Management of Electric Vehicle Battery Charging in Distribution Networks

Thesis Submitted for the Degree of
Doctor of Philosophy

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Declaration

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Summary of Thesis

This thesis investigated the management of electric vehicle battery charging in distribution networks. Different electric vehicle fleet sizes and network locations were considered.

The energy storage capacity and backup generator's energy requirements were calculated to achieve daily energy balance in a low voltage distribution network with micro-generation. The effect of the electric vehicle battery demand as controllable loads on the backup generator energy requirements was assessed. It was found that the use of electric vehicles as controllable loads reduced the energy requirements from the backup generator or made it unnecessary to achieve energy balance.

Two control algorithms for the battery charging management of electric vehicles clustered in battery charging facilities were designed and developed. One algorithm calculates electric vehicle battery charging profiles for vehicles located in a parking space. Different charging policies were investigated, showing the ability of the control algorithm to define the electricity profile of the parking space according to network constraints and the policies' objectives. The second algorithm calculates the number of batteries and chargers that are required to satisfy the battery demand of electric vehicle battery swapping stations. The impact of the number of chargers and batteries on the swapping station's electricity load profile were evaluated.

An agent-based control system was designed and developed for the battery charging management of electric vehicles dispersed in distribution networks. The electric vehicle battery charging schedules are calculated according to electricity prices and distribution network technical constraints.

The real-time operation of the agent-based control system was demonstrated in the laboratory of TECNALIA's research centre in Bilbao, Spain. A series of experiments showed the ability of the control system to operate and manage the electric vehicle battery charging when the distribution network is operated within its loading capacity and when the network technical limits are violated.

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List of Publications

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Journal Papers

1. P. Papadopoulos, S. Skarvelis-Kazakos, I. Grau, L. M. Cipcigan, and N. Jenkins, "Electric vehicles' impact on British distribution networks," *Electrical Systems in Transportation, IE*T, vol.2, no.3, pp.91-102, 2012.
2. I. Grau Unda, P. Papadopoulos, S. Skarvelis-Kazakos, L. M. Cipcigan, N. Jenkins, and E. Zabala, "Management of Electric Vehicle battery charging in distribution networks with Multi-Agent Systems**"** [submitted for publication].

Book Chapters

3. I. Grau Unda, P. Papadopoulos, S. Skarvelis-Kazakos, L. M. Cipcigan and N. Jenkins, "Energy Storage for Balancing a Local Distribution Network Area", Chapter in Energy Storage in the Emerging Era of Smart Grids, InTech, 2011. ISBN 978-953-307-269-2.

Conference Papers

4. I. Grau Unda, P. Papadopoulos, S. Skarvelis-Kazakos, L. M. Cipcigan, and N. Jenkins, "Electric Vehicle Battery Swapping Stations, Calculating Batteries and Chargers to Satisfy Demand", *3rd Int. Conf. Urban Sustainability, Cultural Sustainability, Green Development, Green Structures and Clean Cars*, Barcelona, Spain, 2012.

5. I. Grau Unda, P. Papadopoulos, S. Skarvelis-Kazakos, L.M. Cipcigan and N. Jenkins, "Virtual Power Plants with Electric Vehicles", *2nd European Conf. SmartGrids and E-Mobility*, Brussels, Belgium, 2010.

6. I. Grau Unda, S. Skarvelis-Kazakos, P. Papadopoulos, L.M. Cipcigan and N. Jenkins, "Electric Vehicles Support for Intentional Islanding: a Prediction for 2030", *North American Power Symp. (NAPS)*, Mississippi, US, 2009.

7. I. Grau Unda, L. Cipcigan, N. Jenkins and P. Papadopoulos, “Micro-grid intentional islanding for network emergencies”, *44th Universities Power Engineering Conf., Glasgow,* UK, 2009.
8. P. Papadopoulos, I. Grau Unda, M. Fernández, J. Jimeno, E. Zabala, L. M. Cipcigan, and N. Jenkins, “Analysis of an electric vehicle agent based management model”, *3rd European Conference on Smart Grids and E-Mobility,* Munich, Germany, 2011.
9. E. Karfopoulos, P. Papadopoulos, S. Skarvelis-Kazakos, I. Grau Unda, N. Hatziargyriou, L.M. Cipcigan and N. Jenkins, “Extending the Microgrids Concept to Integrate Electric Vehicles in Power Grids”, *16th Int. Conf. Intelligent System Applications to Power Systems* (ISAP), Crete, Greece, 2011,
10. A. F. Raab, M. Ferdowsi, E. Karfopoulos, I. Grau Unda, S. Skarvelis-Kazakos, P. Papadopoulos, E. Abbasi, K. Strunz, L.M. Cipcigan, N. Hatziargyriou, and N. Jenkins, “Virtual Power Plant Control Concepts with Electric Vehicles”, *16th Int. Conf. on Intelligent System Applications to Power Systems (ISAP),* Crete, Greece, 2011.
11. P. Papadopoulos, S. Skarvelis-Kazakos, I. Grau Unda, L.M. Cipcigan and N. Jenkins, “Predicting Electric Vehicle Impacts on Residential Distribution Networks with Distributed Generation”, *IEEE Vehicle Power and Propulsion Conf. 2010 (VPPC),* Lille, France, 2010.
12. P. Papadopoulos, S. Skarvelis-Kazakos, I. Grau Unda, B. Awad, L. M. Cipcigan, and N. Jenkins, “Electric vehicle impact on distribution networks, a probabilistic approach”, *45th Universities Power Engineering Conf. (UPEC),* Cardiff, UK, 2010.
13. P. Papadopoulos, A. E Umenei, I. Grau Unda, R. Williams, L. Cipcigan, Y. Melikhov, “Effectiveness of a new inductive fault current limiter model in MV networks”, *45th Universities Power Engineering Conf. (UPEC),* Cardiff, UK, 2010.
14. S. Skarvelis-Kazakos, P. Papadopoulos, I. Grau Unda, A. Gerber, L. M. Cipcigan, N. Jenkins and L. Carradore, “Carbon Optimized Virtual Power Plant with Electric Vehicles”, *45th Universities Power Engineering Conf. (UPEC),* Cardiff, UK, 2010.

15. P. Papadopoulos, L. Cipcigan, N. Jenkins, I. Grau Unda, "Distribution networks with electric vehicles", *44th Universities Power Engineering Conf. (UPEC)*, Glasgow UK, 2009.

EUROPEAN PROJECT DELIVERABLES

16. M. Ferdowsi, I. Grau Unda, E. Karfopoulos, P. Papadopoulos, S. Skarvelis-Kazakos, L. M. Cipcigan, A. F. Raab, A. Dimeas, E. Abbasi, and K. Strunz, "Controls and EV aggregation for virtual power plants", Mobile Energy Resources in Grids of Electricity, Deliverable D1.3, 2011, [Online]. Available at: http://www.ev-merge.eu, [Accessed: Dec. 2012].

17. C. L, Moreira, D. Rua, E. Karfopoulos, E., Zountouridou, F. Soares, I. Bourithi, I. Grau Unda, J. A, Peças Lopes, L.M. Cipcigan, L. Seca, M. Moschakis, P. M. Rocha Almeida, P., Moutis, P. Papadopoulos, R. J. Rei, R. J. Bessa, S. Skarvelis-Kazakos, "Extend concepts of MG by identifying several EV smart control approaches to be embedded in the smartgrid concept to manage EV individually or in clusters", Mobile Energy Resources in Grids of Electricity, Deliverable D1.2, 2010, [Online], Available at: http://www.ev-merge.eu, [Accessed: Dec. 2012].

18. C. Sánchez, A. Gonzalez, R. Ferreira, B. Diaz-Guerra, P. Papadopoulos, I. Grau Unda, E. Voumvoulakis, E. Zountouridou, E. Karfopoulos, A. Bourithi, M. Ferdowsi and E. Abbasi, "Scenarios for the evolution of generation system and transmission, distribution, grid evolution requirements for different scenarios of EV penetration in different countries". Mobile Energy Resources in Grids of Electricity, Deliverable D3.1, 2010, [Online], Available at: http://www.ev-merge.eu, [Accessed: Dec. 2012].

19. E. Zabala, P. Papadopoulos, I. Grau Unda, "Technical reporting of the EVOLVE-MAS project", Distributed Energy Resources Research Infrastructures Deliverable, 2011. EU Project No.: 228449, Available at: http://der-ri.net/index.php?id=143. [Accessed: Dec. 2012].

Standards Development and Project Participation

Within the framework of the doctorate degree, the author participated in the following projects and standards development:

1. EU FP7 Project **Mobile Energy Resources in Grids of Electricity (MERGE)** -EU Project Contract No: 241399. Co-author in:

- Deliverable 1.2: Extend Concepts of MG by Identifying Several EV Smart Control Approaches to be embedded in the Smart Grid Concept to manage EV individually or in Clusters.
- Deliverable 1.3: Controls and EV Aggregation for Virtual Power Plants.
- Deliverable 3.1: Scenarios for the evolution of generation system and transmission, distribution, grid evolution requirements for different scenarios of EV penetration in different countries.

2. **IEEE P2030.1™ Guide for Electric-Sourced Transportation Infrastructure** -Task Force 2: Grid Impact: Co-author.
3. EU FP7 Project **Distributed Energy Resources Research Infrastructures (DERri)** - EU Project Contract Number: 228449. DERri project: "Electric Vehicle Operated Low Voltage Electricity networks with Multi-Agent Systems (EVOLVE-MAS)". User member and co-author.

List of abbreviations

AC	Alternate Current
ACL	Agent Communication Language
AID	Agent Identifier
AMS	Agent Management System
AP	Agent Platform
BERR	Department for Business, Enterprise and Regulatory Reform
BESS	Battery Energy Storage System
BMS	Battery Management System
BMW	Bavaria Motor und Wagen
BEV	Battery Electric Vehicle
BRP	Balancing Responsible Party
CO2	Carbon Dioxide
CHP	Combined Heat and Power
CSDER	Communication Services for Distributed Energy Resources
DBQ	Depleted Battery Queue
DC	Direct Current
DECC	Department of Energy and Climate Change
DER	Distributed Energy Resource
DERri	Distributed Energy Resources Research Infrastructures
DF	Directory Facilitator
DfT	Department for Transport
DG	Distributed Generation
DNO	Distribution Network Operator
DoD	Depth of Discharge
DSM	Demand Side Management
DSO	Distribution System Operator
ESS	Energy Storage System
EC	European Commission
EU	European Union
EVPM	Electric Vehicle Parking Manager

EV	Electric Vehicle
FCV	Fuel Cell Vehicles
FIPA	Foundation of Intelligent and Physical Agents
FIPA-ACL	FIPA Agent Communication Language
GB	Great Britain
GHG	Greenhouse Gases
HEV	Hybrid Electric Vehicle
HV	High Voltage
IBM	International Business Machines
ICE	Internal Combustion Engine
ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronic Engineers
IET	Institution of Engineering and Technology
IP	Interaction Protocol
JADE	Java Agent DEvelopment framework
LA	Local Area
LBC	Load Banks Controller
LP	Linear Programming
LV	Low Voltage
MAS	Multi-Agent Systems
MERGE	Mobile Energy Resources in Grids of Electricity
MIP	Mixed Integer Programming
MTP	Message Transport Protocol
MV	Medium Voltage
NTUA	National Technical University of Athens
OFGEM	Office of Gas and Electricity Markets
OP	Operational Period
PG&E	Pacific Gas and Electric Company
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
QP	Quadratic Programming
SoC	State of Charge
SP	Scheduling Period

SSM	Swapping Station Manager
TFT-LCD	Thin Film Transistor- Liquid Crystal Display
ToU	Time of Use
TSO	Transmission System Operator
UK	United Kingdom
US	United States
VPP	Virtual Power Plant
V2G	Vehicle to Grid
μ-CHP	Micro Combined Heat and Power

Chapter 1

Introduction

1.1 Electric Vehicles

Electric Vehicles (EV) are automobiles powered by electric motors. This broad definition embraces different types of EVs. Excluding continuously cabled vehicles such as trams, the EVs are generally classified in three categories: i) Fuel Cell Electric Vehicles (FCEV), ii) Battery Electric Vehicles and iii) Hybrid Electric Vehicles (HEV).

The power source of each EV type is different; the FCEV are powered by fuel cells, BEVs are powered by batteries, and HEVS combine an Internal Combustion Engine (ICE) with an electric motor (generally powered by a battery). Within HEVS, two types exist depending on whether they can recharge the battery from the electricity grid or not. Those with the capability to be connected to the electricity network are referred to as Plug-in Hybrid Electric Vehicles (PHEVs).

In this thesis only EVs which batteries require from the electric power system to be recharged are considered: BEVs and PHEVs. If not mentioned otherwise, the term *EV* in this thesis will refer to these two types of battery electric vehicles.

1.1.1 Towards an Electric Vehicle Future

Electric powered vehicles have more than 175 years of history. According to [1] the first EV was invented in 1834. At the end of the 19th century EVs were manufactured in different countries around the world [2]. Early EV market penetration attempts failed due to EV battery autonomy limitations, the advances in ICEs and the production of ICE vehicles in series [1], [2].

In the last decades an increased interest from the automotive industry with regards to Electric Vehicles has emerged. The three main reasons are:

- Battery technology improvements.

- Finite condition of oil and its price rise in the last decades (Fig. 1.1).
- Governmental incentives and restrictive legislations in vehicle's tail-pipe Green House Gas emissions (GHG).

Recent advances in battery technologies have significantly improved battery performance in terms of energy density (Wh/kg), charge/discharge efficiencies and cost; it is anticipated that further advancements will be succeeded [3].

Incentives provided by governments and local authorities to EV owners are aimed to boost EV adoption by making EVs more cost competitive compared to conventional ICE vehicles. Moreover disincentives in high CO_2 emitting vehicles are also being applied, for which most of EV owners are exempted. In Table 1.1, EV adoption incentives provided by governments and local authorities to EV owners are summarised.

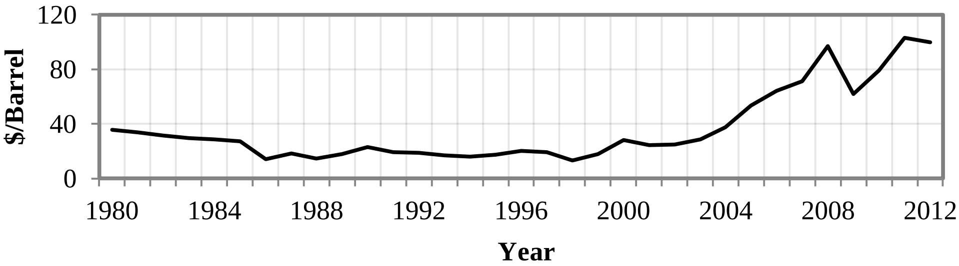

Fig. 1.1. Oil price evolution in the last decades [4]

Table 1.1 Governments and local authorities' incentives to EV owners

Incentive	Description
Reduction in vehicle taxes	Reduction or even exemptions in registration and annual taxes are being applied [5].
Reduction in EV purchase cost	Grants are offered for EV purchasing, in some countries goes up to 25% of the vehicle cost, normally with an upper limit cost (as in UK [6]). In Spain goes up to 30,000€ for large EVs [7].
Miscellaneous	Additional incentives are provided, such as free parking facilities, reduction or exemption of toll payments, or the use of bus lanes (as in Norway) and high occupancy vehicle lanes (as in most US states) [8].
CO_2 emitting penalties	Nineteen of the EU member states have a taxation charge according to vehicle's CO_2 emissions [9]. Vehicle owners are charged when the vehicle exceeds a certain amount of gCO_2/km, the penalties and the gCO_2/km limits vary from country to country.

On the other hand legislations concerning vehicle manufacturers also exist. Legislations in vehicles' emissions are a consequence of the high influence of the transport sector on the total Green House Gas (GHG) emissions. In the European Union (EU), GHG emissions from transport sector accounts for more than 25% of the total emissions, from which more than 70% are emitted in road transportation [10]. European Commission (EC) regulations set actual and future GHG vehicle tail-pipe emissions restrictions:

- Regulation (EC) No 715/2007 [11]: defines the Euro 5 and Euro 6 standards, where limits are set according to the category of each pollutant emission.
- Regulation (EC) No 443/2009 [12]: has set CO_2 tail-pipe emissions limits for new vehicles to 130gCO_2/km in 2015 and to 95gCO_2/km in 2020. In 2012 average EU new vehicle fleet emissions were 132.2gCO_2/km [13].

An indicative of the potential EV uptake in the future is the amount of traditional vehicle automotive companies that have developed or are now developing electric vehicles, as well as the high amount of EV start-up companies. In Table 1.2, some of the traditional and start-ups vehicle companies that have announced EV production plans are shown.

Table 1.2 Traditional and start-up companies with EV production plans

Traditional Vehicle Manufacturers		**Start-up Companies**	
Nissan	[14]	Phoenix Motorcars	[27]
Ford	[15]	Fisker	[28]
Mitsubishi	[16]	BYD Auto	[29]
Toyota	[17]	Liberty Electric Cars	[30]
Honda	[18]	Aixam	[31]
Smart	[19]	Vetrix	[32]
Audi	[20]	Commuter Cars	[33]
BMW	[21]	Dynasty Electric Car Corp	[34]
Chevrolet	[22]	Mahindra Reva	[35]
Volkswagen	[23]	Lightning Car Company	[36]
SEAT	[24]	Tesla Motors	[37]
Renault	[25]	Brammo	[38]
Volvo	[26]	Miles Electric Vehicles	[39]

Fig. 1.2 shows the UK's battery electric vehicle sales in the last years.

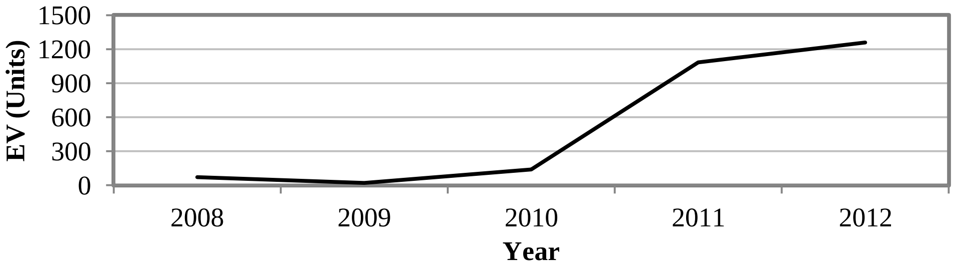

Fig. 1.2 UK's battery electric vehicle sales in the last years [40]

1.2 FUTURE ELECTRICITY NETWORK

Traditionally the electricity flow has been unidirectional: from large generation plants to end consumers, Fig. 1.3. Power systems are broadly classified in four main categories: i) Generation, ii) Transmission, iii) Distribution and iv) Demand.

The bulk energy generated takes place at a number of large power plants (with power rating ranging from hundreds to thousands MWs). The generation power plants are connected to the transmission network, which is utilised to deliver the energy to big consumption areas (regional areas). The transmission network is usually characterised by overhead lines operating at very high voltage levels, in Great Britain (GB) are: 400kV, 275kV and 132kV in some areas [41]. The Transmission System Operator (TSO) operates the transmission network. The TSO is responsible for the real-time balance between generation and demand, ensuring system's stability, security and operation within voltage and frequency limits [42]. In UK, *National Grid* is the TSO which operates three regional transmission systems [42]: i) England and Wales, owned by *National Grid*, ii) southern Scotland, owned by *Scottish Power Transmission Limited* and iii) northern Scotland, owned by *Scottish Hydro-Electric Transmission Limited*.

The distribution network receives the electric current flowing from the transmission network and delivers it to the end customers: industrial, commercial and residential. Within the distribution network different voltage levels are utilised, in GB are: 66kV, 33kV, 22kV, 11kV, 6.6kV, 400V, 230V and 132kV in some areas [41].

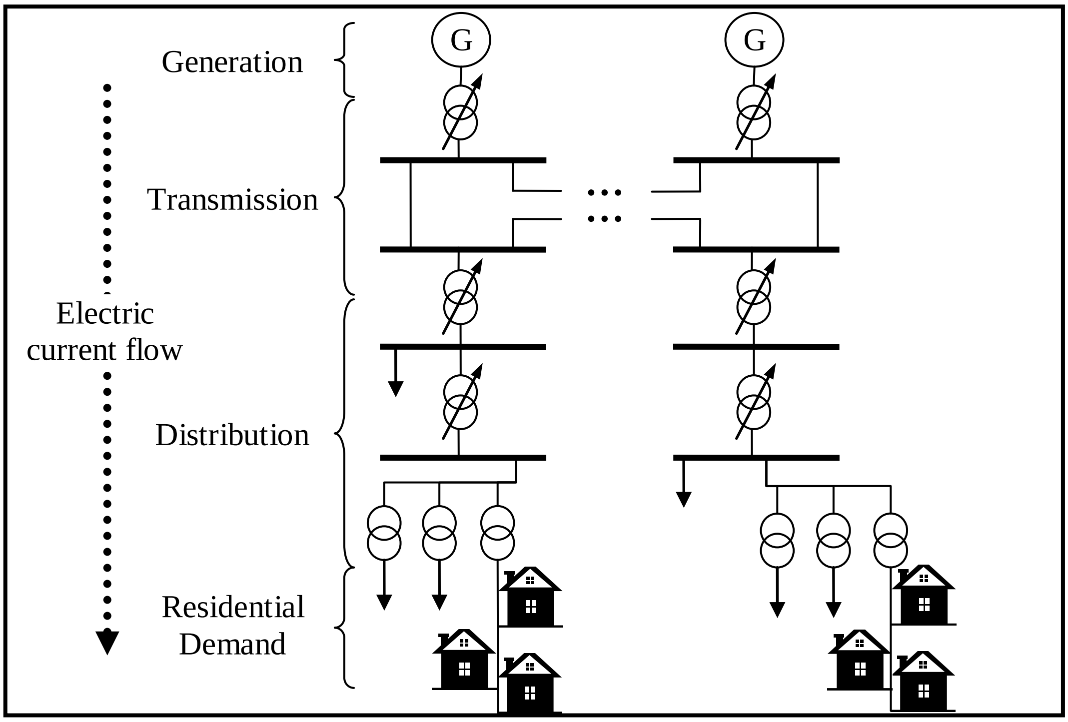

Fig. 1.3 Traditional power systems with unidirectional electricity flow

The Distribution Network Operators (DNOs) own and operate the assets of the distribution networks, and are responsible of the service quality and to maintain voltage fluctuations within operational limits [44]. According to the Office of Gas and Electricity Markets (OFGEM), DNOs must "*permit the development, maintenance, and operation of an efficient, co-ordinated, and economical system for the distribution of electricity*" [45].

1.2.1 Renewable Energy Generation

One of the main drivers that will determine the operation of future power networks is the proliferation of electricity generation from renewable energy sources. An illustrative example is the evolution of electricity generation from renewable sources in the UK (see Fig. 1.4) [46], [47]. Reasons that have promoted their widespread include environmental concerns, energy dependency and market liberalisation. Levels of penetration are expected to keep on growing as a pathway to achieve governmental emission reduction targets. In the UK, the government has committed to produce 15% of its energy from renewable sources in 2020 compared to around 2.25% in 2008 [48].

Distributed Generation (DG), connected to the distribution network and with a power rating usually smaller than 50-100 MW [49], is expected to contribute to the increase of renewable generation. Electricity produced only from micro-generation (maximum power rating up to 50-100kW) could reach up to 100TWh in 2050 in the UK, which is around 25% of the UK's 2005 electricity demand [50]. High penetration of DG will pose significant challenges in traditional system operation, such as the operation within distribution network technical constraints [51] and the shift from conventional unidirectional electricity flow (from power plants to customers), to a bidirectional electricity flow [52].

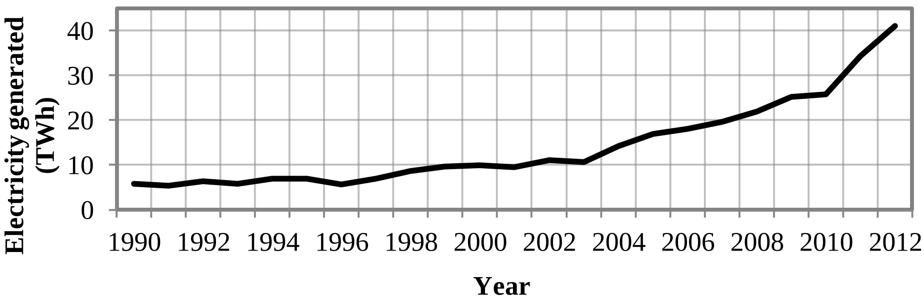

Fig. 1.4 Growth in electricity generation from renewable sources in UK [46], [47]

1.2.2 Electric Vehicle Uptake

High EV market penetration is expected in the forthcoming years, mainly PHEVs and BEVs [3]. According to document [3], the EV uptake projections in the UK for the year 2030 go from 3 millions in the "*business as usual scenario*" to 20.6 millions in the "*extreme range*" scenario. EV battery charging will increase the electricity demand [53] and distribution networks will be required to cope with this increase. EVs, from the electricity network viewpoint, can be seen as:

- Dumb loads, when as any other domestic/industrial device the EVs are connected to the distribution network without any form of control.
- Controllable loads, when the EV battery charging is managed in such a way that the battery charging schedules are defined or can be modified according to the system operator or market players' needs.
- Energy storage systems, when EVs are Vehicle to Grid (V2G) capable, which is when EVs are able to feed electricity back to the grid [54]. Being V2G capable, EVs could be managed as dispersed energy storage resources according to the system operator or market players' needs.

Future distribution networks may not withstand the increase in demand caused by a high EV uptake [55]. EVs charging as dumb loads are expected to charge at their home arrival time, coinciding with distribution system's evening peak demand hours and cause severe congestion problems [55].

1.2.3 Coordination of Distributed Energy Resources

Distribution networks are envisaged to include high amounts of dispersed energy resources [56], Fig. 1.5. These resources are usually referred to as Distributed Energy Resources (DERs) and include: DGs, Energy Storage Systems (ESSs), controllable loads and EVs.

The proliferation of DG across the different levels of the distribution network will modify the electricity generation mix. With an important rise of energy provided from renewable sources, the system's generation and demand balance may no longer be controllable only by the traditional large power plants. Due to the variable nature of most renewable energy technologies, energy storage devices and controllable loads (demand management) "*will play an increasingly important role*" [56].

Traditionally distribution networks operate as passive systems [44], where the majority of the technical problems are resolved at the planning stage [57] and the DGs are connected on a fit and forget basis [56]. To enable a high DG penetration, active network management methods and techniques will be required [56]. Future DNOs are expected to evolve to Distribution System Operators (DSOs) [58].

The management of DERs through aggregation is proposed in the literature [59], [60] as a pathway to achieve high DER penetration, with potential benefits for DER owners and system operators. The aggregation is facilitated by an entity usually referred to as the *Aggregator* [59]. The role of the aggregator consists of clustering dispersed energy resources, managing their demand and generation portfolio as a single entity. The aggregator represents a flexible and larger power entity, enabling DER participation in electricity markets or the provision of services to system operators [59], [60]. Due to DERs' small power ratings, individual participation or provision of services would be unfeasible [59]. The aggregator will serve as an intermediary between the DERs and the system operator or market players.

In order to effectively manage the dispersed resources, Information and Communication Technologies (ICT) will play a key role [61]. The control systems will rely on ICT to provide fast, reliable and secure communication with the distributed network assets and with the different power system stakeholders [62]. Apart from the aforementioned challenges, the communication infrastructure will be required to ensure interoperability between legacy systems, new network DERs and the control centres [62], [63]; according to [62], "*the key challenge is that the overall smart grid system is lacking widely accepted standards*".

In [62] the advantages and disadvantages of different communication technologies for the management of DERs are presented as "*the technology choice that fits one environment may not be suitable for the other*" [62]. Several UK and European projects such as [64]-[67], have and are investigating the ICT requirements and challenges to manage Distributed Energy Resources in future electricity networks.

In [68] an analysis of the communication methods for the management of EVs is provided. The characteristics (range, frequency, bandwidth and standards) and the potential use of the following communication methods are analysed [68]: Digital Subscriber Line (DSL), RS-485, Ethernet, Controller Area Network bus (CAN-bus), Power Line Communications (PLC), Wi-Fi, General Packet Radio Service (GPRS), Bluetooth, Radio Frequency Identification (RFID), Near Field Communication (NFC), ZigBee, Z-Wave and Wavenis.

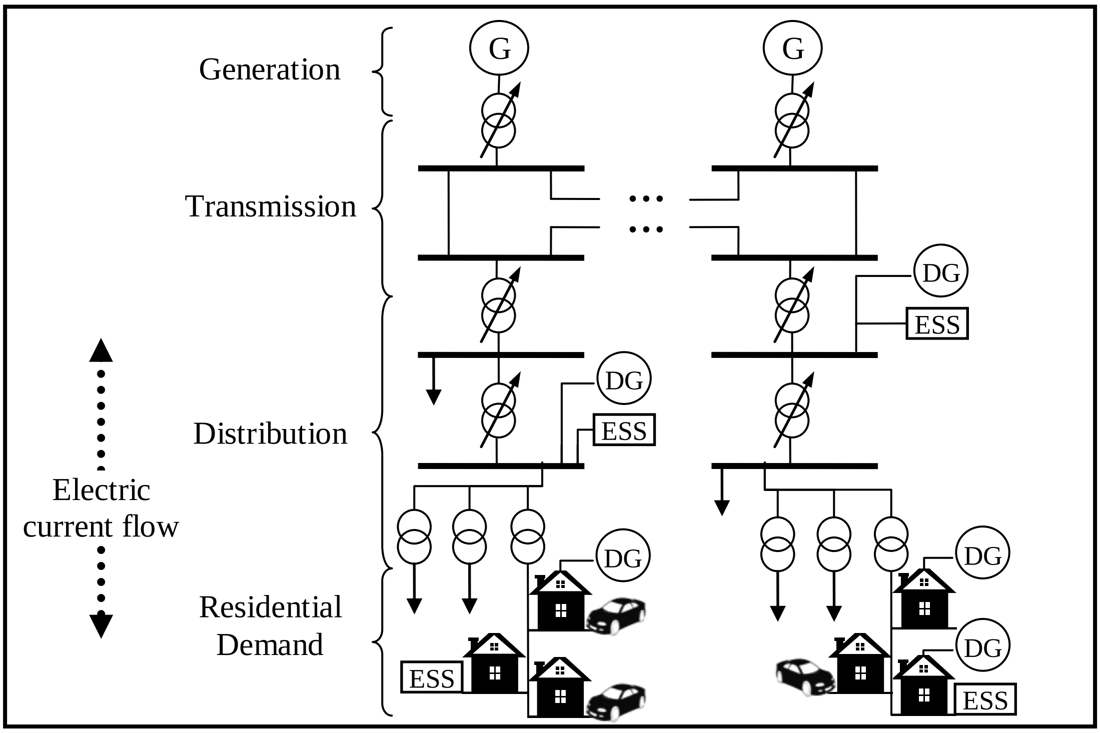

Fig. 1.5 Future power systems with high penetration of DERs

1.3 THESIS OBJECTIVES

The key question that this thesis aims to address is how electric vehicle battery charging can be managed to be integrated in distribution networks.

To answer this question, the following objectives were set:

- Evaluate the energy storage and backup generator requirements in a low voltage distribution network area with micro-generation, to be an energy self-sufficient area (i.e. energy balanced area). Assess the effect of EV battery charging as controllable loads on the backup generator's energy requirements.
- Design and develop EV battery charging control algorithms for EVs clustered in specific battery charging facilities and evaluate the impact on the electricity load profile.
- Design and develop an EV management control system for large population of EVs in distribution networks using Multi-Agent Systems.
- Evaluate the agent-based control system in a laboratory micro-grid.

1.4 THESIS STRUCTURE

Chapter 2: The relevant literature used in the thesis is presented. An overview is given with regards to: i) Energy balanced areas ii) EV charging infrastructure, iii) EV management control approaches, iv) The EV aggregator figure and v) Intelligent agents and Multi-Agent Systems.

Chapter 3: A methodology to obtain the energy storage system capacity and the backup generator energy requirements in an energy balanced local area with micro-generators is presented. The integration of EVs as controllable loads is proposed and a comparison of a non-controlled EV case with a controlled EV case is presented. The impact on the backup generator's energy requirements is shown.

Chapter 4: Control algorithms for two types of EV clusters are proposed: i) EV parking facility, where a case study is provided showing the EV aggregated demand outcome using different charging policies and ii) EV battery swapping station, where a software tool is developed to calculate the number of chargers and batteries required to satisfy the demand. The effect of the number of batteries and chargers used on the electricity load profile is shown in a case study.

Chapter 5: An agent-based control system for the coordination of large population of EVs is presented. The functionalities and interaction of the agents are given. The provision of active demand services in the form of EV demand reduction is described.

Chapter 6: The laboratory demonstration of the Multi-Agent System (MAS) control proposed in Chapter 5 is presented. The laboratory set-up including the adaptation steps to integrate the MAS to the laboratory software and hardware resources are provided. The experiments done to evaluate the control system and the results are presented.

Chapter 7: A summary of the main conclusion of the thesis are provided. Suggestions for future work are given.

Chapter 2

Literature Review

2.1 Energy Balanced Distribution Network Areas

According to a study carried out by the British Transmission System Operator (TSO), *National Grid*, the capacity of installed micro-generators in the UK could grow to as much as 5.8GW by 2030 [69]. Integration of residential micro-generators in the Low Voltage (LV) side of the grid could imply benefits for the customers, not only from an economic point of view but also as an electric supply guarantee. The continuity of the supply could be reached by associating a number of loads (customers) and its micro-generators into different local distribution network areas.

An energy balanced distribution network area is defined as part of a distribution network with the ability to satisfy its electricity demand using only the Distributed Energy Resources (DER) within the area (i.e. zero energy import/export with the main grid) [70].

The operation of energy balanced local areas would increase security of supply to end customers in case of loss of the main grid, if operated off-grid [71]-[73]. Moreover the management of the local area's DERs could enable their market participation or the provision of grid ancillary services [71].

The use of Energy Storage Systems (ESSs) and/or backup generators were proposed in [74]-[81] for achieving energy balanced areas that have installed micro-generators with intermittent or heat-driven power outputs. The absence of electricity demand-follow characteristics of the mentioned generators, requires of a backup generator to inject power during periods of lack of generation, and/or ESSs which bidirectional power flow capabilities enable their operation as a power sink or power source.

The energy that can be provided by the ESS is constrained to its storage capacity (kWh), hence properly ESS sizing as well as the remaining DERs is a key issue in the design of energy balanced areas [74]. In the literature, the optimal size of ESS in balanced areas (with renewable generators and backup generators), is calculated with the objective of minimising system's cost, including operational and fixed costs [75]-[80]; with the target of a yearly energy balance or evaluating the ESS size impact on reliability indices as in [76]-[78],[81]. In [74] no backup generator was considered and the ESS size obtained according to optimal micro-generation penetration levels that ensure yearly energy balance. In the reviewed studies daily or average demand, generation and weather data were input and by defining optimal schedules of the ESS and backup generators, the ESS capacity derived.

