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Use of Active Load Control for Congestion Management

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Abstract

Nowadays the congestion management in power system networks is performed by executing new unit commitment and dispatch procedures, allocating energy producing to different power generators, forcing an inevitable cost augmentation for the network operation. The appearance of new and cheaper technologies, allowed the emergence of the active load control as a congestion management technique. During the performing of this thesis, the validation of the technique is analysed by stipulating the load availability for control on a power network, and attest the safety and efficiency of the active load control by simulation on a realistic distribution grid.

Resumo

Hoje em dia a gestão de congestionamentos na rede eléctrica é efectuada por uma nova execução do despacho económico, alocando a geração de energia a diferentes produtores, forçando um inevitável aumento do custo de operação da rede. O aparecimento de novas e mais baratas tecnologias, permitiu o aparecimento do controlo activo de carga como técnica de gestão de congestionamentos. Durante a execução desta tese, a validação da técnica é analisada pela estipulação de carga disponível para controlo duma rede eléctrica, e pelo atestar da segurança e eficiência do controlo ativo de carga numa simulação de uma rede de distribuição realista.

Acknowledgments

One of the joys of finishing the writing of this thesis, aside the step forward on my academic path, is the opportunity given to me to share some feelings for my family, friends, all those who shared their lives with me. I've learned with all of you!

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To all my friends that I meet in FEUP, I just can say I am very lucky I have lived with you so many unimaginable and unpredictable stories! I am a very lucky guy... To all my friends that built my path and athletes who competed, to all conversations I had.

For the salt water, the scent of the beach, the fruit of the wine... to you my *Lán*... you enlightened me when I most needed. I'm finally in love with life again. Thank you all

André Daniel Magalhães Cardoso

“Vou mostrando como sou
E vou sendo como posso,
Jogando meu corpo no mundo,
Andando por todos os cantos
E pela lei natural dos encontros
Eu deixo e recebo um tanto
E passo aos olhos nus
Ou vestidos de lunetas,
Passado, presente,
Participo sendo o mistério do planeta”

Luis Galvão / Moraes Moreira

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Symbols and Abbreviations

AD	Active Demand
ADA	Appliances Data Acquisition
AMI	Advanced Metering Infrastructure
ANM	Active Network Management
BTN	Baixa Tensão Normal
DG	Distributed Generation
CHP	Combined Heat and Power
DG	Distribution Grid
DLA	Demand Load Aggregator
DMS	Distribution Management System
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
ERSE	Entidade Reguladora dos Serviços Energéticos
ETP	European Technology Platform
EWH	Electric Water Heater
HVAC	Heating, Ventilation and Air Conditioning
FBMC	Flow-based Market Coupling
ICT	Information and Communication Technologies
INE	Instituto Nacional de Estatística
LMP	Locational Marginal Pricing
LVN	Low Voltage Network
MS	Market Splitting
PMS	Power Management System
RPS	Renewable Power Sources
SLC	Shunt Load Control
SLOC	Smart Load Control
TSO	Transmission System Operators
VPP	Virtual Power Plants
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator

Chapter 1

Introduction

For many decades, the capacity of electricity networks in developed country's has played with outstanding success the support of energy producers and consumers needs. These networks concept and architecture were designed considering the prevailing usage of carbon-based technologies of energy generation, with these being located remotely from the major centers of demand.

However, before the great improvement of associated technology and environment concerns, the concepts of energy networks had to be reviewed. New energy challenges and the general conjuncture forced a switch-over on energy policies, for both generation and production sides.

We witnessed the emerge of new and more efficient low carbon generation technologies, improved efficiency on demand side and unimaginable advance on telecommunications and electronics. Moreover, the cost of manufacturing of telecommunications and electronics equipment was very reduced. This enables a greater interaction between customers and the network. Networks drive up to me more based on customer as key piece of the system. Given the actual grid, this is a radical change that means fundamental modifications on network design and control.

Following this context, there were taken measures in order to change energy policies, globally. Several programs and new legislation were launched, as "Energy Independence and Security Act of 2007" in USA [1], or in Europe the set up of European Technology Platform (ETP) Smart Grids, both with similar main objectives. Grabbing the European case, the ETP was launched in 2005, with the aim to create a new joint vision for European networks toward 2020.

ETP managed to gather and unite in the same board representatives of every related areas, namely industry, transmission and distribution system operators (DSO), research body and regulators. Thus, efforts were united to define clear objectives to transform this ambitious vision in reality.

This conjuncture and respective new reality underlines the need of establishing efforts for new objectives for energy network operation, as referred by European Commission's 2006 Green Paper "A European Strategy for Sustainable, Competitive and Secure Energy". According to the European Commission, "...Europe has entered a new energy era. The overriding objectives of European energy policy have to be sustainability, competitiveness and security of supply, necessitating a coherent and consistent set of policies and measures to achieve them." [2].

ETP Smart Grids launched a program of research, development and demonstration that indicates the path to meet electricity supply networks needs of the future. This path fits to all others programs globally. As stated in [2] the program must meet four leading characteristics:

- **Flexible** — satisfy costumer's demands, without losing adaptability capacity to eventual changes or new challenges in the future.
- **Accessible** — all network users must have assured connection access, with special emphasis on renewable power sources, highly efficiency local generation and low carbon technologies.
- **Reliable** — grant and evolute quality and security of supply, contextualizing the requirements caused by new digital era, with the necessary elasticity to hazards and uncertainties.
- **Economic** — afford greater energy value through system improvement, introducing innovative concepts, regulation, efficient energy management and promoting equality conditions to stakeholders.

In order to advance with the project and carry out with the proposed objectives for the future's grids, the coordination of research was and still is essential. It is necessary a lot of research in various areas, but it must be sustained, keeping coherence in the process. Relating technical, commercial and regulatory factors, allowing companies to take business decisions, always in agreement between the parts, creating a stabilized environment is the best way to go forward.

Taking advantage of the latest technologies without discard future developments is essential to ensure success. Advances on simulation modelling tools and data acquisition, information and communication technologies (ICT), advanced materials, electric storage and evolved power electronics open new windows of opportunities at every level. Smart Grids project will stimulate even more innovation on these technologies, resulting on positive effects for economy and business. New job opportunities will emerge, due to new skills requirements and integration of new areas of work. To ensure a successful transition and spring to action, all stakeholders were involved: governments, universities, regulators, consumers, generators, energy traders, transmission and distribution companies, power equipment manufactures and ICT providers. [3].

Synthesizing, this panorama reflects the major value of research community role, because without research there is no innovation, which is critical for development. For all appointed reasons, the studies related to Smart Grids are ample and growing, reflecting the cooperation between research centers, universities and the stakeholders previously referred. This work is one more little step.

1.1 Problem Characterization

This thesis addresses one specific technique of demand side management (DSM), namely the use of active load control for congestion management in distribution network. Related subjects as demand response (DR), load management, direct load control, load characterization and household appliances modelling are addressed in order to attest the technique.

The study is complemented with a distribution grid (DG) operation simulation, in which residential loads are partly characterized by models of household appliances. Then the potential of residential active load for solving congestion events will be identified, analysed and tested on a realistic distribution grid simulation.

1.2 Objectives

The main objective for this thesis is to attest the use of direct load control as a valid solution for congestion management. To achieve this main goal, there are other objectives that have to be reached:

- **Software and hardware identification** — The use of active load control is only viable if there are tools that enable the technique implementation on a real grid.
- **Realistic load profiles generation** — In order to get them most realistic possible simulation of the distribution grid operation.
- **Domestic load identification** — In order to get an approximated value of load liable to use on active control.
- **Congestion management** — The technique is considered viable if it is actually capable of solving congestion events

1.3 Workplan

In order to attend the main objectives for this dissertation, the following procedures were taken by this precise order:

- Literature review related to Smart Grids, DSM, load management, direct load control, household appliances modelling.
- Identifying a software and hardware structure able to support active load control implementation.
- Perceiving different load profiles characteristics and the reasons behind them.
- Load profiles construction.
- Perceiving the liability of household appliances for active control.
- Comprehend the relation between house stocking and the household appliances usage.
- Comprehend the household appliances operation.

- Modelling the household appliances.
- Identify and quantifying available load able for management.
- Applying load reductions on congested grids, and analyse the results.

1.4 Dissertation Structure

This thesis structure is composed by six chapters. A brief summary of each chapter:

- **Chapter one** — Introduces the thesis theme and important subjects related
- **Chapter two** — Contextualizes the thesis theme in the current scientific research panorama related to energy.
- **Chapter three** — Presents some of the literature review used to enable algorithms implementation, and introduces the main concepts considered on the thesis.
- **Chapter four** — Presents and explain in detail the algorithms and procedures implemented on the thesis.
- **Chapter five** — Case study. Application of the algorithms and procedures defined on chapter four on a distribution grid simulation.
- **Chapter six** — Presents the conclusions taken from chapter five results and suggest further studies.

Chapter 2

General Framework

In this chapter will be presented a summary of a broad perspective above energy research paradigm, more concretely the Smart Grids. Following this widespread view, the literature review will slowly deepen and probe subjects related to the dissertation theme, active load control.

2.1 Smart Grids Development

Smart Grids, as previously mentioned in Introduction, is the most common designation for electricity networks of the future. Another designations can be used like intelligrid, future grid or even intragrid. Those are electricity networks that perform with excellence and emphasize key solutions: energy efficiency, DSM and high penetration of renewable power sources (RPS). Smart Grids innovative solutions research involves plenty subjects and different kind of technologies, however combining them is the advantage that makes these solutions so powerful. In a overall perspective, it is acceptable to agglomerate and enumerate them in various concepts that are targets of development[4]. The continuous research related to this concepts will enable to implement new applications on the system, like the use of active load for congestion management,the theme of this dissertation. Thus, synthesizing we can name five major subjects that embrace all areas, that will be discussed on the following sections.

2.1.1 Information and Communications Technologies Applications

To achieve all Smart Grids goals, effecting the reorganization of the network implies the implement of diverse and plentiful innovating solutions. This complex process is already happening and requires a novel ICT based applications capable of provide real time control and communications, portfolio management and adaptive protection. The primary objective is to provide a data exchange infrastructure that serves of basis for most Smart Grids applications, ensuring security. The insertion of ICT infrastructure at all levels of the power system enables upgrading reliability, capacity and DR.

ICT integrates electrical and intelligence structures, which have developed quit well in the last decades, with the common usage of micro-controllers, since they are small, cheap and highly reliable. Intelligence structures allow to create end use components on distribution, transmission and generation that improves electrical and economic efficiencies, accounting energy pricing. Automated communication along the grid elements permits optimal resources dispatch based on price signals and also actions for decreasing distribution boundary operation at peak demand situations. ICT applications are essential for Smart Grids to manage demand side integration, DER, DG, business models, environmental protection and monitoring.

Due to the importance of this matter, there are several programs of ICT research. By example the Olympic Peninsula Project, launched in 2010, focuses on pricing signals between costumers and DSO [5]. In Europe, was made an association with ICT-PSP (Policy Support Programme) under the CIP (Competitiveness and Innovation Program). These referred platforms aim to stimulate innovation an competitiveness through ICT. The project SEESGEN-ICT (Supporting Energy Efficiency in Smart Generation Grids through ICT) leverage the existent know how and structures, adapting them to Smart Grids requirements and objectives [6].

2.1.2 Virtual Power Plants

Renewable power sources and micro-generation integrated is increasing nowadays, reaching larger scale deployment, as can be seen in [7]. However connecting those distributed energy resources (DER) still not have a proper policy. The actual grid was planned for centralized control and large generation, which addresses problems for DER integration, namely costs of investment and operation, and integrity and security of the system. Therefore, transmission system operators (TSO) and DSO increasingly deal with DER being necessary to change control paradigm.

DER single units have small weight on the system, so cannot be manageable on an individual basis. Virtual Power Plants (VPP) circumvents this problem, aggregating DER units into a portfolio similar to actual transmission connected generation. VPP can be described as a multi-fuel, multi-location and multi-owned power station.

One example of research for VPP is the project FENIX (Flexible electricity network to integrate the expected energy evolution) has been launched in 2005 to develop this solution [8].

2.1.3 Distributed Energy Resources Aggregation Business

The objective is mass small groups of industrial, commercial and residential customers, resulting in a large power unit, more visible and easier to deal by the system operators. The concept can involve simultaneous our individually DR and distributed generation (DG). Small load and generation profiles are singularized, creating a large and flexible portfolio, enabling effective operation for DER integration and services provided to the power system.

Smart Grids flexibility and low operation cost enable great exploitation of DER, meeting the goal of low and zero carbon generation technologies usage. Innovative business models, providing solutions based on demand-pull approach, favouring DER integration. Equipment and electric system specifications must guaranty safe DER larger usage on actual grids. Different models are being studied, including by example aggregating DR to balance intermittent generation, integrating residential micro-CHP (Combined Heat and Power) into electricity markets or leveraging flexibility of aggregated CHP units and DR to expand conventional energy business.

This research subject was targeted of great importance at the European Commission 6º framework program [9].

2.1.4 Active Demand in Consumer Networks

Nowadays existing transmission networks are active, but distribution networks are passive, with no significant weight in network operators decisions. To turn them active, the development step by introducing active demand (AD) in consumer networks. The theme of this dissertation is a type of AD. To build up AD, there are commercial and technical frameworks, investigating the efficiency of domestic and small commercial consumer participation in different issues of the power system, namely markets and provision of services.

Aggregating and mediating all the participants in the network is the challenge. Collect on time information from consumers, and conjugate it with markets, networks and power generators, analyse it and decide the possibilities for consumer contribution, changing system operators decisions. An interface between consumers and DSO is essential and a key in the concept. Hardware and software are integrated at consumer side, with wide level of intelligence. Nevertheless, efficiency and secure network operation is indispensable. The markets play a role through pricing and power exchanges.

One example of research for AD is the project ADDRESS (Active distribution networks with full integration of demand and distributed energy resources), co-founded by the European Commission in 2008 and coordinated by ENEL Distribuzione [10].

2.1.5 Active Distribution Network

Passive network management philosophy for DG connection must switch for Active Network Management (ANM). DG as well as direct load control, reactive power compensation and Demand Side Management (DSM) present great controllable resources for active networks. ANM models increase use of DER due to improved efficient utilization of distribution network assets and distribution network supporting by services provided by costumers. The development and test of technical solutions is critical to move forward ANM. Active networks control is based on supervisory control and data acquisition (SCADA), distribution management system (DMS), substation and distribution automation and Advanced Metering Infrastructure (AMI).

ANM encompasses controlling coordinated local voltage, frequency, power flow, fault location schemes, network restoration, island operation, load shedding, and production curtailment features at a decentralized level. This requires hardware working also decentralized. ANM layout predicts a centralized system to assemble the decentralized control systems.

In 2007, European Commission co-founded a project supporting this research, the ADINE [11].

2.2 Demand Side Management

Historically, the models for energy planning had great evolve, due to the first energy crises, on 1973/1974 (oil crises)[12]. In the time, the models were simply econometric, regarding only previous records of energy consumption, in order to forecast future demand/production. Technical/Economical models along with simulation models enabled a more rigidity on demand evolution.

Therefore, a new concept emerged: DSM. DSM is composed by any set of actions aiming reduction of "overspending" energy by suppliers. DSM strategies to improve system efficiency and achieve a cheaper operation cost were at decade 80, in the USA. DSM was regulated with detailed procedures for investigating cost-effectiveness, rate-impact, program deliveries and availability for different group of costumers. Already in that time DSM integration brought many legal issues. DSM strategies were being adopted by other countries, with less or more variants, but the major objective was the same: the least cost option for system performance selected when more supply or less demand were compared on equal terms[6].

Solutions were integrated, aiming on demand reducing and shifting demand from peak periods to off-peak period, resulting in resource optimization. With time advancing, other concerns were taken, and shaped DSM issues. The energy economization wasn't the only goal, but also climate change, system reliability and security were important for market and policies, increasing strongly awareness from business actors, decision makers and general public. The fast developing of technology allowing more sophisticated means provided new opportunities, applying further intelligence and communication in power system operations, as also DER/RPS integration along DSM.

In generality of cases DSM development has been accordingly market liberalization and regulatory regime changes. Despite the circumstances, the main idea is evolving and increase is income for the energy efficiency, taking advantage of new technological possibilities meeting the requirements for energy security and environmental sustainability of the grids.

Energy efficiency has the greatest economical potential to reduce costs and environmental impact, but as DSM actions are delivered in small packages, is weight is harder to be noticed. Aggregating the small resources into larger programs will increase the impact, turning it visible and attractive for further adoption of DSM new possibilities by energy stakeholders and customers.

2.2.1 DSM Development

Load Management (LM) as well as Distributed Storage (DS), are two DSM techniques that are being target of intensive research and development, for medium-term appliance on distributed grids[13]. These solutions permit great evolve on demand management, leveraging the existing infrastructures, increasing grids flexible operation and efficient usage.

Networks dimensioning is based on peak demand, which means that a vast of unused network capacity is available during operation. The possibility of using this capacity would result on more energy transportation by the same network, decreasing or erasing the necessity investments on grids reinforcement.

The key in is this process is to shift the demand of electricity, maneuvering it. In practice, this means to shift transport of electricity through time. There are two methods that can fulfill this purpose, which are incorporated distributed electricity storage in grids, and allow load management of flexible loads (which are not time critical), shifting them through time.

2.2.2 Load Management

LM presupposes that DSO or the costumer itself has the ability to control in an autonomous way, the load demand consonant to grids conjuncture, namely non time critical loads. Thus, it is possible to increase or decrease demand in certain times. The average demand will not be modified; the loads will just be transferred on time, earlier on later than in normal operation. System reliability can be improved, and DER integration easier[14].

The principle is simple: according to availability of non-critical loads, should be increased demand when there are plenty DER and decreased demand on peak times as well as low DER.

As said previously, just some specific loads can be managed by DSO. There are types of load management sets:

- Loads which time is not critical, however with long time constants, operating all over the day. This characteristic facilitates the load management. The consumer appliances that normally gathers them are households thermal processes, including the following: heating, cooling, air conditioner and wash machines.

- Making "behind the meter" load storage. Nevertheless, this load cannot be delivered back to the grid, for technical or institutional issues. The greater example is the charging of electric car. His load is not time critical, and presents storage capabilities although any energy exchange possibilities.

2.2.2.1 Legal Issues

LM implies maneuvering consumer's household appliances and electricity consumption management, conflicting with the fact that costumers are given an unconditional right to use full network's capacity.

To apply the concept, the DSO must guarantee that LM will not cause any kind of inconvenience for the consumer, either at comfort level or breaking appliances normal operation. The regulation will have to be adapted, and compensations studied, regarding consumers satisfaction.

2.2.3 Load Control Strategies

In the traditional grid operation, there is no communication between the network operators and load users. Given the vicissitude of DSM changing paradigm, with the push of load consumers in network operation decision making with information exchange between the parts, its necessary to stipulate and configure methods of control.

The control system nowadays is considered passive: no information exchange[15]. However there are different philosophy for load control depending on how the information exchange affect the control. Enumerating them, we can name four types of control level:

- **Passive** — The way the actual system is implemented. No information is exchanged between customers and DSO. Households appliances work normally without suffering control actions.

- **Active** — One of the options for load control. The DSO sends information about system characteristics and operating parameters that can be exploited by the load consumer. One example is DSO providing the costumer a price signal, what may change the appliances use behaviour, changing demand shape.

- **Interactive** — In interactive load control, the exchange of information is made by both the actors. The functioning principle is similar to Active Control, but taking the example referred previously, the DSO adjust prices signal corresponding to actions taken by the load consumers.

- **Transactive** — Transactive control is a concept more complete and embraces a larger number of possibilities for loads control actions and programs implementention[16]. In this type of strategy, both DSO and consumers receive and send information, and actions are taken according to network conjuncture, e.g. price deviations or grids congestion.

2.2.4 Centralized or Decentralized Control

Independently from source information, the commands for load control can be centralized or decentralized. In practice this means that the orders for load management and response decisions are made by the DSO or by the load consumers themselves.

These two different control strategies imply the analysis of two main characteristics, related to the level and quality of reliability and controllability, that measures the load management technique feasibility[17]. These aspects are:

- **Delay Time** — A good time response, i.e. a small time response is indispensable for grating system stability when applying load control. A fast system response is a key factor to enable the introduction of many load management techniques.

- **Predictability** — The more predictable response is, the less will be the uncertainty and instability on system operation caused by load control actions.

2.3 Congestion Management

When running electricity network operation and scheduling, transmission system operators (TSO) may be faced with transmission congestion. Transmission congestion episodes occurs when the transmission grid is unable to dispatch the schedule production by suppliers to the demand side, due to system technical restrictions, namely voltage, thermal and security constraints of power lines.

The TSO approach to this problem suffered various amendments throughout history, depending on electricity network operation architecture. During the decade of 80 the system was based on companies vertical integration, the system stakeholders were bundled and worked together so when transmission congestion episodes happen they were simple to manage: the system operator could directly re-dispatch generators outputs until the lines congestion was alleviated.

However, several changes were implemented on power system operation in decade of 90. Some sector activities were liberated and energy markets created, starting a new era. This deregulated environment brought many operation issues, whereas congestion management became protuberant. The TSO has to deal with all market players and grant open access to transmission network, giving equal opportunities for the interested. This means that the TSO in unable to directly control the network power flow as formerly.

The electricity trading mechanism has direct influence on network power transactions, so the transmission congestion are managed through electricity prices and penalties application, linking financial methods with physical operation. As the congestion management schemes are heavily related with the power market trading procedures, they vary worldwide. Different countries implies different markets, resulting on contrasting techniques for power dispatching and congestion management approach [18].

To manage congestion episodes, the system operator executes a new dispatch, changing generators outputs and curtailing the power transactions, resorting optimal power flow techniques. If a congestion is foreseen in a power dispatch, it has to be rebuilt with new prices bidding and considering the system technical constraints. There are several congestion management techniques involving power markets mechanisms, has reviewed in [19].

Access to transmission network involve tariffs application, which are regulated. This regulation shall give the correct economic incentives but also facilitate the network physical operation. Congestion management is one the variables attended. This matter was aim of profound research, and there are three main schemes that can be applied according to network decentralization level. Summarizing them:

- **Locational Marginal Pricing** — Locational marginal pricing (LMP) can be also referred as nodal pricing or spot pricing. LMP is most used when there is a pool-based market model implement. The LMP model consists in an electricity market that integers economical and technical specifications, e.g. generation limits, generations costs, line flow limits, demand elasticity, etc. These variables are analysed and processed in order to optimize the network, maximizing social welfare while respecting all system operation constraints. When solving the LMP model optimization problem, the power allocated to each generator is determined as well as the prices in each node of the network. When the market is cleared the generators are dispatched and paid according to the node prices.

