure 35. This would be based on the lowest available supply capacity calculation being either from only the most up-to date P_{gs} as per equation (13) (in the case of the actual non-schedulable load power consumption is equal to or more than that entered by the end-user) or that from the P_{gs0} prior to the operation of the non-schedulable load combined with the its entered consumption level by the end-user of P_{l2} as:

$$\mathrm{P}_{l3} = \mathrm{P}_{l} - \left(\mathrm{P}_{l2} + \mathrm{P}_{\mathrm{gs0}}\right) \quad (20)$$

The algorithm shown in Figure 38 is implemented in the novel ERV charging power management strategy to ensure compliance with EMC standard requirements with regards to the frequency of charging load level variation.

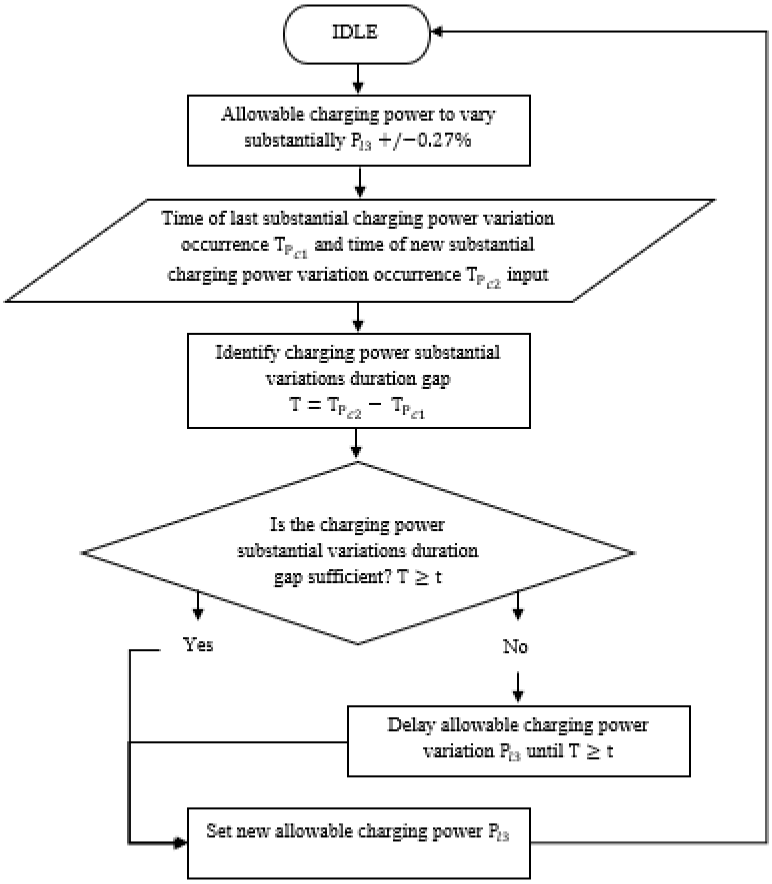

Figure 38 ERV charging rate variation frequency algorithm for EMC compliance

ERV charging rate can be required to substantially change in the following situations:

- Non-charging loads requesting operation, hence, ERV charging rate is required to be lowered
- Or instead, non-charging loads stopping their operation, hence, the ERV charging rate can possibly be increased

In both cases, as shown in Figure 38, a check is performed on the duration gap (T) between the new request $\mathrm{T}_{\mathrm{P}_{c2}}$ of substantial charging power variation and the last one that has occurred $\mathrm{T}_{\mathrm{P}_{c1}}$ utilising equation (21).

$$\mathrm{T} = \mathrm{T}_{\mathrm{P}_{c2}} - \mathrm{T}_{\mathrm{P}_{c1}} \quad (21)$$

After the duration gap is determined, in the case of ERV last substantial charge rate amendment being within a duration less than the threshold time, a delay equivalent to the relevant threshold time is implemented prior to the new substantial charging rate variation implementation. Meanwhile, if the last substantial charging rate variation was previously implemented with a duration gap more than the threshold time, the new substantial charging rate variation is immediately triggered. The new charging rate is set through equations (18) or (20) if the amendment is due to an initiation of a non-charging load. Equation (14) is utilised in the case of the charging rate change originated from a non-charging load stopping its operation.

3.4.2 **Experimentation setup**

The proposed novel power management strategy was assessed using a constructed scaled down laboratory hardware prototype. The construction of the prototype included an RBP, cc-cv charger, power management microcomputer, and load simulators as shown in the overview of Figure 39.

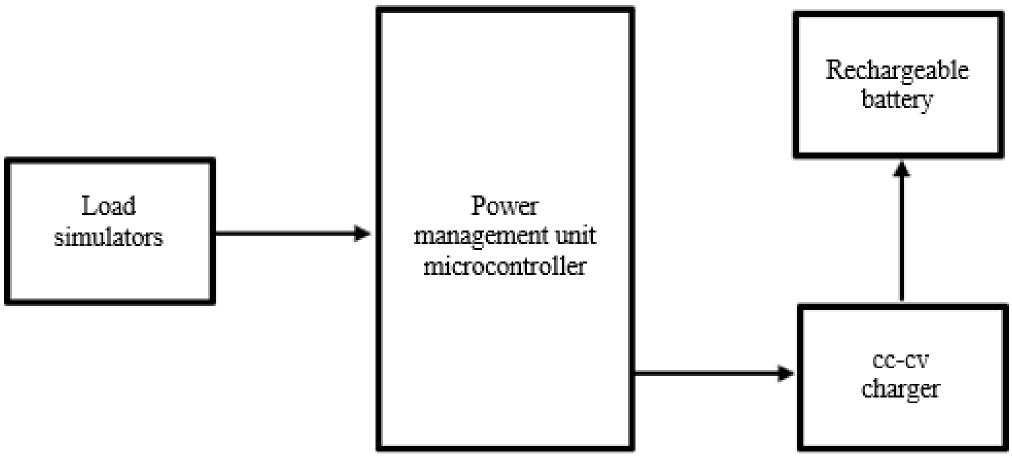

Figure 39 Hardware laboratory prototype overview

The constructed scaled down laboratory hardware prototype of the proposed novel power management strategy is presented in Figure 40.

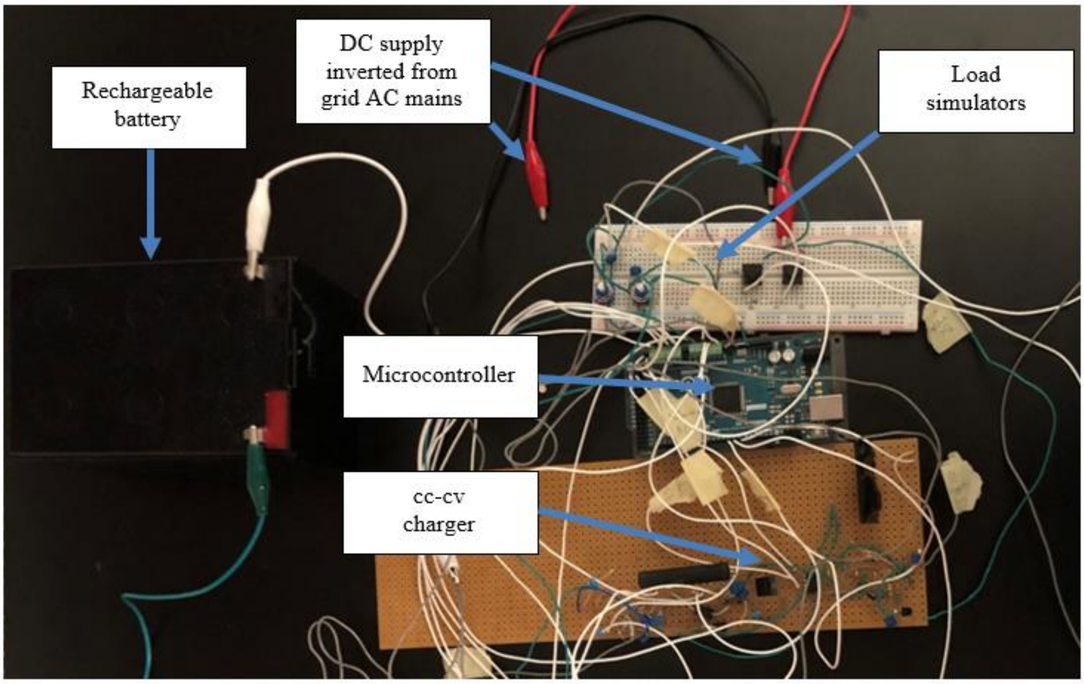

Figure 40 Proposed novel power management strategy prototype

Prior to the construction of the cc-cv charger, it was simulated using PSPICE software. It was tuned together with the RBP to charge at a maximum constant rate of 84.24W if there are no restrictions from the power management unit.

The assessment carried on the power management strategy using the prototype aimed to trial the algorithms implemented to achieve the various functional capabilities which result in the desired features for ERV charging to be implemented in various campgrounds of the leisure industry without infrastructure investment requirement. The different test conditions formulated for the assessment of those algorithms are detailed below separately.

3.4.2.1 Power management unit campground supply capability integration

Test conditions for the algorithm of this capability aim to analyse the capability of the power management unit to adapt its overall loading limit (P_l) in relation to the varying supply capability (P_g) across different campgrounds. Table 2 below highlights the different operational scenarios used for this assessment.

Table 2 Test conditions for the integration of different campground supply capabilities in the proposed power management strategy

Operational scenario P_g (W)
120
80
40

As seen in Table 2, three different operation scenarios are set to be tested where the defined maximum overall loading (P_l) by the proposed power management unit is extracted each time as the measured element of this assessment.

3.4.2.2 ERV charging start-up

In the proposal presented, at the start-up of the ERV charging process, the available supply capacity is assessed in relation to the overall loading from non-charging loads and the campground supply capability. The charging process is then only triggered at a specific rate relative to the available supply capacity ensuring avoidance of overloading of the supply. To analyse the algorithm of this functional capability, various operational scenarios are defined in Table 3.

Table 3 ERV charging start-up test conditions

Operational scenario P_g (W)	Operational scenario P_{gs} (W)
90	0
120	80
40	40

Table 3 highlights three operational scenarios under which testing is to take place. The charging power (P_c), RBP voltage, overall loading (P_{gs}), and power supply capability (P_g) are to be logged throughout all the tests to serve as measurement criteria for the analysis of this functionality.

3.4.2.3 Schedulable load initiation

To eliminate campground supply overloading, the power management strategy is set to proactively control the starting of a schedulable load where it cross-checks the supply's capability with the requested load power operation. Furthermore, it determines if there is sufficient available supply capacity and reduces / stops the ERV charging rate to re-allocate required power for the requested load operation. To assess the algorithm of this capability, the operational scenarios are defined in Table 4.

Table 4 Test conditions for schedulable load initiation

Operational scenario P_g (W)	Operational scenario P_{gs} (W)	Operational scenario P_c (W)	Operational scenario P_{l1} (W)
80	60	60	40
80	80	40	40
50	50	50	40

Test conditions are set via three different operational scenarios in Table 4 where charging power (P_c), RBP voltage, overall loading (P_{gs}), power supply capability (P_g), and the schedulable load request signal are set as measurement elements for this functionality.

3.4.2.4 Operating a non-schedulable load

Similar to the schedulable loads, prior to the start of non-schedulable loads, the capability of the supply is checked in relation to the requested power operation. The ERV charging is requested to stop if the supply capability is compatible with the power required by the non-schedulable load, allowing the non-schedulable load to start. ERV charging is then resumed with a new allocated maximum charging power. Set operational scenarios and their measurement elements are specified in Table 5 to assess this functionality within the proposal.

Table 5 Test conditions for non-schedulable load start-up

Operational scenario P_g (W)	Operational scenario P_{gs} (W)	Operational scenario P_{l3} (W)	Operational scenario P_{l2} (W)
80	50	80	40
50	50	50	30
80	80	40	40

The measurement elements for the tests listed in Table 5 are the RBP voltage, charging power (P_c), overall loading (P_{gs}), power supply capability (P_g), and the non-schedulable load request signal.

3.4.2.5 EMC compliance for ERV charging power variation frequency

For compliance with the EMC standard, the frequency of ERV charging rate variation is required to be controlled to avoid high frequency substantial supply voltage fluctuations. To address this, the proposed novel power management strategy determines the duration gap between the prior substantial ERV charging rate variation and the new one required to be implemented. If the duration gap is less than that of a pre-defined threshold specific to the power supply capability, a delay equivalent to the required threshold is set before the new charging rate variation is triggered.

To pre-define the duration gap required between two consecutive substantial charging rate variations in the power management unit for different supply capability specifications, the results shown in Table 6 were obtained through calculations based on equations (8) to (11).

Table 6 Supply voltage potential fluctuations due to charging power variations at different campground supply capabilities

Campground supply capability scenario (A)	Potential supply voltage fluctuations (%)
15	2.6
10	1.7
6	1

The calculated results in Table 6 highlight the potential supply voltage fluctuation percentage in different chosen campground supply capability scenarios (further scenarios can be implemented in the power management strategy if required). Those percentages are determined based on charging rate variation occurrence from zero to the maximum of the campground supply capability in a step change manner.

Table 6 was then utilised to determine threshold time (T) values via Figure 29 of Section 3.2, which are reflected in Table 7 and integrated within the constructed prototype of the proposed novel power management unit.

Table 7 Threshold duration gap defined in prototype between two substantial charging rate variations

Campground supply capability scenario (A)	Threshold gap duration T (s)
15	60
10	12
6	2.4

The utilised minimum threshold value for a charger rate variation to be considered as substantial within the scaled down constructed prototype is 25W.

Table 8 specifies the operational scenarios required for assessing this functionality within the proposal.

Table 8 Frequency of substantial ERV charging rate variation EMC compliance test conditions

Operational scenario T (s)	Load control type	Operational scenario P_g (W)	Operational scenario P_{gs} (W)	Operational scenario P_{l3} (W)	Operational scenario P_{l1}/P_{l2} (W)
60	SL / NL	80	80	20	-60
12	SL	60	50	60	+40
2.4	NL	40	40	40	+40

The operational scenarios defined in Table 8 include charging power reduction requirement due to schedulable load (SL) and non-schedulable (NL) operation requests and additional charging power possibility due to a SL/NL power consumption reduction. They utilise the ERV charging power (P_c) and power control signal as the main measuring elements of their assessment. However, the RBP voltage, overall loading (P_{gs}), and power supply capability (P_g) are also to be monitored and referred to where relevant.

3.4.3 **Results**

Various results were extracted from the scaled down laboratory hardware prototype constructed for the assessment of the proposed novel ERV charging power management strategy in practical implementation. Those reflect the capability of the utilised algorithms of achieving the desired features in order for the power management strategy to achieve its ultimate goal of enhancing ERV adoption within the leisure industry through eliminating requirement of infrastructure investments.

A simulation was run on the constructed cc-cv charger aspect of the hardware prototype to set a benchmark on its normal conditions operation i.e. what charging currents are supplied to the RBP at its different voltages. This is to be used in the assessment of the practical implementation of the power management strategy and the constructed prototype.

In this section of the chapter, the gathered practical and simulation results are to be highlighted and described separately below. The order in which the results are presented is synchronised with that of experimental setup section of this chapter where the planned tests are demonstrated.

3.4.3.1 CC-CV charger simulation

A simulation on the constructed cc-cv charger is required to understand its operational characteristics defined through its design without any power management constraints. This can be used to ensure that the practical construction of the hardware prototype is accurate in the first place and further identify the impact of the power management algorithm under different mimicked conditions. The extracted simulation result is shown in Figure 41.

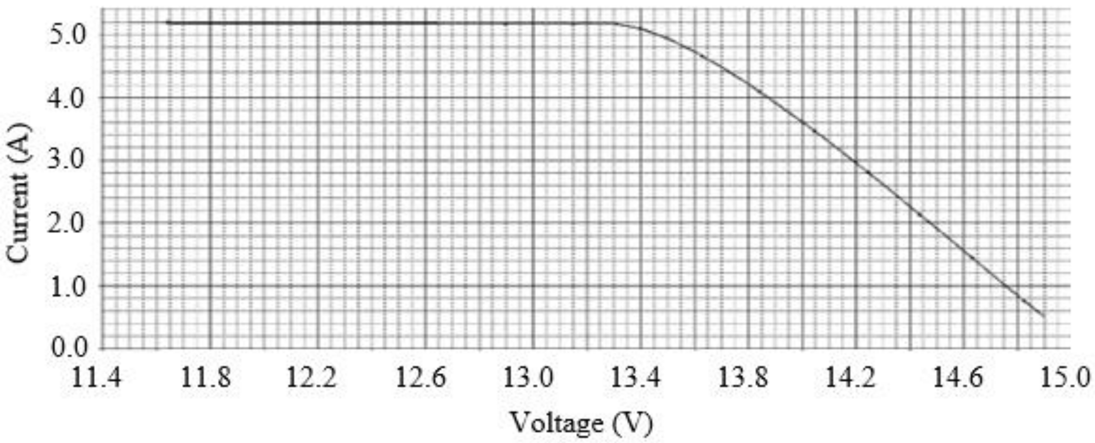

Figure 41 CC-CV charger simulation under no power management constraints

The maximum charging current of the cc-cv charger within its cc stage is set out to be 5.2A (84.25W consumption at the 16.2V supplied voltage) as per Figure 41. The charging current decreases as the charger enters its cv stage at RBP voltage of 13.3V. The charging process is terminated at RBP voltage of 14.9V where the charging current reaches its 0.5A minimum.

3.4.3.2 Power management variable campground supply capability

One of the main parameters utilised within the various algorithms of the proposed novel power management strategy is the campground's supply capability (P_l). This parameter within the proposal is set as a programmable variable parameter, hence, the novel power management strategy can be tailored for the various campground supply limit capabilities. Results were gathered for the implementation of this functionality are reflected in Figure 42.

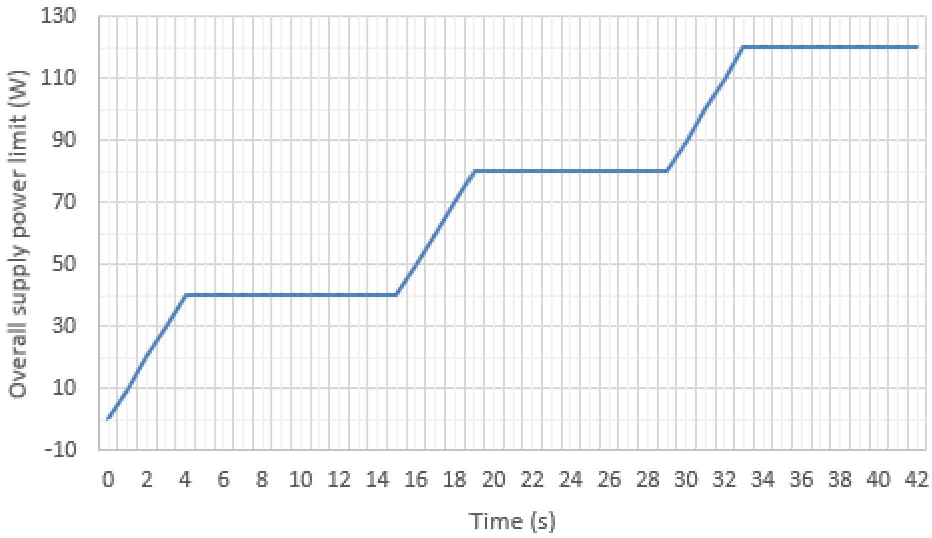

Figure 42 Integration of variable campground supply capability parameter within the proposed novel power management strategy

The results gathered in Figure 42 are the extracted power limits (P_l) from the program utilised within the constructed prototype. The results reflect the mimicked conditions of 40W, 80W, and 120W supply capabilities within the power management strategy operation.

3.4.3.3 ERV charging start up

At the start-up of the ERV charger, the available power is checked in relation to the overall supply capability and the operation of other non-charging loads. Three operational scenarios were defined in the experimental setup section of this chapter to aid the assessment of this functionality within the proposal. The results of those practical tests are shown in Figure 43, Figure 44, and Figure 45.

The result shown in Figure 43 is for an operational scenario of ERV charging start up at a campground of 90W supply capability. Simultaneously, there is no loading from non-charging loads at the time of the start-up process. The demonstrated result includes the power supply limit, the charging power, and the RBP's voltage.

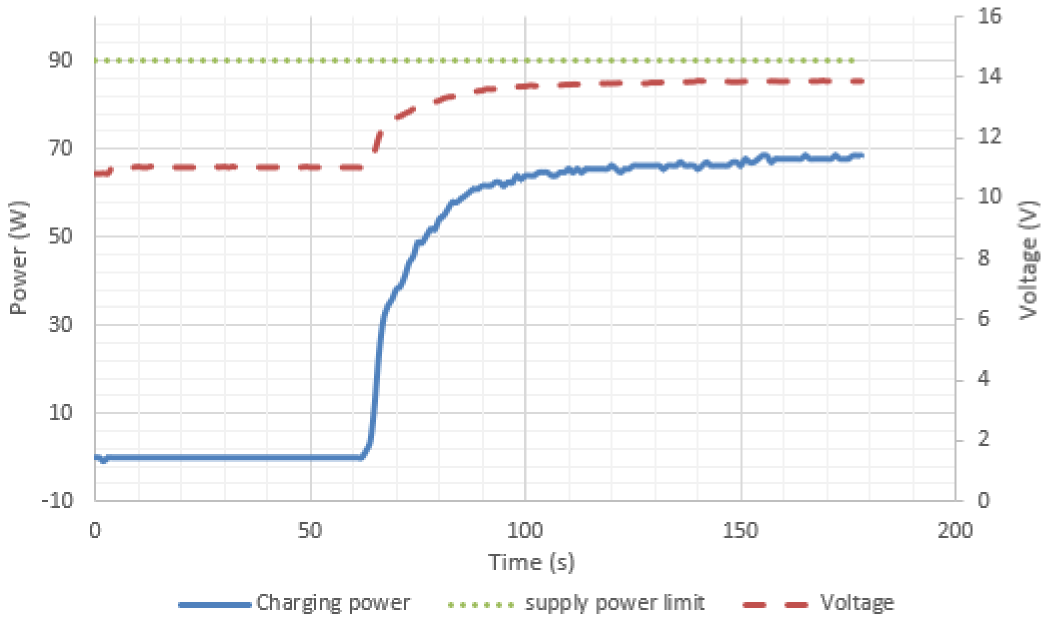

Figure 43 ERV charging start-up at an operational scenario 1

Figure 44 shows the result for operational scenario 2 where at the point of ERV charging start-up, the non-charging loads consumption is at 80W, meanwhile, the power supply capability is of 120W. The result shows the charging conditions in such a scenario with its RBP voltage and charging power being plotted in relation to the power supply capability.

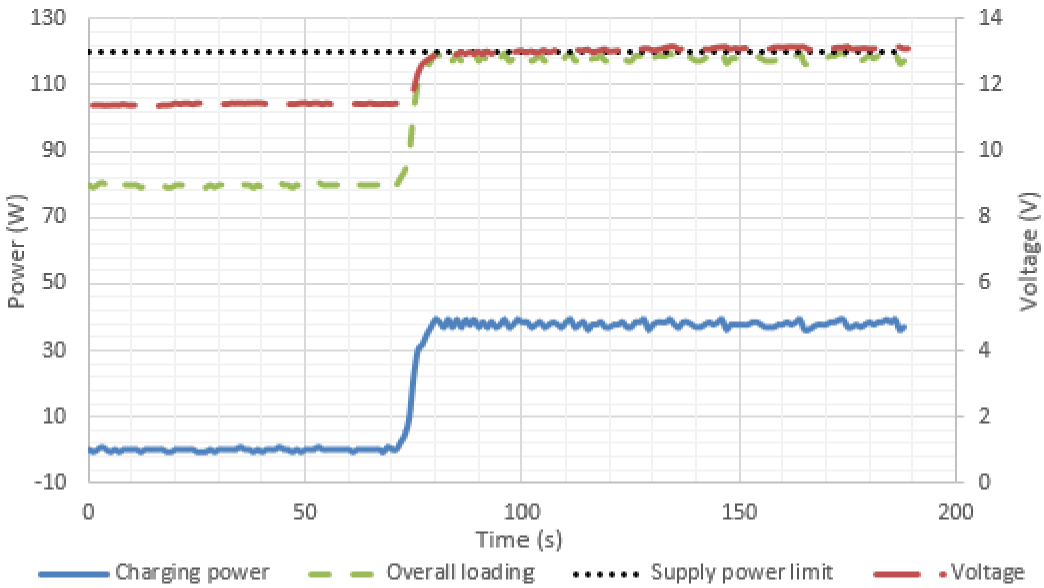

Figure 44 Charging start-up at an operational scenario 2

Result for operational scenario 3 is shown in Figure 45. In this scenario, the power supply limit is set at 40W with a 40W non-charging loading already present at the time of ERV charger start-up. The resultant RBP voltage and charging power at this scenario are presented.

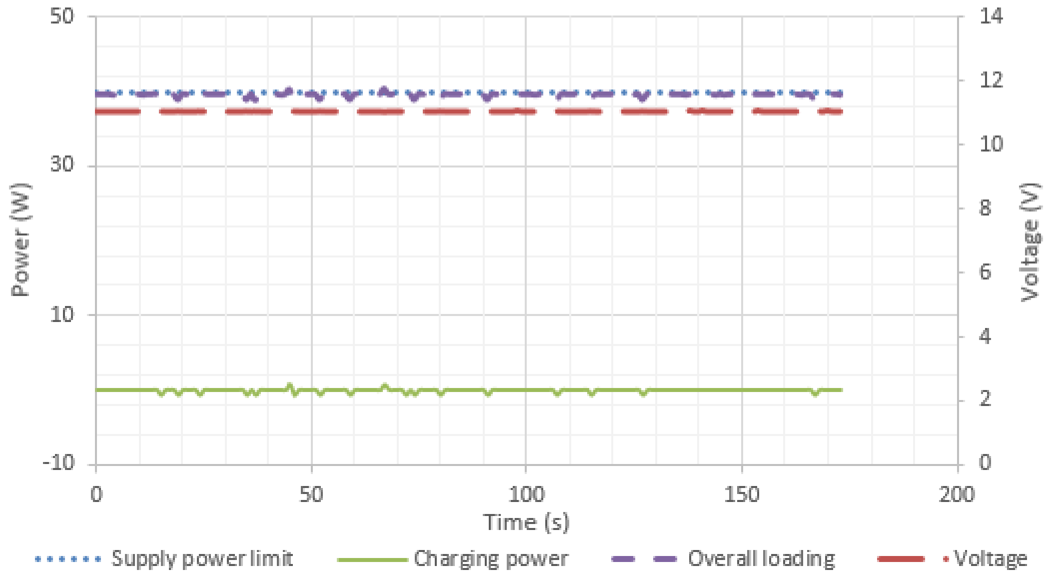

Figure 45 Charging start-up at an operational scenario 3

3.4.3.4 Schedulable load initiation

During the operation of the ERV charger, conditions of other non-charging schedulable loads (such as boiler, space heater, and air conditioner) can vary where more appliances can request operation, hence, reducing the available charging power. The proposed novel power management strategy proactively controls the operation of such loads and charging power in synchronisation with the available overall supply capability. The results for the implementation of the algorithm behind this functionality are gathered at different operating scenarios and presented in Figure 46, Figure 47, and Figure 48. During the testing and extraction of those results, it is assumed that the power management strategy has the power consumption requirement of various schedulable loads pre-defined. This assumption is due to such equipment being within the ERV along with the power management unit from point of manufacture.

An operational scenario 1 is set with a supply capability of 80W, allowable charging power allocation of 80W (no non-charger loading is in operation at the time), and a charger operation at 60W. In this scenario, a schedulable load requests operation at 40W. The result for the practically implemented algorithm within the hardware prototype is shown in Figure 46 reflecting the charging power, RBP voltage, overall supply loading, supply capability, and the schedulable load operation request signal throughout the scenario.

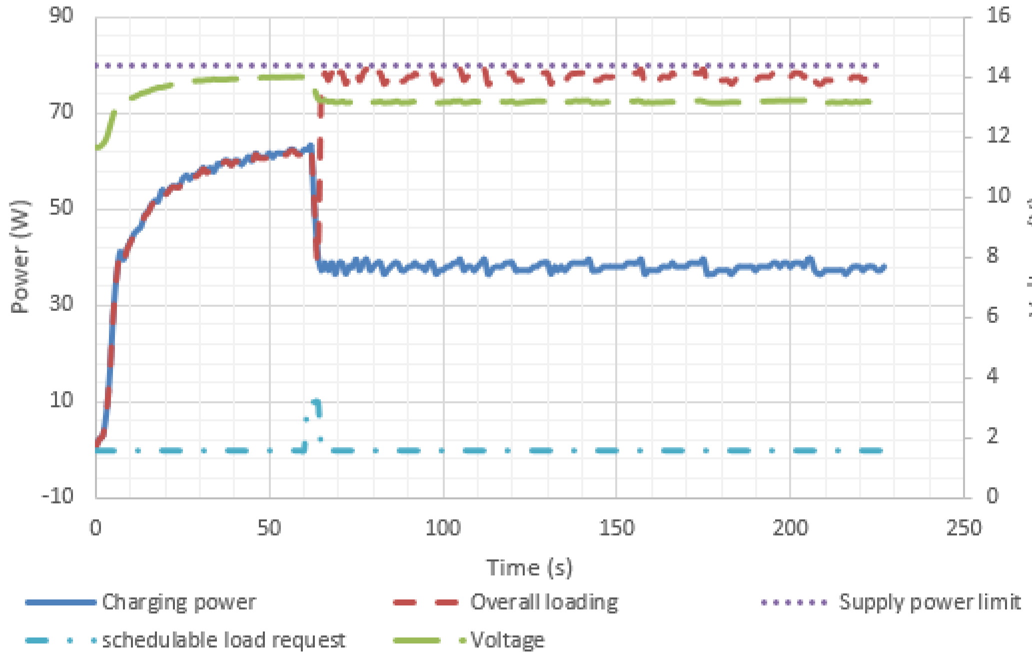

Figure 46 Schedulable load initiation scenario 1

The second operational scenario is defined to undertake a test where there is original non-charging loading of 40W, ERV charging is taking place at 40W, and a supply capability at 80W. During this scenario, a request for operation is made at 40W by a schedulable load. Figure 47 demonstrates the result of the test carried on the prototype for this scenario where the overall loading, supply limit, charging power, schedulable load request for operation, and RBP voltage are highlighted.

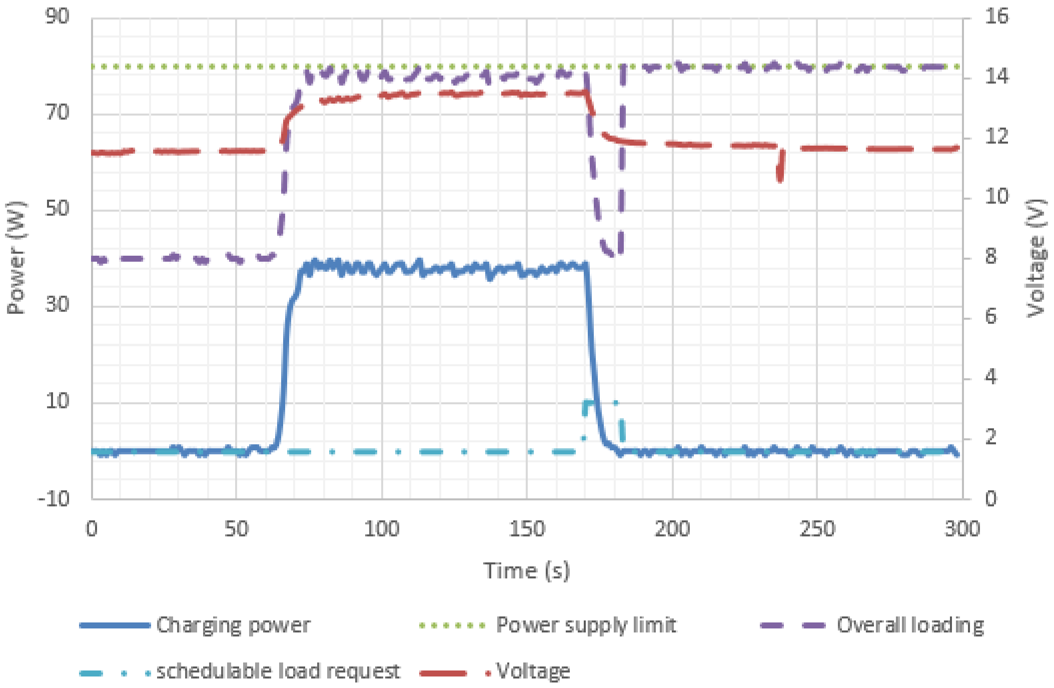

Figure 47 Schedulable load initiation scenario 2

Operational scenario 3 is tested where a supply capability of 50W is present and completely utilised by the ERV charger due to absence of other loading. A request by a schedulable load is initiated for operation at 40W. The result showing the overall loading, supply limit, charging power, schedulable load request, and RBP voltage extracted from the hardware prototype is demonstrated in Figure 48.

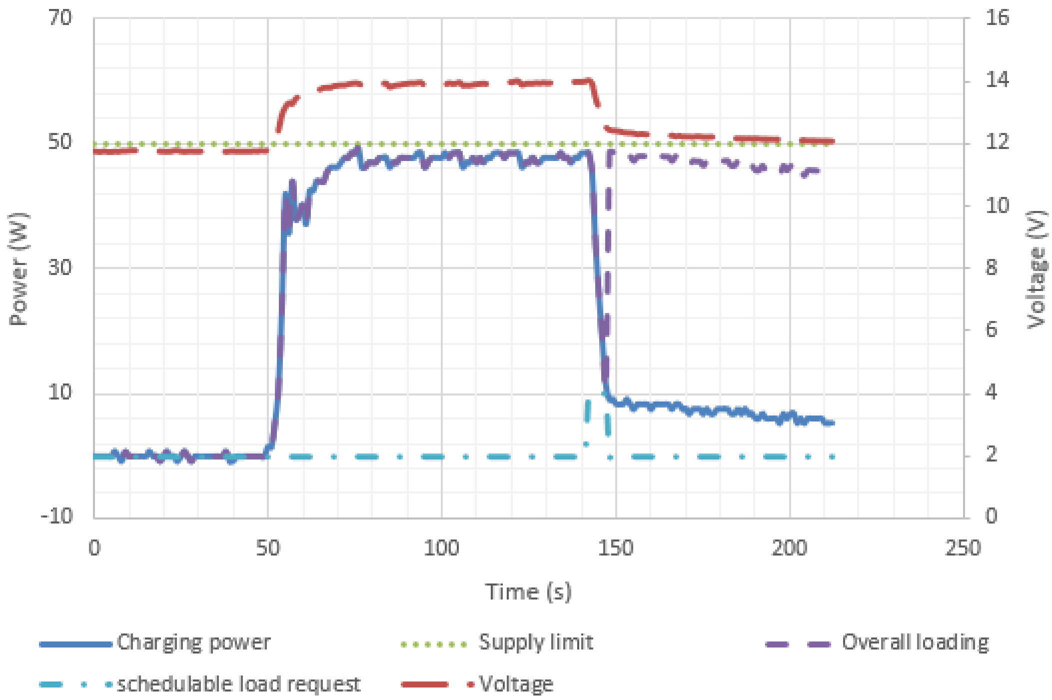

Figure 48 Schedulable load initiation scenario 3

3.4.3.5 Operating a non-schedulable load

Similar to schedulable loads, non-schedulable loads can result in changes within the overall ERV operational conditions which impact the available charging power while it's in situ. Meanwhile, this differs from schedulable loads as non-schedulable loads are usually personal devices brought on-board by the end-user and plugged into the various sockets of the ERV. A control strategy is proposed within the novel power management unit where it proactively stops the charger's operation to allow the initiation of a non-schedulable load. The novel ERV charger power management strategy then revises the available power for the charger and restarts its operation accordingly. The algorithm behind this functionality implemented in the hardware prototype was tested using three different scenarios where the results extracted are shown in Figure 49, Figure 50, and Figure 51.

In operational scenario 1, the power supply capability is set at 80W meanwhile the allocated power availability to the ERV charger is also 80W due to lack of other loading operation. The actual power consumption of the charger is 50W when a request for a non-schedulable load operation is triggered. Figure 49 demonstrates the result of this test with presentation of the RBP voltage, charging power, overall loading, power supply limit, and request signal for the non-schedulable load operation.

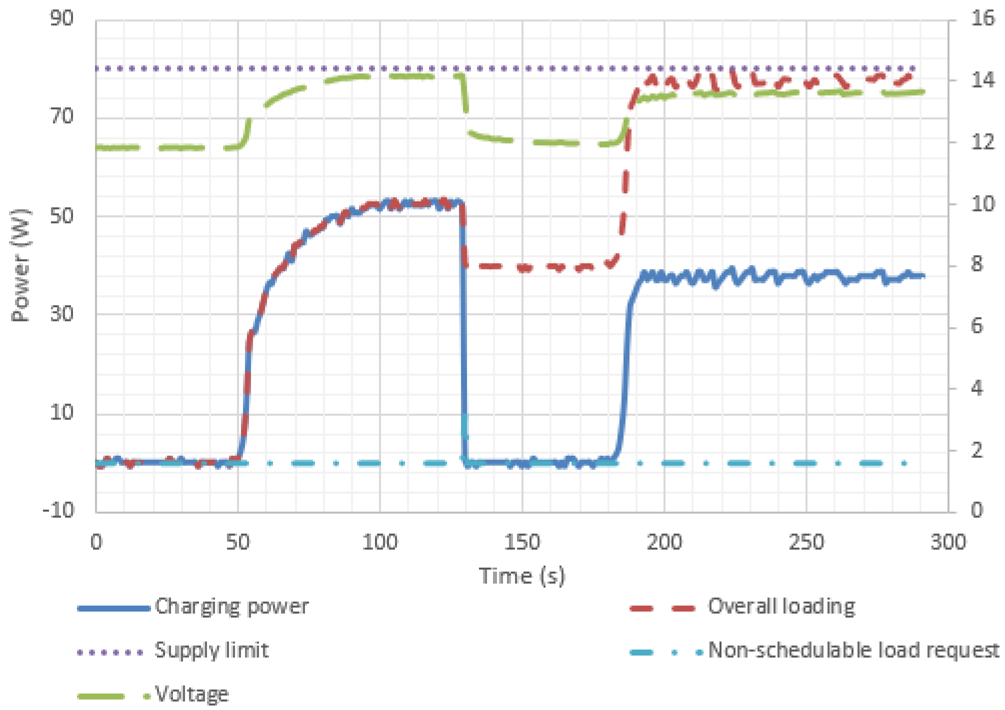

Figure 49 Operation of non-schedulable load scenario 1

Operational scenario 2 compromises of the charging power being at 50W when a non-schedulable load operation request is triggered. The power supply limit is 50W with absence of non-charging load operation at the time. The result gathered for charging power, overall loading, power supply limit, non-schedulable load operation request signal, and RBP voltage throughout the scenario is shown in Figure 50.

