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# Smart Operation of Transformers for Sustainable Electric Vehicles Integration and Model Predictive Control for Energy Monitoring and Management

**Radu Godina**

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Orientador: Prof. Doutor João Paulo da Silva Catalão
Coorientador: Prof. Doutor João Carlos de Oliveira Matias

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This work is dedicated to the cornerstone of who I am today and who will I ever be, my Father, Alexandru Godina (*in memoriam*) and to my mother and sister for their unconditional support and for having always believed in me even at times when even I didn’t believe.

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“Es ist nichts schrecklicher als eine tätige Unwissenheit.”
*"Não há nada mais terrível do que a ignorância em acção."*
Johann Wolfgang von Goethe

# Resumo

Os sistemas de transmissão e distribuição de energia existentes hoje em dia são significativamente dependentes dos transformadores, pese embora sejam mais eficientes e sustentáveis do que os das décadas passadas. No entanto, uma grande parte dos transformadores ao nível da distribuição, juntamente com outras infraestruturas subjacentes, estão em serviço há décadas e encontram-se na fase final do ciclo de vida. Qualquer defeito no funcionamento dos transformadores pode afetar a fiabilidade de toda a rede elétrica, para além de ter um grande impacto económico no sistema.

Os efeitos nefastos associados à poluição do ar em centro urbanos, as mudanças climáticas e a dependência de fontes de energia fósseis têm levado os decisores políticos e os investigadores a explorar alternativas para os veículos convencionais de combustão interna. Uma alternativa é a introdução de veículos elétricos. Uma ampla implementação de tal meio de transporte poderia significar uma redução drástica dos gases de efeito de estufa e poderia reforçar os esforços globais para o cumprimento das metas de redução de emissões de poluentes na atmosfera.

Nesta tese é abordado o tema da elevada penetração dos veículos elétricos e a sua eventual integração numa rede elétrica insular. Posteriormente, são abordadas soluções de redes elétricas inteligentes com tecnologias específicas, tais como sistemas de gestão de energia e contadores inteligentes que promovam o paradigma das casas inteligentes, que também permitem a gestão da procura ativa no sector residencial. No entanto, deslastrando significativamente as cargas para beneficiar de preços mais reduzidos é suscetível de colocar constrangimentos adicionais sobre os sistemas de distribuição, especialmente sobre os transformadores. Os novos tipos de cargas tais como os veículos elétricos podem introduzir ainda mais incertezas sobre a operação desses ativos, sendo uma questão que suscita especial importância. Além disso, com o intuito de melhorar a eficiência do consumo de energia numa habitação, a gestão inteligente da energia é um assunto que também é abordado nesta tese. Uma pletora de metodologias é desenvolvida e testada em vários casos de estudos, a fim de responder às questões anteriormente levantadas.

# Palavras-chave

Transformador a óleo, veículo elétrico, rede insular, sistemas de energia, gestão da energia em casas, modelo térmico do transformador, programação linear inteira-mista, controlo preditivo.

# Abstract

The energy transmission and distribution systems existing today are still significantly dependent on transformers, despite being more efficient and sustainable than those of decades ago. However, a large number of power transformers along with other infrastructures have been in service for decades and are considered to be in their final ageing stage. Any malfunction in the transformers could affect the reliability of the entire electric network and also have great economic impact on the system.

Concerns regarding urban air pollution, climate change, and the dependence on unstable and expensive supplies of fossil fuels have lead policy makers and researchers to explore alternatives to conventional fossil-fuelled internal combustion engine vehicles. One such alternative is the introduction of electric vehicles. A broad implementation of such mean of transportation could signify a drastic reduction in greenhouse gases emissions and could consequently form a compelling argument for the global efforts of meeting the emission reduction targets.

In this thesis the topic of a high penetration of electric vehicles and their possible integration in insular networks is discussed. Subsequently, smart grid solutions with enabling technologies such as energy management systems and smart meters promote the vision of smart households, which also allows for active demand side in the residential sector. However, shifting loads simultaneously to lower price periods is likely to put extra stress on distribution system assets such as distribution transformers. Especially, additional new types of loads/appliances such as electric vehicles can introduce even more uncertainty on the operation of these assets, which is an issue that needs special attention. Additionally, in order to improve the energy consumption efficiency in a household, home energy management systems are also addressed. A considerable number of methodologies developed are tested in several case studies in order to answer the risen questions.

# Keywords

Oil immersed transformer, electric vehicle, insular grid, power systems, home energy management, transformer thermal model, mixed-integer linear programming, model predictive control.

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# Acronyms

| | |
|---|---|
| AC | Air Conditioning |
| ACAP | Portuguese Automobile Association |
| AML | Algebraic Modelling Languages |
| BMW | Bayerische Motoren Werke AG |
| BTU | British Thermal Unit |
| CV | Control Variable |
| DC | Direct Current |
| DG | Distributed Generation |
| DGA | Dissolved Gas Analysis |
| DR | Demand Response |
| DS | Distribution System |
| DV | Disturbance Variable |
| EDA | Eletricidade dos Açores, S.A. |
| EJ | Exajoule ($10^{18}$ joule) |
| LTI | Linear Time-invariant |
| EMS | Energy Management Systems |
| ERSE | Energy Services Regulatory Authority |
| ESS | Energy Storage System. |
| ESS2H | Energy Storage System-to-Home. |
| EU | European Union |
| EV | Electric Vehicle |
| FAA | Ageing Acceleration Factor |
| G20 | Group of Twenty |
| GAMS | General Algebraic Modelling System |
| GHG | Greenhouse Gas |
| GDP | Gross Domestic Product |
| HMI | Human–machine Interaction |
| HVAC | Heating, Ventilation, and Air Conditioning |
| ICO | Internal Combustion Engine |
| IEC | International Electrotechnical Commission |
| IEEE | Institute of Electrical and Electronics Engineers |
| LCA | Life cycle Assessment |
| Li-ion | Lithium-ion |
| LOL | Loss of Life |
| LP | Linear Programming |
| LTI | Linear Time-invariant |
| LVE | Special Low Voltage |

| | |
|---|---|
| LVN | Normal Low Voltage |
| MEF | Major Economies Forum |
| MILP | Mixed-Integer Linear Programming |
| MISO | Midcontinent ISO |
| MOOP | Multi-objective Optimisation Problem |
| MPC | Model Predictive Control |
| MV | Medium Voltage |
| NEEAP | National Energy Efficiency Action Plans |
| ODAF | Oil Directed Air Forced |
| ODWF | Oil Directed Water Forced |
| OEM | Original Equipment Manufacturer |
| OFAF | Oil Forced Air Forced |
| OFWF | Oil Forced Water Forced |
| ONAN | Oil Natural Air Natural |
| ONAF | Oil Natural Air Forced |
| O&M | Operations and Maintenance |
| PDF | Probability Density Function |
| PDT | Power Distribution Transformer |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PID | Proportional–integral–derivative Controller |
| PJM | Pennsylvania New Jersey Maryland Interconnection |
| PV | Photovoltaic |
| PV2H | Photovoltaic-to-Home |
| QP | Quadratic Program |
| RAA | Autonomous Region of Azores |
| RAM | Random-access Memory |
| RES | Renewable Energy Sources |
| RESs | Renewable Energy Systems |
| RF | Refrigerator |
| RMS | Root Mean Square |
| SG | Smart Grid |
| SiNGULAR | Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration |
| SISO | Single-Input and Single-Output |
| SOC | State of Charge |
| SOE | State of Energy |
| SOGEO | Sociedade Geotérmica dos Açores, S.A. |
| SP | Set Point |
| TCO | Total Cost of Ownership |
| UK | United Kingdom |

| | |
|---|---|
| USA | United States of America |
| V2H | Vehicle-to-Home |
| V2G | Vehicle-to-Grid |
| VAT | Value-added Tax |
| WH | Water Heater |

# Nomenclature

| | |
|---|---|
| $A$ | A Matrix. |
| $B$ | The input matrix. |
| $C$ | The output matrix. |
| $b$ | Vector of parameters. |
| $C_{in}$ | The thermal capacitance of the indoor air. |
| $C_p$ | Specific heat of water. |
| $C_w$ | A characteristic of fiber glass. |
| $c$ | The vector of the objective function cost coefficients. |
| $Cost_h$ | Total electrical consumption cost for each smart household of the neighborhood. |
| $D$ | The difference over a small time step. |
| $d$ | The daily distance covered by an EV. |
| $d_R$ | The maximum range of the EV. |
| $Dt$ | Time Step. |
| $E_i$ | The initial SOC of an EV battery. |
| $F_{AA,n}$ | The ageing acceleration factor for the temperature which exists during the time interval $\Delta t_n$. |
| $F_{EQA}$ | The equivalent ageing factor for the total time period. |
| $F_{HL}$ | The harmonic loss factor for winding eddy currents. |
| $F_{HL\text{-}STR}$ | The harmonic loss factor for other stray losses. |
| $g_r$ | Average winding to average oil (in tank) temperature gradient at rated current in K. |
| $H$ | Hot-spot factor. |
| $h$ | The harmonic order. |
| $h_{max}$ | The highest significant harmonic number. |
| $I$ | The RMS load current. |
| $I_h$ | The RMS current at harmonic of order h. |
| $I_r$ | The RMS fundamental current under rated frequency and rated load conditions. |
| $J_u$ | The control signal tracking error. |
| $J_y$ | Optimisation of the error due to the output reference trajectory. |
| $J_{\Delta u}$ | Minimisation of the control signal increments. |
| $J_\varepsilon$ | Representation of constraint violations. |
| $K$ | Load factor (load current/rated current). |
| $k$ | The current sampling instant. |
| $k_{11}$ | Thermal model constant. |
| $k_{21}$ | Thermal model constant. |
| $k_{22}$ | Thermal model constant. |

| | |
|---|---|
| $L$ | Loss of life. |
| $M$ | Control moves – the control horizon. |
| $m$ | Mass of the water. |
| $N$ | Total number of time intervals. |
| $P$ | A set of predicted outputs – the prediction horizon. |
| $P_d$ | Domestic loads in W. |
| $P_{EC}$ | The winding eddy-current losses. |
| $P_{EC-0}$ | The winding eddy-current loss at the measured current and the power frequency. |
| $P_{EV}$ | EV rated charging power in W. |
| $P_f$ | Factory load in W. |
| $P_G$ | The global losses. |
| $P_{h,t}^{EV,used}$ | Power of EV battery used by the household [kW]. |
| $P_{h,t}^{ESS,used}$ | Power of ESS used by the household [kW]. |
| $P_{h,t}^{EV,ch}$ | Charging power of EV [kW]. |
| $P_{h,t}^{ESS,ch}$ | Charging power of ESS [kW]. |
| $P_{h,t}^{grid}$ | Power drawn from the grid by each household [kW]. |
| $P_{h,t}^{in}$ | Inelastic electrical load for each household [kW]. |
| $P_{h,t}^{PV,used}$ | PV power used by the household [kW]. |
| $P_L$ | The losses due to load $I^2R_t$. |
| $P_{LL}$ | The losses related to primary and secondary currents flowing through windings. |
| $P_{LL}\ (pu)$ | The per-unit load loss. |
| $P_{LL-R}$ | The load loss under rated conditions. |
| $P_{LL-R}\ (pu)$ | The per-unit load loss under rated conditions. |
| $P_{NL}$ | The no load losses. |
| $P_{OSL}$ | The other stray losses. |
| $P_{OSL-R}$ | The other stray loss under rated conditions. |
| $P_r$ | Distribution transformer rated power in W. |
| $P_{sl}$ | Pre-set limit. |
| $P_T$ | Total load in W. |
| $P_{\Omega}(t)$ | The remaining EV load that is superior to the $P_{sl}$ in any given instant $t$. |
| $Q_{ac\_ht}$ | The AC power unit thermal source. |
| $Q_{e\_g}$ | Electric rated power. |
| $Q_{in}$ | The heat to be extracted. |
| $R$ | Ratio of load loss to no-load loss at rated current. |
| $R_c$ | The thermal resistance of windows. |
| $R_t$ | Winding resistance at temperature $t$. |
| $R_w$ | The thermal resistance of the wall. |
| $S$ | The set of the feasible solutions. |