- **Market Splitting** — The market splitting (MS) model concept is similar to LMP in the perspective that new prices have to be calculated in case of congestion, in order to respect system operation constraints. The difference is that instead of determining prices for each node, the prices are assigned by zone, composed by a group of nodes. These zones are defined according to a flow analysis and identification of potential congestion problems in certain network areas. Consonant the country market mechanism, when the market is cleared the price may be the same for all network. In that case is added to the model more constraints, the oblige the price to be the same in all zones.

- **Flow-based Market Coupling** — As MS, Flow-based Market Coupling (FBMC)optimizes system operation assigning prices by zones composed by group of nodes. Yet, there are other features in this model. The country borders price zones are taken in consideration, which implies some model amendments and simplifications, according to the country market mechanism.

2.3.1 Demand Side Approach on Congestion Management

The methods presented in 2.3 for congestion management only approach the generation side of the network, considering that the demand variables are fixed. This way, due to nodal prices sensibility, every episode of network congestion results on rising prices and higher operation costs, without consumers response. However, the demand side is effectively a factor to take in account on electricity prices. The lack of demand response was appointed as one of the reasons for California energy crisis in 2000/2001. According to the International Energy Agency, a simple curtailment of 5% in load demand, would result in a 50% price reduction on peak hours during the crisis [20].

Since demand response is improving, the markets pliable for cooperation with demand side and not only analysing supply offers. Several works attest that in case of network congestion episodes, the demand side could be part of the market as an auxiliary service, as in [21]. The introduction of demand side management and load curtailment is an attractive solution for congestion management. In [22] is presented a model where the load contribution for reduction power flow and solve congestion is evaluated, through load management. The electricity grid costumers gain importance on this matter, since they are the basis of load demand. Residential costumers represent an appreciable pie of the load, turning them a good target for load management in order to solve congestion episodes. An approach for the use of residential appliances control for congestion management was made in [23]. It is stated that in a typical peak day on U.S.A., 61% of residential load is liable for load management, which could provide load elasticity to reduce load on buses enough to decrease power flow on transmission lines, and consequently provide congestion management.

The analysis of the effect of load elasticity on the deviation of energy prices can be useful to evaluate the potential of load management for congestion management. Basically, lower deviation means less congestion on transmission lines, so when reducing price deviation the congestion probabilities are also reduced. In figure 2.1, adapted from [20], shows that how much higher the load flexibility is, the lower are the market surplus. The market surplus, as previously referred, is an operation cost augmentation, as a consequence when congestion management is required.

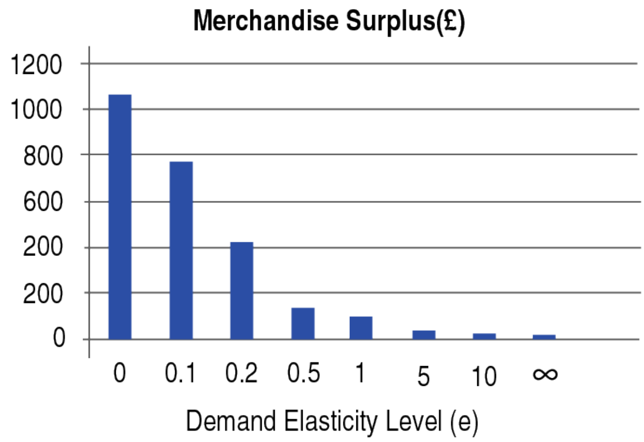

Figure 2.1: System operation costs surplus on markets relation with load elasticity

Chapter 3

Literature Review and Load Modelling Concepts

In this chapter, the following subjects will be addressed: active load control architecture and load modelling. At first, will be presented an active load control scheme, based on already existing structures, designed in order to enable AD techniques. Then, the load modelling procedures, that will be later used for simulations, are explained and demonstrated. Through a flow chart, the loads that will be modelled are enumerated and their relation between each others represented, as well as other significant procedures. In the end of this chapter, as corollary, it will be presented an method that quantifies load available for management on a low voltage network (LVN), based on the models previously presented.

The active load control on households appliances is effective and suitable on non time critical loads, due this his characteristics. About these we can enumerate specific thermal loads and some other appliances: electric water heaters (EWH), cooling devices, HVAC systems, washing machines and electric vehicles. On this work will be studied the control of EWH, fridges, freezes and HVAC systems, applying proper load models, which can provide information about devices work state and power consumption: load behaviour.

To enable these appliances to be controlled it is needed a ICT structure that provides reliable and secure data exchange between the consumers and the DSO. The costumer has a ICT that have to provide information about they behaviour and operation, acquired continuously from measurements appliances. After treating the data, direct load control actions may be applied in order to benefit grid operation.

The concept of active load control on buildings was already been tested with satisfactory results, since some years ago. By example, in New York Times Headquarters building [24], several load management methods were experimented in 2006, realizing that HVAC temperature set points regulation in order to reduce peak demand were in practise effective and compensatory, namely on economic point of view. The peak demand reduction in this example can be observed in figure 3.1, where the power consumption reduction at certain periods was proven to allow several cost savings. Although with some problems at the time, like demand response and posterior demand increase.

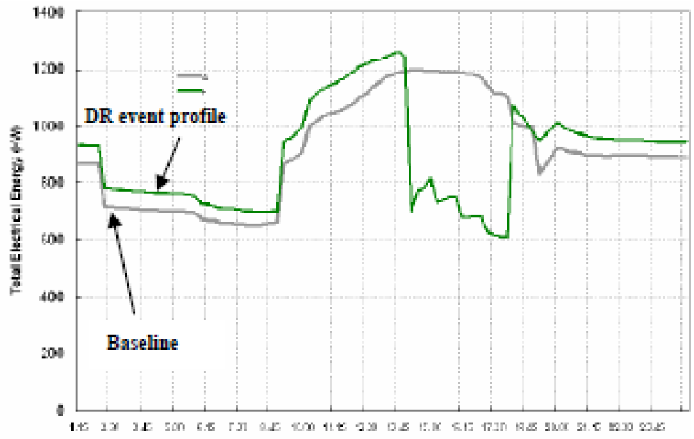

Figure 3.1: Demand profile with and without AD actions in New York Times Headquarters

The procedures established on this thesis do not presupposes temperatures set points changing, but rather the equipments disconnection, by a determined period of time. This is enables to account and stipulate emergency load reserves available to use in case of congestion events on the grid.

3.1 Active Load Control Architecture

A crucial factor to enable effectively active load control with good time response is a powerful ICT structure, as well as reliable power electronics controllers devices, allowing implementation of algorithms for active load management. The communication network encompasses all appliances target of control of each residence building, as well as DSO infrastructures.

There are recent technologies being applied that support demand response necessary ICT, namely Advanced Meter Infrastructure (AMI) and Building Automation Systems (BAS) [25]. These kind technologies, along embedded control systems in appliances are powerful tools that enable demand response in real time.

3.1.1 Data Exchange Architecture

A bidirectional data exchange between clients and DSO can be assured by a wireless network, structured in different modules, similar to the presented in [26], which one with specific functions. Therefore, we have two major parts of the architecture, the client side and DSO side. The network installed at clients residence can establish a connection with DSO, sending and receiving information. The connection could be made either by the grid infrastructures or by internet. The hardware on software installed at residences, according to households load behaviour, reports to DSO the load reserve available for load management cyclically. On the other hand, according to grid conjecture DSO may optionally send load management commands, establishing a centralized control strategy.

In the costumers side, the network has three modules:

- **Appliances Data Acquisition** — All the controlled appliances has a embedded control hardware that gathers and treat the measurements, reporting the equipment functioning state and parameters, e.g. temperature and power consumption.

  These hardware must have electronic capabilities to treat data, to control the device and possess wireless communication, yet it shall have a cost effective and ergonomic design, not causing discomfort for costumers devices usage or increasing expenditure on its application.

- **Smart Load Control** — The data acquired from appliances are dealt, and by algorithms resolution the residence available load for management is calculated by the module Smart Load Control (SLOC). These information is then sent to DSO. The hardware and software of this module is installed in household, and is in permanent communication with Appliances Data Acquisition (ADA) module.

- **Shunt Load Control** — In case of load management commands from DSO, this module proceed to shunt the required load, by shutting down appliances in operation. The respective hardware is embedded on all devices, along with ADA. His design must guarantee equipment safe functioning, regarding power electronics parameters.

  This module is able to work individually at any single appliance, despite the others network modules functioning, so that in case of wireless communications troubles with Smart Load Control (SLC) or ADA or malfunction the appliance still works normally, with no prejudice for the costumer.

The bridge between DSO and the load consumer is made by only one module, who is part of distribution network:

- **Load Management Aggregator** — in a similar manner to SCADA and all adjacent functionalities, Load Management Aggregator (LMA) provides an ergonomic interface between the human operator and digital platform. LMA displays real time information about distribution and transmission network state, as well as information about demand response and load management possibilities at residential level received from SLOC. This module can be integrated in DSO infrastructure or separately. In the last option, it would be necessary to create a new intervener in the electricity network: demand load aggregator (DLA). The DLA is responsible for aggregate an organize all information gathered from SLOC, and take the necessary actions for grid operation optimization: load curtailment and shedding.

For a better understanding, the figure 3.2 shows how this modules interact, as well as costumers, producers and system agents.

3.2 Models and Statistical Data Architecture

Before presenting any models or statistical data related to household appliances and LVN load profiles, in this section is displayed, in the form of a flow chart, the delineated architecture that

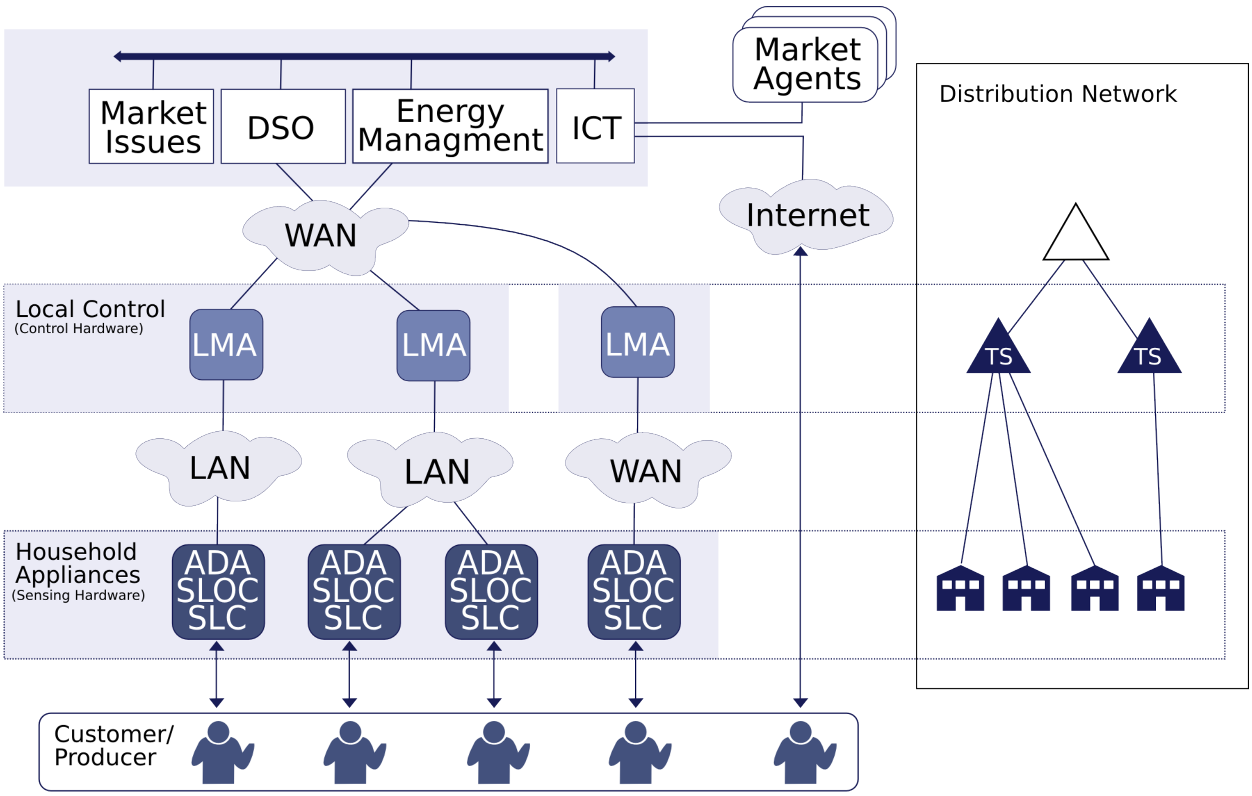

Figure 3.2: Active load control architecture

connects the models and statistical data, with the final objective of create a procedure that enables to project in quantity the load available for control in a given LVN. The models that will be presented in the next sections, refer to LVN load profiles and individual household appliances operation. The data provided by the various load profiles modelled, will be crossed with statistical data related to domestic costumers, namely energy consumptions and equipments possession and usage. The equipments models are analysed as well and then their involvement on grid operation defined. In the figure 3.3, is presented a flow chart that shows the connectivity between models and statistical data available, and the respective outputs required to perform the case study. This way, the following sections on this chapter have a easier perception. Prior to flow chart observation, it shall be noted that the generation of load profiles is required not so only to execute the case study, but also enables the number of LVN domestic costumers to be stipulated. The number of domestic costumers allows to project the equipment functioning on the LVN. In the next sections, the steps presented on figure 3.3 are explained with further detail.

3.2.1 Statistical Data Treatment and Models Implementation

All the algorithms presented in the following sections, as for load profiles generation or household appliances modelling by example, are implemented on the software *Matlab*, provided by [27]. The

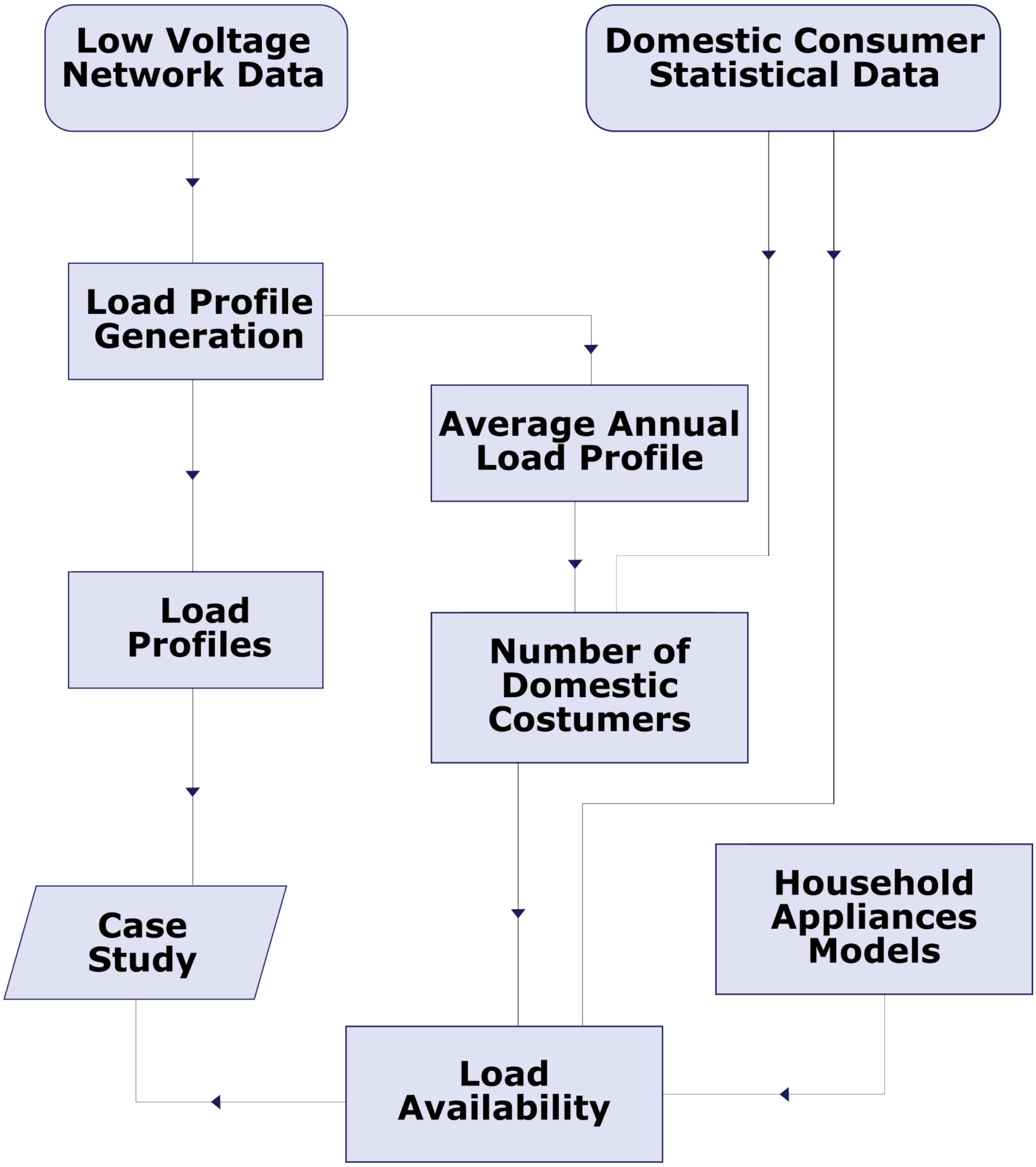

Figure 3.3: Models and data crossing architecture

statistical data treatment required do not carry the same level of calculus complexity, but is as well implemented on *Matlab*.

3.3 Low Voltage Network Load Profiles

The first step to be presented is the load profile generation. To create random LVN load diagrams, that represent with acceptable accuracy the diagrams that can be found in the Portuguese LVN transformer stations nodes, it was created an algorithm that uses expected consumption profiles given by ERSE (Entidade Reguladora dos Serviços Energéticos). ERSE is the Portuguese regulatory entity for energy services, and the referred load profiles can be found in [28]. The Portuguese LVN has two different regimes: BTN and BTE. The term for low voltage applied to normal clients (energy consumption only) are classified as BTN (Baixa Tensão Normal). ERSE classifies BTN in three types [29], according to clients contracted power and annual consumption:

- **BTN A** For clients with contracted power superior to 13.8 kW
- **BTN B** For clients with contracted power inferior or equal to 13.8 kW and annual consumption superior to 7140 kWh
- **BTN C** For clients with contracted power inferior or equal to 13.8 kW and annual consumption inferior or equal to 7140 kWh

These referred profiles, presented by ERSE, provide normalized values for the three BTN types, for each day of the year within a 15 minutes time frame. These preforms 35040 normalized values for the current year for each BTN class. These profiles can be adjusted, according to a specific transformer station characteristics, namely peak loads registered during a year by example. This adjustment provide the transformer stations load profiles.

As the normalized profiles given provide information about LVN load profiles for every day of the year, it is possible to define different load shapes according to the time of the year, i.e. seasons, and day of the week. Different profiles generation allow to make different analysis, resulting on different conclusions.

3.3.1 Load Profile Types

Although a congestion event is more likely to occur during winter, when the load demand is higher, several types of load profile are created. At first, the normalized values were split by day of the week and season, resulting in 21 different groups of normalized values, with the objective of create more accurate load profiles according to different consumption habits by clients during the week and year. Therefore, by season there are two different profiles, Summer/Spring and Winter/Autumn, while by week they separated by Week Days, Saturday and Sunday. The annual average load profile is also calculated. The parameters that preform the different 21 groups are easily consulted on 3.1.

BTN Type	Day of the Week	Season of the year
A	Weekday	Winter and Autumn
B	Saturday	Summer and Spring
C	Sunday	Annual average

Table 3.1: Parameters enumeration for Load Profiles Classification

Each load profile group of normalized values was calculated by the average values, according to the equation 3.1 and respective restrictions. The variables meaning are in table 3.2. Although in 3.1 the representative variable for the normalized values has only one nomenclature x, its varies according to the load profile type required i.

$$x(\bar{t})_{i,j} = \frac{1}{N_i} \sum_{1}^{N_i} x(t)_{i,j} \tag{3.1}$$

Variables	Meaning
i	Load profile type
t	Day time
j	BTN class
x	Normalized value
N	Number of normalized values

Table 3.2: Variables for Load Profile normalized values calculation

The objective of this algorithm, load profile generation, is to simulate load profiles for any existing LVN chosen, during a day time. Therefore, each LVN has a different number of transformer stations, and each transformer station has different peak loads or power capacity installed. In this thesis, the load value used as reference for adjusting the normalized value is the peak load registered during a year.

3.3.2 Load Profile Composition

Another issue on load profiles generation algorithm, is the BTN class contribution for the total load on a transformer station node. On every node of the LVN, the load is composed by different contributions by BTN classes. Nevertheless, in average, the Portuguese LVN possess the follow BTN class contribution percentages in table 3.3. The algorithm assigns random weights of each BTN class per node, but ensuring that the percentages on the aggregated load from all LVN transformer stations approaches closely the average values. It is possible to have null contribution from a BTN class in a node.

BTN A	BTN B	BTN C
25.3	15.7	59.0

Table 3.3: Average BTN classes weight on Portugal

This process of assigning random values for each node for BTN class weight, is implemented on *Matlab*, using a existing function on the *Matlab* library: *mvnrnd*. This function returns random numbers from multivariate normal distribution, with mean MU, covariance σ and population n. The first class to be attributed is class BTN C, then class BTN B. The class BTN A is equal to the remain rate, in order to perform the 100%. The values attributed by the function *mvnrnd* are always checked in order to prevent negative values. If this case happens, negative values, the value to be assigned is null. The parameters defined can be observed in table 3.3, used on equations 3.2 and 3.4. The node composition rates are stored on a array with dimension $[3 \times n]$, represented on equation 3.5.