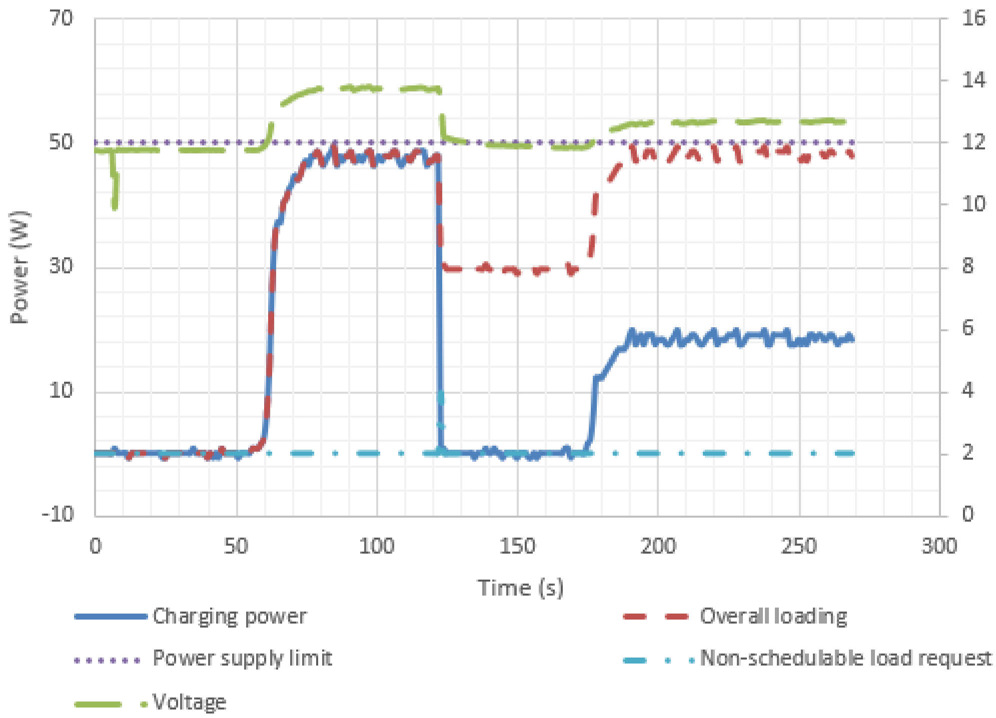

Figure 50 Operation of non-schedulable load scenario 2

Result shown in Figure 51 is for operation scenario 3 where a charging power of 40W, non-charging load of 40W, and supply capability of 80W is present. During these conditions, a request for non-schedulable load operation is initiated. Charging power, overall loading, power supply limit, non-schedulable load operation request signal, and RBP voltage during the testing are captured in Figure 51.

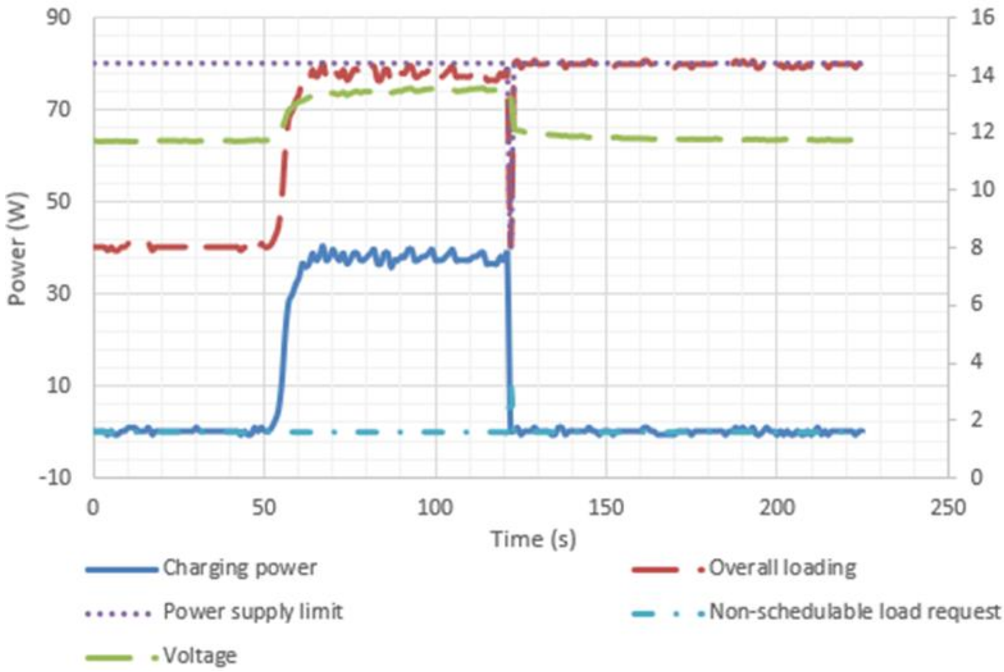

Figure 51 Operation of non-schedulable load scenario 3

3.4.3.6 EMC compliance for ERV charging power variation frequency

The capability of the proposed novel ERV charging power management strategy to vary its charging level is constrained with the frequency it can carry such variation along with other condition considerations previously tested above. This control over the frequency in power variation is a required functionality for its EMC compliance. The implemented algorithm for this functionality within the constructed hardware prototype was tested under various scenarios with extraction of results highlighted in Figure 52, Figure 54, and Figure 53.

Within scenario 1, the operation defined is for an 80W supply capability where charging is taking place at 20W with a non-charging load of 60W in situ. In this scenario, the required maximum charging power variation for compliance is one change every 60 seconds. Within less than 60 seconds of the charger completing its start-up and reaching its charging power of 20W, the non-charging load of 60W is switched off resulting in a capability of increasing the charging power allocation.

Figure 52 shows the result obtained for the testing of this scenario where the charging power, RBP voltage, supply limit, overall loading, and signal for charging power increase possibility are monitored.

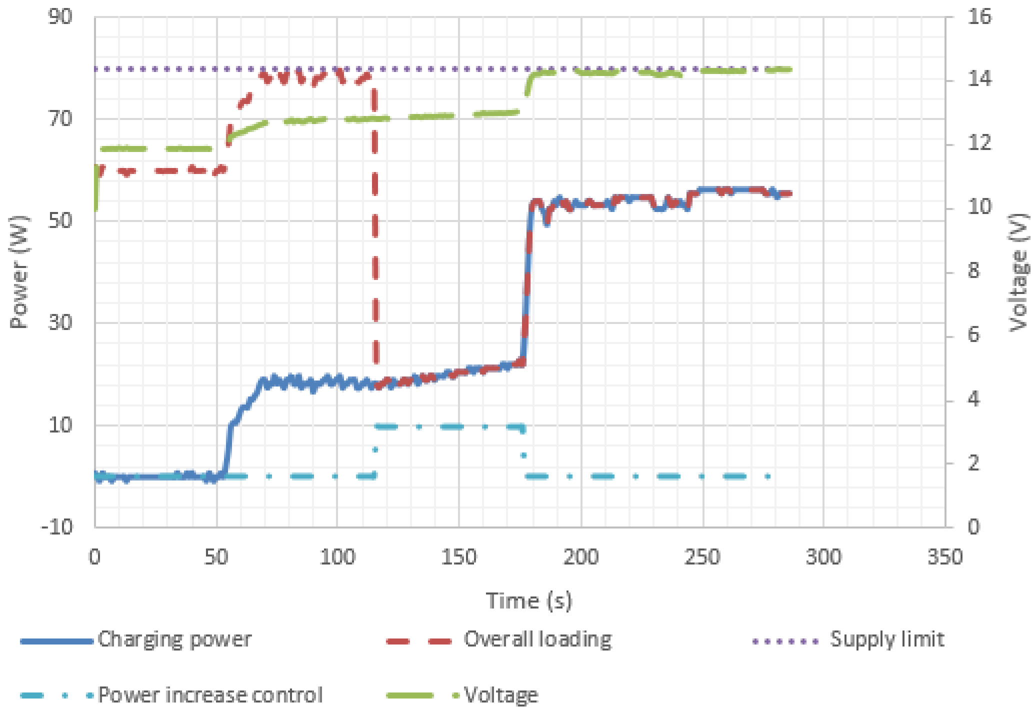

Figure 52 ERV charging power variation frequency power management strategy for EMC compliance scenario 1

In a second operational scenario, charging is set to be carried at 50W with a maximum allocated of 60W being the supply's maximum capability due to absence of other loading sources. The maximum variation frequency of the charging power is defined to be as 12 seconds in this scenario, meanwhile, a request for a schedulable load to operate is initiated within less than 12 seconds of the charging power reaching its maximum rate from start-up power variation process. Information regarding the charging power decrease control signal, charging power, RBP voltage, overall loading, and supply limit were collected and shown in the result of Figure 53.

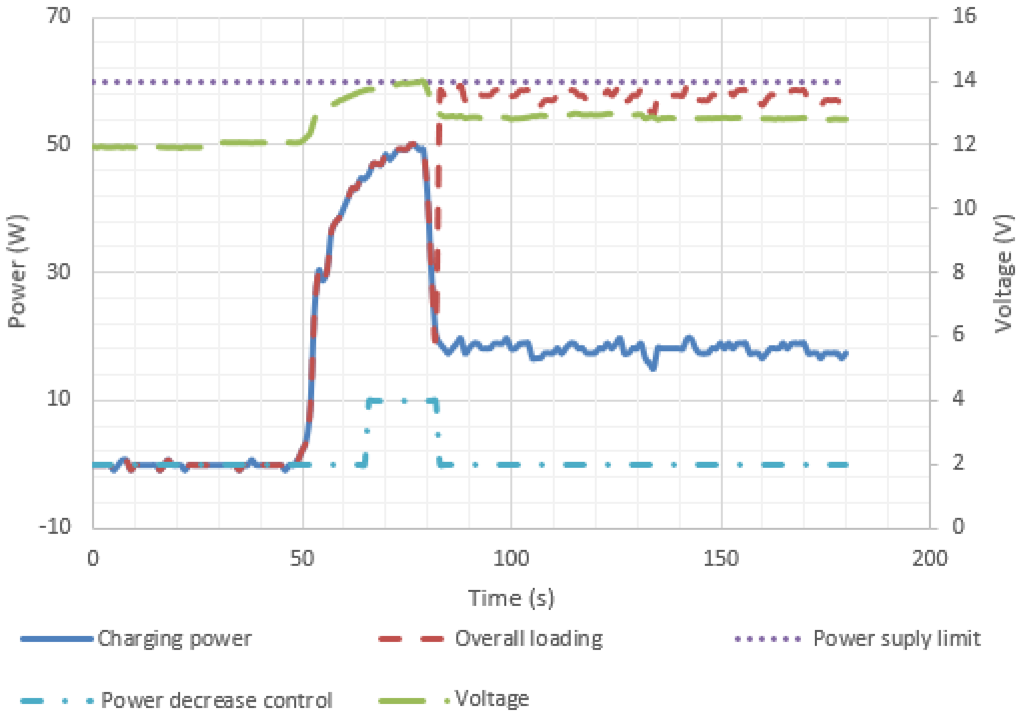

Figure 53 ERV charging power variation frequency power management strategy for EMC compliance scenario 2

A supply capability of 40W where charging operation of 40W is present due to lack of other non-charging operations are the conditions defined for operational scenario 3. Furthermore, a request is made for a non-schedulable load to operate within less than 2.4 seconds of the charging power reaching its maximum charge of 20W. Meanwhile, the scenario sets a maximum frequency of power variation for the charger to be once every 2.4 seconds. The collected result including the RBP voltage, overall loading, charging power, supply limit, and the control signal for charging power decrease due to non-schedulable load request for operation are presented in Figure 54.

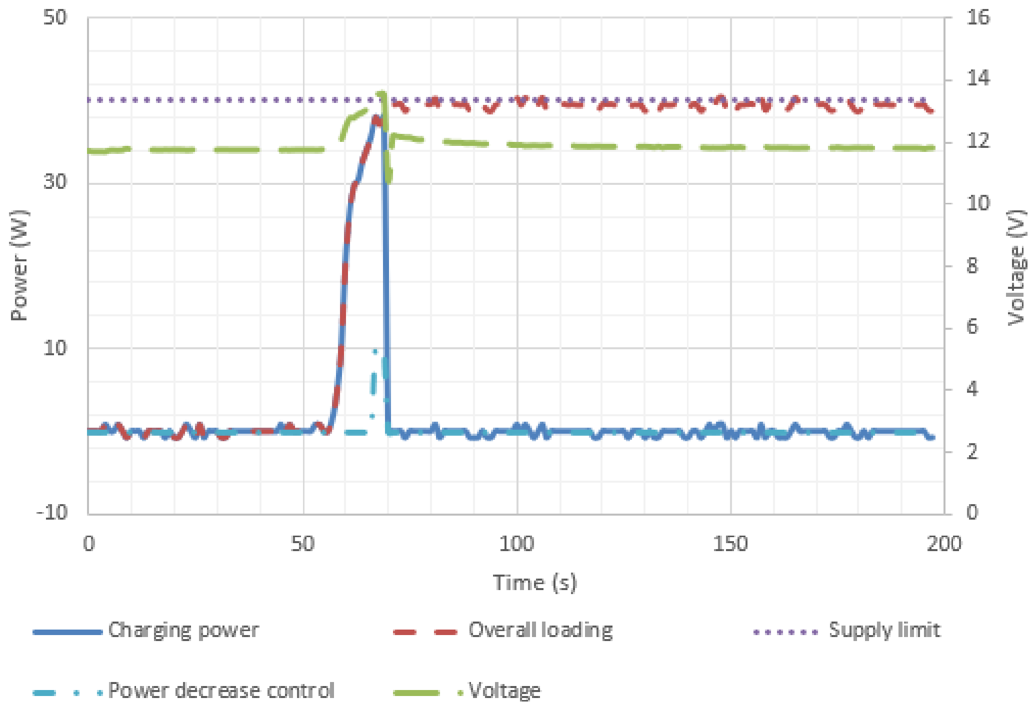

Figure 54 ERV charging power variation frequency power management strategy for EMC compliance scenario 3

3.4.4 **Analysis and discussion**

The collected results for the different tests defined for the proposed novel ERV charging power management strategy are utilised to assess the proposal on both algorithm and constructed hardware prototype levels. This assessment includes the following criteria:

- Accuracy of cc-cv charger implementation via simulation and practical results comparison with no power management constraints

- Success of the various algorithms proposed for achieving their intended functionality
- The capability of the overall proposal of achieving its ultimate goal of enhancing ERV adoption without investment requirement in the leisure market infrastructure
- Identifying any limitations within the proposed strategy

The various results are analysed and discussed within this section of the chapter individually in a synchronised order of their listing in the results section. Apart from the simulation result which is not separately analysed but rather used as an analytical reference within the other results where relevant.

3.4.4.1 Power management variable campground supply capability

The proposed strategy allows for a re-configurable supply capability which is taken under consideration within its power management. This is critical within the leisure industry due to the variability in the campground supply capability across Europe. This provides the end-user with a solution which facilitates their freedom in campground choice regardless of its supply capability. The defined test for this functionality shows the ability of the implemented proposal to vary its supply limit parameter. This is proven through Figure 42 where the power limit parameter (P_l) is extracted and plotted during the mimicking of power limit variation. The result shows the acceptance of three different power settings successfully including 40W, 80W, and 120W.

3.4.4.2 ERV charging start up

In the case of starting up the charging process, the novel proposed power management strategy is set to determine the availability of power for its allocation towards the charging process. This availability is determined through monitoring of the loading caused by non-charging loads and deducting it from the power supply capability.

In the first test carried, at the start-up of ERV charging there was no non-charging loading and 90W supply capability was present. The result in Figure 43 shows a charging power of 68.3W being reached. This charging power was reached at an RBP voltage of 13.87V. Meanwhile, the simulation result for the cc-cv charger shown in Figure 41 demonstrates that at an RBP voltage of 13.87V should be charged 68.04W as per design intent. This indicates that the constructed cc-cv charger prototype is at an accuracy of 0.38%, hence, providing confidence in the practical results extracted. Furthermore, the result in Figure 43 shows that the power management strategy provided a power constraint of 90W which was sufficient for the charger to operate at its maximum rating in relation to its battery SOC.

During the test carried for operational scenario 2, ERV charging start-up occurred when there was non-charger loading of 80W and a power supply capability of 120W. The result for this test in Figure 44 shows that the maximum charger power reached was 39.48W. Simultaneously, the maximum RBP voltage during the test was 13.15V. If the proposed power management strategy wasn't applying any constraints on the cc-cv charger, the charging power should be at its maximum operating level of 84.24W. This demonstrates the start-up algorithm to be effectively operating where it is applying the required constraints on the ERV charger through allocating it with available power. The charging power of 39.48W is 98.7% of that 40W available and allocated power for the ERV charger. Such results indicate the ability of the implemented proposed power management strategy to optimise the ERV charging under different conditions achieving optimised charging speed feature within the proposals goal. Furthermore, the overall loading on the supply is shown in the result to be maintained at a maximum of 119.46W which is 99.55% of its capacity achieving overloading avoidance feature of the proposal at different supply capabilities.

Figure 45 shows the result of test carried for operational scenario 3 where the supply capability was set at 40W and non-charging loading was present at 40W. ERV charging was not initiated due to lack of available power due to its consumption by the non-charging loads. This demonstrates the flexibility which the proposed strategy provides in operating the ERV charger as a secondary consuming load.

Finally, the results from the three different operational scenario tests carried on the ERV charging start-up algorithm further elaborate on its success in being able to operate under variable power supply capabilities which is highlighted in part 3.4.4.1 of this section.

3.4.4.3 Schedulable load initiation

At ERV charging start-up, the charging power allocation is based on the instant parameters collected including that of non-charging loads and power supply capability. The status of schedulable loads (such as the air conditioner and boiler) is not permanent during the charging process. Furthermore, new equipment can request operation, thus, the parameters originally present at ERV charging start-up are variables. In order to maintain avoiding overloading of the supply, the proposed novel management strategy incorporates an algorithm which facilitates proactive control for starting schedulable loads. This ensures that the charging power allocation is varied prior to the starting of a new schedulable load.

In test undertaken for scenario 1 on this function, the ERV charger is operating at 60W with maximum allocation of power at 80W being the maximum supply capability due to no non-charging loads operating. A schedulable load is set out to request operation at 40W. Therefore, the proposed novel management strategy is required to reduce the charger power by 20W prior to the schedulable load operation. The result shown in Figure 46 highlights a maximum charging power of 63W at the point where request for operation is triggered by the schedulable load. The charging power was then reduced to 38.7W where it was maintained at a maximum of 39.49W. Furthermore, the overall loading is seen to be always maintained below 80W throughout the full testing of the scenario. This highlights a successful algorithm and implementation where a schedulable load operation was controlled to allow a sufficient charging power reduction first, thus, eliminating an overloading situation.

Scenario 2 was set out to be tested in a situation of 80W supply capability, 40W charging power and 40W non-charging loading being the resultant of an ERV charger start-up process. During this scenario an additional schedulable load request is initiated for an operation at 40W. Figure 47 shows the result for the testing carried on this scenario where 38.7W was maximum charging power at 13.45V RBP voltage prior to the request made from the schedulable load. The request signal is seen to have lasted for 13 seconds over which the charging power was reducing gradually down to 0W along with a reduction in the overloading which reached 39.24W. At this point the request signal from the schedulable load has been removed and the load was allowed operation at 40W, taking the overall loading back up-to a maximum of 79.75W. The impact of the schedulable load proactive control from the proposed strategy is also successfully observed in this scenario testing. The maximum overall loading of 79.75W throughout the whole test indicate the ability to maintain the specified maximum supply capability to a level of 99.69%.

In the last set of testing carried on operational scenario 3, the conditions defined were a supply capability of 50W, absence of non-charging loads, and charging power at a maximum of 50W. In this scenario the schedulable load makes a request for 40W operation. The result in Figure 48 shows a response from the charging power by reduction from a maximum maintained at 48.6W to 9.11W where the request signal was eliminated. At this point, the overall loading reached a similar level to that of the charger and the schedulable load was allowed operation, taking the overall loading to a maximum of 48.77W. Therefore, the proactive control is further validated in its successful implementation. Meanwhile, the charging power is seen to be gradually decaying reaching as low as 5.3W being 53% of its allocated power of 10W. There are two reasons for this which have been identified:

- The cc-cv charger hardware reaction time is slower than that of the software responsible for the power level control
- When the software sees that the power level of the charger has reached a level below its maximum, it freezes its control signal for power level reduction and only reactivates it to increase the power level via the closed loop control if charger level is 10W less than that of its maximum allocated

The lag between software and hardware in the cc-cv charger can be mitigated through a tighter closed loop control in charging power maintenance at a level of 1W instead of 10W as explained in the second point above.

Apart from the limitation identified in the constructed cc-cv charger hardware prototype, all the results in this section reflect that transients seen in prior ERV charging power management strategies due to their reactive nature have been eliminated successfully in the proposed novel strategy through its proactive functionality. This achieves its relevant feature targets of overloading avoidance and eliminating user inconvenient due to potential supply circuit breaker tripping.

3.4.4.4 Operating a non-schedulable load

Non-schedulable loads are another type of equipment that can change in their operation status from that of initial ERV charging start-up. This results in variation within the parameters that were originally used to set the charging power. The non-schedulable loads can be equipment which are brought on-board by the end-user (hair dryer, laptop charger, kettle etc) to the ERV and therefore are not necessarily integrated with the ERV's power management unit at manufacture. Such load variation can cause supply overloading temporarily which can potentially lead to the circuit breaker tripping. Therefore, the proposed novel strategy is set out with an algorithm which proactively controls the starting of such loads. This is performed by their disconnection from the AC power source unless a request is made for their operation by the end-user manually. This is then accordingly processed by stopping the ERV charger and allowing the non-schedulable load to operate. The ERV charger then awaits validation of power consumption from the non-schedulable load prior to it resuming the charging process at the new available power allocation level.

Testing undertaken for scenario 1 of this algorithm is defined to have the charging power operating at 50W, meanwhile, its maximum allocated power is equivalent to the supply capability of 80W due to non-existence of other loading. The result in Figure 49 shows that a request was made for a non-schedulable load to operate while charging was occurring at 52.4W with an RBP voltage of 14.12V. The algorithm response was to reduce the charging power to 0W, taking the overall loading on the supply to a similar level. The non-schedulable load was then allowed to operate, which took the overall loading to a level of 39.75W reflecting its consumption. After the request signal for non-schedulable load operation was removed in 50 seconds, the charging power starts to increase again to reach and maintain a maximum of 39.48W being 98.7% of the available remaining 40W. This highlights the proactive control of non-schedulable load variation to be successfully achieved and implemented within this testing scenario.

With regards to the second operational scenario testing, a condition was implemented where 50W supply capability is present and being completely consumed by the ERV charger when a request is made for non-schedulable load initiation. Result collected in Figure 50 indicates a charging power maintained below 50W being reduced to 0W at the point of the request. This allowed the non-schedulable load to operate, increasing the overall loading to up-to 29.62W during the time of charger termination. The ERV charger then resumed charging at a maximum of 19.74W, which is 98.7% of the new 20W power allocation (due to new non-charging load 30W consumption). The test shows an effective proactive control implementation for the non-schedulable load operation with termination of ERV charging temporarily prior to additional loading taking place.

The last test carried on this algorithm defined by scenario 3 is constructed to show the ability of the ERV charger to continue its termination due to the new additional non-schedulable loading consuming all remaining supply capacity of 40W. The result in Figure 51 shows that this was successfully achieved as the charging power originally was at a maximum limit of 40W due to non-charging loading presence of 40W with an 80W supply capability limit. The charging power was then terminated at the point of non-schedulable loading request and the overall loading momentarily dipped from 80W to 40W. The overall loading was raised again to 80W at the point of non-schedulable loading signal elimination reflecting its operation. This resulted in 0W available power capacity for the operation of the ERV charger which was also reflected in the result where the ERV charger didn’t regain any charging power through the reaming duration of the test. However, it was observed that the charging power was sometimes fluctuating between +/-0.76W which caused overall loading to be seen at a maximum of 80.79W temporarily, hence, +1% of the supply capability. This is due to the accuracy limitation of the microcomputer utilised in the constructed prototype from which the results were also extracted.

As an overall observation, the results provide assurance in the effective operation of the implemented algorithm for the non-schedulable load operation control. Overloading and potential supply tripping situations were absent from all the results.

3.4.4.5 EMC compliance for ERV charging power variation frequency

For EMC compliance of the ERV charger, its power variation is constrained with a specific frequency in relation to the level in power change. Those frequencies identified have been set out to be tested under different operational scenarios where the proposed novel strategy includes an algorithm to maintain compliance.

In an operational scenario 1, the result in Figure 52 shows that a charging power of maximum 19W was maintained with a power supply capability of 80W and presence of 60W non-charging load. The non-charging loading was eliminated at time 116 seconds. This caused a power increase control signal to be generated. This signal refers to the capability of the charging power to be increased as new allocated power can be set to 80W due to absence of non-charging load. The signal lasted for 61 seconds after which the charging power was increased to a maximum of 55W which is required with an RBP voltage of 14.34V. This result shows that the power management strategy stopped the increase of charging power immediately due to the non-charging load variation occurring prior to the required 60 seconds frequency of charging power variation in this scenario (non-charging load changed 44 seconds after the charging power reached its original allowable maximum of 19W in the 20W allocation). This reflects the algorithm achieving its desired control of 60 seconds between each ERV charging power variation, hence, its EMC compliance within this scenario. An observation is made within the result that the charging power increased by 3W reaching 22W during the waiting period of 60 seconds before allowable power change. This is due to use of open loop control in maintaining the charging power during this phase. This is an acceptable result as 3W power variation is less than the 25W limit set within this constructed prototype which is the limit for the frequency control to be applicable.

During scenario 2, the testing is defined under the condition of a 60W supply capability which is completely allocated to the ERV charger with absence of other loading. However, the actual charging power was set at 50W as required by the RBP due to its voltage at the time. Within this scenario, the required allowable frequency control for the charger power variation was at a maximum of every 12 seconds if exceeding 25W. The result of Figure 53 indicates that a power decrease control signal was generated due to a schedulable load operation request while the charging power was at 45.56W, hence, prior to its maximum level being reached. This caused the ERV charger to continue its power increase for 14 seconds levelling at a maximum of 50W when it was then reduced to a maximum of 19.7W allowing the schedulable load to operate at requested 40W and raise the overall loading to 60W. The result highlights that the desired operation of the proposed strategy to be effectively taking place by delaying the change in power that exceeds 25W by the required 12 seconds within the appropriate circumstances.

In the last operational scenario 3 testing, the defined frequency between ERV charging power variation was set to be a minimum of 2.4 seconds. Within this scenario, a power supply capability of 40W was present which was completely consumed by the charger. A non-schedulable load was set out to trigger a request for operation in less than 2.4 seconds of the charger reaching its maximum power. The result in Figure 54 shows that the signal was generated when the charger was operating at 38W for 2 seconds only after it was reached. The results indicate that the ERV charging power was maintained at that maximum level for 3 seconds before reduced to 0W. The control signal was then eliminated allowing the non-schedulable load to operate at the required 40W where the E-RV charger remained at termination.

It can be observed in all three results that the algorithm implemented in the proposed novel power management strategy was effectively carrying its intended functionality of controlling the ERV charger substantial power variations frequency. Thus, resulting in a complaint operation for the ERV charger.

3.4.5 **Conclusion**

A novel ERV charging power management strategy is proposed to facilitate ERV charging in various leisure industry campgrounds with varying supply capabilities without the need of infrastructure investments. This is to enhance the adoption of ERV, thus, aligning the leisure industry with electrification megatrend. The proposal was tested through a constructed scaled down hardware prototype achieving agreement between its results and that of simulation to a level of 0.38% with regards to the cc-cv charger. Meanwhile, the results indicate that the implemented power management proposal achieved its defined required features to achieve the ultimate goal including:

- Overloading and supply tripping avoidance is always achieved through maintaining overall supply capability at a maximum of +1% of its specification.
- Optimised charging speed is present in all occasions at 98.7% charging power of that available capacity. One exception was observed due to a limitation in the cc-cv charger and not the power management strategy which can be eliminated with an improved hardware and software synchronised charger.

- Facilitating for an EMC complaint charger operation in terms of the frequency at which it varies the charging power substantially is implemented with an accuracy of maximum + 2 seconds than that duration gap required. The hardware and software synchronisation limitation in the constructed cc-cv charger was identified to introduce a low probability of false operation in the proposed novel strategy in real world implementation. This can be resolved again through improved charger construction or can be mitigated within the power management strategy parameters.

In conclusion, the proposed novel power management strategy is advantageous over the prior proposed strategies which can be used in similar application and is proven to be of successful practical operation with identified limitations due to the used charger specifications which should be taken into consideration.

Chapter 4 RBP POWERED SMART APPLIANCE MANAGEMENT STRATEGY

4.1 Introduction

Usability of electric appliances such as microwave ovens are currently limited in recreational vehicles (RVs) due to low electrical supply capability in campgrounds as highlighted in Chapter 2 of the thesis. Such low electric supply capability also limits the performance levels of the electrical appliances.

The low campground supply acts as a bottle neck for the electrification of RV equipment, limiting the reduction of fossil fuel powered appliances dependency. This is due to the requirement of upgrading the electrical supply capability which needs substantial infrastructure upgrade within the leisure industry. Supply-demand management, such as that proposed in the smart grid application, can be utilised to serve as a solution which avoids such investments and accelerates the shift towards electrification within the leisure industry.

The implementation of supply-demand management within the electric recreational vehicle (ERV) can eliminate the potential overloading of the electric supply due to high electric appliance usage. Meanwhile, this doesn't resolve the user inconveniences in the capability of operating multiple electric appliances at operational powers which provide sufficient performance levels. This is due to the electrical supply capability in campgrounds being very low in comparison to that required by many electrical equipment such as the microwave oven as highlighted in Chapter 2 of the thesis.

A novel solution of rechargeable battery pack (RBP) powered smart appliance management strategy is proposed in this chapter. The proposal is based on a microwave oven for the purpose of the thesis, but it can be applied to any other appliance which has energy and power levels that are defined or forecastable for their operation (such as a water boiler). The proposal aims to improve the customers' experience in operating the microwave oven within the future ERV via an RBP. The RBP acts as a buffer energy source, allowing high power consumptions for enhanced performance without the risk of overloading the campground supply. Furthermore, battery depth of discharge (DOD) and excessive discharge rate avoidance constraints highlighted in Chapter 2 are accounted for within the proposal through a novel smart load management strategy. This allows optimisation of the RBP size, weight, and cost aiding in commercial and technical feasibility.

This chapter demonstrates the analysis performed to identify the requirements the novel smart RBP powered smart appliance management solution, presents prior supply-demand management strategies proposed for the smart grid application, analyses those strategies to identify their capabilities in relation to those required for the ERV application, and describes the novel solution proposed.

4.2 RBP powered smart appliance management strategy requirements analysis

Novel solutions are required for the enhancement of electric appliance dependency in the RV application in order to assist the transition towards fully electrified equipment in the future ERV. Those solutions are to be implemented to overcome relevant current limitations within the leisure industry. For example, it can be deduced from relevant literature in Chapter 2 that the main limitation (which is driving all other barriers) for the microwave oven is the low instant power supply capability within European campgrounds, which ranges between 690W and 3450W.

This low campground supply capability has driven the limited cooking performance of the microwave ovens currently used in the RV (Chapter 2 highlights that higher microwave oven power levels provide enhanced cooking performance). Such a low cooking performance is potentially a limiting factor for an end-user to be dependent on such an electrical equipment.

Current microwave ovens within the RV with a cooking performance of 800W would consume 1200W. This consumption requirement limits the usability of the microwave oven in campsites with supply capability ranging between 690W and 1200W. Therefore, its reliability of being able to serve the end-user at different locations is reduced, hence, its dependency. Furthermore, whenever such microwave oven operation is triggered in campsites ranging between 1200W and 3450W, limited power is remaining for other electrical appliances to be operating simultaneously. This can result in overloading scenarios which potentially impact the grid supply quality [117] [118]. User inconvenience is also an outcome of such overloading as this will cause the RV campground AC supply circuit breaker to trip, hence, interrupting all appliances operating within it. For example, in a 6A campground supply capability scenario, if the user starts the microwave oven at the 800W cooking level while a 1000W electric kettle is operating, the supply will be overloaded by 3.6A (i.e. 9.6A overall consumption at 230VAC). Various circuit breakers overloading characteristic were retrieved from Trimble Protect software. Those shown in Figure 55 to Figure 58 were analysed to identify the supply tripping possibility at such overloading of 9.6A on a 6A supply circuit breaker.

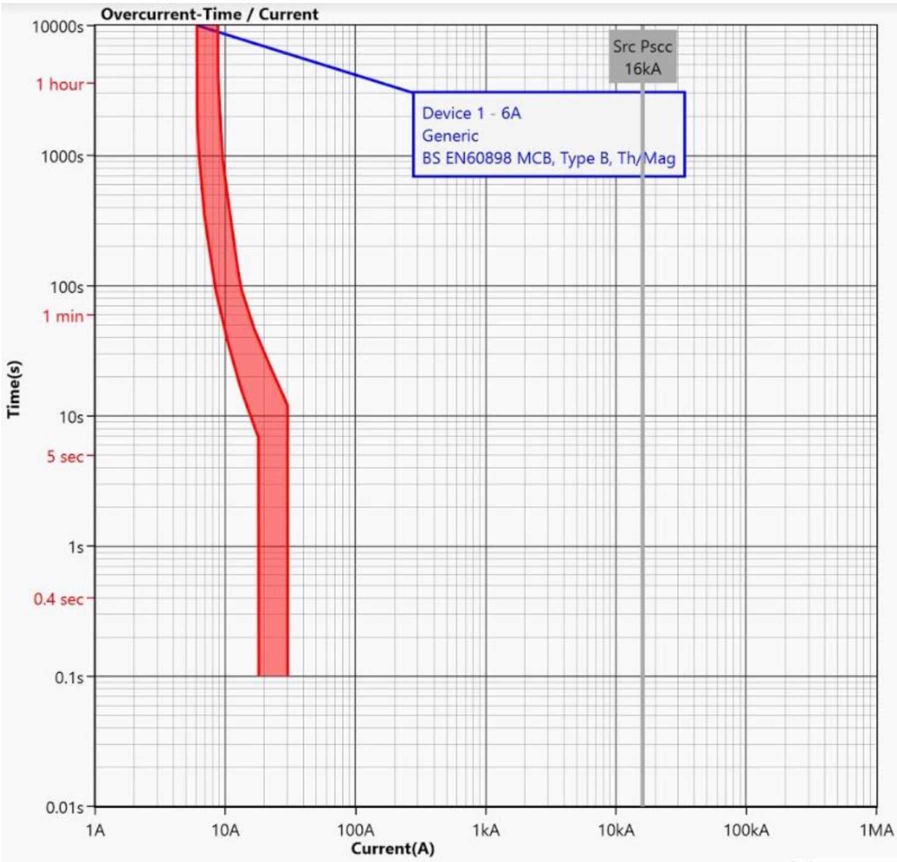

Figure 55 Generic BS EN60898 MCB, Type B 6A

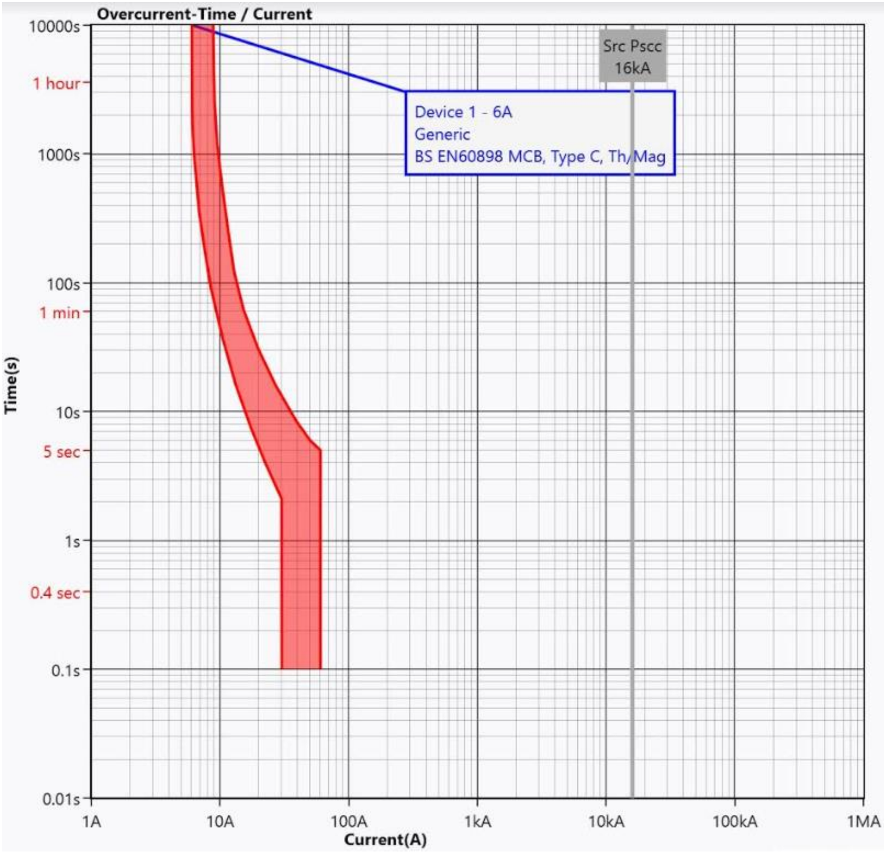

Figure 56 Generic BS EN60898 MCB, Type C 6A

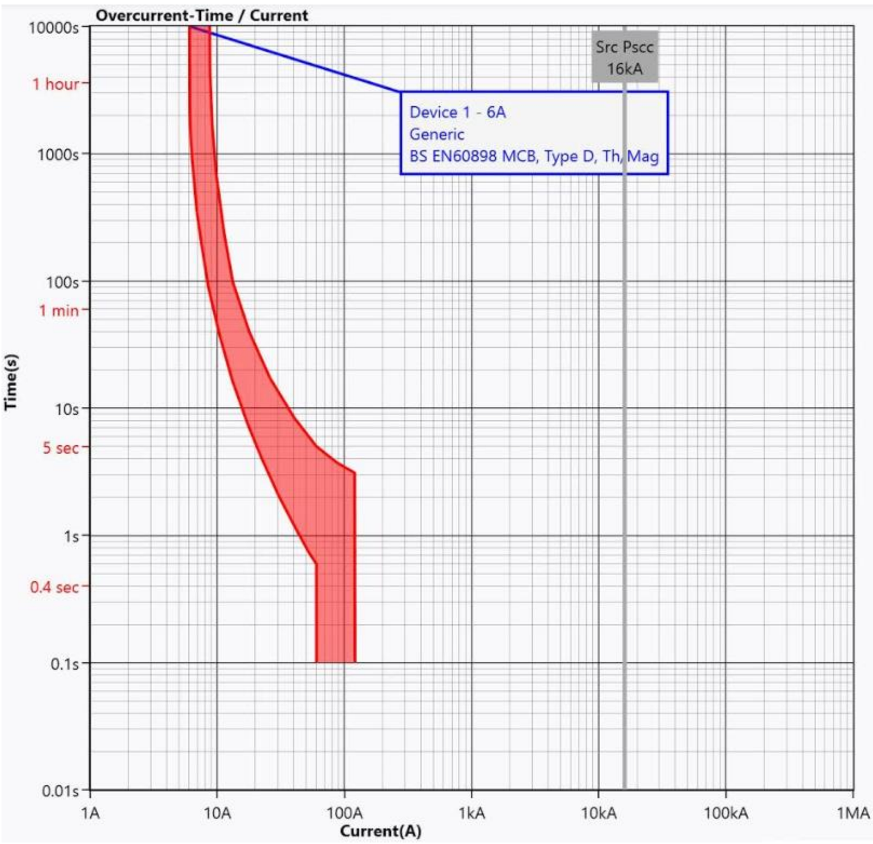

Figure 57 Generic BS EN60898 MCB, Type D 6A

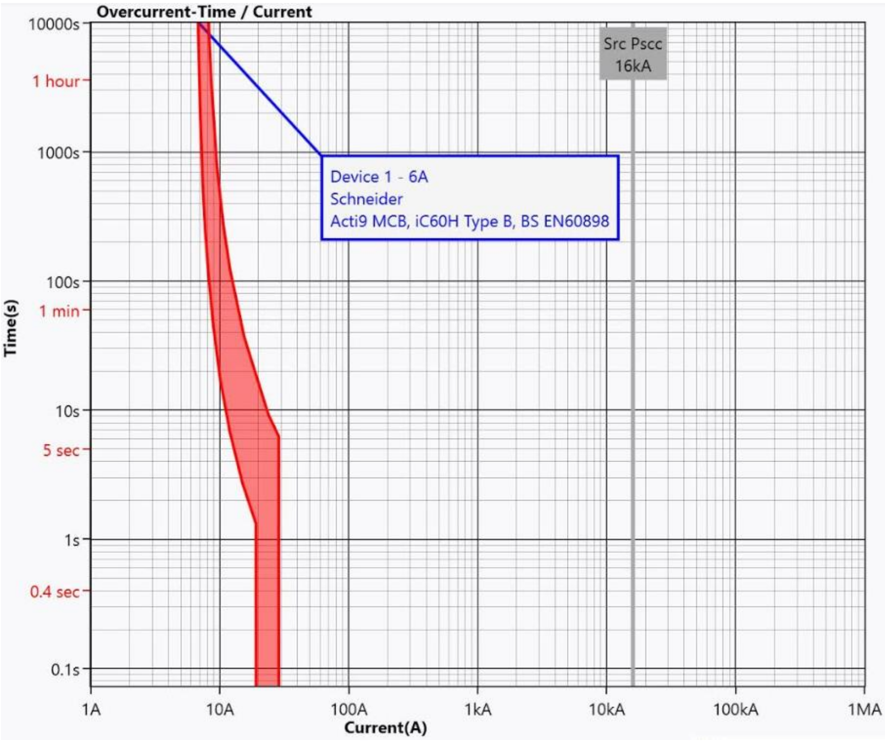

Figure 58 Schneider Anti9 MCB, iC60H Type B 6A, BS EN60898

Figure 55 to Figure 57 highlight the minimum tripping time characteristic required at different currents for different European standard compliant circuit breakers. The figures indicate that an overloading of 9.6A on a 6A circuit breaker would trip the supply within 30 to 40 seconds depending on the circuit breaker type. However, a commercial circuit breaker analysed in Figure 58 shows that the supply would trip within 20 seconds only in such an overloading scenario.