| | |
|---|---|
| $S(t)$ | A binary variable that emulates the turn-on and turn-off of the thermostat. |
| $T_{in}$ | The room’s temperature. |
| $T_{out}$ | The ambient temperature. |
| $T_w$ | The wall temperature. |
| $t$ | Period of the day in time units [h or min]. |
| $\Delta t_n$ | Time interval. |
| $U$ | Input vector. |
| $UA$ | A characteristic of fiber glass. |
| $u$ | Manipulated input for SISO control. |
| $u_k$ | Estimated input signals. |
| $u_{min}$ | The lower bound for the control signal. |
| $u_{max}$ | The upper bound for the control signal. |
| $u(k)$ | The control law. |
| $V$ | Relative ageing rate. |
| $V_{min}$ | Minimum dimensionless controller constant. |
| $V_{max}$ | Maximum dimensionless controller constant. |
| $v$ | The vector of decision variables. |
| $V_n$ | Relative ageing rate during interval *n*. |
| $w_i^u$ | Weighting coefficient that allocates more relevance to the term. |
| $w^{\Delta u}$ | Weighting coefficient that penalises changes in the $u_k$. |
| $w_i^y$ | Weighting coefficient that allocates more relevance to the term. |
| $x$ | Exponential power of total losses versus top-oil (in tank) temperature rise (oil exponent). |
| $y$ | Exponential power of current versus winding temperature rise (winding exponent). |
| $y_{min}$ | The lower limit of process future outputs. |
| $y_{max}$ | The upper limit of process future outputs. |
| $\grave{y}$ | Actual output. |
| $\hat{y}$ | Predicted output. |
| $z_k$ | The QP decision at each control interval. |
| $\varepsilon_k$ | Slack variable at control interval $k$. |
| $\eta$ | Efficiency. |
| $\Theta_a$ | The average ambient temperature in °C. |
| $\Theta_b$ | The bottom oil temperature rise in cooler in K. |
| $\Theta_h$ | Winding hottest-spot temperature in °C. |
| $\Theta_o$ | Top-oil temperature in °C. |
| $\Delta\Theta_c$ | Top oil temperature rise in cooler and winding, in K. |
| $\Delta\Theta_g$ | The hottest-spot conductor rise over top-oil temperature. |

| | |
|---|---|
| $\Delta\Theta_{g,r}$ | The hottest-spot conductor rise over top-oil temperature under rated conditions. |
| $\Delta\Theta_{h,i}$ | Hot-spot-to-top-oil (in tank) gradient at start in K. |
| $\Delta\Theta_{o,i}$ | Top-oil (in tank) temperature rise at start in K. |
| $\Delta\Theta_{h,r}$ | Hot-spot temperature rise at rated current in K. |
| $\Delta\Theta_{o,r}$ | Top-oil temperature rise at rated current in K. |
| $\Delta\Theta_{r}$ | The average winding temperature rise in winding in K. |
| $\Delta\Theta_{w}$ | The top oil temperature rise in winding in K. |
| $\lambda_t^{\mathrm{buy}}$ | Buying price of electrical energy from grid [cents/kWh]. |
| $\mu$ | The natural logarithmic mean. |
| $\rho_{\varepsilon}$ | Constraint violation penalty weight. |
| $\sigma$ | The standard deviation of the corresponding normal distribution. |
| $\tau_o$ | Average oil time constant. |
| $\tau_w$ | Winding time constant. |

# Indices

## Chapters 1 to 4

| | |
|---|---|
| $a$ | Ambient temperature |
| $b$ | Bottom |
| $d$ | Domestic |
| $EC$ | Eddy-current |
| $EV$ | Electric vehicle |
| $f$ | Factory |
| $G$ | Global |
| $h$ | Hot-spot |
| $i$ | At start/initial |
| $in$ | Inelastic |
| $LL$ | Load losses |
| $n$ | Index of the time interval |
| $o$ | Top-oil |
| $R$ | Range |
| $r$ | Rated load |
| $sl$ | Set limit |
| $T$ | Total |
| $t$ | Period of the day index in time units [h or min]. |
| $w$ | Winding |

## Chapter 5

| | |
|---|---|
| $h$ | smart household index |
| $t$ | Period of the day index in time units [h]. |

## Chapter 6

| | |
|---|---|
| $k$ | Sampling instant or control interval |
| $w$ | Wall |

> "There is a single light of science, and to brighten it anywhere is to brighten it everywhere."
>
> *"Existe somente uma luz da ciência, e ao acendê-la em qualquer parte é iluminar tudo à volta."*
>
> Isaac Asimov

# Chapter 1

# Introduction

This introductory chapter aims at provide an overview of the necessary framework of the thesis. This chapter describes briefly the insular power systems, the Azorean Archipelago and especially the island of São Miguel which is a part of it. Furthermore, the topic of high penetration of Electric Vehicles (EVs) and their possible integration in the insular network is discussed. Additionally, in order to improve the energy consumption efficiency of a dwelling, home energy management is addressed. Then, the necessary background on the methodology utilised in this thesis is briefly introduced. In conclusion, the research questions together with the novel contributions of this thesis are listed. The chapter concludes by outlining the structure of the thesis and the notation.

## 1.1 Motivation

In insular power systems the entire electricity power grid infrastructure is physically located in an isolated geographical area surrounded by water. Typically, isolated power systems have several constraints. Such limitations lead to negative outcomes like the dependency on overseas trade, economic weakness reducing the possibilities to play in conventional markets, the oversizing of infrastructures including the electricity industry, and vulnerability to climate change. Additionally, islands are heavily dependent on imported fossil fuels, among other factors that directly affect the insular economy [1]. A new type of end-user appliance/load – electric vehicles (EVs), has recently gained more importance with the electrification of the transport sector, which is traditionally a major fossil fuel consumer. The current status of EV market share globally can be considered low, not exceeding 7% in leading countries such as Norway [2] [3]. Especially for an insular area, the relatively high transportation cost of fossil fuels, the presence of rich potential of renewable energy sources (RES), and the opportunities that emerge from the efficient management of an EV fleet [4] [5] lead to believe that the penetration levels that are likely to be met in such areas in the future will be significantly higher than in continental areas.

Furthermore, government incentive initiatives usually tend to target specific areas such as islands more, and as a result, potential subsidy programs or tax reduction schemes to promote the purchase and use of EVs are very likely to massively motivate users to replace their conventional car with an EV [6].

Motivated by the increasing penetration of EVs and especially by the impact that such electrified means of transportation might have on the ageing of power distribution transformers, as well as by other loads of domestic appliances, this thesis deals with the development of several models that assess the impact of EV loads, as well as other loads of domestic appliances related to price-incentive based demand response (DR), on power distribution transformers, then afterwards schedule the EVs in order to mitigate their impact. Consequently, the thesis also aims to address an alternative way of improving home energy consumption, especially the domestic cooling and heating appliances, normally the highest energy consumers in residential buildings.

## 1.2 Overview of insular power systems

The word island essentially signifies a subcontinental land area that is surrounded by water, which implies a total physical insularity (isolation and/or dispersion) from the mainland. Thus, insular power systems correspond to electric power grid structures in physically isolated geographical areas that are mainly islands in the above sense [7].

Islands are typically categorised as portions of land delimited by water, officially smaller than Greenland, which has 2.2 million square km. Thus, such lands can contain independent island states, archipelagic states, and islands linked with continental countries. Yet they share several features that not only unify them as a different category but underline their overall vulnerability in the context of sustainable development [8]. Therefore, insular areas display several limitations that have to be identified. The narrow variety of resources, inability to reach economies of scale, frequent seasonal variation of population, distance from the mainland, higher infrastructure costs, climatic conditions, and microclimates within the insular area are examples of such type of constraints. Such restrictions lead to numerous negative outcomes, including overseas trade dependency, economic weakness that reduces the chance of gaining access to conventional markets, and the need for oversised infrastructure such as power systems [9]. Considering the mentioned limitations, priority must be given to the fact that insular areas are among the most vulnerable places regarding climate change, as the frequency of natural disasters (mostly tropical storms, typhoons, etc.), which has increased because of climate change, is a more important threat for insular areas than for the mainland [10] [11]. Climatic consequences such as climate variability, increasing sea levels, and irregular climatic conditions also influence the environment of islands [12].

Thus, the general problems of insular areas can mainly be categorised as the dependence on imported fuel, availability of freshwater, management of wastes, and other problems related to climatic conditions [13], which are affected by many factors, including the components of insular economies. The economies of most of the insular areas depend on tourism, which is precisely an advantage motivated by their added geographical value. This leads to oversizing of infrastructure in all fields in order to be adequate for the requirements of the summer period however this means that such infrastructure is considerably underutilised in winter time [9].

The reduction of dependence on imported fuel, particularly for electricity production, is an essential element for the economic sustainability of insular areas. The fossil fuels such as oil, gasoline, and liquefied petroleum gas required for conventional energy sources are generally transported to islands by tankers, which creates both an unsustainable service model principally during peak times and a problematic strategy from an environmental point of view. Also, energy production from fossil fuels is costly, particularly as a result of transportation costs [14]. As a result, the utilisation of local resources predominantly in the form of renewable energy systems (RESs) has become a fundamental aim of many energy policies, particularly during the last decade, and the structures of electric power grids initiated to considerably change with the newly growing interest in RESs. Consequently, insular power systems are contemplated as a laboratory for the study of the impacts of new strategies and technologies [15], which emphasises the need for profounder analysis of insular areas and insular power systems in terms of current status, challenges, and opportunities for future technological advances, ultimately including the use of EVs. Normally, the power system of insular areas includes a single or a few and typically conventional fuel-based generators, particularly in small and very small islands. Consequently, the inertia of the total system is considerably low, and the current standing of insular power systems can be considered untrustworthy as a result of possible outages and fuel shortages for such a reduced number of generating options. The reason is that the majority of the generating units as well as other electrical infrastructure elements are old and require more maintenance than recently installed systems, an issue that reduces both reliability and economic sustainability [16].

### 1.2.1 Current insular economic framework: case of the Azores Islands

The activity of power production in the Autonomous Region of Azores is regulated and consequently is not liberalised. As such, the island utility holds the monopoly, such as production, acquisition, transportation, distribution, sale of electricity and the exercise of other activities related to those and all of them provided by EDA (Eletricidade dos Açores, S.A.), which is based on a broad and complex operating structure whose primary objective is the provision of electricity to all areas of RAA (Autonomous Region of Azores) [17].

### 1.2.1.1 Generation

EDA manages the design and construction of new generating plants and the necessary changes to existing facilities, according to the Company's plans, and ensures the management and maintenance of all production equipment of the various islands [18].

By 2012, the power generation system operated had ten thermoelectric plants with a capacity of 219 MW. There are eight wind farms on the islands of Santa Maria, São Miguel, Terceira, Graciosa, São Jorge, Pico, Faial and Flores, with a total capacity of 25 MW, twelve hydroelectric plants with a total power of 8.2 MW, and also two geothermal power stations belonging to SOGEO (which belongs to EDA), with an output of 23 MW [19].