Based on the reviewed studies, using average daily demand and generation profiles, a methodology is proposed in **Chapter 3** to calculate the ESS capacity and backup generator energy requirements for achieving an energy balanced LV area. The difference with the reviewed studies is that in the proposed methodology no economic optimisation is performed; the aim is to investigate to what extent energy balance can be achieved only with an ESS, hence the use of the ESS is prioritised to that of the backup generator.

The methodology developed is used to assess the impact of EV battery charging as controllable loads on the ESS's and the backup generator's requirements. The integration of EVs in distributed networks is reviewed in the following sections.

2.2 ELECTRIC VEHICLE CHARGING INFRASTRUCTURE

The development of charging points and complementary charging infrastructure is identified in the literature as a key issue for the EV adoption [3]. Apart from being the necessary infrastructure to re-charge EV batteries, a broad recharging infrastructure is identified as an important element to overcome EV customers' range anxiety [3].

Two types of charging infrastructures are currently being developed and implemented to satisfy EV owners' battery charging requirements: i) EV Battery swapping stations and ii) Charging points

2.2.1 EV Battery Swapping Stations

In battery swapping stations, EV owners' depleted batteries are exchanged for fully charged batteries in minutes, assuming a similar role to that of conventional petrol stations. Batteries are replaced using a battery swapping mechanisms, Fig. 2.1, and the battery charging process is responsibility of the swapping station operator who owns the batteries.

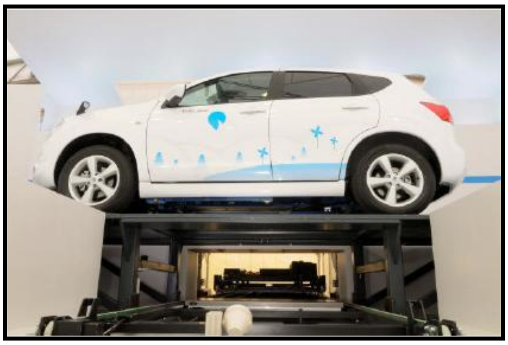

Fig. 2.1. Better Place Company battery swapping mechanism [82]

Several swapping stations have been developed in China and are used by public buses [83]. Better Place Company [82] is developing and implementing swapping stations in different countries, where some pilot projects are being undertaken [84].

In the literature, the studies related to swapping stations focus on:

- Swapping station's optimal location in the electricity network [85], [86].
- Economic feasibility of the swapping station [87].
- Economic scheduling considering renewable energy sources [88]-[90], where the swapping station is assumed to have unlimited number of chargers and the swapping station is treated as a big energy storage system (with a single point of connection to the grid).
- Battery charging management within the swapping station [91], [92].

The work presented in **Chapter 4** is related to the battery charging management within a swapping station as studies [91] and [92].

The study in [91] presents an algorithm in order to charge the batteries making use of renewable energies, where the battery demand is fixed and the State of Charge (SoC) of the depleted batteries identical. The study aims to identify the generation capacity from renewable energy sources to satisfy the electricity demand of the swapping station.

In [92] an analytical method is proposed to obtain the number of required batteries in a swapping station using queueing theory, the battery charging management within the swapping station is similar to the management proposed in chapter 4, where the batteries are charged as soon as a charger within the swapping station is available.

In **Chapter 4**, the number of batteries and chargers required are also calculated; the main difference with regards to study [92] is that a simulation-based approach is used where:

- The EV battery demand probability at each time interval is not constant among all the time intervals, but it is dependent on a user-defined hourly battery demand profile; which is more realistic since the battery demand will be closely related to driving patterns and customers' behaviour.
- Daily simulations are performed and the batteries' and chargers' state are monitored, enabling the possibility to analyse the impact of the number of chargers and batteries on the swapping station's electricity load profile.

The battery charging management proposed in chapter 4 emulates a real-time control approach, which operation is used as the core of a software tool designed to analyse two of the main uncertainties at the swapping station's planning stage:

- Required numbers of batteries and chargers to satisfy demand.
- Impact on the electricity demand profile according to the number of chargers and batteries used.

2.2.2 Charging Points

Using private or public charging points, EV owners plug their EV to the grid and receive the amount of energy according to the time connected and the connection power levels. The utilisation of the electricity distribution network enables the possibility of having battery electricity refuelling points in a broader range of destinations compared to that of ICE vehicles, where the refuelling takes place at designated petrol stations. Charging points will be located in different spots where vehicles tend to have the vehicles parked; this goes from private households (individual or community buildings) to public places such as parking facilities and on-street parking places [93].

Integration of a high EV uptake is foreseen as an important challenge for Distribution Network Operators [94]. Most parking facilities have electrical connections (for lightning, ventilation and facility's electrical devices), similarly on street public parking facilities have accessible electric connection points (from public lights or traffic lights) which will facilitate the installation of charging points. The main concern for DNOs is that distribution networks may not withstand the additional demand from the EV battery charging. Cable thermal limits, voltage violations or transformers overloading may result from the expected new load of a high EV uptake [95], [96].

The impact on the distribution networks will be dependent on the technical characteristics of the charging points and the charging modes used. Different charging modes are identified in [97], and summarised in Table 2.1

Table 2.1 EV charging modes [97]

Charging Mode	Mains Connection	Voltage	Current
Standard charge	1 phase AC connection	≤250V	≤16A/phase
	3 phase AC connection	≤480V	
Fast charge	1 phase AC connection	≤250V	≤32A/phase
	3 phase AC connection	≤480V	
Rapid charge	DC connection	500V	125A

Different EV battery charging management approaches are proposed in the literature in order to facilitate the EV integration within distribution networks constraints, which are reviewed in the following sections.

2.3 EV Battery Charging Management

Most of the installed charging points use an uncontrolled battery charging regime, similar to other battery devices, where EVs are charged in the shortest time possible until the EV battery is fully charged or until removed from the plug [98]. To overcome the associated problems with uncontrolled EV battery charging, the proposed solutions in the literature go from simple fixed Time of Use (ToU) tariff schemes to more complex control approaches, where entities, usually referred to as EV aggregators, manage the EV battery charging.

ToU tariffs are intended to modify users' charging patterns through the incentive of cheaper electricity rates during periods where the network is less loaded. Such schemes do already exist for regular electricity customers, for example the dual tariff scheme Economy 7 in the UK [99]. Some utilities such as NPOWER [100] and British Gas [101] in UK, and Pacific Gas and Electric Company (PG&E) [102] in the US, have already introduced specific ToU tariffs for EV customers; as stated in [102], such tariff "*offers a significant incentive to you to charge your vehicle during the off-peak time period when the demand for electricity is lower*." In Table 2.2 PG&E summer ToU tariffs for EV customers are shown.

In [103] the use of ToU tariffs is reported to reduce voltage violations and network congestion problems compared to the scenario where the EVs are charged without any form of control. It is stated in [103] that the use of ToU tariffs has positive effects on the grid when considering low EV uptake levels. The results of the studies show that, for the considered network, the use of ToU tariffs allows an EV uptake of 14%; beyond this value congestion and voltage violations are reported.

Table 2.2 Pacific Gas and Electric Company EV Time of Use tariffs [102]

	24:00–7:00	7:00–14:00	14:00–21:00	21:00–24:00
Monday, Tuesday, Wednesday, Thursday, Friday	Off Peak 5.0¢/kWh	Partial Peak 10.4¢/kWh	Peak 28.4¢/kWh	Partial Peak
Saturday, Sunday	Off Peak (24:00–17:00)	Off Peak	Off Peak (14:00–17:00); Partial Peak (17:00–21:00)	Off Peak

The concept of aggregation and management of EVs has been proposed in the literature, not only to overcome the associated problems of uncontrolled EV charging, but to maximise the benefits to EV owners by participating in electricity markets. The aggregation and management have also been identified as beneficial to system operators since, through the EV battery charging management, EV aggregators are potential ancillary service providers [104]. In the following sections the figure of the EV aggregator is introduced and battery charging management studies reviewed.

2.3.1 EV Aggregator Definition

An EV aggregator, according to the European project Mobile Energy Resources in Grids of Electricity (MERGE) [68] is an entity that groups and manages the charging demand of plug-in EV end users, and enables their participation in electricity markets.

The figure of the EV aggregator it is also being considered by some authorities as a pathway to incentives the EV adoption. An example is the case of Spain, where an EV management figure has been added to the law regulating the electricity sector (Law No. 54/1997), referred to as system's load manager ("*gestores de cargas del sistema*") [105]. It is defined as an entity with the capability to buy electricity to the market and sell it to the EV customers. The entity is required to have EV charging management capabilities in order to follow demand management programs set by the government or system operator's requirements [105].

The EV aggregated resources may range from a limited number of EVs clustered in a parking facility, to a large EV population dispersed in geographical areas [93]. The ownership of the EV aggregator is open in the literature to different electricity industry or other sector stakeholders [106]. The EV aggregator could be a new market player operating as a standalone entity or be part of an existing electric sector entity [107].

The use of the EV aggregator's management capabilities could be use to participate in "*new types of markets (e.g. "flexibility" markets)*" as proposed in [59] for DER aggregators, in whole sale electricity markets (future, forward and power exchange markets) or in existing UK balancing services (provided to National Grid). The figure of "*Commercial Aggregation Service Providers*" [108] does already exist in the UK, and consists in the "*aggregation of smaller loads from a number of sites*" [109] in order to participate in balancing services such as: Frequency Response, Fast Reserve or Short Term Operating Reserve [109].

To aggregate EV resources and enable their market participation and the provision of ancillary services, the control approaches that have been proposed for the EV management are: i) Centralised and ii) Decentralised.

2.3.2 Centralised Control of EV Resources

In a centralised control approach the EV aggregator is a central coordination unit where the system's decision making is implemented, Fig. 2.2. The EV aggregator generates the EV battery charging schedules according to its goal which are sent and followed by the EVs. The EV aggregator generates individual EV schedules seeking for the best possible aggregated EV demand according to its objectives.

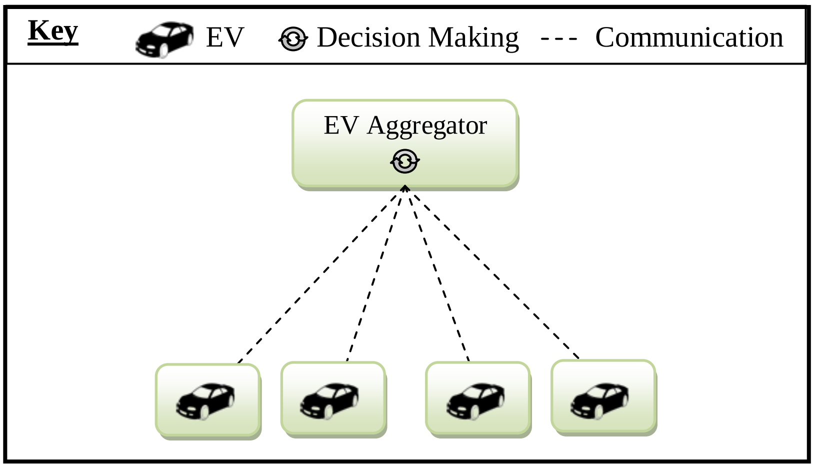

Fig. 2.2 Centralised control of EV resources

According to the management strategies followed, EV aggregators can be classified as:

i) Commercial aggregator: The objective of the aggregator is to manage the EV battery charging in the most economical way [110]-[119].

ii) Technical aggregator: The objective of the aggregator is to provide grid-related services.

A number of studies have examined the use of centralised EV aggregation for technical objectives and in particular to:

- Minimise system losses [120], [121].
- Peak shaving [122].
- Congestion management and voltage regulation [103], [123].
- Maximise power delivered within defined time intervals [124].

The studies [110]-[113] considered both commercial activities and network technical constraints in their coordination processes.

In order to enable technical EV aggregation, prior knowledge of the physical distribution network topology and the connected EV characteristics has been assumed [110]-[113], [120]-[124] . Algorithms that include AC load flows have been used to obtain EV charging schedules that comply with distribution network loading limits and satisfy EV owner battery charging preferences.

The main assumptions used in the centralised coordination approaches are:

- The EV battery charging schedules are left under the management of the EV aggregator, and EVs follow its scheduling commands.
- EV owner preferences and behaviour are known: Energy needs, charger ratings, and grid connection and disconnection time.
- Non-EV system load demand and generation profiles are known.
- When considering market participation: Electricity wholesale prices, electricity tariff zones and service revenues payments are known on a day-ahead basis.
- When considering grid constraints: Full knowledge of the network topology, including the location of generators, non-EV loads and EVs.

The main assumptions are reported as forecasted data; with these data the studies reviewed performed finite-horizon off-line optimisations and management algorithms in order to achieve the EV aggregator's desired goals. As the EV uptake increases, owners' battery charging patterns will become more predictable [93] and as stated in [107], the collection of EV data by the EV aggregator will be used to improve the forecasted data.

A main drawback of centralised control, is the computational intensity and data transfer which will result with large populations of EVs [125], [126].

In **Chapter 3** an off-line centralised optimisation is proposed for the integration of EVs as controllable loads in an energy balanced local area. EV optimal battery charging schedules are calculated with the aim of matching the generation surplus from the micro-generators with the EV demand, minimising the use of the backup generator.

In Chapter 4 a real-time centralised control algorithm is proposed for the management of EV battery charging clustered in a parking facility. EV battery charging schedules are assigned on a first-come first-served basis according to defined charging policies and network technical constraints.

2.3.3 Decentralised Control of EV Resources

In decentralised control, the computational logic is distributed among the EV aggregator and the EVs. Different levels of decentralisation can be found in the literature:

i) Fully decentralised approach: The decision making takes place at the EV, which decides its charging schedules according to signals received from the EV aggregator [127]-[130].

ii) Hierarchical decentralised approach: The EV aggregator uses intermediate aggregation layers, and the decision making is coordinated among the different aggregation layers and the EVs [125], [126], [131]-[133].

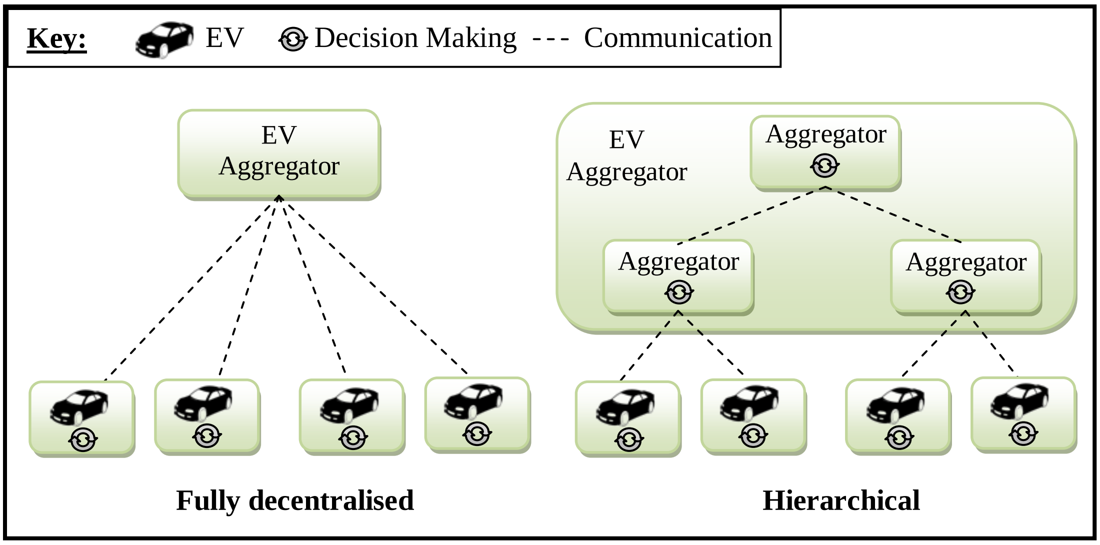

Fig. 2.3 Decentralised control of EV resources

A) Fully Decentralised Approach

In fully decentralised control studies [127]-[129], the charging schedules are decided by the EVs after a negotiation process with the EV aggregator. In these studies:

- The EV aggregator's goal is to achieve a flat demand profile during demand valley periods.
- The EV's goal is to achieve its desired energy minimising the cost of charging.

The negotiation process takes place prior to the EV grid connection period, assuming that the EVs will follow the agreed profiles. The EV aggregator belongs to the utility which has knowledge of the forecasted residential demand. The negotiation between the EV aggregator and the EV agents consists of an iterative process where:

1) The EV aggregator broadcasts electricity prices.
2) The EVs forward their charging plan.
3) The EV aggregator receives the charging plans of all EVs and checks if changes in the aggregated profile are required.

If changes in the aggregated profile are required, the EV aggregator updates the electricity prices and the process restarts at (1). The negotiation process finishes when no modifications are required by the EV aggregator or when the EV charging plans sent by the EVs are no longer modified.

In [130] a real-time fully decentralised approach is presented. The objective of the EV aggregator is to achieve a flat demand profile. The negotiation process is similar to [127]-[129] with the difference that:

- It is a real-time control approach and the negotiation process takes place before each charging time interval.
- The signals sent to the EVs are not price signals, but "*charging signals*" in kWh.
- The decision of the EV agent on whether to charge or not is done according to the service contracted with the EV aggregator and the difference between the charging signal and the EV's State of Charge.

B) Hierarchical Decentralised Control Approach

The use of a hierarchical architecture where the computational logic is distributed among the aggregation layers, enables the intermediate aggregation layers to manage its controlled EV resources locally [125]. The use of intermediate aggregation layers reduces the data transfer with the upper aggregation layer [131] and enhances scalability as provided in [126].

The hierarchical distributed control studies reviewed reported real-time management operation, where the control is performed by the coordination of the different aggregation layers and the EVs. The reviewed studies used Multi-Agent Systems (which is presented in Section 2.4), where each control entity is referred to as agent.

In [126] a hierarchical control system is proposed where the agents are located at the primary and secondary substation levels. The negotiation process with the EV agents is similar to the fully decentralised studies [127]-[129]. The main difference is the use of intermediate layer aggregators which are used to: i) Aggregate the charging profiles of the individual EVs and forward them to the responsible aggregation layer setting the price signals, and ii) Manage the EV battery charging in case network constraints are violated.

In [131] a hierarchical control architecture is presented where the EVs are managed together with other DERs. An internal energy market is in place where the DER agents place their bids and offers reflecting the electricity price they are willing to pay or be paid for. DERs' bid-price-curves are aggregated by concentrator agents and forwarded to an auctioneer agent, which sets a clearance price with the objective of achieving a supply demand balance.

In [125] the control system comprises the following agents: i) Vehicle agent, ii) LV transformer agent and HV transformer agent. The goal of the transformer agents is to avoid overloading and achieve a flat demand profile at the transformer levels (EV demand plus residential demand), while the EV agent goal is to achieve its desired energy. The EV agents send charging requests to the LV transformer agent which forwards the information to the HV transformer agent. After negotiation between the HV and LV transformers agents, the charging decision is sent to the EV agents.

In [132] the control system comprises the following agents: i) Vehicle agent, ii) Transformer agent and ii) Balancing Responsible Party (BRP) agent. The goal of the BRP agent is to minimise imbalance costs, the transformer agent's goal is to avoid overloading, while the EV agent goal is to achieve its desired energy. The EV agents send a charging plan to the transformer agent which forwards it to the BRP agent. With the received information, the BRP agent informs the transformer agent of the amount of energy to be consumed in the following time interval. The transformer agent distributes the energy among the connected EVs.

In [133] the control system comprises the following agents: i) Vehicle agent ii) Aggregator agent and iii) TSO agent. The TSO agent is used as the interface between the agent system and the TSO for frequency regulation services. The goal of the aggregator agent is to maximise its economic revenue by participating in frequency regulation services. The primary goal of the EV agent is to achieve its desired energy and the secondary goal is to make profit by participating in frequency regulation services. When an aggregator agent has the adequate number of EVs to participate in regulation services, places its bids to the TSO agent. The aggregator agent distributes among its EV agents the power modifications requested by the TSO agent.

In the reviewed decentralised studies (hierarchical and fully decentralised) the interaction with the SOs is only reported in [131]-[133]. In [131] a DSO agent is proposed; in case of local congestions, modifies the price signals "*that stimulates certain behavior but does not enforce it*". In [133] a TSO agent is defined with the purpose of providing frequency regulation services, but no distribution network constraints are considered. In [132] the interaction with the TSO is assumed to occur on a day-ahead basis. In the studies [132] and [125] the transformer agents are used to avoid constraints limits violations and to schedule the EVs, whether they belong to a supplier entity or the DSO is not reported.

In Chapter 5 a real-time decentralised hierarchical control is proposed for the management of large population of EVs. The management framework developed within MERGE [134] was adopted. In that framework the EV aggregator is defined as a supplier entity, with the capability to manage and sell electricity to the EVs. The operational framework was further developed at Cardiff University within the EU FP7 project Distributed Energy Resources Research Infrastructures (DERri) [135] with a colleague PhD student [136].

In the control approach proposed, a clear separation is done between the EV aggregator and the DSO, and their interactions defined as shown in Table 2.3 and Table 2.4. On a day-ahead basis the DSO informs the EV aggregator with the power that can be drawn by the EVs at each LV feeder of the distribution network, during each hour of the day: network capacity limits. In order to ensure that the EV charging schedules are within the distribution network limits, the EV aggregator sends the charging schedules to the DSO for technical validation prior to each operational period. If required, the DSO can modify the network capacity limits and inform the EV aggregator; moreover the DSO has the capability to curtail the EV battery charging in case of network constraints violations.

Table 2.3 EV aggregator and DSO objectives

Entity	Objective
DSO	• Ensure operation within network technical constraints
EV aggregator	• Management of EV battery charging schedules according to: i) EV owner preferences, ii) Distribution network constraints and iii) Electricity prices. • Provision of active demand services in the form of demand reduction

Table 2.4 EV aggregator and DSO interactions

Time frame	Interaction
Day-ahead	• The network capacity limits are made available by the DSO to the EV aggregator.
Real-time	• EV schedules are sent to the DSO for technical validation prior to each operational period • If day-ahead network capacity limits need to be modified, the DSO informs with the new limits to the EV aggregator • The DSO agent curtails the charging of EVs in case of network constraints violation.

The EV management system designed in Chapter 5 is a Multi-Agent System. The following section reports the characteristics of agents and Multi-Agent Systems.

2.4 MULTI-AGENT SYSTEMS

2.4.1 Definition of Intelligent Agents and Multi-Agent Systems

A Multi-Agent System (MAS) is a distributed based software system comprising "*two or more agents or intelligent agents*" [137], where the complexity of a problem is split into subtasks that are undertaken by the multiple agents of the system.

According to [138] an agent is a hardware or software entity that receives inputs through sensors or messages from the environment it is placed in and is able to affect the state of the environment through autonomous actions according to its objectives. Devices such as thermostats or relays fall within the agent definition presented, though the potential of MAS is exploited through the use of intelligent agents, which are agents with the following capabilities [138]:

i) Reactivity: "Intelligent agents are able to perceive their environment, and respond in a timely fashion to changes that occur in it in order to satisfy their design objectives."

ii) Pro-activeness: "Intelligent agents are able to exhibit goal-directed behaviour by *taking the initiative* in order to satisfy their design objectives".

iii) Social ability: "Intelligent agents are capable of interacting with other agents (and possibly humans) in order to satisfy their design objectives".

The attributes of intelligent agents defines the MAS control approach as a set of flexible autonomous and goal-oriented agents, where the application problems are divided in subtasks. Each subtask is handled individually by each agent with the capability to coordinate its actions with other agents in the system (through the exchange of messages). The coordination can take place in the form of cooperation when agents seek for common goals or negotiation when seeking for individual goals [139].

Agent-based systems adopt the object-oriented paradigm by encapsulating state and behaviour [140]. The difference relies in the behaviour encapsulation; while objects encapsulate behaviour realisation, agents also encapsulate "*behaviour activation (action choice)*" [140].

Distributed systems such as MAS, grid computing [141] and web services [142] are based on the concept of sharing distributed resources (hardware and/or software) to achieve specific goals [137]. The shared resources can be interconnected by means of Local Area Networks or Wide Area Networks (e.g. Internet) [142]. Common to these technologies is the concept of "*service: an entity that provides a capability to a client via a well-defined message exchange*" [143]. As identified in [137] the main difference of MAS compared to these two technologies is related to the flexible autonomy characteristics of intelligent agents (reactivity, pro-activeness and social ability). Synergies between these technologies could lead to improved grid computing systems, Multi-Agent Systems and web services [137], [143].

2.4.2 Multi-Agent Systems in Power Engineering

The IEEE Power Engineering Society's Multi-Agent Systems (MAS) Working Group, summarised in [137] and [144] the benefits of utilising MAS technology in power system applications as:

- Flexibility: Ability to dynamically react to variations of its environment.
- Extensibility: Ability to easily upgrade or add a new functionality to the system.
- Fault tolerance: Ability to meet its objectives in case of failure of a system's agent.
- Open architectures: The capability to communicate with different agents irrespectively of their programming language. The interoperability of agents from different developers requires of the compliance with messaging standards (Section 2.4.3).
- Distribution: The ability of an agent to be located in different environments while keeping its defined goals and objectives.

According to [137], applications exhibiting one or more of the following characteristics will benefit from using MAS technology:

- Interaction between different conceptual entities, such as the DSO and the EV aggregator.
- Interaction between a large number of entities.
- Sufficient data is available locally, i.e. without the requirement of communication with a central point.

The main fields of MAS application in power engineering were identified in [137] as: i) Monitoring and diagnostics, ii) Protection iii) Modelling and simulation, and iv) Distributed control. Some practical MAS implementations can be found in [145].

The expected increased penetration of DERs in all voltage levels of future distribution networks, has led to an increased interest from researchers and utilities to consider distributed control approaches in substitution of traditional centralised approaches. Several European projects involving research centres, universities and utilities have investigated the use of MAS for the management of DERs in distribution networks [135], [146]-[149]. Distinct examples of laboratories where MAS are being tested for the management of DERs are:

- Micro-grid laboratory in the National Technical University of Athens [150].
- Micro-grid laboratory in Durham University [151].
- Micro-grid DER laboratory of Tecnalia research centre [152].

The laboratory implementation of the MAS control system presented in Chapter 6, undertaken within the framework of DERri [135], took place at the facilities of Tecnalia research centre [153].

2.4.3 Foundation for Intelligent Physical Agents Standards

The Foundation for Intelligent Physical Agents (FIPA) [154] is an IEEE Computing society standard organisation. FIPA has developed a collection of standards and specifications for the interoperability of agents and MAS. According to [145], "*FIPA standards have become the de facto standards for agent development within the power domain*".

The standardised layers used in the exchange of messages in communication systems are covered by FIPA standards [145]; these are [145]:

- "Message transport (the delivery of a message)"
- "Message format (the agent communication language)"
- "Message content (both grammar and vocabulary)"

Multi-Agent Systems within FIPA standards are defined according to the FIPA Agent Management Reference model [155] shown in Fig. 2.4, which defines "*the normative framework within which FIPA agents exist and operate.*" [155].

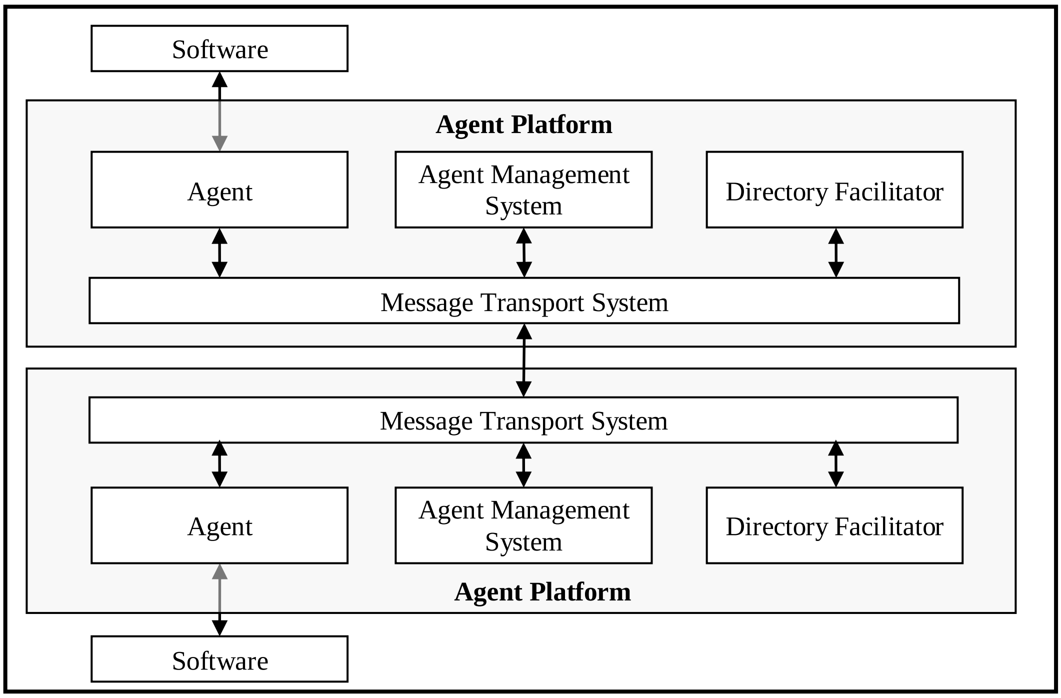

Fig. 2.4 Agent management reference model [155]

The Agent Platform (AP) is the physical structure where the agents are hosted, and comprises apart from the agents:

- Agent Management System (AMS).
- Message Transport System (MTS).
- Directory Facilitator (DF).

Agents are required to register to the AMS, which provides with unique Agent Identifier (AID) to the agents, keeping record of the agents' registration and deregistration. The DF is used by the agents to offer or query services. The MTS manages the exchange of messages between agents in different APs or within the same AP. The communication between agents is performed through messages, which are set according to FIPA Agent Communication Language (FIPA-ACL) described in [156].

The adherence to FIPA standards is not mandatory, though MAS developed within FIPA standards may enhance the scalability, openness and extensibility of the control system. The interoperability among agents is defined according to the message interaction; hence independently of the agents' developer or owner, an ease addition, removal or modification of agents can take place.

2.4.4 Java Agent DEvelopment Framework

The tool used for the MAS implementation of chapter 5 was Java Agent DEvelopment Framework (JADE). JADE is one of the most widely used tools for MAS implementation [139], [145], and according to [144] "*JADE has become a firm favourite with researchers in power engineering*".

JADE is an open-source, FIPA-compliant agent-oriented middleware and it is fully written in JAVA^{TM}. JADE provides programmers with [139]:

- Distributed runtime environment where agents operate autonomously.
- A set of JAVA classes used by the developers to implement the agents' functionalities.
- The Message Transfer System, Agent Management System and Directory Facilitator.
- Set of graphical tools to support developers in monitoring and debugging agents' activity.

The communication between agents is based on asynchronous message passing and compliant with FIPA standards [139]. When a message is sent to the desired agent, the message is stored in the recipient agent's message queue through JADE run-time and the recipient agent is notified. Whether the message is processed by the receiving agent (Agent2 in Fig. 2.5) or not, or when the message is processed is dependent on the agent developer.

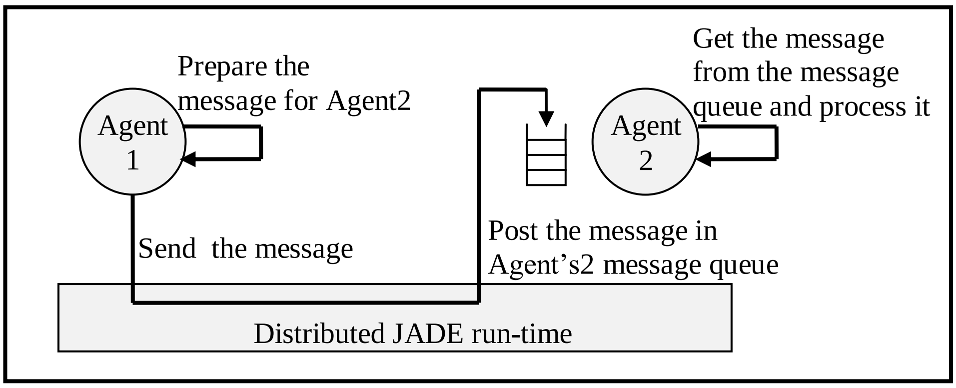

Fig. 2.5 The JADE asynchronous message passing paradigm [139]

JADE implements all FIPA standard Message Transport Protocols (MTPs) in order to ensure interoperability with other (JADE and non-JADE) platforms [139]. HTTP-based protocol is the default MTP used in JADE [139].

2.5 SUMMARY

The relevant literature used in the thesis was presented. The concept of energy balanced area was defined and different approaches for the ESS sizing in balanced energy areas from the literature were provided.

Two types of charging infrastructures for the EV battery charging were presented, charging points and the EV battery swapping station. EV battery swapping stations studies related to the battery charging management were reviewed.

EV management control approaches to overcome the potential impacts of EV battery charging on the distribution network were reviewed, which ranged from simple dual tariff schemes to complex control management concepts.

The figure of the EV aggregator was presented, which is defined as the entity responsible for the EV battery charging management. A differentiation was done according to the control approaches presented in the literature: centralised and decentralised control approach, the relevant literature was reviewed.

The concepts of intelligent agents and Multi-Agent Systems were presented, as well as the potential benefits of such control approach for power system applications. Some of the benefits described are enhanced by the use of standards (FIPA), the Agent Reference Model required to be FIPA-compliant was shown. Characteristics of the tool (JADE) used for the development of the MAS control system were provided.

Chapter 3

Energy Storage System and Backup Generator for Balancing a Local Distribution Network Area

3.1 Introduction

Integration of domestic micro-generators that are usually below 3kWe [157] in the distribution network could provide economic benefits to residential customers and assist in securing electricity supply [158].

An energy balanced local area is defined as a part of a LV distribution network that has the ability to satisfy its electricity demand using only the Distributed Energy Resources (DER) that are installed within the area (i.e. zero energy import/export with the main grid).

The local distribution network area considered in this chapter is a LV (400/230V) part of the UK generic distribution network model described in [159] with installed domestic micro-generators. The micro-generators are assumed to have intermittent or heat-driven power outputs, hence an Energy Storage System (ESS) is considered to balance the daily mismatch between the local area's demand and the energy generated from the micro-generators. In case the energy balance cannot be achieved with the micro-generators and the ESS, a backup generator is also considered.

The minimum ESS capacity (kWh) required to achieve an energy balance area is calculated for different micro-generation penetration levels. For micro-generation penetration levels where the energy balance cannot be achieved with the ESS, the minimum energy that needs to be supplied by the backup generator to achieve energy balance is calculated.