An electric supply infrastructural upgrade at all current European campgrounds is required to overcome the identified current barriers for utilising an electrical equipment such as the microwave oven if not addressed with novel solutions. Furthermore, if complete electrification of the RV appliances is to be supported, this upgrade needs to account for larger and increased number of loads than that of the microwave oven. An electrical supply upgrade of such a scale is potentially an undesirable substantial investment [138] [76] [81]**.**

Utilisation of an RBP as a buffering power source eliminates the need of costly infrastructure upgrades for increasing the microwave oven usability and performance rating without contributing to overloading scenarios due to simultaneous use of other electrical appliances. However, an RBP has operational constraints of its own which vary according to its type and design. This includes energy capacity, DOD, and instant power discharge rate. As presented in Chapter 2, those constraints can be addressed through a well sized RBP in terms of its capacity and instant power discharge capability, that would suffice all possible electrical load simultaneous operations without exceeding any limits. But as also highlighted, such constraints need to be optimised in order to maintain a commercially feasible RBP in terms of its cost, weight, and space claim especially in an automotive application such as that of RV.

4.3 Smart appliance load management strategies

Smart appliances in the residential sector contribute in achieving supply-demand management for the smart grid application [139] [140]. They are required to provide the capability of controlling their loading so that the demand follows the generation. This opposes the current situation where generation is expected to meet any instantaneous supply demand.

Various smart appliance load management strategies have been proposed today in order to fulfil the supply-demand target of the smart grid [141] [142] [143] [144] [145] [146] [147] [148]. All those found are focused on schedulable loads (e.g. washing machine, boiler, heater, dishwasher etc) and propose duration allocation capability for the appliance operation. They don’t consider non-schedulable loads such as microwave ovens where their power demand is for instant operation.

The smart appliance scheduling capabilities found are based on two models of time delay or interrupted operation shown in Figure 59 and Figure 60 respectively [149].

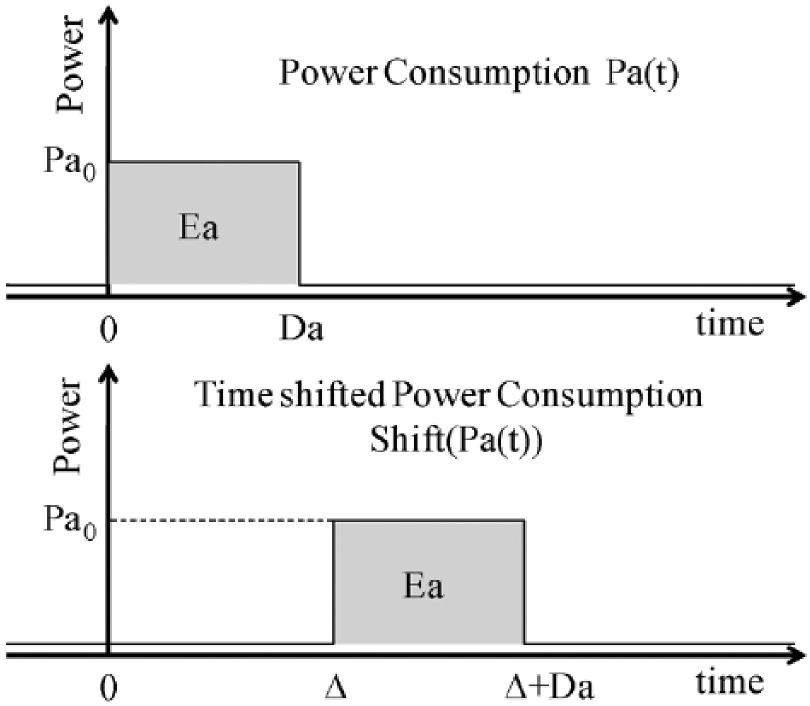

Figure 59 Time delay smart appliance scheduling model [149]

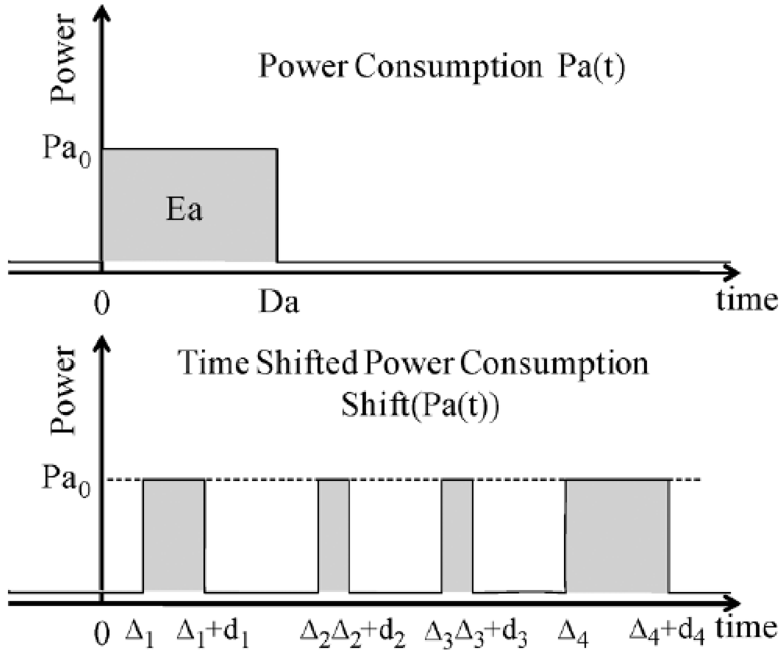

Figure 60 Interrupted operation smart appliance scheduling model [149]

As seen in Figure 59, a schedulable smart appliance can be controlled to start its operation at a specific time through introducing a delay [149]. Advanced smart appliance management strategies further allow its operation to be controlled by periodic on and off switching over a duration of time as shown in Figure 60. This is possible with appliances where their functional operation allows it and can be constrained with certain parameters (e.g. maximum and minimum temperature range not to be exceeded during the off period).

The main differences between the different proposed smart appliance load management strategies are the operational constraints considered and their control priorities. Various proposed strategies are highlighted and analysed in detail below.

4.3.1 **Cost optimisation-based strategy**

The electrical supply cost variation throughout the day is a common proposed approach for smart grid demand management. Various strategies which revolve purely around this approach are proposed in [140] [141] [142] [150] [151] [152] [153] [154].

Such strategies suggest that utilities should vary their supply costs during the day. The cost variation is to be dependent on factors including renewable energy availability and overall demand on the grid. For example, if there is abundance of renewable energy, then the supply price is reduced. However, if the demand on the grid is very high, which results in the need of fossil fuel generation to meet it, then the price is increased. This fluctuation in price is to be communicated to the residential sector and to be used by the smart appliances.

The various smart appliances are to be capable of scheduling their operations in various durations within the day that would meet the end-user constraints. This includes duration window for completion within the day, maximum cost of operation, and performance parameters such as temperature. The rationale behind this strategy proposal is that the smart appliance operational cost being one of the constraints, various loads would operate in different times depending on their urgency. This is due to cost optimised electric usage being an advantage to the end-user. Therefore, the demands are following the instantaneous supply generation capability, which flattens the supply and demand curves, achieving one of the smart grid goals. An example architecture of such a strategy is shown in Figure 61. The various schedulable smart appliances are connected to an energy management system (CAES) which also receives information from the utility regarding prices and from the user for operational constraints [141].

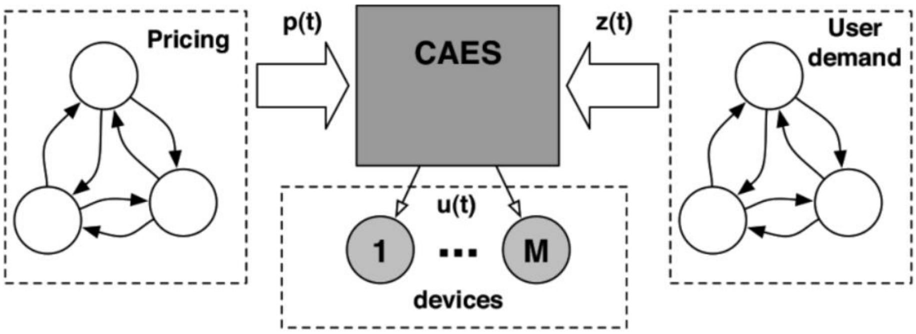

Figure 61 Architecture of a smart appliance management strategy purely based on variable cost of grid electrical supply [141]

This proposed strategy is beneficial to the end-user in terms of cost optimisation. Furthermore, it is of benefit to the grid in relation to optimising the use of renewable energy sources and reducing peak demands. However, such strategy is purely dependant on the change in the end-user behaviour where they would consider cost benefits are a priority over their energy usage requirements. It doesn't consider the instant supply capability to provide forced control of the demand which is required for the implementation of electrified appliances in the ERV due to the low supply capability. Furthermore, the strategy is not based on RBP buffering such as that proposed in this thesis for the capability of electrical appliances such as microwave ovens to operate at higher power levels for enhanced performance. The load management capability is also for schedulable loads only and not for non-schedulable loads such as microwave ovens. Finally, the proposal lacks the ability of varying the loads power demand to achieve higher usability in high loading scenarios on a limited supply such as that in campgrounds.

4.3.2 **Cost optimisation and transformer overloading prevention strategy**

A proposed strategy [143] [144] utilises electrical grid price variation and instant power consumption capability. This schedules various smart appliances based on the fluctuating price and other constraints provided by the end-user such as maximum end time, performance, and maximum operation cost. Such processing of user constraints and energy prices provides a provisional scheduling. The final schedule of a smart appliance is then dependent on the overall loading on the grid through the processing of instant power consumption levels. An example algorithm of such a proposal is shown in Figure 62 [144].

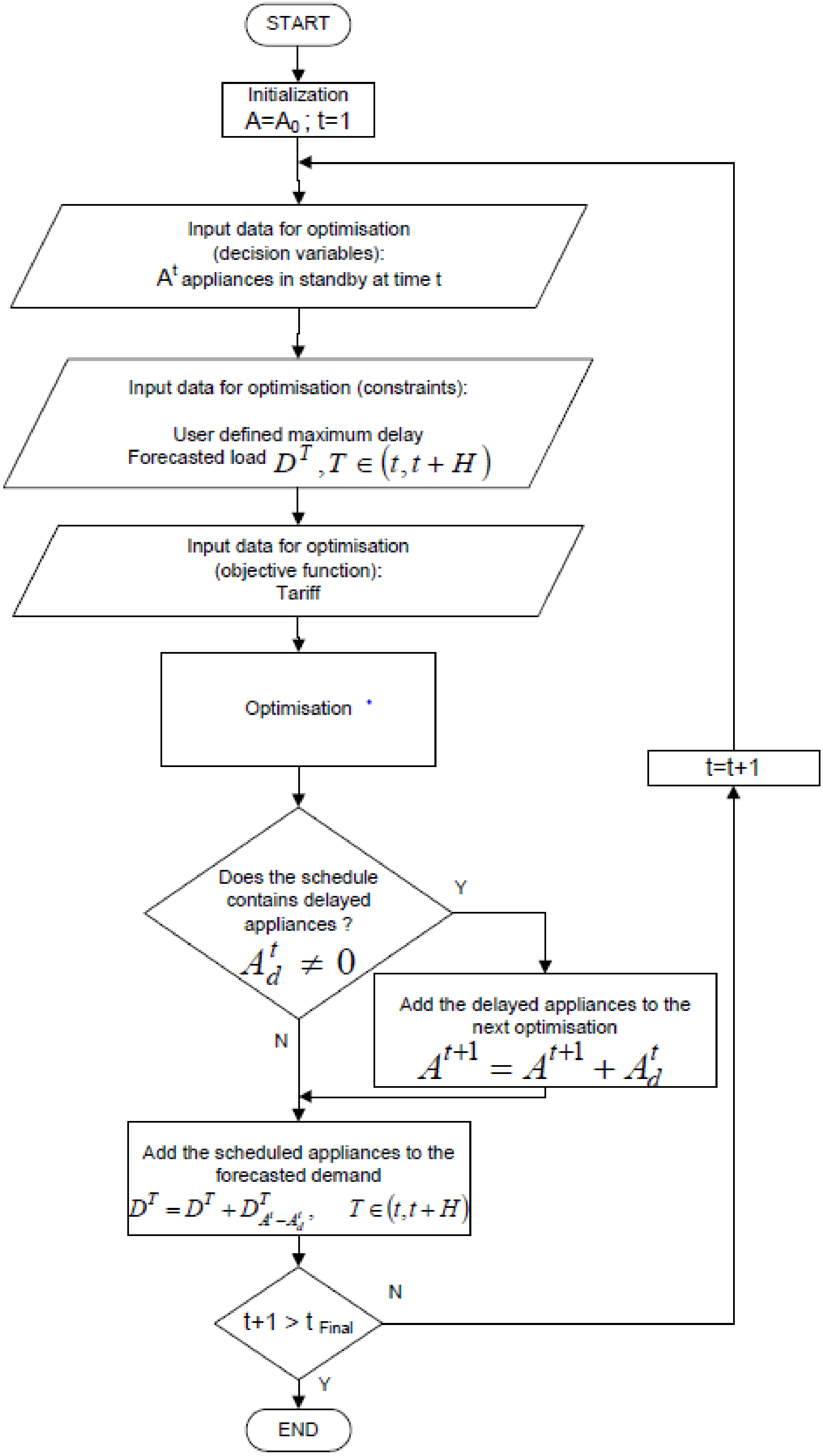

Figure 62 Algorithm for cost optimised and supply overloading preventing smart appliance management strategy [144]

As shown in Figure 62, the energy controller receives information from the end-user with regards to the appliances required to operate and their operational constraints such as maximum cost and allowable delay in initiation [144]. This is then processed along with the measured grid power consumption. The instant consumption level is compared with the transformer supply capability to identify available supply capacity. The schedulable smart appliances are then allocated with operation time slots. Non-schedulable loads such as the microwave oven are operated immediately and considered as inflexible loads.

Proposed strategies of such basis are beneficial for the smart grid application as it manages the supply-demand on the grid and manages the increased electrified loads demand of the future without increased capital investment. The strategy also provides the end-user with cost incentives. A similar strategy is advantageous for the electrification of appliances in the ERV application as it accounts for the supply capability in its control decisions. However, it doesn't provide an RBP buffering facility for enhanced performance power consumption levels at low supply capacity locations such as that in leisure industry campgrounds. The strategy also doesn't include any smart appliance load management functionality for increasing its usability in extremely constrained supply conditions.

4.3.3 **Cost optimisation with RBP powered capable strategy**

Cost optimised smart appliance strategy with the capability of being powered from an RBP was proposed [145] [146] [155]. This strategy aims to provide the end-user with the most cost-effective operation for the various schedulable smart appliances. It achieves this through grid utility price fluctuation processing and cost calculation for using the microgrid RBP as the energy source. This is utilised for operation window allocation for the various smart appliances which is based on either the microgrid RBP or the utility grid supply. The inputted end-user constraints include cost and maximum delay allowed. In the case of those proposed in [146] and [155], a further capability is incorporated which is to utilise the renewable source, such as solar, directly if present. Figure 63 presents the architecture of the proposal in [155] as an example for such a strategy.

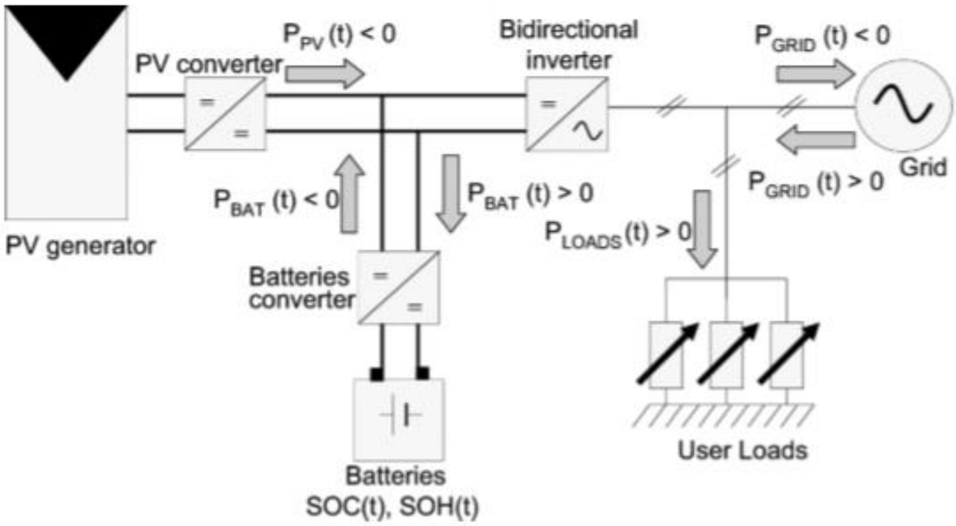

Figure 63 RBP capable and cost optimising smart appliance strategy architecture

The proposed strategy such as that shown in Figure 63 allocates smart appliances with a suitable operational time slot according to user constraints provided. It selects the most favourable energy source (including solar and RBP) amongst the microgrid and the utility grid supply for the smart appliance operation in its allocated time. In the proposal within [145], an operational constraint on the RBP is applied prior to its choice. This is limited to its instant power discharge capability. Both [146] and [155] proposals don't account for the instant discharge capability of an RBP. However, they consider the state of charge (SOC) to identify the capability of an RBP in supplying relevant loads scheduled at different times. The proposed strategy in [146] also factors in the potential of RBP charging from the solar source for estimating its capacity. Furthermore, it accounts for the overload tripping point within the household.

A smart appliance strategy with cost optimisation and RBP powered capability provides the end-user with most cost-effective appliance operation through alternation between energy sources. This automatically provides increased usability as it reduces inconveniences in long delay times. Such a strategy also aids the future smart grid with its goal of supply-demand management. Smart appliance strategy of such capabilities is beneficial for enhancing the adoption of electrified equipment in the ERV as it accounts for the supply capability. The capability of RBP buffering is also incorporated which allows higher performance operation at limited grid supply capability locations. However, the strategy is disadvantageous in relation to its incapability of controlling non-schedulable loads and not providing advanced capabilities of appliance power consumption reduction in order to further improve their usability in applications where RBP size is critical and grid supply is extremely low. Furthermore, the strategy decision is limited to the RBP capacity sufficiency prior to the operation of a specific appliance and doesn't factor in the potential continues charging through other sources such as the grid or solar. Therefore, this limits its enhancement functionality. Finally, both SOC and discharge rate combined RBP constraints are not present in one proposal.

4.3.4 **Cost optimisation and CO2 reduction with RBP powered capable strategy**

In addition to smart appliances being scheduled based on the varying cost of the utility grid supply, proposals including [147] [156] and [157], have incorporated the CO2 levels in their control. The rationale behind this strategy is that grid varying prices are not sufficient in reflecting the need to reduce demand during renewable energy source capacity reduction or occupancy. Therefore, a signal of CO2 level emissions is added within the data processing of the smart appliance management strategy. Such a strategy proposal is reflected in the architecture example in Figure 64 [156].

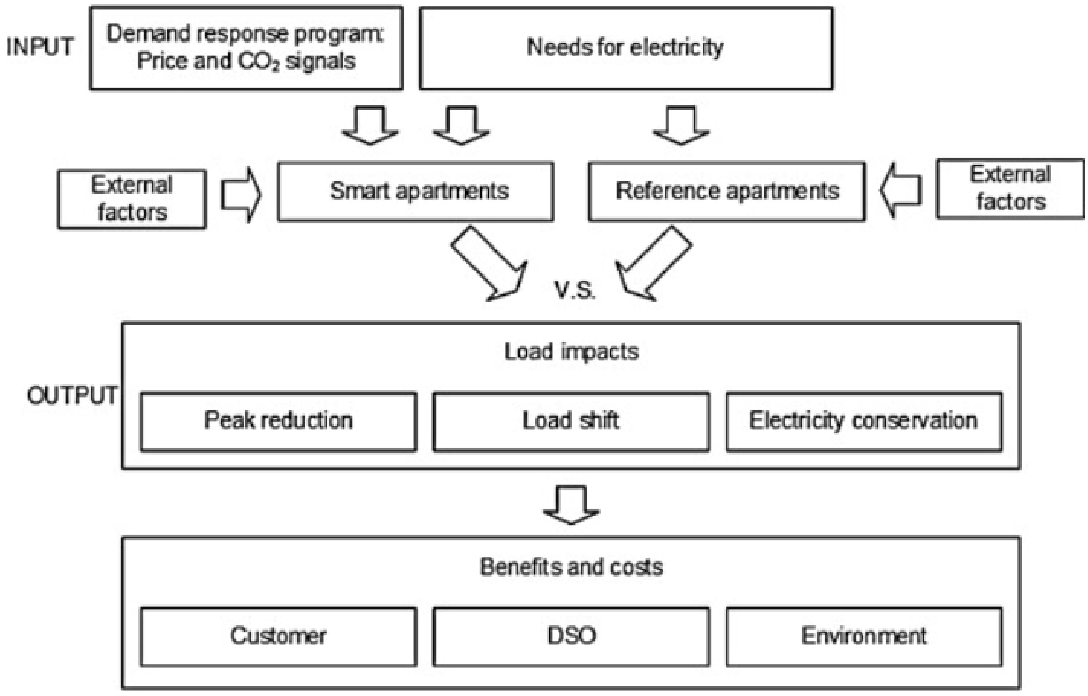

Figure 64 CO2 emissions reduction and cost optimisation smart appliance management strategy [156]

In [147], the strategy is further elaborative where it utilises the RBP capability within the microgrid to assist CO2 level reduction and cost-optimisation. It selects between the RBP and the utility grid as energy sources based on that most favourable considering end-user constraints such as operational cost and defined window of work. The strategy accounts for the RBP SOC in terms of its sufficiency to supply a specific load prior to the allocation decision.

Implementing a smart appliance strategy, such as that in [147], is beneficial for the smart grid application. It provides the end-user with a cost-effective experience and simultaneously manages the supply-demand on the grid. A similar strategy is beneficial for the ERV application as it utilises the RBP as a source of buffer for high power consumption operations, thus enhancing the performance of electrical appliances such as that of microwave ovens. In contrast, the strategy doesn't account for non-schedulable loads or the maximum power discharge capability of an RBP. Furthermore, it lacks smart load management capability of varying the power consumption requirements for enhanced usability. Finally, it doesn't incorporate advanced capability for RBP SOC estimation where potential charging through other energy sources is considered.

4.3.5 **Cost optimisation with variable power boost consumption capable strategy**

Proposed smart appliance strategy in [148] reduces the cost of operation through processing grid price changes. It schedules various smart appliances with consideration of end-user constraints such as that of performance and operational cost. A further reduction in cost capability is implemented which allows the smart appliance to consume more power than that required for its instant operation due to the following reasons:

- Additional power consumed is stored in the appliance in a form which can be utilised during increased utility grid price intervals within its scheduled operation slot.
- Power consumption exceeding that required increases work achievement during periods of reduced grid supply cost within its scheduled window of operation.

The proposed strategy is advantageous to the smart grid application due to its capability of optimising cost for the end-user and flattening the supply-demand ratio of the grid. The power boost capability of consuming additional power in the scenario of achieving more work is potentially disadvantageous as it increases the power losses due to exceeding the appliance normal operation power requirement. Furthermore, this can result in accelerated aging of the operated equipment. Utilising a strategy of such capabilities within the ERV application is not beneficial as it doesn't account for the supply capacity limitation in its control algorithm. The need for RBP powered capability is also absent, which limits the performance of appliances such as that of the microwave oven in locations of limited power availability. Finally, there is no smart load management capability to enhance the usability of schedulable or non-schedulable loads under constrained supply conditions of either the RBP or the grid.

4.4 Novel RBP powered smart appliance management strategy proposal

Microwave ovens are currently limited in their usage within the RV due to low camping ground power supply capability. This results in low dependency on such electrical equipment and increases that of fossil fuel based. With the aim of improving the usability of microwave ovens in the RV, a novel RBP powered smart appliance management strategy is proposed. The objectives of this proposal are the following:

- Facilitate the operation of higher microwave oven power performance
- Optimise microwave oven usability

The objective of facilitating for higher performance operations is achieved by using an RBP as a source of power to the microwave oven. This on its own is not sufficient as it will result in a commercially and technically unfeasible solution due the increased RBP weight, cost, and space claim. Therefore, the introduction of smart appliance management strategy solutions is required in order to provide optimised usability under practicable RBP operational constraints. Those novel smart appliance management solutions and their scope of contribution towards the objectives are:

- Discharge limit, SOC, and DOD are constraints factored for permitting microwave oven operation to avoid the need of utilising over specified RBP to suit all operational scenarios of RBP powered loads within RV.

- The decision behind microwave oven operation allowance is not limited to the instant parameters of the RBP constraints but inclusive of the RBP charging status. This enhances microwave oven usability and can also be utilised to reduce the required RBP specification.
- Alternative microwave power mode to that originally requested is proposed to the end-user in occasions of RBP capacity and/or discharge availability insufficiency. The new suggested power mode includes an amended operational time to equate original cooking energy demanded requested.

The architectural arrangement of the proposed novel RBP powered smart appliance management strategy is presented in this section of the chapter. Further details on algorithms and mathematics specific to each novel solution of the proposal are then explained. The section then is organised to present the experimental set up, results, analysis and discussion, conclusion, and further work of this proposal.

4.4.1 **Architecture and algorithm**

Various parameters are collected and processed within the proposed novel smart appliance management strategy. Those parameters are concerning the energy sources, the loading on the RBP, and the microwave oven. The processing is utilised by the novel proposal to identify the overall condition. This is then used to perform the required control action which is communicated to the microwave oven. The novel strategy proposal implementation is achieved through a central RV microcomputer as per Figure 65.

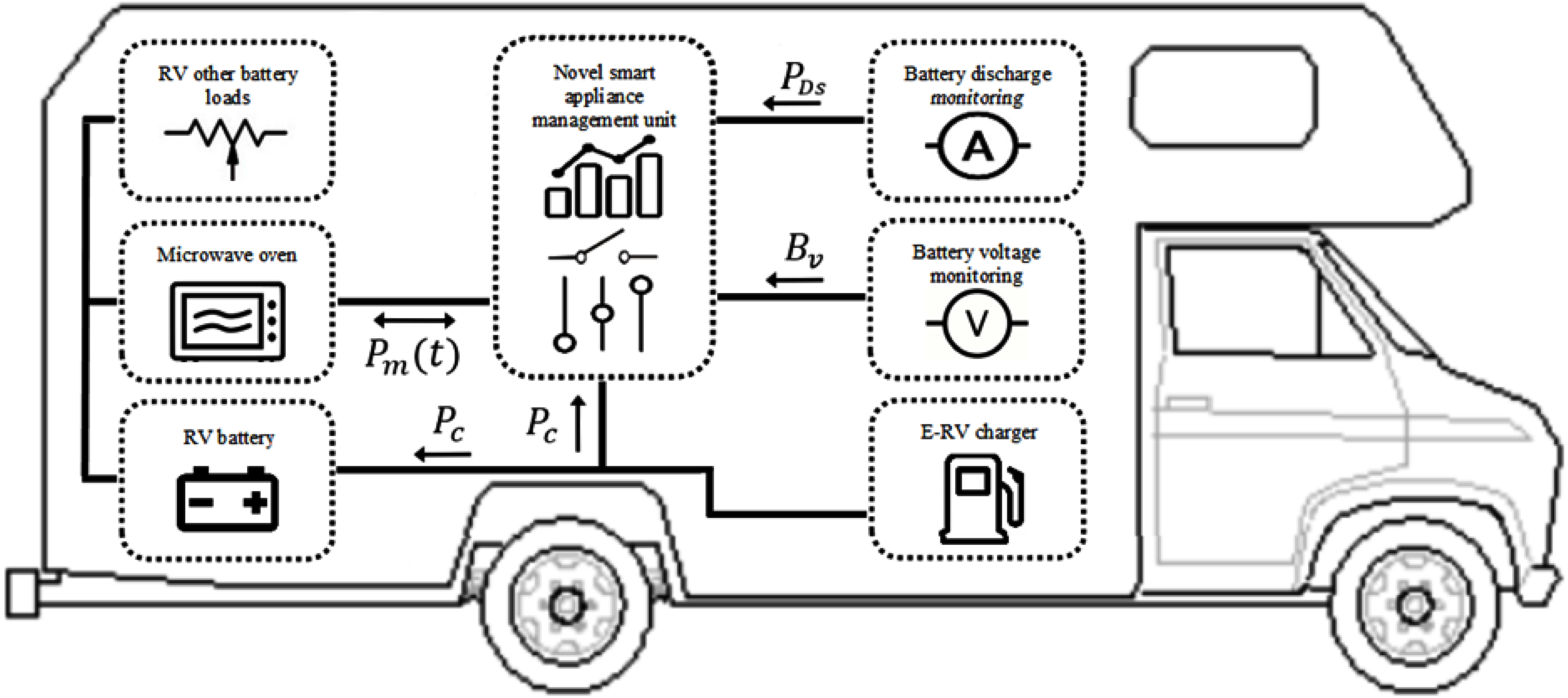

Figure 65 Proposed RBP powered novel smart appliance management strategy architecture

The proposed architecture in Figure 65 shows the processed parameters within the novel smart appliance management strategy:

- Charging power of the RV RBP P_c
- RBP instant power consumption P_{DS}
- RBP voltage is observed with parameter B_v to determine its SOC
- Microwave oven operational power request is communicated with its requested duration $P_m(t)$

The novel smart appliance management strategy, within the central microcomputer, processes the collected parameters in order to allow or refuse the requested power operation of the microwave oven. Whenever the proposed microwave oven operation is rejected, the proposed strategy searches for an alternative operational mode which meets the current constraints of the RBP. This alternative is communicated back to the microwave oven through an updated power value P_m associated with a new operational duration $P_m(t)$.

When microwave oven operation is requested, the first RBP constraint which the proposed strategy performs analysis on is its instant discharge power limit P_D. This is configured within the strategy at the point of its implementation in the RV. For this analysis, the status of charging power P_c is also updated and considered. The algorithm embedded within the smart appliance management strategy which performs this first check is shown in Figure 66.

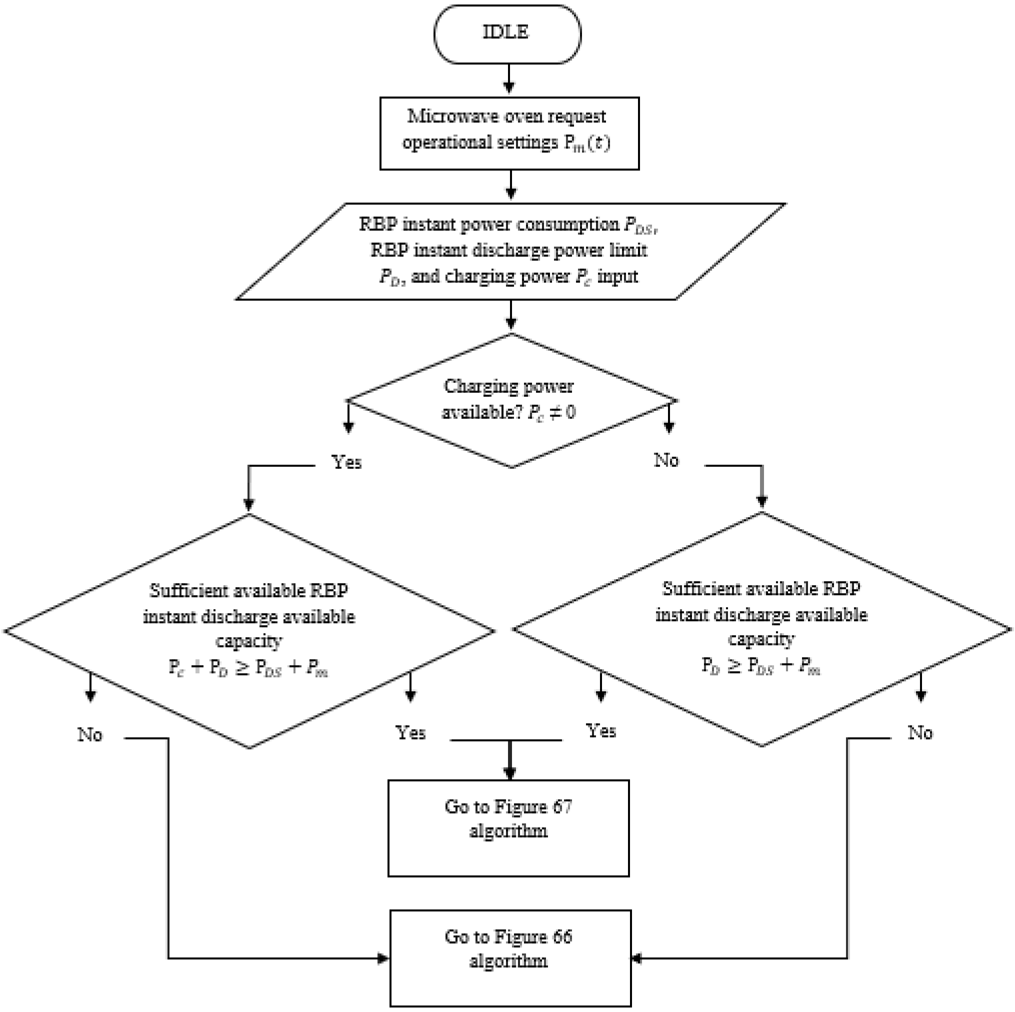

Figure 66 Algorithm for identifying requested microwave oven power suitability in relation to instant discharge RBP constraint

In Figure 66, the current discharge power P_{DS} is captured at the point of the microwave oven request. The status of charging power P_c is then identified including its value (if present). A check is then performed by the management strategy on the suitability of requested microwave power P_m. This is achieved by comparing the available instant discharge power capability of the RBP with its limit P_D. In absence of charging power presence, this check is performed using equation (22).

$$\mathrm{P_D} \geq P_{DS} + P_m \tag{22}$$

If the charging power P_c was present, then the instant RBP discharge power capability check is carried through equation (23).

$$P_c + \mathrm{P_D} \geq P_{DS} + P_m \tag{23}$$

A negative outcome for the instant discharge capability analysis causes another algorithm, shown in Figure 67, to be undertaken. This determines if it is possible to operate the microwave oven at a lower instant discharge power which is suitable for the identified RBP discharge conditions and constraints. The proposal assumes the microwave oven can operate at five different power levels.