Variable	MU	σ
BTN C	0.59	0.01
BTN B	0.157	0.01

n	LVN transformer station
j	BTN class
w	Node composition array
BTNRate	BTN class rate per transformer station

Table 3.4: Parameters used on function *mvnrnd* and variables meaning

$$BTNRate_{C,n} = mvnrnd(MU_j, \sigma_j, n) \times 100 \tag{3.2}$$

$$BTNRate_{B,n} = mvnrnd(MU_j, \sigma_j, n) \times 100 \tag{3.3}$$

$$BTNRate_{A,n} = 100 - (BTNRate_{C,n} - BTNRate_{B,n}) \tag{3.4}$$

$$w_{j,n} = BTNRate_{j,n} \tag{3.5}$$

3.3.3 Load Profile Adjustment to the LVN

As already referred, the load profiles provided by ERSE are built with normalized values. To establish the relation between the normalized values and the chosen LVN load characteristics, a adjustment is made, according to the peak loads registered on the transformer stations.

As referred in Load Profile Composition, each node has is own BTN classes weight, so the adjustment process is sensible to that factor, since the peak load periods differ in each BTN class. Therefore, an individual load profile is composed by a array of dimension $[4 \times 96]$, in order to set in each node separated profiles by BTN class, and for the total load on the transformer station. The load profiles are built for a daytime, in 15 minutes periods, which adds up 96 load values per profile.

The adjustment of the normalized values is made by comparing the transformer station annual peak load, and the higher normalized value on ERSE profiles, individually per each BTN class. This ratio is calculated as in equation 3.6 and is calculated for each LVN transformer station, due to the different peak loads.

$$R_{j,n} = \frac{TSPL_n}{max(x_j)} \tag{3.6}$$

The peak loads are achieved on winter, so this procedure does no fit to Summer/Spring load profiles. To avoid this issue, it is effected an correction, when it comes to Summer/Spring load profiles. This correction is made by calculating a correction factor, to be applied when necessary. The factor is calculated by comparing, individually per each BTN class, the peak normalized values on ERSE profiles with the peak normalized values during Summer/Spring days. This is represented on equation 3.7. Therefore, the ratio for adjustment when it comes to Summer/Spring load profiles is made as in equation 3.8.

$$SSCF_j = \frac{max(x(SS)_j)}{max(x_j)} \tag{3.7}$$

$$RSS_{j,n} = \frac{TSPL_n \times SSCF_j}{max(x_j)} \tag{3.8}$$

Possessing the ratios that enable the profiles adjustment, all necessary data to proceed to the load profiles construction, out for use in the case study. To enable a good analysis, every value of the load profile is able to be observed. Since an individual load profile is stored on a $[4 \times 96]$ array and for *Matlab* practical issues, all the arrays are themselves stored at a cell with dimension equal to the number of transformer stations on the LVN, n. The construction process, according to the season required for study, follow the next equations. It shall be noted that equations 3.10 refer to Summer/Spring load profiles.

$$LoadProfile_{n,j,t} = x(\bar{i})_{t,j} \times R_{j,n} \times w_{j,n} \tag{3.9}$$

$$LoadProfile_{n,j,t} = x(\bar{i})_{t,j} \times RSS_{j,n} \times w_{j,n} \tag{3.10}$$

The variables meaning used on the presented equations are available on table 3.5. Some of the variables were presented before in table 3.2. As it was been referred previously, it shall be noted that all this algorithms are implemented on *Matlab*. It shall be noted that this algorithm besides providing different load profiles for power flow execution on the case study, also provides an average annual load profile, that will be required to relate the LVN and statistical data about domestic consumers.

3.4 Domestic Consumers Statistical Data

Analysing the flow char in figure 3.3, it is possible to observe that some statistical data is required to execute determined algorithms, namely the definition of the number of domestic consumers and the load availability stipulation. This data will be combined with information gathered from load profile generation, and with household appliances modelling, subject addressed later on others

Variables	Values
n	LVN transformer station node
j	BTN class
t	Day time
R	Adjustment ratio for Winter/Autumn
RSS	Adjustment ratio for Summer/Spring
w	BTN class weights
$SSCF$	Peak load correction factor for Summer/Spring
i	Load profile type
x	Normalized values
$x(SS)$	Normalized values only for Summer/Spring
$TSPL$	Transformer station peak load
$LoadProfile$	Load profile out for case study

Table 3.5: Variables for Load Profile values calculation

sections on this thesis. The statistical data required, refers to values of energy consumption in general, and more specific, namely by type of consumption and relating with household appliances usage. The data available reflect the Portuguese average patterns.

3.4.1 Domestic Costumers Stipulation

In 2010, the INE (Instituto Nacional de Estatístisca), the Portuguese statistical national institute, executed an national survey on energy consumption in the domestic sector [30]. Among other things, the study provides information about energy consumption discriminating it by type and areas of usage. By other side, ERSE also provides data about energy consumption on the Portuguese LVN. An accurate stipulation of the number of domestic customers on the LVN, ensures that is also possible to have a good approximation to the number of total household appliances functioning on the grid. However, it is a complex calculation, because a domestic costumer is not constricted to any BTN class, as he is free to chose his contracted power on the energy market, as well as very different consumption behaviour and annual consumption. Thereby, when simulating a load profile, all type of LVN costumers are included: residential, industry, business and hostelry. Summarizing, although it is know that most of domestic costumers fit on BTN C class, due to this class characteristics, but it is impossible to assume that BTN C load shape reflects only domestic clients. Howsoever, there are possible approaches considering average values for LVN load profiles, annual and daily power consumptions, number of costumers, as well as the existing domestic costumers statistical data.

According to data made available by ERSE, in 2010 the BTN had 6026198 clients and the annual electricity consumption were up 20051 GWh [29]. In the other hand, INE allege that there are 3927333 residential buildings consuming electricity energy [30]. They also state that the total electricity energy used reaches approximately 14442 GWh. The collected data are available on table 3.6.

Factor	Values
BTN costumers	6026198
Domestic costumers consuming electricity	3927333
BTN energy consumption	20051 GWh
Domestic costumers power consumption	14442 GWh

Table 3.6: Statistical Data gathered related to LVN domestic costumers

The procedure for stipulating the number of domestic consumers is sustained on one simplification: the load profile on the substation for a given LVN correspond to the Portuguese average consumption behaviour, i.e. in the aggregation of the load profiles from the transformer stations is considered to reflect the Portuguese average, but the same is not true for an individual transformer station node.

The data on table 3.6 allows to proceed to some assumptions, with accurate precision, like the weight of the residential load on the LVN operation (should be noted that this value is for annual load) and average load per residence. The necessary calculation are shown on equations 3.11 and 3.12.

$$Residential\ Load\ Weight\ on\ LVN = \frac{14442104354}{20051000000} \times 100 = 72.03\% \tag{3.11}$$

$$Average\ load\ for\ domestic\ costumer = \frac{14442104354}{3927333} = 3677.3\ (kWh/Costumer) \tag{3.12}$$

By combining this data with the created load profiles for a LVN, and assuming the simplification previously stated, it is possible to get an approximated stipulation of the number of domestic constumers on the LVN . This stipulation is made by following the steps below.

1. The annual average load shape is provided by the algorithm load profile generator. This profile enable to calculate the daily average load consumption in the LVN, in kWh. The calculus is shown on equation 3.13. It shall be noted that the time frame used is 15 minutes, as previously referred.

$$DailyLVNconsumption = Load\bar{P}rofile_{i,j} \times hour(kWh) \tag{3.13}$$

2. The daily average load multiplied by the number of days of the corresponding year gives the annual LVN consumption, as in equation 3.14.

$$AnnualLVNconsumption = DailyLVNconsumption \times Days(kWh) \tag{3.14}$$

3. Possessing the LVN global power consumption, it is possible to apply the previous average residential load weight on the Portuguese grid. Assuming that the LVN corresponds to the average, applying the 72.03% gives the total domestic consumption in an LVN, as in equation 3.15.

$$Residential\ annual\ consumption = Annual\ LVN\ consumption \times 72.03\%(kWh) \quad (3.15)$$

4. Finally, in this step we stipulate the number of residential costumers. Possessing the residential annual load, and assuming the Portuguese average domestic costumer consumption, dividing it provides an approximated number of domestic costumers on the LVN, as in 3.16. As the result is probably an fractional number, it is rounded by the minimum, aiming to the worst case.

$$Domestic\ costumers = \frac{Residential\ annual\ consumption}{Average\ load\ for\ domestic\ costumer} \quad (3.16)$$

In order to execute the steps announced behind, there are two values that will be needed, namely the residential load weight, and the average domestic costumer consumption. This values are available on table 3.7.

Factor	Values
Average residential load weight on LVN	72.03 %
Average load for domestic costumer	3667.3 (kWh)

Table 3.7: Average values used for domestic costumer stipulation

Its imperative to underline that these obtained values spin through the Portuguese average consumption behaviour. Influence factors, namely geography, demography, lodging characteristics, costumers health and education level of the used LVN are not taken in consideration, as well as individual transformer station nodes.

3.4.2 Household Aplliances on Domestic Costumers

In the previous section Domestic Costumers Stipulation, it is defined a procedure that stipulates the number of domestic costumers on a given LVN. However, every costumers as different needs and consumption habits, as well different equipments possession. Considering an certain population, it is possible to stipulate the number and type of equipments operating on a given LVN. All the chosen equipment are non time critical, and their power consumption is related to thermal mass heating or cooling, as referred on chapter 2. Thereby, the household appliances that will be modelled and simulated on this work are electric water heaters, fridges, freezes and HVAC systems, as previously stated on page 15. Some of the domestic costumers possess more than one unit of the same equipment, but they are also accounted and considered an operational. Thus, according to data available by INE in [30], in Portugal, the percentages of possession of the equipment to model are the shown on table 3.8.

Before presenting the possession rate, it shall be referred that there are three types of fridges considered:

- Fridge. This equipment is composed by only one storage structure and temperature.
- Fridge with freezer. This equipment is composed by two storage structures with different doors and temperatures.
- Combined fridge freezer. This equipment is composed by two storage structures with only one door but and different storages temperatures.

The HVAC systems are also accounted by different types, more concretely two of them: for heating and for cooling. Although HVAC systems allegedly are able to heat or cool the air on a infrastructure, most of HVAC equipment for domestic use have only one ability/usage. Among others, one of the reasons for this fact is Portugal mild climate. Different and suitable solutions for heat/cool are more commonly used.

Household Appliance	**Possession rate (%)**
Electric Water Heater	11.2
Fridge	5.7
Fridge with Freezer	58.3
Combined Fridge Freezer	37.6
Freezer	47.6
HVAC for Heating	10.67
HVAC for Cooling	2.02

Table 3.8: Possession rates of Household Appliances

Applying this data on the number of domestic costumer for a given LVN, it is possible to stipulate the number of equipments operating on the grid, just as in equation 3.17,3.18,3.19,3.20,3.21,3.22 and 3.23. Once again, fractional results are rounded by the minimum, pointing to the worst case. The abbreviations used to represent household can be observed on table 3.9.

$$EWH\ equipments\ on\ LVN = Domestic\ costumers \times 11.2\% \tag{3.17}$$

$$F_1\ equipments\ on\ LVN = Domestic\ costumers \times 5.7\% \tag{3.18}$$

$$F_2\ equipments\ on\ LVN = Domestic\ costumers \times 58.3\% \tag{3.19}$$

Abbreviation	Meaning
EWH	Electric Water Heater
F_1	Fridge
F_2	Fridge with Freezer
F_3	Combined Fridge Freezer
F_4	Freezer
$HVAC_1$	HVAC for Heating
$HVAC_2$	HVAC for Cooling

Table 3.9: Abbreviations used for household appliances

$$F_3 \ equipments \ on \ LVN = Domestic \ costumers \times 37.6\% \tag{3.20}$$

$$F_4 \ equipments \ on \ LVN = Domestic \ costumers \times 47.6\% \tag{3.21}$$

$$HVAC_1 \ equipments \ on \ LVN = Domestic \ costumers \times 10.67\% \tag{3.22}$$

$$HVAC_2 \ equipments \ on \ LVN = Domestic \ costumers \times 2.02\% \tag{3.23}$$

3.4.3 Household Appliances Load Weight on LVN

In the survey on energy consumption in the domestic sector provided by INE, the load consumption from certain household appliances is available. This enables to analyse their load weight on the LVN operation, considering as well the average possession rates and energy consumption. This data correspond to annual usage, and can be observed on tables 3.10 and 3.11, is possible to observe the gathered data from [30], as well as some required assumptions computed, since some values are provided on tep and need to be converted to MWh and kWh. The conversion rate is shown on equation 3.24. The tables contain information about total consumption in Portugal and per Portuguese costumer that uses the household appliance (which implies a different sampling) respectively. It shall be noted that there are no data about fridges and freezers power consumption, so the related data presented is about kitchen equipments, and the INE population sample used for EWH only considered lodges with water piping system installed.

$$tep = 11.63MWh \tag{3.24}$$

Source	Energy Consumption (tep)	Electricity Rate (%)	Power Consumption (MWh)
Water Heating	583040	3.37	228401.57
Space Heating	533892	13.93	864667.24
Space Cooling	13107	100	152434.41
Kitchen	971933	34.22	3867637.91

Table 3.10: Total energy and electricity consumption by source on 2010 in Portugal

Source	Electricity Consumption (kWh)
Water Heating	430.31
Space Heating	418.68
Space Cooling	174.45
Kitchen	988.55

Table 3.11: Average consumption per costumer by source on 2010 in Portugal

3.5 Electric Water Heater Load Model

To simulate the household appliance EWH functioning and analyse his power consumption as well as duty cycles, it is used a simplified model developed in [31]. This model demonstrates the heat transfer process, stipulating the work state of the heating device and temperatures variations. The EWH heating resistance only works on on /off state, so his load corresponds to heating resistance power consumption.

This work applies only the one node model, that considers that the water in the tank has a uniform temperature. Thus the inlet water in the bottom of the EWH, where the thermostat is placed, will supposedly have the same temperature that the outlet water in the top of the EWH. Normally, the device is in on working state whenever there is cold water inside the EWH, more concretely on the bottom. This temperature differences inside EWH tank will not be calculated.

As the household appliances modelling and simulation serve mere indicators to measure their power consumption impact on the grid, there are different features to be model beside equipment functioning: power capacity and usage habits.

3.5.1 Electric Water Heater Operation Model

The heat transfer process on a EWH, as stated in [31] can be modelled as a first order differential equation:

$$Q_{elec} - mC_p(T_W - T_{Inlet}) + UA_{wh}(T_{Amb} - T_W) = C_w \frac{dT_w}{dt} \tag{3.25}$$

The meaning of the variables on the equation and corresponding units of measurement can be verified in table 3.12.

	Variables	Units of measurement
Q_{elec}	Heating capacity of the resistor	BTU/hour
m	Hot water flow rate	$lb/hour$
C_p	Thermal capacitance	$BTU/(lb*{}^{o}F)$
T_W	Water inside tank temperature	${}^{o}F$
T_{Inlet}	Inlet water tank temperature	${}^{o}F$
T_{amb}	EWH local room temperature	${}^{o}F$
C_w	Thermal capacitance	$BTU/{}^{o}F$

Table 3.12: Variables and respective units of measurement for EWH Model

This model calculates the actual temperature of the water inside the tank. This temperature serves to evaluate if the device must be on or off. To control the switching of the EWH, it is designed a set point temperature T_{WSet}, and a bandwidth for thermostat action T_{WBand}. The switching logic, represented by EWH_{State} depends on water temperature and water consumption, and is the follow:

$$If: \quad T_W \geq T_{WSet} + T_{WBand} \ \wedge \ m = 0 \,, \qquad EWH_{State} = 0 \tag{3.26}$$

$$If: \quad T_W \leq T_{WSet} - T_{WBand} \,, \qquad EWH_{State} = 1 \tag{3.27}$$

The most common set point temperature T_{WBand} in EWH devices is 60^{o}C, and the thermostat bandwidth T_{WBand} is 2^{o}C. The other parameters needed for model application vary, according with simulations objectives. The calculation of the first order differential equation has a one second resolution, but the switching logic is verified in five minutes time frames, to respect EWH hardware operation (heater resistance and thermostat).

Next, its possible to observe a individual EWH behaviour simulation, namely temperature and power consumption. The parameters used in this example are in table 3.13. Given the parameters units of measurement used in model application, they are already converted for S.I. for better understanding. In this case the water consumption and environment temperatures are random, as an example. The simulation is for a day time.

Variables	Values	Units of measurement
Q_{elec}	2	kW
C_p	1	$BTU/(lb*{}^{o}F)$
T_{Inlet}	15	${}^{o}C$
T_{amb}	10	${}^{o}C$
C_w	471.11	$BTU/{}^{o}F$

Table 3.13: Parameters for individual EWH simulation

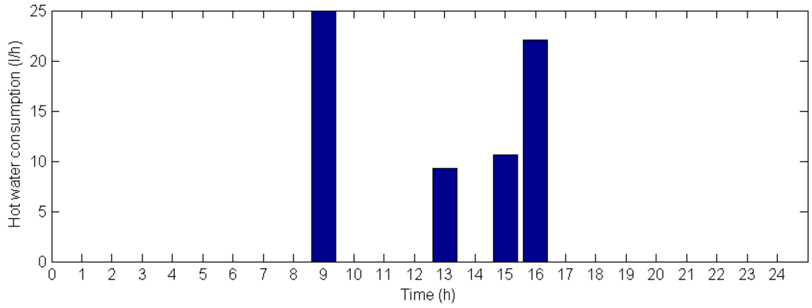

Figure 3.4: Hot water consumption for a single EWH simulation

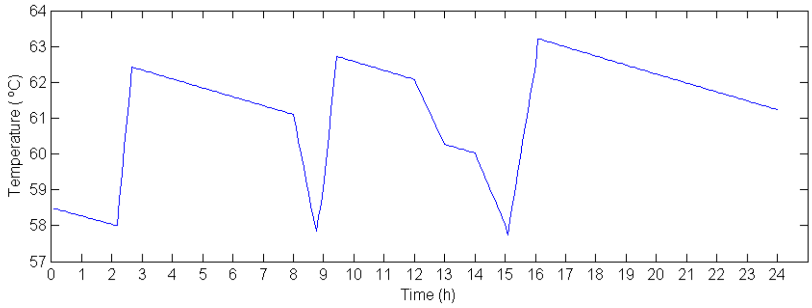

Figure 3.5: Temperature behaviour for a single EWH

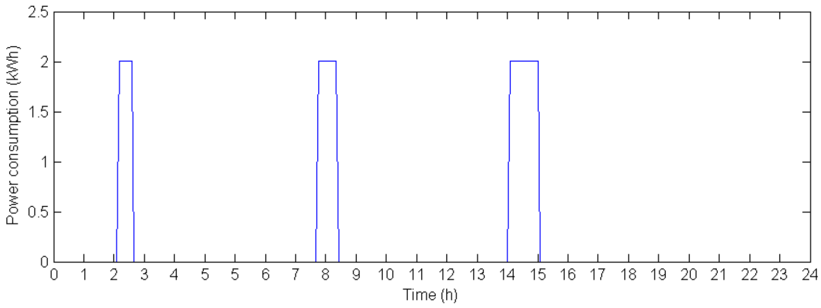

Figure 3.6: Power consumption behaviour for a single EWH

For solving the water temperature differential equation it is used numerical analysis, more concretely the method Runge-Kutta of forth order with five minutes resolution. This is proceeded by the *Matlbab* function $ode45$, with the following setting: $odeset('Abstol', 1e-2, 'Reltol', 1e-2)$.

3.6 HVAC for Heating Load Model

To model the household appliance HVAC functioning and analyse his power consumption as well as his duty cycle, it is used a simplified model developed in [32]. This model demonstrates the heat transfer process, stipulating the work state of the heating device and temperatures variations. The HVAC heating system is considered to work only on on/off state, so his load corresponds to the power capacity.

3.6.1 HVAC Operation Model

Since this thesis preforms to residential load modelling, normally corresponding to small building the simplified model fits and can be used with good approximation to more accurate models. The model is derived from a simplified equivalent thermal parameters model, as stated in [32]. The model was targeted of several simplifications, enable the calculation of the room temperature variation, according to outdoor temperature, room air mass resistance, HVAC parameter and respective state of work. The heat transfer process has the following model according HVAC state, represented by variable $HVAC_{State}$ logic value, following the patterns defined on equations 3.28.

$$If: HVAC_{State} = 0, \quad T_{Room}^{t+1} = T_{Amb}^{t+1} - (T_{Amb}^{t+1} - T_{Room}^{t})e^{\frac{\Delta t}{RC}} \tag{3.28}$$

$$If: HVAC_{State} = 1, \quad T_{Room}^{t+1} = T_{Amb}^{t+1} + QR - (T_{Amb}^{t+1} + QR - T_{Room}^{t})e^{\frac{\Delta t}{RC}} \tag{3.29}$$

The variables R ,Q and C are curve fitting parameters, framing the performance curves produce by precise physical model. These simplification technique used, presents reasonable results and enables the simulation of large number of HVAC appliances with no computational problems. The variables and respective units of measurement used on the heat transfer model can be observed in table 3.14. The author establishes a relation between HVAC power and C fit curve, although they have the same unit of measurement. HVAC power used to calculate the household appliance power consumption. As most of the appliances with thermostatic control, the working state of the HVAC depends on temperature measures by the thermostat, respecting the temperature set points regulated by the user and the respective equipment bandwidth. As such, the on/off state logical value is defined by the equations 3.30.

	Variables	**Units of measurement**
Q	Equivalent heat rate	W
R	Equivalent thermal resistance	$^{o}C/W$
C	Equivalent heat capacity	$J/^{o}C$
T_{Room}	Temperature in HVAC room	^{o}C
T_{Amb}	Ambient temperature	^{o}C
Δt	Time Step	minute

Table 3.14: Variables and respective units of measurement for HVAC Model

$$If: \quad T_H \geq T_{HWSet} + T_{HWBand} \,, \quad HVAC_{State} = 0 \tag{3.30}$$

$$If: \quad T_H \quad \leq \quad T_{HWSet} - T_{HWBand} \ , \qquad HVAC_{State} = 1 \tag{3.31}$$

As in section Electric Water Heater Load Model, an example of individual HVAC behaviour is presented, namely temperature and power consumption. The parameters used are in table 3.15.

Variables	Values	Units of measurement
Q	800	W
R	0.1208	$^oC/W$
C	3599.3	$J/^oC$
T_{Room}	20	^oC
T_{Amb}	10	^oC
Δt	1	m

Table 3.15: Parameters for individual HVAC simulation

The results of individual simulation are shown on figures 3.7 and 3.8. Since the environment temperatures are considered constant, the room temperature values controlled by the HVAC, presents a recurring pattern, as well as the power consumption. However, it shall be stated that at the time that LVN load peaks are most likely, the environment temperatures are closer to the used on the model.