The effect of controlling Electric Vehicle (EV) battery charging in the energy requirements of the backup generator and the ESS is evaluated in a case study.

3.2 BALANCING A LOCAL AREA WITH AN ENERGY STORAGE SYSTEM AND A BACKUP GENERATOR

The calculations are performed for different micro-generation penetration levels, using average daily micro-generation and demand profiles. For each penetration level, the steps followed to obtain the ESS's capacity and backup generator's energy requirements are shown in Fig. 3.1.

Voltages in low voltage feeders are calculated for each time interval. Voltage profile modifications in LV radial distribution feeders are identified in the literature as one of the main steady-state constraints limiting micro-generation penetration [49], [159] and [160]. Micro-generation penetration levels for which voltage violations are recorded, are excluded from the calculation process.

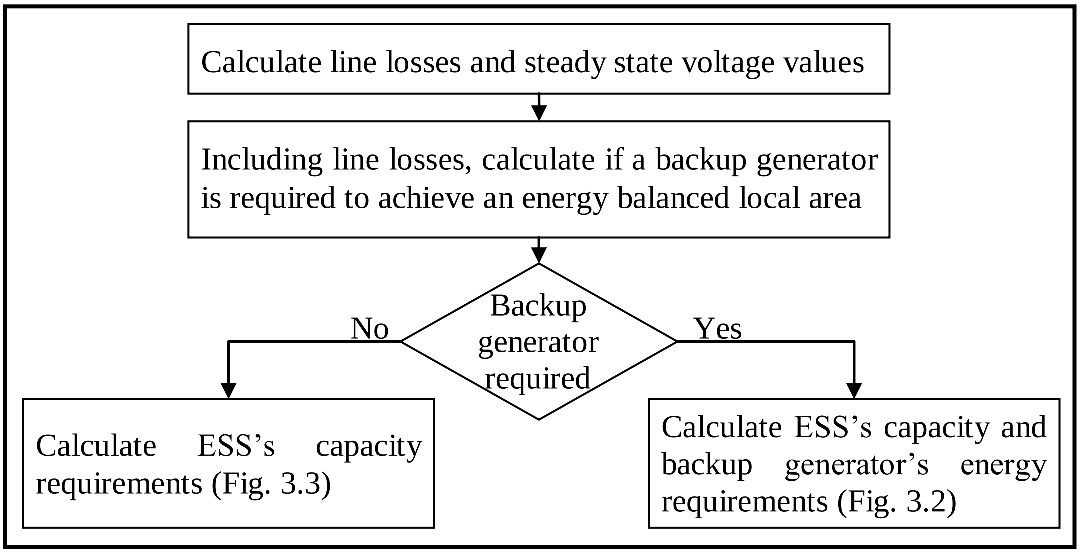

Fig. 3.1 Steps followed to obtain the ESS's capacity and backup generator's energy requirements

3.2.1 Assumptions Used in the Calculation Process

The main assumptions used in the calculation process are:

- The micro-generation and demand profiles have constant power values at each half hour time interval.
- A Battery Energy Storage System (BESS) is considered with constant charge efficiency (ηch) and constant discharge efficiency (ηdch).
- Backup generator's efficiencies are not considered.

3.2.2 Calculation of Steady State Voltage Values and Power Lines Losses

Sequential power flows are performed and the power lines losses and the voltage steady state measurements are recorded. A Newton-Raphson load flow algorithm developed at Cardiff University [161] and adapted to the UK generic distribution network model in [162] is used. The Newton-Raphson process is a widely used method for solving load flow problems in power systems [163]. Compared to alternative processes, the Newton-Raphson method has a fast convergence while being "*at the same time economical in computer time*" [163].

The Energy Storage System and the backup generator act as a:

i) Load at time intervals where the local area's generation is higher than the demand. The load value is set as the difference between the time interval's generation and demand.

ii) Generator at time intervals where the local area's demand is higher than the generation. The generator output is set as the difference between the time interval's demand and generation.

The local area is connected to the upstream network. Two operation modes could be adopted: i) Exchanging electricity with the grid, without considering the ESS and backup generator and ii) Exchanging electricity with the ESS and backup generator (i.e. zero energy import/export with the main grid). In order to find the limit of micro-generation sources that can be connected to the local area, voltage measurements are recorded for both operation modes.

The output of the power lines losses is used in the calculation to determine if a backup generator is required to achieve an energy balanced local area, as shown in the following section.

3.2.3 Calculation to Determine if a Backup Generator is Required to Achieve an Energy Balanced Local Area

The energy generated by the micro-generators is used to serve the residential demand.

- At time intervals where there is a generation surplus from the micro-generators, the energy is stored in the ESS.
- At time intervals where there is a lack of generation, the energy is provided by the Energy Storage System (ESS); if there is no energy stored in the ESS, the energy is supplied by the backup generator.

A backup generator is required in case the total energy stored in the ESS multiplied by the round trip efficiency (charge/discharge cycle efficiency), cannot cover the demand of the time intervals where there is a lack of generation, as in equation (3.1).

$$\sum_{t=1}^{Tf} Egen_t - \sum_{t=1}^{Tf} Edem_t < 0 \qquad (3.1)$$

Where:

$$Egen_t = \begin{cases} [(Gen_t - Dem_t) - Losses_t] \times \eta ch \times \eta dch, & Gen_t - Dem_t > 0 \\ 0, & Gen_t - Dem_t < 0 \end{cases}$$

$$Edem_t = \begin{cases} 0, & Gen_t - Dem_t > 0 \\ [(Dem_t - Gen_t) + Losses_t], & Gen_t - Dem_t < 0 \end{cases}$$

t is the time interval,

Tf is the daily final time interval,

$Egen_t$ is the usable energy stored in the Energy Storage System during periods with generation surplus from the micro-generators in kWh,

$Edem_t$ is the local area's demand in kWh not covered by the micro-generators,

Gen_t is the energy generated by the micro-generators in kWh,

Dem_t is the residential demand in kWh,

$Losses_t$ is the power lines losses in kWh,

ηch is the Energy Storage System's charge efficiency and

ηdch is the Energy Storage System's discharge efficiency.

The need of a backup generator in order to achieve an energy balanced local area determines the calculations for the ESS capacity requirements, as shown in Sections 3.2.4 and 3.2.5.

3.2.4 Calculation of ESS's Capacity and Backup Generator's Energy Requirements. Case 1: Backup Generator Required

An algorithm is developed to calculate the ESS's capacity and the backup generator's energy requirements, when a backup generator is needed to achieve an energy balanced local area. The aim of the calculation process is to find the minimum ESS capacity required to absorb the energy during periods with generation surplus from the micro-generators. By making use of all the energy from the micro-generators the backup energy requirements are minimised.

In order to find the minimum ESS capacity required, the use of the ESS is prioritised to the backup generator in the calculation process. That is, if there is energy in the ESS and there is a lack of generation, the energy is supplied by the ESS. Such policy is adopted in order to record the charge and discharge cycle of the ESS without the influence of the backup generator. The maximum ESS's State of Charge (SoC) recorded, will determine the minimum ESS capacity required in order to absorb the energy during intervals with generation surplus from the micro-generators.

The algorithm is executed for two consecutive days (i.e. 96 half hour time intervals), and the initial SoC value is set as zero (SoC_1=0). The whole process is shown in the flow chart of Fig. 3.2. The calculations performed are described as follows.

At time intervals where the generation is higher than the demand ($Gen_t > Dem_t$), the energy is stored in the ESS (E_{in}) [equation (3.2)], increasing the ESS's State of Charge as shown in equation (3.3).

$$Ein_t = [(Gen_t - Dem_t) - Losses_t] \times \eta ch \tag{3.2}$$

$$SoC_{t+1} = SoC_t + Ein_t \tag{3.3}$$

At time intervals where the demand is higher than the generation, the algorithm checks if there is energy available in the ESS (SoC_t >0).

i) If there is no energy available in the ESS ($SoC_t = 0$), the energy is supplied by the backup generator (E_{Bup}), as shown in equation (3.4).

$$EBup_t = Edem_t = (Dem_t - Gen_t) + Losses_t \tag{3.4}$$

Since no energy is available in the ESS ($SoC_t = 0$), SoC_{t+1} remains equal to zero, as shown in equation (3.5).

$$SoC_{t+1} = 0 \tag{3.5}$$

ii) If there is energy in the ESS for covering the demand, the energy is exported from the ESS (E_{out}), as shown in equation (3.6), reducing the ESS's State of Charge.

$$Eout_t = [(Dem_t - Gen_t) + Losses_t]/\eta\text{dch} \tag{3.6}$$

The ESS's State of Charge is obtained subtracting to the ESS' SoC (SoC_t) the exported energy (E_{out}), as shown in equation (3.7).

$$SoC_{t+1} = SoC_t - Eout_t \tag{3.7}$$

iii) If there is energy in the ESS but not enough to cover the demand, the energy exported from the ESS (E_{out}) is its available energy (i.e. its SoC), as shown in equation (3.8).

$$Eout_t = SoC_t \tag{3.8}$$

The demand not covered by the ESS (considering the discharge efficiency), is supplied by the backup generator (E_{Bup}), as shown in equation (3.9).

$$EBup_t = (Edem_t) - (SoC_t \times \eta\text{dch}) \tag{3.9}$$

Since all the energy available in the ESS is used, the ESS's State of Charge becomes zero, as shown in equation (3.10).

$$SoC_{t+1} = 0 \tag{3.10}$$

The evolution of the Energy Storage System's SoC is recorded; the maximum value out of all the time intervals determines the required capacity of the ESS (E_{ESS}) as shown in equation (3.11).

$$E_{ESS} = \text{Max}(SoC_t) \tag{3.11}$$

The energy required to be supplied by the backup generator (E_{Bup}) is obtained using the second simulated day (t=49 to t=96), with equation (3.12). The reason for choosing the second simulated day is that in the first simulated day the ESS starts with a zero SoC, whereas in the second day, the ESS's State of Charge (SoC) can be positive if during the last periods of the day, the overall generation is higher than the demand (i.e. there is energy stored in the ESS at the beginning of the day). This implies that part of the demand will be covered with the energy stored in the ESS instead of the backup generator.

$$EBup = \sum_{t=49}^{t=96} EBup_t \tag{3.12}$$

Fig. 3.2 depicts the developed algorithm.

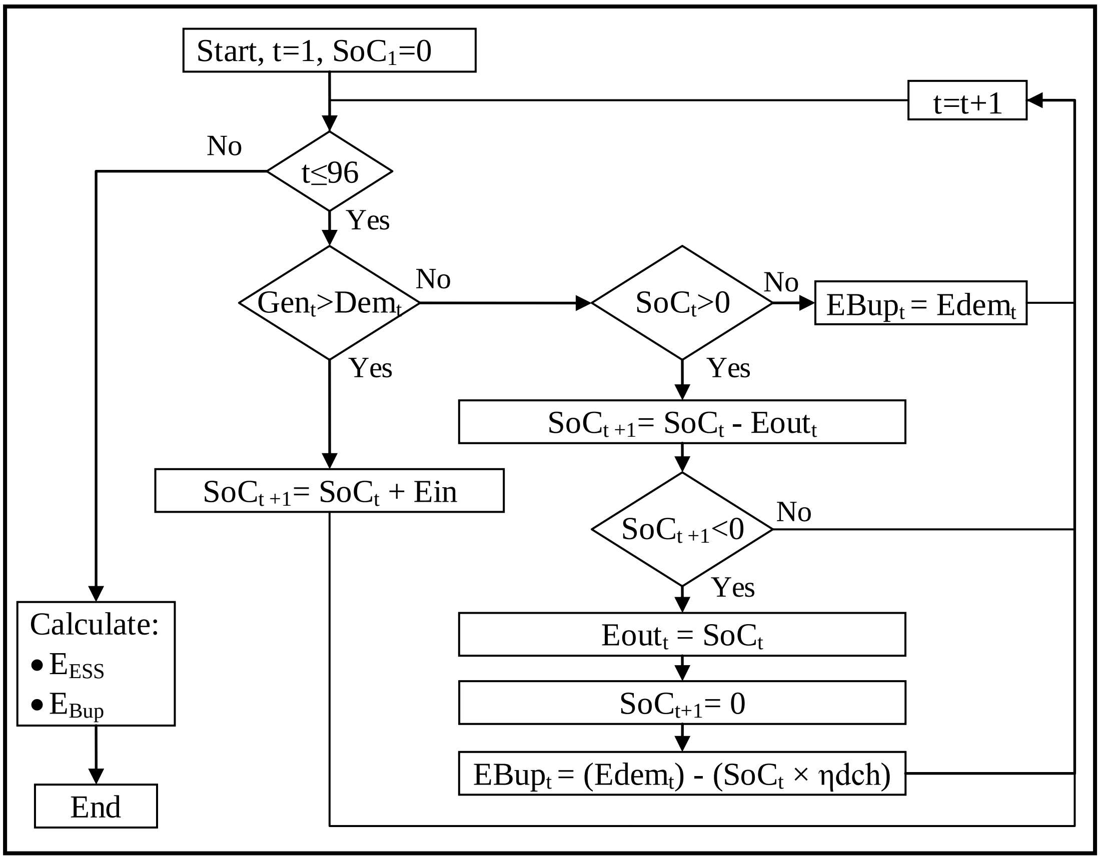

Fig. 3.2 Calculation of the ESS's capacity and the backup generator's energy requirements to achieve an energy balanced local area

3.2.5 Calculation of the ESS's Capacity Requirements. Case 2: No Backup Generator Required

An algorithm is developed to calculate the ESS's capacity required, when no backup generator is needed to achieve an energy balanced local area. The aim of the calculation process is to find the minimum ESS capacity required to supply the residential demand during periods of lack of generation.

The overall generation is higher than the demand, hence there is no need for all the generation surplus from the micro-generators to be stored in the ESS in order to satisfy the residential demand. In Case 1 (backup generator required), the evolution of the SoC is recorded; an initial zero SoC is assigned and the generation surplus from the micro-generators is stored in the ESS. In this case, when no backup generator is required, an initial 100% SoC (i.e. ESS fully charged) is assigned and the ESS's capacity is calculated according to the energy that needs to be exported from the ESS (to the local area) during time intervals where the demand is higher than the generation.

Since the 100% SoC (i.e. battery capacity) is the unknown value aim of the calculation, the variable used in the case when no backup generation is required, is the Depth of Discharge (DoD). The DoD is the opposite of the State of Charge, i.e. DoD = 1-SoC (in per unit); a zero DoD implies that the ESS is fully charged. For the ESS capacity calculations an initial zero DoD is assigned and its evolution recorded.

The algorithm is executed for two consecutive days (i.e. 96 half hour time intervals), and the initial DoD value is set as zero ($DoD_1=0$). The whole process is shown in the flow chart of Fig. 3.3. The calculations performed are described as follows.

At time intervals where the demand is higher than the generation ($Dem_t>Gen_t$), the energy is provided by the ESS, increasing the Depth of Discharge (DoD), as shown in equation (3.13). The DoD is increased according to the energy that needs to be exported from the ESS (*Eout*), as shown in equation (3.6).

$$DoD_{t+1} = DoD_t + Eout_t \tag{3.13}$$

At time intervals where the generation is higher than the demand, if the ESS is not fully charged ($DoD_t>0$), the energy is imported to the ESS, reducing the DoD as shown in equation (3.14). The DoD is reduced according to the energy imported to the ESS (*Ein*), as shown in equation (3.2).

$$DoD_{t+1} = DoD_t - Ein_t \tag{3.14}$$

If the generation surplus from the micro-generators is higher than what the ESS can store (DoD_t), the energy imported to the ESS (*Ein*) is calculated with equation (3.15) and the DoD becomes zero, as shown in equation (3.16), i.e. the ESS becomes fully charged.

$$Ein_t = DoD_t \tag{3.15}$$

$$DoD_{t+1} = 0 \tag{3.16}$$

The evolution of the ESS's Depth of Discharge is recorded; the maximum value out of all the time intervals determines the required capacity of the ESS (E_{ESS}) as shown in equation (3.17).

$$E_{ESS} = \mathrm{Max}(DoD_t) \tag{3.17}$$

Fig. 3.3 depicts the developed algorithm.

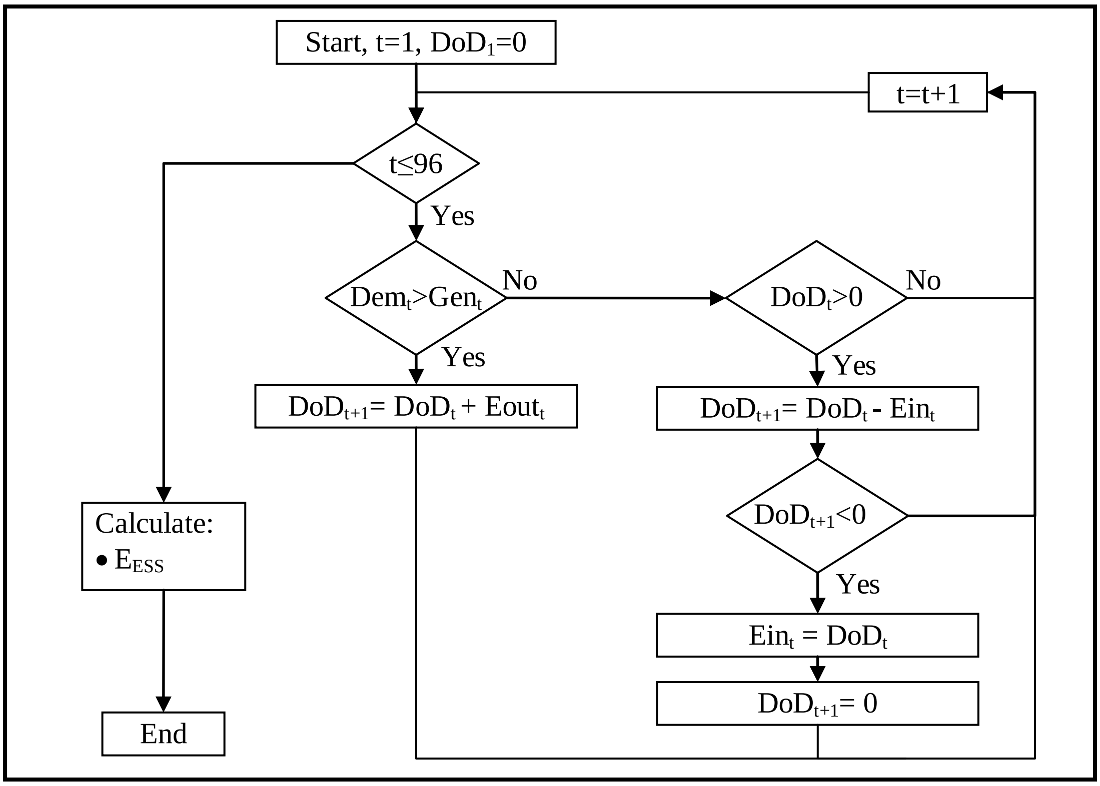

Fig. 3.3 Calculation of the ESS's capacity requirements to achieve an energy balanced local area

3.2.6 Case Studies

Generation profiles from two technologies were considered, PhotoVoltaics (PV) and micro-Combined Heat and Power (μ-CHP). The penetration levels used for each micro-generator ranged from 0% to 100% in steps of 10% (100% penetration being equivalent to each customer having installed a micro-generator).

The studies were performed for summer and winter seasons. The output of the studies show, for each combination of micro-generation penetration levels, for summer and winter the:

A) Steady state voltage violations.

B) Power line losses.

C) Energy Storage System's capacity requirements.

D) Backup generator's energy requirements.

The outputs of the case studies were obtained using the algorithms described in the previous subsections, which were developed and implemented in JAVA^{TM}.

3.2.7 Network Model used in the Case Studies

The network model used in the studies is based on the LV side of a UK generic urban distribution network [159]. The UK generic distribution network comprises two 33/11.5 kV 15 MVA transformers at the HV/MV primary substation, which are equipped with on-load tap changers. The substation feeds six 11kV feeders; each feeder supplying eight MV/LV substations.

The LV side of the UK generic network (Fig. 3.4) is connected to an 11/0.433 kV, 500kVA transformer. The transformer feeds 384 customers evenly distributed among 4 radial feeders. Single phase customers are considered with their connections evenly distributed across the three phases. Three feeders are modelled as lumped loads (96 residential customers each), and one feeder is modelled in detail. The detailed radial feeder consists of four segments with 24 lumped customers each. Details of the whole network can be found in [159] and [94].

The local area used for the studies was the detailed feeder, as shown in Fig. 3.4, supplying 96 customers. The residential loads were modelled as purely resistive loads with constant power.

The micro-generators were modelled as purely resistive negative loads with constant power.

The backup generator and the ESS were located next to the closest segment to the transformer (Fig. 3.4). The backup generator and the ESS were modelled as a positive or negative resistive load, depending if they acted as a generator or as a load, with constant power.

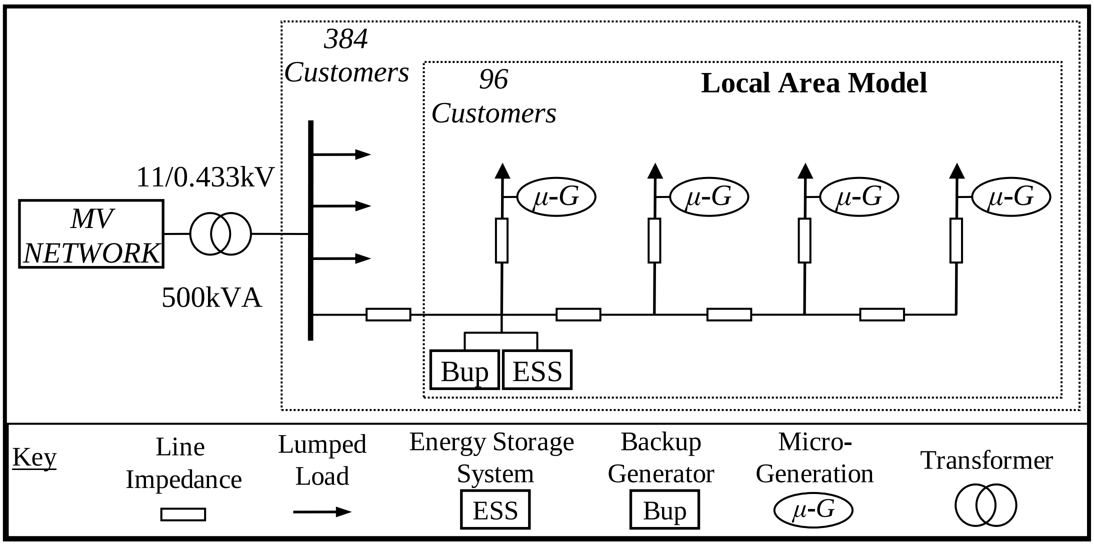

Fig. 3.4 Local area model based on a UK generic distribution network

3.2.8 Input Data and Assumptions Used in the Case Studies

Average half hourly summer and winter residential load profiles were drawn from [164], with typical minimum and maximum values acquired from the Electricity Association [159]. These are 0.16kW for a summer minimum and 1.3kW for a winter maximum residential load.

Generation profiles for PV and μ-CHP were drawn from [165] for winter and summer average days. The PV considered had a maximum power output of 1.2kW [165] and the μ-CHP profiles were scaled to a maximum electrical power output of 1.5kWe [166]. A uniform penetration among the four segments was considered (i.e. same penetration per 24 customers).

The generation and demand profiles used are shown in Fig. 3.5 and Fig. 3.6.

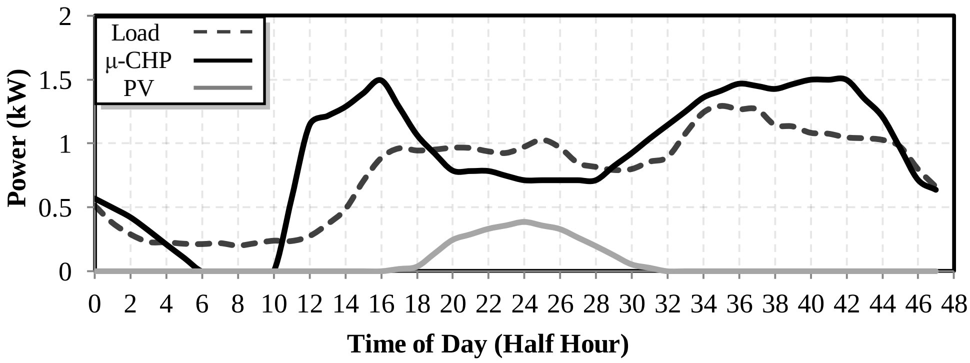

Fig. 3.5 Winter average daily generation and demand profiles

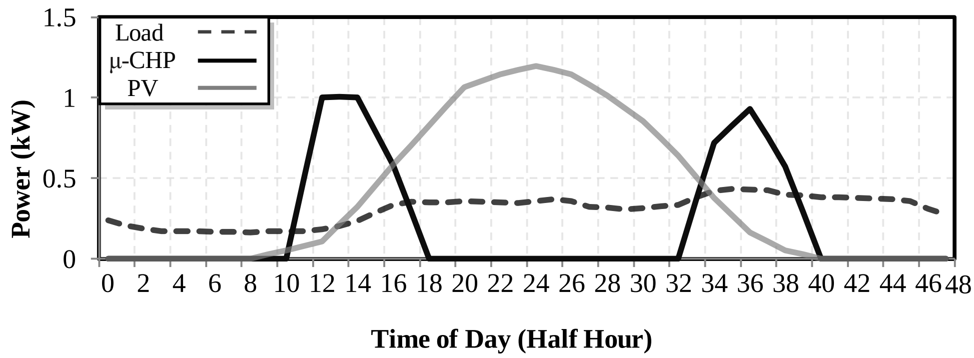

Fig. 3.6 Summer average daily generation and demand profiles

A round-trip efficiency of 72% was assumed for the Battery Energy Storage System (BESS) [167], with constant charge efficiency (ηch) of 85% and constant discharge efficiency (ηdch) of 85%.

3.2.9 Results of the Case Studies

A) Steady State Voltage Violations

The voltage limits used were those defined by the Electricity Safety, Quality and Continuity Regulations [168], which allow a maximum variation of 10% above or 6% below the 230V nominal single phase voltage [168].

Fig. 3.7 shows the combinations of PV and µ-CHP for which voltage violations were recorded. For both operation modes: i) Exchanging electricity with the grid and ii) Exchanging electricity with the ESS and backup generator; voltage violations were found only during the summer season (overvoltage). Fig. 3.7 shows the voltage violations recorded at the remote feeder segment.

Steady state overvoltage violations were recorded at certain time intervals where the generation exceeded the demand. Higher micro-generation penetration levels were within voltage limits when exchanging electricity with the ESS and the backup generator. The reason is that at time intervals with a generation surplus from the micro-generators the ESS acted as a load, reducing the voltage at its grid connection point. Since the local area model is a radial feeder, the voltage reduction at the ESS's grid connection point, allowed a higher micro-generation penetration within upper voltage limits, as shown in Fig. 3.7.

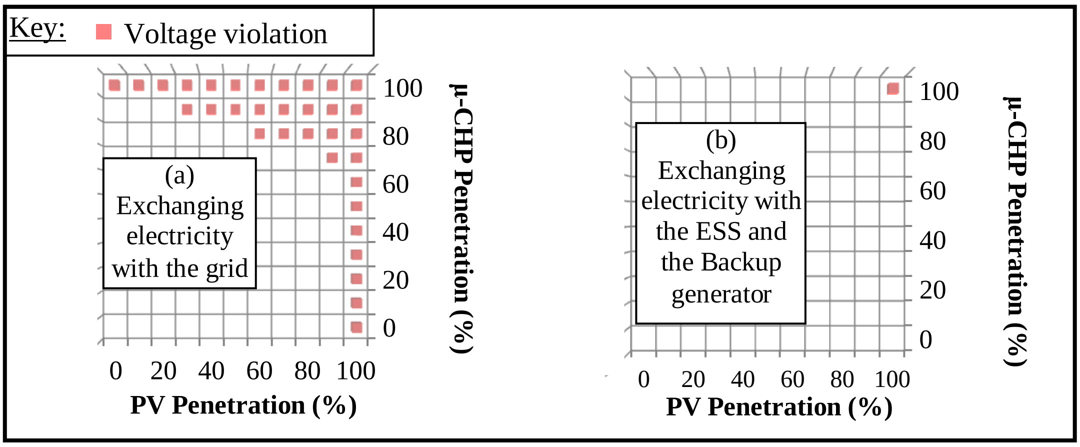

Fig. 3.7 Steady state voltage upper limit violations during the summer season

The results of the following sections show the calculations' output for micro-generation combinations where no voltage violations were recorded, considering the most restrictive operation mode [Fig. 3.7 (a)]. Combinations with voltage violations are marked in red in the results of the following sections.

B) Power Line Losses

Fig. 3.8 shows the power line losses for all micro-generation penetration levels, for both summer and winter seasons.

The micro-generators were located next to the end customers; hence as the micro-generation penetration increased, a higher fraction of the demand was covered on the spot. This reduced the flow of current across the power lines and hence the overall power line losses. This was true until a higher micro-generation penetration implied a higher amount of energy exported from the local area, when the overall power line losses increased as the micro-generation penetration increased.

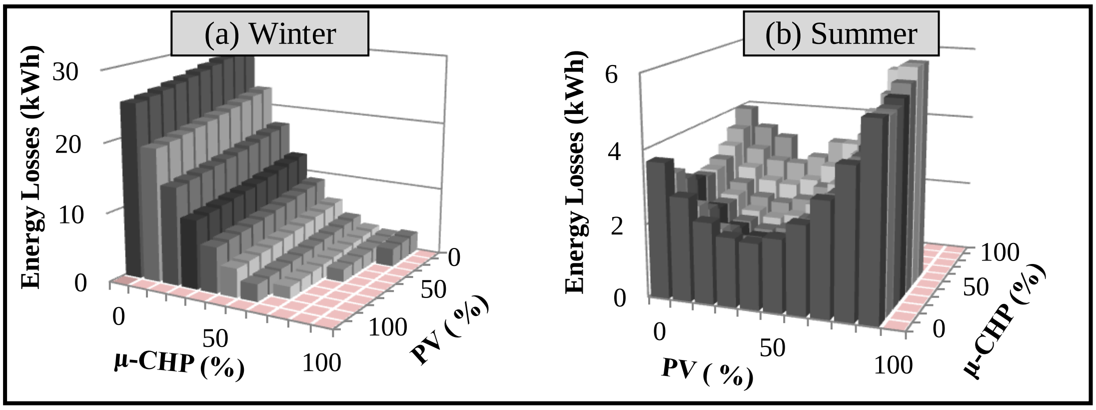

Fig. 3.8 Power lines losses in the local area

C) Energy Storage System's Capacity Requirements

Fig. 3.9 shows the ESS's capacity requirements for all studied micro-generation penetration levels, for summer and winter seasons.

During the winter season, the ESS's capacity requirements increased as the micro-generation penetration increased (mainly μ-CHP), until a μ-CHP penetration of 90% and a PV penetration of 10% [Fig. 3.9(a)]. For these micro-generation penetration levels, no backup generation was required, as shown in Fig. 3.10(a), reducing the ESS's capacity requirements as the micro-generation penetration increased.

During the summer season, for combinations with high penetration levels of μ-CHP and PV there was not a decrease in the ESS's capacity, but it remained almost constant, Fig. 3.9(b). The reason for this is that for the micro-generation profiles used, no energy was generated from time interval 40 to time interval 9 (Fig. 3.6), hence irrespectively of the high micro-generation penetration levels, the ESS needed to have the capacity to cover the demand of the aforementioned time intervals.

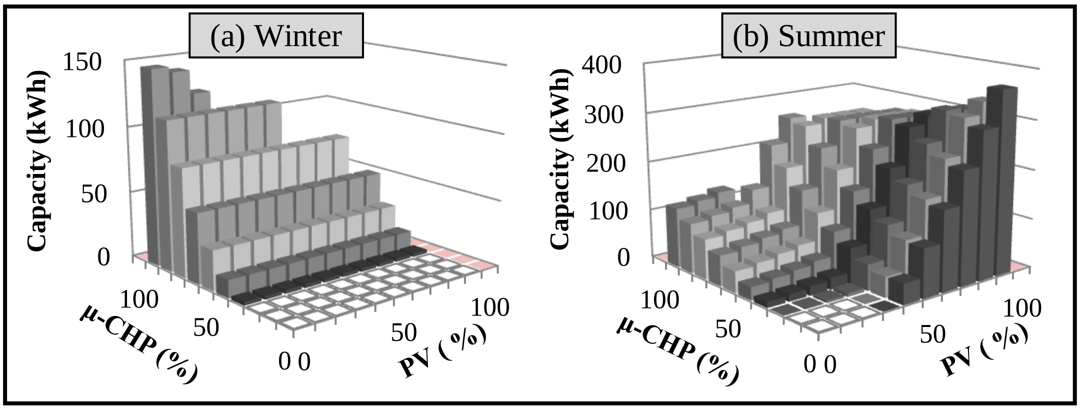

Fig. 3.9 Winter and summer season Energy Storage System's capacity requirements

D) Backup Generator's Energy Requirements

Fig. 3.10 shows the backup generator's energy requirements to achieve an energy balanced local area, for all studied micro-generation penetration levels and both summer and winter seasons.

During the winter season the backup generator energy requirements were mainly determined by the μ-CHP penetration Fig. 3.10(a), whereas during the summer season the PV penetration had a higher influence in the energy requirements, [Fig. 3.10 (b)].

For combinations where no backup generator was required, the energy balance was achieved only with the ESS.

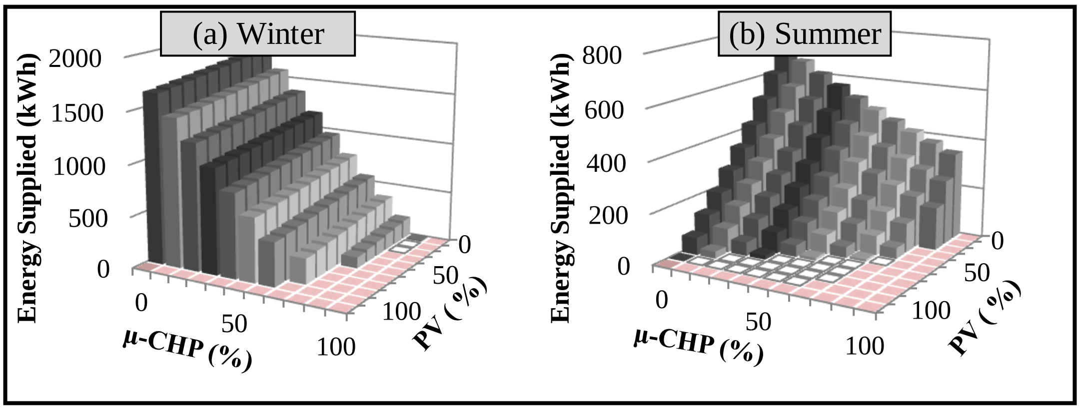

Fig. 3.10 Winter and summer season backup generator's energy requirements

Fig. 3.10 shows that for the modelled area there is not a fixed combination of micro-generators which ensures the energy balance only using the ESS during winter and summer season. As shown in Fig. 3.10 (a), during the winter season the energy balance only with the ESS is achieved for a μ-CHP penetration of 90% and a PV penetration of 10% or 20%. Fig. 3.10 (b) shows that for those combinations, energy from the backup generator was required to achieve the energy balance during summer season.