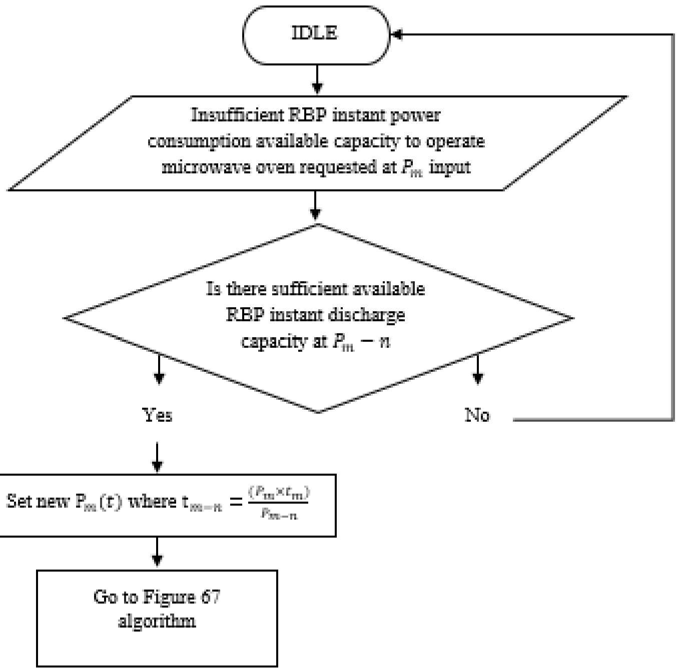

Figure 67 Algorithm for determining alternative microwave oven operational mode to suit RBP instant power discharge constraints

The algorithm in Figure 67 identifies the possibility of operating the microwave oven on a lower power level. This is achieved by checking the RBP instant discharge capability using microwave oven levels lower than that originally requested P_{m-n}. This is performed with the relevant equations of (22) and (23). If a new power setting is identified to allow the microwave oven operation, then a new microwave operating time at that new power level P_{m-n} is defined using equation (24).

$$t_{m-n} = \frac{(P_m \times t_m)}{P_{m-n}} \tag{24}$$

The new operation time proposed by the novel smart appliance management strategy using equation (24) will result in maintaining the original energy operation requested by the end-user but at a new power level which is suitable for the RBP available instant discharge capability. With no new power level possibility identified, the microwave oven is not allowed to operate.

After the RBP discharge capability constraint analysis is complete, the novel management strategy performs a further check at the power level identified to be suitable for the instant discharge constraint. This is the availability of RBP capacity to supply the desired energy consumption for the microwave oven operation. The charging status P_c is also considered within this analysis of the management strategy algorithm shown in Figure 68.

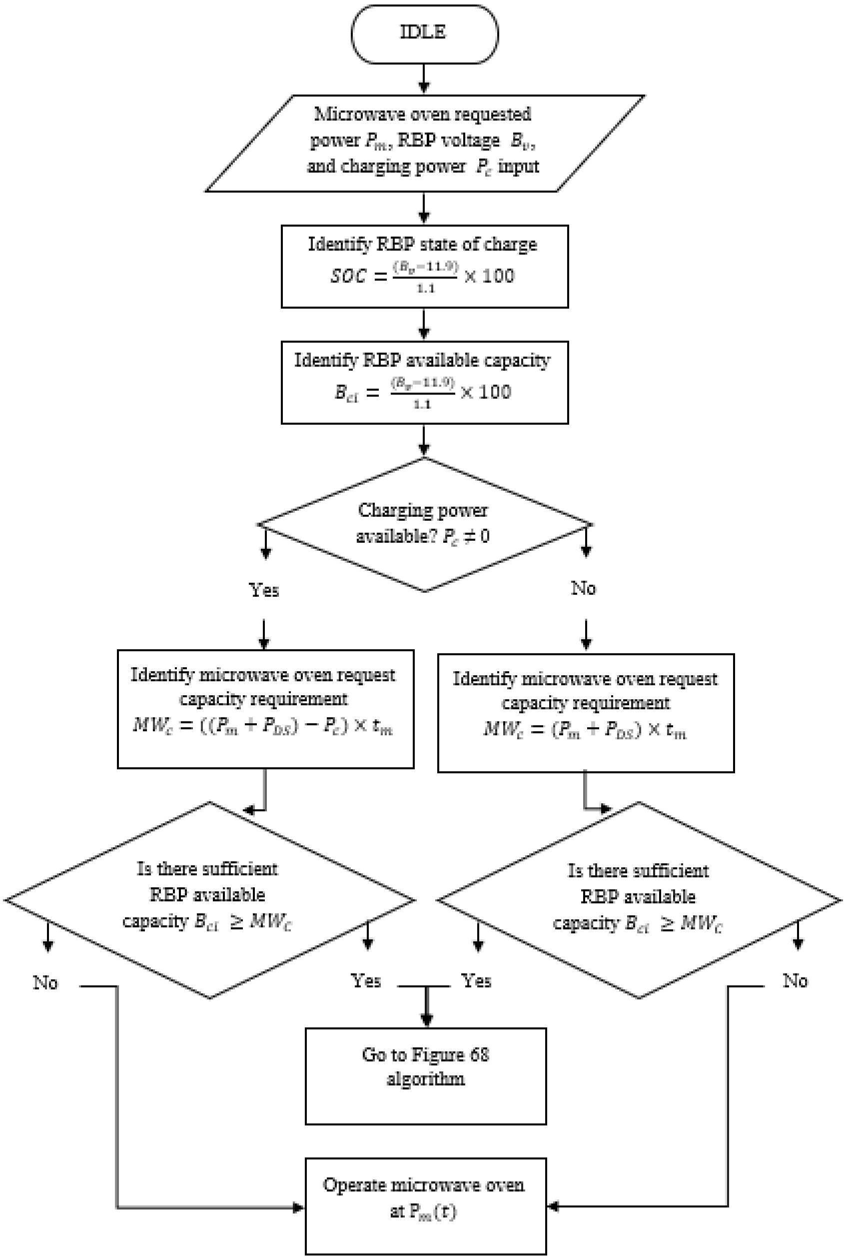

Figure 68 Proposed strategy algorithm to identify RBP supply capacity availability for microwave oven energy requested

Figure 68 demonstrates the algorithm for determining if sufficient RBP capacity is present for the requested microwave oven operation energy consumption E_m. This calculates the RBP SOC through the collected RBP voltage information B_v and equation (25).

$$SOC = \frac{(B_v - 11.9)}{1.1} \times 100 \qquad (25)$$

In equation (25), the proposal assumes that maximum DOD of the RBP is reached at 11.9V. The DOD parameter within the proposal is reconfigurable at the point of implementation within the RV. The monitored RBP voltage B_v is used to determine the RBP SOC with its maximum level being represented at 13V. The instant available RBP capacity (Wh) is then determined utilising the SOC as per equation (26).

$$B_{ci} = \frac{SOC}{100} \times B_{cn} \qquad (26)$$

The available RBP capacity (B_{ci}) calculation of equation (26) is performed in relation to the nominal RBP capacity (B_{cn}) which is configurable. This is then compared with the microwave oven operation capacity requirement (Wh) calculated in equation (27).

$$MW_c = (P_m + P_{DS}) \times t_m \qquad (27)$$

In equation (27), the required microwave oven capacity (MW_c) is calculated assuming that the current non-microwave oven loading (P_{DS}) is to continue its operation at a constant level throughout its operational time (t_m). If the available RBP capacity (B_{ci}) exceeds or equals that needed for the microwave oven operation (MW_c), then the microwave oven operation is permitted. If insufficient RBP capacity is identified and no charging power is present, the microwave oven operation is refused. However, with presence of charging power, further calculation is undertaken to determine if RBP capacity available is sufficient with the consideration of the charging power. This results in a new microwave oven capacity requirement utilising equation (28).

$$MW_c = ((P_m + P_{DS}) - P_c) \times t_m \qquad (28)$$

The proposed management strategy assumes that if the RBP is at 80% or more of its capacity then it will be capable of supplying various microwave oven operational scenarios without charging power dependency. The charging power (P_c) is then assumed to be of stable rate (because in cc charge mode) in situations where its consideration is required within microwave oven operational capacity determination. Therefore, in equation (28), a new microwave oven capacity requirement from the RBP is calculated by deducting the power provided from the charger (P_c). This updated capacity requirement is then compared with the available RBP capacity. Sufficient RBP capacity availability will allow triggering of the microwave oven. However, if this is false, the novel management strategy goes through a final algorithm shown in Figure 69. This analyses the capability of running the microwave oven at a lower power consumption rate which is compatible with the available RBP capacity and charger rate.

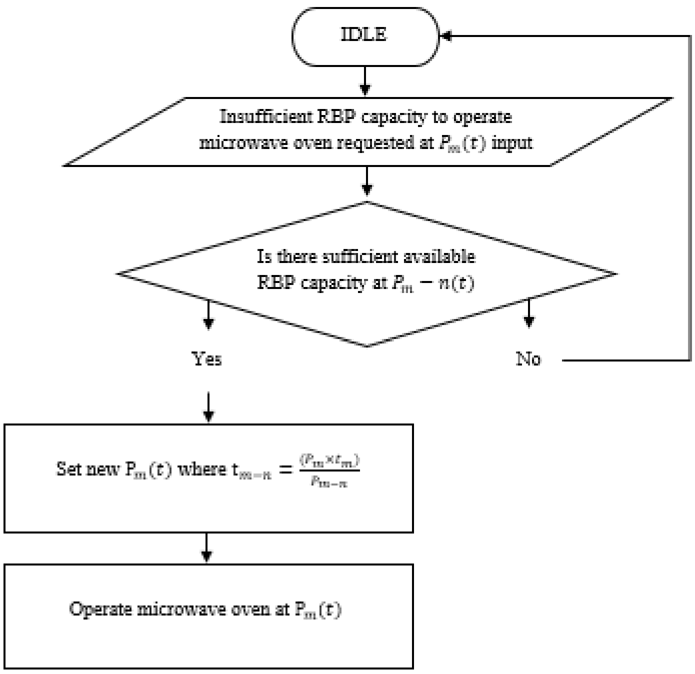

Figure 69 Proposed management strategy algorithm to identify possibility of new microwave oven operational power and time to suit RBP capacity constraint

Figure 69 algorithm performs equation (24) to determine the new required operational time at the lower power levels than that originally received. A new RBP energy requirement is then defined and analysed using equation (28). Microwave oven operation is permitted with positive outcome. However, it is rejected if no new power level was found to result in operational suitability with the RBP capacity constraint.

4.4.2 **Experimental setup**

A scaled down laboratory hardware prototype was constructed for assessing the novel RBP powered smart appliance management strategy proposal. The constructed prototype compromised of the following:

- Smart appliance management unit
- RBP
- Non-microwave oven load simulator
- Microwave oven interface
- Microwave oven load simulator
- RBP charger

The arrangement of the constructed prototype functional blocks is shown in Figure 70.

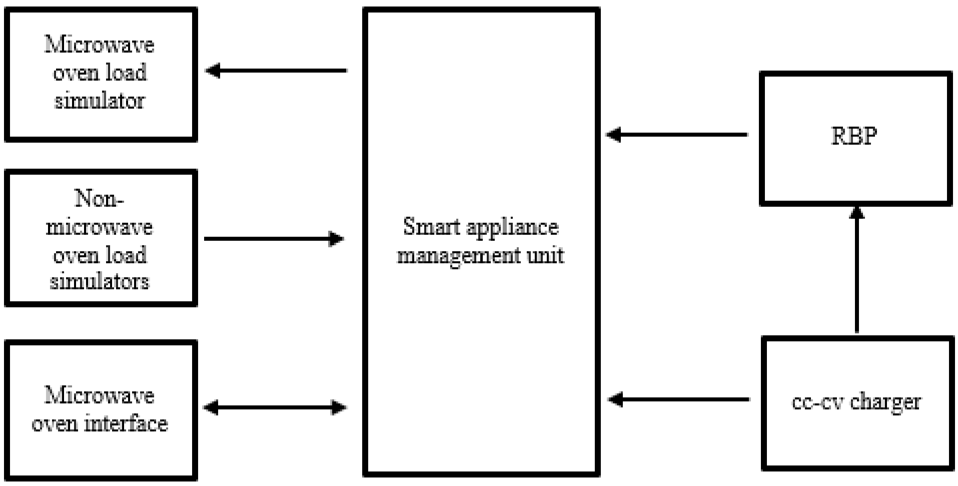

Figure 70 Constructed prototype architecture of smart appliance management strategy proposal

The scaled down laboratory hardware constructed prototype of the proposed novel smart appliance management strategy is shown in Figure 71.

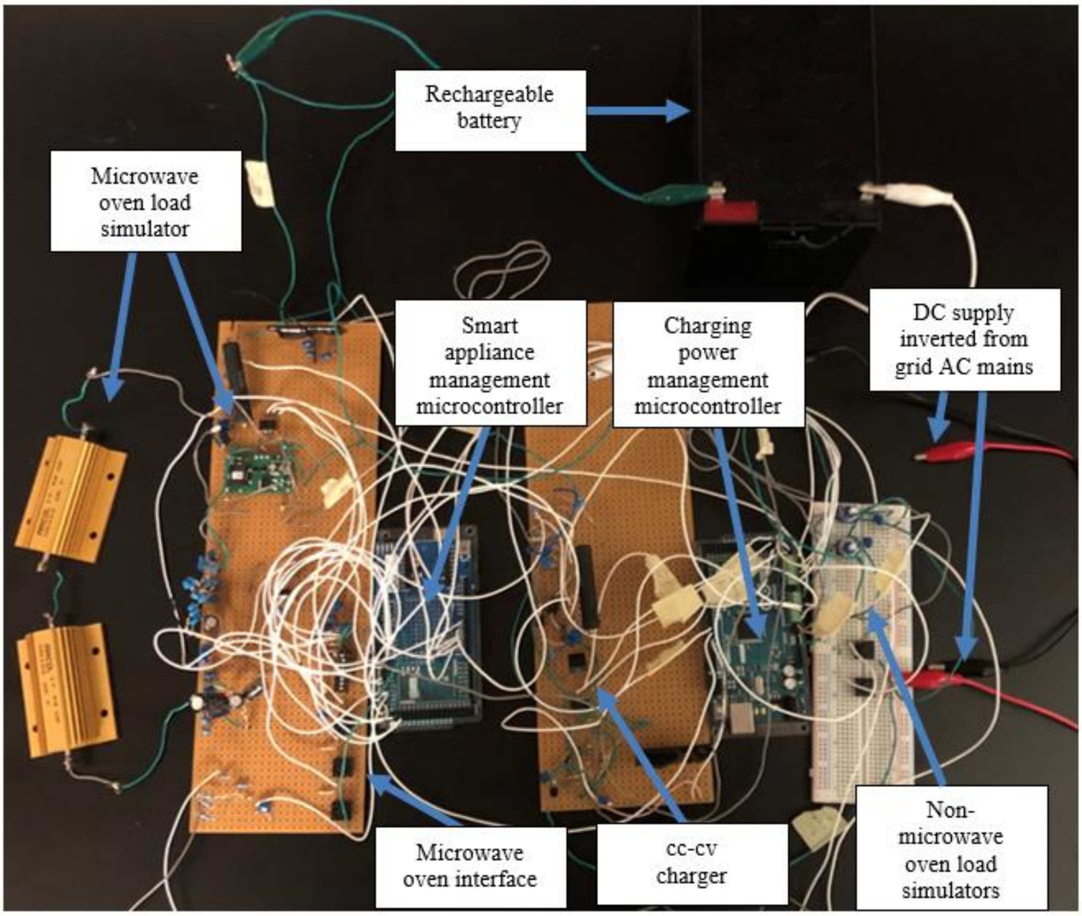

Figure 71 Proposed novel smart appliance management strategy prototype

The microwave oven interface within the practical set-up was constructed to incorporate 5 defined power levels: 1400W, 1000W, 800W, 600W, and 400W. The practical set-up was utilised to test the different algorithms within the proposed management strategy. Those algorithms are categorised into two applications of RBP discharge constraint and RBP capacity constraint. The tests defined for those two categories and their algorithms are presented. Furthermore, their expected results based on theoretical calculations from the relevant algorithms and equations (previously highlighted in this chapter) were determined (presented in part 4.4.3 of this section).

4.4.2.1 RBP discharge constraint

The RBP discharge constraint functionality aims to avoid the operation of the microwave oven at a power level which would result in the RBP instant discharge capability to be exceeded. Within this category, there are two algorithms which can be applied. The first one is where the microwave oven power level request is identified to be adequate for that available RBP discharge power capability. If the microwave oven power requested is determined to be exceeding the discharge limit, a second algorithm is performed. The proposed management strategy searches for an alternative power level and operational time which are compliant with the RBP discharge limit. Both algorithms are set to be tested using five different scenarios defined in Table 9.

Table 9 RBP discharge constraint experimental set-up test protocol

Operational scenario P_D (W)	Operational scenario P_{DS} (W)	Operational scenario P_c (W)	Operational scenario P_m (W)	Operational scenario t_m (Minutes)
1600	1500	0	1400	1
1600	1000	0	400	3
1600	1600	650	400	3
1600	1900	570	400	3
1600	1500	550	1400	3

In the tests of Table 9, various operational scenarios are defined including that of charging power availability. The tests aim to test the discharge power constraint only, therefore, the RBP voltage is set to be equivalent to a level of capacity more than that required by the microwave oven. During the tests, the discharge power (P_{DS}), microwave oven settings ($P_m(t)$), RBP discharge limit (P_D), and microwave oven status control are to be monitored and logged.

4.4.2.2 RBP capacity constraint

The proposed novel management strategy is not to permit microwave oven operation at energy consumption levels which will result in exceeding the RBP capacity constraint. The is achieved via an algorithm which determines if the requested energy consumption at the defined power level and time duration would meet the capacity constraint or not. In the case of positive identification, the microwave oven operation is allowed. On the contrary, if the outcome is negative, another algorithm is initiated. This captures the possibility of utilising a lower power level and an extended operational duration to achieve an RBP compatible energy consumption requirement. Available charging power is considered in the algorithm. The test protocol formulated for those algorithms is presented in Table 10.

Table 10 RBP capacity constraint experimental set-up test protocol

Operational scenario B_{cn} (Wh)	Operational scenario P_{DS} (W)	Operational scenario P_c (W)	Operational scenario P_m (W)	Operational scenario t_m (Minutes)	Operational scenario B_{ci} (Wh)
200	0	0	600	3	100
200	190	0	1400	5	100
200	100	600	800	9	130
200	400	500	1400	7	140
200	0	260	1400	5	80
200	0	250	1400	11	80
200	800	400	800	10	120

The defined tests within Table 10 avoid the presence of any instant RBP discharge constraint to focus the aim of the testing towards the capacity constraint algorithms. The RBP voltage levels are varied to provide the suitable testing condition with different capacity availabilities. The microwave oven settings ($P_m(t)$), RBP available capacity (B_{ci}), microwave oven operational capacity (MW_c), and its status control signal are the set of measurables throughout the tests for analysis purposes.

4.4.3 **Results**

Extraction of the different results for the defined tests carried on the scaled down hardware prototype was performed. The results collected are to be used in the analysis of the proposed novel smart appliance management strategy. The results highlight the level of success for the proposed algorithms and their implementation in achieving the desired aim of increasing the microwave oven dependency in the ERV. The proposal is set to reach this goal without needing to upgrade the campsite infrastructure which comes at a high expense.

In order to facilitate effective analysis on the proposal, theoretical results were calculated for the different test scenarios carried. Those are deduced from algorithms in Figure 66 and Figure 67 and their relevant equations (22), (23), and (24).

The theoretical and practical results are presented in this section for each application category of RBP instant discharge and capacity constraints. The order of presentation follows that utilised in the experimental setup section of this chapter.

4.4.3.1 RBP instant discharge constraint

The request for microwave oven operation at a certain power level and time duration $P_m(t)$, triggers an algorithm which performs analysis on the capability of such microwave oven operation in relation to the constraints and current conditions of instant RBP discharge. With negative outcome of this analysis, further algorithm is undertaken to identify any capability of operating the microwave oven at a lower power level but with a duration that results in an energy input equating to that originally requested.

During the testing carried on both algorithms, the main parameter which is resultant from the proposal capability and the success in implementation is the final operational microwave oven setting ($P_m(t)$). The theoretical results for the various carried tests (defined in Table 9) are presented in Table 11 below.

Table 11 RBP discharge constraint experimental set-up test protocol theoretical results

Operational scenario P_m (W)	Operational scenario t_m (Minutes)
0	0
400	3
400	3
0	0
600	7

Figure 72 shows the practical result of operational scenario one where the test defined sets the instant discharge power limit of the RBP to be 1600W and the discharge rate of the non-microwave oven operation at 1500W. The operation request was made at 1400W for 1 minute. Charging power was not applied within the test.

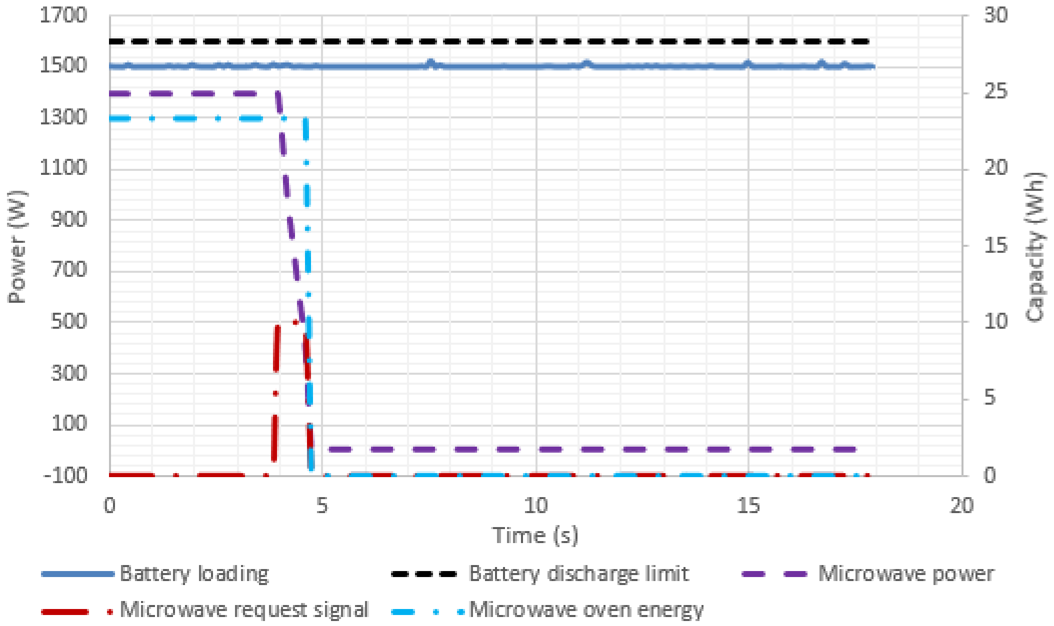

Figure 72 Practical result for scenario 1 test performed on the hardware prototype of proposed management strategy RBP instant discharge constraint algorithms

The result for operational scenario two practical testing is demonstrated in Figure 73. In this scenario, the instant discharge capability of the RBP was set at 1600W with an actual discharge of 1000W at the point of microwave oven request. This request was set at 400W for 3 minutes. Furthermore, charging power was set to 0W throughout the test.

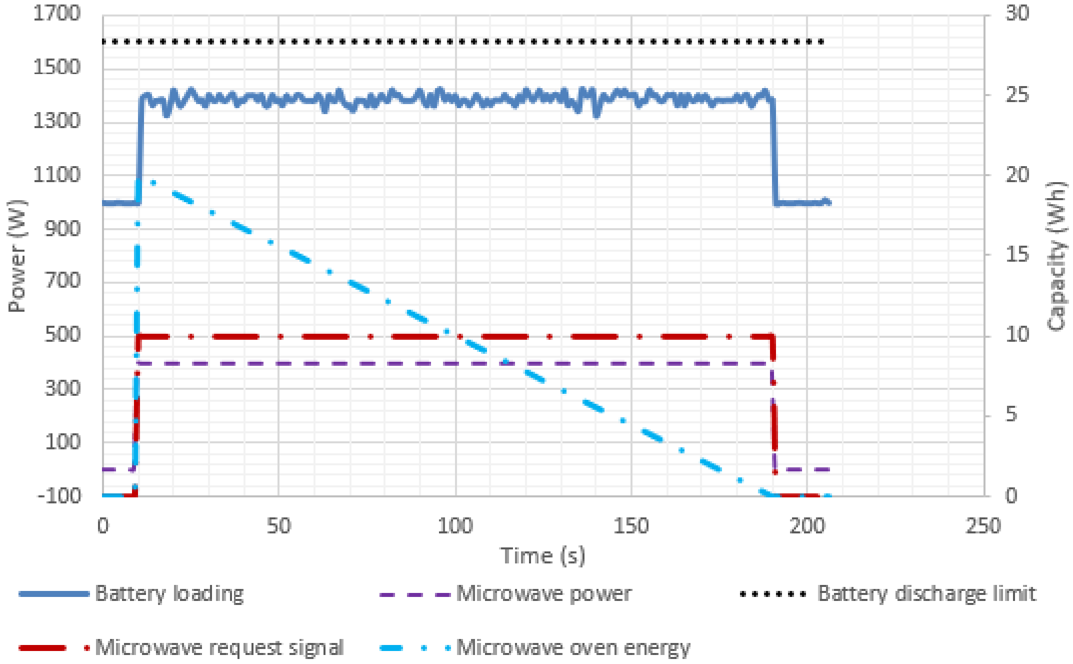

Figure 73 Practical result for scenario 2 test performed on the hardware prototype of proposed management strategy RBP instant discharge constraint algorithms

Scenario three practical testing was defined with a microwave oven request for operation at 400W for 3 minutes. This request was made at the point of 1600W instant discharge presence on a 1600W maximum discharge capable RBP. However, the charging power was set to 600W. The result for the testing carried on this scenario is highlighted in Figure 74.

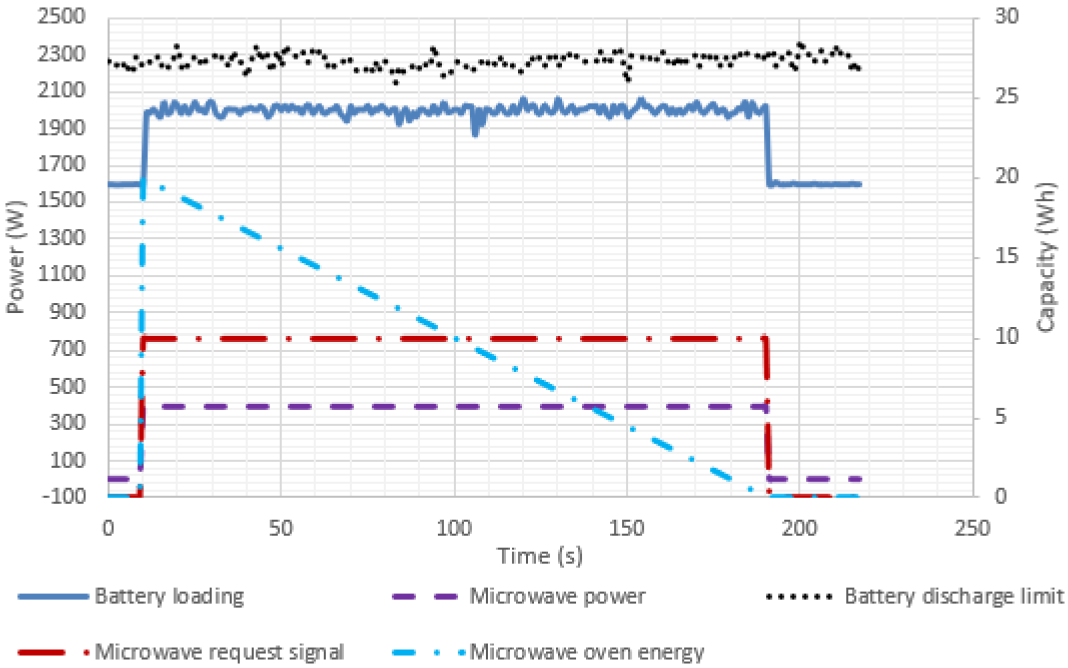

Figure 74 Practical result for scenario 3 test performed on the hardware prototype of proposed management strategy RBP instant discharge constraint algorithms

The fourth scenario testing result extraction is reflected in Figure 75. The results were collected under the condition of 1900W instant discharge and 1600W maximum supply limit RBP. However, 570W charging was present at the request of microwave oven operation for 400W and 3 minutes.

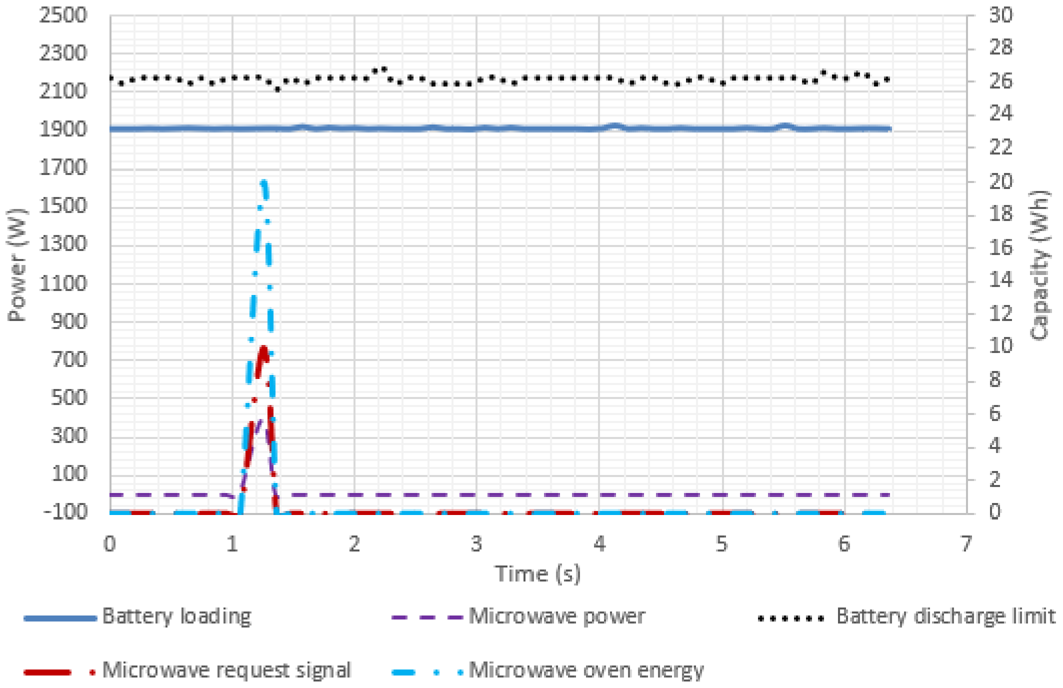

Figure 75 Practical result for scenario 4 test performed on the hardware prototype of proposed management strategy RBP instant discharge constraint algorithms

The practical result in Figure 76 is for testing scenario five. During the testing, RBP discharge limit was set at 1600W and the other loads were defined to operate at 1600W. The request made by the microwave oven was 1400W for 3 minutes with the presence of 600W charging power.

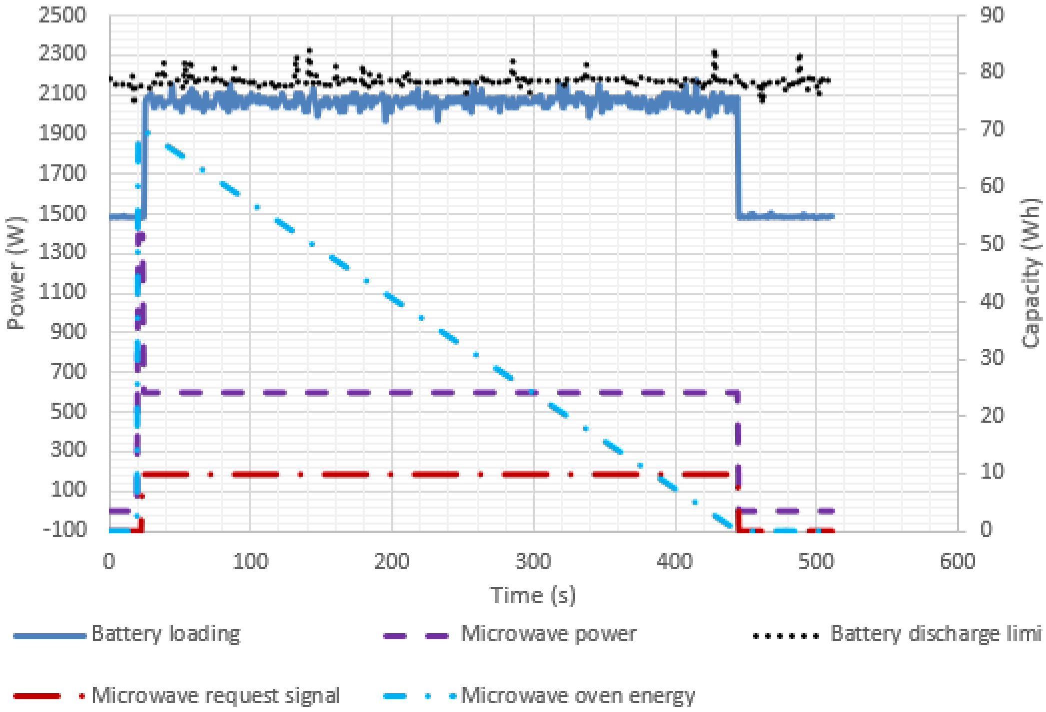

Figure 76 Practical result for scenario 5 test performed on the hardware prototype of proposed management strategy RBP instant discharge constraint algorithms

4.4.3.2 RBP capacity constraint

A second set of analysis is carried with the microwave oven request for operation at power level and time duration $P_m(t)$. This is performed post instant discharge constraint analysis success. The algorithm aims to confirm RBP capacity availability for the requested microwave energy operation. In the case of determining insufficiency for supplying the energy consumption at the requested power level, a further algorithm is performed. It analyses potential for use of lower power level and extended duration with relation to available charging power to reduce required RBP energy consumption, hence, available capacity sufficiency.

The main measurable resultant from the proposal algorithm during the tests is the final microwave oven status with its power and duration setting ($P_m(t)$). Theoretical results were calculated through appropriate equations (24) to (28) with reference to algorithms in Figure 68 and Figure 69. This was performed for the various defined testing scenarios in Table 10. Those results are shown in Table 12 and are to be utilised within the assessment of the proposal.

Table 12 Experimental set-up test protocol theoretical results for RBP capacity constraint algorithms

Operational scenario P_m (W)	Operational scenario t_m (Minutes)
600	3
0	0
800	9
600	16.33
800	8.75
0	0
0	0

Practical result for the testing carried under scenario one conditions is reflected in Figure 77. The conditions of the test compromise of 200Wh RBP capacity limit, 0W instant discharge from other loads, 600W for 3 minutes microwave operation request, 0W charging power, and 100Wh available RBP capacity.

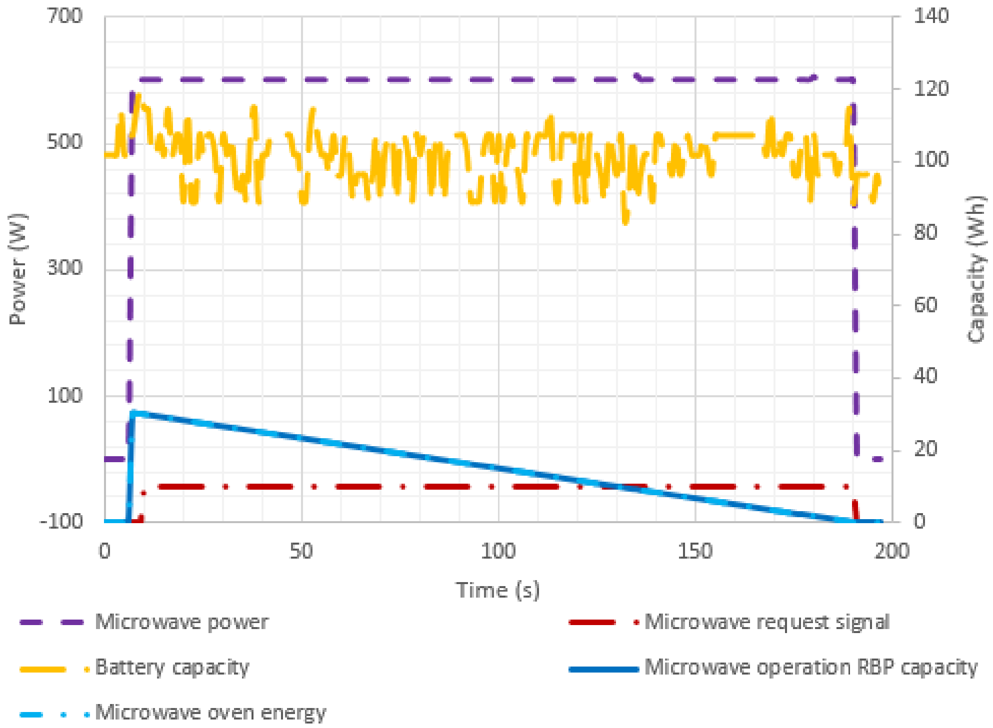

Figure 77 Hardware prototype practical test scenario 1 result for proposed management strategy RBP capacity constraint algorithms

The result in Figure 78 is for scenario two defined practical testing. This incorporates a microwave oven request for operation at 1400W for 5 minutes, 100Wh available RBP capacity, 200Wh RBP capacity limit, 0W charging power, and 190W instant discharge level from non-microwave loading.