The annual electricity production in 2012 reached 804.6 GWh, facing a decrease of 4.2% over the previous year. Of this production, the thermoelectric park contributed 72.0%, with a dominance of the fuel production, reflected by 63.3% [18].

Geothermal sources are the most significant of the renewable energies since they contributed 16.7% of the total and 31.9% on the island of Sao Miguel [20]. The energy sources of hydro, wind and other origin registered -13.9%, 90.0% and -5.4% with respect to the previous year's variations. The reason behind the growth of wind power in November 2011 was the new wind farm at Graminhais (São Miguel Island) with an installed capacity of 9 MW [18]. The electricity generation in GWh by origin throughout 2008—2012 of the autonomous regions of the Azores Archipelago is presented in Table 1.1. The evolution of the generation of the entire Azorean Archipelago can be seen in Figure 1.1. The generation per energy source in the first 9 months of 2015 is shown in Figure 1.2.

Table 1.1 - Electricity generation (GWh) of the autonomous regions of the Azores Archipelago.

| **Generation in kWh** | **Registered Values** | | | | |
|---|---|---|---|---|---|
| | *January to September 2014* | *(%)* | *January to September 2015* | *(%)* | Evolution in % |
| **Total** | *590 874 135* | *100* | *592 497 669* | *100* | *0,274767* |
| Thermal Origin | 379 735 913 | 64,27 | 393 491 307 | 66,4123 | 3,622358 |
| Fuel Oil | 326 978 864 | 55,34 | 338 995 214 | 57,21461 | 3,674962 |
| Diesel | 52 757 041 | 8,93 | 54496080 | 9,197687 | 3,296316 |
| Renewable Origin | 211 138 222 | 35,7332 | 199 006 362 | 33,5877 | -5,74593 |
| Hydro | 17 915 590 | 3,032048 | 17016461 | 2,871988 | -5,01869 |
| Geothermal | 135 850 132 | 22,99 | 135 852 552 | 22,92879 | 0,001781 |
| Wind | 56 934 473 | 9,64 | 45791918 | 7,728624 | -19,5708 |
| Microgeneration | 280 708 | 0,047 | 288957 | 0,048769 | 2,93865 |
| Other | 157 311 | 0,027 | 56460,88 | 0,009529 | -64,1087 |

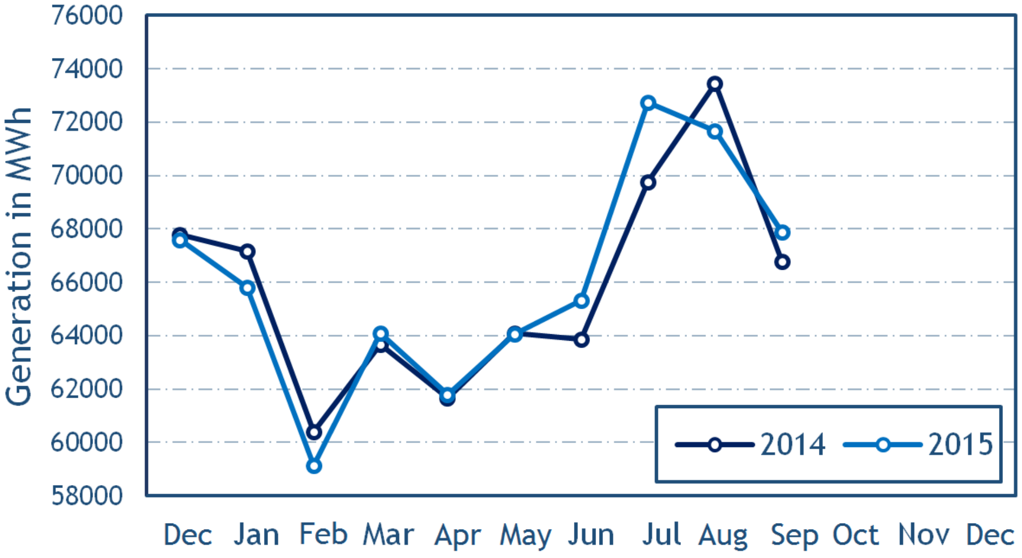

Figure 1.1 – The power generation of the Azorean Archipelago during the years 2014 and 2015.

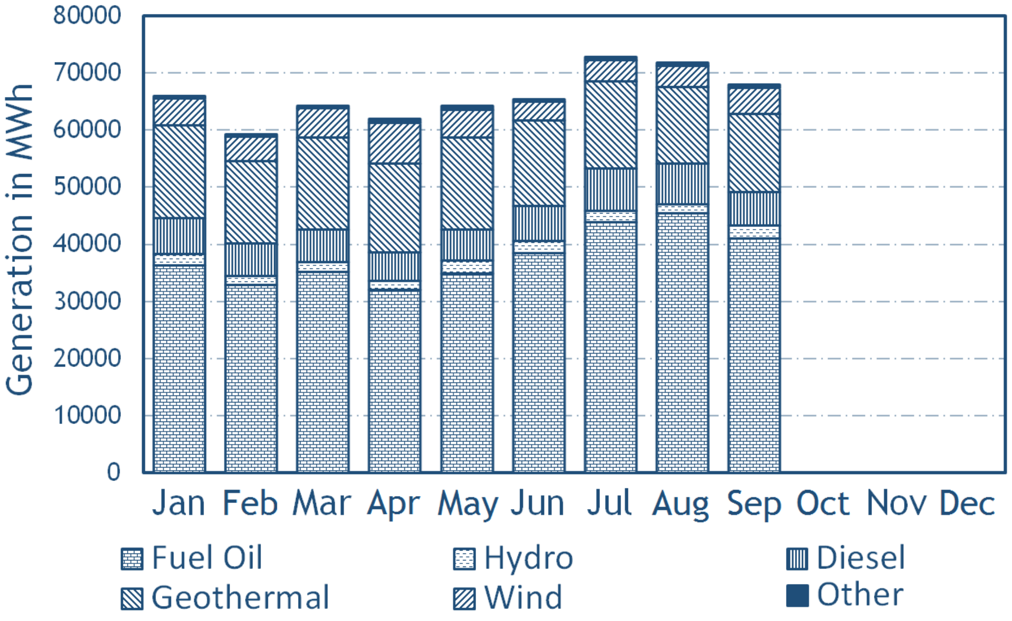

Figure 1.2 – The generation per energy source of the first 9 months of 2015.

The islands of São Miguel and Terceira contributed 52.8% and 26.2%, respectively, of the total energy supply to the network. The plants at Caldeirão, in San Miguel, and Belo Jardim, on Terceira, have a corresponding output at about 52% of the total energy emitted in the region. This shows how hard it is to reach the benefits of economies of scale given the geographical discontinuity of the region [18]. The emission of electricity by island throughout 2008—2012 of the Azores Archipelago can be observed in Table 1.2.

Table 1.2 - Emission of electricity by island throughout the years of 2008 – 2012 in GWh.

| | 2008 | 2009 | 2010 | 2011 | 2012 | Var.% 11/12 |
|---|---|---|---|---|---|---|
| Santa Maria | 19,7 | 20,4 | 21,5 | 21,0 | 19,8 | -5,6 |
| São Miguel | 435,3 | 437,1 | 447,6 | 440,2 | 415,1 | -5,7 |
| Terceira | 203,5 | 204,2 | 20,8 | 208,3 | 206,2 | -1,0 |
| Graciosa | 13,3 | 13,3 | 13,7 | 13,3 | 13,0 | -2,1 |
| São Jorge | 27,3 | 28,8 | 30,3 | 30,5 | 29,4 | -3,3 |
| Pico | 42,9 | 43,9 | 46,1 | 46,5 | 43,9 | -5,7 |
| Faial | 50,6 | 50,2 | 50,7 | 49,6 | 46,5 | -6,3 |
| Flores | 11,4 | 11,7 | 11,9 | 11,5 | 10,8 | -6,1 |
| Corvo | 1,2 | 1,3 | 1,3 | 1,3 | 1,3 | -1,7 |
| **Total** | **805,2** | **810,9** | **831,4** | **822,3** | **786,0** | **-4,4** |

### 1.2.1.2 Transportation and Distribution

The EDA, S. A., as the concessionaire of the Transmission and Distribution of Electricity in the Autonomous Region of Azores, manages this activity through a process of continuous improvements in efficiency and productivity. Under the concession contract for the management system, transmission and distribution of electricity signed with the Autonomous Region of the Azores, the EDA has a responsibility to pursue the activity that is the object of the concession for a period of 50 years beginning from October 12th, 2000, the date of approval of Resolution Nº 181/2000 published in the Official Journal, Issue I, Nº 41/2000 [21].

The distribution systems of electric power are not the same on every island. Thus, in São Miguel, Terceira and Pico islands with larger areas, there is a network of transportation and a MV (medium voltage) distribution with different voltage levels [19].

As for Graciosa, São Jorge, Faial, Flores and Corvo, the MV distribution networks have 15 kV voltage. On the island of Santa Maria there is an underground network of MT 6 kV near to the thermal power station of the airport, and in the remaining islands MT distribution is provided with overhead and underground infrastructure at the level of 10 kV [19].

### 1.2.1.3 Retailing and Commercialisation

In the Autonomous Region of Azores, the activity of the sale of power and energy-related services is managed by ERSE - the Energy Services Regulatory Authority contending with EDA and therefore acting as a guarantee for the supply of electricity to consumers, particularly the most vulnerable, in terms of quality and continuity of service [22].

Electricity rates charged to consumers are set annually by ERSE according to the rules laid down in the Tariff Regulations, where, besides the methodology for determining the level of income to provide for each rate, the tariff calculation methodology and the manner of determining the tariff structure are set out [22] [23].

Since 2010, it has achieved an effective convergence in terms of the average price for the types of electricity supplies to MV, LVN and LVE, which was preserved in 2012.

In 2012, electricity consumption reached 731 GWh, resulting in an overall decrease of -5.1% over the previous year, verifying a declining demand in both voltage levels, corresponding to -3.5% in medium voltage and low voltage at -6.1%. In the same year, the distribution network supplied 121,943 customers, representing an increase of 0.2% [18]. The number of clients and the amount of power consumption from 2008 to 2012 are shown in Table 1.3.

The market in the region is characterised by its small size and high dispersion, with a predominance of trade and consumer services (including utilities), with 45.0% of the consumption structure, followed by domestic and industrial uses, with 34.1% and 16.4%, respectively. It should also be noted that the islands of St. Miguel and Terceira were responsible for 78.9% of the supply of electricity and for 73.3% of the contracts with customers [18].

### 1.2.2 The Case of São Miguel

São Miguel Island is the main and most populated island in the Portuguese archipelago of the Azores. The island has around 140,000 inhabitants and covers 760 km$^2$ and has 45,000 local people in the largest city in the archipelago, Ponta Delgada. Due to the predominance of volcanic cones and craters in the interior of the island, human settlement has developed mostly along coastal and interior plains. The primary sector is the main economic activity of São Miguel, such as the production of dairy products, cereals, tea, fruits and wine. However, the largest source of revenue is the tourism sector [24] [25].

As of December 31, 2014, the electrical system of São Miguel Island is comprised of eleven electric power generation plants and eleven substations. The T&D system comprises a transmission network of 60 kV and a MV distribution network with voltage levels of 10 and 30 kV [19].