The energy balance considering the minimum energy required to be supplied by the backup generator for both seasons was achieved for a μ-CHP penetration of 80% and a PV penetration of 50%. The ESS's and backup generator's energy requirements for winter and summer seasons, with a μ-CHP penetration of 80% and a PV penetration of 50%, are summarised in Table 3.1.

Table 3.1 Energy Storage System's and backup generator's requirements

Backup Generator	**Energy (kWh)**	
	Summer	Winter
	0	108
Energy Storage System	**Capacity (kWh)**	
	Summer	Winter
	279	113

3.3 Addition of Electric Vehicles as Controllable Loads in an Energy Balanced Local Area

This section investigates the use of Electric Vehicle battery charging as controllable loads. Optimal EV battery charging schedules are calculated with the aim of:

i) Reducing the ESS's exchange of energy and hence it's associated energy losses due to the round trip efficiency.

ii) Reducing the energy requirements from the backup generator (if required to achieve an energy balanced local area).

3.3.1 Calculation of Optimal EV Battery Charging Schedules

Optimal EV battery charging schedules are calculated with the objective of minimising the exchange of energy between the local area and the ESS and backup generator. The aim is to utilise the generation surplus from the micro-generators to charge the EVs (i.e. match the generation surplus from the micro-generators with the EV aggregated demand).

The EV's energy demand (E_n) at every time interval assigned to charge is obtained with equation (3.18).

$$E_n = P \times e_B \times e_{Ch} \times 0.5\ \text{h} \tag{3.18}$$

Where:

P is the charger power rating in kW,

e_B is the EV battery efficiency,

e_{Ch} is the charger efficiency and

h is hour (half hourly time intervals are used).

The optimisation is formulated as a linearly constrained problem with a quadratic objective function. The Linear Programming (LP) solver of IBM ILOG CPLEX [169], which can solve extensions of LP problems such as Quadratic Programming (QP) problems and Mixed Integer Programming (MIP) problems [170], is used in order to find the optimal charging schedules.

The objective function is the sum of the square difference of the generation and demand mismatch (Gen_t - Dem_t) and the aggregated EV demand per time interval, as shown in equation (3.19).

$$minimise\ Z = \sum_{t=1}^{Tf}\left[\left(Gen_t - Dem_t\right) - \left(\sum_{n=1}^{N} En_t\right)\right]^2 \qquad (3.19)$$

Where:

t is the time interval,

T_f *is* the final time interval,

Gen is the energy generated by the micro-generators in kWh,

Dem is the domestic demand in kWh,

n is the Electric Vehicle,

N is the total number of EVs connected and

E_{nt} is the energy in kWh delivered to EV *n* during time interval *t*.

Subject to:

$$\sum_{t=in}^{Tn} En_t = Edn \qquad \text{for } n=\{1,...,N\} \qquad (3.20)$$

Where:

n is the Electric Vehicle,

E_{dn} is the desired energy in kWh at the end of the charging period of EV n,

E_{nt} is the energy in kWh delivered to EV n during time interval t,

i_n is the connection time interval of EV n ,

T_n is the disconnection time interval of EV n and

N is total number of EVs connected.

3.3.2 EV Related Assumptions Used in the Case Studies

Domestic EV battery charging is considered with a 13A and 230V connection [168], [171]. The EVs are charged at a constant 2.99kW power rating (unit power factor).

UK EV trials showed that average EV battery charging times were between 2-3 hours [172]. 3 hours are used in the studies. With a 2.99kW constant power rating, a constant EV charger efficiency of 87% [173] and a constant battery efficiency of 85% [174], a daily energy demand of 6.6kWh is derived.

The EV uptake used is the low EV uptake levels defined in [3] for the year 2030, which results in a 12.5% share of the vehicles according to [94]. The EVs are uniformly distributed among the network nodes, i.e. same amount of EVs per LV segment (3 EVs per 24 customers). The EVs are assumed to be connected to the grid from 18:00 to 7:00.

The main EV related assumptions used are summarised in Table 3.2.

Table 3.2 EV related assumptions

EV uptake	12.5%
EV energy daily demand	6.6 kWh
EV grid connection period	18:00 - 7:00
Charger power rating	2.99kW

3.3.3 Description of the Case Studies

Optimal EV battery charging profiles are calculated for winter and summer seasons. A comparison of the backup generator's energy requirements is performed for the case when the EVs' battery charging is not managed and the case when the EVs' battery charging follow the optimal charging profiles. In Case Studies 1, 2 and 3 the micro-generation penetration levels considered were: PV 50% and μ-CHP 80%.

In the case studies, the battery charging profiles of the EVs not being managed are obtained assuming all EVs start charging at 18:00 and charge continuously for 6 half hourly time intervals.

Table 3.3 Description of the case studies

Case	Description
Case Study 1 *Fig. 3.12(a)* *Fig. 3.13(a)*	Optimal EV charging schedules are calculated for the lowest level of aggregation of the local area model (Fig. 3.4), consisting of 24 residential customers and 3 EVs.
Case Study 2 *Table 3.4* *Table 3.5*	No EV charging management. Using the methodology presented in Section 3.2, ESS's and backup generator's energy requirements are calculated to achieve an energy balanced local area (96 customers and 12 EVs).
Case Study 3 *Table 3.4* *Table 3.5*	EV charging management. Using the methodology presented in Section 3.2, ESS's and backup generator's energy requirements are calculated to achieve an energy balanced local area. The EV load per 24 customers was added using the output of the optimisation from *Case Study 1*.
Case study 4 *Fig. 3.14*	For all micro-generation penetration levels, optimal EV charging schedules are calculated. The backup generator's energy savings compared to the case where EVs are not controlled are calculated.

The process to obtain the ESS and backup generator requirements is shown in Fig. 3.11.

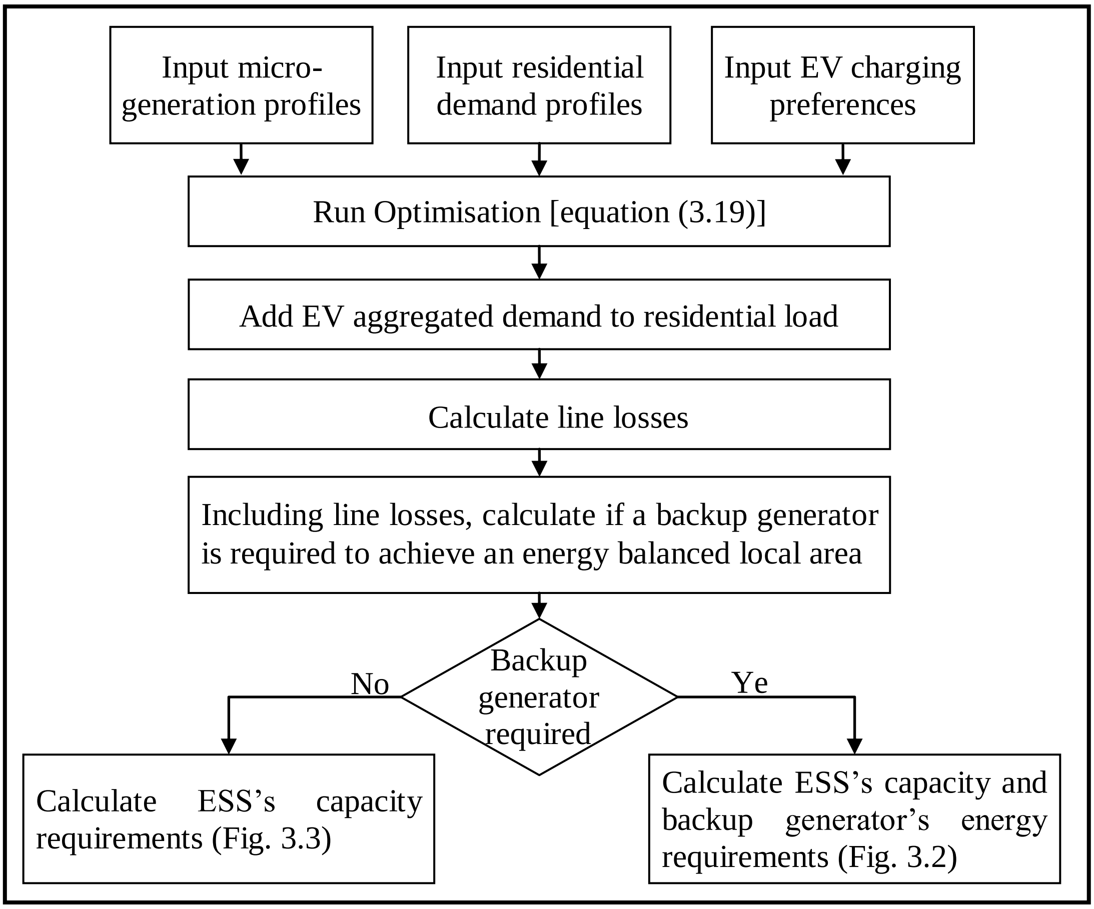

Fig. 3.11 Steps followed to obtain the ESS's capacity and backup generator's energy requirements with EVs

3.3.4 Results of the Case Studies

Fig. 3.12 and Fig. 3.13 show the EV battery aggregated demand profiles per 24 customers when the EVs followed the optimal charging schedules and when the EV battery charging was not managed. The grey bars show the difference between the energy generated by the micro-generators and the residential demand without considering the EV battery demand (values are positive when the generation is higher than the demand). The red bars show the EV battery aggregated energy demand. The black bars show the difference between energy generated by the micro-generators and the total demand (residential demand plus EV demand).

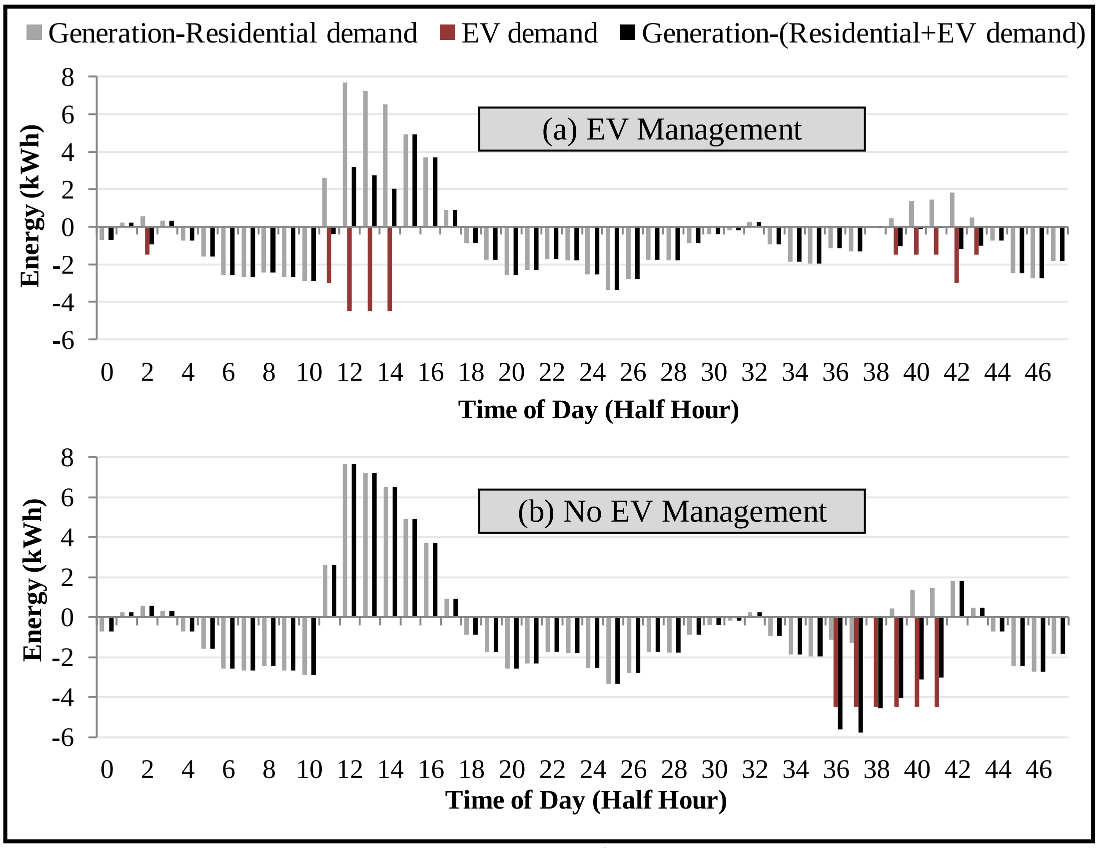

Fig. 3.12 Winter energy profile per 24 customers

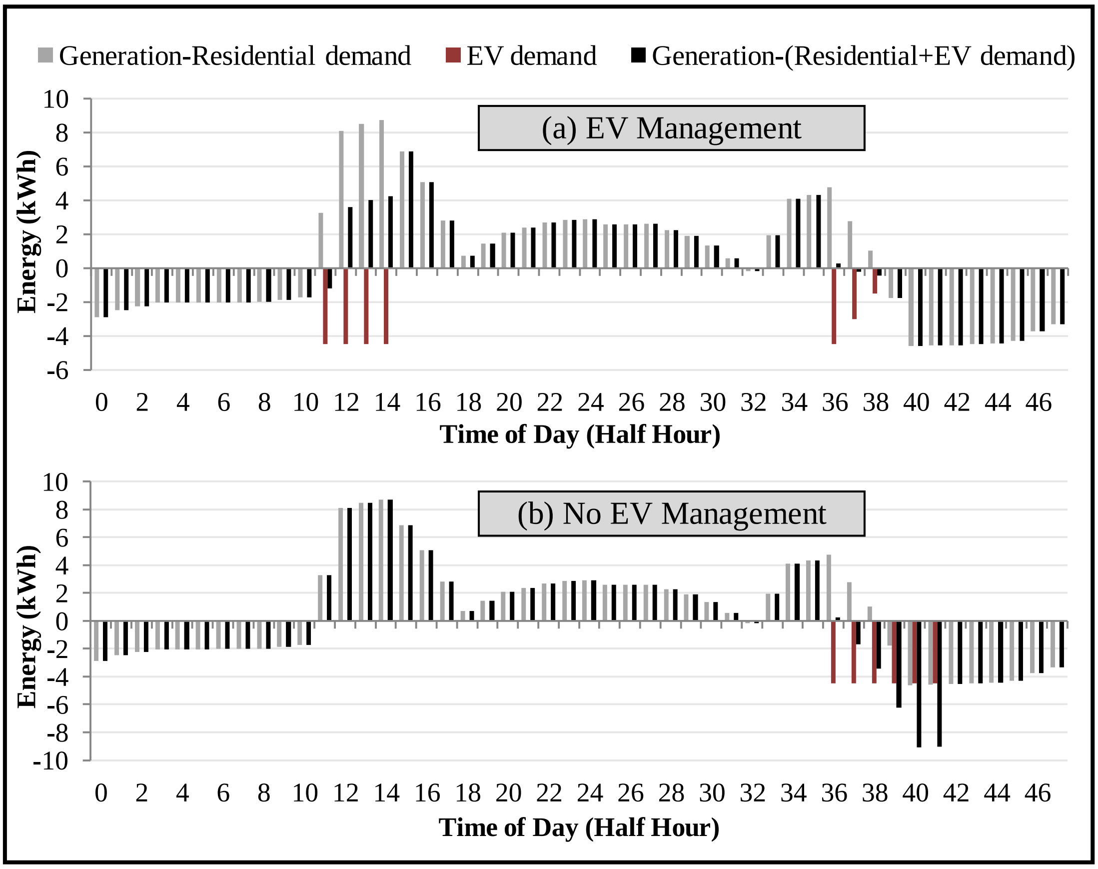

Fig. 3.13 Summer energy profile per 24 customers

During the winter season, when the EVs were charged following the optimal charging profiles, an 83% of the EV demand was supplied from the generation surplus from the micro-generators compared to the 12% when not being managed. Table 3.4 shows that the EV battery charging management reduced the energy needed to be supplied by the backup generator. The average daily energy savings were 10.5%.

Table 3.4 Winter season ESS and backup generator's requirements

	No EV Management	**EV Management**
Back up Generator	Energy (kWh)	
	212	190
Energy Storage System	Capacity (kWh)	
	113	59

During the summer season, when the EVs were charged following the optimal charging profiles, a 93% of the EV demand was supplied from the generation surplus from the micro-generators compared to the 31% when not being managed. Table 3.5 shows that the EV battery charging management reduced the energy needed to be supplied by the backup generator. The average daily energy savings were 27%.

Table 3.5 Summer season ESS and backup generator's requirements

	No EV Management	**With EV Management**
Back up Generator	Energy (kWh)	
	74	54
Energy Storage System	Capacity (kWh)	
	279	223

Fig. 3.14 shows the backup generator's daily energy savings (in %) when the EVs followed the optimal charging schedules compared to the case where the EVs were not controlled, for winter and summer seasons and for all micro-generation penetration levels.

In order to assess the management of EV battery charging on the backup generator's energy requirements, the voltage limit violations constraints used were those of the less restrictive operation mode [Fig. 3.7(b)], where voltage violations were only recorded for a μ-CHP penetration of 100% and a PV penetration of 100%.

The green bars of Fig. 3.14 show the micro-generation combinations for which the use of EVs as controllable loads, avoided the requirement of a backup generator to achieve the energy balance.

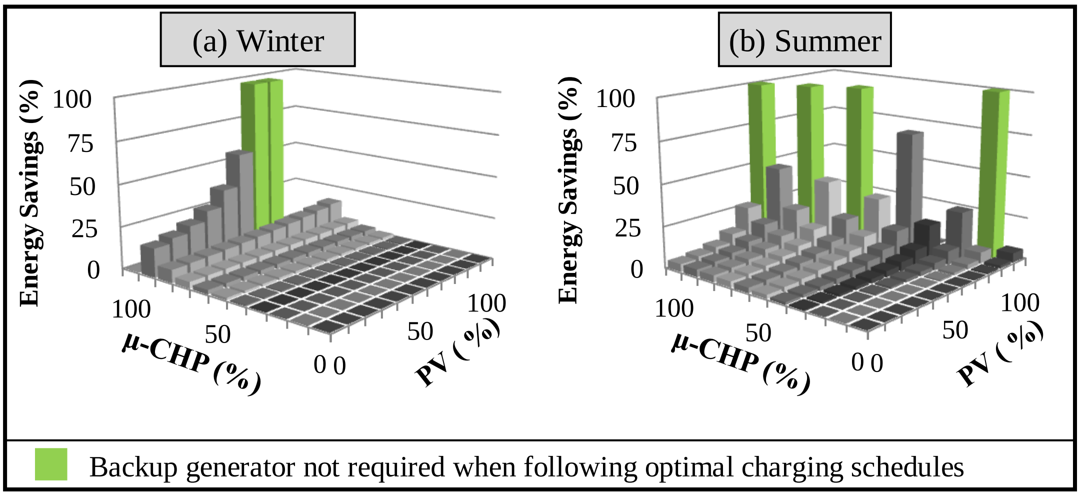

Fig. 3.14 Backup generator's energy savings when following optimal charging schedules for winter and summer seasons.

Fig. 3.14 shows how as the micro-generation penetration increased, the backup generator's energy savings increased. This occurred since more EV demand was supplied from the generation surplus from the micro-generators. The green bars show the penetration levels for which the energy savings were 100%; this means that when the EVs followed the optimal charging schedules no backup generator was required to achieve the energy balance.

3.4 SUMMARY

A methodology to obtain the ESS's capacity and backup generator's energy requirements in order to achieve an energy balanced local area was presented. The methodology consisted of three steps:

i) Calculation of power lines losses and steady state voltage values, through sequential power flows.

ii) Calculation to determine the need of a backup generator to achieve an energy balanced local area.

iii) Calculation of the ESS's and the backup generator's energy requirements

Different penetration levels of PV and μ-CHP were studied and the ESS' capacity and the backup generator's energy requirements calculated. For the LV distribution network model used, the maximum micro-generation penetration was constrained due to steady state overvoltage limits violations. It was shown that the energy balance for typical winter and summer days, that minimised the energy requirements from a backup generator, was achieved with a PV penetration of 50% (1.2 kW) and a μ-CHP of 80% (1.5 kWe).

The addition of Electric Vehicles (EVs) battery charging as controllable loads was considered in the energy balanced local area. Optimal EV battery charging schedules were calculated with the aim of minimising the exchange of energy with the ESS and the backup generator (i.e. matching the generation surplus from the micro-generators with the EV aggregated demand). The EV uptake used was the low EV uptake levels defined for the year 2030 in [3] and [94].

It was found that the control of the EV battery charging reduced the energy requirements from the backup generator or made it unnecessary (compared to the case where the EVs were charged without any form of control).

CHAPTER 4

BATTERY CHARGING MANAGEMENT OF CLUSTERS OF ELECTRIC VEHICLES

4.1 INTRODUCTION

This chapter investigates the battery charging management of EVs that are clustered and their batteries charged in a specific battery charging facility.

Two types of EV cluster charging infrastructures are considered:

i) EV parking facility: EVs are considered to be parked and their batteries charged in the same parking space. The operation of an EV Parking Manager (EVPM) is proposed. Different charging policies are described and its effects on the EV aggregated demand shown through a set of case studies

ii) EV battery swapping station: EVs are considered to exchange a depleted battery for a fully charged battery at the swapping station. The operation of an EV battery Swapping Station Manager (SSM) is proposed. The developed algorithms defining the operation of the swapping station are used to determine the number of chargers and batteries required to satisfy a daily battery demand. Finally, the effect of the number of batteries and chargers on the swapping station's load profile is shown in a case study.

Although both types of cluster have different characteristics, from the system operator's viewpoint they are seen as a single manageable big load.

4.2 ELECTRIC VEHICLE PARKING MANAGER

The role of the EV Parking Manager (EVPM) software is to calculate and assign battery charging schedules to the EVs connected in the parking facility.

The EVPM operation proposed in this chapter is defined with the aim of:

- Providing EVs' customers desired demand within network technical constraints.
- Providing controllability (flexibility) in the EVs' battery charging schedules.

Two control approaches are considered:

i) Load control approach, where maximum active power values are defined during certain (or all) time intervals.

ii) Price control approach, where different costs of electricity are assigned to the time intervals.

4.2.1 Assumptions

The EV battery charging schedules set by the EV Parking Manager (EVPM) are followed by the EVs' chargers. A two way communication between the EVs' chargers and the EVPM is assumed.

The EV Parking Manager has the kW loading capacity limits of the distribution network to which the parking facility's charging infrastructure is connected to (according to the distribution network technical constraints). The loading capacity limits are assumed to be made available by the DSO.

The EV batteries are considered as purely resistive loads that charge at a constant power rating.

4.2.2 Operation

The EV Parking Manager calculates and assigns battery charging schedules to EVs on a first-come first-served basis (Fig. 4.1). The EV charging schedules are calculated according to:

- EV owner requirements and charging characteristics: Energy requirements, connection duration, EV battery efficiency, charger's power rating and charger's efficiency.
- Loading capacity limits: The aggregated scheduled demand of the connected EVs, together with the network loading capacity limits, determines the maximum load that can be drawn at each time interval by the EVs to be connected.

- EV Parking Manager (EVPM) charging policy.

Within the charging policy the two control approaches are considered (load control approach and price control approach). The EVPM charging policy is defined by:

i) EVPM time interval scheduling priority: Defines the time intervals' priority when assigning the EV's charging schedule. Setting the time interval scheduling priority allows the EVPM to follow different strategies such as: charge EVs in the shortest time possible or charge EVs according to electricity prices.

ii) EVPM loading capacity limits: Defines the EVPM's desired maximum load values at different time intervals (below the distribution network loading capacity limit values). Setting the loading capacity limits, allows the EVPM to follow different strategies such as: ensure defined maximum demand values during intervals with high imbalance costs or satisfy demand requirements set by the network operator.

The battery charging schedules once assigned to the EVs are not modified unless instructed by the EV Parking Manager. A change in the charging schedules will be required in case the desired energy of an EV cannot be delivered due to network loading capacity limits, and only through the re-scheduling of the connected EVs, the demand of the EV can be accommodated.

For each EV, the steps followed to define the battery charging schedule by the EV Parking Manager are:

i) Calculates the number of charging time intervals required by the EV according to its energy requirements (kWh) and charging characteristics (battery charging efficiency, charger efficiency and charger power rating in kW).

ii) Defines the EV battery charging schedule according to the network loading capacity limits and the charging policy (scheduling function).

iii) If the required charging time intervals cannot be assigned, re-schedules the connected EVs (re-scheduling function).

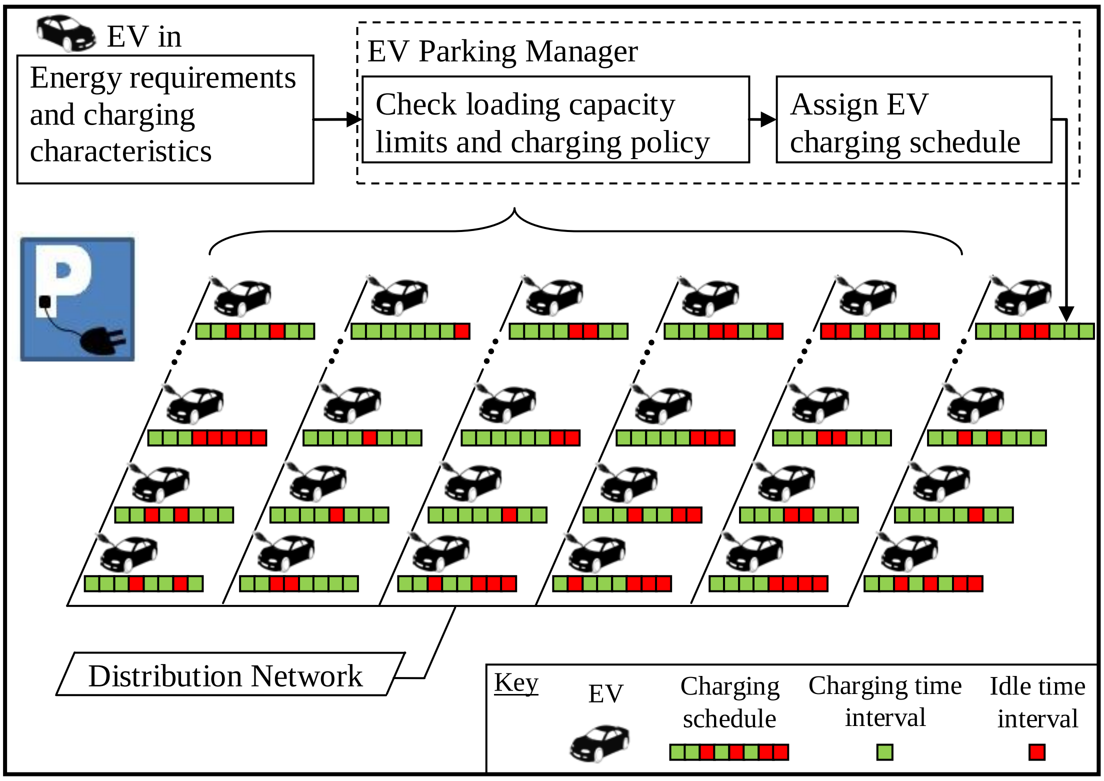

Fig. 4.1 EV Parking Manager operation

4.2.3 EV Parking Manager Case Studies

A JAVA™ based software tool was developed to emulate the EV Parking Manager (EVPM) operation for different user-defined case studies. The tool accepts inputs from the user in order to create battery charging schedules for a number of EVs, considering the distribution network loading capacity limits, EVs' charging characteristics and the EVPM charging policies. A schematic of the tool is given in Fig. 4.2. The process to obtain the EV charging schedules is shown in Fig. 4.3.

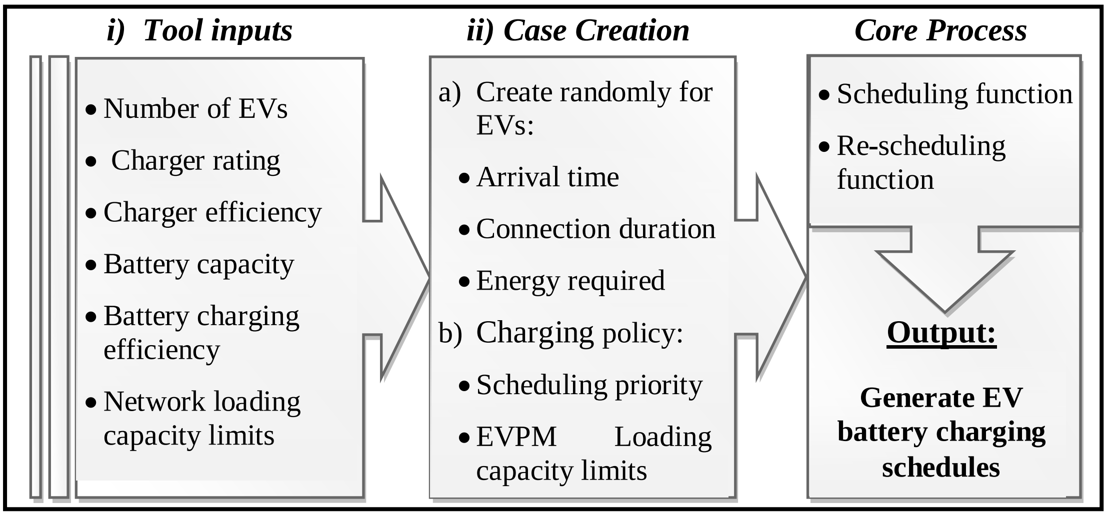

Fig. 4.2 Schematic description of the software tool

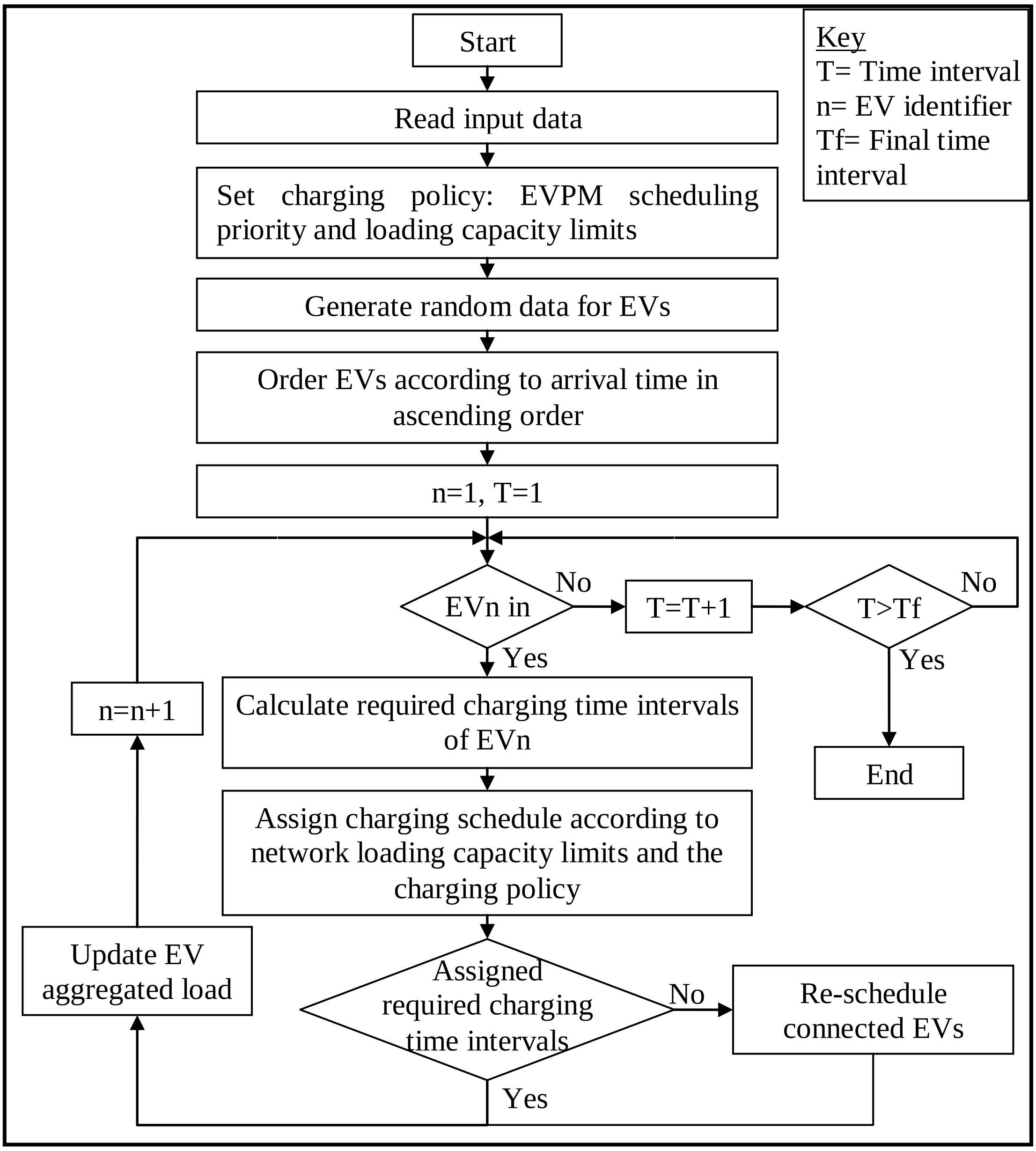

Fig. 4.3 EV battery charging schedules calculation process

4.2.4 Input Data and Assumptions Used in the EV Parking Manager Case Studies

The EV Parking Manager (EVPM) controls the EV battery charging of a parking facility which is located in a commercial building. The building is connected to MV/LV transformer as a single load. The transformer's rating sets the distribution network capacity limits. The building's daily electricity demand (without EVs) is shown in Fig. 4.4, with constant power values at each half hour time interval. The EV aggregated demand at each time interval is limited to the difference between the transformer rating and the building's demand (Fig. 4.4). Half hour summer spot electricity prices were drawn from [175]. The assumptions used in the case studies are summarised in Table 4.1 and Table 4.2.