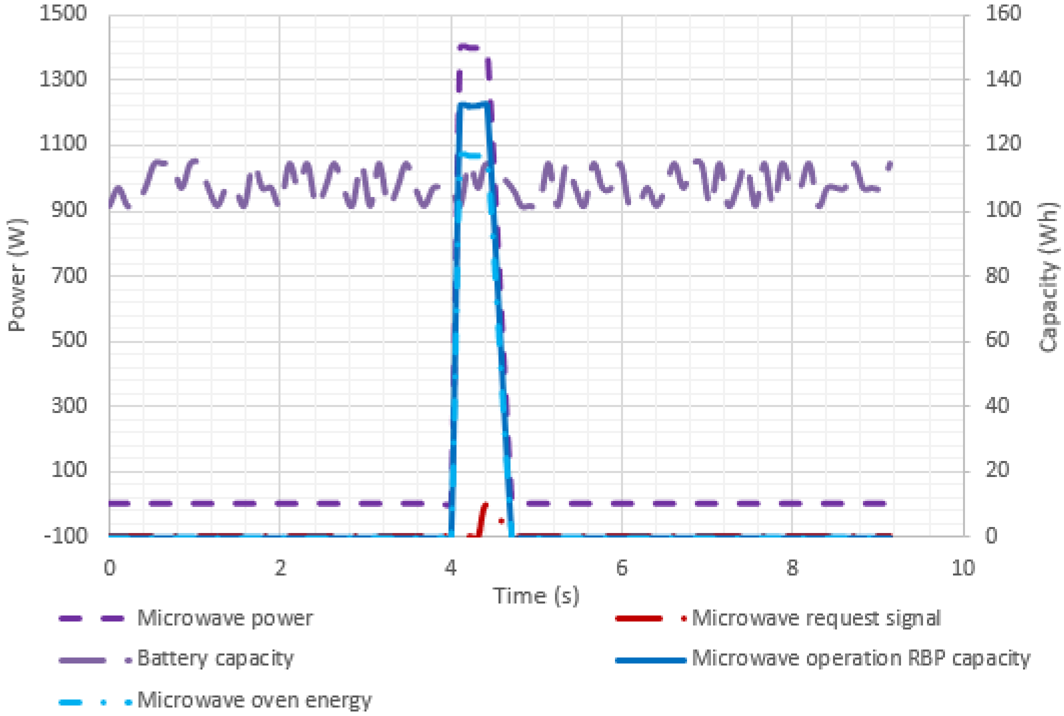

Figure 78 Hardware prototype practical test scenario 2 result for proposed management strategy RBP capacity constraint algorithms

Operational scenario three included an RBP available capacity of 130Wh, microwave oven request at 800W for 9 minutes, 600W charging power availability, 100W of non-microwave oven loading, and RBP capacity specification of 200Wh. The result for this test is presented in Figure 79.

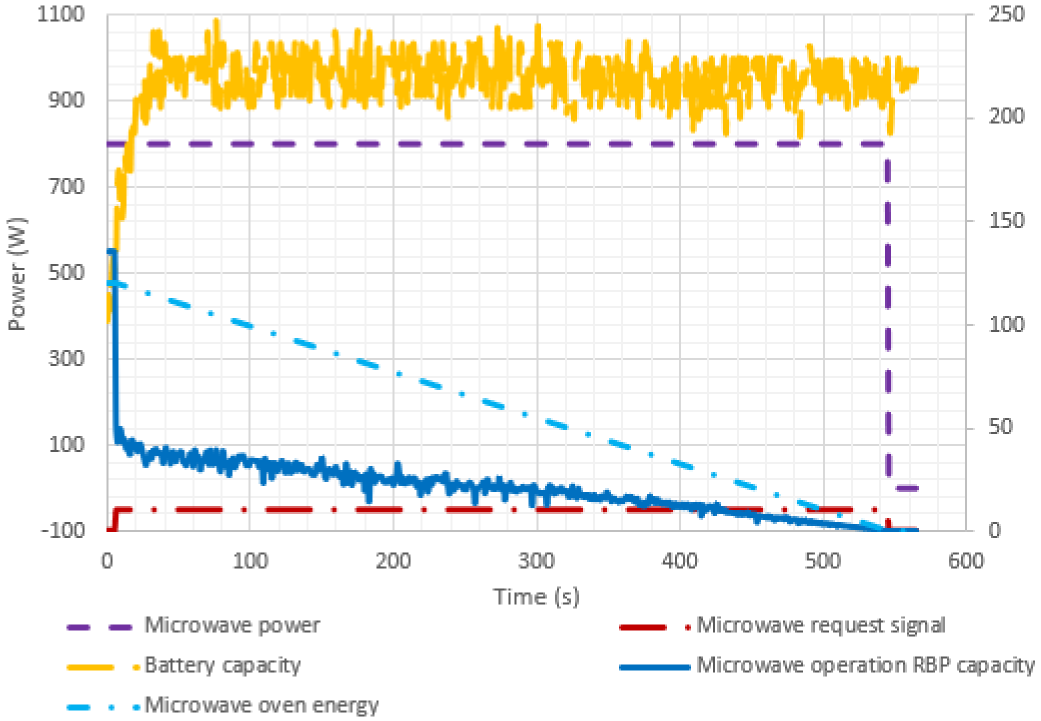

Figure 79 Hardware prototype practical test scenario 3 result for proposed management strategy RBP capacity constraint algorithms

The fourth operational scenario testing result of Figure 80 was extracted for a microwave oven operational request of 1400W for 7 minutes. The RBP 100% SOC capacity was set to 200Wh, a charging power of 500W was provided, the RBP available capacity was at 140Wh, and 400W non-microwave oven loading was present.

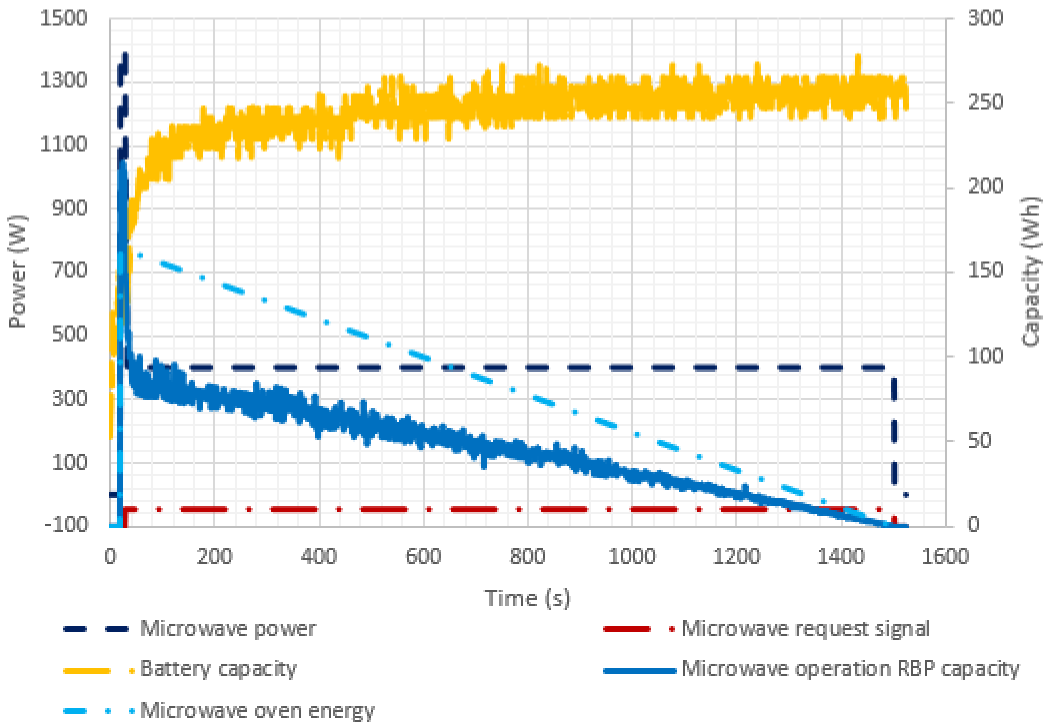

Figure 80 Hardware prototype practical test scenario 4 result for proposed management strategy RBP capacity constraint algorithms

Testing scenario five was with a microwave oven request of 14000W for 5 minutes, 260W charging power, 0W current loading, 200Wh RBP capacity, and 80Wh obtainable RBP capacity. Result gathered for this scenario is shown in Figure 81 below.

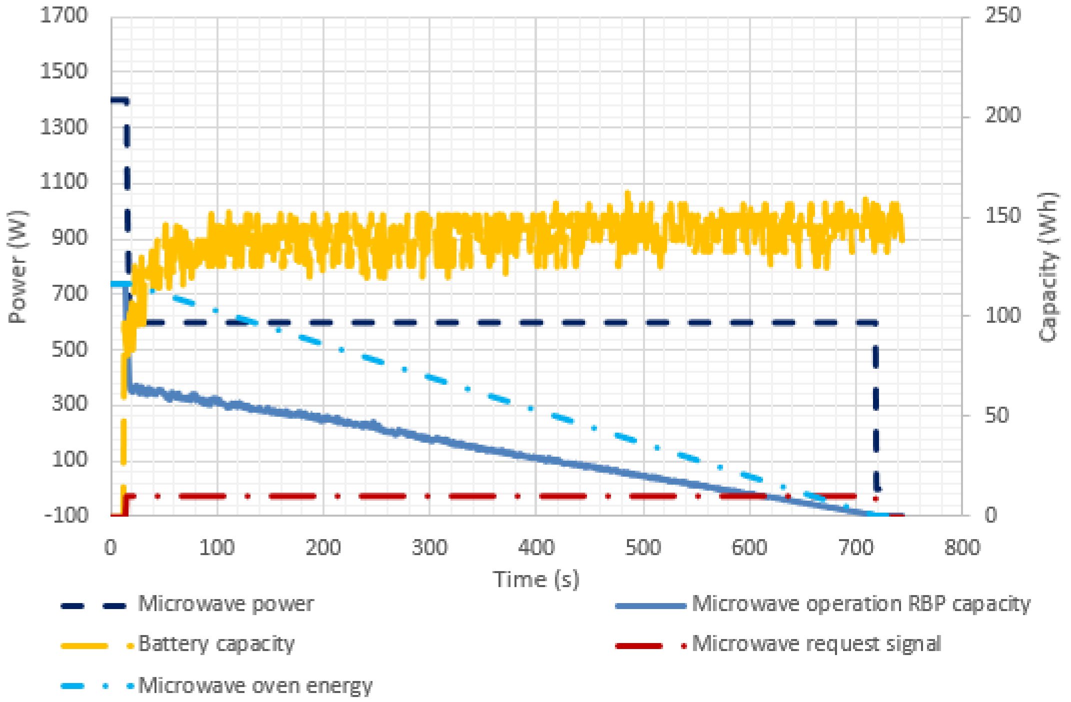

Figure 81 Hardware prototype practical test scenario 5 result for proposed management strategy RBP capacity constraint algorithms

Scenario six was set to have a microwave oven request of 14000W for 11 minutes with an available RBP capacity of 80Wh. Furthermore, a charging power of 250W, no non-microwave loading, and 200Wh RBP nominal capacity were present. Extracted results throughout the testing are presented in Figure 82.

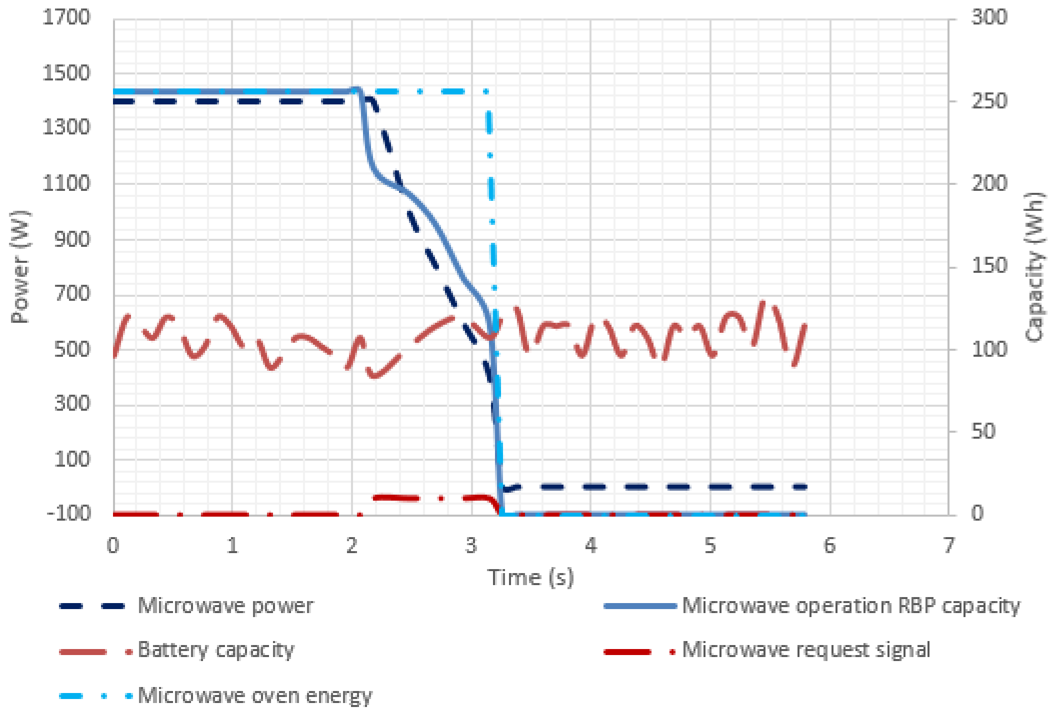

Figure 82 Hardware prototype practical test scenario 6 result for proposed management strategy RBP capacity constraint algorithms

Results of the final testing scenario seven are shown in Figure 83. During the testing, charging power of 400W, 800W non-microwave discharge power, and 200Wh nominal RBP capacity were set. The microwave operation request made is 800W for 10 minutes.

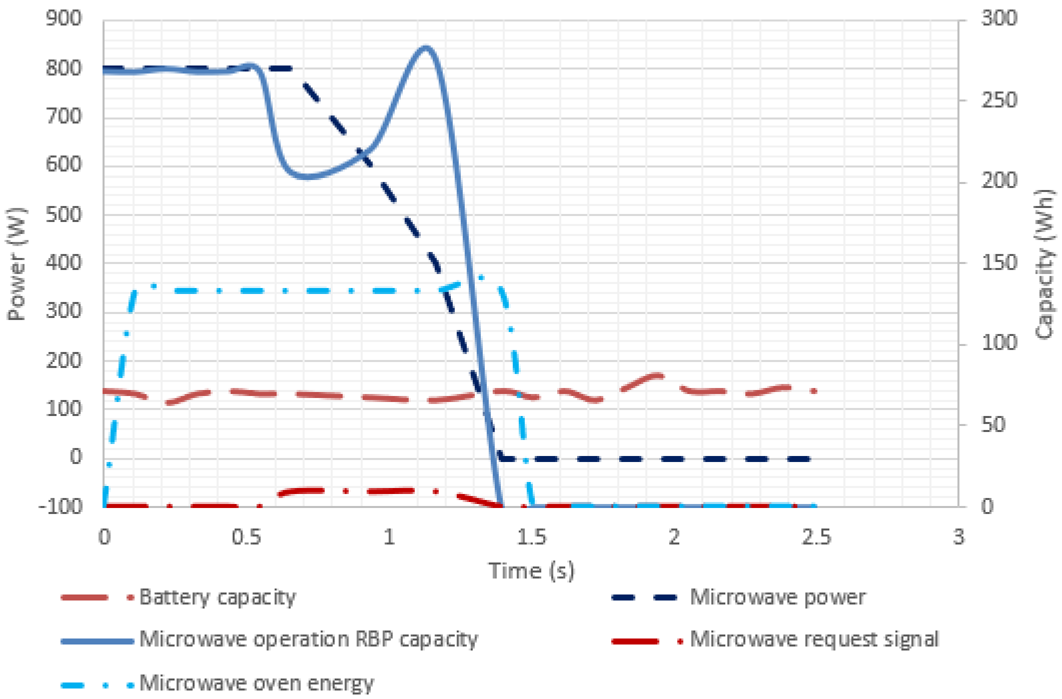

Figure 83 Hardware prototype practical test scenario 7 result for proposed management strategy RBP capacity constraint algorithms

4.4.4 **Analysis and discussion**

Results gathered from the experimental set up for the proposed novel smart appliance management strategy reflects its success in implementation and algorithms capability of achieving their intended functionality. The practical and theoretical results were also compared in the assessment of the proposal which is of the following scope:

- The practical results accuracy in comparison with that of theoretically calculated relevant results
- Fulfilment of defined functionality by the implemented algorithms
- Overall proposal success in reaching its aim. This is the increase of microwave oven dependency due to enhanced usability without upgraded infrastructure investment requirement

- Identification of proposal limitations

The analysis and discussion of the various results for the assessment of the proposed strategy is provided within this section in a synchronised order of the results listing within part 4.4.3. The theoretical results are referred to wherever relevant within the analysis and discussion.

4.4.4.1 RBP instant discharge constraint

The request of microwave oven operation initialises a check performed by the proposed novel smart appliance strategy to determine if sufficient RBP discharge power capability is available in relation to its limit. The charging power present, if any, is considered within this process. The microwave oven operation allowance is only provided with determination of the RBP discharge capability not being exceeded. Furthermore, the proposed strategy provides the flexibility of operating the microwave oven at lower power levels over a longer time providing an equivalent energy input as that originally requested. This allows the operation of the microwave oven in a manner which results in adhering with the instant discharge RBP constraint. Thus, increases the usability of the microwave oven, reduces the RBP specification required for the application, and utilises the available discharge RBP supply capability in an optimised form.

During scenario one testing of the RBP instant discharge constrain functionality, a request for microwave operation at 400W for 3 minutes was produced. No charging power was available, and the non-microwave oven loading was present at 1500W. Due to the RBP discharge power limit being 1600W, the microwave oven operation request should be refused according to the theoretical results in Table 11. The practical result collected in Figure 72 shows that the microwave request for operation was triggered and rejected within 0.785 seconds. The rejection was only produced after the implemented strategy proposal seeking alternative microwave oven settings without any success. This is seen with the microwave oven power setting reducing from 1400W to 400W gradually prior to the removal of the microwave request signal and its energy requirement reaching 0Wh. Furthermore, the microwave oven energy requirement is seen to be stable at 23.33Wh throughout the analysis of alternative microwave oven settings which reflects 100% accuracy in its proposed operational time which is amended each time with relevant power reduction. Therefore, the practical result is in agreement with that theoretically calculated. This demonstrates effective operation of the proposed microwave oven alternative setting identification within its RBP instant discharge constraint algorithms. Avoiding RBP discharge parameter exceedance with the lack of charging power was also successful.

Further testing carried within scenario 2 was defined to have 1000W non-microwave oven loading, 1600W RBP discharge limit, and no charging power. Therefore, within the practical testing, a microwave oven operation request at 400W for 3 minutes should be permitted as per the theoretical result in Table 11. The result in Figure 73, collected from the hardware prototype, reflects that the microwave operation was permitted at 400W. The microwave request signal is observed throughout a duration of 3 minutes where the microwave oven energy gradually reduced from 20Wh to 0Wh. Furthermore, the allowance of microwave oven operation is shown in the overall RBP loading increasing from 1000W to 1400W. This increase appeared with the microwave request signal triggering and ended after 3 minutes to return to 1000W. The practical result shows that the algorithm behind the RBP discharge constraint functionality is of successful design and implementation. Allowing the microwave oven operation when sufficient RBP instant discharge power is present in relation to its limit during the absence of charging power.

In the third scenario testing, charging power was set at 650W, non-microwave RBP loading was present at 1600W, and the RBP discharge limit constraint was of 1600W. Within those conditions, the theoretical result in Table 11 highlights that a microwave oven request of 400W for 3 minutes should be accepted. This is aligned with the result extracted from practical testing seen in Figure 74. The operation of the microwave oven is observed in its energy level reducing over 3 minutes from 20Wh to 0Wh. The result also reflects the RBP discharge limit to be at 2250W. This highlights the consideration of the proposed strategy for the available 650W charging as it amended the RBP discharge limit accordingly in real-time. This consideration was the reason behind the proposed strategy allowance for the microwave oven operation. The practical result demonstrates the ability of the proposed novel strategy to factor in the availability of RBP charging in its decision, hence, achieving its desired functionality in enhancing the microwave oven usability. Additionally, this reduces RBP specifications required due to charging power utilisation.

The capability of the proposed strategy to avoid RBP discharge limit exceedance even within the presence of charging power was tested in scenario four. A charging power of 570W was applied to an RBP with a discharge limit of 1600W. The microwave oven request of 400W for 3 minutes was triggered with the presence of 1900W non-microwave oven loading. According to the theoretical result calculated for this scenario in Table 11, such request should be denied because the microwave oven operation would result in an overall RBP loading of 2300W. Such overall loading is in exceedance of the RBP discharge limit of 2170W (considering the charging power availability). The result of the practical test in Figure 75 shows the RBP discharge limit at an average of 2153.7W throughout the testing period. This indicates the successful consideration of available charging power within the RBP discharge limit setting. Non-microwave RBP loading was also present at 1900W prior to the microwave oven request. Agreeing with the theoretical result, the practical result highlights the rejection of the microwave oven request for operation as the RBP loading didn't vary from its 1900W level. Furthermore, the microwave oven energy was stable at 20Wh and then reduced to 0Wh after its request signal was eliminated within 0.105 seconds from the request initiation.

In the final testing of scenario five, a request for microwave oven operation, at 1400W for 3 minutes, was initiated during the presence of 550W RBP charging power. The RBP discharge limit was set to 1600W and non-microwave loading was present at 1500W. Microwave oven request at mentioned conditions should be accepted at a new setting of 600W for 7 minutes according to the theoretical result in Table 11. This is due to the proposal algorithm for the RBP discharge limit being set out to enhance the usability of the microwave oven through determining lower microwave power setting operation that aligns with the available instant discharge power. The capability was confirmed practically as indicated in Figure 76. The microwave oven operated at 600W for 7 minutes although originally requested at 1400W for 3 minutes. The RBP discharge limit was seen within the result to be at 2150W. This shows the consideration of the available charging power, thus, contributing towards increasing the microwave oven usage potential. Furthermore, the overall loading is shown to be increased from 1500W to around 2100W with the microwave oven operation. This consumption is just below the RBP discharge limit of 2150W which highlights an optimised use of available power to a level of 96.67%

(in relation to that allowable) due to the alternative microwave oven setting permitting its operation. Finally, the variation in microwave oven operational setting maintained the original energy requested with 100% accuracy as the microwave oven energy was stable at 70Wh during the power setting reduction search.

Considering all results extracted from testing the functionality of RBP instant power constraint within the novel smart appliance strategy, all the capabilities of RBP instant power limit compliance, real-time variation of RBP discharge limit with consideration of charging power available, and enhanced microwave oven usability through setting flexibility for available discharge power optimisation were accurately and successfully achieved.

4.4.4.2 RBP capacity constraint

The second constraint, which is to be considered upon microwave oven operation request, is the available RBP capacity. The proposed smart appliance management strategy determines the required microwave oven operation energy capacity from the RBP. This includes the present non-microwave loading which it assumes to be present for the whole duration of the microwave oven operation. If the required operational capacity is equal to or less than that available within the RBP, then the initiation of the microwave oven is permitted. The proposal factors in the availability of charging power within this analysis. Furthermore, alternative microwave oven operational settings can be set by the proposed strategy in the case of such possibility being present when originally requested setting don’t meet the available RBP capacity. This results in enhanced usability of the microwave oven, with reduced RBP specification requirements, and optimised utilisation of available RBP capacity.

Test scenario one carried on this functionality of the novel proposal was defined to operate a microwave oven at 600W for 3 minutes. This was to be initiated with 100Wh available RBP capacity, no charging power applied, and absence of non-microwave oven loading. The theoretical result for this scenario in Table 12 indicates that the microwave oven request should be permitted. This is due to the required operational capacity from the RBP being less than 100Wh. The collected practical result within Figure 77 shows agreement with the theoretical result as the microwave oven operation was allowed. This is reflected in the progression of microwave oven energy from 30Wh to 0Wh over 3 minutes. The operation began at the point of microwave request signal triggering which was eliminated after the 3 minutes required. This highlights the successful implementation of the proposed algorithm in allowing the microwave oven operation where sufficient RBP capacity is identified without the presence of charging power or other loading sources.

During scenario two, the test was defined for the proposed strategy to receive microwave oven operation request at 1400W for 5 minutes. This was to be produced while 190W non-microwave loading being present, available RBP capacity set at 100Wh, and no charging power applied. The theoretical result for such scenario (Table 12) highlights the incapability of accepting the microwave oven operation with no other alternative microwave oven setting being present. Figure 78 demonstrates the practical result gathered which is aligned with the theoretical analysis. The microwave oven energy is observed to be at 116.67Wh at the point of the request initiation and then immediately reduced to 0Wh after the duration of 0.29 seconds taken by the proposed strategy to terminate the request. Prior to the termination, it is demonstrated in the practical result that the strategy did not perform a search on alternative microwave setting. This is a positive outcome as there was no available charging power to be utilised in such analysis. Therefore, the implemented strategy achieved its intent in not granting microwave oven operation under circumstance which would result in RBP discharge beyond its DOD limit.

In scenario three testing, a microwave oven request was made for operation at 800W for 9 minutes. 130Wh available RBP capacity, 600W charging power, and 100W non-microwave oven loading were the conditions present upon the microwave oven request. Table 12 presents the theoretical analysis result to accept the microwave oven operation request. This is in agreement with the practical result of Figure 74. It can be observed within the practical result that the required RBP capacity for the microwave oven operation (along with the originally present RBP loading) was initially calculated to be at around 135Wh. However, the available RBP capacity was at 132Wh at the time of request. The microwave oven operational capacity requirement then dropped to 51.36Wh where its operation was permitted. This is indicated by its gradual energy requirement decrease over 9 minutes. This demonstrates the functional ability embedded in the proposal to consider the charging power available in aiding the final decision of microwave oven operation permission.

In turn, this determines the true requirement of RBP capacity for the microwave oven operation, enhancing the microwave oven usability, and optimising available RBP capacity.

Scenario four compromised of 140Wh available RBP capacity, 400W non-microwave loading, 500W charging power, and microwave oven request at 1400W for 7 minutes. Such scenario theoretically will result in microwave oven operation at 600W for 16.33 minutes (Table 12) as the originally requested microwave oven operational setting together with the existing RBP loading results in an operational RBP capacity requirement exceeding that available (even with the consideration of available charging). The practical result in Figure 80 shows that during the laboratory hardware testing, the microwave oven operated at 400W for 24.5 minutes. The result is one power level less than that theoretically anticipated, hence, the operation was of longer duration. This is due to the RBP available capacity varying at a substantial level which impacted the result. Available RBP capacity at the point of microwave oven request trigger was 145.46Wh. This available capacity level reduced to 125.46Wh while an alternative microwave oven setting was being searched for by the proposed strategy. Such reduced capacity level is less than the required RBP capacity for microwave oven operation (136.11Wh) determined by the strategy if it is to operate at 600W for 16.33 minutes. Therefore, the 600W operation was dismissed in the practical set-up testing and an energy requirement of 114.75Wh was allowed at microwave setting of 400W for 24.5 minutes. The substantial variation within the available RBP capacity parameter being processed by the strategy is due to the limited range of 1.1V used to determine the RBP SOC, thus, its capacity. This limitation of the hardware prototype is due to the method utilised for the SOC and capacity determination rather than the smart appliance strategy itself. Given the processed parameters, the proposal made the appropriate alternative microwave oven setting to an accuracy of 100% as the microwave oven energy is observed within the result to be constant at 163.33Wh during the microwave setting variations. Therefore, successfully achieving its functionality of facilitating flexible operational levels for enhanced usability and usage of available RBP capacity in an optimised manner. Finally, the RBP available capacity is seen to drastically increase within the first 54 seconds of the test, reaching a supposed capacity level which exceeds its nominal. This further indicates that the utilised method for its determination is not accurate. As the RBP

SOC and capacity level identification method are not within the scope of this thesis, this can be disregarded within the assessment of the proposed smart appliance strategy itself.

Fifth scenario testing incorporated the microwave oven operation at 1400W for 5 minutes. The conditions of the RBP were set at a charging power of 260W, RBP available capacity of 80Wh, and non-microwave loading of 0W. The permission of microwave oven operation at 800W for 8.75 minutes is the theoretical result for this scenario (show in Table 12). Practical result of Figure 81 shows the power level being reduced from 1400W to 600W prior to authorising the microwave oven operation. Similar to the practical outcome of scenario four, the accuracy level of final operating microwave oven setting in relation with energy input originally requested is 100% as no deviation from the 116.67Wh was identified due to the power variation. However, the microwave oven operating power is again one level lower than that theoretically calculated and accordingly of extended duration. This is also due to the instability of the RBP available capacity reading where the processed parameter varied from 83.63Wh at the point of microwave request to 78.19Wh when the implemented strategy proposal was performing possibility analysis for an 800W operation. At 800W for 8.75 minutes, the required microwave oven operational capacity from the RBP would be 78.65Wh, hence, exceeding that seen to be available at the time of the assessment. The strategy therefore reduced the power level operation to 600W and extended operational time to 11.67 minutes where the required RBP capacity from the microwave oven operation was reduced to 65Wh, thus, allowing its operation at this setting. This limitation of SOC and capacity determination method revealed the capability of the implemented strategy to avoid exceeding the RBP capacity DOD level to an accuracy level of 0.59%. Dismissing the limitation imposed on the testing of this scenario, the capability of the proposal to vary the microwave oven settings to meet RBP capacity constraints under the condition of charging power availability and lack of non-microwave oven loading was demonstrated.

RBP charging of 250W, lack of non-microwave oven loading, and RBP available capacity of 80Wh were conditions set for scenario six testing. A microwave oven operation request was to be triggered at 1400W for 11 minutes within those conditions. According to Table 12, theoretically the microwave oven operation should be rejected because even at the lowest power level possible and charging power available considered, the required RBP capacity would still exceed that of 80Wh available. This was successfully replicated practically as shown in Figure 82. It is observed in the practical result that the microwave oven setting was reduced from 1400W to 400W, successfully maintaining the microwave oven energy at 256.67Wh before the operation request was refused. The decision was made by the strategy within 1.081 seconds from the request. Effective operation of the capacity constraint functionality is demonstrated within the practical result where microwave oven operation was rejected after factoring in available charging power and exploring alternative setting.

Final testing of scenario seven for the proposed smart appliance management strategy was based on a microwave oven operational request at 800W for 10 minutes. At the point of request, 400W charging power, 800W non-microwave oven loading, and 120Wh RBP capacity were set to be present. Theoretically, Table 12 presents the result to be the incapability of microwave oven operation at any setting. The practical result of Figure 83 demonstrates a similar outcome to that theoretically calculated. It shows the rejections of microwave oven operation after factoring in the available charging power and assessing the possibility of operating at lower levels within 0.738 seconds from the original request creation. It can be observed within the practical result that the required microwave oven operation capacity from the RBP initially was reduced from its maximum of 267.95Wh to 205.84Wh when the charging power available was considered. But this capacity requirement level increased to 219.84Wh with the assessment of 600W microwave operation for 13.33 minutes. Then further increased to 274.7Wh with the strategy’s assessment for the operation at 400W for 20 minutes. This highlights a limitation in the algorithm of the proposal in assuming that the non-microwave loading is continuously present at the same level for the duration of the microwave oven operation. The is because at high non-microwave loading levels, it results in increased RBP capacity requirements. At reduced microwave power settings, the increased operating duration which the non-microwave loading is assumed also to be in-situ, creates increased RBP capacity requirements.

Overall, the results from the practical testing highlight the proposed novel smart appliance strategy to effectively control the operation of the microwave oven in relation to the available RBP capacity. The various capabilities of charging power consideration, excessive DOD avoidance, flexible microwave oven operation for enhanced usability, and optimised use of available RBP capacity were all successfully obtained. However, two limitations were identified in the practical prototype constructed. The first limitation is the instability of the RBP available capacity parameter. This resulted in lower microwave oven power level operations than theoretically determined, hence, reduces the optimisation of available RBP capacity. Such limitation is due to the utilised method in SOC and available capacity determination and not of direct relation to the smart appliance strategy proposed itself. The second limitation is of the proposed strategy itself where it assumes the non-microwave loading to be present throughout the whole operational duration of the microwave oven. Such assumption is not necessarily accurate and causes incapability of operating the microwave oven when high levels of non-microwave loading are present, hence, reducing its usability.

4.4.5 **Conclusion**

A novel RBP powered smart appliance management strategy proposal is presented with the aim of enhancing the usability of electrical ERV equipment within the low grid supply capability environment present in camping grounds. The proposal facilitates higher power performances of the appliances while ensuring the RBP constraints of instant discharge and capacity are not exceeded. Furthermore, intelligent solutions are incorporated which optimise the RBP constraints specification, aiding the commercial feasibility of the RBP and maintaining enhanced usability of the electrical appliances.

A scaled down hardware prototype was constructed with integration of the novel proposal. Results extracted from performed tests on the prototype are in agreement with theoretical results derived from proposal algorithms and their relevant mathematical equations. The results for the individual solutions of the novel smart appliance management strategy, integrated to achieve its overall goal, show their successful implementation achieving their desired functionality:

- Avoidance of exceeding the RBP instant discharge limit capability was successfully performed whenever requested microwave operation would result in an overloading situation.
- Use of available charging power to increase the RBP discharge limit, thus, enhancing the microwave oven usability and reducing the required

RBP specification was always observed when charging power was present.

- Flexibility in microwave oven settings was performed to an accuracy level of 100% in comparison to originally requested energy input providing enhanced usability. It achieved an optimised use of available discharge power to a level of 96.67%.
- Microwave oven request rejection in the case of it resulting in RBP discharge limit exceedance is achieved within 0.785 seconds which includes the strategy performing a microwave oven setting reduction capability analysis.
- Elimination of potential RBP discharge beyond set DOD, due to microwave oven operation RBP capacity requirement exceeding that of available, was achieved with +0.59% accuracy.
- Factoring in available charging power to the RBP in identifying the actual required capacity for the microwave oven operation, resulting in increased usability with reduced RBP specification requirements, was demonstrated.
- Microwave oven setting variation was performed with 100% accuracy in relation to energy input requirement maintenance, resulting in improved usability and maximised usage of available RBP capacity.
- In the case of microwave oven alternative operational setting search for capacity purposes is performed with a negative outcome, the decision can take up-to 1.081s to be generated.

The proposed novel smart appliance management strategy is of capabilities which provide advantages in its implementation within the ERV application over prior proposed strategies which are of potential use in such sector. The proposal is practically proven through a scaled down laboratory constructed prototype where its results were compared with those of theoretical analysis. Limitation due to the used SOC and capacity identification method was identified along with a further limitation of the proposed strategy regarding the assumption of continues stable presence of non-microwave oven loading.

Chapter 5 ERV POWER MANAGEMENT STRATEGY

5.1 Introduction

Electrification of the recreational vehicle (RV) involves the two aspects of drivetrain and appliances. It is evident from literature in Chapter 2 that the implementation of both electrification aspects requires either novel solutions or an upgrade in the leisure industry infrastructure. However, substantial costs accompany performing an infrastructure upgrade in the campsites, which would result in a limited ERV adoption rate. Furthermore, such upgrades for substantial electrical loads would potentially lead to the supply grid itself requiring further upgrades.

Chapter 3 and Chapter 4 proposed novel solutions for both RV electrification aspects identified. The first proposal focused on the charging of onboard electric recreational vehicle (ERV) drivetrain and back-up rechargeable battery packs (RBPs) utilising a novel ERV charging power management unit. It eliminates the need for a campsite infrastructural upgrade to accommodate this additional substantial grid supply loading. This is achieved via its smart capabilities in pro-actively controlling the charging rate and non-charging loads operations. The latter proposal is a novel RBP powered smart appliance management strategy. This facilitates the increased dependency on electrical loads by utilising an RBP as means of a buffer, alleviating high instant demand levels on the camping ground electrical grid supply. In turn, the strategy within the proposal manages the load demand levels in relation to the RBP constraints (capacity and instant discharge).

A holistic and novel power management strategy can be derived from both proposals previously made in this thesis, forming a platform for the future ERV. This sets a first step towards ERV implementation in a manner which allows high adoption rate and can be further elaborated on in the future. The proposal also allows integration with the smart grid. This chapter will present the novel ERV power management strategy via theoretical and simulation models. Furthermore, its scope of scalability, a conclusion, and the further work required for its commercial implementation will be highlighted.

5.2 Novel ERV central controller power management strategy proposal

A proposal was made in Chapter 3 defining a novel ERV charging power management strategy, which monitors overall campsite grid supply loading conditions in relation to its capability. The strategy initiates control actions based on performed processing of the parameters monitored. The controls are set to proactively manage both the ERV charging rate and the operation of grid supplied loads in a suitable manner. Chapter 4 then proposed the use of an RBP as a source of power for smart appliances (e.g. the microwave oven discussed in the chapter) within the RV. Their operation is managed via a novel smart appliance strategy. Both proposals can be combined into one novel smart central controller management strategy within the future ERV, which manages both its charging and non-charging loads.

The novel ERV central controller management strategy is to be connected to all on-board loads. Those will be in direct communication with the central controller, receiving instructions including start, stop, and operational power level constraints where applicable. The control instructions introduced by the proposed ERV management strategy are based on measured parameters of the grid supply, RBP, and operational loads. Furthermore, the campground supply capability is to be a variable parameter determined by a central campsite controller which is in communication with the smart grid. This variation is to be determined through various conditions such as grid supply costs and C02 levels. The proposal architecture, detailed description of its operation, and the relevant algorithms responsible for those operations are presented below.

5.2.1 Architecture and algorithms

The proposal of the novel ERV central controller management strategy consists of three main management elements:

- ERV drivetrain and backup RBPs charging
- AC powered smart appliances - both time (schedulable / non-schedulable) and user (non-schedulable) dependant
- RBP powered smart appliances - both time (schedulable / non-schedulable) and user (non-schedulable) dependant

Non-schedulable appliances are required to operate immediately when requested by the end-user. Furthermore, their request for operation is based on the users' behaviour and cannot be anticipated. Examples of such appliances include the microwave oven, kettle, television, and hair dryer. On the contrary, the operation of schedulable appliances can be delayed and/or anticipated. Examples of such appliances include the washing machine, dish washer, and space heater.

In this proposal, non-schedulable appliances are categorised as either time or user dependant. However, schedulable appliances are always considered to be time-dependant. Time dependant non-schedulable appliances are those with capability of determining their energy consumption requirement for an operational cycle (such as the microwave oven). Those which are user dependant, their energy consumption cannot be forecasted due to the user having control over their operation (such as the television).

The proposal assumes that all time dependant smart appliances incorporate a level of intelligence that allows them to determine their operational duration requirement at a specific performance power. For example, a water boiler, is to be capable of monitoring its temperature, hence, estimating time required for its assumed full capacity to reach a set point through calculations at a specific heating power input. Based on this assumption, the central controller applies its relevant management strategy on the time dependant smart appliances. The overall architecture of the proposal is shown in Figure 84.