Table 1.3 - Number of customers and power consumption from 2008 to 2012 in GWh.

| | 2008 | 2009 | 2010 | 2011 | 2012 | Var.% 11/12 |
|---|---|---|---|---|---|---|
| Nº of Clients | 117 413 | 119 356 | 121 164 | 121 715 | 121 943 | 0,2 |
| LV | 116 763 | 118 692 | 120 485 | 121 025 | 121183 | 0,1 |
| MV | 650 | 664 | 679 | 690 | 760 | 10,1 |
| Power Consumption (GWh): | 753,7 | 756,7 | 778,6 | 770,8 | 731,3 | -5,1 |
| Domestic | 253,5 | 256,5 | 271,3 | 266,8 | 249,3 | -6,6 |
| Trade and Services | 252,3 | 251,0 | 256,4 | 254,5 | 246 | -3,3 |
| Public Services | 89,0 | 87,8 | 89,6 | 87,5 | 82,9 | -5,2 |
| Industrial | 125,6 | 127,3 | 127,5 | 127,2 | 119,6 | -6,0 |
| Public Illumination | 33,4 | 34,2 | 33,7 | 34,8 | 33,5 | -3,7 |

The evolution of the monthly consumption of electricity during the first nine months of the years 2014 and 2015 [26] is shown in Figure 1.3. Also, during the same months the accumulated consumption in 2015 was of 13,822 MWh. The main consuming sector is Business and Services, totalling as much as 41.5%, followed by the domestic sector with 31.6%. The accumulated consumption per sector in the first nine months of 2015 can be observed in Figure 1.4.

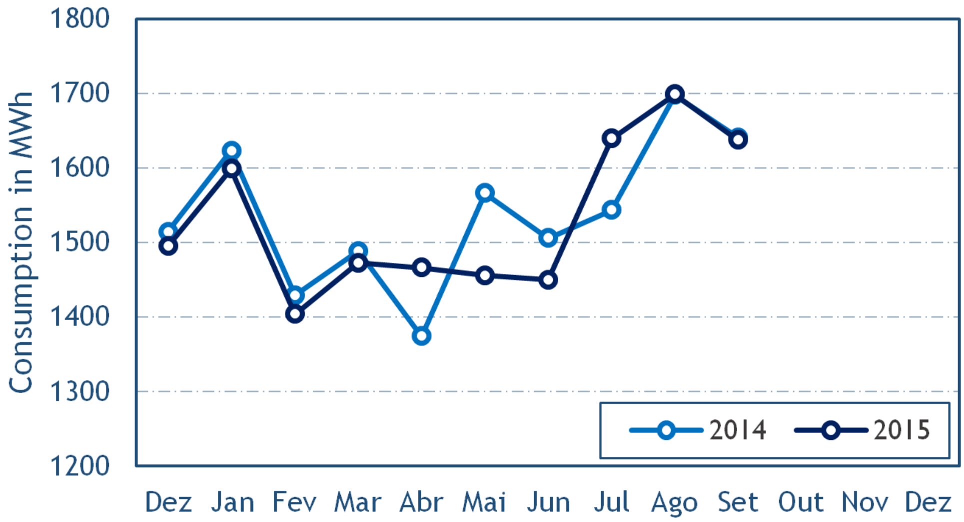

Figure 1.3 – The power consumption of São Miguel during the years 2014 and 2015 [26].

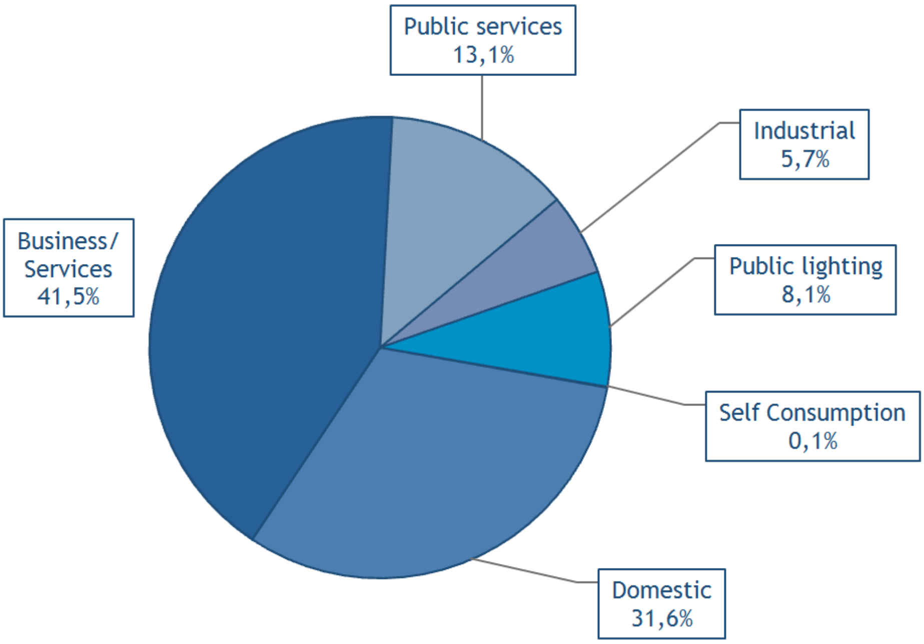

Figure 1.4 – The accumulated consumption per sector of the first 9 months of 2015 [26].

## 1.3 Challenges and Opportunities of High Penetration of Electric Vehicles

Currently the sales of EV are increasing worldwide and also in such a developed market as U.S. However, EVs represent less than 1% of all new EVs sold, nonetheless [27]. Up to this point, due to such factors as an almost absent charging infrastructure, a restricted driving range, and prolonged charging battery times have delayed the EV technology challenge to grow into a large-scale viable alternative to conventional fossil-fuelled internal combustion engine (ICO) vehicles [28] [29] [30] [31]. Figure 1.5 shows the percentage of the peer-reviewed published articles by some countries during the years 2009—2014 on EVs and grid-integrated technologies [32].

An increasing penetration of EVs has the potential to considerably diminish the oil dependency, to reduce the noise and greenhouse gas (GHG) emissions, and to increase the energy efficiency of the transportation sector. Various automotive brands have manufactured pioneering models of EVs and in several countries from Europe the battery charging infrastructure for EVs is continually developed and increased. Besides, various research projects and funding programs have been initiated, targeting the development of different segments of the EV technology. Enterprises, researchers and policy makers indicate that in the not-too-distant future EVs could reach a substantial market penetration [33] [34]. In Norway, a country where the EV segment experienced such evolution, the top-selling car models in September, October, and December of 2013 were battery EVs. In November of 2014, EVs reached 12% of sales in Norway [35]. The global EV and PHEV sales until the year 2014 and variation in percentage are shown in Figure 1.6.

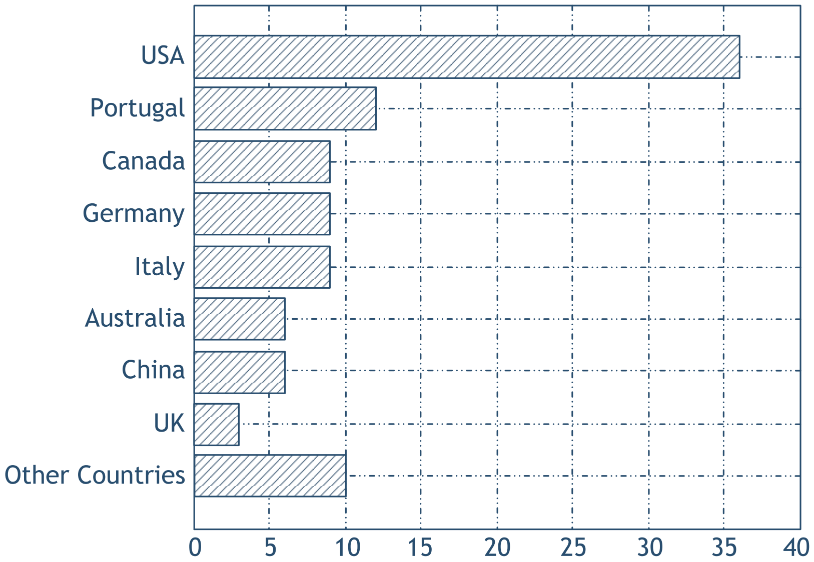

Figure 1.5 – The percentage of published articles related to EVs from different countries [32].

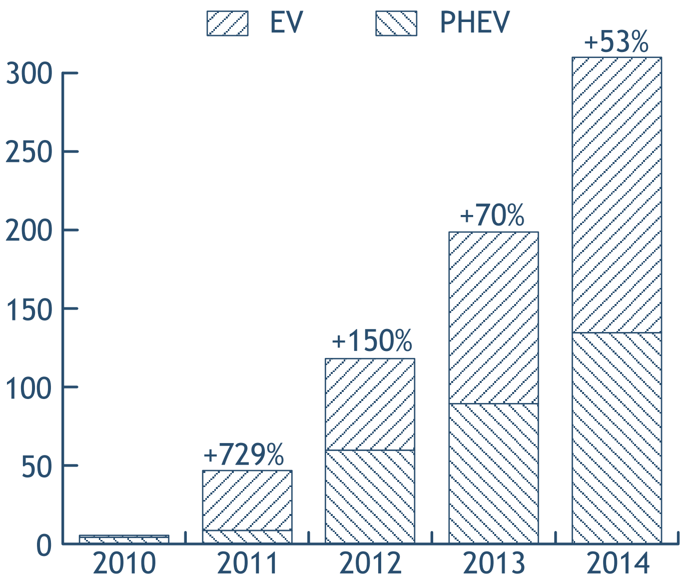

Figure 1.6 – Global EV and PHEV sales until the year of 2014 and variation in% [35].

The progressively growing drive supporting EV market penetration – both from the side of the consumer and from the automotive industry – indicates that EVs will play an important role in mobility of Europe in the following years [36].

The following few years after 2016 will be a time of great challenges and additional maturation for the automotive industry in EV market. As a direct consequence of EU regulation on EVs, alternatives available in the market are likely to increase. The pace of penetration in the market and adoption of EVs will be determined by quite a lot of factors in besides the fleet emission regulation, such as the cost of the fuel and the price of the battery pack enhancement [37].

Granting several elements such as design, brand, and performance are all vital customer concerns, three main reasons for early EV implementation and acceptance materialise [35]:

- The reduction of the carbon footprint– The aspiration to reduce the carbon footprint is an instigator for globally concerned customers to purchase EVs [38]. Several are actually eager to purchase a premium for the low-emission alternatives to the ICO. For instance, 29% of Norwegian EV customers state that the environmental issues are their main motive for buying them [39] [40].
- Driving and usage benefits – Supplementary benefits are offered to the owners of EVs by several policy makers in order to encourage and boost the sales of EVs. These benefits comprise privileged parking authorisations in compact urban regions (e.g., Amsterdam) or the permission to utilise the taxi and bus lanes and economise a substantial time for the duration of traffic congestion (e.g., Oslo) [41].

- The savings of cost - Without the aid of subsidies, EVs are considerably more expensive than ICO cars. However, in many particular circumstances, due to the government subsidy packages, some EVs happen to be less expensive than the ICO alternatives. Customers aiming to take advantage from such kinds of schemes are persuaded to acquire EVs, for the reason that EVs deliver a low-priced transportation alternative during episodes of elevated fossil fuel prices in the world. For example, in Norway, EVs are more attractive than ICO cars on a Total Cost of Ownership (TCO) basis as a result of subsidies that include exemption from purchase tax, VAT, toll road charges, registration tax, and annual circulation tax [42] [43].