Table 4.1 EVPM case studies input data

Input	**Description**
Number of EVs	120 EVs in total. 25% Battery Electric Vehicle (BEV) with 35kWh battery capacity [3]. 75% Plug-in Hybrid Electric Vehicle (PHEV) with 9kWh battery capacity [3].
EV batteries and charger characteristics	EV battery efficiency: 85% [174]. Charger efficiency: 87% [173]. Charger power rating: 2.99kW (13A, 230V) [168], [171].
Building´s demand	Typical weekly commercial load profile from [176], scaled to a maximum value of 400kW.
Network constraints	Transformer rating (500kVA)

Table 4.2 EVPM case studies random generated data for each EV

Input	**Description**
Type of EV (BEV or PHEV)	Modelled as a random number with a uniform distribution (using the tool input percentages shown in *Number of EVs*, Table 4.1).
Required energy	Modelled as a random number with a uniform distribution. The energy requirements were constraint to a minimum 10% of the battery capacity and a maximum 80% of the battery capacity [94].
Arrival time	Modelled by a normal distribution with 9 a.m. as mean and with a standard deviation of 1 hour (9 a.m. was assumed to be the arrival peak time).
Connection duration	Modelled by a normal distribution with 8 (hours) as mean and with a standard deviation of 1 hour (an average of 8 hours connection was assumed).

4.2.5 Description of the EV Parking Manager Case Studies

Three case studies were conducted using the developed tool. The aim of the case studies was to show the EVPM capabilities to manage the EV battery charging within network loading capacity limits and using different charging policies.

In Case study 1, the EVPM’s policy was to charge the EVs in the shortest time possible. The scheduling priority was set in an ascending order according to the EVs’ connected time intervals.

In Case study 2, the EVPM’s policy was to charge the EVs minimising the cost of charging. Electricity prices were assigned to each half hour time interval and the scheduling priority was set according to the electricity prices.

In Case study 3 the EVPM’s policy was to charge the EVs following a day-ahead aggregated demand profile. The day-ahead demand profile defines the EVPM loading capacity limits. The process followed by the EVPM when following a day-ahead profile for each EV is:

1) At the EV’s arrival, the charging time intervals are assigned with the policy to charge the EVs in the shortest time possible and according to the capacity limits set by the day-ahead profile.
2) If it is not possible to assign all the required charging time intervals within the day-ahead loading limits, the remaining charging time intervals are assigned with the following modifications: i) The scheduling priority is set according to the electricity prices and ii) The day-ahead loading limits are removed and only the network loading limits (transformer) are considered.

The scheduling priority is modified, from charge in the shortest time possible to charge following electricity prices, in order to have an excess of demand (higher than the day-ahead schedule) during time intervals with lower electricity prices. At the arrival of the following EV, the process restarts at (1).

A reference case with no EV control is shown in Fig. 4.4(a). The reference case, Case study 1 and Case study 2 used the same random generated data for each EV. In Case study 3 a new set of random data was generated and the day-ahead profile used was the EV aggregated demand outcome of Case study 2.

The charging policies of the case studies are summarised in Table 4.3.

Table 4.3 Charging policies

Case Study	**Charging Policy**
Case Study 1. *Fig. 4.4(b)*	Charge EVs in the shortest time possible.
Case Study 2. *Fig. 4.4(c)*	Charge EVs using the cheapest time intervals.
Case Study 3. *Fig. 4.4(d)*	Charge EVs following a day-ahead profile.

4.2.6 Results of the EV Parking Manager Case Studies

Fig. 4.4(a) shows the loading of the transformer with no control. In order to emulate the no control case, EVs were charged continuously from their time of connection until their required SoC was achieved. The red area shows the EV demand, the dark grey area the commercial building's demand and the light grey area the aggregate demand (EV plus building demand). The red line shows the transformer loading limit. The green bars show the EV arrival times (right axis) and the orange bars the departure times (right axis). It can be seen how with no control, the transformer loading limit was breached (light grey area).

Fig. 4.4(b) shows the results of Case study 1. The EV demand was satisfied without exceeding the transformer loading limit.

Fig. 4.4(c) shows the results of Case study 2. The EV demand was satisfied during the cheap hours of the day. The black dotted line shows the electricity prices used (right axis).

Fig. 4.4(d) shows the results of Case study 3. The EV demand followed the day-ahead aggregated schedule [blue line in Fig. 4.4(d)]. It can be seen how most of the demand exceeding the day-ahead profile was assigned during time intervals with lower electricity prices.

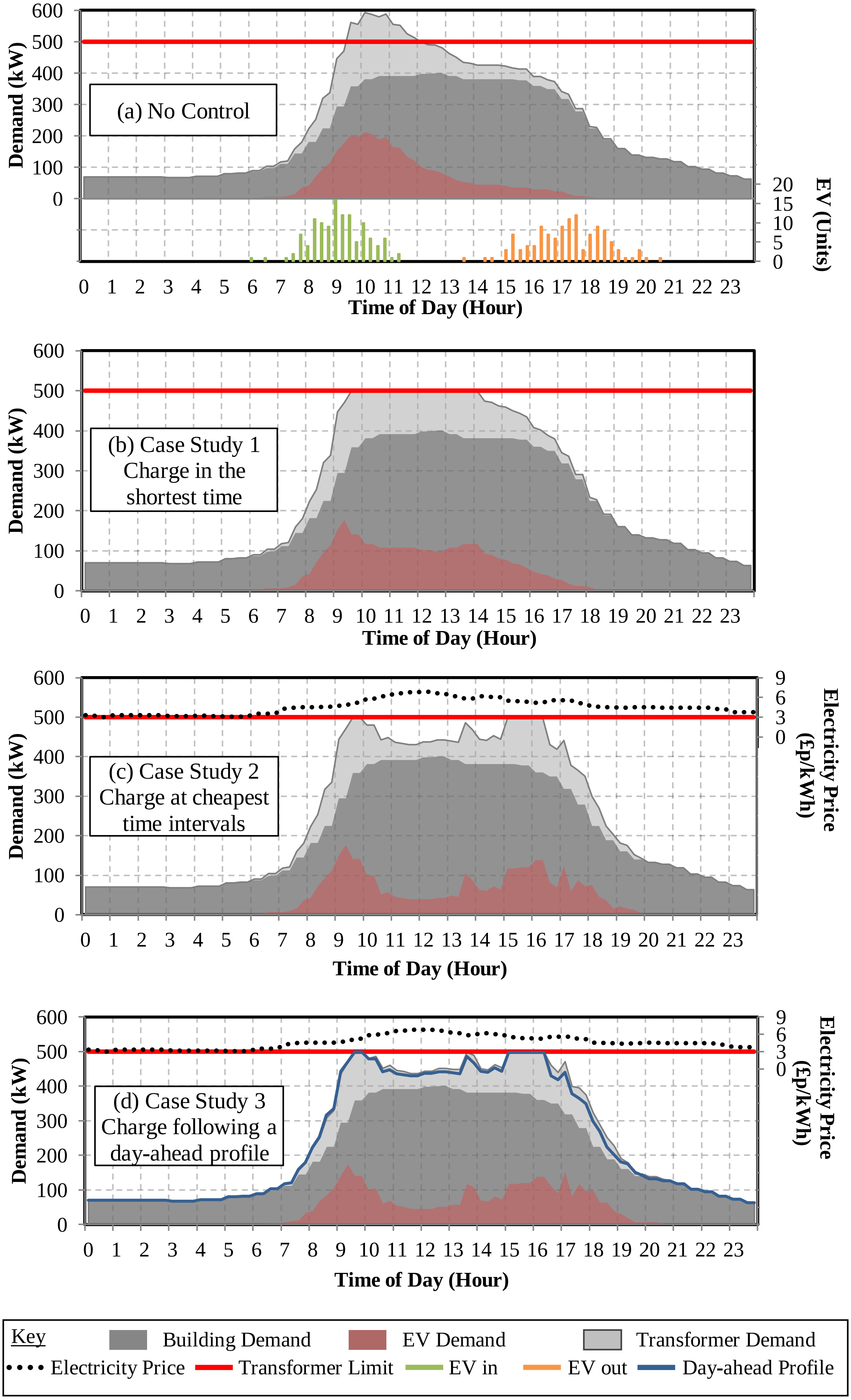

Fig. 4.4 Transformer loading with no EV control and results of the case studies

4.3 Swapping Station Manager

In this section the battery charging management of a battery swapping station is presented. Based on the proposed operation, a software tool is developed to calculate the number of chargers and batteries required to satisfy the battery demand of the swapping station.

The Swapping Station Manager (SSM) software manages the battery charging in a battery swapping station, providing fully charged batteries to the EVs, in exchange for their depleted batteries.

4.3.1 Assumptions

The Swapping Station Manager manages the EV battery charging according to:

- The available charging points within a swapping station.
- The available batteries of a swapping station.

The batteries within the swapping station can be in three different states:

i) Charging: The battery is connected to a charger.

ii) Fully charged: The battery is charged and ready to be swapped.

iii) Depleted: The battery provided by the EV remains in this state until it is placed in a charger. In this research, batteries in this state are referred to as being in the Depleted Battery Queue (DBQ).

4.3.2 Operation

The swapping station operation aims to charge the batteries as soon as a depleted battery is exchanged by an EV (if there are available chargers), or as soon as a charger becomes available. This ensures that the swapping station has at every time interval the maximum possible charged batteries.

The process followed by the Swapping Station Manager when an EV arrives at the swapping station (Fig. 4.5) is to:

i) Remove the depleted battery and allocate it to:

  - A charger, if there are chargers available.
  - The Depleted Battery Queue, if no charger is available.

ii) Deliver a fully charged battery to the EV.

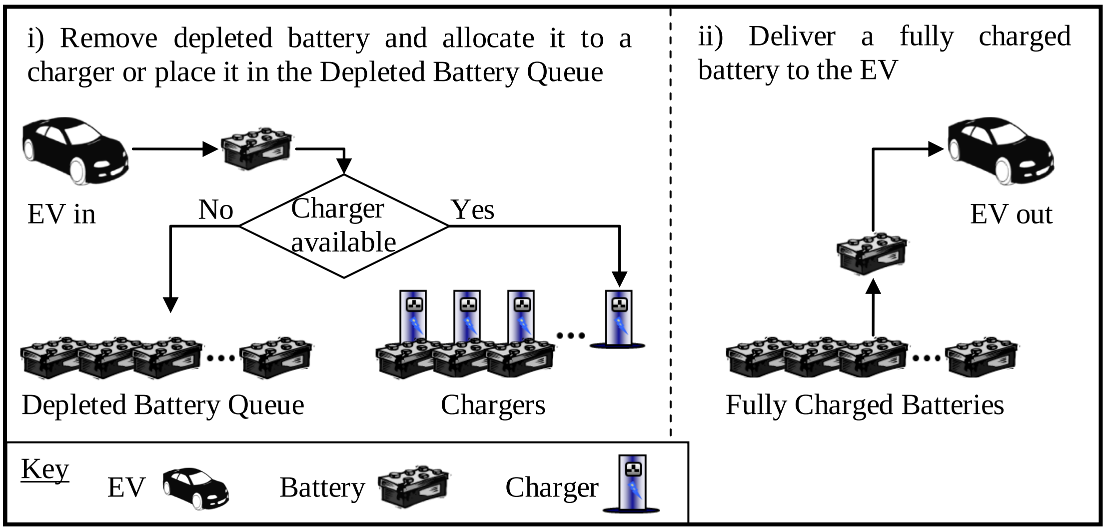

Fig. 4.5 Swapping Station Manager process at an EV's arrival

The process followed by the Swapping Station Manager when a battery reaches the fully charged state in a charger (Fig. 4.6) is to:

i) Remove the battery from the charger.

ii) If there are batteries in the Depleted Battery Queue, assign a battery to the charger that has become available.

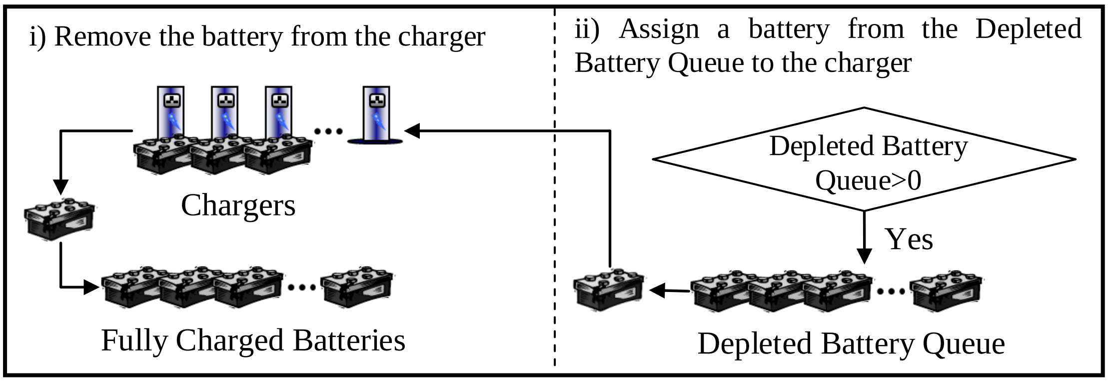

Fig. 4.6 Swapping Station Manager batteries' state updating

4.3.3 Calculation of Required Batteries and Chargers for a Swapping Station

A software tool was developed in JAVA™ to calculate the number of chargers and batteries required to satisfy a given daily battery swap demand (based on the SSM operation described). The tool calculates the probability of the battery daily demand not being satisfied for different combinations of chargers and batteries. The minimum number of batteries and chargers required by a swapping station are derived from those combinations with a 0% probability of the battery demand not being satisfied. The swapping station requirements (batteries and chargers) depend on different factors presented in Table 4.4, which are also the input data for the SSM software tool.

Table 4.4 Software tool inputs

Input	Description
Battery demand	Number of batteries swapped at each hour.
EV arrival time within each hour	Time when an EV requests a fully charged battery.
Battery characteristics	Capacity in kWh and efficiency.
Charger characteristics	Power rating in kW and efficiency.
Swap duration	Time, in minutes, required by the swapping station to swap the battery.
Depleted battery SoC	State of Charge (SoC), in percentage, of the depleted battery exchanged.
Tool search space	
Batteries search space	Minimum and maximum number of batteries investigated.
Chargers search space	Minimum and maximum number of chargers investigated.

The *EV Arrival time within each hour* and the *Depleted batteries' SoC* are modelled as random numbers. For each combination of chargers and batteries, the tool runs a user-defined number of simulations. For each simulation:

- A daily horizon is considered.
- A new set of random data is generated.
- The algorithm records if the battery demand is not satisfied. The battery demand is not satisfied if at the arrival time of an EV, no battery is available to be swapped (i.e. fully charged).

For each combination of chargers and batteries, the probability of the battery demand not being satisfied is calculated dividing the number of times the battery demand is not satisfied, by the number of daily simulations.

A schematic of the tool is given in Fig. 4.7.

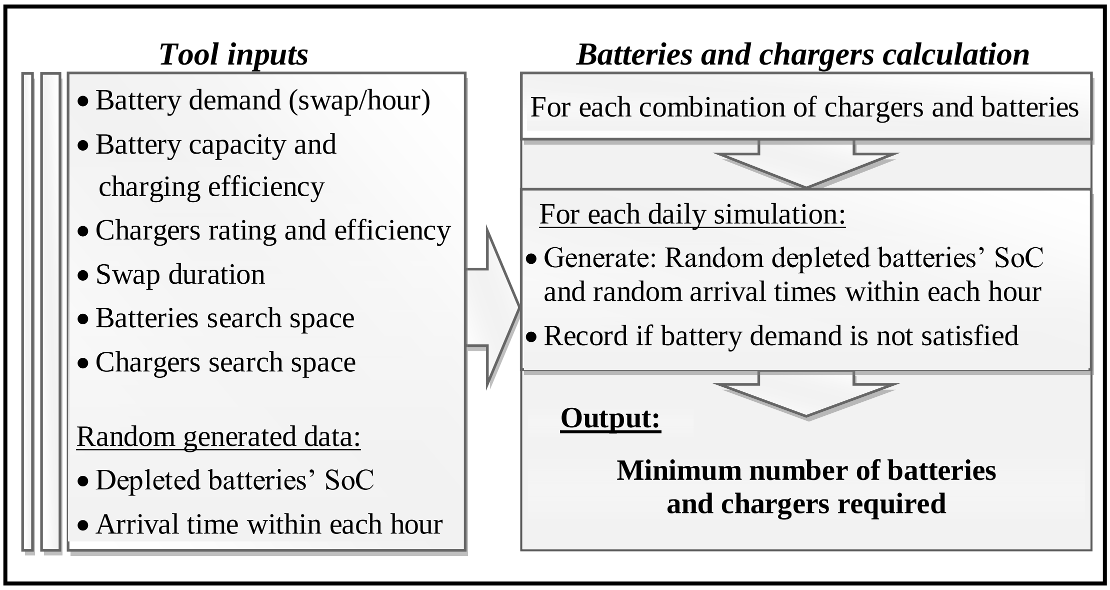

Fig. 4.7 Schematic description of the software tool

The computational procedure is shown in Fig. 4.8. The algorithm is run at time intervals of one minute.

At each time interval the algorithm checks if any of the chargers have a fully charged battery. If a battery is charged, the number of fully charged batteries (B in Fig. 4.8) increases by one. If there are batteries in the Depleted Battery Queue, a battery is placed in the charger. This process is shown in the box *batteries' state updating* of Fig. 4.8.

Once the state of all batteries placed in the chargers is examined, the algorithm checks if an EV has arrived at the swapping station. When an EV arrives:

- If there are no fully charged batteries available to swap, the algorithm records that the battery demand is not satisfied, and a new simulation is run.
- If there are batteries available (B>0, in Fig. 4.8), the battery delivered to the EV decrements the number of fully charged batteries by one. Thereafter, depending on the chargers' availability, the EV's depleted battery is placed in a charger or in the Depleted Battery Queue.

This process is shown in the box *Process at an EV's arrival* of Fig. 4.8.

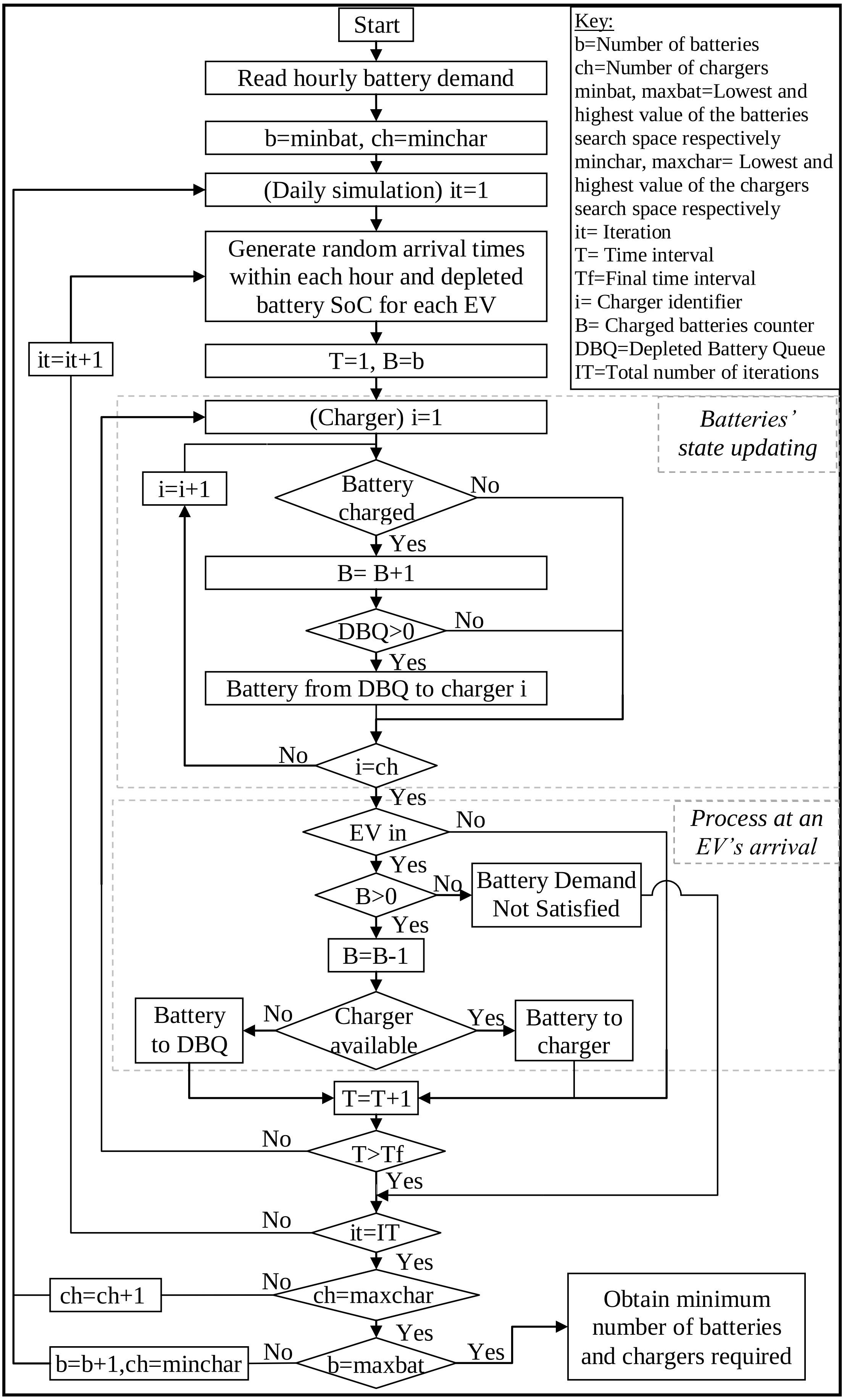

Fig. 4.8 Batteries and chargers requirements calculation process

4.3.4 Input Data and Assumptions Used in the Swapping Station Manager Case Studies

The chargers within the swapping station have the same power rating and the same charging efficiency.

The hourly battery demand follows the utilisation pattern of a petrol station [91]. The maximum number of batteries swapped per hour is determined by the time required to swap each battery [91]. The swap duration is assumed to be 5 minutes, hence the maximum batteries swapped per hour are 12. Fig. 4.9 shows the hourly battery demand used.

Batteries are modelled as purely resistive loads, charged at a constant power rating. All batteries have the same energy capacity and the same charging efficiency. The State of Charge (SoC) of the depleted batteries is modelled as a random number with a normal distribution: mean 20% and a standard deviation of 10%. The batteries used in each simulation are fully charged at the beginning of the day.

The arrival times of the EVs within each hour are modelled as random numbers with a uniform distribution, with the following constraint: two arrivals cannot occur within the time required to swap the battery. If a car arrives when another EV is swapping its battery, the new EV waits until the swap is finished. The input data and assumptions used in the case studies are summarised in Table 4.5 and Table 4.6.

Table 4.5 SSM case studies input data

Input	**Description**
Battery demand (swap/hour)	Distribution of Fig. 4.9 [91].
Batteries swapped/day	69 [91].
Swap duration	5 minutes [91].
Battery capacity	35kWh [3].
Battery efficiency	85% [174].
Charger rating	43.64kW (3Φ, 400V, 63A) [177].
Charger efficiency	87% [173].
Daily simulations (iterations)	10000.
Batteries search space	1-20.
Chargers search space	1-20.

Table 4.6 SSM case studies random generated data for each EV

Input	Description
Arrival time within each hour	Uniform distribution.
Depleted batteries' SoC.	Normal distribution. Mean=20%. Standard deviation=10%.

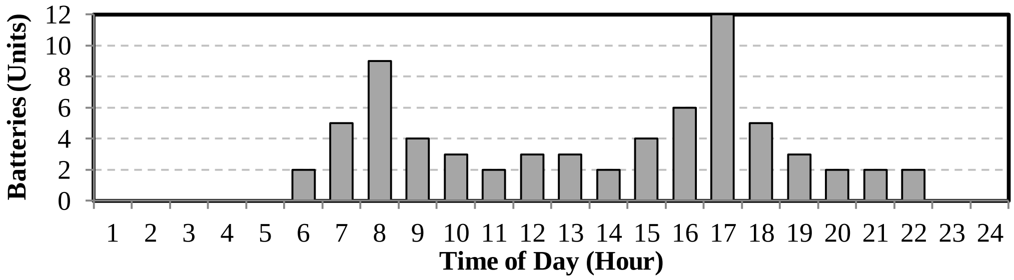

Fig. 4.9 Daily battery swap demand (adapted from [91])

4.3.5 Description of the of the Swapping Station Manager Case Studies

Two case studies were conducted. In Case study 1 the number of chargers and batteries required in order to satisfy a daily battery demand are calculated. In Case study 2, for different combinations of chargers and batteries, the simulated chargers were monitored and the load profile of the swapping station was obtained. The description of the case studies is provided in Table 4.7.

Table 4.7 Description of the case studies

Case	Description
Case Study 1 *Fig.* 4.10, *Table 4.8*	Using the described tool, the probability of battery demand not being satisfied is investigated for different combination of batteries and chargers (Fig. 4.10). For those combinations with a 0% probability of the battery demand not being satisfied, the minimum number of required batteries and chargers are obtained (Table 4.8).
Case Study 2 *Fig. 4.11*	Using the output of Table 4.8, two daily simulations were run, one using the minimum number of batteries required, and the second simulation using the minimum number of chargers required. The same random data were used in both simulations (i.e. same energy consumed by the swapping station). Both demand profiles were plotted.

4.3.6 Results of the of the Swapping Station Manager Case Studies

In Fig. 4.10, the probability of the battery demand not being satisfied is shown for different combinations of chargers and batteries. The range of chargers and batteries used in Fig. 4.10, shows the minimum number of batteries and chargers required in order to satisfy the daily battery demand (with a 0% probability of the battery demand not being satisfied). It can be seen how the required number of chargers was increased as the number of batteries was reduced, and conversely.

In Table 4.8 the minimum number of batteries and chargers required to satisfy the EV daily battery demand are shown.

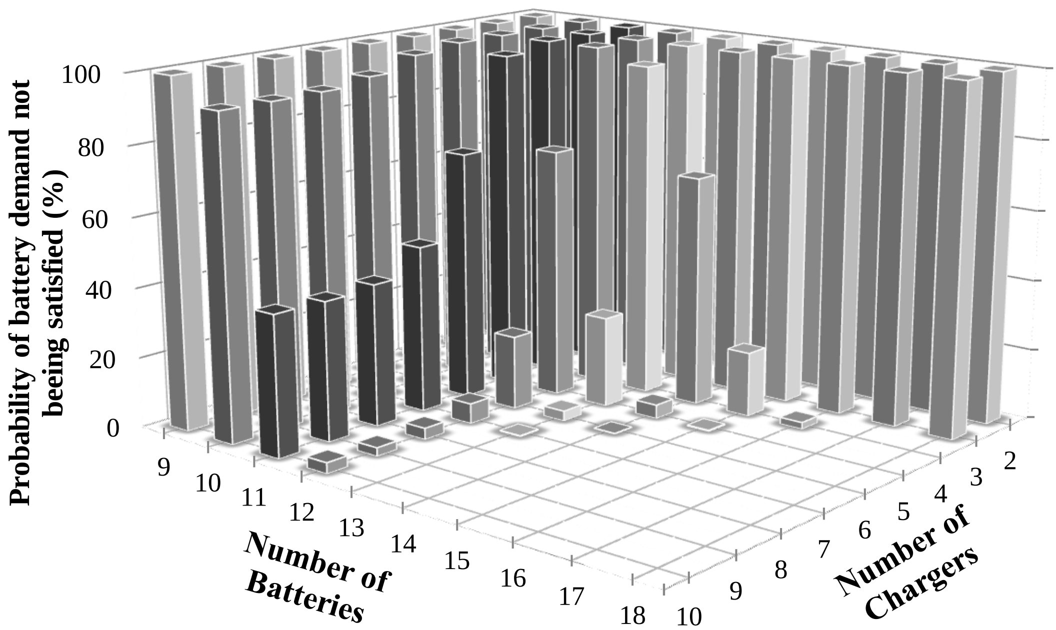

Fig. 4.10 Probability of battery demand not being satisfied for different combinations of batteries and chargers

Table 4.8 Minimum number of batteries and chargers required

Minimum number of batteries	13		Minimum number of chargers	4
Required number of chargers	≥ 8		Required number of batteries	≥ 17

Fig. 4.11 shows the effect of the number of chargers and batteries on the swapping station's load profile. The grey line shows the load profile when the swapping station operated with the minimum number of chargers (4) and with 17 batteries in stock.

The black line shows the load profile when the swapping station operated with the minimum number of batteries (13) and 8 chargers.

From Fig 4.11 it can be seen how, although for both combinations the energy supplied to the swapping station was the same, the load profiles differed.

For the simulation where the minimum number of batteries was considered (black line in Fig. 4.11), two demand peaks of 349kW were obtained (8 chargers with 43.64kW power rating were used). The peaks in demand coincided with the battery swap demand peaks showed in Fig. 4.9.

For the simulation where the minimum number of chargers was considered (grey line in Fig. 4.11), a flatter demand profile was obtained, which remained constant almost during all the simulated day at 174.56kW (when 4 chargers with 43.64kW power rating were used).

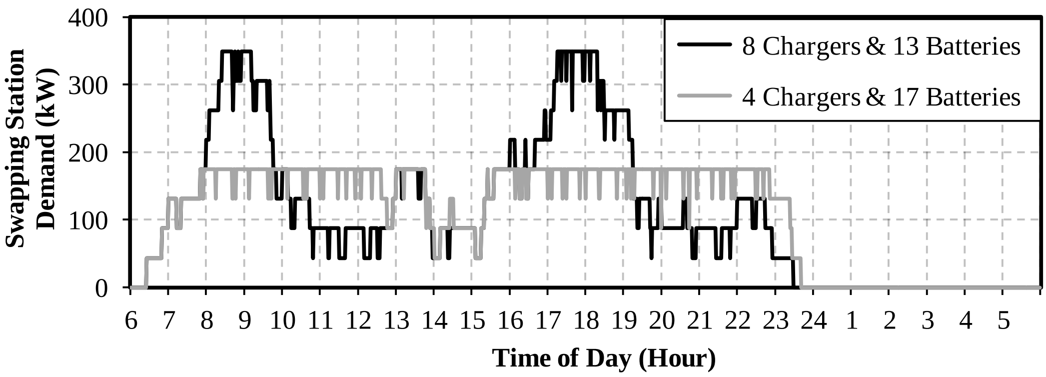

Fig. 4.11 Load profiles of a battery swapping station

4.4 SUMMARY

The EV battery management for two types of EV cluster infrastructures was considered:

i) EV Parking facility: managed by the **EV Parking Manager** (EVPM).

ii) EV battery swapping station: managed by the **Swapping Station Manager** (SSM).

For the **EV Parking Manager** operation proposed, the EVs' required charging time intervals were calculated according to the EV owners demand requirements and charging characteristics. The charging schedules were defined considering the network loading capacity limits and the charging policy.

Using a developed JAVA™ software tool that emulated the EVPM operation, three case studies were defined and the EV aggregated demand plotted. In the first case study the EVs were charged in the shortest time possible, in the second case study the EVs were charged using the cheapest time intervals, and in the third case study the EVs were charged following a day-ahead profile.

For the **Swapping Station Manager** operation proposed, a JAVA™ software tool was developed for the calculation of the minimum number of batteries and chargers required to satisfy a specific battery daily demand. The tool runs daily simulations where the EV arrival times and the depleted batteries' SoC are modelled as random numbers. A case study was conducted and the minimum number of required batteries and chargers calculated. The swapping station required a minimum number of 13 batteries (with a number of chargers ≥ 8) or a minimum number of 4 chargers (with a number of batteries ≥ 17).

Using the number of required batteries and chargers obtained in the case study, the effect of the number of chargers and chargers on the swapping station's load profile was shown through a second case study. For the same energy supplied to the swapping station, the number of chargers and batteries determined the shape and the peak demand values of the load profiles.

Chapter 5

Management of Electric Vehicle Battery Charging with a Multi-Agent System

5.1 Introduction

A Multi-Agent System (MAS) is presented that coordinates the EV battery charging according to:

- EV owner preferences.
- Distribution network constraints.
- Electricity prices.

The Multi-Agent System has a hierarchical architecture, according to the voltage levels (Fig. 5.1), and consists of:

i) The **Electric Vehicle aggregator,** which is responsible for the EV battery charging management. It comprises three types of agents: EV agent, Local Area agent and Coordinator agent.

ii) The **Distribution System Operator (DSO),** which is responsible for the operation of the distribution network within technical constraints. It comprises one type of agent: DSO agent.

The Multi-Agent System hierarchy and the sequence of communications between the agents were developed in collaboration with a colleague PhD student P. Papadopoulos. The decision making process of each agent and the algorithms presented in this chapter are the contribution of the author.

5.2 Multi-Agent System Hierarchy

The location of the agents in a power distribution network is shown in Fig. 5.1.

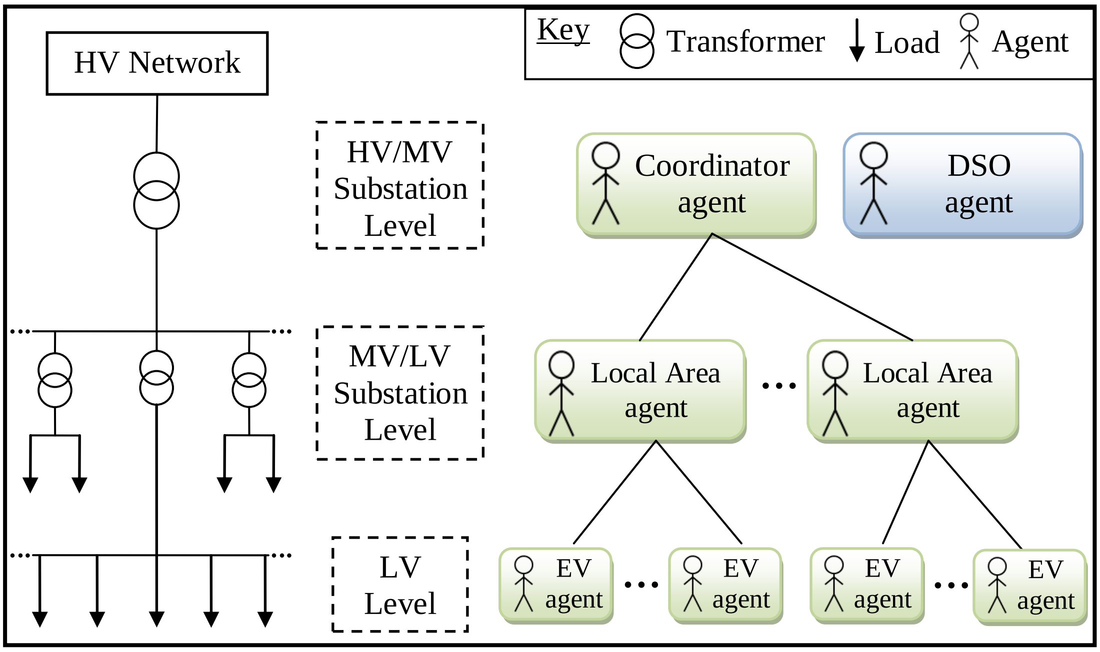

Fig. 5.1 Multi-Agent System hierarchy

The **EV agent** is located in the EV. The EV agent:

- Sends the EV owner preferences to the Local Area agent.
- Receives the charging set points from the Local Area agent and sends them to the EV battery inverter.