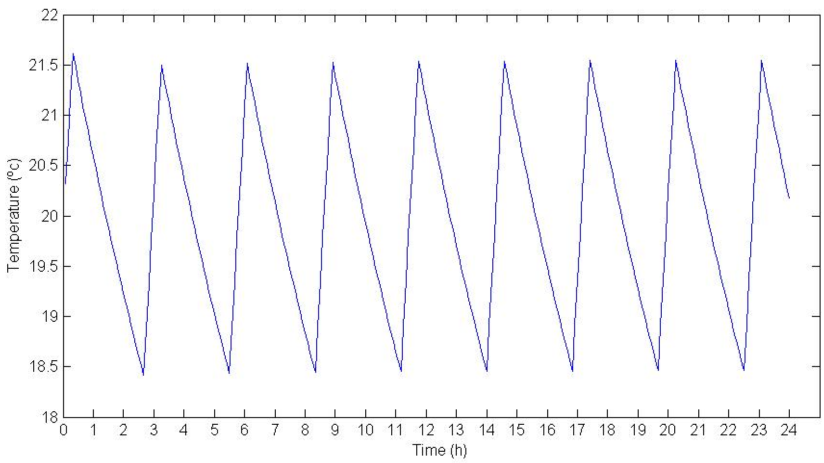

Figure 3.7: Temperature behaviour for a single HVAC simulation for 10^oc environment temperature

3.7 Fridge and Freezer Load Model

To model the household appliances related to cooling storage, namely fridge, freezer, combined fridge freezer and fridge with freezer, it is used a simplified model developed in [33]. This modelling will enable to analyse their functioning patterns, more specifically power consumption, tem-

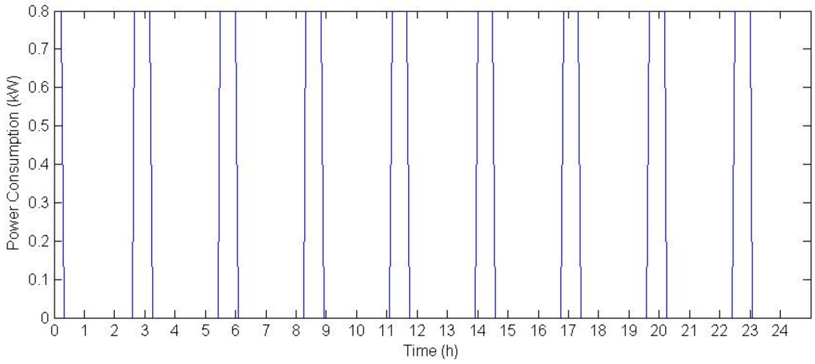

Figure 3.8: Power consumption behaviour for a single HVAC simulation for $10^{o}c$ environment temperature

perature and duty cycles. In a similar mode as HVAC, the model demonstrates the heat transfer process, stipulating the work state of the heating device and temperatures variations. The HVAC heating system is considered to work only on on/off state, so his load corresponds to the power capacity.

3.7.1 Fridge and Freezer Operation Model

As already referred, there are four types of storage cooling devices. If on one hand we have the fridge and freezer that can be modelled exactly has in [33], the combined fridge freezer and fridge with freezer have different operation methods, since they have separated storages compartments and the compressor has to satisfy temperature requirements for both. Nowadays, the combined fridge freezer and fridge and freezer have only on compressor working, that requires more power consumption. The difference between the only one storage compartment lies on the valves working method. Hereupon, in order to surpass this issue, it be considered a major simplification: the combined fridge freezer and the fridge with freezer patterns are the same, and related to individual fridge and freezer patterns, with a weight of 50% for the freezer section (the freezer compartment in this two equipments is smaller than a normal freezer). Beside this simplification, there are other two: it is considered that the environment temperature is constant and the doors open and close events not taken into account. All this simplifications may induce errors but the indicators needed for this thesis are acceptable. Therefore, the models presented refer to individual fridge and freezer.

The heat transfer process has the following model according to the device state, represented by variable $FState$ logic value, following the patterns defined on equations 3.32, 3.34 and 3.34.

$$If : F_{State} = 0, \quad T_{i+1} = \varepsilon(T_i - T_{Amb}) + T_{Amb} \tag{3.32}$$

$$If: F_{State} = 1, \quad T_{i+1} = \varepsilon(T_i - T_{Amb}) + T_{Amb} - \eta\frac{P}{A}(1-\varepsilon) \tag{3.33}$$

$$Where: \quad \varepsilon = e^{\frac{\Delta t A}{m_c}} \tag{3.34}$$

This simplified model presents reasonable results and enables the simulation of a large number of devices without computational problems. The variables and respective units of measurement used on the heat transfer model can be observed in table 3.16. As most of the appliances with thermostatic control, the working state of the storage cooling devices depends on temperature measures by the thermostat, respecting the temperature set points regulated by the user and the respective equipment bandwidth. As such, the on/off state logical value is defined by the equations 3.35 and 3.36.

	Variables	**Units of measurement**
T	Temperature on storage compartment	^oC
T_{Amb}	Environment temperature	^oC
η	Yield	-
P	Power consumption	W
A	Thermal conductivity	kWh/K
m_c	Thermal mass	kWh/K
Δt	Time Step	min

Table 3.16: Variables and respective units of measurement for fridge and freezer models

$$If: \quad T_i \geq T_{FSet} + T_{FBand}\ , \quad F_{State} = 0 \tag{3.35}$$

$$If: \quad T_i \leq T_{FSet} - T_{FBand}\ , \quad F_{State} = 1 \tag{3.36}$$

As in section Electric Water Heater Load Model, an example of individual fridge and of the freezer behaviour is presented, namely temperature and power consumption. The parameters used are in table 3.17.

The results of individual simulation are shown on figures 3.9 and 3.10. Once again, since the environment temperatures are considered constant, and because the door open and close events are not taken into consideration, the temperature inside the storage compartment of the fridge presents a recurring pattern, as well as the power consumption. The storage cooling devices work all day, so it is not expected to verify strong variations from load demand contribution for the LVN from them. The environment temperature chosen for the simulation is 15^oc, higher than the considered 10^oc for the HVAC, in order to account the heat on the fridge location spot.

For the simulation of the freezer, there were a few aspects to take into consideration even if very subjective, relatively to the fridge simulation. Although the model used is the same, the power

Variables	Values	Units of measurement
P_{F_1}	70	W
P_{F_4}	100	W
A	3.21	kWh/K
m_c for F_1	5	kWh/K
m_c for F_4	10	kWh/K
η for F_1	3	-
η for F_4	4.5	-
T_{Amb} for F_1	25	^oC
T_{Amb} for F_4	15	^oC
Δt	1	m

Table 3.17: Parameters for individual fridge and freezer simulation

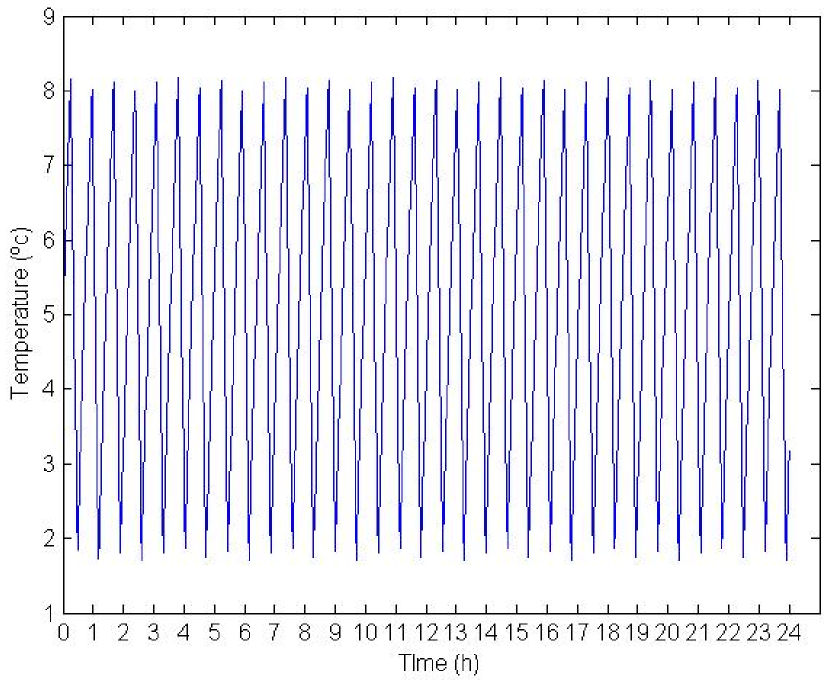

Figure 3.9: Temperature behaviour for a single fridge simulation for 25^oc environment temperature

capacity, thermal mass yield are not the same. The freezer is considered to have a slightly yield because it opened less times. The thermal mass is also higher because normally, a freezer tend to be more occupied, instead of a fridge which as more empty space, due to ergonomic issues. The power consumption of the freezer, as a similar pattern to the fridge, so it is not represented. The combined fridge freezer and the fridge with freezer are not simulated, but the procedure to account their respective power consumption in later discussed on this thesis with further detail.

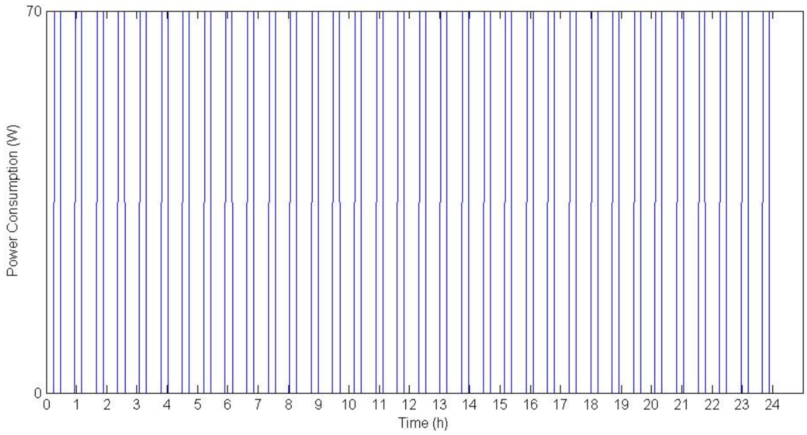

Figure 3.10: Power consumption behaviour for a single fridge simulation for 25^{o}c environment temperature

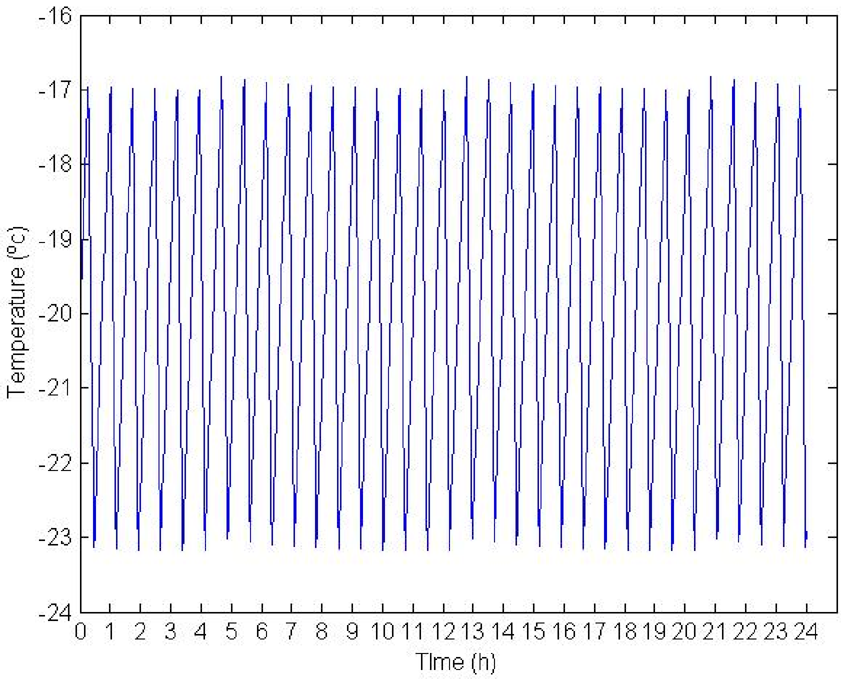

Figure 3.11: Power consumption behaviour for a single freezer simulation for 15^{o}c environment temperature

3.8 Load Availability

In order to analyse the number of equipments available for management in the LVN, on a random time of the day, there are some aspect that shall be known. To shut down an equipment, it must be working and presenting conditions so that if it is actually turned off, the costumer normal household appliance usage is not harmed. Therefore, in order to enable a definition in quantity of these equipments, there are three factors to take into account. These factors will be used later in the case study for defining in a determined period, the rate load availability from global LVN load. The factors are:

- **Equipment on/off state daily rate** — It is possible to establish a relation that enables to define the number of equipments (for each type) working on the LVN, i.e. with power consumption for a daytime, for determined time frames. These are annual average patterns.
- **On-line state working time periods** — Some equipments have an average working time, since it begins to consume power, i.e., achieving the on state. This information allows to evaluate the equipment control decisions. The values reflect average population patterns, since every costumer as his own patterns.
- **Term conditions for control** — It is necessary to establish the term conditions for enable the control of the equipment, shunting it from on state for off state during a time frame, namely 15 minutes. This period respect household appliances hardware requirements and load profile modelling construction in this thesis. Since the equipments to manage are all related to thermal mass manipulation, the decision on turning it off is made by analysing his temperature, which must be at least at the set point defined. The temperature can also be higher or lower than the set point, depending on being a heating or cooling device respectively.

In the next chapter Load Simulations and Case Study Preparation, this subject will analysed with further detail, in order to enable the stipulation off load available for management in kWh for a certain period of time.

Chapter 4

Load Simulations and Case Study Preparation

In this chapter, the models developed in chapter Literature Review and Load Modelling Concepts will be simulated and analysed, in order to prepare the case study. This thesis is based on the definition in quantity of available load for management, that will be further tested for solving congestion events. Hereupon, this thesis presents two different procedures in order to quantify the available load, which share the same concept. Both ways use the same load profiles, yet the results shall be different. One procedure analyses the load profiles and stipulate the available load, the other procedure simulates individual domestic consumers and respective household appliances, determining the available load through the equipment state and data. In order to get a better perspective on the procedures differences, the figure 4.1 presents a flow chart that shows the algorithms in common between both procedures and the factors that make them different.

As it is possible to observer in the flow chart, the same load profiles are used as reference, and the number of domestic consumers stipulated by the same equations demonstrated in section Domestic Costumers Stipulation. The differences start from here, and the final results for available load will be defined as *Load Availability I* and *Load Availability II*. Both definitions follow the concepts in section Load Availability, however the path for the load quantifying is different. The main difference between both is that in *Load Availability II* the household appliances are simulated for a daytime, always providing information about temperature and power consumption. Following, there is brief explanation of both procedures, before further detail in the upcoming sections:

- ***Load Availability I***— This procedure needs as inputs the number of domestic costumers on the LVN, as well as information about household appliances functioning. Combining this statistical data, it is possible to quantify the load available for a certain period (t) of the day.

- ***Load Availability II***— This procedure needs as inputs the number of domestic costumers on the LVN. With this data, an algorithm will simulate residences and respective characterization, as well as equipments assignment with different characteristic according to the

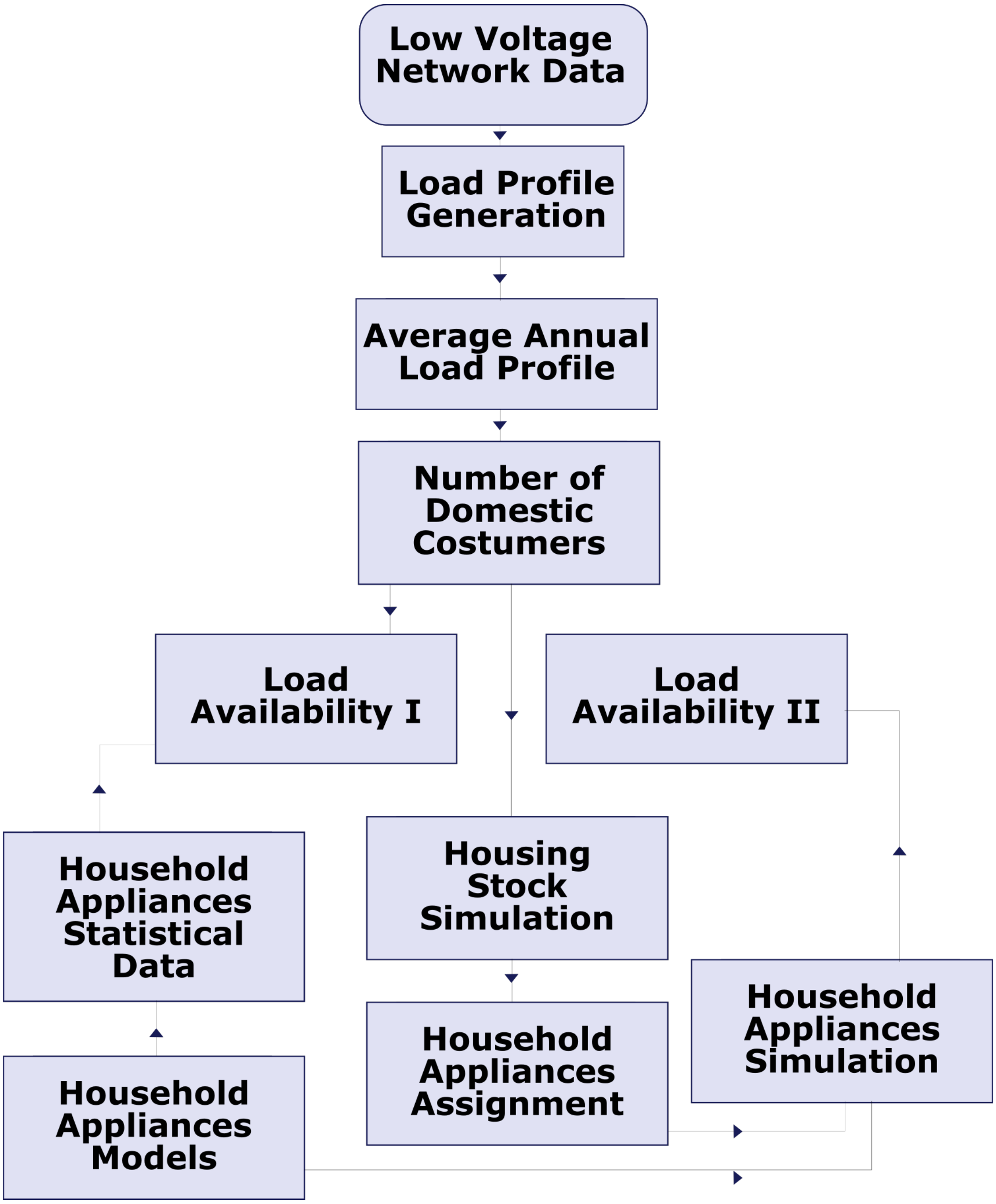

Figure 4.1: Models and data crossing architecture

residence. The equipment operation are then simulated for a daytime. For a certain period (t), all the equipments states are analysed and the available load quantified.

In the next sections, the procedures will be presented, at first the common issues between procedures, and then *Load Availability I* followed by *Load Availability II*. Both procedures are implement on *Matlab*.

4.1 Load Profiles

As referred on section Low Voltage Network Load Profiles, the load profile generation algorithm provides different types of load profiles, enabling different studies. Regardless the types chosen for the case study, in this section some examples of load profiles will be presented, for the global consumption of an LVN, as well for a single node, in order to retain the differences between nodes on the LVN.

The annual load profile is required for the number of costumers on the LVN. In the next figures 4.2, 4.3 and 4.4 it is possible to compare the annual average load, with the different load profiles types. The load profiles types chosen are Winter/Autumn an Summer/Spring on a weekday.

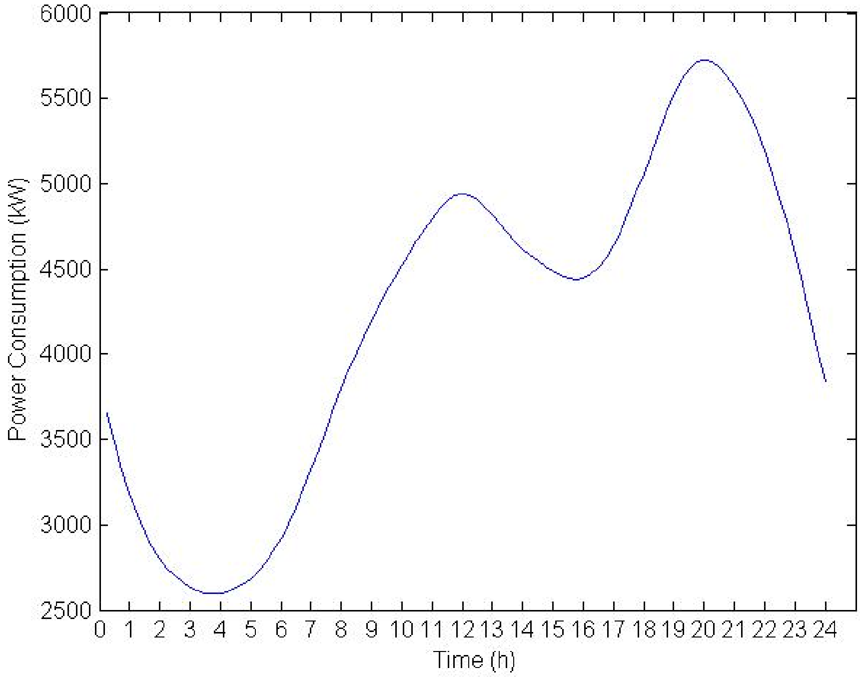

Figure 4.2: Annual average LVN load profile example

It is possible to observe the peak loads magnitude variation between the three load profiles. As expected, on Summer/Spring, there are two peaks, on during the lunchtime and other at dinner. It shall be noted that this load profiles refer to global consumption on the LVN. In this example 20 transformer nodes were considered. As stated in section Low Voltage Network Load Profiles there are 6 types of load profiles, regarding day of the week and season. In figure 4.5 it is possible to observe the differences between all load profile types. For reference, the annual average load is the dark blue shape.

The load profiles presented show the global consumption. However in global consumption it is no possible to observe the differences caused by different BTN classes contribution. In figures 4.6 and 4.7 it is possible to observe two transformer stations nodes with analogue characteristics.