Acknowledged obstacles to EV acceptance are based on widespread research concerning the main consumer factors influencing vehicle acquisition. Given that the attitudinal factors that most intensely differentiate consumer segments as shown below, together with broader vehicle purchase conditions, the crucial attributes affecting the purchase of EVs are: vehicle price and running costs, brand and segment supply, access to charging facilities, driving range and charging time and the receptiveness of consumer to EVs. By excluding the reduced running costs, the following characteristics all currently act as obstacles to EV acceptance [44]:

- EVs display a high price over non-EVs - As vehicle price is the upmost significant factor influencing the choice of the vehicle, financial incentives are currently essential to counterbalance the higher purchase price of EVs and decrease the TCO, even in such scenarios where creative acquisition incentives are utilised such as the battery leasing. Since consumers display high discounting rates for upcoming expenses, the prospective running cost savings existing due to the EVs happen to be not enough to offset the EV capital premium as supposed by the majority of EV customers. Despite the fact that, in certain conditions, the existing encouragements turn the four-year TCO of EVs competitive with ICO vehicles. Budget forecasts indicate that without aiding measures the EVs capital cost premium is going to continue an obstacle until at least 2030, particularly in the case of EVs [45].
- The current supply of EVs is still narrow - The vehicle segment choice by the customer has to do with the consumer requirements of comfort and size, expediency. While the brand alternative shows namely factors of emotion such as brand affection by the reason of loyalty being strong between car customers. According to OEM declarations of succession of model releases until 2015, the global image for brand supply of EVs in the next dozens of months is remarkably improving. As an example, the top 3 car manufacturers were represented by the end of 2013 in the UK. Yet many will be by the end of 2015 [46]. Nevertheless, the quantity of supply concerning the diversity of models differs throughout vehicle segments and types of EVs. The general panorama in case of EVs is in a better shape than for PHEVs [44].

- The overall concern of the EV's long charging times and short range - Far-reaching tests and present utilisation of charging infrastructure points toward the fact that the use of easily and public easy to get to charging networks is decreased. The customers of EVs will prefer as an alternative to utilise the nocturnal off peak hours charging, and/or at work during the working period. The degree of the preference of the utilisation of the off peak nocturnal charging sites is elevated between new EV customers, indicating that access to the infrastructure is not a central obstacle to initial EV implementation concerning the real necessity based on the characteristically daily travelled distance [47]. On the other hand, likely EV customers and EV owners normally request an upgraded and improved public charging infrastructure. The reason behind such type of behaviour is the customers' perceived necessity to move to more extended distances than the currently ones existing in the case of EVs [48]. The recharging period is constantly described as an obstacle by the EV customers, even though the EVs can recharge overnight [49] [50]. The research made in [44] indicates that a network of fast chargers have the opportunity to be the most effective method to counterpart the charging during off-peak hours and encourage a high penetration of EVs.
- Almost the entire private ICO vehicle customers do not seem to be very interested in EVs - Customer acceptance of EVs, also perceived as the inclination to contemplate the acquiring of an EV, differs given to the nature of the customer, with the main part of particular consumers perceive the present EV models available in the market inappropriately developed and unevolved and incapable [51]. The doubt concerning other remaining issues and details, also add to the customers' unwillingness to acquire EVs [52]. A sign to customer acceptance is the awareness of the consumer of the EV current state of the art [53]. For example, proof gathered in [44] indicates that car customers in the UK presently show a reduced awareness of the EVs and their accompanying benefits and possible and current incentives.

In Figure 1.7 it can be observed the key countries of EV sales [54]. Norway, the Netherlands, USA and Sweden are the leading markets in absolute terms. In a peculiar case, in Estonia can be witnessed high percentage sales due to uncommon conditions in which the Mitsubishi brand offered 500 i-MiEVs units, along with technical support, to the Estonian Government in order to benefit from EU Emissions Trading Scheme allowances. Countries such as the Netherlands and Norway are leaders of percentage sales. The aforementioned nations have major programs of incentives for the implementation of EVs in the market. Both countries have been bringing much attention since previous and current incentive schemes offer interesting lessons [55].

It is worth noting that in a few select countries, namely Switzerland, Austria and Belgium, the major percentage of sales are represented by quadricycles such as the Renault Twizy Z.E. [54].

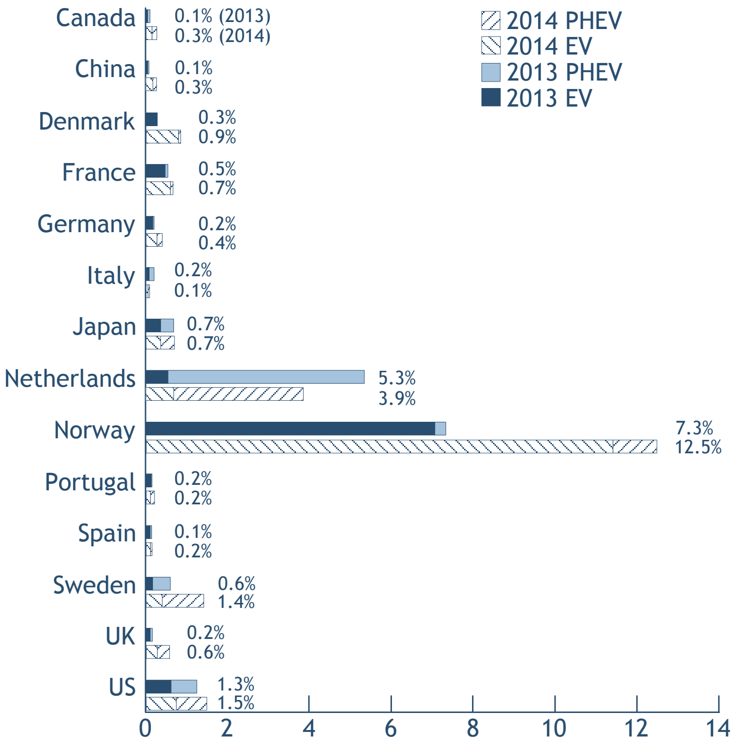

Figure 1.7 – Market sales shares of EVs for 2013 (colours) and 2014 (pattern) in % [54].

EVs can also turn out to be integral parts of a smart grid, since they are able of performing valuable services to power systems other than just consuming power [56]. On the transmission system level, EVs are regarded as an important means of balancing the intermittent renewable energy resources such as wind power [57]. This is because EVs can be used to absorb the energy during periods of high electricity penetration and feed the electricity back into the grid when the demand is high or in situations of insufficient electricity generation [58]. An effective penetration of EVs, however, relies on how well their effect on the electric grid is conveyed. The penetration levels of EVs estimated over the next ten years are anticipated to have a negligible impact on the power system. Yet, local distribution grids, mostly the ones that supply high populated cities, could have a necessity for an improvement of the distribution infrastructure in order to adjust to the charging requirements of EVs [59] [60].

### 1.3.1 The current EV scenario in Portugal

Cabinet Resolution nº 20/2009, 20 February [61], created the Program for Electric Mobility, under the NEEAP, in order to launch and promote electric mobility in Portugal. The Resolution nº 81/2009 [62], 7 September, adopted a set of measures for the implementation of this program including the approval and timing of the phases of the program and the creation of additional incentives to promote the access to and widespread use of electric vehicles [63]. However, while EVs have been identified as the vehicle of the future, in Portugal so far this has not been successful. Most analysts believe that while there are still major obstacles to overcome, especially the autonomy and the price, consumers will still hesitate to change their behaviour.

In Portugal, sales still have a minimal value and as of 2014 – 2,215 EVs, hybrids and plug-in hybrids were sold. This year a significant increase in sales of more environmentally friendly cars is expected [64].

On the other hand, Portugal is a world pioneer in the promotion of the EV, with the governmental plan of Electric Mobility and the deployment of a public recharging infrastructure in the country [65]. However, the volume of sales of EVs and PHEV in Portugal is still minimal, although the 2014 statistics represent the best year ever for this segment. The positive signals given by the market for EVs were BMW, with the i3, and Nissan, a veteran in this sector since 2011, with the Leaf [66].

## 1.4 Home Energy Management

The energetic status of the world has been intensely altered during the last 40 years, not only by the increase in demand for all of the energy sources but also the role of each source at a global level. With a growing interest in using alternative energy sources for generating electricity, the main developed countries have put in place investment plans and incentive policies for implementing them. Consequently, given any type of scenario, the energetic efficiency optimization of any sort of system is a strategic factor in sustainable energy management for all types of energy buildings, and thus has been a major focus for researchers, stakeholders and policy makers [67] [68] [69] [70].

Facing a constant growing demand for energy, out of the box strategies have to be applied at various stages of human activity. All the sectors have to endorse efficient use of energy, sectors such as the industrial and the residential sectors, in which studies stated that the last has been accountable for 31% of the global energy requirements that includes domestic consumers [71] [72].

This signifies that a growing amount of electronic appliances and devices in a typical dwelling create space for efficiency increases on energy consumption and combined operations can be made to tackle energy waste in dwellings [73]. A possibility is implementing new tariff policies related to demand response programs that assist the customer with the alteration of their electricity consuming behaviours. An alternative method consists in modernizing the control equipment specifically the domestic appliances working with regulating temperature [70].

Facing an increased demand for energy, alternative strategies have to be applied at different levels of human activity, not only in the industrial sector to endorse efficient use of energy, but also in the residential sectors in which studies have stated that it has been responsible for 31% of the worldwide energy needs, which include to a large extent domestic consumers [74]. The residential space-heating energy per dwelling can be seen in Figure 1.8. The housing industry has been accused of causing environmental problems ranging from excessive energy consumption to pollution of the surrounding environment.

Consequently, one of the methods towards the goal of reducing the energetic demand is by modernizing the control technology that runs such types of home appliances [75]. This signifies that the increasing number of electronic devices and appliances in the average home create opportunities to achieve efficiency gains on energy usage and that concerted actions can be developed to address energy saving in households [76] [77].

Strategies combined with energy-efficient devices and renewable energy technologies have been applied in buildings to improve thermal comfort and reduce energy end-use for many years [78]. One way is by introducing innovative tariff schemes based on demand response programs that help consumers to change their energy consumption habits. By lowering the peak demand, the utilisation of the available grid capacity is improved [79]. Another approach relies on updating control technology, namely domestic appliances operated with regulation temperature [80].

In general, in a typical residential home, the appliances with higher electricity consumption are those that provide heating and cooling services (AC, WH, and on a more reduced scale the RF). Numbers referred to UE-27 reveal that space heating for housing contributes around 70% of the household electricity bill, while domestic water heating stands at 10% [81]. The effective potential for energy savings as a result of adopting energy-efficiency measures can reach 30% [82].