The **Local Area agent** is located at the MV/LV substation level. The Local Area agent:

- Calculates the optimal battery charging schedules of the EVs.
- Sends the aggregated EV load demand to the Coordinator agent.

The **Coordinator agent** is located at the HV/MV substation level. The Coordinator agent:

- Aggregates the demand of the Local Area agents and sends it to the DSO agent.

The **DSO agent** is located at the HV/MV substation level. The DSO agent is located within the substation; similarly to what it is proposed in the UK's EV management project "Innovation squared (I^2EV)" [178], where devices are planned to be located in the substations in order to manage the EV load at the distribution network feeders [179] .The DSO agent:

- Validates the EV load demand.

- Restores normal operating conditions curtailing EV battery charging, in the case that distribution network technical limits are violated.

5.3 Assumptions Used in the Multi-Agent System Development

5.3.1 Modelling Assumptions

EV batteries are assumed to be charged at constant power rate. The charger rated power is assumed to be of 2.99kW (13A, 230V) [168], [171].

The DSO agent monitors continuously the distribution network nodes. The monitoring system provides the DSO agent with real-time voltage, real power and reactive power measurements. The DSO agent is responsible for the operation of the distribution network within the following technical constraints: i) Steady state voltage limits, ii) Transformers loading limits and iii) LV cables loading limits.

5.3.2 Time line

The operation of the MAS consists of a Scheduling Period (SP) and an Operational Period (OP) at every hour. The decided set points for the hour T+1 are the result of the Scheduling Period of the hour T, as shown in Table 5.1.

Table 5.1 MAS operation time line

Hour T	**Hour T+1**	**Hour T+2**	...
Operational Period (OP) **OP_T**	**OP_{T+1}** (Application of set points of **SP_T**)	**OP_{T+2}** (Application of set points of **SP_{T+1}**)	...
Scheduling Period (SP) **SP_T** (Calculation of set points for T+1)	**SP_{T+1}** (Calculation of set points for T+2)	**SP_{T+2}** (Calculation of set points for T+3)	...

5.3.3 DSO Network Limits Matrix and Technical Validation

The DSO agent calculates the Network Limits Matrix. The Network Limits Matrix consists of the maximum power that can be drawn by the EVs at each LV feeder of the distribution network, during each hour of the day. The concept of the Network Limits Matrix was firstly proposed in [59] for the market participation of DERs. The Network Limits Matrix is used by the Local Area agents to schedule the EV battery charging.

The technical validation of the aggregated EV load demand is done by the DSO agent for every Operational Period to ensure operation within distribution network technical constraints. The DSO agent is assumed to have the forecasted demand of the non-EV loads of the network.

During the Scheduling Period (hour T), the aggregated EV load demand for the following Operational Period (hour T+1) is sent to the DSO agent for technical validation. If the charging set points are not validated, the DSO agent updates the Network Limits Matrix and informs the Coordinator agent.

5.3.4 Operational Modes

Two operational modes are defined:

i) During **normal operation** the distribution network is operated within technical limits.

ii) During **emergency operation** the voltage limits are violated and/or transformers and cables are overloaded.

5.4 Normal Operation when the Network is Within Technical Limits

During normal operation the Local Area agents calculate the optimal charging set points for each Operational Period. The set points are calculated based on the information received from the EV agents (charging preferences) and the Coordinator agent (network loading capacity limits and electricity prices) as shown in Fig. 5.2.

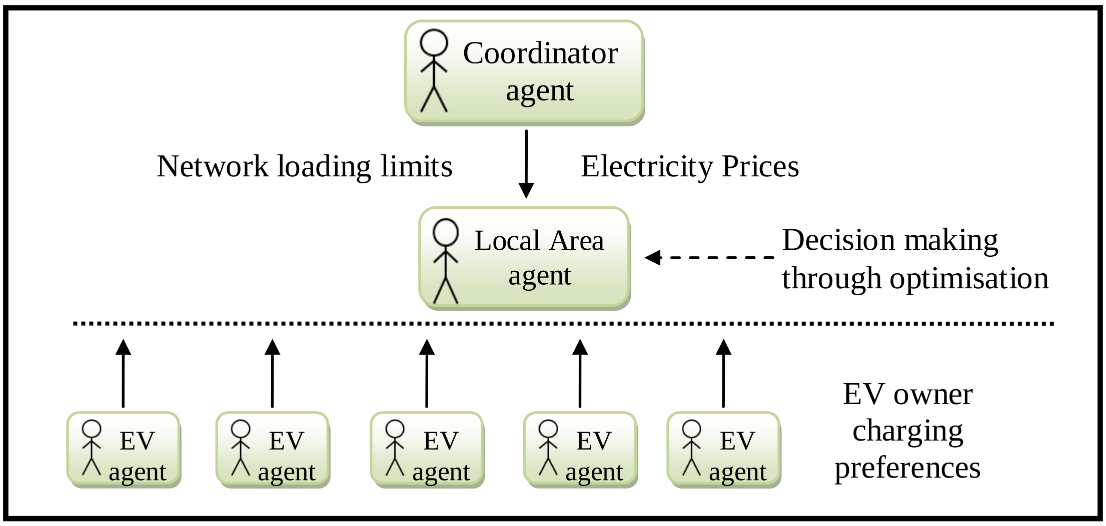

Fig. 5.2 Local Area agent decision making

Fig. 5.3 shows the algorithm of the Multi-Agent System during normal operation.

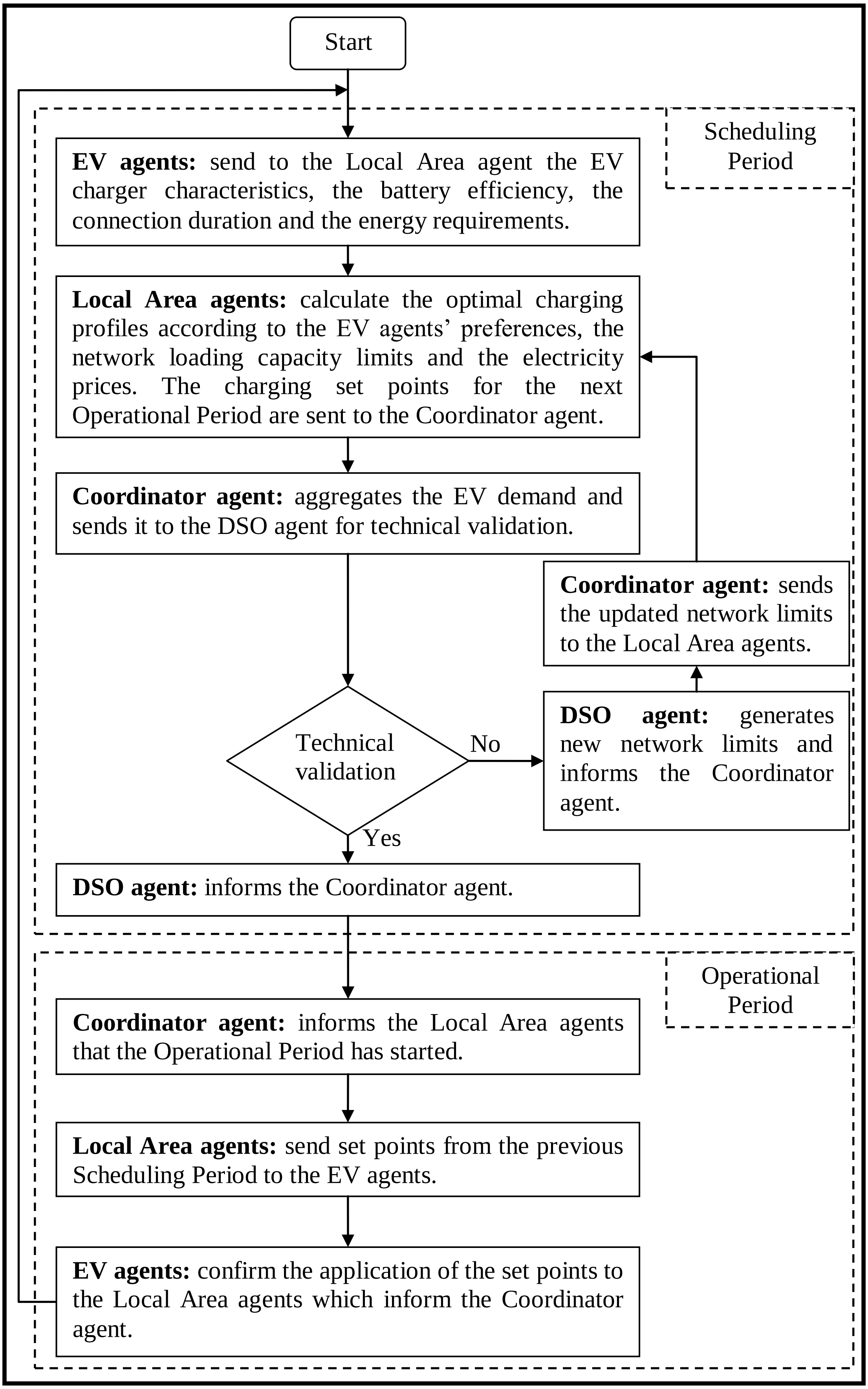

Fig. 5.3 MAS normal operation algorithm

In APPENDIX A, the exchange of messages during normal operation is presented in Unified Modelling Language (UML) notation.

5.4.1 Electric Vehicle Agent

At the beginning of each Scheduling Period the EV agent sends to the Local Area agent the following information:

- Actual SoC in kWh.
- Desired SoC at the end of the charging session in kWh.
- Connection duration in hours.
- Charger efficiency.
- Charger power rating in kW.
- EV battery efficiency.

This information is used by the Local Area agent to:

- Monitor the EV's State of Charge.
- Deal with possible changes in users' preferences (change in departure time or in final SoC requirements).
- Calculate EV optimal charging profiles for the following Operational Periods.

At the beginning of every Operational Period the EV agent receives the charging set point from the Local Area agent.

5.4.2 Local Area Agent

The optimal EV charging schedules are calculated at the Local Area agents at every Scheduling Period. The objective of the Local Area agent is to deliver the desired energy to the EV owners, within technical constraints, minimising the cost.

The optimal charging schedules are obtained using the information received at the beginning of each Scheduling Period from:

i) The Coordinator agent, which comprises:

- The loading capacity limits contained in the Network Limits Matrix.
- The electricity prices for each hour.

ii) The EV agents, which comprises:

- EV owners' preferences, as presented in Section 5.4.1.

The energy in kWh delivered to each EV (*En*) at every hour assigned to charge is obtained with equation (5.1).

$$E_n = e_B \times P \times e_{Ch} \times 1\,h \tag{5.1}$$

Where:

e_B is the EV battery efficiency,

P is the charger power rating in kW,

e_{Ch} is the charger efficiency and

h is hour (hourly operational periods are used).

The Linear Programming (LP) solver IBM ILOG CPLEX [169] is used in order to find the optimal charging schedules. The objective function is formulated as follows:

$$minimise\ \mathrm{Z} = \sum_{t=T}^{Tf} \sum_{n=1}^{N} E_{n\,t} \times p_t \tag{5.2}$$

Where:

t is the hourly time interval,

T is the hour of the following operational period,

Tf is the final operational period,

n is the Electric Vehicle,

N is the total EVs connected to the Local Area agent,

E_{nt} is the energy in kWh delivered to EV n during hour t and

p_t is the electricity price of hour t in £/kWh.

Subject to:

$$\sum_{t=i_n}^{Tf_n} E_{n\,t} \geq E_{dn} \qquad \text{for } n=\{1,...,N\} \tag{5.3}$$

$$\sum_{n=1}^{N_s} P_{n\,t} \leq L_{s\,t} \qquad \begin{cases} \text{for } t=\{1,...,Tf\} \\ \text{for } s=\{1,...,S\} \end{cases} \tag{5.4}$$

Where:

t is the hourly time interval,

n the Electric Vehicle

i_n is the connection hour of EV n,

Tf_n is the disconnection hour of EV n,

E_{nt} is the energy in kWh delivered to EV n during hour t,

E_{dn} is the desired energy in kWh at the end of the charging period of EV n,

s is the network feeder,

S is the number of feeders,

Tf is the total number of hours,

N_s is the total number of EVs connected at feeder s,

P_{nt} is the power rating in kW of EV n for hour t and

L_{st} is the loading capacity limit in kW at feeder s for each hour t.

5.4.3 Coordinator Agent

The Coordinator agent starts the Operational Period and the Scheduling Period. The Coordinator agent acts as an intermediary between the Local Area agents and the DSO agent during normal operation.

At the beginning of each Scheduling Period the Coordinator agent sends to the Local Area agents the:

- The loading capacity limits.
- The hourly electricity prices.

The Coordinator agent receives from the Local Area agents the following information about the next Operational Period:

- Aggregated EV load demand.
- EV Curtailment factors. The Curtailment factors are used by the DSO agent to choose which EVs to curtail in case of an emergency situation (Section 5.5).

The Coordinator agent aggregates the demand (per node) of all Local Area agents and forwards it to the DSO agent for technical validation. Together with the EV demand, the EV Curtailment factors are sent to the DSO agent.

The outcome of the validation process received from the DSO agent is sent by the Coordinator agent to the Local Area agents.

5.4.4 DSO Agent

The DSO agent is responsible for ensuring that the distribution network (downstream the HV/MV substation) is operated within its technical limits. The DSO agent:

i) Sends the Network Limits Matrix to the Coordinator agent. The matrix includes the capacity limits (in kW) for all low voltage feeders for each hour of the day.

ii) At every Scheduling Period evaluates, by running a power flow, the aggregated EV load demand proposal sent by the Coordinator agent for the Operational Period.

    - If the charging set points are validated (i.e. no constraint violation are foreseen after running the power flow by the DSO agent), the DSO agent informs the Coordinator agent. The Coordinator agent informs the Local Area agents that the charging set points are validated.
    - If the charging set points are not validated, the DSO agent updates the Network Limits Matrix and forwards it to the Coordinator agent, which in turn sends it to the Local Area agents. New EV charging schedules are calculated by the Local Area agents and the validation process is repeated.

5.5 Emergency Operation when the Network is Not Within Technical Limits

Emergency operation in this research means that the distribution network steady state voltage limits are violated or low voltage cables and distribution transformers are overloaded.

The DSO agent monitors continuously the network nodes. If a limit breach is detected, the DSO agent curtails EVs based on their Curtailment factor until normal operation is restored. The Curtailment factor is described in detail in Section 5.5.2.

When an emergency situation is detected:

i) The DSO agent sends a curtailment instruction to the EV agent with the highest Curtailment factor in the network location where the emergency has been detected.

ii) The EV agent curtails the charging current of the EV and informs the DSO agent.

iii) The DSO agent checks if the system has returned to normal operation. If not, it sends a curtailment instruction to another EV agent according to the Curtailment factor priority list.

5.5.1 Electric Vehicle Agent

The Electric Vehicle agent receives a curtailment instruction from the DSO agent. The EV agent sends a set point of zero current to the EV battery inverter and sends a confirmation message to the DSO agent.

5.5.2 Local Area Agent

The Curtailment factors calculated for each EV agent by the Local Area agent are used by the DSO agent in case of emergency situation. The Curtailment factors are:

i) Calculated at every Scheduling Period (hour T), for the following Operational Period (hour T+1).

ii) Sent to the Coordinator agent, which are in turn sent to the DSO agent. The Curtailment factors are used by the DSO agent during hour T+1, in case of an emergency situation.

The calculation of the EV curtailment factors is done after the optimal schedules are obtained [equation (5.2)]. The Local Area agent checks all the time intervals (hours) that the EV agent is connected starting from hour T+1. For each EV agent the Local Area agent:

i) Checks if it is assigned to be charging at the Operational Period (T+1), for which the Curtailment factor is being calculated. If it is not assigned to be charging, the Curtailment factor is set to zero (an EV not assigned to be charging cannot be curtailed).

ii) Checks all the time intervals (hours) that the EV is connected starting from hour T+2 and records the number of hours that the EV is connected and not scheduled to charge (i.e. idle).

The Curtailment factor (*Cf*) calculation process is shown in Fig. 5.4.

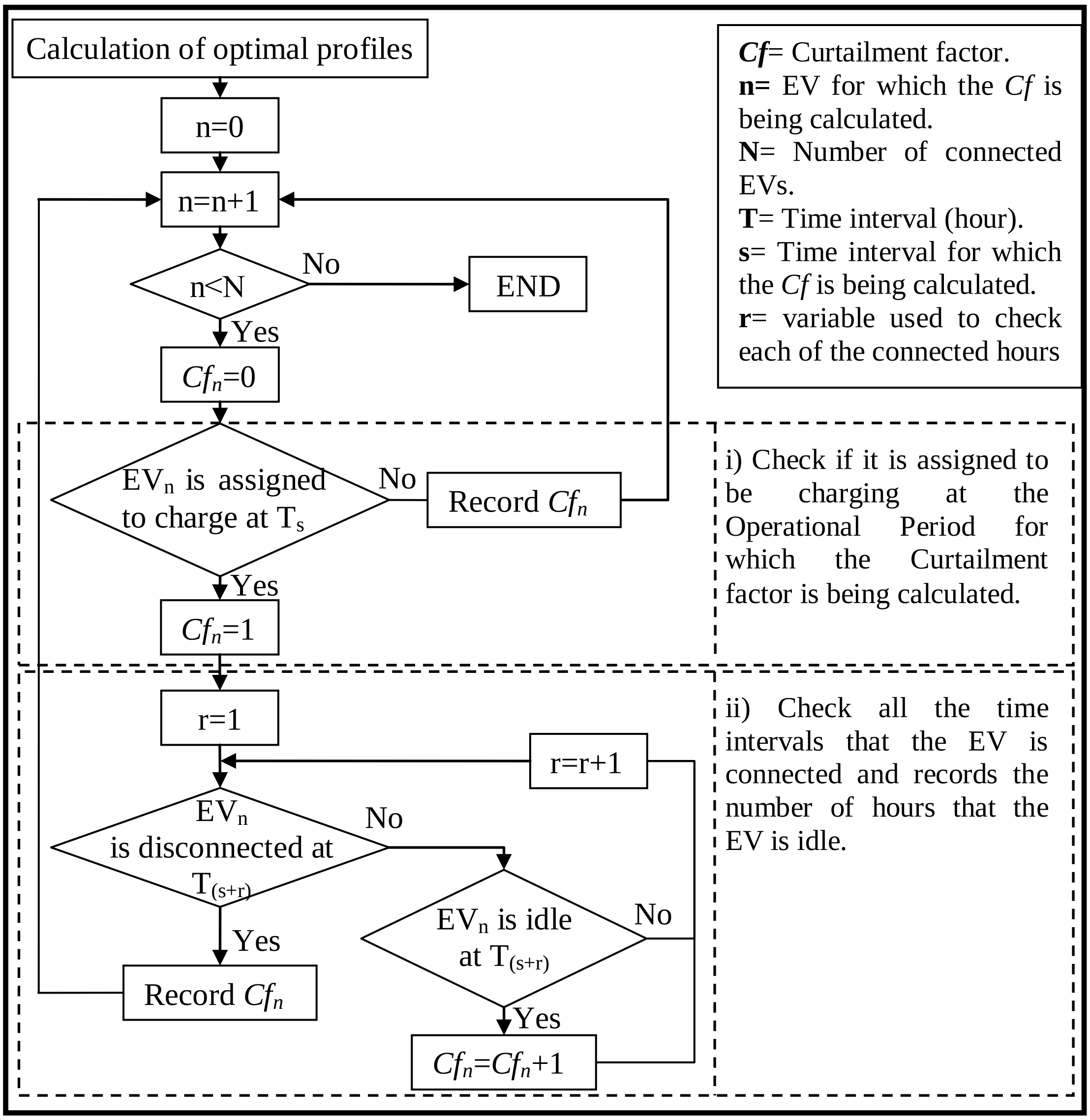

Fig. 5.4.Local Area agent Curtailment factor calculation

The priority list, sent to the Coordinator agent in ascendant order, is based on the EVs' Curtailment factors (*Cf)*. EVs with higher Curtailment factors will be curtailed first in case of emergency.

The Curtailment factors ensure that the EV agents curtailed are those which have more idle hours scheduled. Having more idle hours scheduled gives the opportunity to the Local Area agent to re-assign a new charging schedule to the EV agent and satisfy its demand, if curtailed by the DSO agent.

5.5.3 DSO Agent

The DSO agent decides which EVs to curtail based on:

- The network location where the emergency has been detected.
- The EVs Curtailment factor.

The network location where the emergency is detected will determine the EVs that can be curtailed in order to restore the system to normal operating conditions. For example, if overloading is detected in a transformer, the eligible EVs to be curtailed would be the ones downstream of such transformer.

The process followed at the DSO agent is shown in Fig. 5.5.

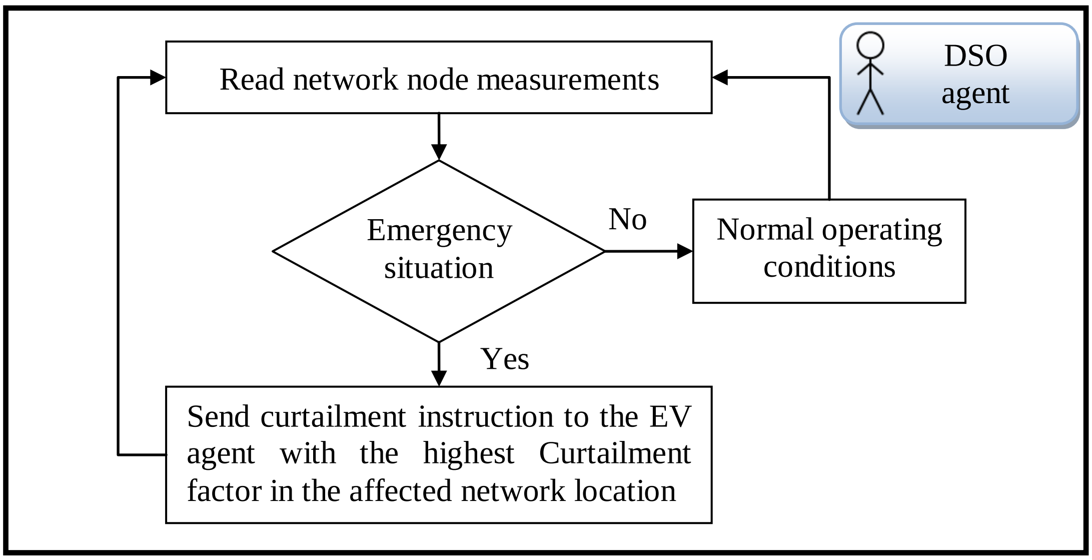

Fig. 5.5 DSO agent emergency operation algorithm

5.6 Demand Reduction Service Provided by the Local Area Agents

Active demand is defined in [59] as "*the active participation of domestic and small commercial consumers in the power system markets and in the provision of services to the different power system participants*."

In this Multi-Agent System active demand is provided by the Local Area agents, after a Coordinator agent request for demand reduction at a specific time interval (hour). Active demand services are contracted "*based on estimated consumptions of group of customers*", according to [180]. A forecasted EV aggregated load demand at the Coordinator agent and at the Local Area agents is assumed for the provision of demand reduction service.

The volume of the aggregated EV load demand (kWh) is not modified, hence a demand reduction at a specific hour implies that the demand is shifted to other hours. The cost of the demand reduction service is defined by the time intervals (hours) to where the demand is displaced to.

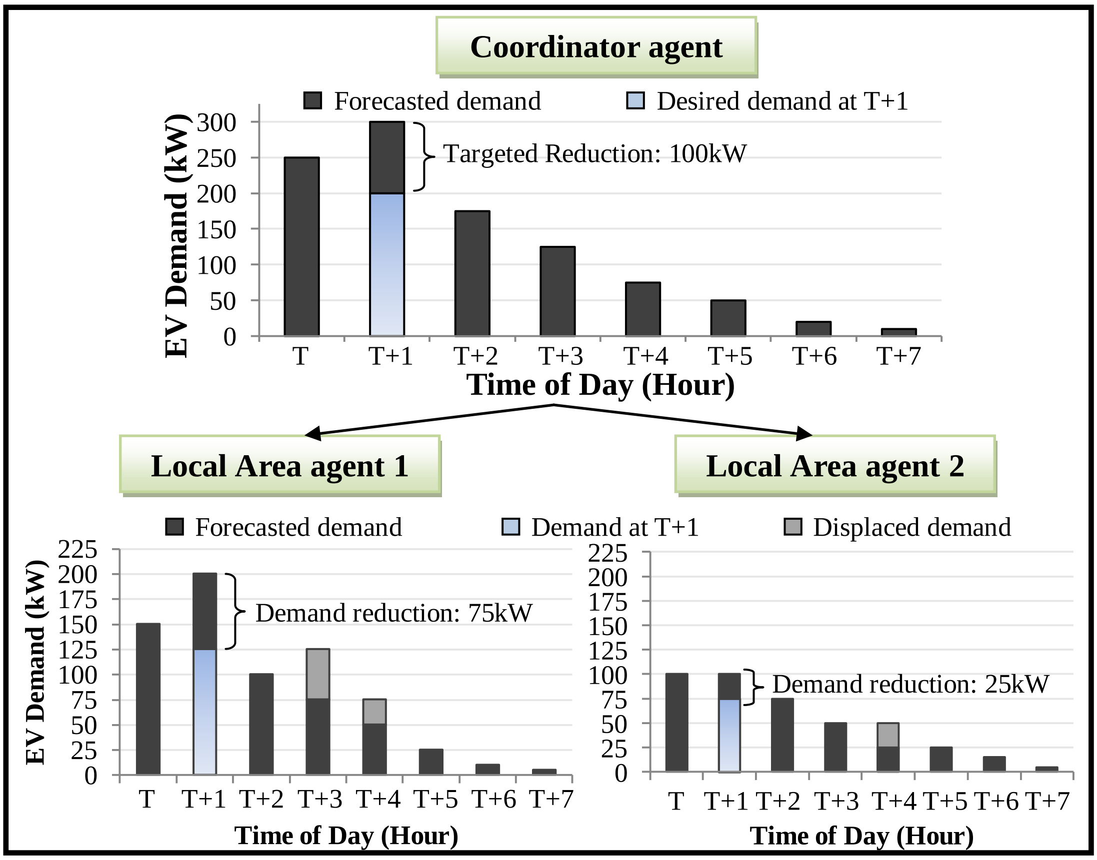

Fig. 5.6 Example of active demand service provision adapted from [180]

Fig. 5.6 shows a graphical example of the provision of active demand service by two Local Area agents. A demand reduction is requested by the Coordinator agent for hour T+1, the reduction is provided by the Local Area agents. The demand reduction provided by the Local Area agents can be seen, as well as the displaced demand due to the demand reduction.

5.6.1 Local Area Agent

After a demand reduction request from the Coordinator agent, the Local Area agent:

i) Calculates the optimal EV battery charging schedules (of the connected EVs). The aggregated demand output is referred to as the *Optimal Schedule.*

ii) Calculates the *Demand Reduction Schedule:* The *Demand Reduction Schedule* is the aggregated EV optimal charging schedules with the minimum possible load assigned to the time interval for which the demand reduction has been requested.

iii) Compares the *Optimal Schedule* with the *Demand Reduction Schedule*.

iv) Sends the demand reduction offer to the Coordinator agent. The demand reduction offer consists of the demand that can be reduced at the requested time interval and the cost (defined by to which time intervals the demand is shifted to).

The *Demand Reduction Schedule* is obtained with the optimisation presented in Section 5.4.2, setting the electricity price of the hour for which the demand reduction is requested, p_t in the objective function (5.2), as the highest value. Thus the specific hour will be assigned the minimum possible load.

The demand reduction offer calculated by the Local Area agent (output from the comparison of the *Optimal Schedule* with the *Demand Reduction Schedule*), is sent to the Coordinator agent in the form of a matrix (Table 5.2).

Each row of the matrix (Table 5.2) contains the number of EVs (*N*), with their charger power rating (*P*), which demand is displaced to the same hour (i.e. with the same electricity price, *p*).

Table 5.2 Demand reduction matrix

Local Area agent *a*		
Number of EVs (Units)	**Power Rating (kW)**	**Electricity Price (£p/kWh)**
N_{a1}	P_{a1}	p_{a1}
N_{a2}	P_{a2}	p_{a2}
...	...	...
N_{aM}	P_{aM}	p_{aM}

An example is shown in Fig. 5.7. In this example a Local Area agent is considered. A reduction request occurs during hour 9 and the reduction request is for hour 15. In Fig. 5.7 the black bars show the aggregated EV load demand of the *Optimal Schedule*. The black dotted line represents the electricity prices. The grey bars represent the aggregated EV load demand of the *Demand Reduction Schedule* with the highest electricity price assigned to hour 15. The electricity price used at hour 15 in order to obtain the *Demand Reduction Schedule* is represented with a black "**X**" in Fig. 5.7.

Table 5.3 shows the demand reduction matrix sent to the Coordinator agent. An extra column (*Displaced to hour*) has been added in Table 5.3 which shows the hour to which the EV demand would be displaced.

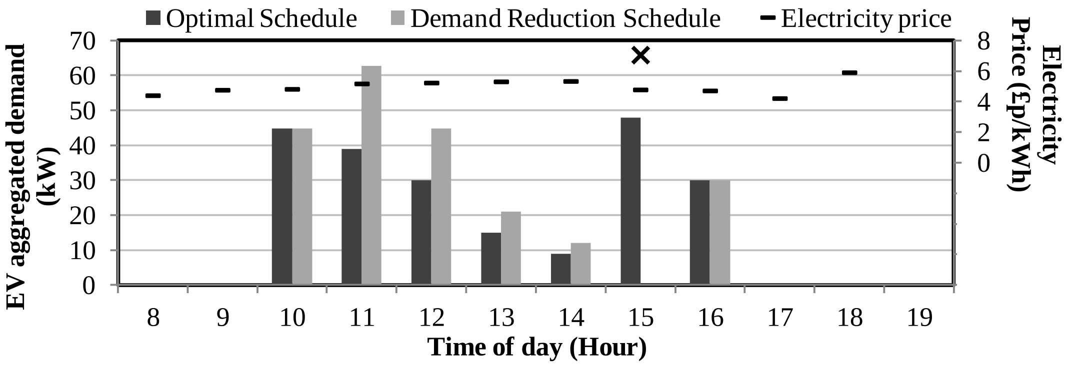

Fig. 5.7 Optimal Schedule and Demand Reduction Schedule comparison

Table 5.3 Demand reduction matrix example

Number of EVs (Units)	Power Rating (kW)	Electricity Price (£p/kWh)	Displaced to Hour
8	2.99	5.13	11
5	2.99	5.19	12
2	2.99	5.27	13
1	2.99	5.29	14

After receiving the accepted demand reduction (D_a) from the Coordinator agent, the Local Area agent defines its maximum demand (L_{LA}) at the hour for which the reduction was requested (tr) with equation (5.5).

$$L_{LA\,tr} = D_{fLA\,tr} - D_{a\,tr} \tag{5.5}$$

Where:

tr is the time interval (hour) for which the demand reduction was requested,

D_{fLA} is the forecasted EV aggregated demand of the Local Area agent in kW and

Da is the accepted demand reduction from the Coordinator agent in kW.

In order to satisfy the demand reduction accepted by the Coordinator agent, the Local Area agent adds the Local Area agent maximum demand (L_{LA}) as a constraint in the optimisations run at the following Scheduling Periods with equation (5.6).

$$\sum_{n=1}^{N} P_{n\,tr} \leq L_{LA\,tr} \tag{5.6}$$

Where:

n is the EV,

N is the total number of EVs connected to the Local Area agent,

P_n is the power rating of each EV n in kW and

L_{LA} is the defined maximum demand set by the Local Area agent after the accepted demand reduction from the Coordinator agent, equation (5.5).

5.6.2 Coordinator Agent

The process followed by the Coordinator agent during the provision of demand reduction service is as follows:

i) Requests the demand reduction capabilities from the Local Area agents for a specific hour.

ii) Receives from the Local Area agents a matrix with the reduction capabilities and the associated cost (demand reduction matrix).

iii) Calculates the optimal combination in order to achieve the targeted demand reduction.

iv) Informs with the output of the optimisation to the respective Local Area agents.

The process followed by the Coordinator agent during the provision of demand reduction service is shown in Fig. 5.8.

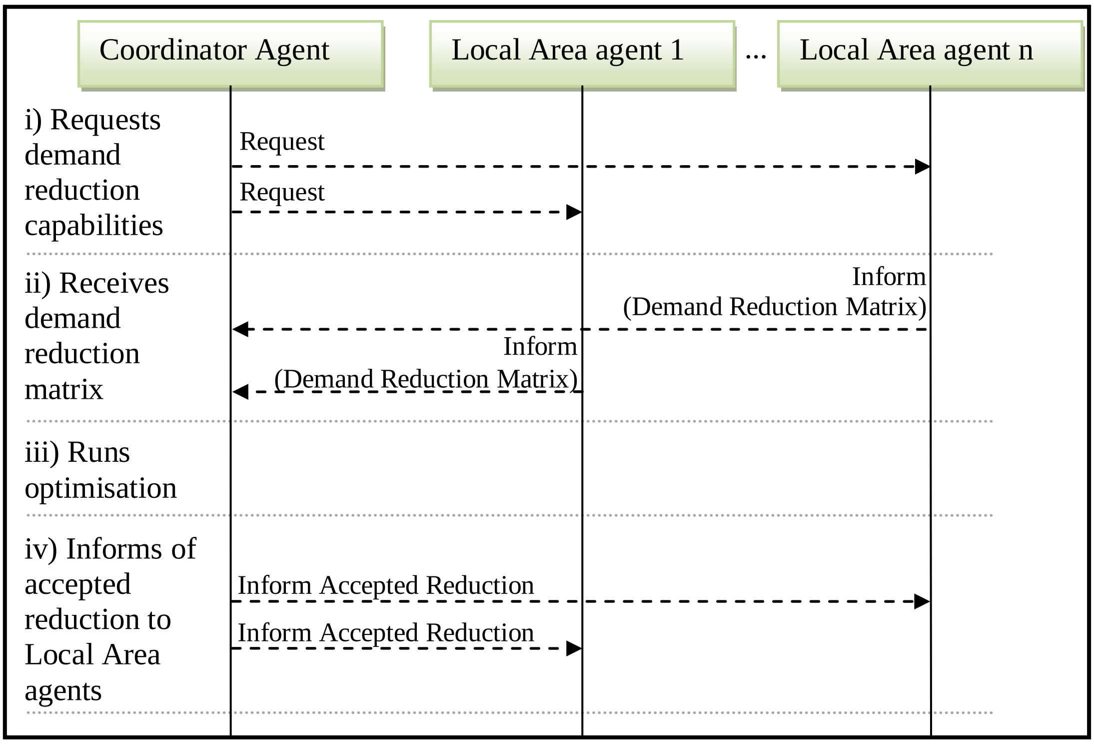

Fig. 5.8 Demand reduction service sequence diagram

Based on the demand reduction matrices received from the Local Area agents, the Coordinator agent finds the optimal combination in order to achieve the desired reduction target at the minimum cost. The optimisation is done with the Linear Programming (LP) solver IBM ILOG CPLEX [169]. The objective function is formulated as follows:

$$minimise\ Z = \sum_{a=1}^{A} \sum_{m=1}^{aM} (X_{am} \times P_{am} \times 1\text{h}) \times p_{am} \tag{5.7}$$

Where:

a is the identifier of each Local Area agent,

A is the number of Local Area agents,

m is each of the different offers of the Local Area agent (each row of the demand reduction matrix, Table 5.2),

aM is the number of different offers of each Local Area agent a (total number of rows of the demand reduction matrix, Table 5.2),

p_{am} is the electricity price in £/kWh of the hour to where the demand is displaced,

P_{am} is the power rating in kW,

h is hour and

X_{am} is the EV (units) with a power rating of P_{am} and an associated cost of p_{am}. (Outcome of the optimisation).