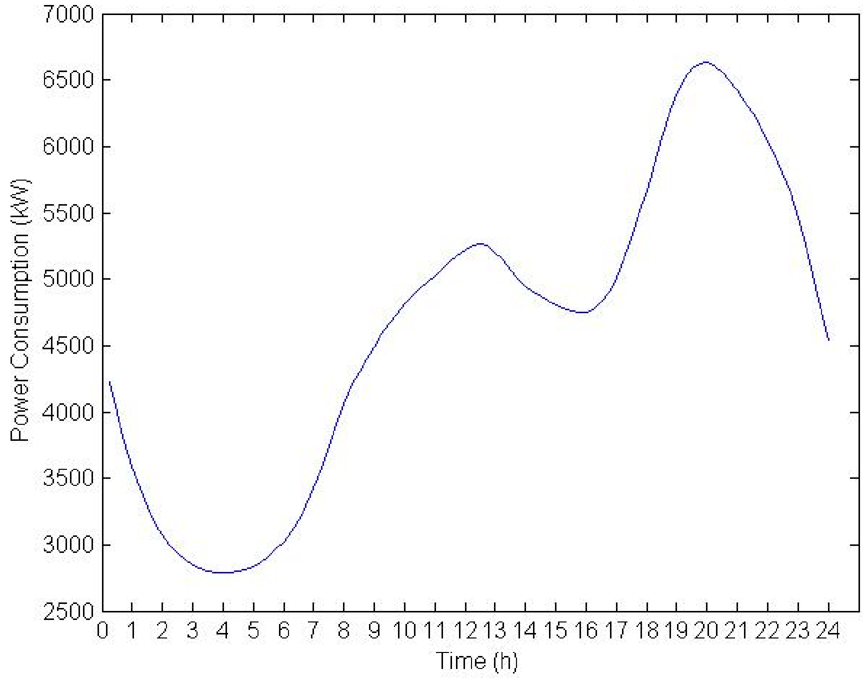

Figure 4.3: Winter/Autumn on weekday LVN load profile example

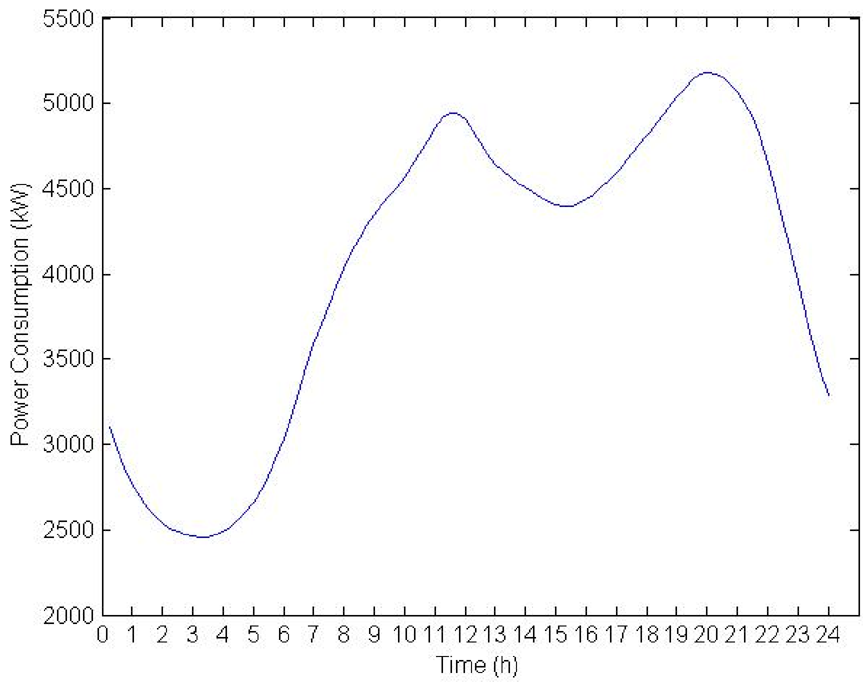

Figure 4.4: Summer/Spring on weekday LVN load profile example

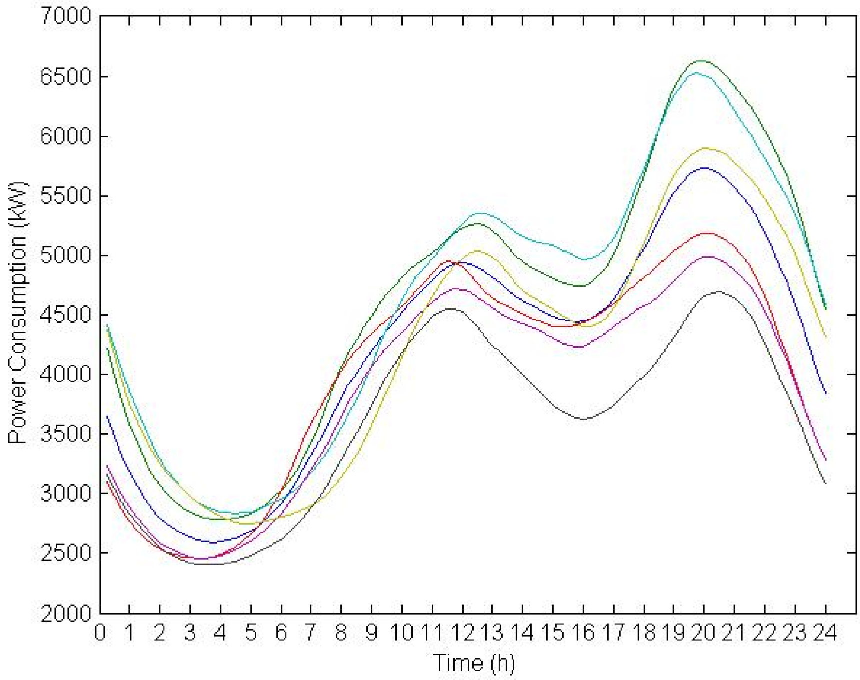

Figure 4.5: Comparation between LVN load profiles types and annual average load

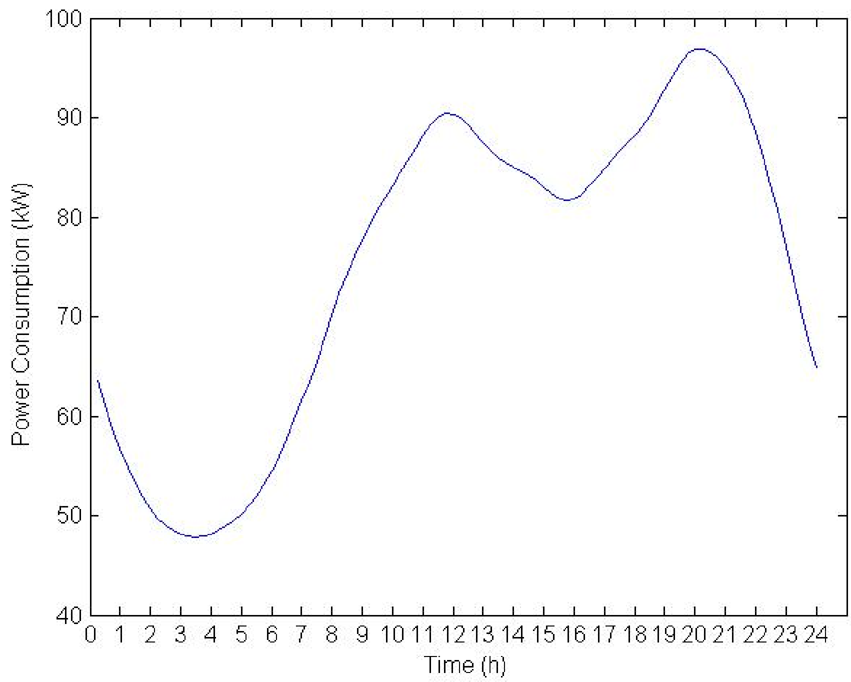

Figure 4.6: Single node transformer station load profile example

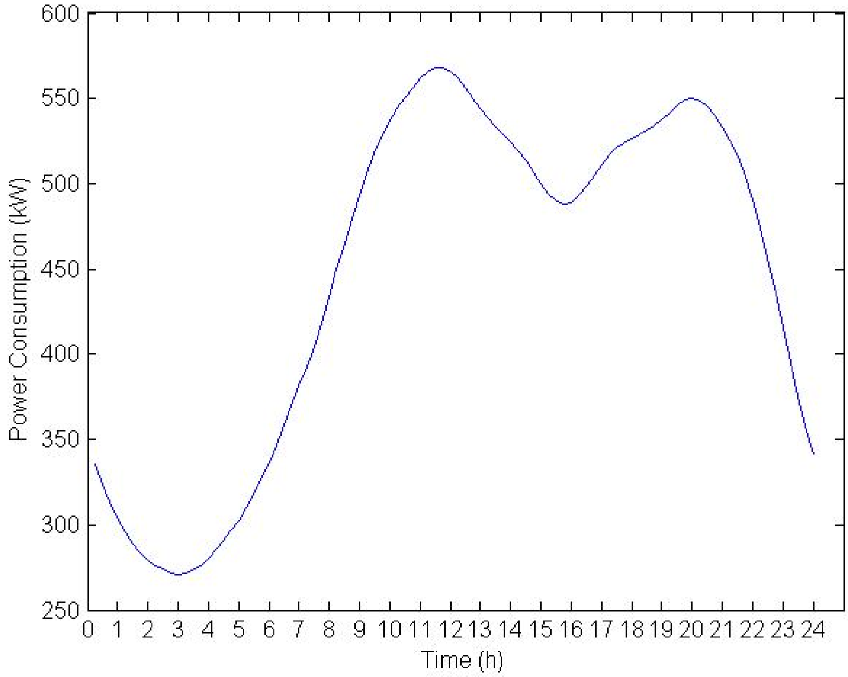

Figure 4.7: Single node transformer station load profile example

The load profile on figure 4.6 has BTN classes contribution closely to Portuguese average referred on page 21. The load profile on 4.7 has more BTN A weight on the load, and null contribution from BTN B class, wich means that the this transformer station is more likely to provide power to the industrial sector. It is also verified that one transformer station has a higher power consumption and contribution for the global consumption of the LVN. In the figures 4.8 and 4.9, it is possible to observe the respective load for each BTN class, for both load profiles.

As it is possible to observe, as expected there are different peak loads and different shapes according to the BTN class. It shall be noted as well that the load type chosen for these examples is the Winter/Autumn for a weekday. Finally, in the figure 4.10 it is possible to see how two different transformer stations contribute for the global consumption in the LVN.

The fact of assigning different BTN classes contributions per node, implies that every single node would have different costumers characterization, namely industry, commerce and domestic, which means that the load available for management varies from node to node, no only because his peak load registered during a year.

This procedure has the intention to aboard that issue, however the available load for management is stipulated on the global consumption from the LVN. In the case study this subject is analysed with further detail.

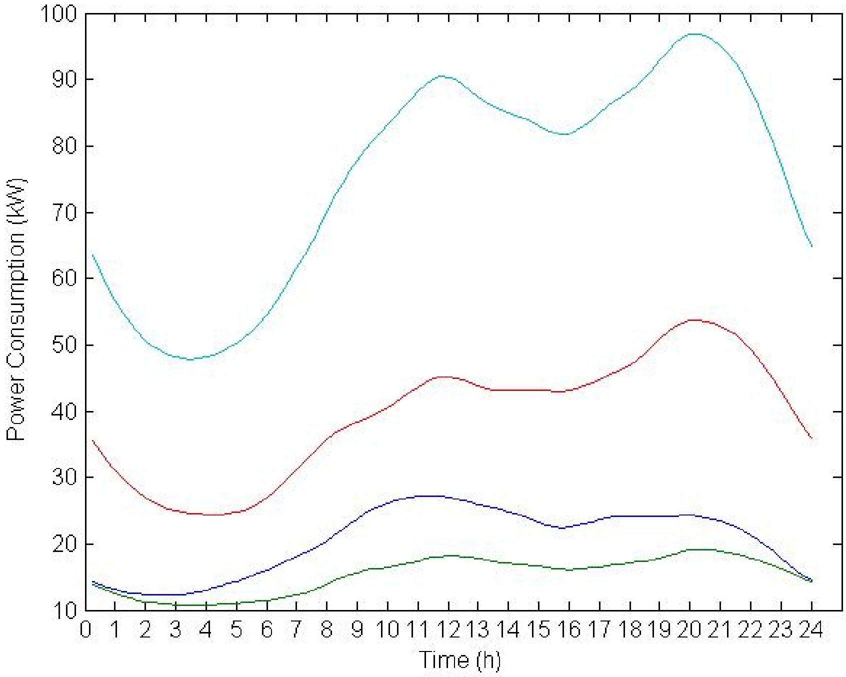

Figure 4.8: BTN classes contribution on from load profile 4.6 example

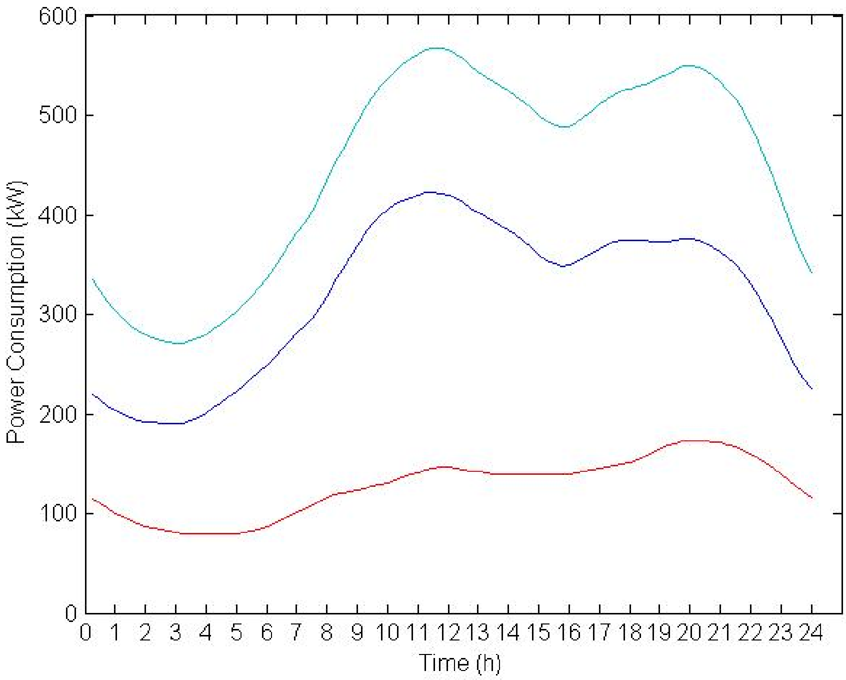

Figure 4.9: BTN classes contribution on from load profile 4.7 example

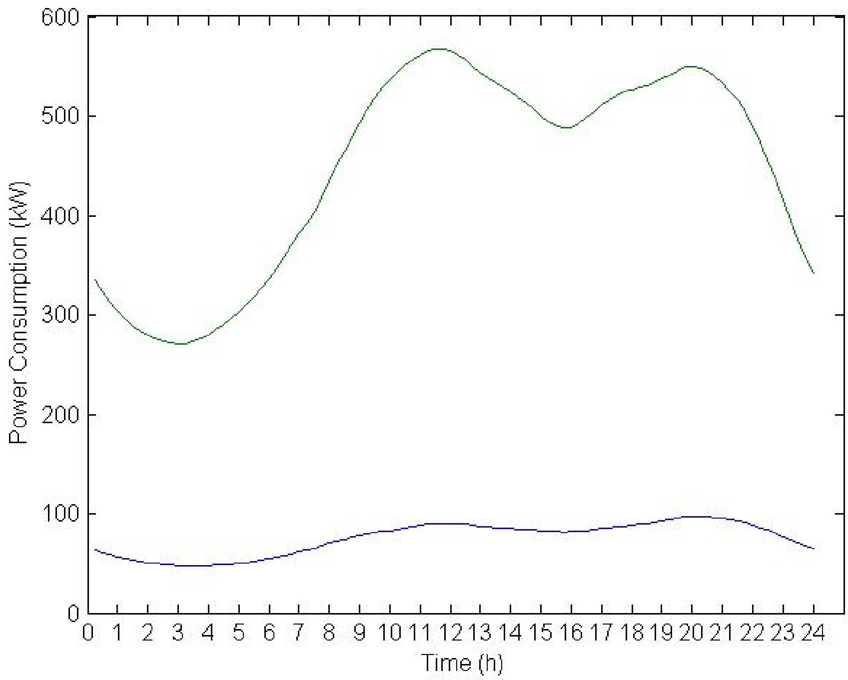

Figure 4.10: Comparison between profile 4.6 and profile 4.7

4.2 Load Availability I Procedure

This first procedure for quantifying the load availability for management during LVN operation, is the main indicator in thesis for determining the viability of use of active load control for congestion management concept. This indicator is primordial because is targeted with less random variables, being less subjective than procedure Load Availability II. This procedure consists on leaching from the a certain domestic costumer population, the load from household appliances able to be active controlled. This means that there are several stipulations, namely the number of equipments operating, and the operation patterns. In the next sections, this subject is analysed with further detail. It shall be noted that the calculation of the number of domestic costumers was already explained on section Domestic Costumers Stipulation.

4.2.1 Electric Water Heater Data for Control Enabling

The individual EWH operation has been previously discussed in section Electric Water Heater Load Model, where is possible to verify how the equipment operates when there is hot water consumption by the domestic costumer. However, to draw conclusions about these equipments contribution for the global consumption on the LVN, it is necessary to know the hot water consumptions per costumer. Since there are not specific studies about hot water consumption by domestic costumers, the values used as reference are available on [34]. Also in [34], it is possible to observe the load demand from EHW for a daytime, given an determined number of equipments operating. The average hot water consumption on a hourly basis can be observed on figure 4.11.

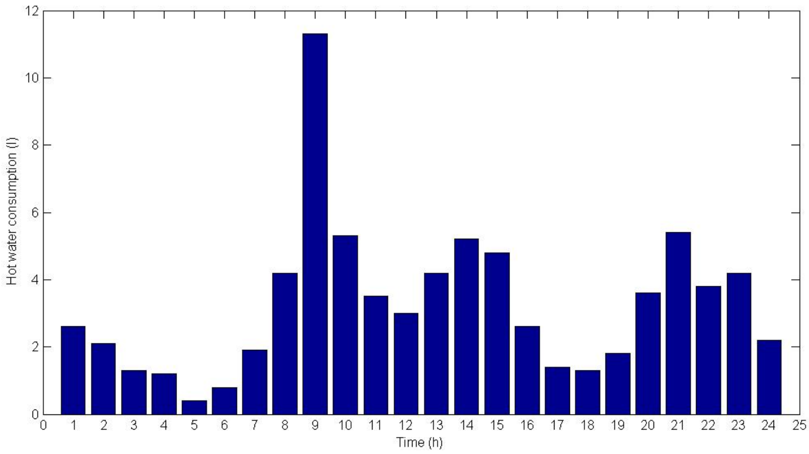

Figure 4.11: Hot water average consumption per hour

Hereupon, conjugating information of hot water average consumption, the load demand and EWH operation, it is possible to define a rate for the number of equipments in on-line state per determined period of time. This relation is based on the hot water array, and presented in the follow equations 4.1, 4.2, 4.3 and 4.4.

$$If: \quad HWC_i > 5.4 \quad ,Prob_{On,t} = HWC_i/23 \tag{4.1}$$

$$If: \quad 5.4 \geq HWC_i > 4.3 \quad ,Prob_{On,t} = HWC_i/18 \tag{4.2}$$

$$If: \quad 4.3 \geq HWC_i > 3.8 \quad ,Prob_{On,t} = HWC_i/16.5 \tag{4.3}$$

$$If: \quad HWC_i \leq 3.8 \quad ,Prob_{On,t} = HWC_i/15.2 \tag{4.4}$$

The relation intents to demonstrate that the EWH working state depends not so only on the quantity of hot water consumption per hour, but also on the hot water consumption events. The application of this relation provides the following rates presented on figure 4.12. The values are presented on 15 minutes time frame, like the load profiles.

Analysing the model implemented in section Electric Water Heater Load Model, it is possible to conclude that an on-line working period last in average for 45 minutes. Therefore it is possible to stipulate an approximated probability for the equipment to be on the required temperature in order enable control, in the case of the EWH, $60^{o}c$. The probability for the EWH be on the

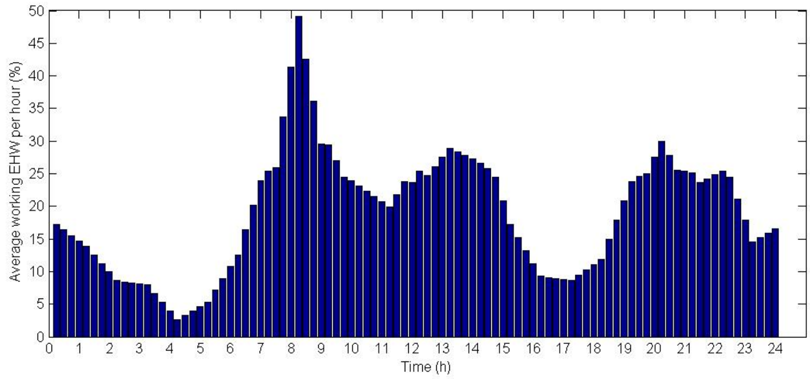

Figure 4.12: Rate of EHW working per 15 minutes time frame

required temperature stands for 33.33%. With these data possession it is possible to calculate the *Load Availability I* corresponding to the EHW, as in equation 4.5. In table 4.1 are presented the variables meanings.

$$LoadAvailabilityI_{EWH} = n \times \bar{P}_n \times Prob_{On,t} \times Prob_{TSet} \tag{4.5}$$

Variables	Meaning
$LoadAvailabilityI_{EWH}$	Available load for control from EWH
n	Number of EWH equipments on the LVN
t	Time period of the day
$\bar{P}_n$	Average power capacity of EWH on the LVN
$Prob_{On}$	On state probability
$Prob_{TSet}$	Required temperature probability
$Prob_{TSet}$	33.33(%)

Table 4.1: Variables for Load availability I for EWH

4.2.2 HVAC Data for Control Enabling

The individual HVAC operation has been previously discussed in section HVAC for Heating Load Model, and from there it is possible to draw some conclusions about these equipments contribution for the global consumption on the LVN. Analysing the functioning patterns, it is possible to define the HVAC daily duty cycle and the average time period in on-line work state. It shall be noted that those conclusions are possible due to the simplifications assumed, namely constant environment temperature, as well as the equipment being always turned on.