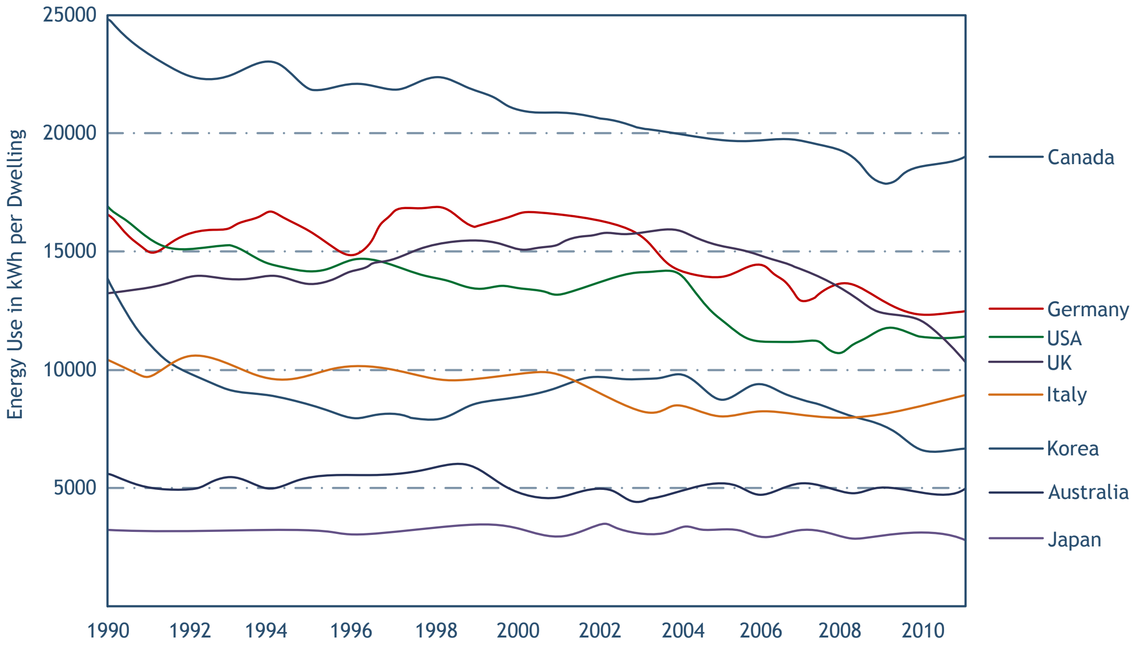

Figure 1.8 – Residential space-heating energy use per dwelling [70].

In this respect, one of the ways to help reach the objective of reducing energy consumption is through updating the control technology that operates this class of operated domestic appliance. In fact, heating and cooling equipment uses a conventional ON-OFF device to regulate the temperature. Due to its simplicity and low manufacturing cost, this solution has been the main choice by appliance brands for decades [83].

Alternative control methods have been researched to address rational energy utilisation of electric loads of appliances in residential homes, such as residential energy monitoring and management based on fuzzy logic [84], artificial neural networks, PID control, and model predictive control (MPC), among others [85].

Regarding the field of optimization, researchers throughout the world have been making an effort in introducing better control schemes, both in industry and domestic sectors, for all types of loads from small lamps to large motors. Much of the reduction was due to mechanical improvements; however, with the advancing of the years' new types of control arise [86].

## 1.5 Background on the Employed Methodologies

The mathematical models developed in this thesis are based on well-established methods, namely, mixed-integer linear programming (MILP), multi-objective optimisation, stochastic programming and model predictive control. In this section the fundamental concepts pertaining to the methodologies employed in this thesis are briefly discussed.

### 1.5.1 Mixed-integer linear programming

Mixed-integer programming is a subset of the broader field of mathematical programming. Mathematical programming formulations include a set of variables that represent actions that can be taken in the system being modelled. One then attempts to optimise (either in the minimisation or maximisation sense) a function of these variables, which maps each possible set of decisions into a single score that assesses the quality of the solution. These scores are often in units of currency representing the total cost incurred or revenue gained. The limitations of the system are included as a set of constraints, which are usually stated by restricting functions of the decision variables to be equal to, not more than and not less than, a certain numerical value. Another type of constraint can simply restrict the set of values to which a variable might be assigned [87].

Several applications involve decisions that are discrete, while some other decisions are continuous in nature. On the surface, the ability to enumerate all possible values that a discrete decision can take seems appealing; however, in most applications, the discrete variables are interrelated, requiring an enumeration of all combinations of values that the entire set of discrete variables can take [88].

Since the invention of the simplex method, linear programming (LP) has found a wide range of optimisation applications in many scientific fields because of its computational efficiency. However, the non-linear nature of most real-life problems and the fact that the efficient solution of large-scale non-linear programs is yet to be addressed, require that the non-linear relations are approximated by linear expressions (linearisation). Despite its computational advantages, LP may prove an insufficient framework to model a wide range of real-life optimisation problems. On the other hand, the possibility of considering variables that can represent discrete decisions provides an efficient and flexible framework to formulate a range of engineering problems since it allows addressing a range of non-linearities such as defining alternative sets of constraints, formulating conditionals, modelling discontinuous functions, etc. [89]. Linear programs that involve variables that can only take integer values are denominated mixed-integer linear programs (MILP). The standard form of a MILP optimisation problem [90] (without loss of generality a minimisation problem is considered) is represented by (1.1), where $c$ is the vector of the objective function cost coefficients, $b$ is a vector of parameters, $A$ is a matrix and $v$ is the vector of decision variables, some of which are integers, all of appropriate dimensions.

$$\begin{aligned}&\min f(v) = c^T v\\&\text{subject to}\\&Av = b\\&v \geq 0\\&y \in \mathbb{Z} \subseteq v\end{aligned} \tag{1.1}$$

If all the decision variables are required to be integers, then the aforementioned problem is a (pure) integer linear program, while if all the decision variables must take either the value 0 or 1, the problem (1.1) is called a 0 – 1 linear program.

Nowadays, large instances of MILP problems can be solved efficiently using reliable commercial solvers such as the IBM ILOG CPLEX [91], that may incorporate a variety of solution algorithms such as the branch-bound, Gomory cuts and the branch-cut algorithms or different heuristic-based solution approaches. Furthermore, high-level programming languages known as algebraic modelling languages (AML) such as the General Algebraic Modelling System (GAMS) [92] allow the straightforward computer implementation of large-scale mathematical programming problems. There is an abundant literature concerning the use of the MILP framework in formulating optimisation models and relevant solution algorithms. Exhaustive treatment of these aspects is out of the focus of this thesis; however, the interested reader is addressed to [93], [94] and [95].

#### 1.5.1.1 Multi-objective optimisation

The MILP optimisation problem described in Section 1.5.1 involves the optimisation (minimisation or maximisation) of a single objective function over the set of the feasible solutions $S$ defined by its constraints.

The optimal solution of the minimisation problem (1.1) is:

$$x^* \in S \tag{1.2}$$

such that:

$$f(x^*) \le f(x),\ x \in S \tag{1.3}$$

On the other hand, as the name suggests, multi-objective optimisation deals with more than one objective. Unlike in the case of the single objective optimisation, there is not in general a single solution 1 that simultaneously optimises all the objective functions.

Without loss of generality, the compact form of a multi-objective optimisation problem (MOOP) in which all the objective functions must be minimised is presented in (1.4).

$$\begin{aligned} &\min_{x} f(x) = \left[f_1(x), f_2(x), \cdots, f_N(x)\right] \\ &\text{subject to } x \in S \end{aligned} \tag{1.4}$$

As it may be noticed, a vector of objective functions must be optimised. Thus, in addition to the decision variable space, the objective functions constitute a multi-dimensional space, known as the objective space. The mapping between the m-dimensional decision variable space and the $N$ – dimensional objective space is denoted as:

$$f : X^m \mapsto F^N \tag{1.5}$$

Figure 1.9 illustrates the mapping between a 3-dimensional decision variable space and a 2-dimensional objective space. It should be stated that the mapping between the two spaces is not necessarily one-to-one [96].

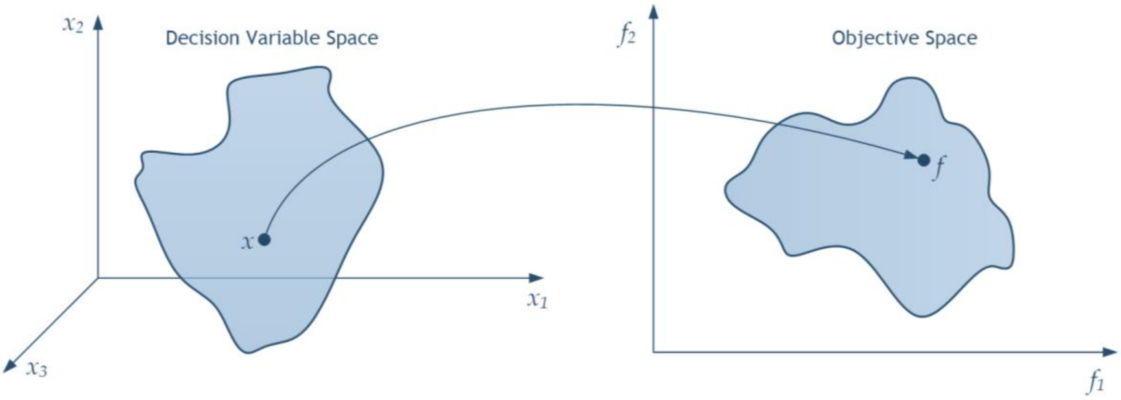

Figure 1.9 – Mapping between decision variable space and objective space [96].

The fact that the multi-objective problems constitute a multi-dimensional objective space leads to two cases of multi-objective problems, depending on whether the objectives are conflicting or not. In the special case that the optimisation of any arbitrary objective function leads to the improvement of all the objective functions, it is implied that the different objectives are not conflicting.

As a result, the MOOP can be solved either by optimizing an arbitrary objective function or by combining the multiple objectives into a single scalar function. However, in the majority of multi-objective problems a set of trade-offs between the different objectives is sought, rather than a unique optimal solution. Assuming that there exist $N$ different objective functions to be optimised, at least N possible extreme solutions exist, representing the best achievable result for each individual objective at the expense of all the others. Any other existing solutions represent different degrees of relative optimality among the N objectives. It becomes evident that the classical concept of optimality is not valid in the case of multi-objective optimisation [97].

## 1.5.2 Model Predictive Control

Model Predictive Control (MPC) is an important advanced control technique for difficult multivariable control problems. The basic MPC concept can be summarised as follows. Suppose that we wish to control a multiple-input, multiple-output process while satisfying inequality constraints on the input and output variables. If a reasonably accurate dynamic model of the process is available, model and current measurements can be used to predict future values of the outputs. Then the appropriate changes in the input variables can be calculated based on both predictions and measurements [98]. In essence, the changes in the individual input variables are coordinated after considering the input—output relationships represented by the process model. In MPC applications, the output variables are also referred to as controlled variables or CVs, while the input variables are also called manipulated variables or MVs. Measured disturbance variables are known as DVs or feedforward variables. These terms will be used interchangeably in this thesis [99].

Model predictive control offers several important advantages:

- The process model captures the dynamic and static interactions between input, output, and disturbance variables,
- Constraints on inputs and outputs are considered in a systematic manner,
- The control calculations can be coordinated with the calculation of optimum set points,
- Accurate model predictions can provide early warnings of potential problems. Clearly, the success of MPC (or any other model-based approach) depends on the accuracy of the process model. Inaccurate predictions can make matters worse, instead of better.

The overall objectives of an MPC controller have been summarised in [100]:

- Prevent violations of input and output constraints.
- Drive some output variables to their optimal set points, while maintaining other outputs within specified ranges.
- Prevent excessive movement of the input variables.
- Control as many process variables as possible when a sensor or actuator is not available.

A block diagram of a model predictive control system is shown in Figure 1.10. A process model is used to predict the current values of the output variables. The residuals, the differences between the actual and predicted outputs, serve as the feedback signal to a prediction block. The predictions are used in two types of MPC calculations that are performed at each sampling instant: set-point calculations and control calculations. Inequality constraints on the input and output variables, such as upper and lower limits, can be included in either type of calculation [101].

The set points for the control calculations, also called targets, are calculated from an economic optimisation based on a steady-state model of the process, traditionally, a linear model. Typical optimisation objectives include maximizing a profit function, minimizing a cost function, or maximizing a production rate [102]. The optimum values of set points change frequently due to varying process conditions, especially changes in the inequality constraints. The constraint changes are due to variations in process conditions, equipment, and instrumentation, as well as economic data such as prices and costs. In MPC the set points are typically calculated each time the control calculations are performed. The MPC calculations are based on current measurements and predictions of the future values of the outputs. The objective of the MPC control calculations is to determine a sequence of control moves (that is, manipulated input changes) so that the predicted response moves to the set point in an optimal manner. The actual output $\grave{y}$, predicted output $\hat{y}$ and manipulated input $u$ for Single-Input and Single-Output (SISO) control are shown in Figure 1.11.