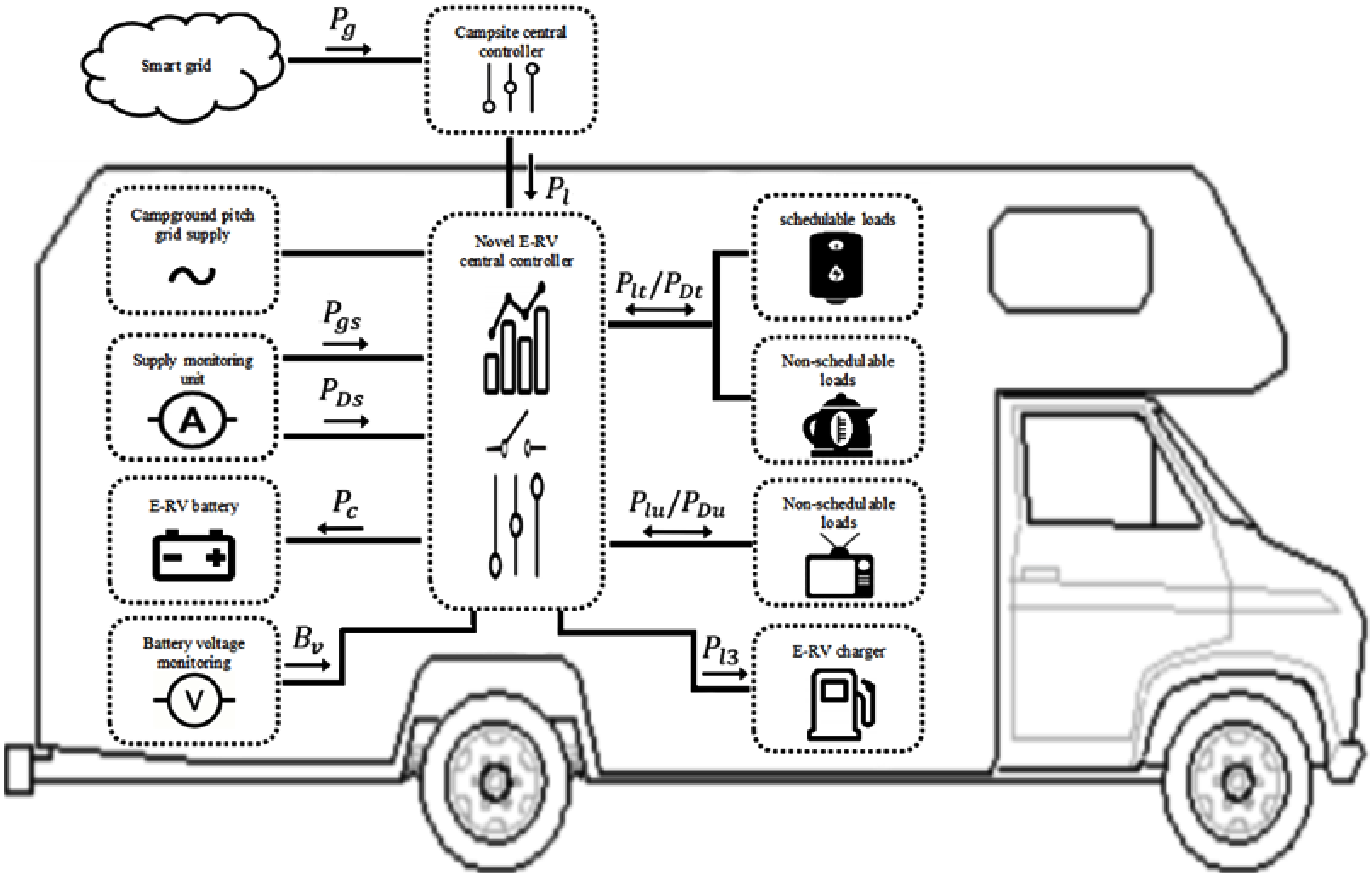

Figure 84 Novel ERV central controller management strategy proposal architecture

The management elements within the proposed architecture of Figure 84 are described and discussed below separately.

5.2.1.1 ERV RBP charging management

In the proposed architecture of Figure 84, the ERV charging aspect of the central controller strategy operates in the same manner as that described in Chapter 3 However, it has an additional functionality of grid supply capability limit (P_l) variation. The central controller strategy can manage amendments within the grid supply limit of the ERV while in-situ. Those are triggered via updates received from the campsite central controller.

In occasions where the variation in the AC supply capability limit is increased from that of the present, the algorithm in Figure 85 is performed by the proposed ERV central controller management strategy.

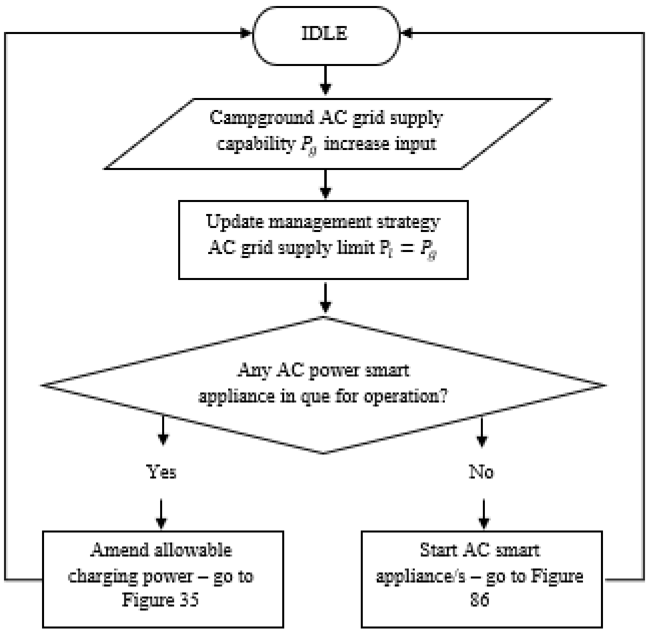

Figure 85 Proposed strategy algorithm when increased AC supply capability is introduced while in-situ

The algorithm in Figure 85 implements the change in the AC supply capability immediately, due to its increased nature. Then, it checks if there are any AC powered smart appliances queued for operation due to lack of available AC supply capacity prior to the capability increase. If present, the relevant smart appliances are operated accordingly, through a separate algorithm discussed in Section 5.2.1.2. If there are no queued AC powered appliances, the ERV charging power allocation is increased using the algorithm in Figure 35 (in Chapter 3 of the thesis).

In the case of a reduced AC supply capability, the central controller initiates the algorithm shown in Figure 86.

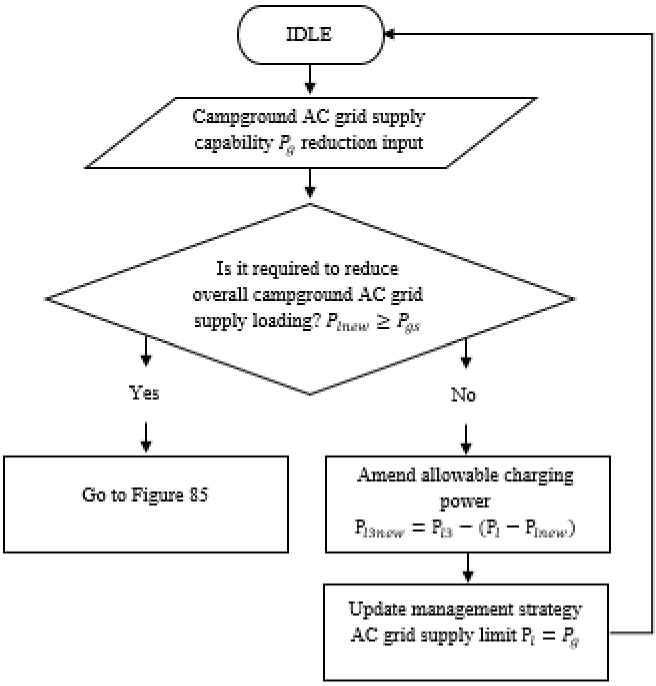

Figure 86 Strategy proposal algorithm for identifying impact on ERV AC supply loading due to reduced AC supply capability limit while in-situ

Within Figure 86 algorithm, the check performed to determine the requirement for variation within the ERV AC loading utilises equation (29).

$$P_{lnew} \geq P_{gs} \tag{29}$$

If the ERV AC loading (P_{gs}) is seen to be lower than the new ERV AC supply capability limit (P_{lnew}), it is determined that no variation in the ERV loading is required. However, the allocated maximum charging power (P_{l3}) is amended to ensure no overloading occurs due to any charger level changes. This allocation update is performed using equation (30).

$$\mathrm{P}_{l3new} = \mathrm{P}_{l3} - (\mathrm{P}_l - \mathrm{P}_{lnew}) \tag{30}$$

The new charging power allocation (P_{l3new}) is determined by reducing the current charging power allocation (P_{l3}) by the level of AC supply capability reduction.

If equation (29) highlights that the present loading (P_{gs}) is to exceed reduced AC supply capability (P_{lnew}), a requirement of ERV loading variation is identified. This is addressed in Figure 87 algorithm, where the ERV charging level is reduced and AC supply powered smart appliances are terminated, where required. However, the ERV charging variation is to be implemented with consideration of any impact on RBP powered smart appliances. This is where RBP powered smart appliance operations are based on an increased RBP discharge limit due to present charging level.

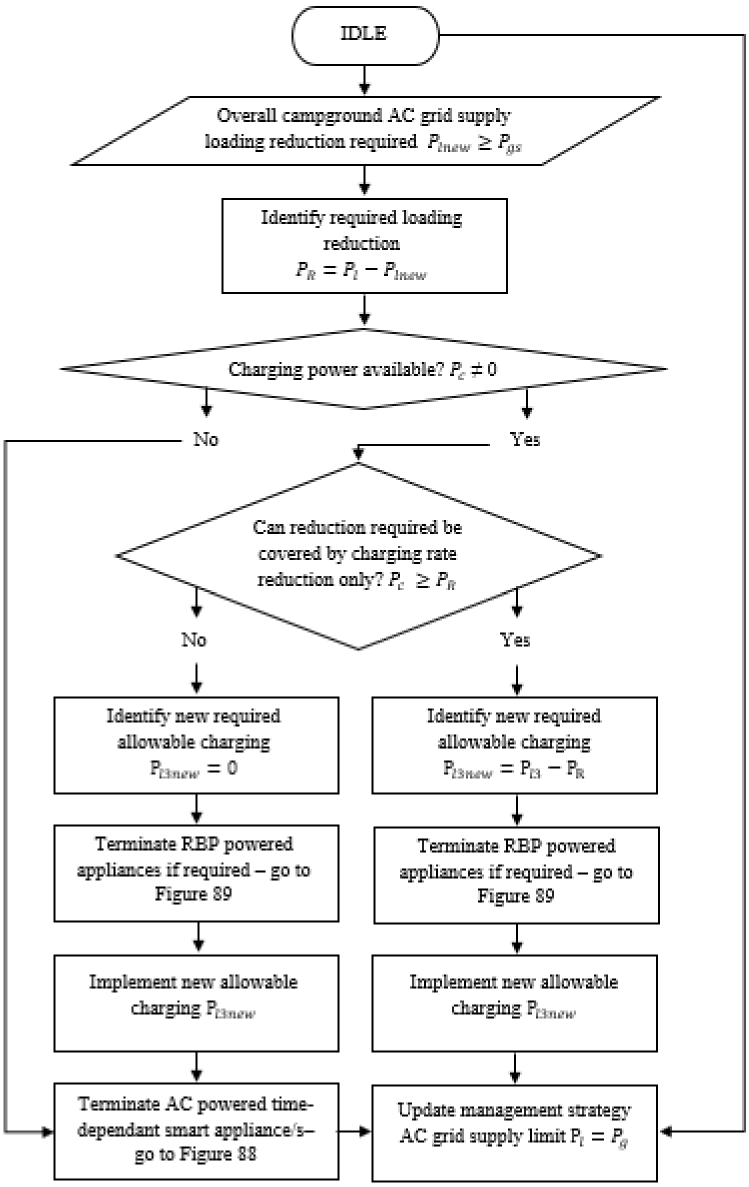

Figure 87 Algorithm for reducing ERV AC supply loading when required due to AC supply capability reduction while in-situ

In Figure 87 algorithm, the presence of ERV charging is identified when a requirement for ERV AC loading reduction is triggered. With presence of ERV charging, the required AC supply consumption reduction by the ERV is calculated via equation (31).

$$P_R = P_l - P_{lnew} \tag{31}$$

The required power reduction (P_R) is then compared to the present charging power allocation (P_{l3}). If the charging power allocation is less than the required power reduction, then the new charging power allocation (P_{l3new}) is set to 0W without being communicated to the charger for implementation.

However, if the charging power allocation is equivalent to or exceeds the required ERV power reduction, then the new charger power allocation (P_{l3new}) is determined via equation (32). However, this is not communicated to the charger for implementation.

$$\mathrm{P}_{l3new} = \mathrm{P}_{l3} - \mathrm{P_R} \tag{32}$$

After the new charging power allocation (P_{l3new}) is identified, required RBP powered smart appliance terminations are performed using a separate algorithm demonstrated in Section 5.2.1.3. This occurs prior to implementing the updated charging power allocation.

Once relevant RBP powered smart appliance terminations are achieved, the ERV charging new power allocation (P_{l3new}) is implemented. If the implementation of the new ERV charger power allocation is solely sufficient to cover the required AC consumption reduction requirement, the new AC supply capability limit for the ERV is then immediately updated. On the contrary, if the new charger power allocation is not sufficient on its own, then the relevant AC smart appliances are terminated prior to the new AC supply capability limit being imposed. The performed actions for AC smart appliances termination occur in a separate algorithm, presented in Section 5.2.1.2, whenever required.

Another difference within the ERV charging management element of the proposed strategy, in relation to its similarity to that in Chapter 3, is the algorithm for ERV charging management functionality when an AC powered non-schedulable appliance operation is requested. This is no longer included within the proposed ERV central controller management strategy as all appliances are in direct communication with the central controller. Therefore, the algorithm for the ERV charging management applied in Chapter 3 for the operation of schedulable appliances is applied within this proposal for all AC powered smart appliances with some amendments which are highlighted in Section 5.2.1.2.

5.2.1.2 AC powered smart appliances management

For the start-up of all AC powered smart appliances, the proposed central controller utilises a similar management strategy to that of AC powered scheduled appliances in the ERV charging management strategy of Chapter 3. However, the algorithm is amended to consider the impact on RBP powered appliances which depend on the available charging power for their initiation. Furthermore, the algorithm includes the functionality of varying the requested smart appliance operational settings if it is of time dependant nature. The algorithm for this AC power smart appliances start-up management within the central controller strategy is shown in Figure 88.

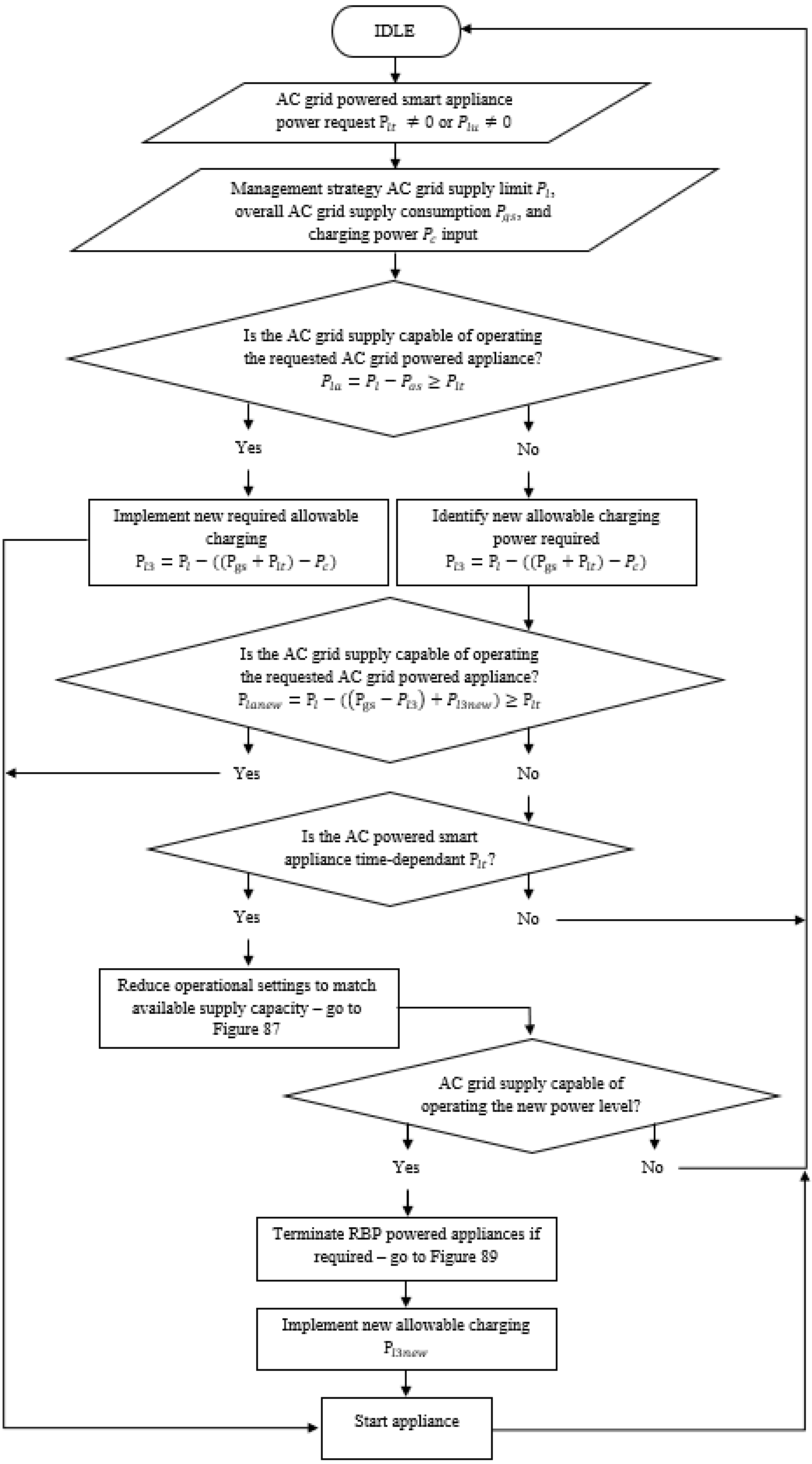

Figure 88 Algorithm of proposal for the start-up of AC powered smart appliances

In the algorithm of Figure 88, the AC powered smart appliance start-up is triggered with a request signal which includes the power requirement. The available supply capacity in relation to other present loading is then identified via equation (33) (the equations referred to within this algorithm are based on a time dependant smart appliance scenario, relevant for both schedulable and non-schedulable appliances, however, they are also applicable for user dependant non-schedulable smart appliances (P_{lu})).

$$\mathrm{P}_{la} = \mathrm{P}_{l} - \mathrm{P}_{\mathrm{gs}} \geq P_{lt} \quad (33)$$

With a positive outcome, a new maximum charging power allocation is identified and implemented, prior to the appliance start-up, utilising equation (34). However, with a negative outcome of equation (33), the strategy determines a new maximum charging power allocation using equation (34), but without implementing the change within the charger itself.

$$\mathrm{P}_{l3} = \mathrm{P}_{l} - ((\mathrm{P}_{\mathrm{gs}} + \mathrm{P}_{lt}) - P_{c}) \quad (34)$$

The unimplemented new maximum charging power allocation is then utilised to re-asses the supply capacity sufficiency using equation (35).

$$\mathrm{P}_{lanew} = \mathrm{P}_{l} - ((\mathrm{P}_{\mathrm{gs}} - P_{l3}) + P_{l3new}) \geq \mathrm{P}_{lt} \quad (35)$$

If sufficient supply capacity is identified with the new charging power allocation, then it is applied within a different algorithm (shown in Section 5.2.1.3). The algorithm stops the operation of RBP power smart appliances whenever required. However, if insufficient supply capacity is highlighted with the new charging power allocation, the nature of the smart appliance requesting the operation is determined. If the request is made from a user dependant smart appliance, then it is declined. If the request for operation is made from a time-dependent smart appliance, an attempt is carried on altering its operational settings via a separate algorithm of Figure 89. In the case of a positive outcome, where the requested operational settings are amended to suit the available capacity, the new charging power allocation is utilised within the algorithm presented in Section 5.2.1.3. If there is a negative outcome of the operational settings variation attempt, the request is denied. If sufficient supply capacity is identified at a later stage (due to increase in AC supply limit or other loads completing their operation), the algorithm presented in Figure 88 is re-triggered to re-evaluate the potential of operating previously denied appliances. The ERV charging power variation management strategy within this proposal is also incorporated in an EMC complaint form as per the algorithm shown in Figure 38.

The algorithm of Figure 89 is triggered for varying the operational settings of the time-dependent smart appliances when insufficient capacity is identified within algorithm of Figure 88.

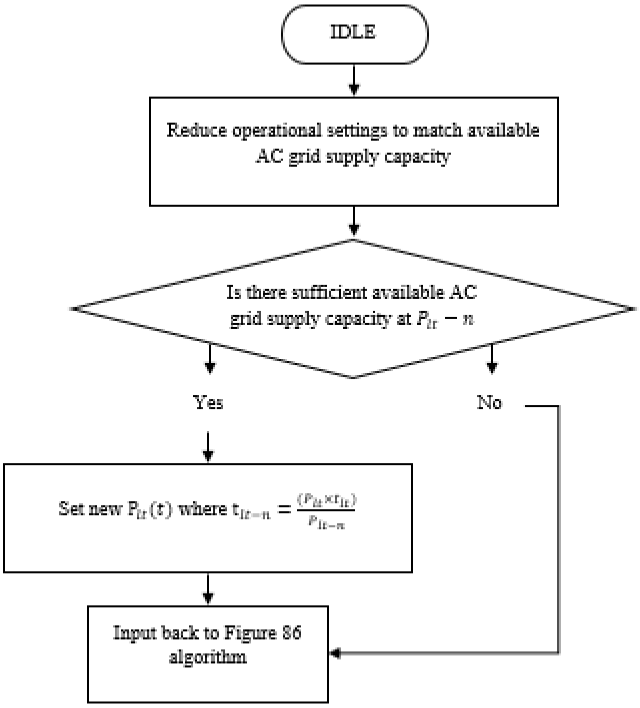

Figure 89 Algorithm for AC powered time-dependent smart appliance operational settings variation

In the algorithm of Figure 89, the proposed central controller management strategy performs a search for a lower operational power setting (P_{lt-n}) than that originally requested. Equation (35) is utilised within this search for lower power settings where it is assumed that each smart appliance has a set of limited power levels at which it can operate. If a new power setting (P_{lt-n}) which is suitable for the current supply capacity is identified, the requested operational time is respectively varied via equation (36).

$$t_{lt-n} = \frac{(P_{lt} \times t_{lt})}{P_{lt-n}} \tag{36}$$

This change in operational time with respect to the varied power level maintains the originally requested operational energy level. The new operational settings are then fed back into the AC powered smart appliance start-up algorithm of Figure 88. If the search for a new power level is unsuccessful, this is also communicated back into the algorithm of Figure 88.

The proposed ERV central controller management strategy can receive instructions from the campsite central controller to reduce or increase the ERV AC grid supply capability limit as earlier presented. In such situation, if a reduction in ERV charging power is not sufficient to meet the new AC grid supply capability, AC powered time-dependent smart appliances are terminated to aid compliance with the new limit (as highlighted in Figure 86 and Figure 87). The control algorithm responsible for such termination of AC powered time-dependent smart appliances is shown in Figure 90.

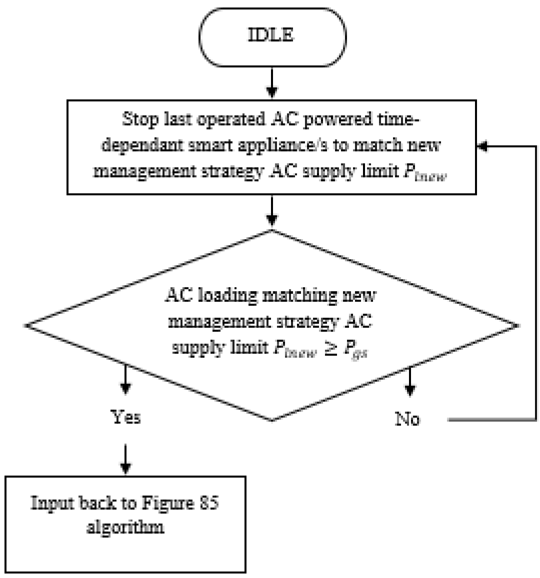

Figure 90 AC powered time-dependent smart appliances termination algorithm aiding AC grid supply limit variations in-situ

The Algorithm in Figure 90 is triggered to immediately switch off the last time-dependent AC powered smart appliance to begin its operation. Then it performs a check on the current AC loading in comparison with the new AC grid supply limit capability. If the AC loading is still too great, the loop for terminating further appliances repeats. This continues until the check performed on the AC loading with regards to the new AC supply limit is successful. This information is then passed back to the algorithm in Figure 85 to update the new AC grid supply capability limit. Finally, after the completion of the algorithm shown in Figure 85, the last AC powered time-dependent smart appliance to be terminated undergoes algorithms of Figure 88 and Figure 89 in attempt to resume its operation if sufficient AC grid supply capacity is present. The remaining terminated AC powered time-dependent smart appliances are then accordingly queued for continuation of their operations when suitable conditions arise. It is to be noted that the implementation of this algorithm is set to be EMC complaint following the algorithm of Figure 38 in Chapter 3 of the thesis.

5.2.1.3 RBP powered smart appliances management

The proposed ERV central controller strategy utilises the management strategy in Chapter 4 for RBP powered smart appliances to monitor and control the operation of the RBP powered schedulable and non-schedulable on-board appliances. However, the method utilised to identify energy capacity requirements of a smart appliance at its operational request (which assumes all operational RBP powered appliances are to remain in-situ throughout the duration of the newly requested appliance) within the strategy of Chapter 4 is altered. This is to allow a more accurate calculation, thus, alleviating the limitation identified in Chapter 4 of the thesis. Furthermore, this facilitates the integration of multiple smart appliances within the RBP powered management strategy.

At an operational request from an RBP powered smart appliance, the new method within the proposed ERV central controller firstly identifies the remining energy requirement for all operating RBP powered time-dependent smart appliances using equation (37).

$$E_{Dt} = P_{Dt1}(t_{Dt1}) + P_{Dtn}(t_{Dtn}) \tag{37}$$

Equation (38) is then used to finally identify the required energy to operate the new smart appliance without considering any available charging power (the equations of this algorithm are based on a time-dependent smart appliance scenario, relevant for both schedulable and non-schedulable appliances, however, they also apply to new user-dependent non-schedulable smart appliances (E_{Dunr})).

$$E_{Dtnr} = P_{Dtnr}(t_{Dtnr}) + E_{Dt} + P_{Du}(t_{max}) \tag{38}$$

In equation (38), the required energy for operating the new time-dependant appliance (E_{Dtnr}) assumes that user dependant non-schedulable appliances will operate for the duration (t_{max}) of the longest operational time present out of all the RBP powered appliances in-situ and the new smart appliance requesting operation. In contrast to the method utilised in Chapter 4 which applies its operational conditions assumption on all present RBP loading, equation (38) of this proposal only applies the assumption on the user dependant non-schedulable appliances; thus, is a more accurate energy requirement calculation.

Where required, the available charging power can be factored in, as per equation (39), for determining the energy requirement for the RBP powered time-dependant appliance requesting operation.

$$E_{Dtnr} = (P_{Dtnr}(t_{Dtnr}) + E_{DT} + P_{Du}(t_{max})) - P_c(t_{\max}) \quad (39)$$

The RBP powered smart appliance management strategy element of this proposal has further additional functionalities to that of Chapter 4:

- Operating RBP powered time-dependent smart appliances are to be interrupted if required due to the need of charging power level reduction
- Those appliances are then to be re-assessed to determine if they can resume their operation at a similar or alternative power and time settings ($P_{Dt}(t)$ / $P_{Du}(t)$)

The algorithm for interrupting operating RBP powered smart appliances where required is shown in Figure 91.

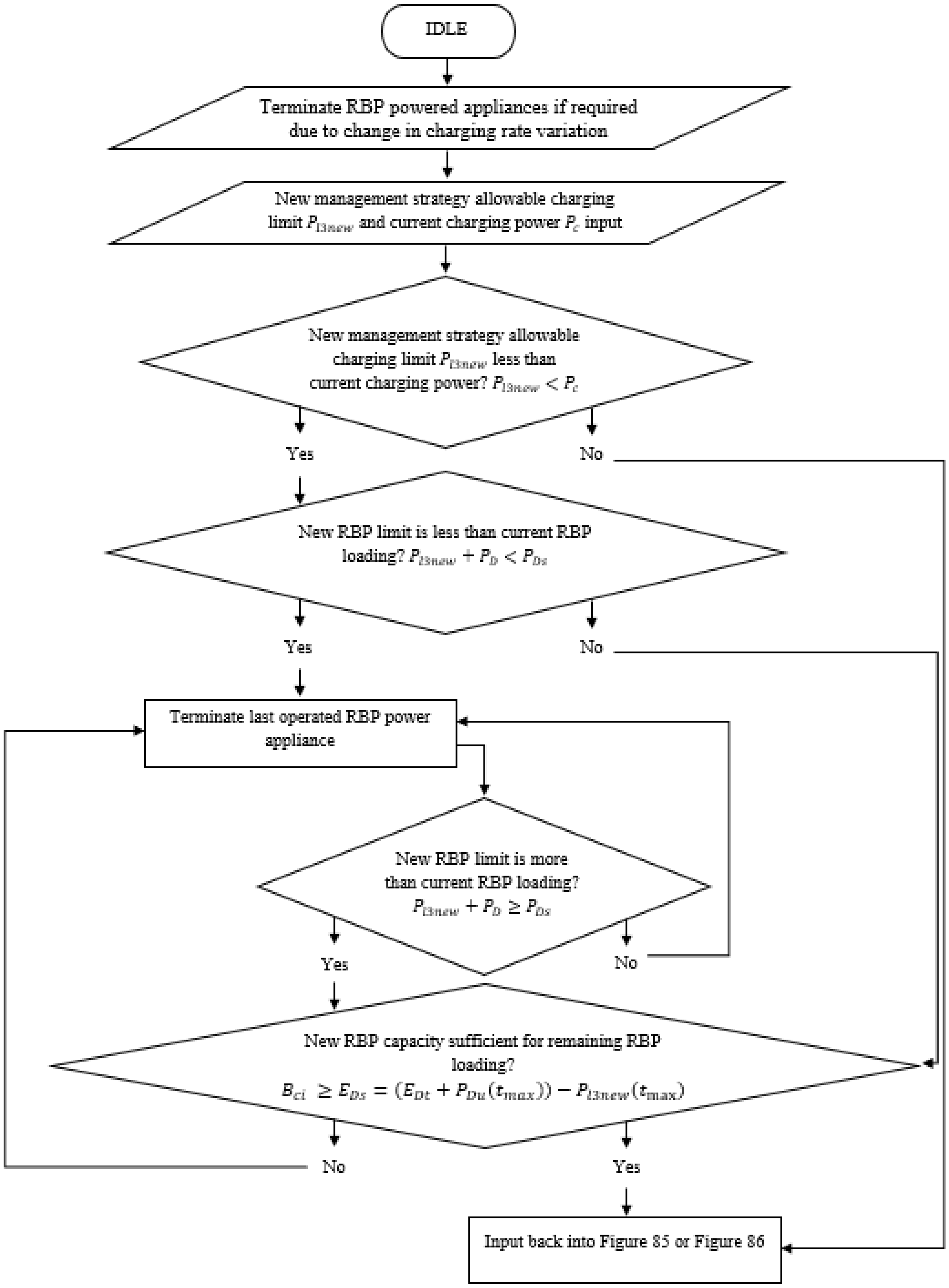

Figure 91 Algorithm for terminating battery powered appliances if required when charging power is to be reduced

In Figure 91, the algorithm first checks if the new charging power allocation P_{l3new} is going to be more or less than that the actual current charging power P_c. In the case of the new charging power allocation being more than the actual current charging rate, no RBP powered smart appliance terminations need to be performed. An RBP instant discharge constraint is initiated using the new charging power allocation if the current charging rate is greater than the original. This check is performed via equation (40).

$$P_{l3new} + \mathrm{P_D} \geq P_{Ds} \quad (40)$$

In the above equation, the current RBP discharge (P_{Ds}) is compared to the new RBP instant discharge limit (P_D) which would be effective with the implementation of the newly allocated charging power. If the new RBP discharge limit is equal to or exceeding that of current RBP discharge, then a capacity check is triggered. However, if the RBP discharge is exceeding the new limit P_D, the last RBP powered time-dependant smart appliance operated is terminated. The instant discharge RBP constraint check is then performed again. This is to be repeated as many times as required, until the instant discharge P_{Ds} check is successful for the new RBP discharge limit P_D.

The RBP capacity constraint check in Figure 91 is performed using equation (41), considering the new charging power allocation and the remaining RBP powered smart appliances in operation.

$$E_{Ds} = (E_{Dt} + P_{Du}(t_{max})) - P_{l3new}(t_{\mathrm{max}}) \quad (41)$$

If the energy requirement to maintain operation of remaining RBP powered smart appliances (E_{Ds}) is less than the available RBP capacity (identified in equation (26)), then the algorithm allows the charging power allocation change to be implemented within its relevant algorithm. However, if E_{Ds} exceeds the available RBP capacity, time dependant RBP powered smart appliances are terminated consequently until the RBP capacity is met (starting with the last operated RBP powered smart appliance).

After completion of Figure 91 algorithm and implementation of updated charging power allocation, an attempt is made to resume the operation of the last RBP powered smart appliance to be terminated (where present and possible) as per start-up algorithms within Chapter 4 of this thesis. The other terminated smart appliances are queued for resuming their operation whenever the suitable conditions are present.

5.2.2 **Simulation set-up**

A simulation model was built in Simulink to assess the proposed ERV central controller management strategy. The model was constructed from a central controller management unit, campsite controller signal simulator, RBP charger, AC smart appliances, and RBP powered smart appliances shown in Figure 92.

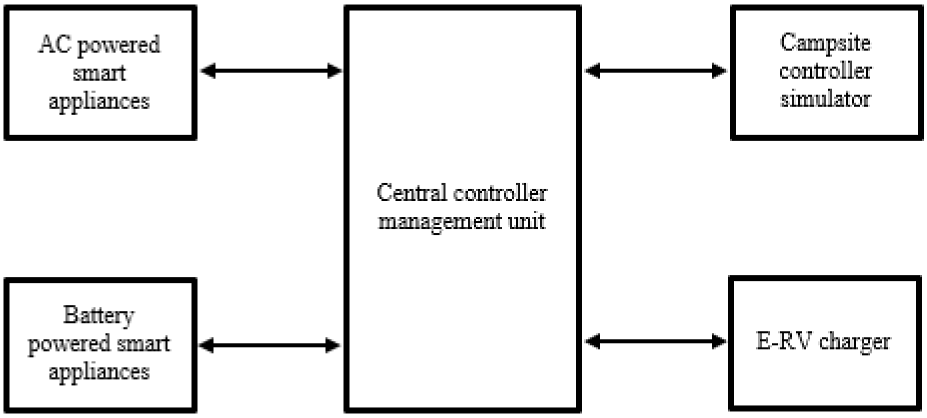

Figure 92 simulation model overview

The aim of the central controller management strategy evaluation is to ensure that the various additional and amended functional capabilities from Chapter 3 and Chapter 4 are achieved successfully. The evaluation also demonstrates the operation and success of the overall proposed central ERV management strategy, which is to serve as platform for increased adoption of future ERVs. Furthermore, theoretical calculations from the relevant algorithms and equations (previously highlighted in this chapter) are utilised for comparison purposes (presented in part 5.2.3). The different test conditions created for the various assessments are detailed below separately.

5.2.2.1 ERV RBP charging management

Various test scenarios were set to analyse ERV charging management capability aspects; e.g. to manage the ERV charging power (P_c) in relation to an in-situ varying campground grid supply limit (P_g), AC powered smart appliance loading (P_{ls}), and RBP smart appliance loading (P_{DS}). Table 13 below presents the different test scenarios utilised and their relevant measurement elements for this assessment.

Table 13 Test scenarios for the ERV BRP charging management aspect in the proposed novel ERV central controller management strategy

Initial P_g (W)	Updated P_g (W)	P_{ls} (W)	AC powered appliances in que	P_{DS} (W)	P_D (W)	Measured Elements
100	150	75	No	NA	NA	P_l & P_c
100	150	90	Yes	NA	NA	P_l & P_c
150	100	15	NA	160	70	P_l & P_c
150	100	110	NA	110	70	P_l & P_c
150	100	15	NA	135	70	P_l & P_c & P_{l3}

Five different test scenarios are set for testing as per Table 13. Implemented ERV campground grid supply limit (P_l), ERV charging power (P_c), and central controller maximum ERV charging power allocation (P_{l3}) are extracted, where relevant, for the assessment of this management aspect of the central controller strategy.

5.2.2.2 AC powered smart appliances management

In the proposal presented, the operation of AC powered smart appliances (P_{lt1}, P_{lt2}, and P_{lt3}) are managed in relation to various parameters including implemented ERV campground grid supply limit (P_l), ERV charging power (P_c), AC loading (P_{gs}), and RBP smart appliance loading (P_{DS}). To analyse this capability, various test scenarios are defined in Table 14.

Table 14 Test scenarios for the AC powered smart appliances management aspect in the proposed novel ERV central controller management strategy

Initial P_l (W)	Updated P_l (W)	P_c (W)	P_{lt1} (W)	P_{lt2} (W)	P_{lt3} (W)	P_{DS} (W)	Measured Elements
100	100	85	15	30	NA	120	NA
100	100	20	15	30	NA	NA	P_{l3}
150	100	135	15	30	NA	160	NA
150	100	70	80	30	NA	110	NA
100	150	85	15	30	60	120	AC_{QUE}

Table 14 presents the test scenarios to be undertaken, where the measured elements for assessment purposes include the signal representing P_{lt3} being in the queue for operation (AC_{QUE}), the central controller maximum ERV charging power allocation (P_{l3}), and monitoring the state of all other pre-set parameters within the table.

5.2.2.3 RBP powered smart appliance management

The RBP powered smart appliances (P_{Dt1}, P_{Dt2}, and P_{DU1}) are managed within the proposed central controller strategy to ensure RBP parameters are not exceeded. This is achieved through the monitoring of ERV charging power (P_c), total RBP smart appliance loading (P_{DS}), capacity requirement for a newly starting RBP powered appliance (E_{Dt}), and available RBP capacity (B_{ci}). Table 15 highlights the defined tests for the assessment of this capability.