Therefore using the models referred, and defining a set point temperature of 20 ^{o}c for all the HVAC systems, the duty cycles and on-line work state periods, according to the environment temperature are displayed on table 4.2. For the HVAC system were considered four different environment temperatures. Since the model presented in [32] uses a five minutes time frame, the on-line work states time period vary as well in five minutes minimum.

Temperature (^oc)	**Duty cycle (%)**	**On-line work state period (min)**
0	41.67	50
5	31.43	45
10	20.83	40
15	10.59	35

Table 4.2: HVAC daytime working rates by temperature

Analysing table 4.2, we can assume that the probability of a equipment being in on-line state, for a determined temperature, is equal to the daytime working rate. On the other hand, since the temperature increase and decrease rate inside the residence is constant, as shown in [32] and HVAC for Heating Load Model, we can calculate the probability of the temperature being at desired value for enabling the HVAC equipment. The probabilities are defined on table 4.3. It shall be noted that the required temperature for enabling control is the defined set point temperature of the equipment.

Temperature (^oc)	**On-line State(%)**	**Temperature on required value(%)**
0	41.67	30
5	31.43	33.33
10	20.83	37.5
15	10.59	42.86

Table 4.3: HVAC control probabilities by temperature

To calculate the *Load Availability I* corresponding to the HVAC systems operating on the LVN, it is necessary to conjugate stipulations of number of HVAC equipments and his average power installed, existing in the LVN, with the parameters available on table 4.3, as shown in equation 4.6. The variables are detailed on table 4.4. It shall be noted that time variable is not included, since it is considered that this household appliance works all daytime at the same environment temperature.

$$LoadAvailabilityI_{HVAC_H} = n \times \bar{P}_n \times Prob_{On,t} \times Prob_{TSet,t} \tag{4.6}$$

4.2.3 Fridge and Freezer Data for Control Enabling

The individual fridge and freezer operation has been previously discussed in section Fridge and Freezer Load Model, and from there it is possible to draw some conclusions about these equipments contribution for the global consumption on the LVN. Analysing the functioning patterns, it

Variables	Meaning
$LoadAvailabilityI_{HVAC_H}$	Available load for control from HVAC
n	Number of HVAC equipments on the LVN
t	Environment temperature class
$\bar{P}_n$	Average power capacity of HVAC on the LVN
$Prob_{On}$	On state probability
$Prob_{TSet}$	Required temperature probability

Table 4.4: Variables for Load availability I for HVAC for heating

is possible to define the storage cooling equipments daily duty cycle and their average time period in on-line work state. It shall be noted that those conclusions are possible due to the simplifications assumed, namely constant environment temperature, as well as non accounting door open and close events.

One issue that as referred in Fridge and Freezer Load Model, was the fact of the model used in [33], only fit for individual fridge or freezer. Therefore, it is assumed that the combined fridge freezer and fridge with freezer will have equal patterns, resulting on aggregating both fridge and freezer operations characteristics. However, since the freezer storage compartment is smaller, the effort made by the compressor is considered to be 50% of a normal freezer. This prevails not so only for power consumption, but also for duty cycles and on-line work state time periods.

Therefore using the models referred, and defining a set point temperature of 5 ^{o}c for the fridge and -20^{o}c for the freezer, the duty cycles and on-line work state periods according to the environment temperature (installation spot) are displayed on table 4.5 and 4.6. For the storage cooling devices are considered two different environment temperatures, 15^{o}c and 25^{o}c.

Storage cooling device type	Duty cycle (%)	On-line work state period (min)
Fridge	15.278	11
Fridge with Freezer	27.882	11
Combined Fridge Freezer	27.882	11
Freezer	25.208	11

Table 4.5: Fridge and Freezer daytime working rates relation with equipment characteristics at 15^{o}c

Storage cooling device type	Duty cycle (%)	On-line work state period (min)
Fridge	30.694	13
Fridge with Freezer	46.736	12.75
Combined Fridge Freezer	46.736	12.75
Freezer	32.083	12.5

Table 4.6: Fridge and Freezer daytime working rates relation with equipment characteristics at 25^{o}c

Analysing tables 4.5 and 4.6, we can assume that the probability of a equipment being in on-line state, for a determined temperature, is equal to the daytime working rate. The on-line work state time periods for the storage cooling devices are all inferior to a 15 minutes time frame, used for the load profiles construction. Therefore, it is considered that there a 50% probability of the equipment being on the required temperature. It shall be noted that the required temperature for enabling control is the defined set point temperature of the equipment. The probabilities for control enabling are defined on table 4.7 and 4.8, according to the environment temperature.

Storage cooling device type	On State(%)	Temperature on required value(%)
Fridge	15.278	50
Fridge and Freezer	27.882	50
Combined Fridge and Freezer	27.882	50
Freezer	25.208	50

Table 4.7: Fridge and Freezer control probabilities at $15^{o}c$

Storage cooling device type	On State(%)	Temperature on required value(%)
Fridge	30.694	50
Fridge and Freezer	46.736	50
Combined Fridge Freezer	46.736	50
Freezer	32.083	50

Table 4.8: Fridge and Freezer control probabilities at $25^{o}c$

To calculate the *Load Availability I* corresponding to the storage cooling devices operating on the LVN, it is necessary to conjugate stipulations of the number of equipments and their average power installed existing in the LVN, with the parameters available on table 4.7 or 4.8, as shown in equation 4.7. The variables are detailed on table 4.9. It shall be noted that time variable is not included, since it is considered that these household appliances work all daytime at the same environment temperature.

$$LoadAvailabilityI_{F_x} = n_x \times \bar{P_{n,x}} \times Prob_{On,x,t} \times Prob_{TSet,x} \tag{4.7}$$

4.3 Load Availability II Procedure

This second procedure for quantifying the load availability for management, is target of many subjective factors that influence the value presented, relatively to *Load Availability I* procedure. This procedure consists on simulating the house stocking and household appliances on the LVN, after possess the number of costumers in the LVN stipulation. The operation of the equipments is simulated, and then is it proceed a verification on equipments states, namely temperature and

Variables	Meaning
$LoadAvailabilityI_{F_x}$	Available load for control from storage cooling devices
x	Storage cooling device type
t	Environment temperature
n	Number of equipments on the LVN by type
$\bar{P_{n,x}}$	Average power capacity of equipments on the LVN by type
$Prob_{On,x}$	On state probability by type
$Prob_{TSet}$	Required temperature probability by type

Table 4.9: Variables for Load availability I for fridges and freezers

power consumption. The household appliances are simulated for a daytime and the verification is made for every 15 minute time frame, according to the load profiles construction time frame.

There a few steps that shall be execute in order to enable a acceptable simulation of the household appliances on the grid:

- **House Stocking**— Given the number of domestic costumers on the LVN, it is possible to characterize each residence, namely typology and number of dwellers, respecting statistical data available.

- **Household Appliances Assignment**— For each residence, there is a certain number of equipments operating with different characterization according to the residence typology and dwellers.

- **Household Appliances Characterization**— For each residence, the equipments possessed have their power consumption and usage pattern (just for the EWH) defined. This characterization depends on residence typology and number of dwellers.

In the next sections, these both steps will be addressed with further detail.

4.3.1 House Stocking Generation

The house stocking generation is an algorithm that attributes to each domestic costumer typology and number on dwellers in the respective residence. This process is not random, contrariwise it follows statistical data available, in order to have the most realist set of costumers, for a good approximation to the average LVN operation. The residences characterization is needed because the household appliances operating in the LVN have different characteristics and usage, according to typology and dwellers. If in the procedure *Load Availability I* the domestic costumers are treated as equal, in *Load Availability II* they are treated individually. This algorithm is implemented on *Matlab*.

The first parameter to assign to a individual domestic profile is the residence typology. There are six types of typologies embraced in this work, and each one with a associated probability, according to [35]. The typologies and respective probabilities are assigned in table 4.10. It shall be noted that there are houses with no classification on statistical data, that are not accounted on typology attribution process.

Typology	Probability (%)
T0	1.31
T1	6.85
T2	23.56
T3	26.58
T4	9.31
T5	6.51
Non identified	25.88

Table 4.10: Typology distribution for residential buildings

In implementation, individual residence characteristics are assigned on array $Profile$. This is mentioned because it is possible to check individually, after running the algorithm, the residence profiles.

Each residence has the number of dwellers defined. This number depends on residence typology and statistical data. The Portugal census in 2011 [35] contains a study involving 3.991.112 lodges, presenting a relation between the number of rooms of a residence and the number of dwellers accommodated, displayed on table 4.11. However, to use this data in the assigning process, it is necessary to stablish a relation between typology and number of rooms of the residence. The construction of this association is available on table 4.12.

	Rooms									
Dwe.	1	2	3	4	5	6	7	8	9	10
1	11454	36469	145254	288199	206946	75675	31654	13859	7158	6697
2	4483	22404	120383	412689	403129	159569	74863	33805	17499	15782
3	1509	9188	56731	289303	339551	134169	64741	31524	16878	16061
4	659	3954	23716	141490	258402	117466	61679	30386	16472	16166
5	230	1192	5920	32521	65944	35467	20498	11240	6363	6470
6	126	375	1713	9000	19627	11737	7534	4129	2605	2759
7	56	119	489	2356	5248	3454	2162	1375	783	938
8	21	34	191	852	1853	1271	767	469	341	357
9	19	28	133	577	1263	1045	515	341	238	351
Total	18557	73763	354530	1176987	1301963	539853	264413	127128	68337	65581

Table 4.11: Residential distribution by number of dwellers and available rooms in a residence

With the presupposed relation established on 4.12 and the data available on 4.11, it is possible to determinate a probability that indicates the number of dwellers of a residence by her typology. Notice that percentages too low, are considered null. Hence, the sum of all percentage by typology may not be 100%. The values obtained are displayed on table 4.14. The method for distribution of

Typology	Rooms (a,b)
T0	1 to 2
T1	2 to 3
T2	3 to 5
T3	4 to 6
T4	6 to 8
T5	8 to 10

Table 4.12: Relation between typology and residence number of rooms

dwellers by typology calculation is shown below, on equation 4.8. On table are listed the variables and respective meaning.

Factor	**Values**
x	Typology index
d	Dwellers index
a,b	Room range per typology
$R_{d,r}$	Number of dwellers and available rooms
$T_{x,d}$	Number of dwellers probability per typology

Table 4.13: Variables and respective label for relation between typology and dwellers calculus

$$T_{x,d} = \sum_{r=a}^{b} \frac{R_{d,r}}{R_{t,r}} \times 100 \tag{4.8}$$

(4.9)

	Dwellers								
Typology	1	2	3	4	5	6	7	8	9
T0	51.91	29.12	11.59	5.00	1.54	0.54	0.19	0	0
T1	42.43	33,34	15.39	6.46	1.66	0.49	0.14	0	0
T2	22.60	33.04	24.20	14.95	3.68	1.07	0.39	0	0
T3	18.91	32.31	25.28	17.14	4.44	1.34	0.37	0	0
T4	13.01	28.80	24.74	22.50	7.22	2.51	0.75	0	0
T5	10.62	25.70	24.69	24.14	9.22	3.64	1.19	0.8	0

Table 4.14: Dwellers distribution by typology in percentage

4.3.2 Household Appliances Assignment

The second step consists in assigning equipments per residence. In this process the typology and number of dwellers is not taken into account. The algorithm assigns equipments according to the statistical previously shown on section Household Aplliances on Domestic Costumers, on table tab3421. In table 4.15 , is possible to observe an example of household appliances assignment, for a node with 20 domestic costumers, in order to better perceive the method, and the statistical data significance on the algorithm. The abbreviations are detailed on table 3.9. It is possible to notice that most of the residences, possess more than one storage cooling device, which reflects the Portuguese panorama, due to Portugal climate characteristics.

Index	T_x	*Dwellers*	*EWH*	F_1	F_2	F_3	F_4	$HVAC_1$	$HVAC_2$
1	4	3	1	0	0	1	0	0	0
2	2	1	0	0	0	0	1	0	0
3	3	2	0	0	1	0	0	1	0
4	4	3	0	1	1	0	0	0	0
5	3	2	1	0	1	1	0	0	0
6	2	2	0	0	0	1	0	0	1
7	3	4	0	0	0	1	0	0	0
8	1	3	0	0	0	1	1	0	0
9	3	4	0	0	0	1	1	0	0
10	2	2	0	0	0	0	1	0	0
11	1	3	0	0	0	1	1	0	0
12	1	1	0	0	1	1	1	1	0
13	3	3	0	0	0	1	0	0	0
14	4	2	1	0	0	1	1	0	0
15	2	3	0	0	0	0	1	0	0
16	0	1	0	0	1	1	1	0	0
17	1	4	1	0	1	1	1	0	0
18	1	4	0	1	0	1	0	0	0
19	2	2	0	0	0	1	0	0	0
20	3	2	1	0	1	0	0	0	0

Table 4.15: House stocking and household appliances assignment example

It shall be noted that in this assigning process, factors like level of instruction or monetary possessions are not taken into account, the process follows the Portuguese average rate of household appliances possession.

4.3.3 Electric Water Heaters Characterization

On the EWH characterization process there are two different characteristics that depending on the residence, are attributed: power capacity and hot water usage. The environment and the inlet water temperatures are considered constant for all residences.

The power capacity of each EWH depends on the respective residence typology. The numbers of dwellers is not taking on account because it is considered that the EWH is chosen during the lodge construction, before being indwelt. The power assigned was chosen by consulting EWH catalogues for sale and analysing their water storage capacity. The relation between the lodge typology and power is shown on table 4.16.

Typology	**Power** *kW*
T0	1
T1	1.2
T2	1.5
T3	1.8
T4	2
T5	2.2

Table 4.16: Relation Between Residence Typology and EWH Power

As referred in section Electric Water Heater Data for Control Enabling it was used as reference the values specified on [34]. To assign hot water consumptions for each domestic costumer, it was established a relation between the number of dwellers and the referred average values. Furthermore, as this available value are hourly, for a better simulation, they are randomly split in fifteen minutes time frames. As consequence the water flow increase in each hot water consumption event, which enables to achieve more realistic values when applying the model presented in sectionElectric Water Heater Load Model. An example of these hot water consumption distribution is shown on figure 4.13.

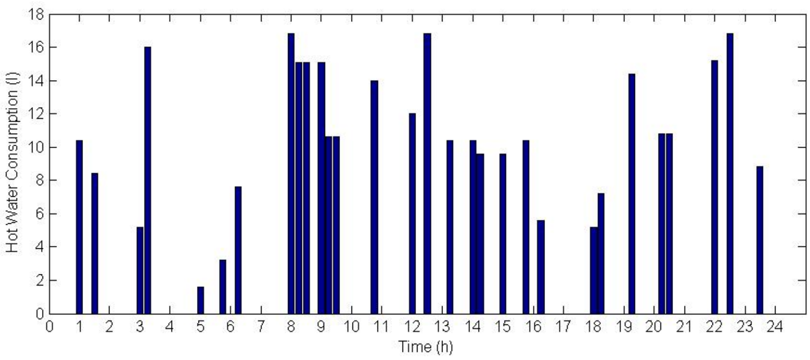

Figure 4.13: Hot water consumption distribution example

4.3.4 HVAC Characterization

There are no specific studies about HVAC utilization patterns by the users, so the only characteristic assigned for the residences possessing this equipment is the power capacity. The values used are based on sale catalogues analysis, and vary according to the respective lodge typology, due to the direct relation between number of rooms and air mass that the equipment must warm. This relation is shown on table 4.17.

Typology	**Power** W
T0	800
T1	800
T2	1200
T3	1200
T4	1600
T5	1600

Table 4.17: Relation between residence typology and HVAC power

4.3.5 Fridge and Freezer Characterization

As for the HVAC systems, there are no specific studies about fridge and freezer utilization patterns by the users, so the only characteristic assigned for the residences possessing this equipment is the power capacity. The values used are based on sale catalogues analysis, and vary according to the respective lodge dwellers, due to the direct relation between number of dwellers and the level of storage for cooling required. This relation is shown on table 4.18.

Dwellers	F_1 (W)	F_2 (W)	F_3 (W)	F_4 (W)
1	70	100	100	60
2	70	100	100	60
3	90	130	130	80
4	90	130	130	80
5	110	160	160	100
6	110	160	160	100
7	130	190	190	120

Table 4.18: Relation between residence dwellers and type of storage cooling device power

4.3.6 EWH Control Enabling

To enable control on individual EWH equipment, he must be in on-line work state and his temperature must be least at the set point value, namely $60^{o}c$. Theses conditions are verified inside a loop for the all the domestic costumers that possess an EWH, as in equation 4.10, with respective variables specified on table 4.19.

$$If : EWH_{State,i,t} = 1 \ \wedge \ T_{i,t} \quad \geq 60, \qquad LoadAvailabilityII_{EWH} + EWH_{Power,i} \tag{4.10}$$

Variables	Meaning
$LoadAvailabilityII_{EWH}$	Available load from EWH
i	LVN costumer index
$EWH_{State,i,t}$	EWH work state for costumer i
T_i	EWH temperature
$EWH_{Power,i}$	EWH power consumption for costumer i

Table 4.19: Variables for Load availability II for EWH

4.3.7 HVAC Control Enabling

To enable control on individual HVAC equipment, he must be in on-line work state and his temperature must be least at the set point value, namely 20^{o}c. Theses conditions are verified inside a loop for the all the domestic costumers that possess an HVAC system, as in equation 4.11, with respective variables specified on table 4.20.

$$If : HVAC_{State,i,t} = 1 \ \wedge \ T_{i,t} \ \ \geq 20, \quad LoadAvailabilityII_{HVAC_H} + HVAC_{Power,i} \tag{4.11}$$

Variables	Meaning
$LoadAvailabilityII_{HVAC_H}$	Available load from HVAC
i	LVN costumer index
$HVAC_{State,i,t}$	HVAC work state for costumer i
T_i	HVAC temperature
$HVAC_{Power,i}$	HVAC power consumption for costumer i

Table 4.20: Variables for Load availability II for HVAC for heating

4.3.8 Fridge and Freezer Control Enabling

To enable control on individual fridge or freezer equipment, he must be in on-line work state and his temperature must be least at the set point value, namely 5^{o}c or less for the fridge storage compartment and -20^{o}c or less for the freezer compartment. Theses conditions are verified inside a loop for the all the domestic costumers that possess an HVAC system, as in equations 4.12 for fridges and 4.13 for freezers, with respective variables specified on table 4.21.

$$If : F_{State,x,i,t} = 1 \ \wedge \ T_{i,t} \ \ \leq 5, \quad LoadAvailabilityII_{F_x} + F_{Power,x,i} \tag{4.12}$$

$$If : F_{State,x,i,t} = 1 \ \wedge \ T_{i,t} \ \ \leq -20, \quad LoadAvailabilityII_{F_x} + F_{Power,x,i} \tag{4.13}$$

Variables	Meaning
$LoadAvailabilityII_{F_x}$	Available load from storage cooling device
i	LVN costumer index
x	Storage cooling device type
$F_{State,i,t}$	Storage cooling device work state for costumer i
T_i	Storage cooling devicetemperature
$F_{Power,x,i}$	Storage cooling device power consumption for costumer i

Table 4.21: Variables for Load availability II for HVAC for heating

4.4 Matlab Algorithm Architecture

As stated before, all the algorithms in this thesis were implemented on *Matlab*. In this section, it is presented synthetically, the code architecture, in the form of a flow chart on figure 4.14. There are 6 classes that compose the main code, then each class has their group of functions and outputs. Since the number of functions used is too large, they are no presented.

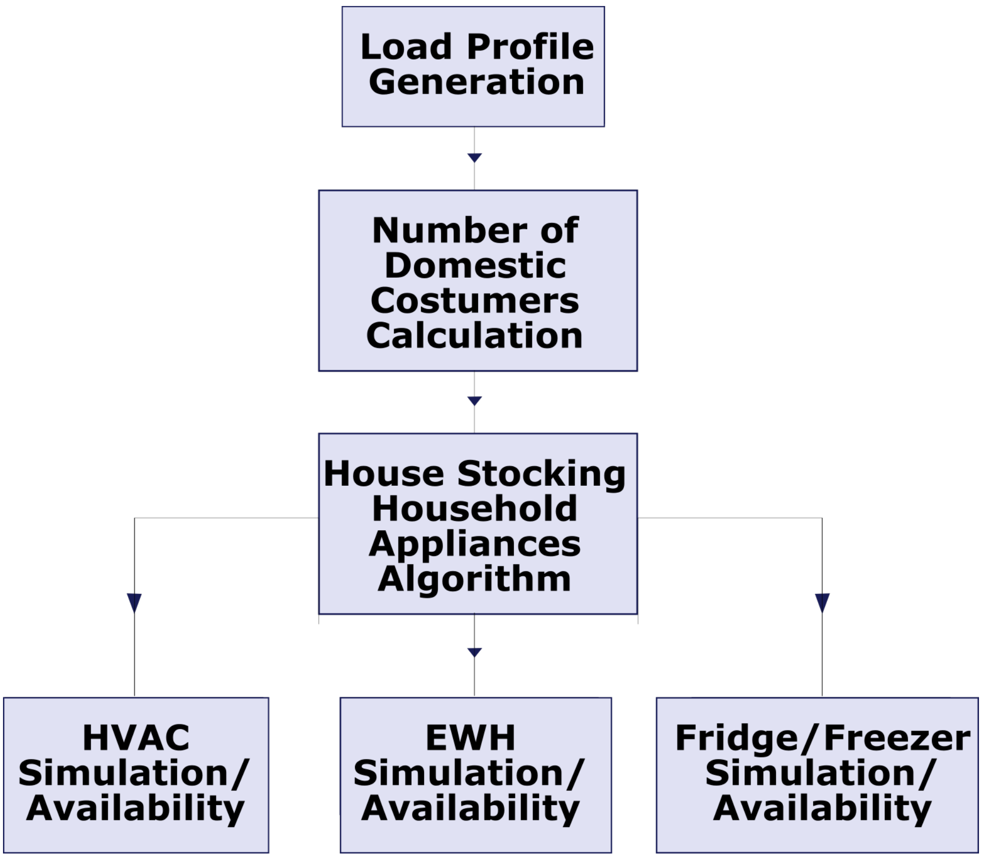

Figure 4.14: Algorithms implemented on *Matlab* architecture

Chapter 5

Case Study

In this chapter, will be applied the procedures and assumptions studied on previous chapters, namely the construction of load profiles, domestic costumers stipulation, household appliances assignment, characterization and simulation, load availability stipulations. The DG used is realistic and is analysed with and without congestion event. Finally, the use of load control for solving the congestion event is analysed.