Subject to:

$$X_{am} \leq N_{am} \tag{5.8}$$

$$\sum_{a=1}^{A} \sum_{m=1}^{aM} (X_{am} \times P_{am}) \geq D_R \tag{5.9}$$

Where:

N_{am} is the number of EVs (units) offered by the Local Area agent with a power rating of P_{am} and an associated cost of p_{am} (Table 5.2) and

D_R is the targeted demand reduction set by the Coordinator agent in kW.

The information sent by the Coordinator agent to each Local Area agent is their accepted demand reduction (Da) for the requested hour in kW.

5.7 SUMMARY

A Multi-Agent System for the management of EV battery charging was presented. The Multi-Agent System is composed of:

i) The Electric Vehicle aggregator, which comprises three types of agents:

- EV agent, located in the EV.
- Local Area agent, located at the MV/LV substation level.
- Coordinator agent, located at the HV/MV substation level.

ii) The Distribution System Operator (DSO), which comprises one type of agent:

- DSO agent, located at the HV/MV substation level.

The operation of the Multi-Agent System was presented for the two operational modes considered:

i) Normal operation: The distribution network is operated within voltage limits, transformers loading limits and cables loading limits. The aim of the MAS is to satisfy the EV owners demand at the minimum cost.

ii) Emergency operation: The voltage limits are violated and/or transformers and cables are overloaded. The aim of the MAS is to restore the distribution network to normal operation conditions through the curtailment of EVs.

Finally, the provision of demand reduction by the Local Area agents after a demand reduction request from the Coordinator agent is presented for the proposed Multi-Agent System.

Chapter 6

Management of Electric Vehicle Battery Charging with a Multi-Agent System: Laboratory Demonstration

6.1 Introduction

The operation of the Multi-Agent System proposed in Chapter 5 has been demonstrated through a set of laboratory experiments. The experimental work was undertaken at the facilities of Tecnalia research center [153] in Bilbao, Spain.

The micro-grid at Tecnalia's facilities was used to perform the experiments. The micro-grid topology for demonstrating the operation of the Multi-Agent System was set up in collaboration with Tecnalia's staff.

This work was undertaken within the framework of the EU FP7 project Distributed Energy Resources Research Infrastructures (DERri) [135]. The project was developed in collaboration with a colleague PhD student. The fact sheet of the deliverable can be found in [136].

6.2 Laboratory Setup

The objective was to configure a laboratory-scale setup of a Local LV area. The modelled area was the LV side of a MV/LV substation of the UK generic distribution network [159], where the residential load was replaced by a lumped load of a workplace and EV charging points. The EV load was managed by a Local Area agent, as shown in Fig. 6.1.

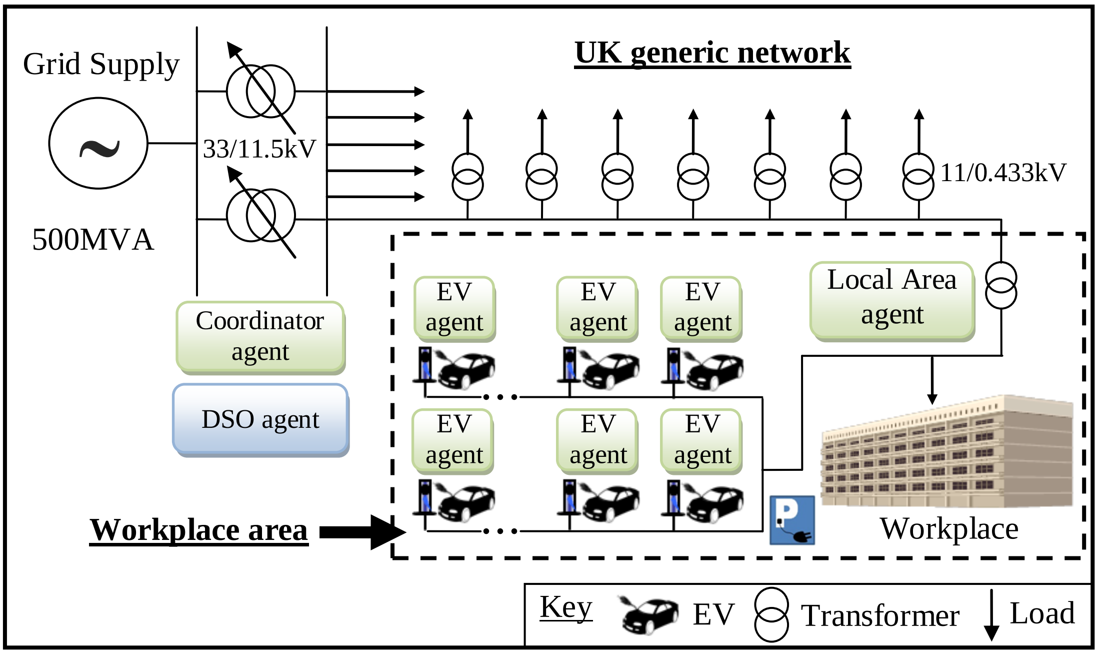

Fig. 6.1 UK generic network and workplace area modelled in the laboratory

6.2.1 Tecnalia Laboratory Resources Used

The laboratory consists of a micro-grid where different Distributed Energy Resources (DERs) can be connected to, for testing purposes. The laboratory DERs can be found in [181]. The resources used for the experiments were:

A) Tecnalia's micro-grid.

B) Avtron K595 resistive load bank.

C) Avtron Millennium resistive load bank.

D) GaugeTech DMMS300 meter.

E) EV-ON platform.

F) Communication Services for Distributed Energy Resources (CSDER) software.

A) Tecnalia's Micro-grid

Tecnalia's micro-grid is a three phase LV micro-grid (400V, 50Hz) coupled to the main grid through two 1250kVA transformers. It can be operated in islanded or grid connected mode. The experiments were conducted in grid connected mode. The DER resources are connected to the micro-grid through a switchboard, which allows the configuration of different network topologies.

B) Avtron K595 Resistive Load Bank

The Avtron K595 resistive load bank has a maximum load of 38.61kW. It comprises 7 independent load steps of: 0.35, 0.75, 1.39, 2.78, 5.56, 11.11 and 16.67kW. It has a three phase connection to the micro-grid's switchboard.

Fig. 6.2 Tecnalia's Avtron K595 resistive load bank

The role of the Avtron K595 load bank was to simulate part of the load of the workplace and the connected EVs. The full load was simulated by combining the Avtron K595 load bank with the Avtron Millennium load bank. This was achieved through the Load Bank Controller agent presented in Section 6.2.2.

C) Avtron Millennium Resistive Load Bank

The Avtron Millennium resistive load bank has a maximum load of 150kW. It comprises 6 independent load steps of: 5.0, 10.0, 10.0, 25.0, 50.0 and 50.0kW. It has a three phase connection to the micro-grid's switchboard.

Fig. 6.3 Tecnalia's Avtron Millennium resistive load bank

D) GaugeTech DMMS300 Meter

The GaugeTech DMMS300 meter provides real power, reactive power and voltage measurements. It provides a graphical interface for measurement readings as well as connections to transfer data to a monitoring system. It is connected to the switchboard busbar.

Fig. 6.4 GaugeTech DMMS300 meter

The role of the GaugeTech DMMS300 meter was to transfer the measurements to the Multi-Agent System in order to monitor the loading conditions of the micro-grid.

E) Communication Services for Distributed Energy Resources (CSDER) Software

The CSDER is a communication software module developed at Tecnalia for the EU project More Microgrids [182]. It translates the communication protocols of the different DERs to a form of the IEC 61850 based protocol [182].

The CSDER *"enables the easy integration of different devices into the micro-grid by just developing the specific communication component adapter to the gateway software*" [183]. The CSDER was implemented in JAVA^{TM} and therefore was readily usable for the MAS testing.

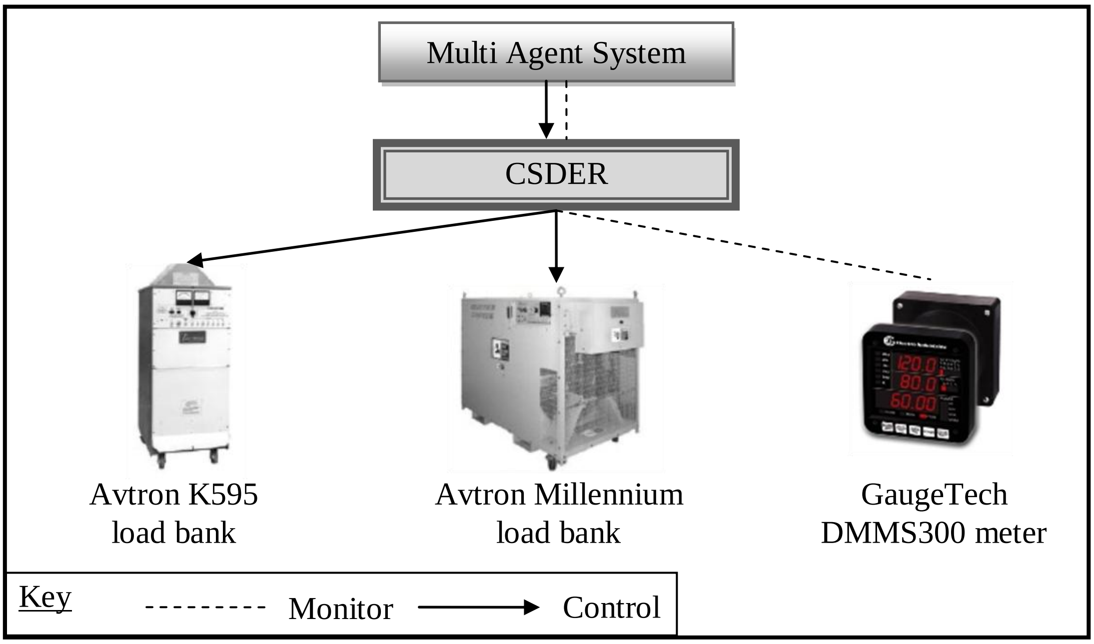

Fig. 6.5 CSDER as gateway between the MAS and the laboratory resources [184]-[186]

The role of the CSDER was to act as gateway between the Tecnalia laboratory resources used and the Multi-Agent System. Through the CSDER, the MAS was able to monitor the GaugeTech DMMS300 meter, and to control the load banks, as shown in Fig. 6.5.

F) EV-ON Platform

The aim of the EV-ON platform developed at Tecnalia Laboratory is the development and implementation of EV smart charging algorithms [187]. The platform (Fig. 6.6) comprises two separate packages (hardware and software), each of them emulating:

i) An EV charging point.

ii) The charging system of a vehicle.

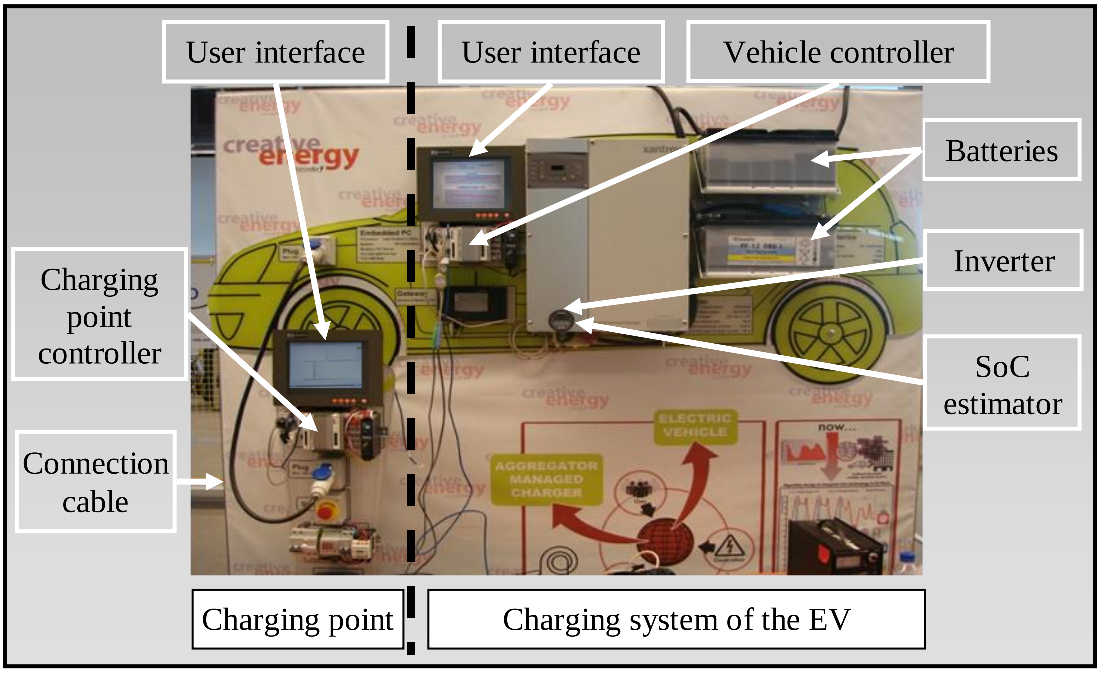

Fig. 6.6 EV-ON platform

The EV charging schedules are set through the user interface module of the charging point [98], hence the smart charging algorithms are implemented in the charging point. The charging system of the EV emulates a simplified Battery Management System (BMS), where information from the battery (such as SoC, voltage or current values) can be retrieved and commands can be sent (charging set points).

The role of the EV-ON platform during the experiments was to simulate a single EV.

The platform was developed using commercial hardware, the components used in the experiments are presented in Table 6.1.

Table 6.1 EV-ON platform hardware components used [187]

Charging System of the EV	
Controller	Industrial embedded PC (Beckhoff CX 1030) with Windows XP embedded operating system.
Plug	SCAME (Libera series for EVs).
User interface	Axiomtek PANEL 6100-O/P 10.4. Industrial Thin Film Transistor-Liquid Crystal Display (TFT-LCD) monitor with touch screen.
SoC estimator	Xantrex DC-LINK PRO
Inverter	Xantrex SW4024. Standard battery inverter.
Batteries	Classic™ FF 12 080 2. Standard vented Pb batteries.
Charging Point	
Controller	Industrial embedded PC (Beckhoff CX 1030) with Windows XP embedded operating system.
Plug	SCAME (Libera series for EVs).
User interface	Axiomtek PANEL 6100-O/P 10.4. Industrial TFT-LCD monitor with touch screen.

6.2.2 Multi-Agent System Adaptation to Laboratory Resources

The MAS was adapted to the laboratory resources, the MAS adjustments included the following:

A) Adaptation of EV-ON Platform's Software to an EV Agent

An EV agent was adapted to the EV-ON platform. The EV agent was configured in order to acquire measurements from the SoC estimator, and to transfer the charging set points received from the Local Area agent (in case of emergency from the DSO agent) to the battery inverter.

The EV-ON platform software (charging point and charging system of the vehicle) are implemented in JAVA™, being readily usable with the Multi-Agent System.

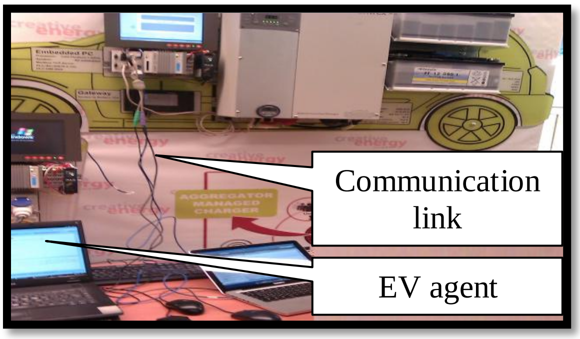

Fig. 6.7 EV agent adapted to the EV-ON platform

B) DSO Agent Adaptation

The DSO agent was configured to retrieve the measurements from the GaugeTech DMMS300 meter, through the CSDER. The CSDER software is also implemented in JAVA^{TM}, and hence compatible with the Multi-Agent System.

A data acquisition loop was developed using the JADE ready-made class TickerBehaviour [188]. The GaugeTech measurements were monitored through the DSO agent. If a network violation was detected, a curtailment instruction was sent to the load banks through the Load Bank Controller agent, as described in the following section.

The power flows performed by the DSO agent used the simulated UK generic network (Fig. 6.1), where the workplace and the EV loads were considered as a lumped load downstream of the MV/LV substation.

C) Load Bank Controller Agent Development

The Load Bank Controller agent was developed for the laboratory testing. The purpose of the agent was to calculate the combination of load bank steps that should be on, in order to achieve the desired system loading conditions at every time interval: workplace load plus EV aggregated demand. The EV loading conditions set by the Local Area agent were transferred, at each Operational Period, to the load banks through the Load Bank Controller agent. Similarly, in case of emergency, the DSO agent curtailed the EV loading through the Load Bank Controller agent. The commands were sent to the load banks through the CSDER gateway.

The Load Bank Controller agent calculated the combination of the 13 independent load steps (7 from the Avtron K595 and 6 from the Avtron Millennium load banks) which gave the closest value to the desired demand values.

The workplace demand was input at the Load Bank Controller agent prior to each experiment. At the beginning of each Operational Period, the Load Bank Controller agent read the workplace demand of the corresponding time interval and received the aggregated EV demand from the Local Area agent.

Prior to the calculation of the load steps combination, the Load Bank Controller agent applied a demand scaling factor. The demand scaling factor was required to scale down the simulated local area demand to the laboratory load banks capacity. The demand scaling factor (DS_f) was obtained with equation (6.1).

$$DS_f = \frac{P_{LA}^{Max}}{P_{lab}^{Max}} = \frac{785.90\,\text{kW}}{188.61\,\text{kW}} = 4.17 \qquad (6.1)$$

Where:

P_{LA}^{Max} is the maximum load demand that can be achieved in the simulated Local Area during the experiments. It equals the sum of the workplace maximum demand and the maximum EV demand, and

P_{lab}^{Max} is the maximum load demand that can be achieved combining both resistive load banks.

The process followed to set the load steps at the load banks according to the loading conditions during normal operation is shown in Fig. 6.8.

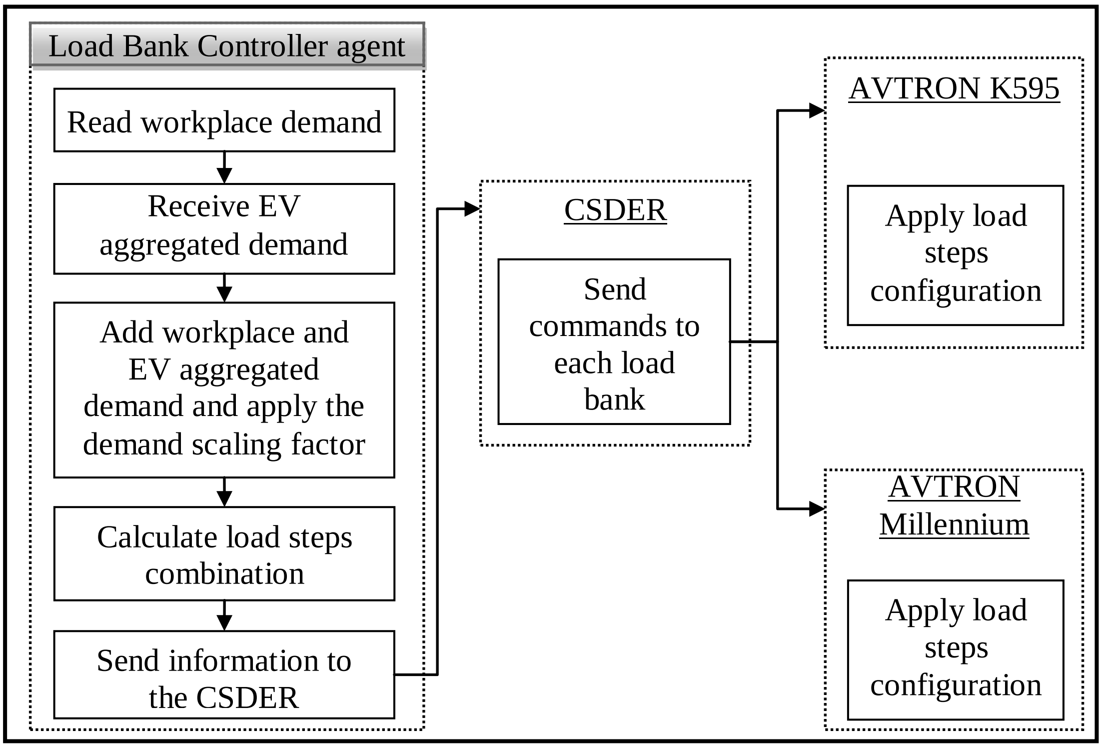

Fig. 6.8 Process to set the system's loading conditions at each Operational Period

In case of an emergency situation, the steps followed by the Load Bank Controller agent were the following:

i) Receive the demand that needs to be reduced from the DSO agent (i.e. demand of the EV being curtailed).

ii) Subtract the received demand from the actual Local Area demand and apply the demand scaling factor.

iii) Calculate the combination of the load steps.

iv) Send the load steps configuration to the respective load banks through the CSDER.

In APPENDIX B two examples are provided for the load steps calculation during normal operation and emergency operation.

6.2.3 Laboratory Configuration

In Fig. 6.9 the laboratory configuration is shown, which consisted of:

i) The laboratory equipment, which are the resources mentioned in the previous sub-sections.

ii) The CSDER gateway. The server hosting the CSDER was installed in the Tecnalia research center facilities. Ethernet connections were available within the DER laboratoty.

iii) The control system, formed by the Multi-Agent System components. The Multi-Agent System was hosted in one computer and comprised:

- 60 EV agents, one EV agent being adapted to the EV-ON platform software.
- One Local Area agent.
- One Coordinator agent.
- One DSO agent.

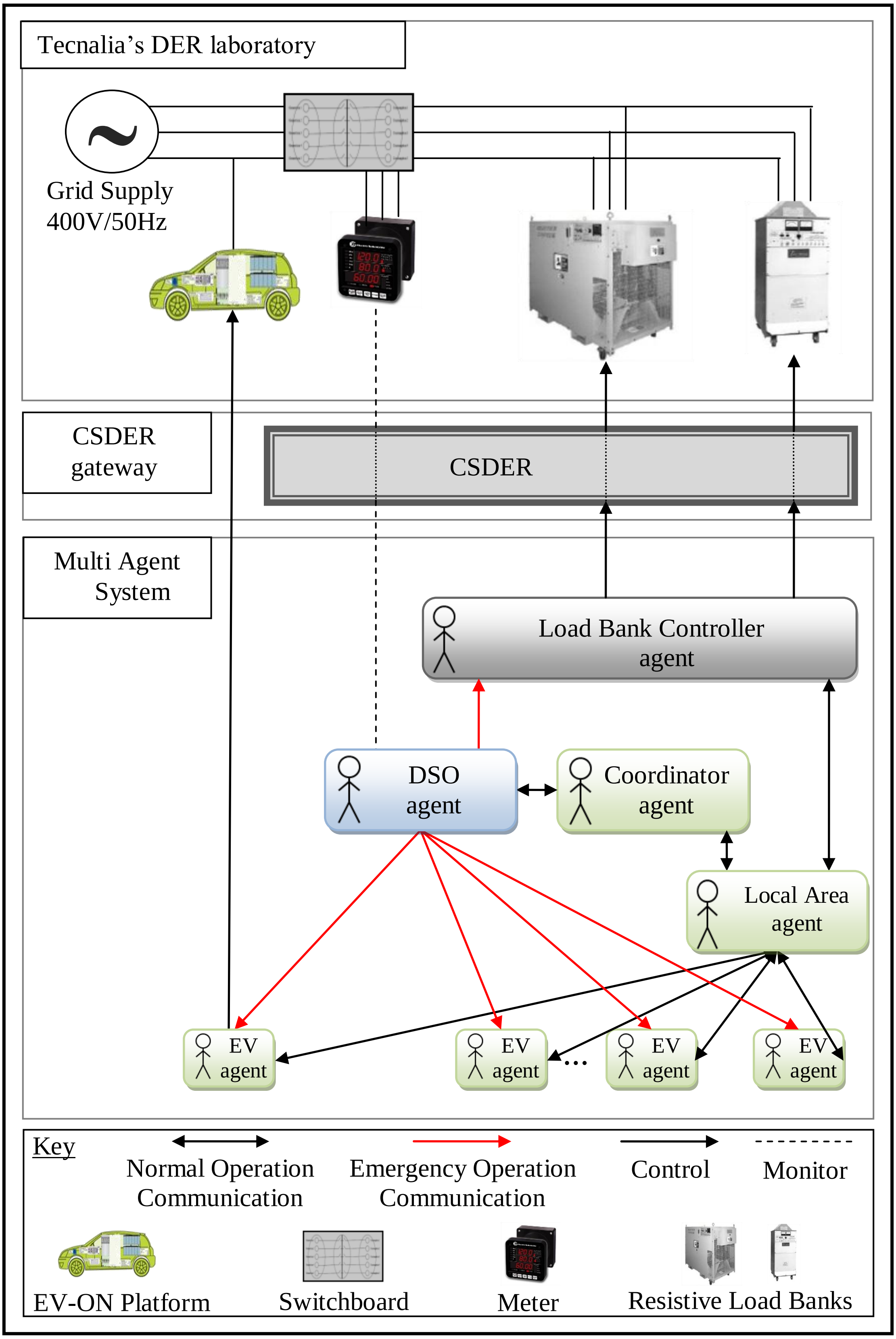

Fig. 6.9 Laboratory network configuration used for the experiments

6.3 EXPERIMENTAL PROCEDURE

6.3.1 Experiments Input Data and Assumptions

A case study for the year 2030 was tested. An office building with a parking facility with charging points for EVs was considered.

Office load: The office load profile was obtained from [189]. In the UK each employee occupies on average 15m^2, according to [190]. A maximum average value of 60W power demand is accounted for each m^2 in medium size offices (2000-10000m^2) [191]. Finally, a yearly load increase of 1% was considered, similar to that of residential areas [192]. Assuming an office of 500 employees, the profile was scaled to a maximum value of 606.5kW.

EV uptake: The EV uptake used was the low EV uptake levels defined in [3] for the year 2030, which results approximately in a 12% share of the vehicles according to [94]. From the EV share, 66% were PHEVs and 33% BEVs [94]. Since 500 employees were assumed, 60 EVs were considered (40 PHEVs and 20 BEVs).

EV demand: All the EVs were assumed to require the same energy based on average travelled distances. The daily energy requirements were obtained from 2030 data projections from [3]. The used data and the calculated daily energy requirements are shown in Table 6.2.

Table 6.2 EV daily energy requirements based on 2030 projections from [3]

Average annual vehicle distance travelled	21.331 km
Daily average distance	58.44 km
Vehicle efficiency	0.11kWh/km
Daily energy requirement	**6.42kWh**

EVs arrival and departure time: All the EVs were assumed to arrive at the office between 8 a.m. and 10 a.m. The commuting peak time in the UK is around 8:30 according to [193], the assumed arrival time peak was at 9 a.m. In the same document [193], the difference between the morning and the evening commuting peak is of eight hours, hence a connection of eight hours was assumed for all EVs. The arrival time distribution used in the experiments is shown in Table 6.3.

Table 6.3 EVs arrival and departure time distribution

PHEVs	BEVs	Arrival Time	Departure Time
15	-	8:00	16:00
10	20	9:00	17:00
15	-	10:00	18:00

EV characteristics: The PHEVs were assumed to have a battery of 9kWh and the BEVs of 35kWh [3]. The initial SoC assigned to the PHEVs and the BEVS was 20%. The charger's efficiency was of 87% [173] and the EV battery charging efficiency 85% [174].

Electricity prices: The electricity prices considered were the winter hourly average electricity prices of 2010 drawn from [194].

6.3.2 Experimental Parameters

The technical constraint considered in the experiments was the transformer's rating (scaled), the transformer was assumed to have a 700kVA loading capacity. For the purpose of the experiments the value was scaled down to 167.8kW, using the demand scaling factor.

Each experiment consisted of 24 hourly time intervals. The hourly time intervals were scaled to one minute time intervals in order to emulate the behaviour of a lithium-ion battery, using the lead-acid batteries in the EV-ON platform. For low duration time intervals the charging behaviour of the EV-ON platform batteries at 13A and 230V, were found empirically to have a comparable behaviour to that of a lithium-ion battery (i.e. constant power consumption).

6.3.3 Micro-Grid Emulator

Tecnalia's micro-grid emulator is a JAVA™ based software which includes the CSDER emulator and those laboratory resources which can be mapped through the CSDER.

The Multi-Agent System was tested in the first place using the micro-grid emulator. The results obtained with the micro-grid emulator were then used to compare and validate the laboratory experiments. The Multi-Agent System and the micro-grid emulator were hosted in one computer as shown in Fig. 6.10.

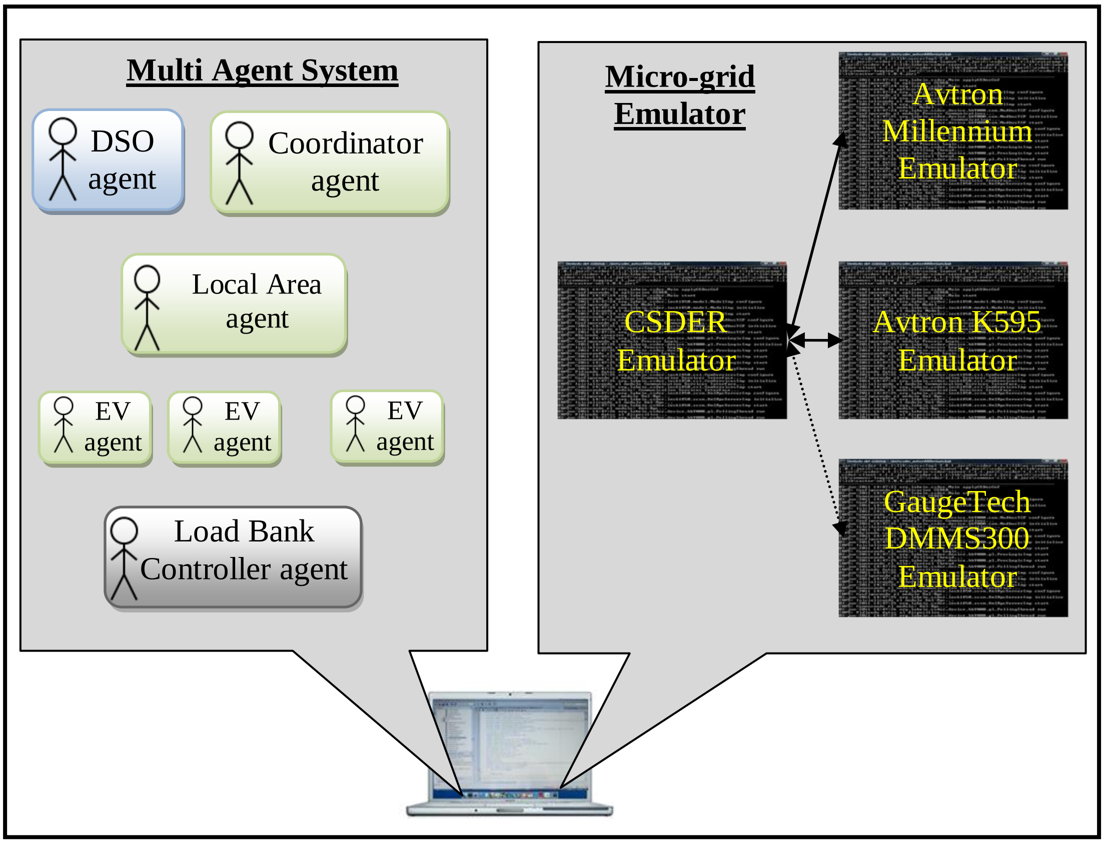

Fig. 6.10 Multi-Agent System using the micro-grid emulator

The power dissipation of Tecnalia's laboratory load banks steps is defined according to a rated voltage of 400V. Therefore voltage deviations from the rated values at the load banks terminals affect the actual power being dissipated. Tecnalia's load bank emulators do not consider the voltage applied at their terminals, and the power dissipated depends only on the load steps position (on/off). This means that the capacity of each load step is defined considering the rated voltage value of 400V independently of the voltage values at the micro-grid emulator. The voltage measurements at the switchboard during the experiments were always below 400V (average voltage value of 388V). For this reason the real power measurements obtained from the laboratory GaugeTech DMMS300 meter, were below to those obtained with the micro-grid emulator for all experiments, as shown in Fig. 6.11, Fig. 6.12, Fig. 6.13 and Fig. 6.15.

6.4 Experiments

The experiments completed in order to evaluate the Multi-Agent System were the following:

i) Validated operation.

ii) Technical invalidation.

iii) Emergency operation.

iv) Demand reduction service.

For each experiment two sets of results are shown. Each set of results was obtained using:

i) Tecnalia's micro-grid emulator.

ii) Tecnalia's laboratory resources presented in Section 6.2.1.

The demand profile of the EV agent adapted to the EV-ON platform is shown. The EV agent adapted to the platform represented a PHEV, connected at 10:00.

6.4.1 Validated Operation Experiment

The aim of this experiment was to evaluate the behaviour of the control system under normal operating conditions (i.e. no technical constraints violations) and where the network capacity limits remained unaltered due to the absence of a technical invalidation from the DSO agent. The results are shown in Fig. 6.11. On the left axis the *Emulator Measurements* (black line) and the *Laboratory Measurements* (grey line) show the total demand (EV aggregated demand plus office demand) at the transformer's level, the grey area shows the office demand. On the right axis, the black dotted line shows the electricity prices; on the bottom right the green line shows the EV-ON demand.