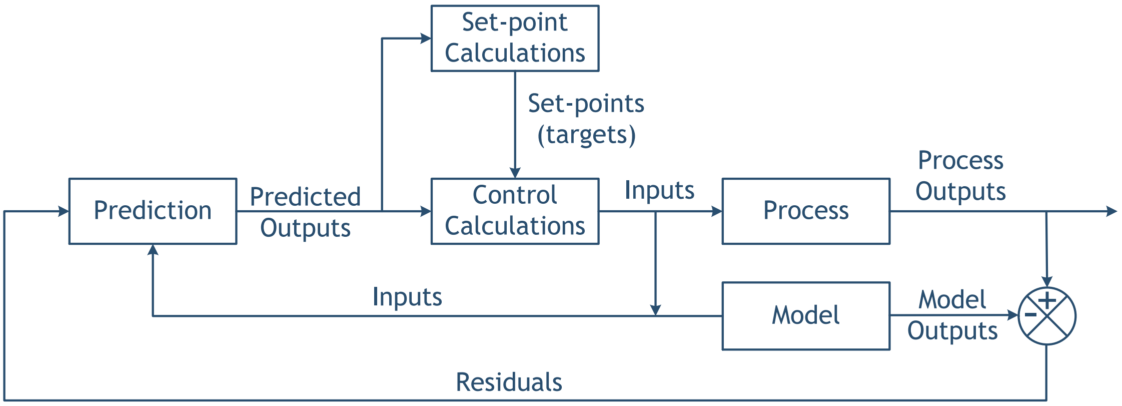

Figure 1.10 – Block diagram for model predictive control [99].

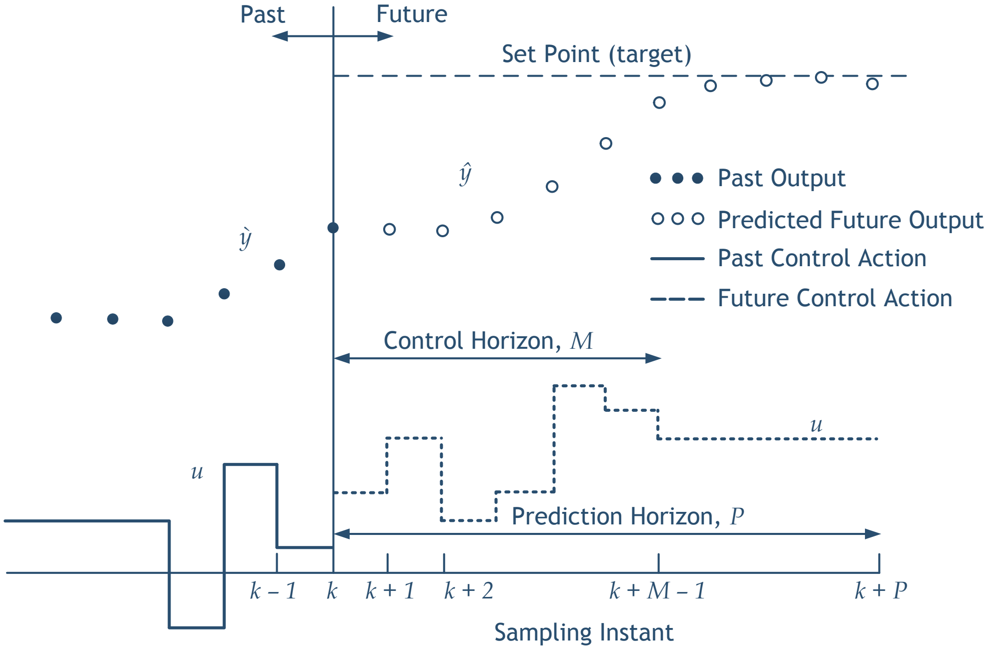

Figure 1.11 - Basic concept for model predictive control [99].

At the current sampling instant, denoted by $k$, the MPC strategy calculates a set of $M$ values of the input $\{u(k+i-1), i=1, 2,\ldots, M\}$. The set consists of the current input $u(k)$ and $M-1$ future inputs. The input is held constant after the $M$ control moves. The inputs are calculated so that a set of $P$ predicted outputs $\{\hat{y}\ (k+i), i=1, 2,\ldots, P\}$ reaches the set point in an optimal manner. The control calculations are based on optimizing an objective function. The number of predictions $P$ is referred to as the prediction horizon while the number of control moves M is called the control horizon [103].

A distinguishing feature of MPC is its receding horizon approach. Although a sequence of M control moves is calculated at each sampling instant, only the first move is actually implemented.

Then a new sequence is calculated at the next sampling instant, after new measurements become available; again only the first input move is implemented. This procedure is repeated at each sampling instant [104].

## 1.6 Research Questions and Contribution of the Thesis

The thesis aims to investigate and model the impact of EV loads, as well as other loads of domestic appliances, on power distribution transformers and then schedule the EVs in order to mitigate their impact. Subsequently, the thesis also aims to address an alternative way of improving home energy consumption.

In particular, the following research questions will be addressed:

- Will the effect of EVs, domestic appliance loads and other key factors on oil-transformer ageing be significant? In order to address the upcoming challenges, are the currently available transformer protections adequate?
- Will power distribution transformers situated on islands, both residential and private, be capable of withstanding the increasing penetration of EVs?
- Can all employees' EVs completely recharge during their working shift at a factory while at the same time avoiding overloading the power distribution transformer?
- Based on the different capacities of EVs, will price-incentive based DR have any impact on a neighbourhood distribution transformer ageing?
- Does an alternative control strategy in cooling and heating domestic equipment have the capability to improve energy consumption efficiency with the goal of reducing electricity bills?

The contributions of the thesis may be summarised as follows:

- A thorough discussion of the external factors that might affect the insulation ageing of oil-transformers and possible solutions for their mitigation, such as smart transformer protections and monitoring systems.
- The development of a model which analyses and assesses the impact of increasing penetration of EV loads on power distribution transformer ageing.
- The development of a smart EV scheduler for EV charging at work that avoids the overloading of the power distribution transformer while fully recharging the EV batteries in a timely manner.
- The development of an MILP model, composed of a neighbourhood composed of smart households with different end-user profiles, which assesses the impacts of price-incentive based DR on a neighbourhood distribution transformer ageing.
- The presentation of a novel approach through an alternative control strategy for domestic cooling and heating equipment in order to improve the energy consumption efficiency of a dwelling.

## 1.7 Organisation of the Thesis

Within the framework of the work programme proposed at the beginning of the PhD course, the thesis comprises seven chapters which are organised as follows. Chapter 1 is the introductory chapter of the thesis. In Chapter 2 a broad review is presented of the overall literature of oil-transformers and the effect of loads and other key factors that influence their ageing. In Chapter 3 an estimation of the influence of simultaneous charging of EVs on the dielectric oil deterioration of two power distribution transformers, one in a residential area and other at a private industrial client, is applied.

Chapter 4 proposes a case study of overloading prevention of an industry client power distribution transformer in an island in Portugal employing a new smart EV charging scheduler. An MILP model of the impact of a time-varying Demand Response (DR) scheme on the ageing of a distribution transformer serving a residential neighbourhood is applied in Chapter 5. In Chapter 6 MPC techniques are used as an alternative way of improving the energy consumption of dwellings. Finally, Chapter 7 concludes the thesis.

In more detail, Chapter 2 presents a comprehensive review and the analysis and discussion of the existing studies in the literature on the effect of loads and other key factors on oil-transformers ageing. The state-of-the-art was extensively reviewed, each factor was analysed in detail, and useful comparative tables were created. Then, a smart transformer protection was researched in order to address the upcoming challenges. Finally, a monitoring system was well thought out to ensure the reliability and sustainability of the transformer. An example is on-line monitoring of the transformer condition, either by monitoring the winding temperature or through dissolved gas analysis.

The part of the work presented in Chapter 3 focuses on a model that allows the evaluation of the effect of EVs charging loads on the thermal ageing of two real distribution transformers, one supplying a residential area and the other a private industrial client, which in turn are part of an isolated electrical grid on São Miguel Island, Azores, Portugal. The method takes into account the uncertainty of EV battery charging loads, i.e., the randomness of the travel habits of the EV user before recharging (recorded in 2011), the initial battery state-of-charge (SOC), and different charging modes. The novelty of this study compared to relevant studies in the literature is the real data, the study of the particular case of an island with high penetration of EVs, and the EV charging at work during three different shifts considering an industrial load.

Chapter 4 consists of a model that evaluates the effect of EVs charging loads on the thermal ageing of a real distribution transformer, supplying a private industrial client, the same as in Chapter 3, and then schedules the charging of the EV in an optimal manner that makes it possible to avoid the overloading of the aforementioned transformer through the development of a smart EV scheduler.

In Chapter 5 the focus is on the consideration of the impact of a time-varying DR scheme on the ageing of a distribution transformer serving a residential neighbourhood. Such considerations are important in order to investigate potential trade-offs between the benefits that emerge from rendering available dynamic tariffs to residential end-users and the inefficient utilisation of the DS infrastructure. In this chapter, the impact of the operation of a neighbourhood of smart households contracted under a time-varying pricing scheme on the local distribution transformer ageing is studied, which has not yet been considered in the relevant literature. This is the major contribution of the presented chapter.

Furthermore, the effect of the possibility of EVs covering a portion of the household load through vehicle-to-home (V2H) mode is analysed. An MILP model of a neighbourhood composed of smart households with different end-user profiles was developed.

In Chapter 6 the MPC techniques are employed as an alternative way of improving the energy usage of households. Three domestic loads are simulated in order to observe the impact of adjusting the MPC weights. The simulation is focused on each domestic appliance, which requires personalised weights tuning in order to reach the target of reducing to a minimum the energy consumption. On the other hand, having a multi-tariff system, a curve of the costs was elaborated and assessed. Therefore, it is possible to have different goals during the day, and so to determine the possible savings for each appliance that can be achieved during off-peak, mid-peak, and on-peak by providing simulations over 24 hours in the household.

Finally, Chapter 7 presents the main conclusions of this work related to assessing, modelling and scheduling the impact of EV loads, as well as other conventional loads, on power distribution transformers plus the alternative way of improving home energy consumption. Guidelines for future research and contributory work in such fields of research are provided. In addition, this chapter reports the scientific contributions that resulted from this and similar research work and that were published in journals, as book chapters or in conference proceedings.

## 1.8 Notation

The current thesis utilises the notation frequently used in the scientific literature, harmonizing the common aspects in all sections whenever possible. However, whenever necessary, in each section a suitable notation may be used. The mathematical formulas will be identified with reference to the subsection in which they appear and not in a sequential manner throughout the thesis, restarting them whenever a new section or subsection is created. Furthermore, figures and tables will be identified with reference to the section in which they are inserted and not in a sequential manner throughout the thesis. Mathematical formulas are identified by parentheses (x.x) and called “Equation (x.x)” and references are identified by square brackets [xx]. The acronyms used in this thesis are structured under synthesis of names and technical information coming from both the Portuguese and English languages, as accepted in the technical and scientific community.