5.1 Case Study Architecture

In the figure 5.1, the algorithm architecture for the case study is presented by a flowchart. It is possible to observe that after the load profile generation, the power flow is calculated for period t, without congestion event. Then a congestion event is forced by augmenting the load, applying the same augmentation rate per each transformer station node. The load management features are then applied.

As dubbed on chapter Load Simulations and Case Study Preparation, there are two procedures for load availability stipulation: *Load Availability I* and *Load Availability II*. The procedure that will be applied on congestion management is the first one, *Load Availability I*. It shall be noted that the load used as reference for load control, i.e. for load availability stipulations is the load profile used on the normal operation, the used on the first power flow calculation. The load control is then applied with different weights for period t, and for each one a power flow is calculated. A new power flow is calculated for $t+1$, in order to take conclusions from load control possible consequences.

The outputs presented on the flow chart refer to load profiles for the global DG or individual nodes, the power lines operation conditions, as well as voltage profiles on the most significant branches/buses. Other issue that will be analysed is the contribution of BTN classes on different transformer station nodes.

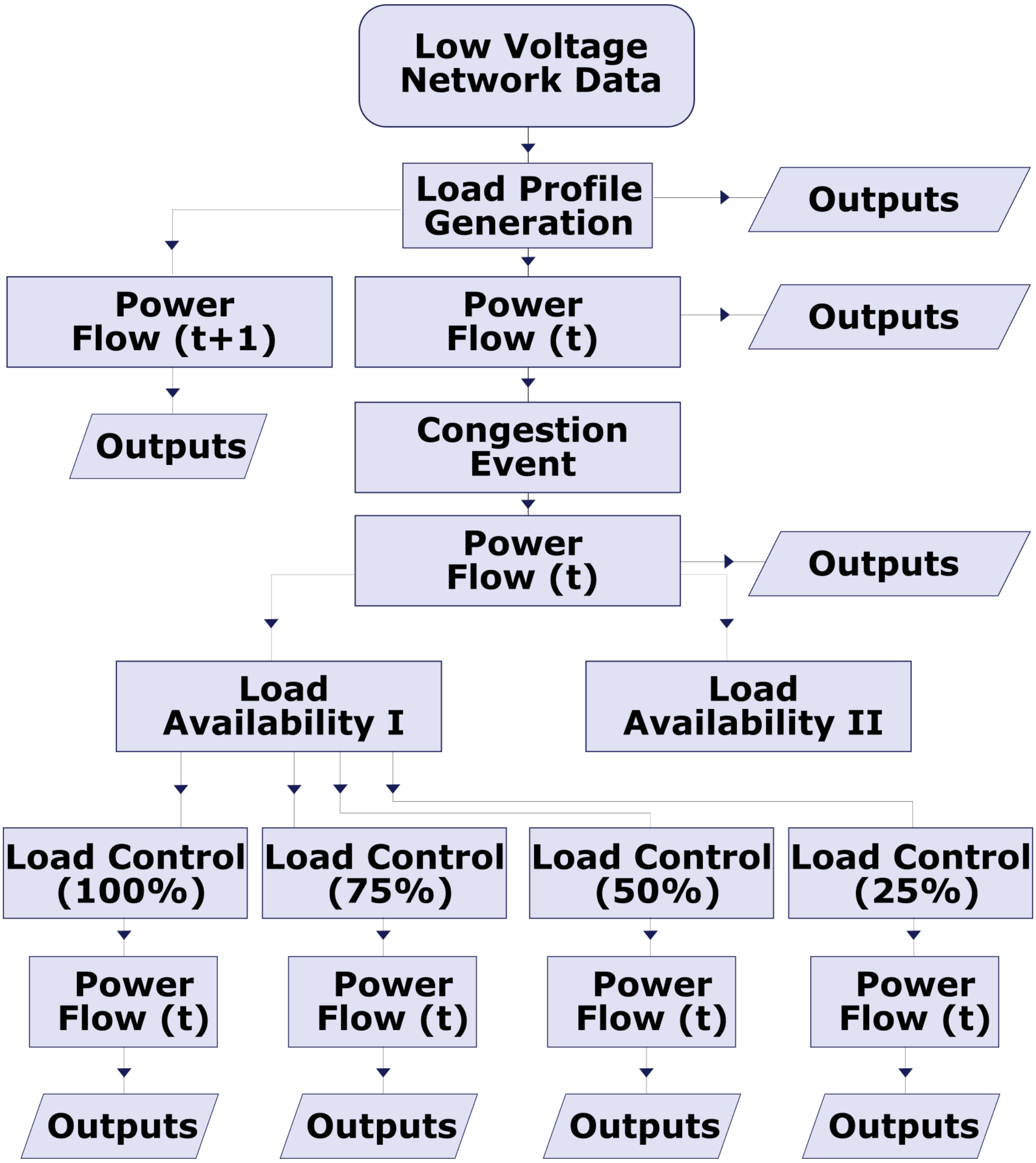

Figure 5.1: Case Study Architecture

5.2 Distribution Grid Characterization

The chosen DG for the study case, is an underground grid that operates at 10 kV. In order to validate the usage of backup load provided by load management, and analyse the difference on power lines operation, the chosen grid must be radial, which can be verified on figure 5.2, where is presented the DG diagram. This DG contains 47 transformer stations nodes from medium voltage to low voltage. Has previously stated on chapter Load Profile Adjustment to the LVN, the registered annual peak loads are used for the construction of load profiles. These values can be consulted of table 5.1.

It shall be noted that the different weight of BTN classes is accounted on individual nodes, with percussions on the global load for the DG, however when it comes to stipulate the number of domestic costumers and residential load, the values considered correspond to the Portuguese average.

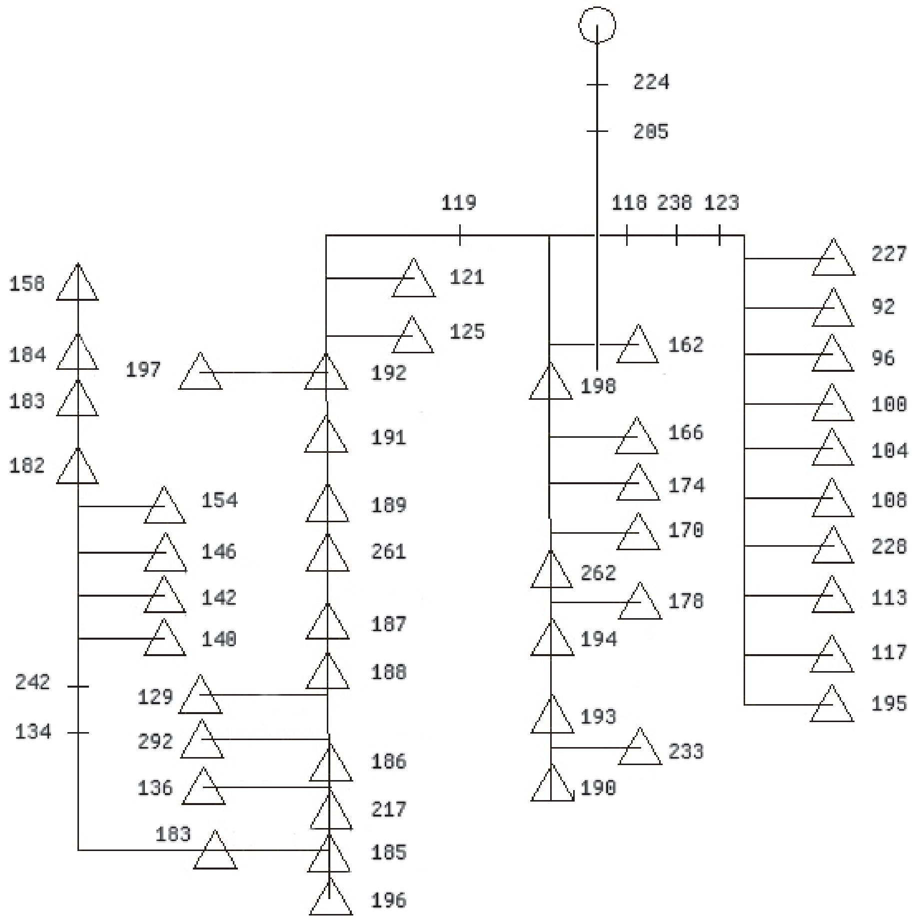

Figure 5.2: Distribution grid diagram

5.3 DG Load Profiles

In the following figures, it is possible to observe the DG load profile generated for the case study. The profile represents a typical Winter/Autumn situation, on a week day. With these load profiles, the grid is able to operate normally, with no congestion events.

The figure 5.3 shows the global DG load, aggregating the demand from the 47 transformer stations. It possible to observe that the peak load is verified at 8 pm, with 14875 kW. In the same figure it is also presented the respective BTN classes contributions. The red shape represents class C, the dark blue class A and the green represents class B. The BTN classes contribution for the load profiles in each transformer station node can be observed on table 5.2.

Index	Load (kW)	Index	Load (kW)	Index	Load (kW)
1	155	**17**	595.2	**32**	102.3
2	294.5	**18**	678.9	**33**	437.1
3	858.7	**19**	294.5	**34**	675.8
4	713	**20**	139.5	**35**	288.3
5	399.9	**21**	449.5	**36**	1215.2
6	858.7	**22**	179.8	**37**	108.5
7	372	**23**	65.1	**38**	99.2
8	161.2	**24**	830.8	**39**	709.9
9	471.2	**25**	319.3	**40**	744
10	136.4	**26**	384.4	**41**	294.5
11	942.4	**27**	18.6	**43**	89.9
12	235.6	**28**	895.9	**44**	189.1
13	275.9	**29**	895.9	**45**	564.2
14	145.7	**30**	192.2	**46**	545.6
15	241.8	**31**	71.3	**47**	24.8
16	74.4	**32**	179.8	-	-

Table 5.1: Transformer station nodes and respective annual peak loads registered

Analysing the figure 5.3, it is possible to verify that in the peak load period, most of the load corresponds from class BTN C, with a weight of 58.6%. The BTN A contributes with 3947.92 kW, class B with 2210.34 kW and classe C with 8716.98 kW.

Index	A (%)	B(%)	C(%)	Index	A(%)	B(%)	C(%)	Index	A(%)	B(%)	C(%)
1	13	23	64	**17**	19	23	58	**32**	38	14	48
2	0	28	72	**18**	7	31	62	**33**	35	0	65
3	33	15	52	**19**	34	5	61	**34**	56	0	44
4	25	13	62	**20**	41	3	56	**35**	37	11	52
5	17	41	42	**21**	38	0	62	**36**	28	22	50
6	36	9	55	**22**	38	11	51	**37**	29	4	67
7	44	0	56	**23**	6	38	56	**38**	49	0	51
8	32	24	44	**24**	3	29	68	**39**	51	0	49
9	25	23	52	**25**	31	22	47	**40**	0	20	80
10	6	30	64	**26**	41	0	59	**41**	32	27	41
11	32	23	45	**27**	21	27	52	**43**	37	0	63
12	10	24	66	**28**	35	0	65	**44**	52	3	45
13	27	11	62	**29**	26	8	66	**45**	53	8	39
14	18	12	70	**30**	1	29	70	**46**	38	15	47
15	8	25	67	**31**	2	20	78	**47**	35	0	65
16	34	1	65	**32**	17	20	63	-	-	-	-

Table 5.2: BTN class contribution per node

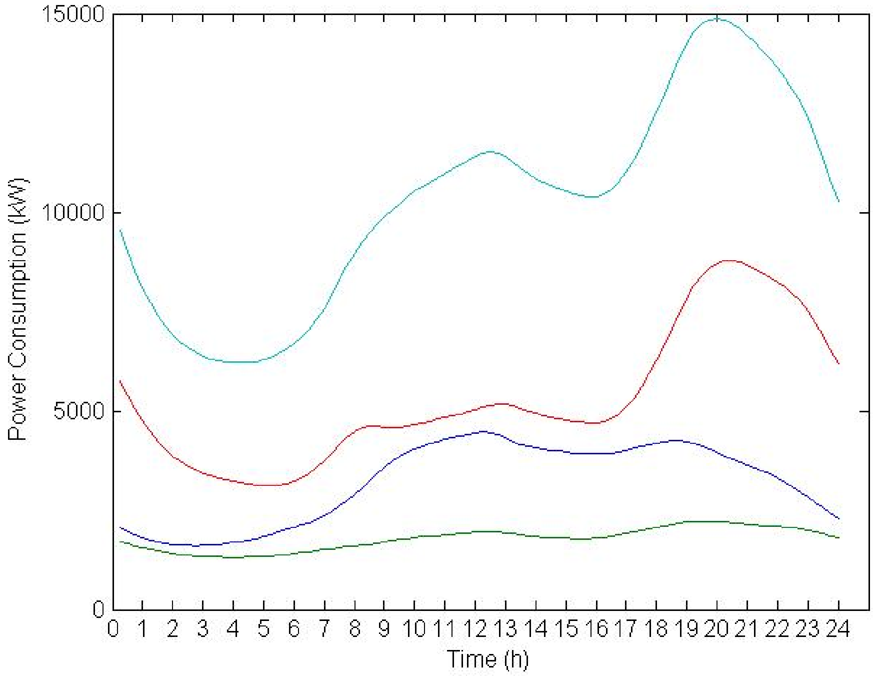

Figure 5.3: Case study load profile and respective BTN classes contributions

5.4 DG Power Flow Results

As previously stated, the peak load for the DG on Winter/Autumn load profile is observed at 8 pm. Taking in account that the load profiles are calculated in 15 minutes periods, the peak happens at the time frame number 80. At this period, the loads in each transformer station node are presented on table 5.3. These are the load values that will be used to run a power flow and examine the DG operation conditions. It is possible to observe that the load values and inferior than the annual peak loads registered, as expected, representing an average Winter/Autumn situation on a week day.

The most significant power flow results, i.e., the power lines where is verified a higher usage of the line capacity, are available in the table 5.4. The power flow calculation is executed in *MatPower*, software provided by [27]. The table 5.4 provides information about the electric current circulating, active and reactive power flow, maximum current permissible per branch and a rate of power line usage.

It is possible to observe that the higher line usage rate stands at 93.56%, with 402.43 *A* circulating. Therefore, the operations conditions are acceptable, though they are close to the grid operation limits and hence close to a congestion event. The power line with higher capacity usage, namely the branch that connects bus 118 to bus 238, is located near the substation, as it can be observed in figure 5.2.

In the table 5.5, it is possible to observe the voltage profiles, and verify if there are buses with

Index	**Load** (kW)	**Index**	**Load** (kW)	**Index**	**Load** (kW)
1	125.54	**17**	479.27	**32**	80.99
2	241.30	**18**	552.22	**33**	348.02
3	683.07	**19**	234.49	**34**	526.94
4	571.86	**20**	110.35	**35**	228.61
5	321.53	**21**	356.83	**36**	970.12
6	681.84	**22**	142.43	**37**	86.83
7	293.56	**23**	52.93	**38**	77.89
8	128.13	**24**	678.64	**39**	556.31
9	377.20	**25**	254.15	**40**	610.51
10	111.08	**26**	304.25	**41**	233.96
11	749.23	**27**	14.94	**43**	71.44
12	191.34	**28**	713.31	**44**	147.95
13	220.94	**29**	718.54	**45**	440.56
14	117.68	**30**	157.30	**46**	431.87
15	196.71	**31**	58.40	**47**	19.75
16	59.28	**32**	145.14	-	-

Table 5.3: Loads per transformer station node at DG peak load period

Bus i	**Bus k**	$\mathbf{P_{ik}}(MW)$	$\mathbf{Q_{ik}}(MW)$	$\mathbf{I_{Max}}(A)$	$\mathbf{I_{ik}}(A)$	**Line**$(\%)$
118	238	6.970	3.956	430.13	402.43	93.56
205	224	-7.141	-4.024	479.78	412.30	85.94
119	205	-7.098	-4.019	479.78	409.83	85.42
123	238	-6.902	-3.947	479.78	398.50	83.06
134	242	3.468	2.512	251.72	200.25	79.55

Table 5.4: Normal DG operation: top 5 capacity usage power lines

variations excessively high. For the normal operation, the highest variation for voltage magnitude is verified in bus 195, more concretely 5,68%. This is expected due to the fact that the bus 195 possesses the higher load demand, related to the transformer station with index number 36.

Bus i	$\mathbf{U_i}$**(pu)**	$\Delta \mathbf{U_i}\%$
195	0.9432	5.68
117	0.9478	5.22
113	0.9484	5.16
260	0.9488	5.12
108	0.9488	5.12

Table 5.5: Normal DG operation: top 5 voltage magnitude variation buses

5.5 LVN Available Load for Management Calculation

As referred on chapter Load Simulations and Case Study Preparation, there are two procedures for load availability stipulation. In this section the *Load Availability I* calculation steps are presented, while *Load Availability II*, as it is provided directly by the *Matlab* algorithm, is only presented and used as indicator for further analysis.

5.5.1 LVN Load Availability I

In order to calculate the *Load Availability I* it is at first necessary to stipulate the number of domestic costumers of the LVN, as announced at chapter Domestic Costumers Stipulation, and then apply the procedure defined in section Load Availability I Procedure. To proceed to the number of costumers stipulation it is necessary to analyse the annual average load profile. For this LVN the average annual consumption pattern is presented on figure 5.4. In this case, and applying the equation 3.13, the daily average consumption for this LVN during the year is 224121.2 kWh.

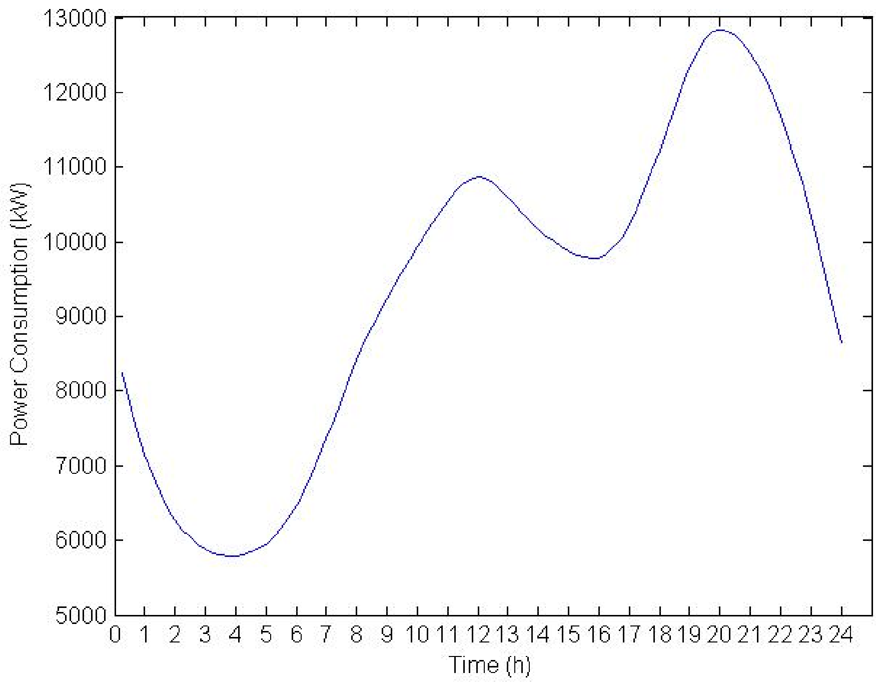

Figure 5.4: Annual average load profile for DG case

The next step is to calculate the annual DG consumption, using equation 3.13. The normalized profiles used for this case remit to the year 2012. Therefore, the annual DG consumption obtained is 82028359.2 kWh, as shown in 5.1.

$$AnnualDGconsumption = 224121.2 \times 366 = 82028359.2 (kWh) \tag{5.1}$$

Applying the residential load weight and then dividing by the average residential consumption, as in equations 3.14 and 3.15, the number of costumers obtained for this case is 16068 (rounded by the minimum), as shown in 5.2.

$$Residential\ number\ of\ Costumers = \frac{82477417.39 \times 0.7203}{3677.3} \simeq 16068 \tag{5.2}$$

With the number of costumers stipulation defined, it is possible to proceed to calculate the load availability for management through procedure *Load Availability I*. The average power capacity of the each household appliance considered, is defined according to sections House Stocking Generation, Electric Water Heaters Characterization, HVAC Characterization and Fridge and Freezer Characterization. Depending on the household appliance, the power defined is related to the prevailing typology and dwellers number per residence. For EWH and HVAC systems, the power is defined for the second prevailing typology T_2. For the storage cooling devices, the power is defined for the prevailing number of dwellers per residence, namely 2. This way, the load available for management is calculated for the worst case scenario. The values for power per equipment are presented on table 5.6.