The results show how the total demand did not exceed the transformer loading limit. The demand was satisfied for all EVs. The simulated EV of the EV-ON platform was assigned to charge during the time intervals (13:00 to 16:00), as shown in Fig. 6.11.

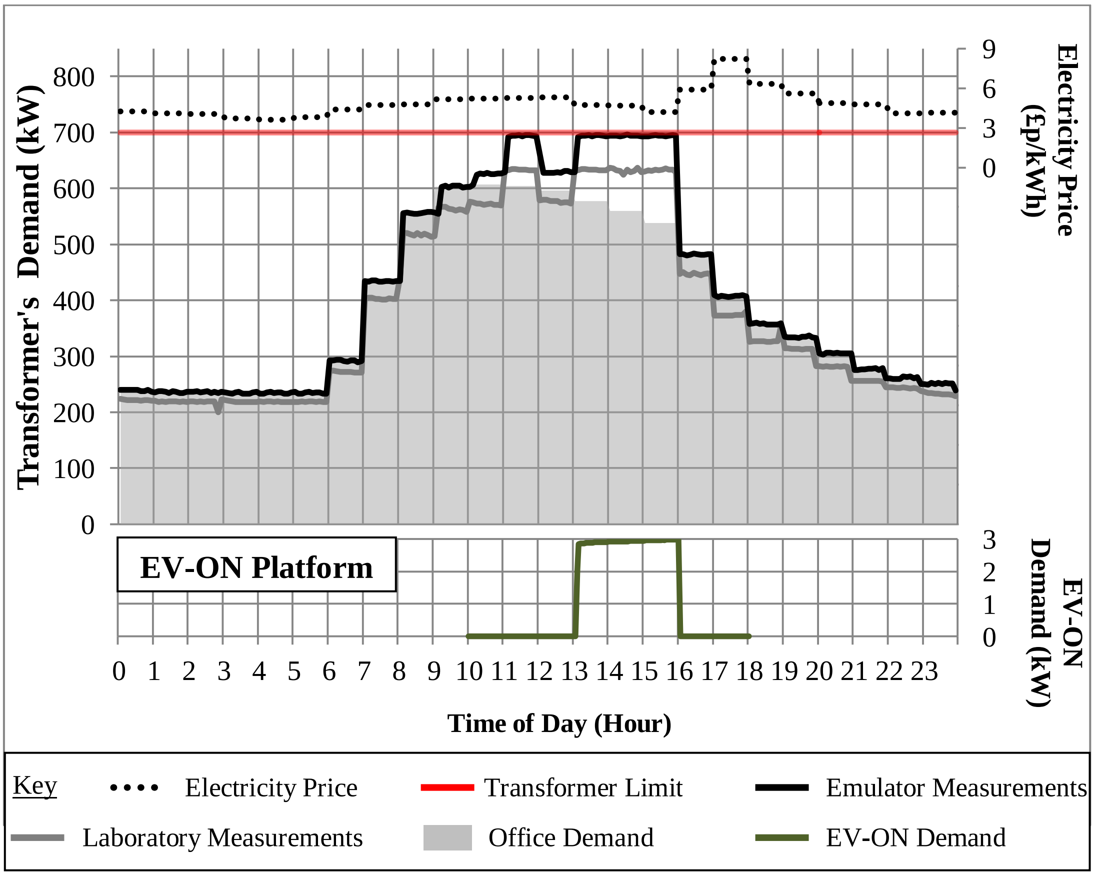

Fig. 6.11 Results of the experiment: Validated operation

6.4.2 Technical Invalidation Experiment

The aim of this experiment was to evaluate the behaviour of the control system under normal operating conditions, with the EV charging set points not being validated at a specific Operational Period by the DSO agent.

A technical invalidation was set by manually increasing the forecasted office load for an Operational Period at the DSO agent (prior to technical validation), emulating a short term forecasted demand increase. The demand was increased by 50kW for the Operational Period 15:00 to 16:00, and it is represented with the magenta area in Fig. 6.12.

In Fig. 6.12, it can be seen that the technical invalidation caused the EV aggregated demand to be displaced to the cheapest time interval for which the EVs were still connected (16:00 to 17:00). A total of 17 EVs were rescheduled. The total demand did not exceed the transformer loading limit. The demand was satisfied for all EVs.

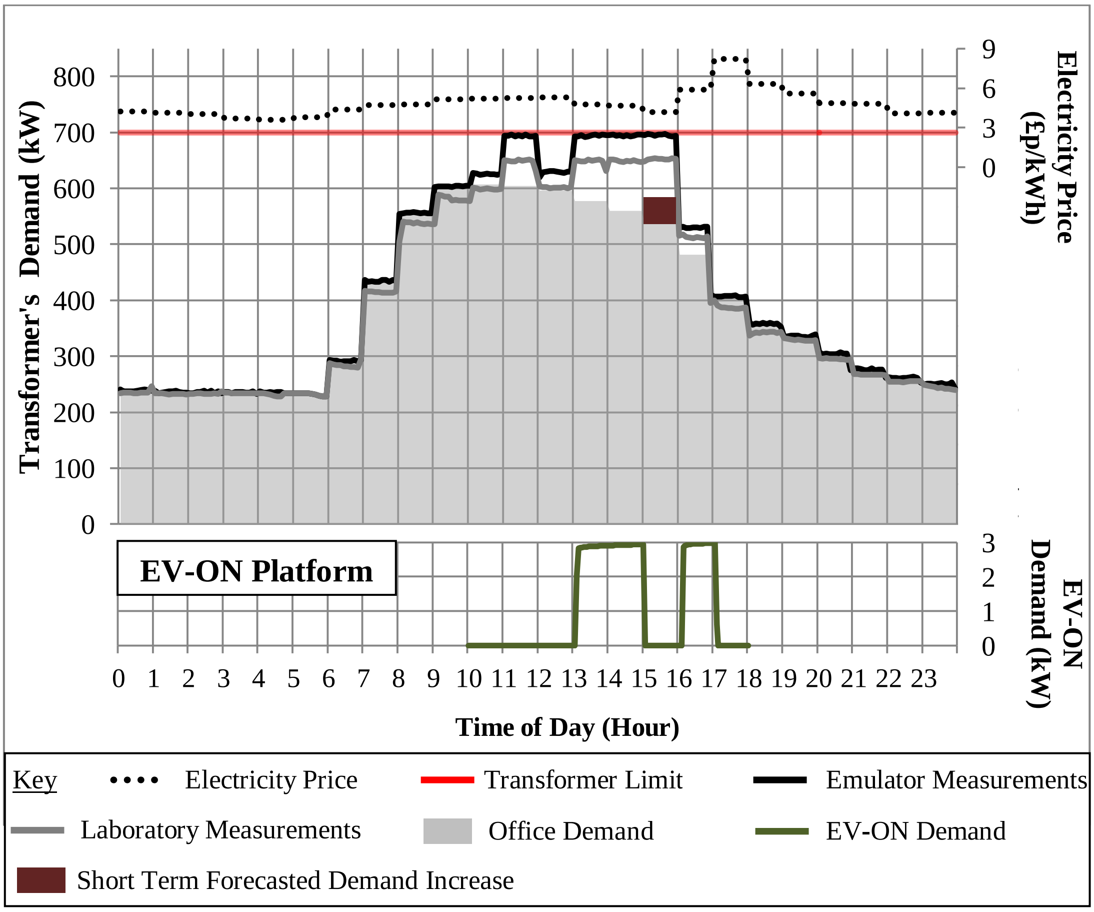

Fig. 6.12 Results of the experiment: Technical invalidation

The Local Area agent was manually instructed to select the EV agent adapted to the EV-ON platform after the technical invalidation occurred. Thus the EV agent adapted to the EV-ON platform belonged to the group of EVs which demand was displaced to time interval 16:00 to 17:00, as shown in Fig. 6.12.

6.4.3 Emergency Operation Experiment

The aim of this experiment was to evaluate the behaviour of the control system after a network constraint violation (transformer overloading for the purpose of the experiments).

The emergency situation was generated by modifying the workplace loading data from the Load Bank Controller agent at time interval 14:00 to 15:00, emulating an unforeseen increase of demand. Since this time interval was already close to the transformer limit, a load increase caused a transformer's limit violation. For the simulations run with the emulator, at time interval 14:00 to 15:00 the office loading value was increased by 15kW (magenta area in Fig. 6.13). Due to the difference between the emulator's loading values and the laboratory values, during the laboratory experiments the office load was increased by 55kW (magenta plus dark grey area in Fig. 6.13) in order to achieve a loading value higher than the transformer limit. The results are shown in Fig. 6.13.

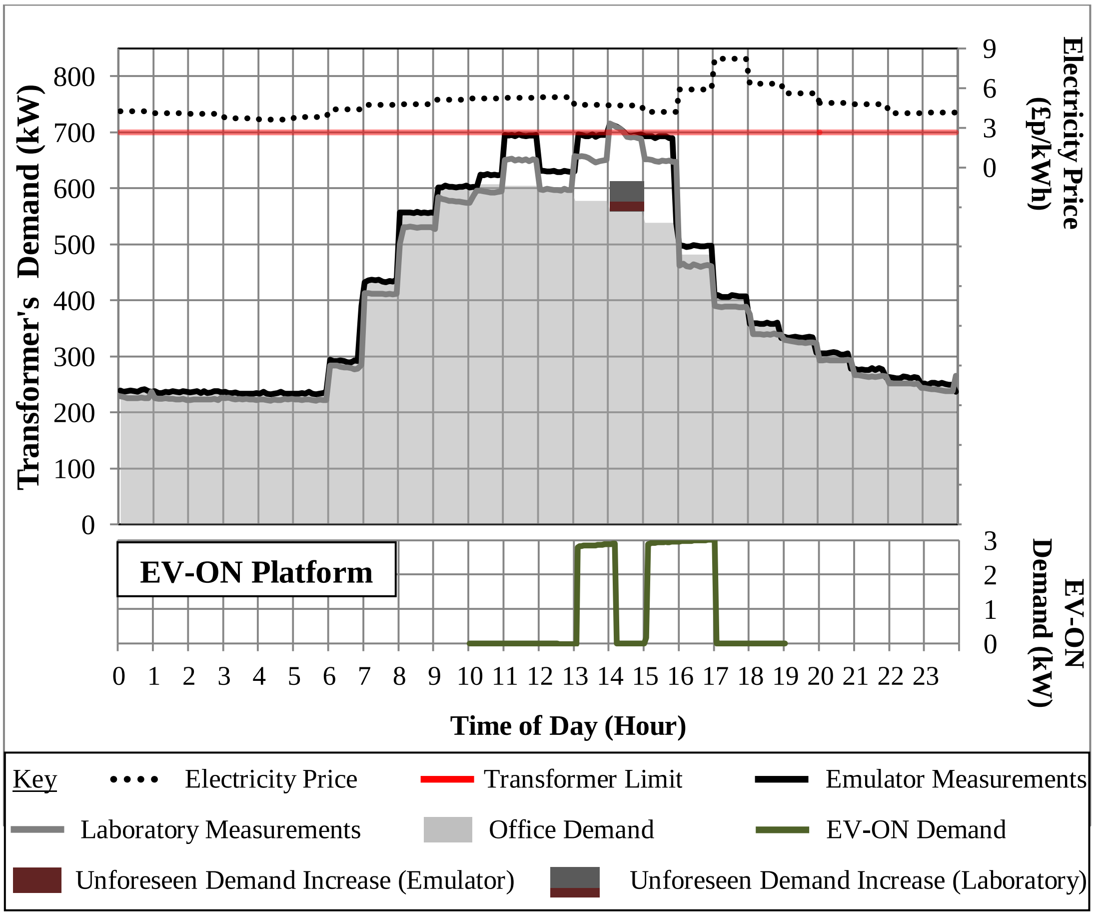

Fig. 6.13 Results of the experiment: Emergency operation

From Fig. 6.13 it can be seen how the transformer loading limit was breached at time interval 14:00 to 15:00, and through the curtailment of EVs the system was restored to normal operating conditions. Six EVs were curtailed. The load of the curtailed EVs was displaced to time interval 16:00 to 17:00. The EVs curtailed belonged to the group of EVs which departure time was at 18:00 since they had the highest Curtailment factors. As described in Chapter 5, the DSO agent curtails the EVs with the highest Curtailment factors (i.e. more idle hours scheduled).

The departure time of the EV agent adapted to the EV-ON platform was delayed in one hour, in such way it had the highest Curtailment factor and was selected to be curtailed, as shown in Fig. 6.13.

6.4.4 Demand Reduction Service Experiment

The aim of this experiment was to evaluate the behaviour of the control system when providing active demand service in the form of demand reduction.

A demand reduction was requested by the Coordinator agent to the Local Area agent at time interval 11:00 to 12:00, for time interval 15:00 to 16:00.

As mentioned in Chapter 5, the Local Area agent sets its reduction offer by comparing the *Optimal Schedule* with the *Demand Reduction Schedule* (optimal EV aggregated demand with the minimum load assigned at the required time interval). In Fig. 6.14 the comparison done at the Local Area agent is shown. The demand reduction matrix sent to the Coordinator agent is shown in Table 6.4.

The demand could not be displaced to time intervals 13:00 to 14:00 and 14:00 to 15:00, since an increase in demand would cause a transformer loading limit violation, as shown in Fig. 6.15.

The targeted demand reduction at the Coordinator agent was arbitrarily set to 50kW, hence 17 EVs needed to be re-scheduled (17×2.99kW=50.83kW).

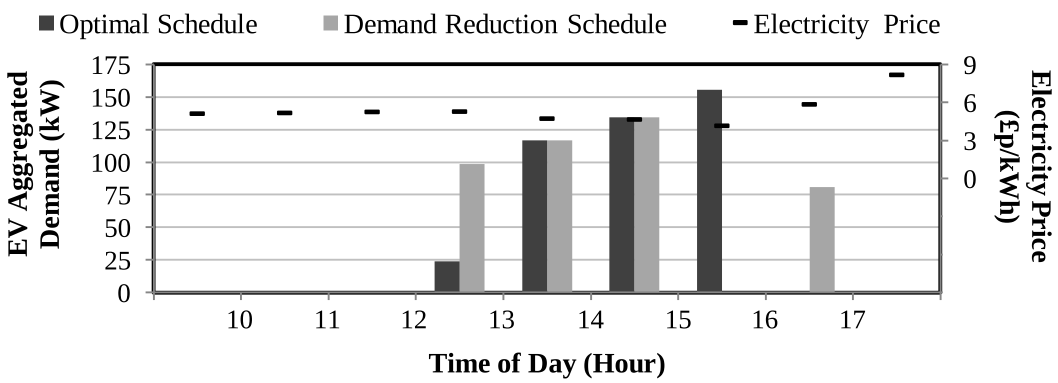

Fig. 6.14 Demand reduction offer calculation at the Local Area agent

Table 6.4 Demand reduction matrix sent to the Coordinator agent

EV (Units)	Power Rating (kW)	Cost (£p/kWh)
25	2.99	5.29 (time interval 12)
27	2.99	5.86 (time interval 16)

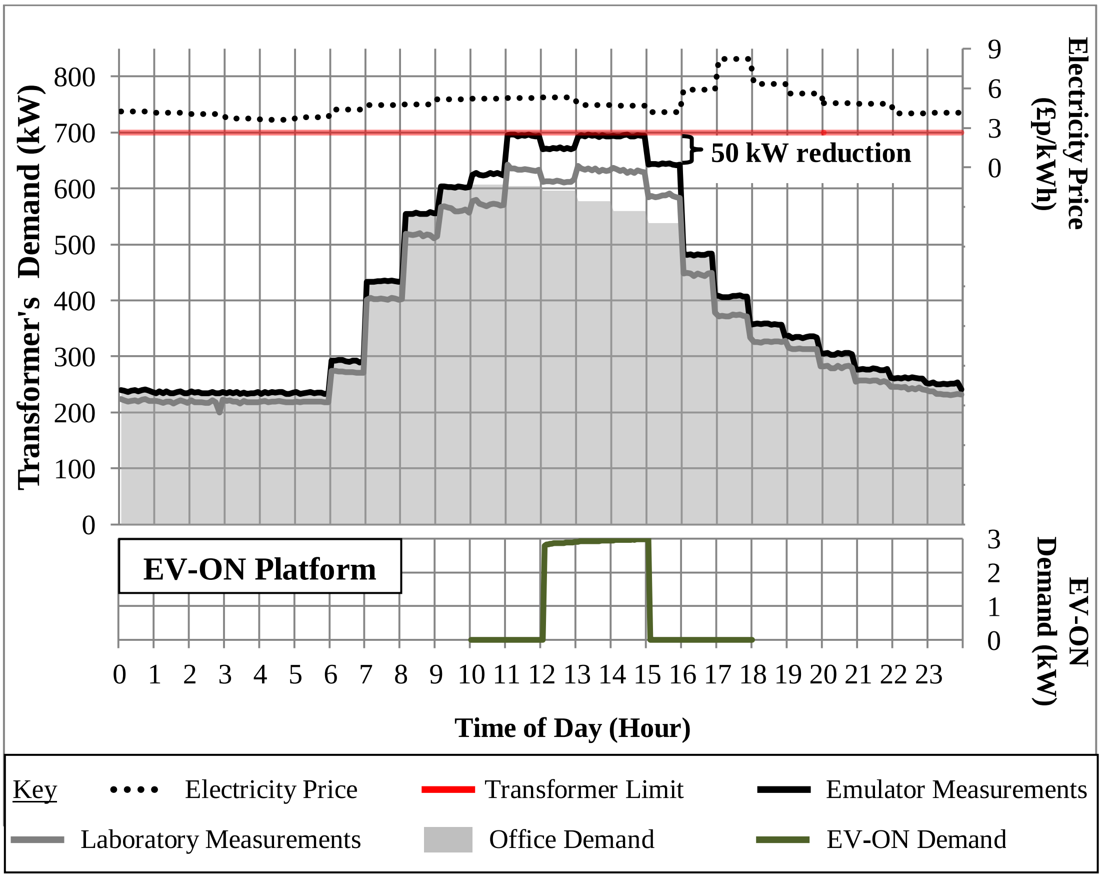

Fig. 6.15 Results of the experiment: Demand reduction service

From Fig. 6.15 it can be seen how a reduction of 50kW was achieved at time interval 15:00 to 16:00. Due to the demand reduction, the EV demand of 17 EVs was displaced to time interval 12:00 to 13:00, which included the EV agent adapted to the EV-ON platform.

6.5 Summary

The operation of the Multi-Agent System that was presented in Chapter 5 was demonstrated experimentally through a set of four experiments at Tecnalia's research laboratory facilities.

The main purpose of the tests was to verify that the control system was able to operate under real (laboratory) conditions, through a laboratory-scale setup, using real hardware and communications software.

A LV area of a distribution network was emulated using Tecnalia's micro-grid. A 500 employee office with 60 EV charging points was managed by a Local Area agent, located at the MV/LV substation level. An agent was developed specifically for the laboratory implementation, the Load Bank Controller agent, which was required in order to set the system loading conditions.

Four experiments were described and demonstrated in the laboratory facilities of Tecnalia, which showed the capabilities of the MAS to:

i) Manage the EV charging schedules according to electricity prices and network constraints.

ii) Adapt the charging schedules after a short term forecast load increase (Technical invalidation experiment).

iii) Reduce EV loading conditions in case of emergency situation, restoring the system to normal operation conditions (Emergency experiment).

iv) Provide demand reduction if requested by the Coordinator agent (Demand reduction service experiment).

In order to move from the laboratory work towards a real implementation, different aspects would need to be considered such as: market regulatory framework for the participation of EV aggregators, accepted latencies in communication infrastructure, interoperability with legacy systems, or contractual aspects among existing and new power systems' stakeholders.

Chapter 7

Conclusions and Future Work

This thesis investigated the management of electric vehicle battery charging in distribution networks. Different EV fleet sizes and network locations were considered:

- EVs located in residential, low voltage energy balanced areas with micro-generation.
- EVs clustered in commercial-industrial areas.
- EVs dispersed in distribution networks.

7.1 Contributions

The main contributions of this thesis are summarised:

- The requirements of an energy storage system's capacity and a backup generator's energy to achieve energy balanced LV areas were calculated. The effect on the backup generator's energy requirements of using EVs as controllable loads was assessed.
- Two Control algorithms for the battery charging management of clustered EVs were developed.
    - One algorithm calculates EV battery charging profiles for EVs located in an EV parking space. Three charging policies were designed and implemented.
    - The second algorithm calculates the number of batteries and chargers that are required to satisfy the battery demand of EV battery swapping stations.
- An agent-based system that manages the battery charging of dispersed EVs in distribution networks was designed and developed.
- The real-time operation of the Multi-Agent System was demonstrated in a laboratory environment.

7.2 Energy Balanced Area

An energy balanced area was defined as the physical part of a low voltage power distribution network, with the ability to satisfy its electricity demand with locally installed micro-generators and distributed energy resources. An Energy Storage System and a backup generator were used to balance the daily mismatch between the local area's demand and the energy generated from the micro-generators.

7.2.1 ESS and Backup Generator Energy Requirements

The Energy Storage System capacity and the backup generator energy requirements to achieve energy balance in local distribution network areas were calculated. These requirements were calculated for various micro-generation penetration levels. Steady state voltage limits of LV feeders were considered in the calculations.

Case studies were performed using a LV distribution network model based on a UK generic distribution network model for different penetration levels of PV and μ-CHP. The ESS capacity and backup generator energy requirements for all studied penetration levels were reported.

In the modelled area, the maximum micro-generation penetration was constrained due to steady state overvoltage limits violations. It was shown that the energy balance for typical winter and summer days, that minimised the energy requirements from a backup generator, was achieved with:

- A PV penetration of **50%** (1.2kW) and a μ-CHP of **80%** (1.5kWe).
- An ESS with a capacity of **279kWh** (Maximum of winter and summer capacity requirements).
- A daily energy supplied from the backup generator during winter season of **108kWh.** During summer season no backup generator was required.

7.2.2 Integration of EVs as Controllable Loads

The use of Electric Vehicle batteries as controllable loads was investigated in the energy balanced local area. Optimal EV battery charging schedules were calculated with the objective of minimising the exchange of energy with the ESS and the backup generator (i.e. matching the generation surplus from the micro-generators with the EV aggregated demand).

The effect of the EV battery optimal charging schedules on the electricity demand profile was evaluated in a case study. Optimal EV charging profiles were compared with uncontrolled EV charging profiles.

It was found that the control of the EV battery charging reduced the energy requirements from the backup generator or made it unnecessary (compared to the case where the EVs were charged without any form of control). For a 50% PV and an 80% μ-CHP penetration it was found that:

- In the **Uncontrolled EV charging** case**:** The EV demand supplied from micro-generation surplus was **12%** during winter season and **31%** during summer season.
- In the **Controlled EV charging** case **:** The EV demand supplied from micro-generation surplus was **83%** during winter season and **93%** during summer season
- The **backup generator energy savings in the Controlled EV charging** case were **10.5%** during winter season and **27%** during summer season.

7.3 BATTERY CHARGING MANAGEMENT OF CLUSTERED EVS

7.3.1 EV Parking Space

The management of EV battery charging of clustered EVs in a parking area was investigated. A control algorithm was designed to provide controllability and flexibility of EV battery charging, maintaining the distribution network within loading capacity limits. The control algorithm emulates real-time operation where the EV battery schedules are assigned on a first-come first-served basis.

The EV parking Manager charging policies are defined according to the:

i) Time interval priority: defines the time intervals' priority when assigning the EV battery charging schedules.

ii) Loading capacity limits: defines the maximum desired power values at any (or all) time intervals.

It was shown that the control algorithm enabled the EV battery charging schedules to be managed within network loading capacity and following different charging policies:

- Charge EVs in the shortest time possible.
- Charge EVs according to electricity prices.
- Charge EVs according to a given day-ahead demand profile and electricity prices.

7.3.2 EV Battery Swapping Station

Battery swapping stations are charging infrastructures that provide fully charged batteries to EV owners in exchange for their depleted batteries. A software tool was developed to analyse two of the main uncertainties at the swapping station's planning stage:

- Batteries and chargers required to satisfy a given battery demand.
- Impact of the number of batteries and chargers on the electricity load profile.

The software tool follows the policy of maintaining continuously the maximum possible number of charged batteries. The EV arrival times within each hour at the swapping station and the State of Charge of their batteries are modelled as random numbers and:

i) Simulations are performed for all possible combinations of chargers and batteries with a daily horizon,

ii) The probability of the demand not being satisfied is obtained, and

iii) The combinations of batteries and chargers that satisfy the demand are derived.

A case study was conducted and the minimum number of required batteries and chargers calculated. The swapping station required:

- A minimum number of **13 batteries** with a number of **chargers ≥ 8,** or
- A minimum number of **4 chargers** with a number of **batteries ≥ 17**.

The impact of the number of chargers and batteries on the swapping station load profile was evaluated. Two daily simulations were run with the same battery demand and it was shown that:

- For the minimum number of required batteries (13 with 8 chargers), two demand peaks of **349kW** were obtained (8 chargers with 43.64kW power rating were used). The peak values coincided with the battery swap demand peaks.
- For the minimum number of chargers required (4 with 17 batteries), a flat demand profile was obtained, which remained constant almost during all the simulated day at **175kW** (when 4 chargers with 43.64kW power rating were used).

7.4 BATTERY CHARGING MANAGEMENT OF DISPERSED EVS IN DISTRIBUTION NETWORKS

An agent-based system that manages the battery charging of large populations of dispersed EVs in distribution networks was designed and developed. A hierarchical decentralised control approach was used. The control system comprises two entities:

i) The EV aggregator is responsible for the management of EV battery charging according to electricity prices, distribution network loading capacity and EV owners´ preferences. The EV aggregator comprises three types of agents:

   - EV agent, located in the EV.
   - Local Area agent, located at the MV/LV substation level.
   - Coordinator agent, located at the HV/MV substation level.

ii) The DSO is responsible for monitoring the distribution network and ensuring operation within network technical limits (i.e. avoid voltage violations, cables and transformers overloading). It comprises one type of agent:

   - DSO agent, located at the HV/MV substation level.

The operational framework of the Multi-Agent System, the interaction between the system agents and their functionalities were provided. The control system operates and manages the EV battery charging when the distribution network is operated within its loading capacity and when the network technical limits are violated. In the latter, the DSO agent curtails autonomously the battery charging of

EVs to restore normal operating conditions. The provision of active demand in the form of demand reduction was implemented.

7.4.1 Agent-Based System Laboratory Demonstration

The Multi-Agent System was tested in the laboratory of the research centre Tecnalia. A workplace area with an EV parking space was emulated using the equipment of the laboratory.

- The loading conditions were simulated using two controllable load banks and were controlled by an agent that was designed and implemented specifically for the laboratory demonstration.
- An EV agent was adapted to the EV-ON platform, which is a set of software and hardware resources that emulates an EV.
- A monitoring device was used to record system loading conditions and for the continuous monitoring of the DSO agent.

Four experiments were conducted, which demonstrated the ability of the control system to:

- Manage the EV battery charging according to electricity prices and distribution network loading capacity.
- Modify and adapt the EV battery charging schedules after a short term load increase foreseen by the DSO.
- Restore system to normal operation conditions after network constraints violations through the EV battery charging curtailment.
- Provide active demand service in the form of demand reduction.

7.5 FUTURE WORK

The work presented in this thesis can be extended in the following ways:

1. Load forecasting techniques can be investigated to provide accurate EV load forecasts and enhance the developed control systems.
2. Different battery models based on the currently available EVs can be inserted in the control algorithms.

3. Application of EV Vehicle to Grid (V2G) capabilities on the developed policies and enhancement with additional policies.
4. Study of communication systems that can be used for EV management.

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Appendix A

Exchange of Signals During the Multi-Agent System Normal Operation

1. The Coordinator agent informs the Local Area agents that the Operational Period has started.
2. The Local Area agents send the charging set points to the EV agents (calculated in the previous Scheduling Period).
3. The EV agents confirm the receipt of the set points.
4. The Local Area agents confirm the initiation of the Operational Period.
5. The Coordinator agent requests the Local Area agents to start the Scheduling Period.
6. The Local Area agents inform the EV agents that the Scheduling Period has started.
7. The EV agents send their preferences to the Local Area agent.
8. The Local Area agents calculate the optimal profiles and inform the Coordinator agent with the aggregated EV load demand of their nodes.
9. The Coordinator agent sends the aggregated EV load per node for the next hour to the DSO agent requesting technical validation.
10. The DSO agent proceeds with the technical validation procedure and informs the Coordinator agent with the output of the validation process.
11. If there are technical constraint violations, the DSO agent informs the Coordinator agent and forwards an updated network capacity limits matrix.
12. The Coordinator agent sends this information to the Local Area agents and requests them to re-calculate the schedules with the updated network limits.
13. The Local Area agents submit the new schedules to the Coordinator agent.

14. The Coordinator agent sends to the DSO agent the re-calculated charging set points.

15. If the schedules are validated, the Coordinator agent informs the Local Area agents that the charging set points are validated.

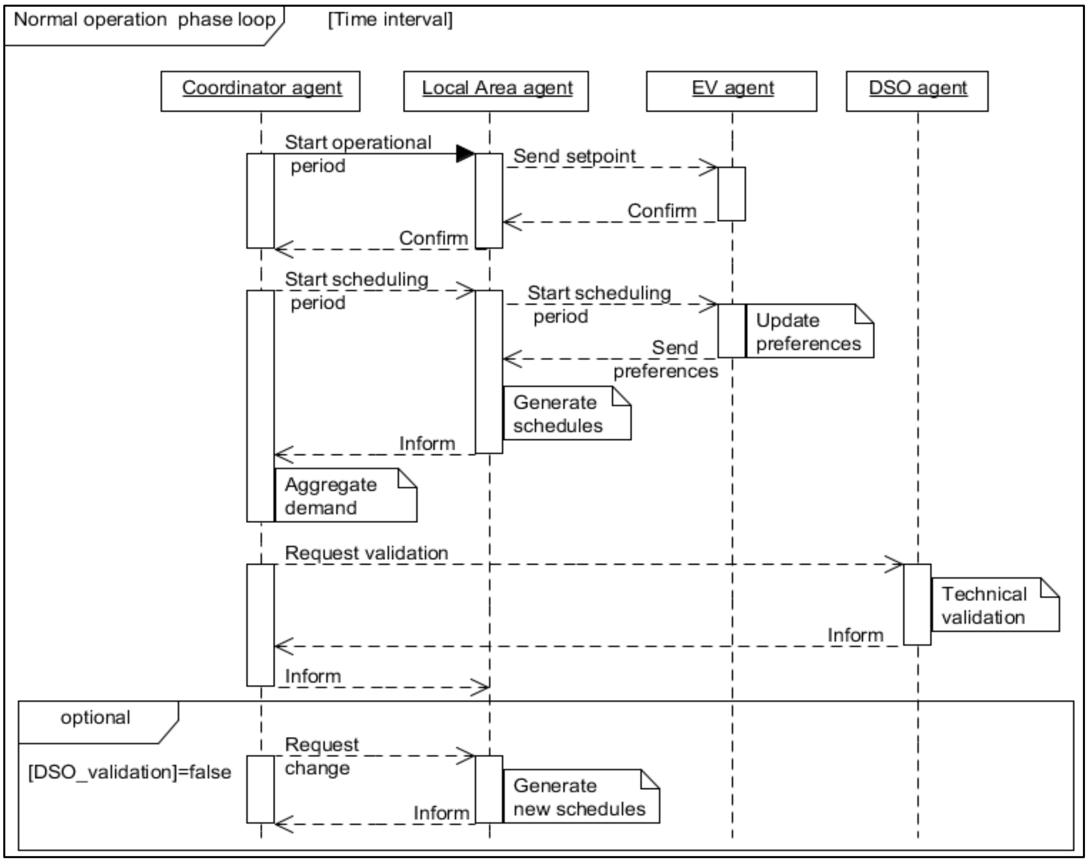

Fig. A.1 Messages exchanged during the MAS normal operation

Appendix B

Load Bank Controller Agent Calculation Examples

In this Appendix, the process followed at the Load Bank Controller agent is presented through two examples. In the first example the process followed during normal operation is presented. In the second example the process followed during emergency operation is presented.

A) Normal operation

The example presented is for time step 12. The process followed at the beginning of the Operational Period by the Load Bank Controller agent is shown in Table B. 1.

Table B. 1 Load Bank Controller agent process during normal operation

<table>
<tr><td>1) Reads the office demand</td><td>
<table>
<tr><th>Hour</th><td>...</td><td>11</td><td>12</td><td>13</td><td>...</td></tr>
<tr><th>Load(kW)</th><td>...</td><td>607.5</td><td>604.8</td><td>596.7</td><td>...</td></tr>
</table>
</td></tr>
<tr><td>2) Receives the EV demand from the Local Area agent</td><td>56.81 kW</td></tr>
<tr><td>3) Adds workplace demand and EV aggregated demand</td><td>604.8 + 56.81= 661.61kW</td></tr>
<tr><td>4) Applies the scaling factor</td><td>661.61/4.17=158.66 kW</td></tr>
<tr><td>5) Calculates the load steps combination</td><td>
Closest value obtained: 158.69kW
Load banks Configuration:
<table>
<tr><th colspan="7">Avtron K595</th></tr>
<tr><td>0.35</td><td>0.75</td><td>1.39</td><td>2.78</td><td>5.56</td><td>11.11</td><td>16.67</td></tr>
<tr><td>on</td><td>off</td><td>off</td><td>off</td><td>on</td><td>on</td><td>on</td></tr>
</table>
<table>
<tr><th colspan="6">Avtron Millennium</th></tr>
<tr><td>5</td><td>10</td><td>10</td><td>25</td><td>50</td><td>50</td></tr>
<tr><td>off</td><td>off</td><td>off</td><td>on</td><td>on</td><td>on</td></tr>
</table>
</td></tr>
<tr><td colspan="2">6) Sends load steps state to the respective load banks through the CSDER</td></tr>
</table>

B) Emergency Operation

An emergency situation is simulated during the time interval presented in the previous example. The process followed by the Load Bank Controller agent after a technical constraint violation is detected by the DSO agent, is shown in Table B. 2.

Table B. 2 Load Bank Controller agent process during emergency operation

1) Receives the demand reduction from DSO agent	-2.99kW
2) Subtracts the received demand from the actual Local Area demand	661.61 - 2.99 = 658.62kW
3) Applies the demand scaling factor	658.62/4.17=157.95 kW
4) Calculates the load steps combination	Closest value obtained: 157.98kW Load banks Configuration: (see load bank tables below)
5) Sends load steps state to the respective load banks through the CSDER	

Avtron K595

0.35	0.75	1.39	2.78	5.56	11.11	16.67
off	on	off	off	on	off	on

Avtron Millennium

5	10	10	25	50	50
off	off	on	on	on	on