Table 15 Test scenarios for the RBP powered smart appliances management aspect in the proposed novel ERV central controller management strategy

Initial P_c (W)	Updated P_c (W)	P_{Dt1} (W)	t_{Dt1} (mins)	P_{Dt2} (W)	t_{Dt2} (mins)	P_{DU1} (W)	P_D (W)	B_{ci} (Wh)	Other measured elements
135	85	100	NA	60	NA	0	70	NA	DC_{QUE}
135	85	50	NA	60	NA	0	70	NA	NA
135	NA	100	5	400	10	70	NA	70	DC_{QUE} & E_{Dt2}
135	NA	200	5	400	10	70	NA	70	DC_{QUE} & E_{Dt2}

The measured elements of the test scenario defined in Table 15 are to include the required capacity for operating P_{Dt2} (E_{Dt2}), signal representing P_{Dt2} being in the queue for operation (DC_{QUE}), and monitoring the state of all other pre-set parameters within the table.

5.2.3 **Results**

The simulation model and the different test scenarios were utilised to extract relevant results used in the evaluation of the proposed ERV central controller management strategy. The aim is to assess the success of the overall system operation in relation to the desired functionality – i.e. manage the operation of the different loads in an optimised manner, considering the available power sources - creating a platform that facilitates increased adoption of ERVs through a commercially feasible solution.

Theoretical results were also calculated in order to assist in an effective analysis of the various undergone test scenarios. These results were achieved from relevant algorithms and equations highlighted within the chapter.

Collected theoretical and simulation results are presented and described below separately for each management aspect in the same order of that presented within the simulation setup section of this chapter.

5.2.3.1 ERV RBP charging management

In the proposed ERV central controller management strategy, an in-situ varying campground grid supply limit is accepted to achieve integration with the smart grid. This signal (P_g) is received from a campground controller and utilised within the ERV central controller for proactive management of the maximum allowable charging rate (P_{l3}), AC smart appliance loading (P_{ls}), and RBP powered smart appliances (P_{DS}) accordingly. The theoretical results of all test scenarios defined are presented below in Table 16.

Table 16 theoretical results of all test scenarios for the ERV BRP charging management aspect

Initial P_g (W)	Updated P_g (W)	P_l (W)	P_{ls} (W)	P_c (W)	P_{DS} (W)	P_{l3} (W)
100	150	150	75	75	NA	NA
100	150	150	125	25	NA	NA
150	100	100	15	85	130	NA
150	100	100	80	First 0 then 20	50	NA
150	100	100	15	40	NA	85

On increase of the grid supply limit from the campground controller (P_g), the ERV central controller accordingly increases its P_l limit and allows increase in the charging rate (P_c), if there are no AC powered smart appliances (AC_{QUE}) in the queue of operation. Simulation result representing such test scenario was collected to reflect this functionality in Figure 93.

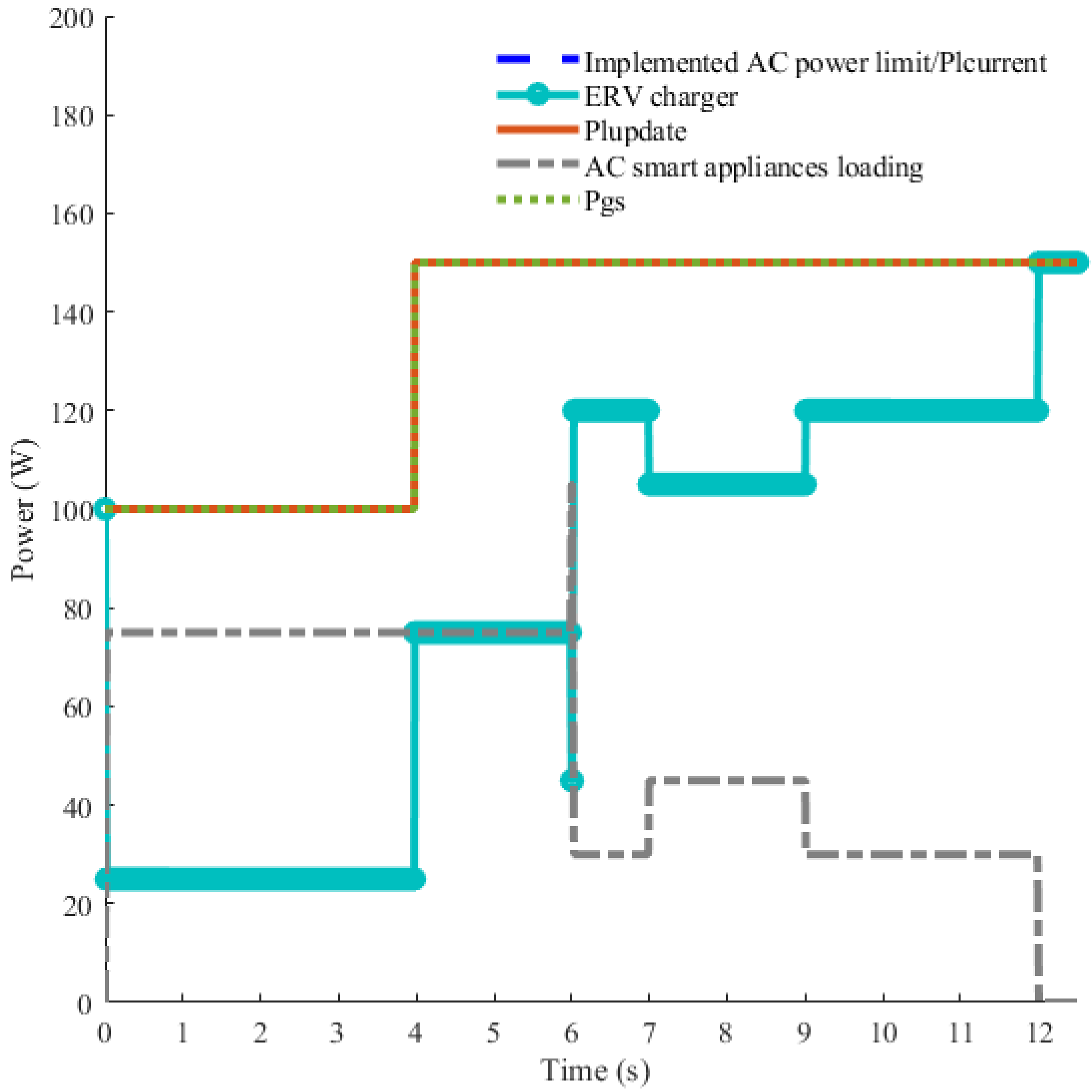

Figure 93 Integration of in-situ variable campground supply capability parameter scenario 1 simulation result

In the proposed management strategy, queued AC powered smart appliances operation are prioritised over RBP charging. Therefore, when supply limit is increased from the campground controller (P_g), the ERV central controller accordingly increases its P_l limit and allows queued AC powered smart appliances (AC_{QUE}) to operate where present. This is demonstrated in the simulation result in Figure 94.

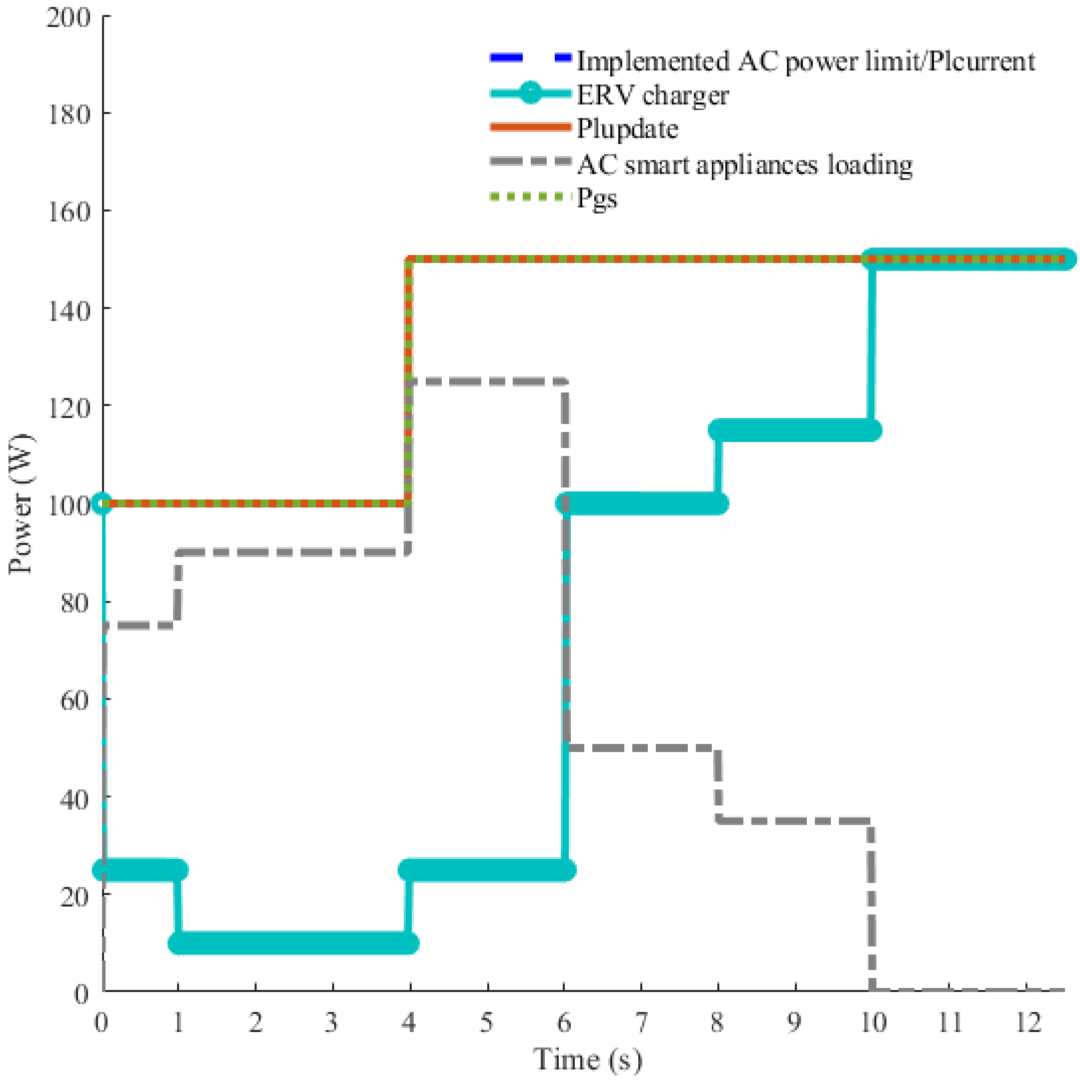

Figure 94 Integration of in-situ variable campground supply capability parameter scenario 2 simulation result

In the scenario of decreased supply limit from the campground controller (P_g), the ERV central controller ensures that the current AC loading, both from smart appliances and charging loads, is managed prior to implementation of the P_l limit decrease. The RBP charging loads are the first to be reduced in attempt of balancing the loading on the grid supply P_{gs} in relation to the new limit P_l. Where reduction of charging rate P_c on its own is sufficient, AC powered smart appliances operation P_{ls} are not interrupted. However, prior to the implementation of the charging rate P_c reduction, the RBP powered smart appliances loading P_{DS} is reduced if their operation is dependent on the original charging rate to not exceed the instant discharge limit P_D. Figure 95 below, presents a simulation of such a scenario to assess its capability.

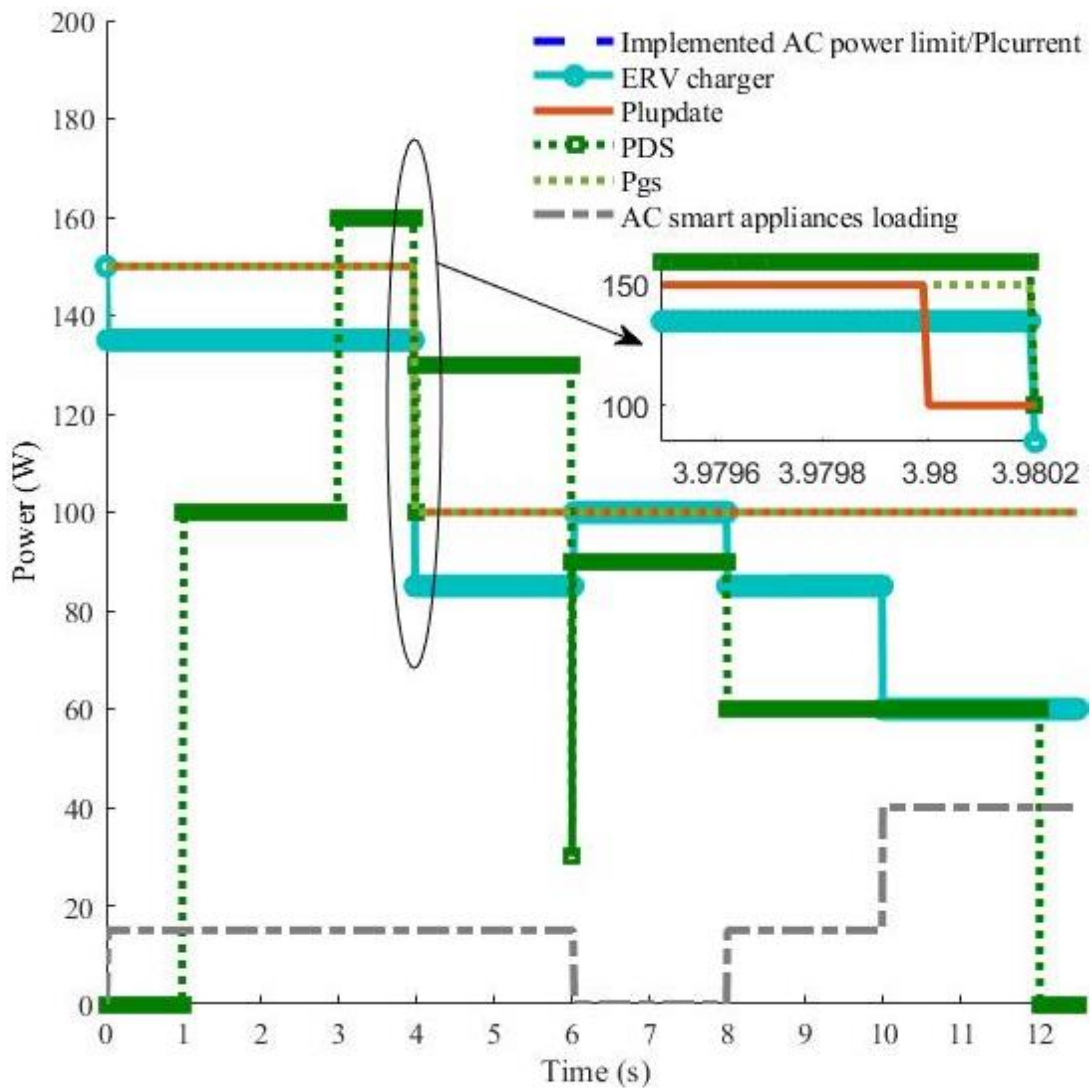

Figure 95 Integration of in-situ variable campground supply capability parameter scenario 3 simulation result

Where sole reduction of charging rate P_c is inadequate for the implementation of a reduced grid supply limit P_l, AC powered smart appliances operation P_{ls} are decreased. The central controller strategy would set the charging rate P_c to 0W to minimise AC powered smart appliances operation interruption for the achievement of supply and load balance on the new campground grid limit P_g. RBP powered smart appliances loading is respectively reduced where relevant prior to such reduction of the charging rate P_c. This capability is presented in the simulation result in Figure 96.

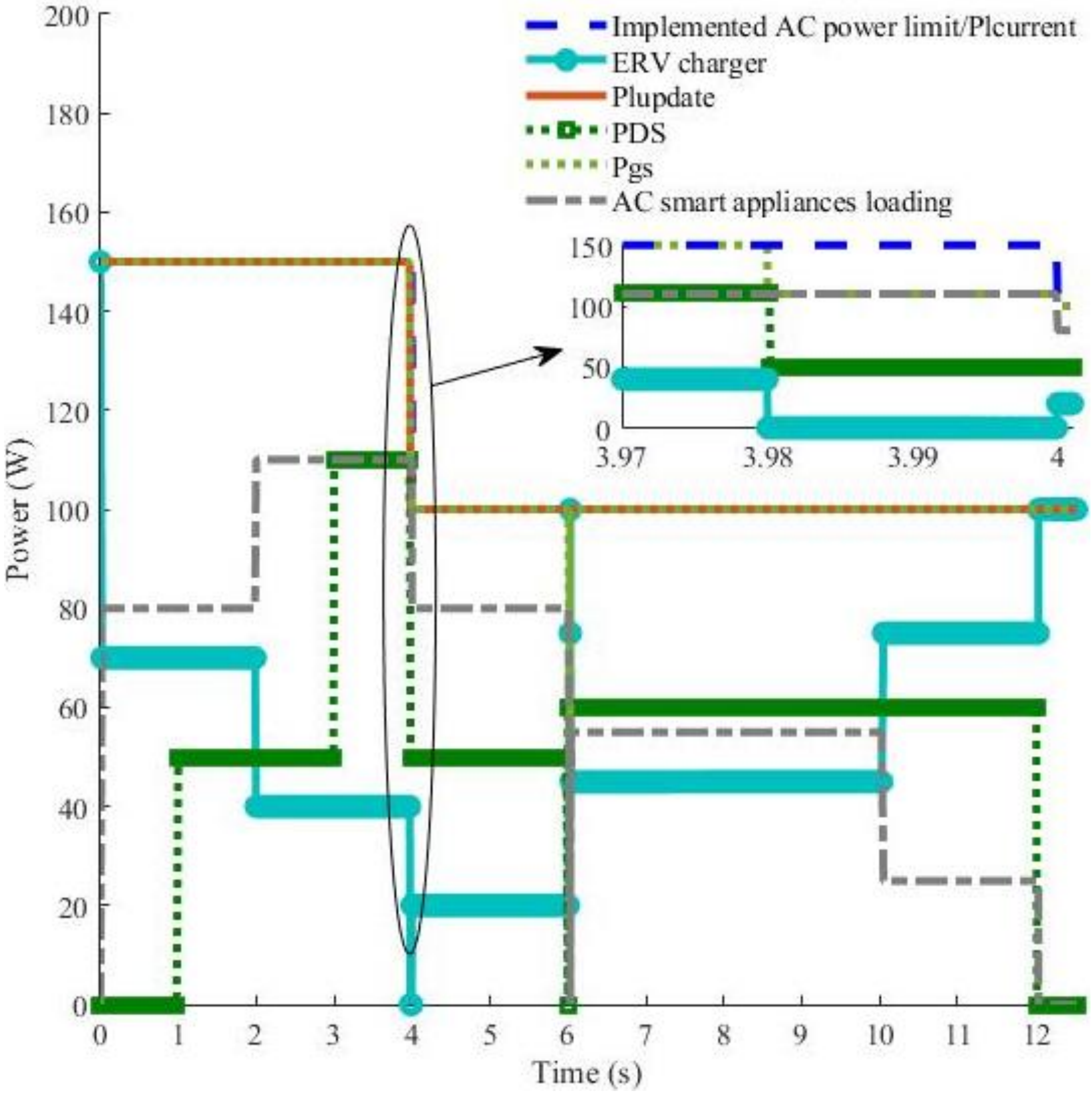

Figure 96 Integration of in-situ variable campground supply capability parameter scenario 4 simulation result

In the scenario of no AC loading P_{gs} reduction required to maintain a balanced supply and demand with a reduced campground grid supply limit P_g, no interruption is applied to the charging rate P_c or the AC powered smart appliances P_{ls}. However, the maximum charging power allocation P_{l3} provided by the central controller of the ERV to the RBP charger is accordingly reduced to avoid future overloading situation. The result of this scenario simulation is presented in Figure 97.

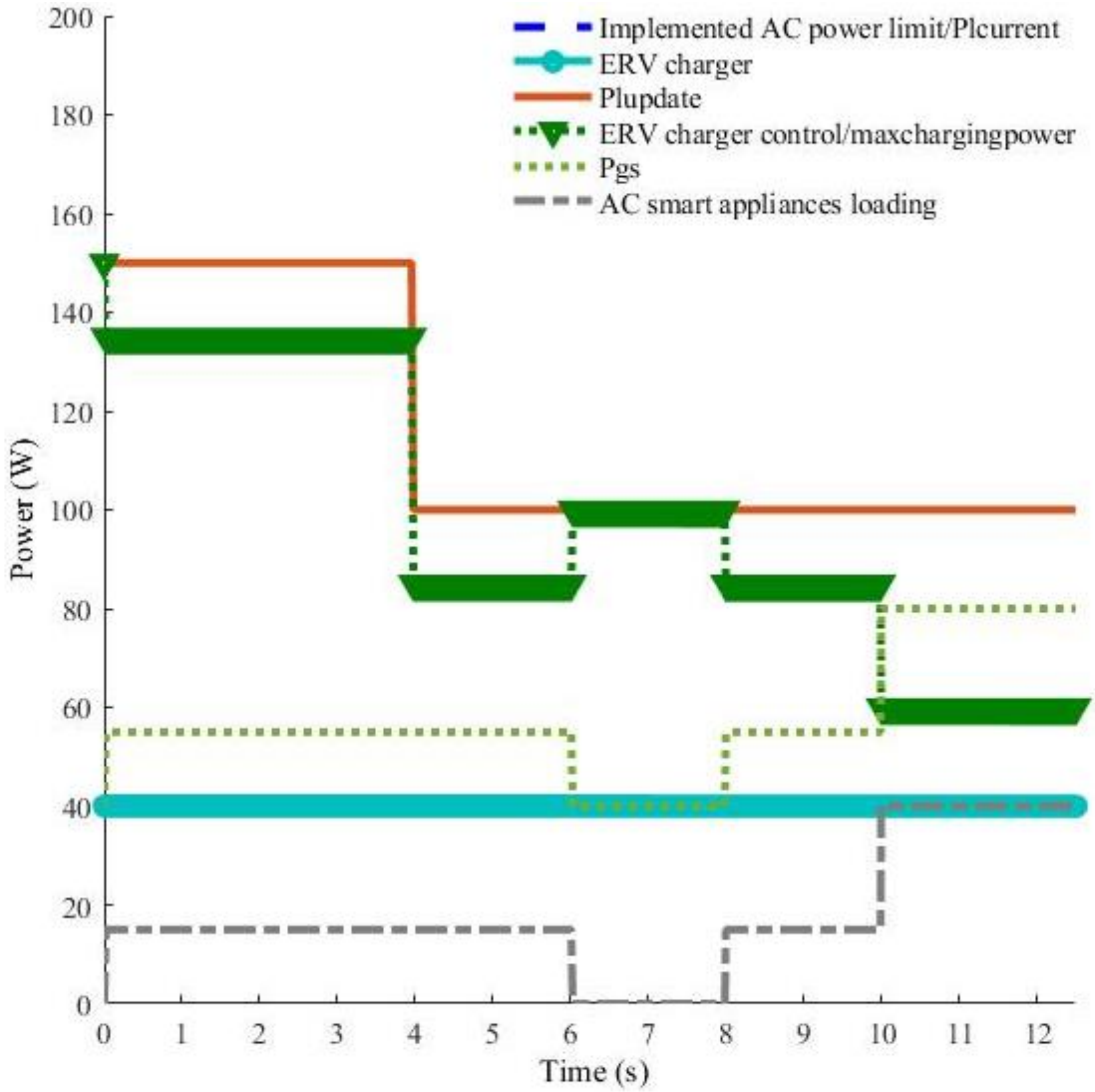

Figure 97 Integration of in-situ variable campground supply capability parameter scenario 5 simulation result

5.2.3.2 AC powered smart appliance management

AC powered smart appliances are manged proactively within the proposed ERV central controller management strategy. This is achieved through monitoring various relevant parameters according to the scenario. Parameters influencing the management of such appliances include the variable in-situ campground grid supply limit (P_g), overall AC loading (P_{gs}), the implemented ERV grid supply limit (P_l), and operating AC smart appliances (P_{ls}). The theoretical results of all test scenarios defined for the assessment of this management capability are presented below in Table 17.

Table 17 theoretical results of all test scenarios for the AC powered smart appliance management aspect

Initial P_l (W)	Updated P_l (W)	P_c (W)	P_{lt1} (W)	P_{lt2} (W)	P_{lt3} (W)	P_{l3} (W)	AC_{OUE}
100	100	55	15	30	NA	NA	NA
100	100	20	15	30	NA	55	NA
150	100	85	15	30	NA	NA	NA
150	100	40	80	30	NA	NA	NA
100	150	45	15	30	60	NA	P_{lt3}

AC powered smart appliances take priority over RBP charging loads within the proposed strategy. On request of operation by a new AC smart appliance (P_{lt2}), the available grid supply capacity is identified. If sufficient capacity for the operation of P_{lt2} is absent, the ERV charging (P_c) is reduced respectively to ensure the operations of AC powered smart appliances (P_{ls}) are optimised. Simulation result collected from the relevant test scenario for the assessment of this function is shown in Figure 98.

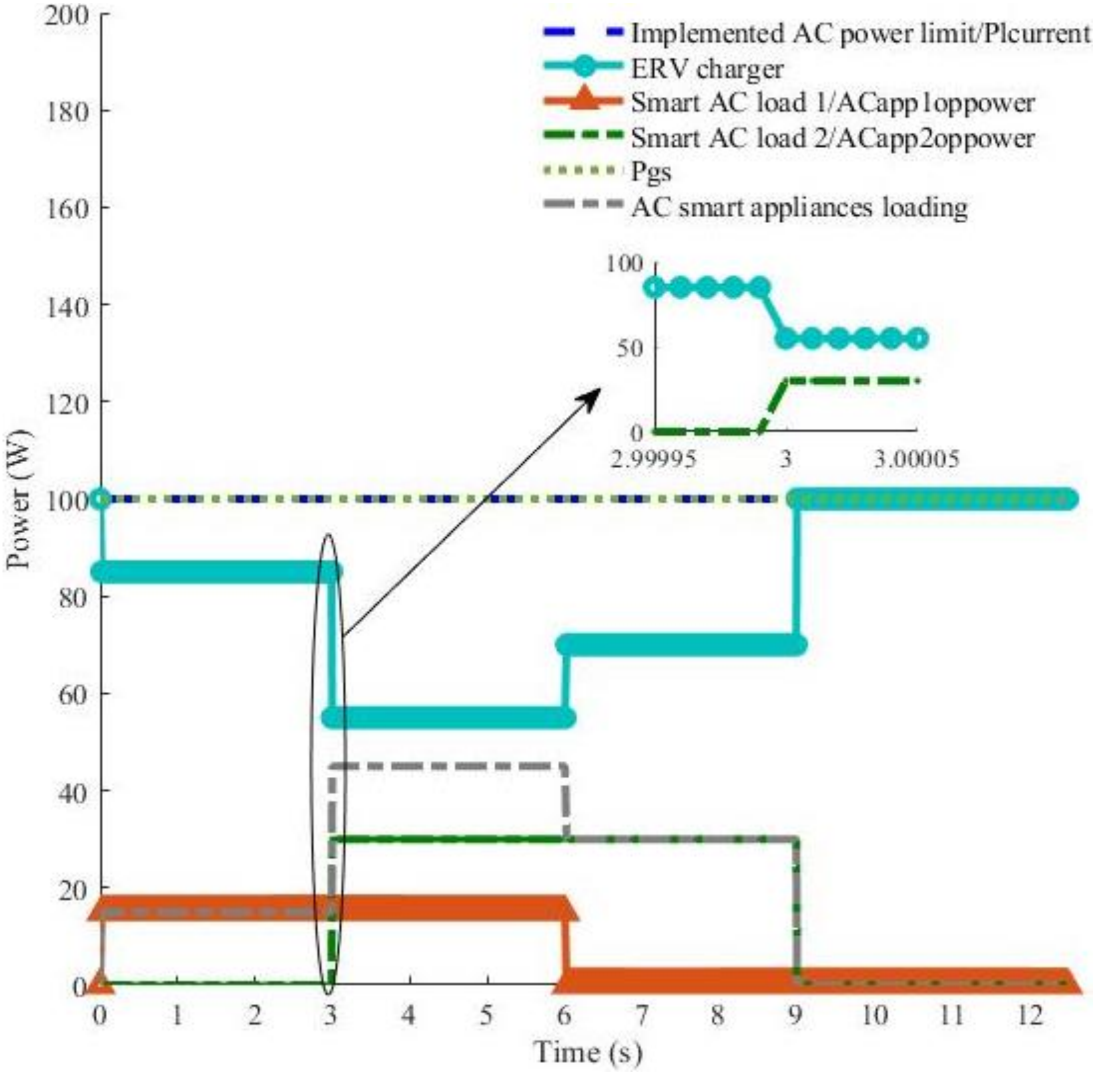

Figure 98 AC powered smart appliances operation management scenario 1 simulation result

Whenever available grid supply capacity is sufficient in relation to that required by a new AC powered smart appliances (P_{lt2}), existing RBP charging load is not interrupted (P_c). However, prior to the operation of P_{lt2}, the charging maximum power allocation P_{l3} provided to the charger by the central controller is lowered respectively to ensure no grid supply overloading exists in a future occasion. Figure 99 presents the simulation result extracted from the test scenario representing this capability.

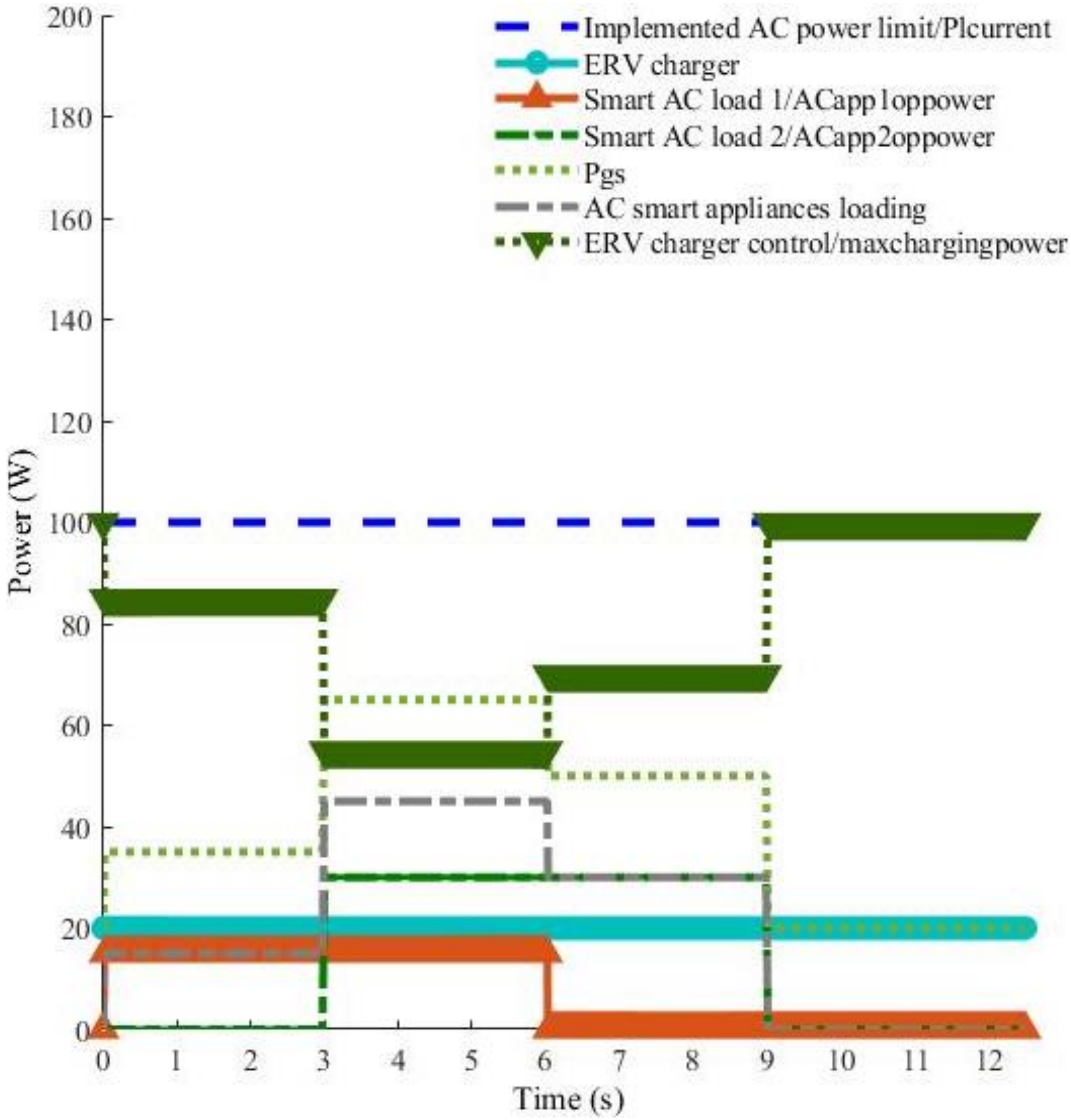

Figure 99 AC powered smart appliances operation management scenario 2 simulation result

The operation of all AC powered smart appliances (P_{ls}) can be interrupted if required in the balancing of supply and consumption levels at the point of grid supply limit (P_l) reduction. This is required only when ERV charging rate (P_c) reduction to 0W is identified to be not adequate to address the new reduced level of grid supply capability (P_l). However, if no interference with the operation AC powered smart appliances (P_{ls}) is required, this facility is not triggered. Figure 100 presents the simulation result of such scenario.

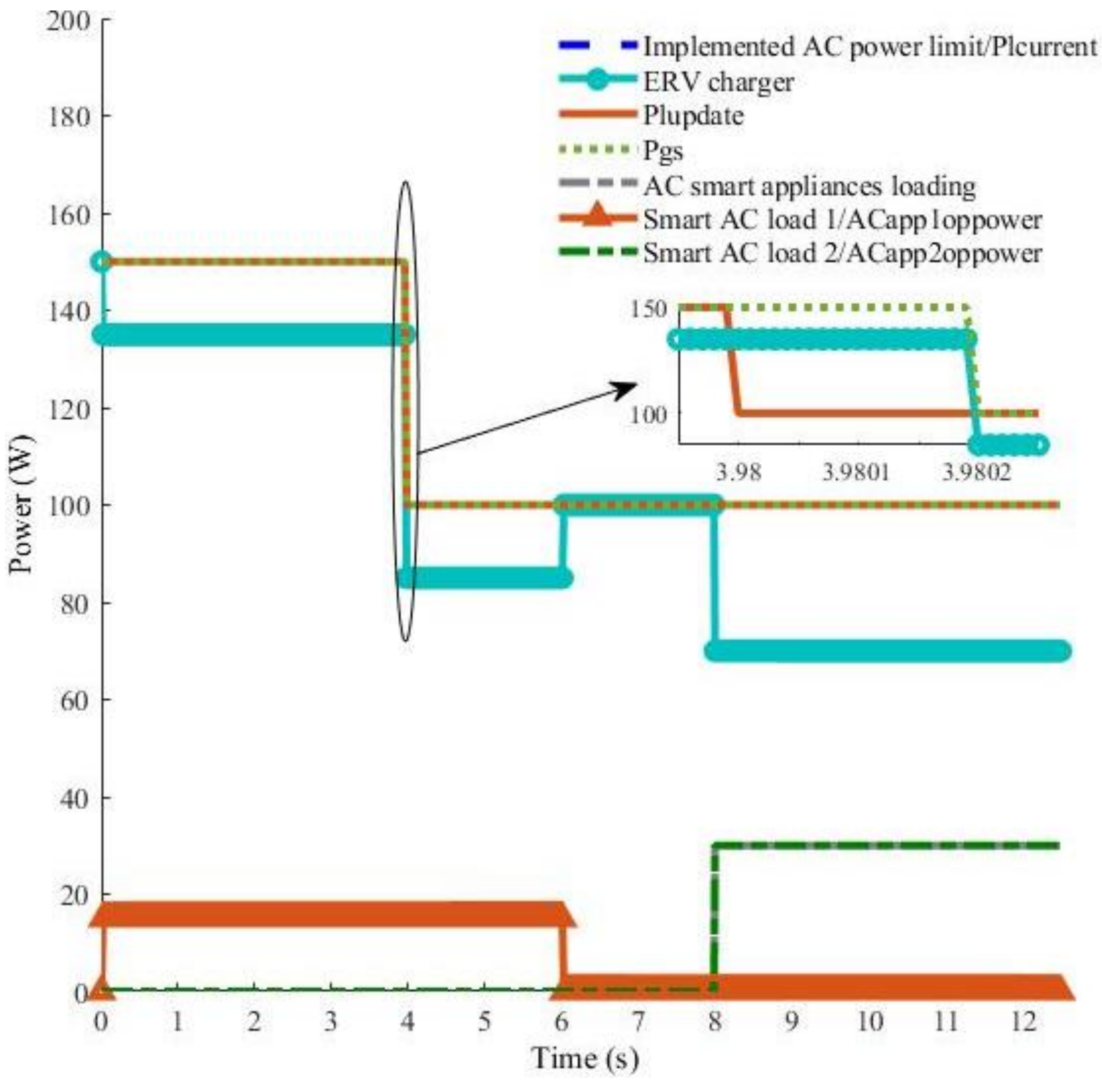

Figure 100 In AC powered smart appliances operation management scenario 3 simulation result

In the occasions where the termination of AC powered smart appliances operation (P_{ls}) is required to fulfil new supply (P_l) and demand (P_{gs}) balance, it occurs in a sequential manner starting with the time dependant appliance of most recent operation (P_{lt2}). At each appliance termination, the status of overall AC loading (P_{gs}) and supply (P_l) balance is checked to ensure optimised operation of the appliances. This capability is demonstrated in the simulation result in Figure 101.