$EWH\ (kW)$	$F_1\ (W)$	$F_2\ (W)$	$F_3\ (W)$	$F_4\ (W)$	$HVAC_H\ (kW)$
1.5	70	100	100	60	1.2

Table 5.6: Average power capacity definition per household appliance type

Below, *Load Availability I* per equipment calculation is demonstrated. It shall be noted that the load profile used represents a typical Winter/Autumn situation, so the environment temperature considered is $10^{o}c$, which implies a temperature of $15^{o}c$ for the storage cooling devices. Since it is defined to calculate the worst case scenario, the necessary rounding is always for the minimum value. At first, the number of equipments operating on the LVN is stipulated based on 3.8. The HVAC for cooling are not taken in account since it is Winter/Autumn season.

$$EWH\ equipments = 16068 \times 0.112 \simeq 1799 \tag{5.3}$$

$$Fridge\ equipments = 16068 \times 0.057 \simeq 915 \tag{5.4}$$

$$Fridge\ with\ Freezer\ equipments = 16068 \times 0.583 \simeq 9367 \tag{5.5}$$

$$Combined\ Fridge\ and\ Freezer\ equipments = 16068 \times 0.376 \simeq 6041 \tag{5.6}$$

$$Freezer\ equipments = 16068 \times 0.476 \simeq 7648 \tag{5.7}$$

$$HVAC\ equipments = 16068 \times 0.1067 \simeq 1714 \tag{5.8}$$

With the number of household appliances able to control defined, it is possible to stipulate the *Load Availability I*. The data and equations required for the necessary calculations is presented on chapter 46. For the EWH, at 8 pm the probability of the equipment being in on state is 27.5%, as defined in figure 4.11. For the remaining equipments, the rates needed can be observed on tables 4.3 and 4.7.

$$LoadAvailabilityI_{EWH} = 1799 \times 1.5 \times 0.275 \times 0.333 = 246(kWh) \tag{5.9}$$

$$LoadAvailabilityI_{F_1} = 915 \times 0.07 \times 0.15278 \times 0.5 = 4.83(kWh) \tag{5.10}$$

$$LoadAvailabilityI_{F_2} = 9367 \times 0.1 \times 0.27882 \times 0.5 = 130.5(kWh) \tag{5.11}$$

$$LoadAvailabilityI_{F_3} = 6041 \times 0.1 \times 0.27882 \times 0.5 = 84.2(kWh) \tag{5.12}$$

$$LoadAvailabilityI_{F_4} = 7648 \times 0.06 \times 0.25208 \times 0.5 = 57.78(kWh) \tag{5.13}$$

$$LoadAvailabilityI_{HVAC_H} = 1714 \times 1.2 \times 0.2083 \times 0.375 = 159.6(kWh) \tag{5.14}$$

As it is possible to see in equation 5.15, the total available load for management in this case is stipulated as 586.22 kWh. This value represents 4.591% of total power consumption during the

DG peak load period.

$$LoadAvailabilityI = 246 + 4.83 + 130.5 + 84.2 + 57.78 + 159.6 = 682.91(kWh) \quad (5.15)$$

5.5.2 LVN Load Availability II

The *Load Availability II* is provided by the *Matlab* simulation of the LVN operation. The results obtained are used as an indicator in order to achieve more precise conclusions about the viability of active load control for congestion management. As referred on section Load Availability II Procedure, the algorithm constructed, simulates the house stocking and household appliances existing on the LVN, given the number of domestic costumers. The equipments operation is then simulated for a daytime, the availability analysed accordingly to sections EWH Control Enabling, HVAC Control Enabling and Fridge and Freezer Control Enabling.

In the tables 5.7 and 5.8 it is possible to verify the house stocking and the household appliances existing on the LVN simulation.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Typology	203	1712	4660	6466	1721	1306	-	-
Dwellers	-	3756	5125	3593	2759	620	183	25

Table 5.7: House stocking of LVN simulation

Household Appliance	**Quantity**
EWH	1009
F_1	612
F_2	9961
F_3	7787
F_4	7202
$HVAC_1$	1476

Table 5.8: Household appliances operating on the LVN simulation

It is possible to observe that the number of equipments in the simulation differ from the stipulated on procedure *Load Availability I*. This is caused by the randomness induced by the implemented algorithm, that assigns households appliances to each domestic costumer.

The algorithm implemented allows to check each equipment operation patterns. As an example, in the figure 5.5 it possible to observe the temperature behaviour of on single EWH operating on the grid.

However, the aggregation of all equipments is the base of the load availability for load control. In figure 5.6 it is possible to observe the global consumption for the EWH for a daytime. This algorithm is performed for all the household appliances except for the HVAC system for cooling.

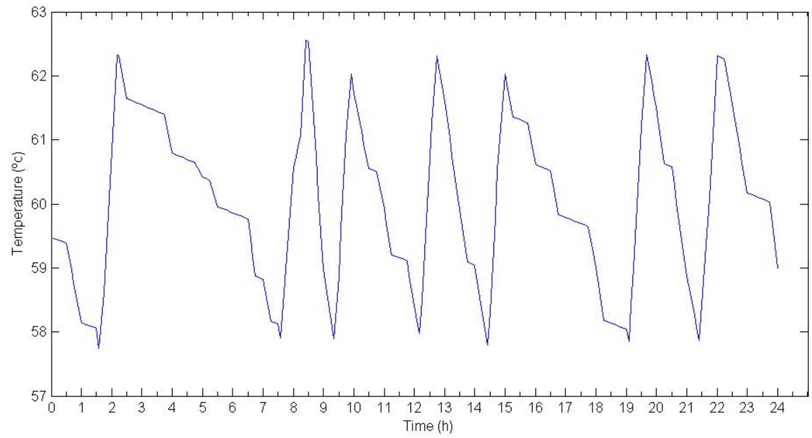

Figure 5.5: Individual EWH temperature for a daytime

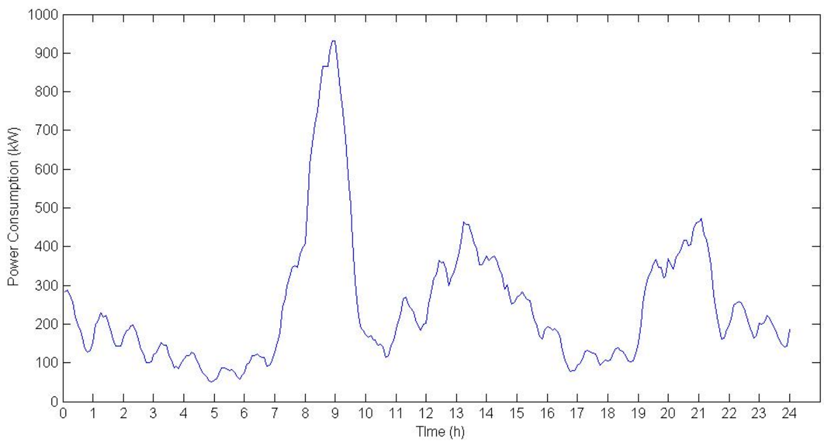

Figure 5.6: Global EWH power consumption for a daytime

The *Matlab* simulation provides for every time frame, the available load for management, for each equipment. The aggregation of this availability, by household appliance type, can be verified in the follow equations. The *Load Availability II* quantity is defined on equation 5.22, with the value of 706.2 kWh. It shall be noted that these values refer to the peak load period at 8 pm, in the time frame number 80.

$$LoadAvailabilityII_{EWH} = 64.82(kWh) \tag{5.16}$$

$$LoadAvailabilityII_{F_1} = 93.82(kWh) \tag{5.17}$$

$$LoadAvailabilityII_{F_2} = 11.35(kWh) \tag{5.18}$$

$$LoadAvailabilityII_{F_3} = 11.51(kWh) \tag{5.19}$$

$$LoadAvailabilityII_{F_4} = 18.33(kWh) \tag{5.20}$$

$$LoadAvailabilityII_{HVAC_H} = 506.4kWh \tag{5.21}$$

$$LoadAvailabilityII = 64.82 + 93.82 + 11.35 + 11.51 + 18.33 + 506.4 = 706.2(kWh) \tag{5.22}$$

As it is possible to observe, the storage cooling devices as the HVAC system have very different values for load availability. The assigning of the initial temperature and work logical state is the main reason to induce errors on the results. Anyway, the values obtained for procedure *Load Availability II* only differs in 23.29 *kW* from procedure *Load Availability I*, a variation of 3.41%.

5.6 DG Congestion Event and Load Control Actions

During normal operation, the DG presents a 93.56% maximum rate of power line usage. Therefore, in order to induce a congestion event, it will be applied an load augmentation of 8%. The power flow data is presented on table 5.9.

Bus i	**Bus k**	$\mathbf{P_{ik}}(MW)$	$\mathbf{Q_{ik}}(MW)$	$\mathbf{I_{Max}}(A)$	$\mathbf{I_{ik}}(A)$	**Line**(%)
118	238	7.548	4.200	430.13	435.81	101.32
205	224	-7.737	-4.274	479.78	446.67	93.10
119	205	-7.687	-4.267	479.78	443.80	92.50
123	238	-7.469	-4.189	479.78	431.24	89.88
134	242	3.748	2.636	251.72	216.41	85.97

Table 5.9: Congested DG operation: top 5 capacity usage power lines

As it is possible to observe, a load augmentation of 8% induces a congestion event, being verified on the branch that connects the bus 118 to bus 238. The line usage is stands at 101.32%, with 435.81 *A* circulating. In table 5.10 are presented the most significant voltage profiles to analyse. As expected, the bus of the transformer station with higher load demand presents the higher variation of voltage magnitude.

Bus i	**U_i(pu)**	**$\Delta U_i\%$**
195	0.9384	6.16
117	0.9434	5.66
113	0.9440	5.60
260	0.9444	5.56
108	0.9444	5.56

Table 5.10: Congested DG operation: top 5 voltage magnitude variation buses

To solve the congestion event with active load control, the load will be reduced according to the *Load Availability I* values calculated. As the congestion issue happens in power line right next to the substation, it is possible to reduce the global load by applying an reduction rate equal in all transformer station nodes. For testing different scenarios, the load reduction will be applied with different rates for the *Load Availability I*, namely 100%, 75%, 50% and 25%. The results obtained for power flows and voltage profiles are shown below, on table 5.11, 5.12, 5.13, 5.14, 5.15, 5.16, 5.17 and 5.18.

Bus i	**Bus k**	**$P_{ik}(MW)$**	**$Q_{ik}(MW)$**	**$I_{Max}(A)$**	**$I_{ik}(A)$**	**Line(%)**
118	238	7.190	4.051	430.13	415.11	96.51
205	224	-7.367	-4.120	479.78	425.34	88.65
119	205	-7.322	-4.114	479.78	422.73	88.11
123	238	-7.118	-4.041	479.78	410.94	85.65
134	242	3.575	2.561	251.72	206.39	81.99

Table 5.11: 100% of load control application: top 5 capacity usage power lines

Bus i	**U_i(pu)**	**$\Delta U_i\%$**
195	0.9414	5.86
117	0.9461	5.39
113	0.9467	5.33
260	0.9471	5.29
108	0.9471	5.29

Table 5.12: 100% of load control application: top 5 voltage magnitude variation buses

The use of 100% of the load available for control, solves the congestion event. The maximum power line capacity usage stands at 96.51%, with 415.11 A circulating. The voltage profiles are acceptable, with the higher voltage magnitude variation standing at 5.86%.

Bus i	**Bus k**	$\mathbf{P_{ik}}(MW)$	$\mathbf{Q_{ik}}(MW)$	$\mathbf{I_{Max}}(A)$	$\mathbf{I_{ik}}(A)$	**Line**$(\%)$
118	238	7.279	4.086	430.13	420.27	97.71
205	224	-7.459	-4.157	479.78	430.66	89.76
119	205	-7.413	-4.151	479.78	427.99	89.21
123	238	-7.205	-4.076	479.78	416.01	86.71
134	242	3.618	2.579	251.72	208.90	82.99

Table 5.13: 75% of load control application: top 5 capacity usage power lines

Bus i	$\mathbf{U_i}$**(pu)**	$\Delta\mathbf{U_i}\%$
195	0.9407	5.93
117	0.9454	5.46
113	0.9460	5.40
260	0.9464	5.36
108	0.9464	5.36

Table 5.14: 75% of load control application: top 5 voltage magnitude variation buses

When using 75% of total load available for control, the congestion event is also resolved with success. The maximum power line capacity usage stands at 97.71%, with 420.27 *A* circulating and the voltage profiles are acceptable, with the higher voltage magnitude variation standing at 5.93%.

Bus i	**Bus k**	$\mathbf{P_{ik}}(MW)$	$\mathbf{Q_{ik}}(MW)$	$\mathbf{I_{Max}}(A)$	$\mathbf{I_{ik}}(A)$	**Line**$(\%)$
118	238	7.369	4.126	430.13	425.45	98.91
205	224	-7.552	-4.197	479.78	435.99	90.87
119	205	-7.504	-4.191	479.78	433.25	90.30
123	238	-7.293	-4.115	479.78	421.08	87.77
134	242	3.662	2.598	251.72	211.40	83.98

Table 5.15: 50% of load control application: top 5 capacity usage power lines

Bus i	$\mathbf{U_i}$**(pu)**	$\Delta\mathbf{U_i}\%$
195	0.9399	6.01
117	0.9448	5.52
113	0.9453	5.47
260	0.9458	5.42
108	0.9458	5.42

Table 5.16: 50% of load control application: top 5 voltage magnitude variation buses

Even reducing the rate of load available for control usage for 50%, the congestion event is able to be successfully solved, although one of the power lines being close to operational limits. The maximum power line capacity usage stands at 98.91%, with 425.45 A circulating and the voltage profiles are acceptable, with the higher voltage magnitude variation standing at 6.01%.

Bus i	**Bus k**	$\mathbf{P_{ik}}(MW)$	$\mathbf{Q_{ik}}(MW)$	$\mathbf{I_{Max}}(A)$	$\mathbf{I_{ik}}(A)$	**Line**(%)
118	238	7.459	4.164	430.13	430.63	100.12
205	224	-7.644	-4.236	479.78	441.33	91.99
119	205	-7.596	-4.230	479.78	438.53	91.40
123	238	-7.381	-4.153	479.78	426.16	88.82
134	242	3.705	2.617	251.72	213.91	84.98

Table 5.17: 25% of load control application: top 5 capacity usage power lines

Bus i	$\mathbf{U_i}$**(pu)**	$\Delta\mathbf{U_i}$%
195	0.9392	6.08
117	0.9441	5.59
113	0.9446	5.54
260	0.9451	5.49
108	0.9451	5.49

Table 5.18: 25% of load control application: top 5 voltage magnitude variation buses

When using only 25% of the available load for control, the congestion event is not solved, despite the power line operating slightly above the operational limits. The maximum power line capacity usage stands at 100.12%, with 430.63 A circulating. The voltage profiles as expected are once again acceptable, with the higher voltage magnitude variation standing at 6.08%.

5.7 DG Operation after Peak Load without Load Control Actions

In order to analyse possible consequences of active load control in the DG operation, in the following periods to control actions, its is presented the loads in each transformer station and power flow results in the following period exactly after control actions. In tables 5.19 and 5.20 are presented the referred load in each transformer station node and the power flow results.

It is possible to observe that the power line with higher capacity usage, has declined the usage rate in 0.21%, standing at 93.35% with 401.51 A circulating. It shall be noted, as previously stated that the higher power line capacity usage is verified in the branch right after the substation.

Index	Load (kW)	Index	Load (kW)	Index	Load (kW)
1	124.84	**17**	477.64	**32**	81.14
2	239.09	**18**	548.83	**33**	347.31
3	683.16	**19**	234.15	**34**	529.98
4	570.06	**20**	110.43	**35**	228.80
5	321.31	**21**	356.50	**36**	969.79
6	681.89	**22**	142.60	**37**	86.53
7	293.93	**23**	52.66	**38**	78.14
8	128.33	**24**	673.27	**39**	558.47
9	376.74	**25**	254.34	**40**	604.03
10	110.33	**26**	304.30	**41**	234.44
11	750.22	**27**	14.91	**43**	71.34
12	190.11	**28**	711.87	**44**	148.67
13	220.32	**29**	715.85	**45**	443.30
14	116.99	**30**	155.95	**46**	432.72
15	195.35	**31**	57.82	**47**	19.71
16	59.15	**32**	144.46	-	-

Table 5.19: Loads per transformer station node at DG after peak load period without load control actions

Bus i	Bus k	$P_{ik}(MW)$	$Q_{ik}(MW)$	$I_{Max}(A)$	$I_{ik}(A)$	Line(%)
118	238	6.954	3.950	430.13	401.51	93.35
205	224	-7.125	-4.018	479.78	411.37	85.74
119	205	-7.083	-4.012	479.78	408.92	85.23
123	238	-6.887	-3.941	479.78	397.60	82.87
134	242	3.454	2.505	251.72	199.42	79.22

Table 5.20: DG operation after peak load period without load control actions: top 5 capacity usage power lines

5.8 Individual Node Analysis

In the next figures, it is possible to analyse two transformer station nodes with analogue BTN classes contributions. The figure 5.7 shows the transformer station with higher BTN class A contribution, while 5.8 shows the transformer station with higher BTN class C contribution, with null BTN A contribution. It is possible to observe that the transformer 41 has a higher load weight during the DG peak load period than transformer station 45. It shall be noted that, as referred in Literature Review and Load Modelling Concepts, although not strictly, due to which BTN class characteristics, class A is more related to the industrial sector, and class C to domestic sector. Each node contributions rates can be observed on table 5.2.

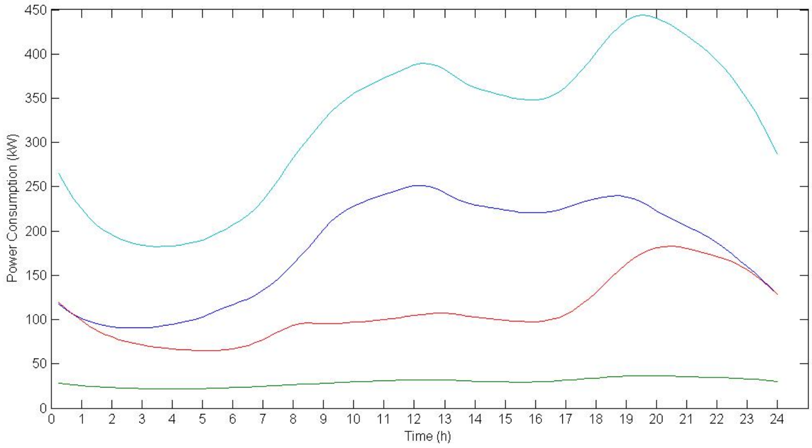

Figure 5.7: Transformer station with higher BTN class A contribution, index 45

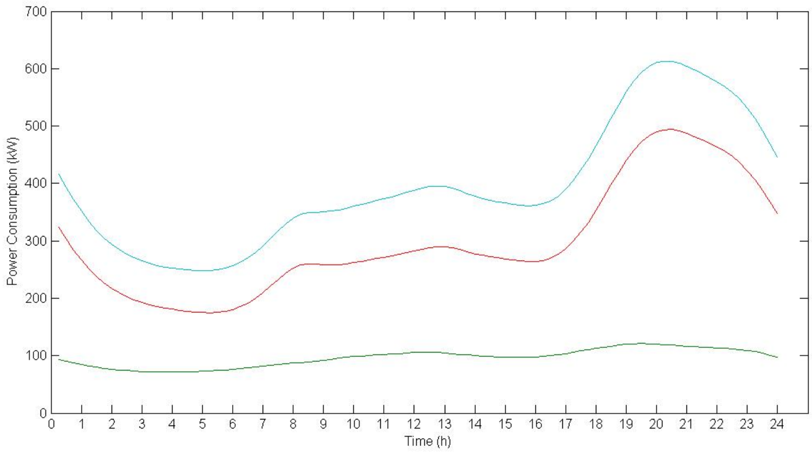

Figure 5.8: Transformer station with higher BTN class C contribution, index 41

Chapter 6

Conclusion

In this final chapter will be presented at first the drawn conclusions for the results obtained and for last an enumeration of suggestions for future works, related to this thesis.

6.1 Results Analysis and Conclusions

The required technology to perform active load control on household appliances, namely hardware and software, is already developed and tested, so currently this concept is practicable and can be implemented. If actually implemented, this thesis results shown that it would be a viable solution for solving LVN congestion events.

The procedure used to validate the load availability during the LVN operation, stipulates values for the Portuguese average consumption patterns, so it is subjected to several arbitrariness and random factors that are difficult to considerate with precision. However, the procedures used appoint for the worst case scenario, with the intent to ensure that the load availability is actually able to be used, i.e., it would be possible to control the equipments without causing problems on the domestic costumer. This is due to the fact of considering non time critical loads, where the power consumption is related to thermal heating or cooling. Details like opening the fridge or disconnect the HVAC system during the morning by example, are not take into consideration, but if they were, the load consumption from the equipments would be even bigger, leading to the load availability for control to increase.

The results achieved on the case study, demonstrate that for a LVN network with high use of power lines capacity, namely 93.56% , the use of active load control was able to solve an hypothetical congestion event. In the case study an congestion event as caused by a 8% load augmentation, an improbable situation, however the active load control would solve the situation by using a fraction of all available load for control. The calculation of a power flow in a following period to the peak load demonstrated a tiny reduction on the global load demand, which combined with load available for control with origin of different equipments permit to safely execute the load control actions.

Even considering that the procedures used on this thesis are affected with considerable errors, and the rates of available load would be inferior, the validation of the technique would not be concerned. The power flow analysis, namely voltage profiles shown that the load reduction do not affect the voltage magnitude on the buses significantly.

One of the issues of this thesis, is the stipulation of the residential load weight, and number of costumers. In this thesis the values considered, represented Portuguese average and aggregating the LVN global load. In practice this would not be possible, since each transformer station has his own costumers characterization, and the load availabilities should be analysed individually. Nevertheless, as it is impossible to characterize the grid costumers only based on BTN classes contribution, the load availability presented is an valid indicator.

One main conclusion of this thesis that can be drawn, is the fact that active load control is indeed a good practice for congestion managements in grids mostly characterized by domestic costumers. A given LVN that only contains domestic costumers, would have a high rate of load available for control, enabling load control in different time periods, without serious consequences on the following time periods after the load control. This is even further consolidated if the housing stock of a certain grid is characterized by high power installed and household appliances with high power capacity. This thesis appoints for a 72.03% rate of residential load on the Portuguese LVN, which means that this congestion management technique would be viable for most of the Portuguese power network. In grids characterized by industrial and commerce sectors, the use of active load control for congestion management could not be so effective. Another conclusion drawn is that the LVN peak loads, when it is more susceptible to happen a congestion event, normally occur around 8 pm. At this time period, the biggest contribution for LVN global stems for BTN class C, the class more related to domestic costumers. This is a good indicator for the technique validation.

Hereupon, considering the facts previously mentioned, it is secure to state that the use of active load control is indeed an effective and viable congestion management method, that if applied, is able to reduce the LVN operation economic costs, increase demand elasticity as well as improve the power system efficiency.

6.2 Future Work

During the thesis, it was noticed the lack of accuracy in some modelling performed, due to the non-existence of data about some consumption patterns, like hot water by example. A better characterization of domestic costumers behaviour would allow better simulations and available load for control stipulations.

Other issue is the characterization of the LVN costumers. For now, ERSE classifies the LVN consumption by three BTN classes, and there is no discrimination of the type of costumers. This is a big handicap for the technique validation for a certain grid, since if it would be possible to know in advantage the type of consumption of the grid, it also would be easier to guarantee if the use active load control would be effective.

The LVN used for the case study does not have renewable energy production penetration. An future study would obligatory to include them, in order to preform more incisive studies about power flows and voltage profiles sensibility to the technique usage.

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