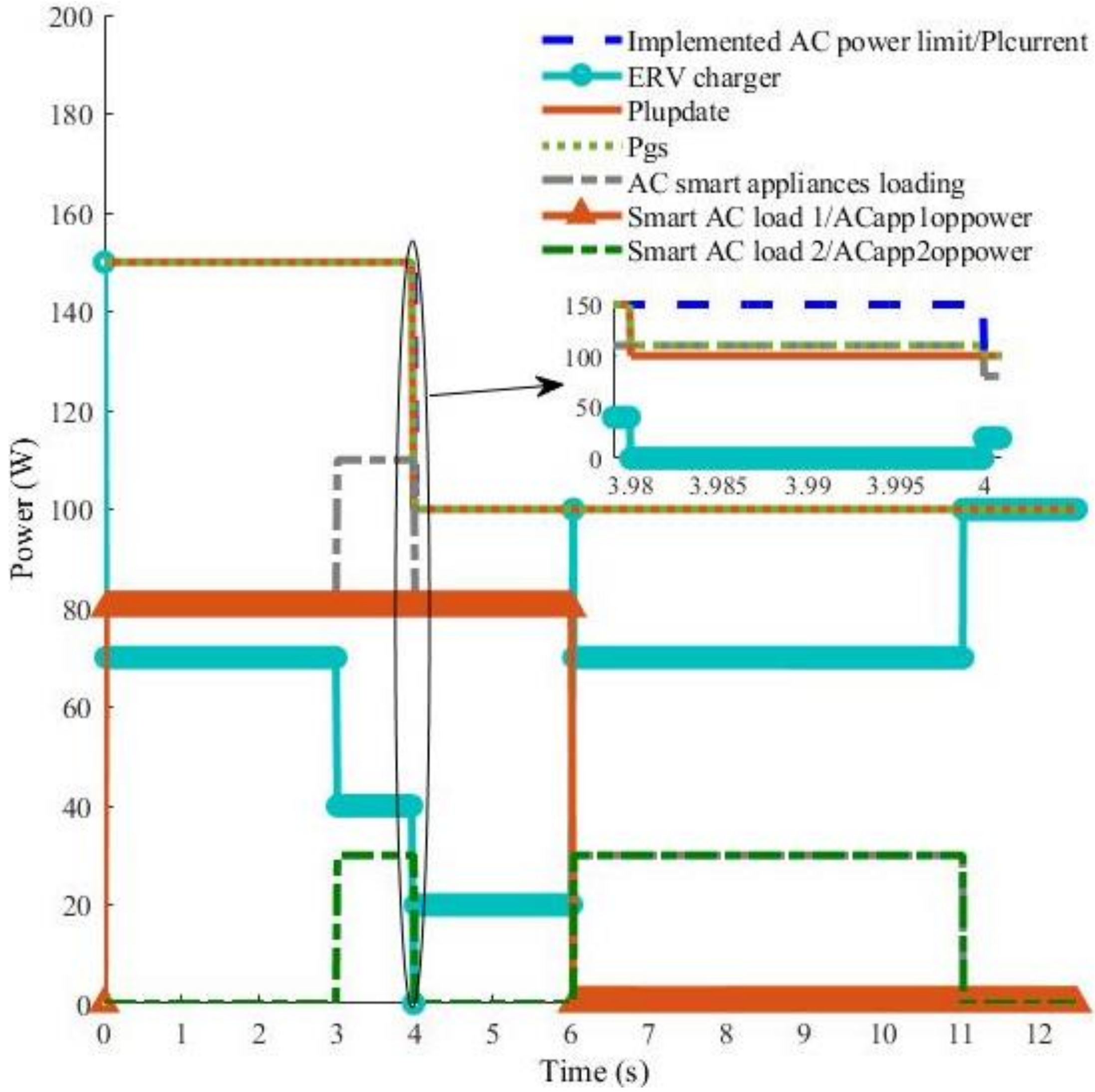

Figure 101 AC powered smart appliances operation management scenario 4 simulation result

AC powered smart appliance (P_{lt3}) request for operation can be rejected in the case of insufficient supply capacity. In such situation, the appliance is placed in a queue (AC_{QUE}) where it can operate when the required supply capacity becomes available. Such capacity can become present due to the increase in the grid supply limit (P_l) being increased or other AC powered smart appliances completing their operation. The simulation result of such scenario is presented in Figure 102.

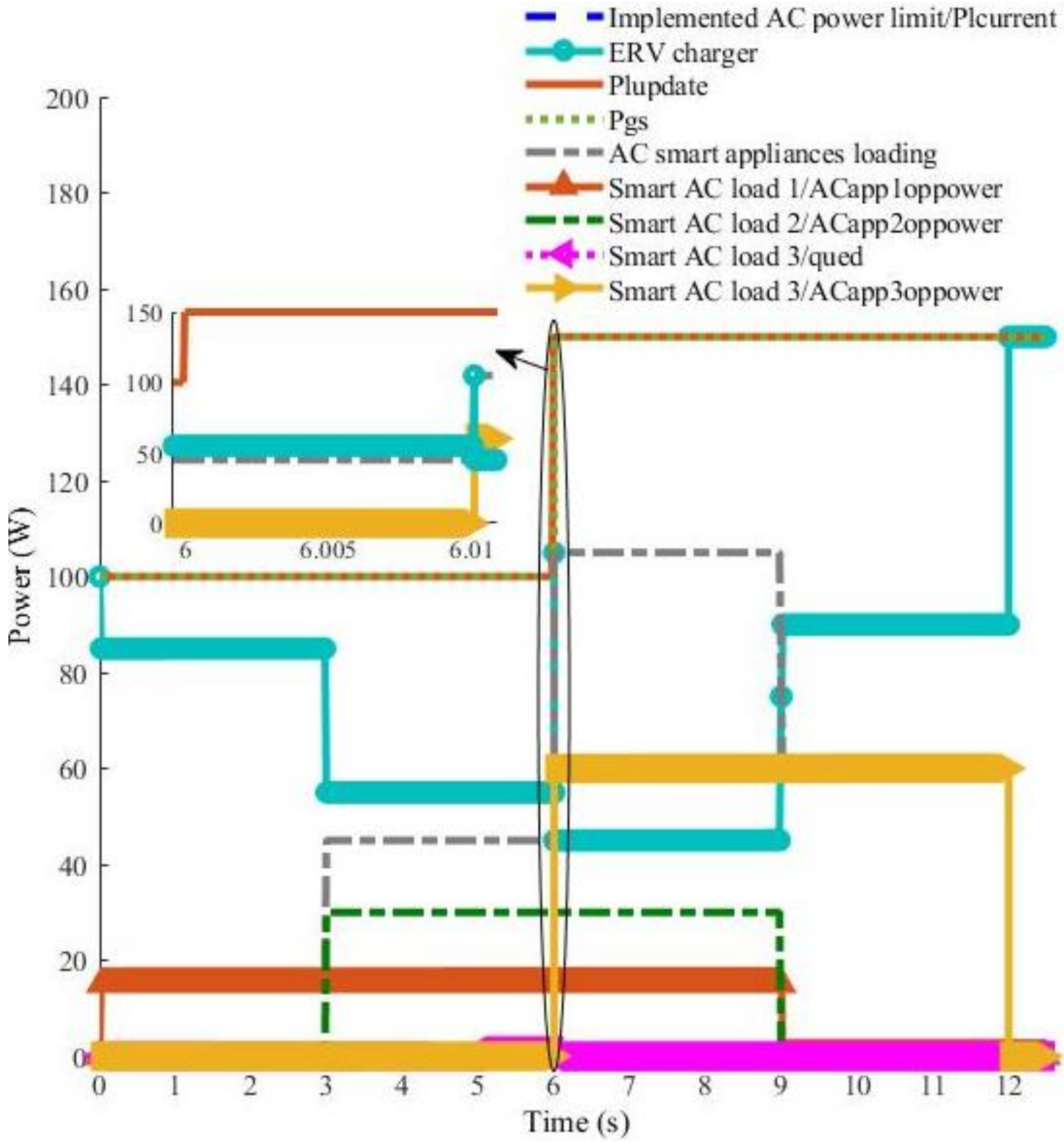

Figure 102 AC powered smart appliances operation management scenario 5 simulation result

5.2.3.3 RBP powered smart appliance management

The operation of RBP powered smart appliances (P_{DS}) is managed within the proposed central controller strategy. This is to ensure the RBP instant discharge (P_{DS}) and capacity (B_{ci}) are not exceeding their limits. Parameters monitored for the central controller to trigger relevant management actions are the required operation capacity for an RBP powered smart appliance (E_{Dt2}), charging level (P_c), overall RBP discharge rate (P_{DS}) and the RBP capacity (B_{ci}). Results from the theoretical calculations of all defined test scenarios are demonstrated in Table 18.

Table 18 theoretical results of all test scenarios for the RBP powered smart appliances management aspect

P_{Dt1} (W)	t_{Dt1} (mins)	P_{Dt2} (W)	t_{Dt2} (mins)	P_{DU1} (W)	P_D Implemented (W)	E_{Dt2} (Wh)	DC_{QUE} (W)
100	NA	0	NA	0	155	NA	P_{Dt2}
50	NA	60	NA	0	155	NA	NA
100	5	400	10	70	NA	64.01	NA
200	5	400	10	70	NA	72.33	P_{Dt2}

Within the proposed management strategy, the presence of RBP charging results in an increased instant discharge limit (P_D). Therefore, RBP powered smart appliances are proactively managed prior to any charging rate (P_c) changes. For example, if the charging rate (P_c) is to be reduced due to a change in the grid supply limit (P_l), the RBP loading is reviewed to ensure its new instant discharge limit (P_D) to be implemented is still adequate for the existing loading. Whenever the existing loading (P_{DS}) is identified to exceed the new discharge limit (P_D), RBP powered smart appliances are interrupted accordingly to ensure that the RBP discharge remains within its limits. Interruptions are applied to the most recently operated appliance (P_{Dt2}). Those interrupted appliances are then placed in a queue (DC_{QUE}) for their operation to be resumed whenever sufficient discharge levels are available, either due to increase in charging levels (P_c) or completing operations of other RBP loads (P_{Dt1}). Figure 103 demonstrates the result extracted from the simulation of such test scenario.

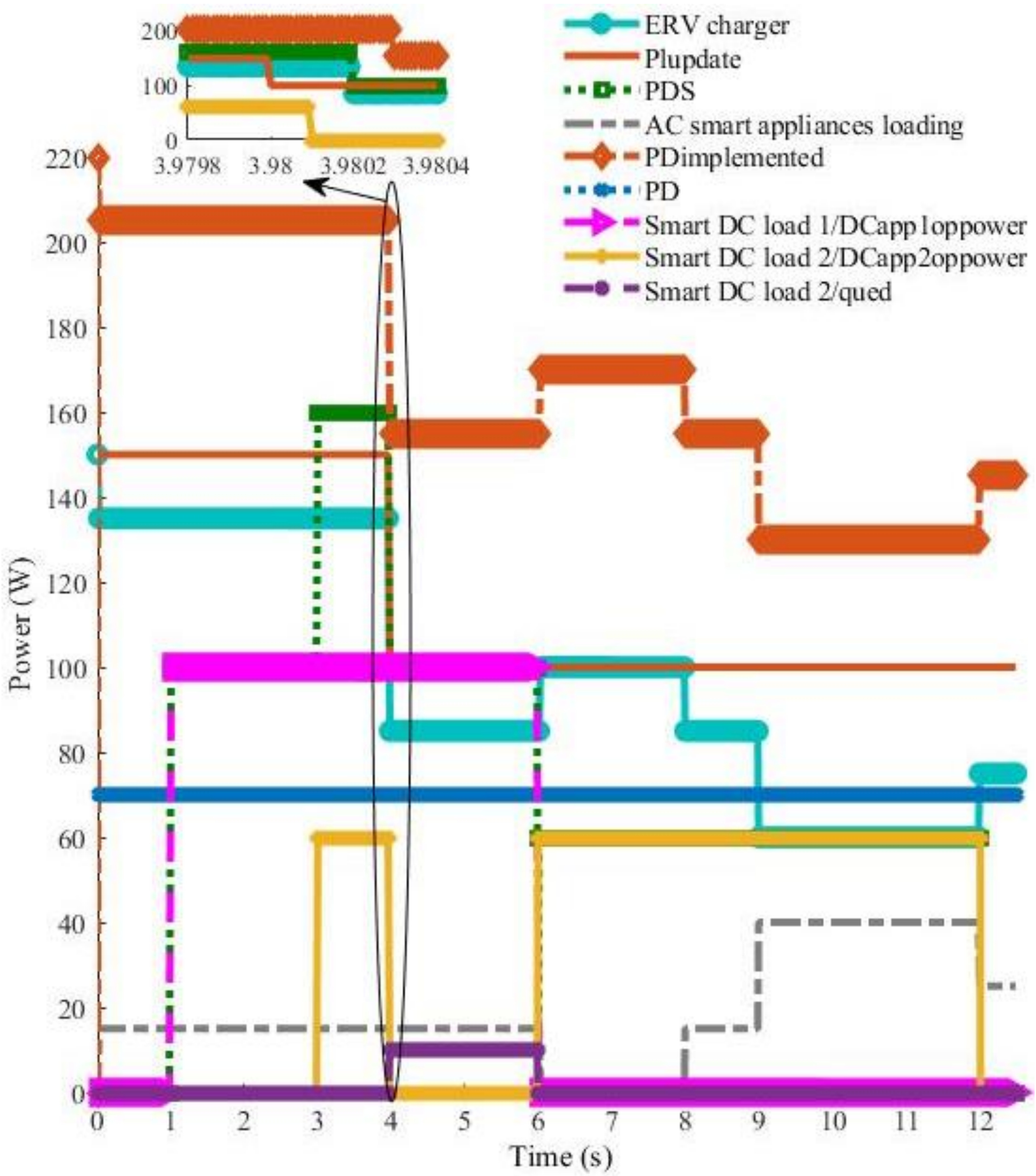

Figure 103 RBP powered smart appliances operation management scenario 1 simulation result

In the case of reduction in the charging rate (hence, the RBP discharge limit (P_D)), RBP powered smart appliances are to continue their operation if the overall loading (P_{DS}) remains within its limits. Extracted result from the test scenario simulation representing this capability is presented in Figure 104.

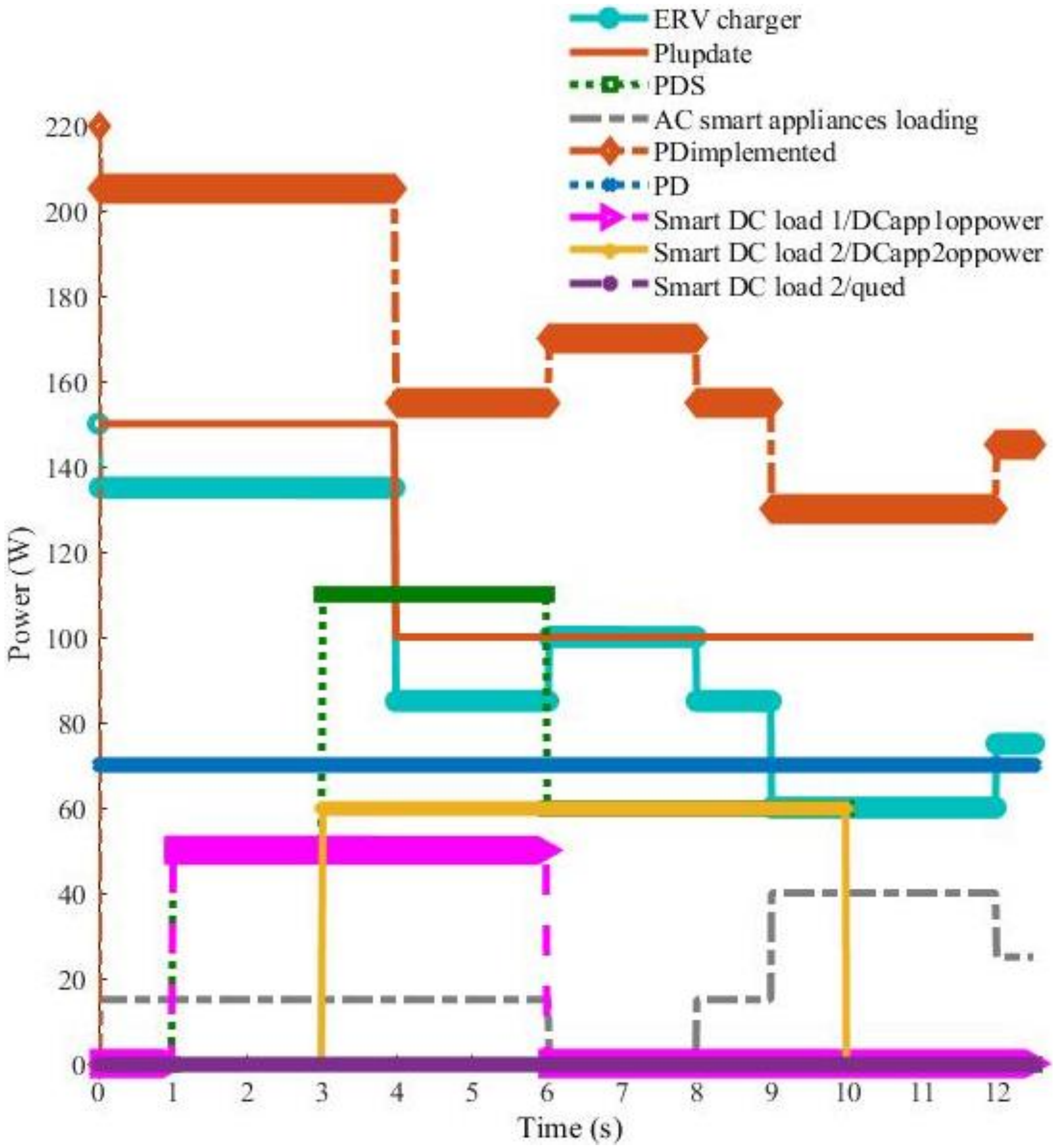

Figure 104 RBP powered smart appliances operation management scenario 2 simulation result

RBP available capacity (B_{ci}) is another parameter which the central controller management strategy monitors for the control the RBP powered smart appliances. At the request of operation from an RBP powered appliance (P_{Dt2}), its required capacity for operation (E_{Dt2}) is identified and compared to that available (B_{ci}). The calculation of the required capacity considers multiple factors including other time-dependent

RBP powered loads (P_{Dt1}), user-dependent RBP loads (P_{DU1}), and available RBP charging (P_c). The operation of the RBP powered smart appliance (P_{Dt2}) is permitted if sufficient RBP capacity (B_{ci}) is available in relation to its required operating capacity (E_{Dt2}). Figure 105 presents simulation extracted result for such test scenario.

Figure 105 RBP powered smart appliances operation management scenario 3 simulation result

Whenever RBP available capacity (B_{ci}) is not sufficient in relation to the required capacity (E_{Dt2}) for the operation of a RBP powered smart appliance (P_{Dt2}), the appliance is placed in a queue (DC_{QUE}) to start or resume its operation with presence of sufficient capacity. Simulation result of relevant test scenario is demonstrated in Figure 106.

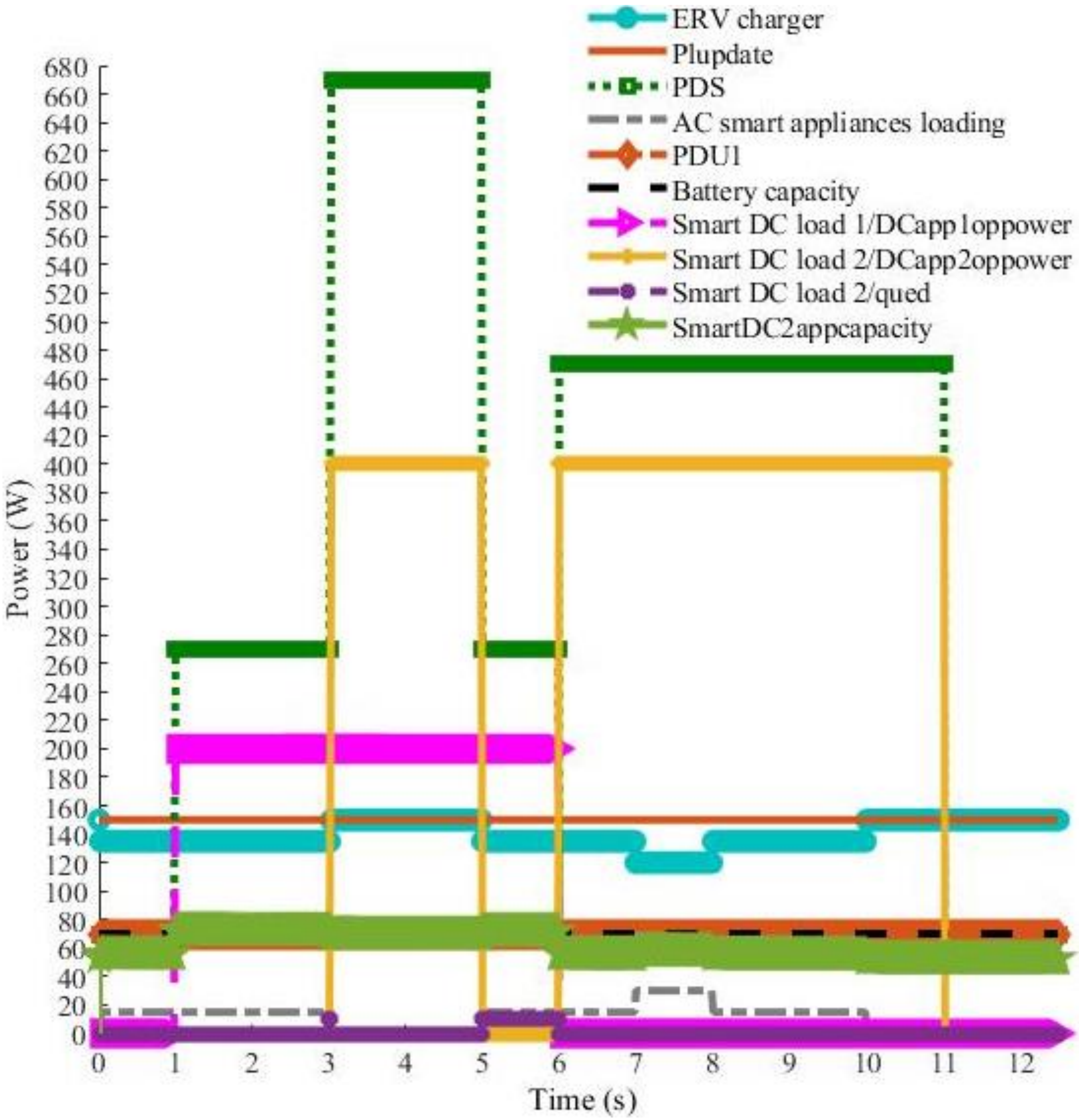

Figure 106 RBP powered smart appliances operation management scenario 4 simulation result

5.2.4 **Analysis and discussion**

The simulation model of the proposed ERV central controller management strategy was utilised to gather results from various test scenarios. Those results are used to evaluate the different capabilities within the proposal. This evaluation involves the following criteria:

- The accuracy of the simulation results in relation to that of theoretical calculations
- Achievement of intent functionality by the different algorithms implemented
- Success of the overall system in optimising the operation of various loads in relation to available power sources. This is to be achieved in a manner that allows smart grid integration and eliminates any requirements for infrastructural upgrade investments, hence, enhancing the ERV adoption
- Identification of any limitations within the proposal

The analysis and discussion of the various results are presented individually within this section in the same order as the results section. The theoretical results are not separately analysed but used as an analytical tool for the simulation results where relevant.

5.2.4.1 ERV BRP charging management

Campgrounds within the leisure industry vary in their grid supply capability, therefore, the functionality of a re-configurable grid supply limit within the ERV central controller is important as it provides the user with flexibility in campground choice. Furthermore, this grid supply capability limit imposed by the campground can be encouraged to further vary within the day in the future for smart grid integration. The proposed ERV central controller management strategy facilitates for this integration via the capability of in-situ re-configuration of the grid supply limit. However, this capability is implemented with pro-active control for both grid and RBP loads to ensure other limits are not exceeded.

The first defined simulation test scenario for this functionality sets the conditions to have a 50W grid supply capability increase (P_g). The result in Figure 93 shows successful implementation where the ERV grid supply limit (P_l) and the ERV charging rate (P_c) were increased by 50W. The increased grid capacity was utilised to increase the charging rate (P_c) due to no AC powered smart appliances present in the queue for operation. This results in optimised use of available power due to increase in grid capability, hence, an enhanced speed of RBP charging. The simulation result is in agreement with that of theoretical calculations reflecting accurate implementation of the simulation model.

In the second test scenario, AC powered smart appliance is set to be in the queue (AC_{QUE}) for operation at the time of an increased grid supply capability (P_g). In such conditions, the theoretical results in Table 16 highlight the use of increased grid supply capability (P_g) to operate the queued (AC_{QUE}) AC loading (P_{ls}). Figure 94 presents the result for the simulation of this test scenario which is in agreement with the theoretical analysis. The simulation result shows an increase in the AC power smart appliances loading (P_{ls}) by 35W. However, due to the grid supply limit (P_l) increase being of 50W, the ERV charging rate (P_c) was also allowed a 15W increase.

In an occasion of grid supply capability (P_g) reduction, the ERV charging rate (P_c) is reduced accordingly prior to the implementation of the new AC supply limit (P_l). Furthermore, prior to the implementation of the ERV charging rate (P_c) reduction, any lowering in the RBP loading (P_{DS}) is carried to maintain the new discharge rate (P_D) to be implemented. The reduction in RBP loading is to be compliant with the new limit influenced by the reduction in the charging rate (P_c). The theoretical and simulation results of Table 16 and Figure 95 are matching for this scenario where the grid supply capability (P_g) is reduced by 50W. Prior to the reduction implementation, the RBP loading (P_{DS}) was lowered by 30W and the ERV charging rate (P_c) was reduced by 50W. The delay between the grid supply capability (P_g) reduction decision and the actual ERV AC supply limit update (P_l) was 0.0002 seconds. This delay reflects the implementation of the required changes to maintain limits compliant operations prior to the update in the ERV AC supply limit update (P_l).

A fourth scenario carried sets the sole ERV charging rate (P_c) reduction (even if to 0W) to be inadequate for meeting the grid supply capability (P_g) reduction. The theoretical result of Table 16 for this scenario, demonstrates that the AC power smart appliance loading (P_{ls}) is to be reduced by 30W and the charging rate (P_c) is to be reduced by 20W in order to accommodate for the reduction in AC supply limit (P_l). The simulation result in Figure 96 presents agreement with that of theoretical, where the charging rate (P_c) drops to 20W from being originally at 40W. Furthermore, P_c initially reduces to 0W to minimise the AC power smart appliances loading (P_{ls}) reduction, providing them with optimised operation. After the reduction of the charging power to 0W was identified to be insufficient, the simulation results show a reduction in the AC power smart appliance loading by 30W. A 0.02 seconds delay was present within the simulation result, between the grid supply capability (P_g) reduction decision and the actual ERV AC supply limit update (P_l), highlighting the response speed of the loads to achieve new limits compliant status prior to their implementation.

In a final test scenario five, the charging rate (P_c) was set at 40W, meanwhile, its allowed allocated maximum by the central controller was 135W at the point of a 50W grid supply (P_g) reduction request. In such scenario, both theoretical and simulation results, of Table 16 and Figure 97 respectively, indicate an implementation of the new ERV AC supply limit (P_l) without impact on any operating loads.

5.2.4.2 AC powered smart appliance management

The AC powered smart appliances are managed pro-actively by the proposed ERV central controller strategy. This can occur both at start-up and while in-situ. Factors influencing such management include the grid supply limit (P_g), ERV supply limit (P_l), RBP charging (P_c), all operating AC powered smart appliances (P_{ls}), and those AC powered appliances placed in the queue (AC_{QUE}).

In the first test scenario carried, an AC powered smart appliance (P_{lt2}) requests operation at 30W. Furthermore, the 100W overall AC supply limit (P_l) was set to be consumed (P_{gs}) by RBP charging (P_c) at 85W and an AC powered smart appliance (P_{lt1}) at 15W. The theoretical result in Table 17 highlights a reduction in the charging rate by 30W to accommodate to the request by P_{lt2} and allowing its operation. Figure 98 presents the simulation result for this test scenario that is in agreement with that of theorical calculation. The reduction on the ERV charging was imposed immediately, allowing P_{lt2} to operate with no delay from point of request. Furthermore, the result demonstrates the increase of the charging rate (P_c) after P_{lt1}

completes its operation, resulting in optimised charging rate (P_c) in relation to available AC power capacity (P_l) and operating AC loads (P_{ls}).

In another test scenario two, the charging rate (P_c) was at 20W, meanwhile, its maximum allowable allocated by the central controller was 85W when the AC powered smart appliance P_{lt2} requested operation. Furthermore, AC powered smart appliance P_{lt1} was operating at 15W, thus, leaving an available AC supply capacity of 65W in relation to the limit (P_l) of 100W. Both simulation and theoretical results in Figure 99 and Table 17 respectively, show allowance of the requested appliance P_{lt2} operation immediately at the point of request at 30W.

In the case of grid supply limit (P_g) reduction requirement, the AC powered smart appliances (P_{ls}) might be subject to interruption if required for the balance between the new ERV supply limit (P_l) to be implemented and the loading (P_{gs}). However, the operation of AC powered smart appliances (P_{ls}) takes priority over the ERV charging (P_c). Test scenario three was carried to demonstrate such conditions, where at point of grid supply (P_g) reduction request, there was one AC powered smart appliance P_{lt1} operating at 15W and the remainder of the AC supply limit (P_l) of 150W was utilised in the RBP charging at 135W. As the reduction in grid supply limit (P_g) was set to be by 50W, both the theoretical and simulation results of Table 17 and Figure 100 demonstrated a decrease in the charging rate by 50W and no impact on the AC powered appliance P_{lt1} operation. The reduction in the ERV charging rate and the implementation of the new ERV supply limit occurred within 0.0002 seconds within the simulation model.

In test scenario four, conditions were set to trigger interruption in the AC powered smart appliances (P_{ls}) to meet the 50W grid supply (P_g) reduction requirement. At the point of the reduction request, there was AC powered appliance P_{lt1} operating at 80W, AC powered smart appliance P_{lt2} operating at 30W, and charging P_c at 40W which covered the overall available supply limit P_l of 150W. The simulation result in Figure 101 matched the theoretical result in Table 17. Both results highlight a reduction in the ERV charging P_c to 0W at first instance. This was identified as inadequate compensate the overall decrease of 50W in the ERV AC supply limit P_l to be implemented. Therefore, the most recently operated AC powered smart appliance P_{lt2} was interrupted, hence, making 20W of the new ERV AC supply limit P_l available for the ERV charging P_c facility. The delay within the simulation model for implementing the new ERV AC supply limit was 0.02 seconds. Furthermore, its seen in the simulation model that the interrupted P_{lt2} regained operation at second 6 when further AC supply capacity was made available due to P_{lt1} completing its operation.

Whenever operating AC powered smart appliances (P_{ls}) are interrupted or are not allowed operation due to insufficient AC supply, they are placed in a queue (AC_{QUE}). Those appliances can resume or start their operation when sufficient AC supply capacity is present, either due to increase in P_l and/or other AC powered smart appliances completing their operation. In scenario test five this functionality was tested by triggering a request by AC powered smart appliance P_{lt3} to operate at 60W. P_{lt1} was operating at 15W, P_{lt2} was operating at 30W, RBP charging was set at 55W, and P_l was set to 100W. Both results of simulation and theoretical calculations in Figure 102 and Table 17 respectively are in agreement where P_{lt3} request for operation was rejected initially and placed in the queue (AC_{QUE}) for one second. Furthermore, both highlight P_{lt3} to be allowed operation at requested 60W when P_l was increased to 150W. However, prior to allowing the operation of P_{lt3}, the ERV charging rate P_c was reduced by 10W to facilitate the 60W operation beyond the 50W supply limit P_l increase. Within the simulation model, it took 0.01 seconds for P_{lt3} to gain operation from the point of P_l increase.

5.2.4.3 RBP powered smart appliance management

The RBP powered smart appliances operation (P_{DS}) are managed within the proposed ERV central controller strategy to maintain the RBP operation within its instant discharge (P_D) and available capacity (B_{ci}) limits. This ensures an extended lifespan and reliable operation of the RBP. For effective management strategy application, different parameters are monitored such as the RBP charging (P_c), RBP powered smart appliances loading (P_{DS}), the remaining and / or requested operational time of the RBP powered smart appliances (t_{Dtn}), and RBP powered smart appliances placed in the queue (DC_{QUE}). The management of the RBP powered smart appliance is triggered at both start-up and during operation if interruptions are required to accommodate for varying RBP charging (P_c) levels.

In test scenario one, RBP powered loads P_{Dt1} and P_{Dt2} operated at 100W and 60W respectively. The instant discharge limit P_D was at 205W due to the present charging rate P_c of 135W in addition to the original P_D limit of 70W. A reduction in P_g by 50W was introduced in the fourth second. Both theoretical and simulation results in Table 18 and Figure 103 respectively demonstrate termination of P_{Dt2} at that point to maintain the instant discharge RBP level within its new P_D to be implemented with 50W reduced P_c. Furthermore, the terminated P_{Dt2} was placed in the queue (DC_{QUE}), where its operation was resumed with the increase in charging rate P_c by 15W due to reduction in AC smart appliance loading P_{ls}. The reduction of P_c and termination of the P_{Dt2} was achieved within 0.0004 seconds from the point of P_g reduction in the simulation model.

In test scenario two, a reduction in AC supply limit P_g by 50W was triggered, however, due to RBP powered appliances loading P_{DS} being at 110W and the updated P_D was 155W, no interruptions to RBP powered appliances was applied. This was reflected in both simulation and theoretical results of Figure 105 and Table 18.

Available RBP capacity (B_{ci}) is another parameter that the ERV central controller management strategy addresses, both at the start-up of an RBP powered smart appliance and with variations in the charging rate (P_c). The proposal calculates the required RBP capacity E_{Dt2} for the operation of P_{Dt2} using its power requirement, the operational (remaining) time t_{Dt2}, capacity requirements of other time-dependent RBP powered smart appliances operating E_{Dt1}, user-dependent RBP powered smart appliance loading P_{DU1}, and P_c. Operational scenario three tests this capability through request for operation triggered by P_{Dt2} at 400W for 10 minutes. This was set to occur when P_c was at 135W, P_{Dt1} was operating at 100W with remaining duration of 4.95 minutes, P_{DU1} operating at 70W, and B_{ci} was at 70Wh. This resulted in immediate acceptance of operational request made by P_{Dt2}, both through theoretical calculations and simulation in Table 18 and Figure 105 respectively.

In the final test scenario implemented, an operational request at 400W for 10 minutes was also made by P_{Dt2}. However, with one difference from test scenario three, which is the time-dependent RBP powered smart appliance P_{Dt1} operating at 200W with remaining duration of 4.95 minutes. Both theoretically and in simulation, this resulted in increase of required operational capacity E_{Dt2} from 64.01 (Wh) in test scenario three to 72.33 (Wh) in test scenario four. Therefore, both results in Figure 106 and Table 18 indicate that P_{Dt2} was allowed to operate in a queued manner depending on the fluctuations of P_c and P_{Dt1} completing its operation. Effective and optimised management of RBP loading is reflected through those results.

5.2.5 **Scalability**

The proposed novel ERV central controller management strategy serves as a first step towards RV electrification. However, this proposal can be expanded to incorporate further capabilities such as:

- Management of power sources utilised for different ERV appliances providing optimum performance.
- Utilisation of the drivetrain RBP via the V2G facility in a manner which minimizes its lifespan degradation.
- Prioritisation protocol dependant on user constraints and forecasted grid information of supply capability.

In addition to its flexibility in capabilities expansion, the proposed management strategy can be utilised within various applications such as houses.

5.2.6 **Conclusion**

A novel ERV central controller management strategy is proposed to serve as the future ERV platform, facilitating its adoption due to the ability in eliminating the need for infrastructural investments within the leisure industry. The proposed strategy is based on three main management elements of RBP charging, AC powered smart appliances, and RBP powered smart appliances. Those management elements were further developed via combining both proposals in Chapter 3 and Chapter 4 of the thesis, amendments on certain capabilities of both chapter proposals, and additional capabilities to form a holistic novel ERV solution. The proposal architectural arrangement and the algorithms behind its various capabilities were presented. The overall solution, with a focus on the additional and amended capabilities, was evaluated and discussed using theoretical and simulation results where the following outcomes were identified:

- Smart grid integration capability via an in-situ AC supply reconfiguration functionality was successfully implemented.
- Smart appliances operation and RBP charging were optimised through intelligent use of available AC grid and RBP supply capacities.
- Operational parameters of both AC grid and RBP supplies were successfully kept within defined limits effectively through proactive and holistic control of all loads.
- Agreement between theoretical and simulation results was achieved at in all test scenarios reflecting successful implementation of the simulation model.
- All control actions within the simulation model were achieve within 0.02 seconds or less.
- No limitations were identified in the proposed management strategy which reflects its strong accuracy and capability.

Finally, the proposal's scalability to include additional capabilities and to be implemented within different applications was also highlighted.

Chapter 6 GENERAL CONCLUSION AND FURTHER WORK

6.1 General conclusion

This thesis has proposed a novel central controller smart grid management strategy for the future ERV platform. The proposal achieves smart capabilities and functions which allow the ERV to operate its loads in an optimised and adequate manner in relation to the available supply sources at any instance, without requiring investments in upgrading the current electrical infrastructure on both leisure industry and main grid levels. The novel proposal is holistic as it incorporates capabilities for electric RV drivetrain and back-up RBP charging management, RBP powered smart appliances management, and AC powered smart appliances management. Furthermore, RBP operations are maintained within their specified essential parameters, hence, enhancing its reliability and lifespan. Finally, the proposal is scalable, being capable of integrating additional functions in the future and being utilised in different applications.

The architecture and relevant algorithms of the overall proposal and its specific elements were presented and described within Chapter 3 to Chapter 5 of the thesis. The capabilities and functions achieved in the proposed architecture and algorithms were both simulated and tested practically utilising scaled down laboratory prototypes. Furthermore, theoretical calculations and assessments were carried for analysis and evaluation.

The analysis of the obtained results from theoretical calculations, simulations, and laboratory prototype testing of the overall proposal demonstrated successful achievement of overcoming identified challenges in the electrification of the RV. Therefore, in conclusion, the proposed novel smart central controller management strategy, is an effective solution for electrifying RVs in order to support the overall electrification trend. The implementation of the proposed novel solution will aid reduction of fossil fuel utilisation within the leisure industry at an enhanced rate, thus, reducing environmental concerns.

6.2 Further work

There are further works that are required for the novel ERV central controller management strategy proposal of this thesis to be effectively implemented commercially:

- Incorporate smart capability within set point driven appliances, such as water heaters, to forecast their operational time at different power levels for the desired set point to be achieved.
- Achieve direct communication between the central controller and non-schedulable loads.
- Develop RBP charger circuitry of increased response rate in order to eliminate any limitations on its charging rate control.
- Investigate and utilise RBP SOC identification methods of sufficient accuracy for optimised and more accurate ERV central controller management strategy operations.
- Investigate and develop a quality of service guarantee scheme.

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