> “Science is the great antidote to the poison of enthusiasm and superstition.”
>
> *"A ciência é derradeiro antídoto contro o venêno do entusiasmo e da superstição."*
>
> Adam Smith

# Chapter 2

# Effect of Loads and Other Key Factors on Oil-Transformers Ageing: Sustainability Benefits and Challenges

Transformers are one of the more expensive elements of equipment found in a distribution network. The transformer’s role has not changed over the last decades. With a simple construction and at the same time mechanically robust, it has safeguarded a long term service that in average can reach half a century. Today, with a continuous trend to supply a growing number of non-linear loads along with distributed generation (DG) notion, a new challenge has risen in terms of the transformer sustainability with one of the possible consequences being the accelerated ageing. In this chapter a careful review will be made of the existing studies in the literature of the effect of loads and other key factors on oil-transformers ageing. The state-of-the-art will be reviewed, each factor will be analysed in detail. The manufacturing process and the life cycle assessment (LCA) of a typical transformer will be addressed. A case study will be analysed of a transformer that was unusually overloaded due to an abnormal event caused by the induction motors that operate at a factory. Finally, in the end a smart transformer protection is sought in order to monitor and protect it from the upcoming challenges.

## 2.1 Introduction

The transmission and distribution systems existing today are much more far-reaching and extensive and are significantly dependent on transformers, which in turn are considerably more efficient and sustainable than those of a century ago [105]. Yet, a large population of power transformers alongside with other power system grid infrastructures have been in service for decades and are considered to be in their final ageing stage. Contrariwise, due to economy and business growth in our era, the electricity demand is rising quickly [106].

The power transformer is the one of the most important as well as one of the most costly elements in the electricity grid. Effective transmission and distribution of electricity through different voltage levels is possible through the use of power transformers. Any malfunction of this element may affect the reliability of the entire network and could have considerable economic impact on the system [105] [107] [108] [109]. As a result, methods to mitigate the ageing and loss of life (LOL) of the transformer are intensely researched in order to make more sustainable this essential part of electric network, and consequently, to ensure the sustainability of the whole system.

Skilled planning and correct controlling needs to be taken into account with the aim of using power transformers with efficiency. Generally, transformers are designed to function within its nameplate ratings, yet, in certain situations, they are loaded over the nameplate ratings due to any failure or fault in power systems, the existence of possible contingencies on the transmission lines and/or economic considerations [110] [111]. However, in order to support the overloading of the existing transformer the installation of an extra transformer is not needed. Yet, when the power transformer is overloaded beyond its nameplate ratings there are risks and consequences which can originate failures as a result. If the overloading is not operated with the proper evaluation it may cause damage and failures which is not always as easily apparent. Such type of failures can be classified as short-term and/or long-term failures. One of the main consequences of overloading power transformers is the accelerated ageing [110] [112] [113] [114].

By overloading the power transformers is caused an increase of operation temperature. It is a recognised fact that the ageing of power transformers is influenced by the operating temperature [110] [111] [115] [116]. Since the operating temperature varies according to the loading of a transformer, a model was developed for the heat transfer characteristics between oil and windings, with the purpose of making a prediction of the hot-spot temperature ($\Theta_h$) in the transformer as a function of the load, while taking the cooling characteristics into account. An accurate modelling of $\Theta_h$ is decisive to precisely predict the transformer ageing [117].

The integrity evaluation of the transformer is complex but indispensable to avoid permanent damages with consequent substantial impacts on transmission and distribution network services and on maintenance costs as a result of outages. The accelerated degradation of its solid insulating system i.e., oil impregnated cellulosic insulation materials, is among the causes which can result in transformer failures (i.e., $\Theta_h$ rise over the limits, partial discharges) and strongly depends on the operating condition of the transformer. In fact, at times the degradation of transformer’s dielectric parts start much earlier than the intended end-of-life of the transformer, which is generally predicted as being 30 years [115] [116]. This can occur due to an accelerated thermal ageing of both the insulating paper and oil.

Despite the fact that the regeneration of a degraded insulating oil can be effectuated by appropriate treatments or even by the exchange with a new compatible oil, the restoration of degraded paper entails costly and invasive operations that have to be primarily performed by the manufacturer, since it might implicate the total replacement of transformer windings. Consequently, generally the end of useful life of a transformer is largely dependent on the thermal deterioration of insulation papers and that an accurate monitoring of parameters related to this process is essential for utilities to verify the condition of transformers [108].

Generally, due to the low load factor and other requirements, the operation efficiency of power transformers is poor and thus unsustainable. They are traditionally designed and operated with loading between 40%–60% in order to maintain reliability during contingencies [118]. For example, approximately 25% of distribution assets in the United States of America are used only for 440 h of peak load [119]. Additionally, due to the load growth, at substations is needed an upgrade of power transformers. The traditional method which consists in the reinforcement due to an increasing load is highly costly. Consequently, utilities tend to intensify the utilisation of already installed assets which results into highly utilised systems [120]. As a result, new solutions for load modification in the grid need to be implemented during contingencies in order to mitigate the LOL. Therefore, transformer utilisation efficiency can be increased and economic savings can be accomplished in terms of postponed reinforcements and thus, the overall sustainability is increased as well [119].

In this chapter a survey of the available literature is made for the factors that influence the insulating paper and oil ageing, such as the electric vehicles (EVs), harmonics, ambient temperature ($\Theta_a$), demand response (DR), DG and experimental loads created specifically to study the impact on the transformer. This chapter is organised in six sections as follows. Section 2.2 explores the mathematical formulation behind the $\Theta_h$ and the paper and oil insulation ageing. In Section 2.3 the literature is revised and each of the factors that influence the transformer ageing are thoroughly analysed. In Section 2.4 is analysed a transformer that was overloaded as a result of an atypical event caused by induction motors at a factory. Section 2.5 presents the aspects of protection of the transformer, particularly a $\Theta_h$ relay. Finally, section 2.6 concludes the study.

## 2.2 State of the Art

When transformers operate – tend to generate quantities of heat. The conversion of the energy inside the transformer is the reason of this heat. The generated heat varies with the load that is applied to the transformer. Higher the load, higher will be the generated heat, which is due to the copper winding and also due to the core losses that occur during the operation of the transformer [107]. The generation of heat cannot be avoided and consequently there is a standard limit that is given to a particular transformer in regard to the rise in the heat.

The aforementioned limit varies from transformer to transformer and depends on the material that is utilised in the transformer. Also it has to be taken into considerations the standardised safety regulations and the thermal dependency of other elements that are adjacent to the transformer and work along with it. Different cooling elements exist today that are utilised to regulate the heating of the transformer. Consequently, transformers can be classified into different types based on their insulation material and cooling process [121].

The primary classification would be according to the thermal insulation material and one type is the oil filled transformers which use mineral based oil and cellulose paper in their insulation. Such types of transformers are usually unexpansive and they have varied applications. The use of oil as insulation material has proven to be very thermally efficient and to be displaying unique dielectric properties, leading to the most of the remaining transformer designs being made keeping oil filled ones as reference [122].

However, oil filled transformers display an evident weakness which is the flammability, consequently there should be extreme caution that should be taken while such transformers are installed and operations of maintenance are performed. Oil-transformers are restricted only to outdoor installations and indoor installations have to be monitored with great caution [107].

The second classification based on thermal insulation is the dry category of transformers which do not make use of mineral oil for the insulation. The most common mean of insulation this of such type of transformers is to the use of a moisture resistant polyester sealant. Most often the highest quality of this type of transformers is achieved through the use a sealant that is applied with a process known as the vacuum pressure impregnation [123]. Transformers manufactured with this method will display high resistance to chemical contaminants. On the other hand, the performance of dry transformers under overload is limited and in such conditions the temperatures usually peak sharply above the standardised temperature range. For dry transformers in order to perform over the rated load, additional cooling fans have to be installed with the purpose to accelerate through forced convection the dissipation of heat [105].

## 2.2.1 Types of Transformers

### 2.2.1.1 Small Distribution Transformers

The single phase transformers are typically made with wound core system and rectangular windings. Such types of transformers are usually in use in the British Standard countries and in USA and particularly adapted for small power systems. The power range usually varies from 50 to 200 kVA within 35 kV and the represent an economical option for certain networks, particularly those with low population densities. The main advantages are the small production costs and with the possibility of good automation [124].

### 2.2.1.2 Distribution Transformers

These three phase transformers are immersed in liquid oil as dielectric insulation and enclosed in a tank with cooling system and recently they are built hermetically sealed with the purpose of reduced maintenance and better quality. The power range is usually from 200 to 2000 kVA within 35 kV and the main use is the distribution of energy in cities and centre with different houses. The main advantage is the great extension of use in different outdoor applications [105].

### 2.2.1.3 Cast Resin Transformers

Such types of transformers with solid cast windings of epoxy D resin were developed in Europe, and this transformer design started to be broadly accepted in the United States in the 1980’s. The cast resin transformers are typically three-phase and the power range varies usually from 250 to 4000 kVA within 35 kV. They are mostly used is in underground systems, mines and skyscrapers and the main benefits are the fireproof and explosion-proof, particularly when adapted for indoor applications [125]. Over 100,000 units have proven themselves in power distribution or converter operation all around the globe [126].

### 2.2.1.4 Large Distribution Transformers

The main purpose of the large distribution transformers is receiving energy delivered by higher voltage levels and to transform and distribute it to lower voltage substations or directly to large industrial consumers. Such transformers, which are three-phase and with copper or aluminium windings, are typically immersed in liquid oil as dielectric insulation and enclosed in a tank with cooling system and can be manufactured with on-load tap changer or off-circuit tap changer. Transformers built with on-load tap changer typically have a separate tap winding. Power range usually varies from 2000 to 2500 kVA up to 36 kV and the main use is in industrial applications, grid interconnections, and special applications as furnace or railway [105] [124].

### 2.2.1.5 Medium Power Transformers

Medium power transformers are three phase or one phase transformers with a power range from 30 to 250 MVA and a voltage of over 72.5 kV and are used as network and generator step-up transformers, adapted for grid interconnections for small distance transmission lines until 220 kV. Such transformers have tank-attached radiators or separate radiator banks. The main use is in interconnecting grids and the main advantages are the high tension and high power capacity [126].

### 2.2.1.6 Large Power Transformers

The large power transformers are adapted for grid interconnections for large distance and depending on the on-site requirements they can be designed as multi-winding transformers or autotransformers, in 3-phase or 1-phase versions.

The transmission lines are above 220 kV and the power range is typically above 250 MVA and up to and more than 1,000 MVA and voltages are up to 1,200 kV. The main use is in interconnecting grids and main power stations and the main advantages are the high tension and high power. These transformers can also be step-down transformers which transform the voltage down from the transmission voltage level to a proper distribution voltage level. The power rating of such types of transformers may range up to the power rating of the transmission line [126].

### 2.2.2 Cooling Methods for Oil Immersed Transformers

The heat generated in transformer windings through resistive and other losses must be transferred into and taken out by the transformer oil. The winding copper maintains its mechanical strength up to a few hundred degrees Celsius. The transformer oil does not degrade considerably below around 140 ºC however paper insulation deteriorates greatly if its temperature rises above about 90 ºC [116].

The cooling oil flow must, consequently, guarantee that the insulation temperature is kept below this temperature as far as possible. The study of the permitted temperature rises given in [116] demonstrated that a number of different values are permitted and that these depend on the method of oil circulation and thus different cooling modes are defined [105].

#### 2.2.2.1 Oil Natural Air Natural (ONAN)

ONAN is the most common transformer cooling system where the natural convection of the oil is used for cooling. In such method the hot oil flows to the upper part of the transformer tank and the left empty location is occupied by cold oil. The hot oil which flowed to the upper side will dissipate heat in the atmosphere and will cool down and as a consequence, the transformer oil in the tank will continuously circulate when the transformer is loaded. In order to increase the effective surface area of the in order to accelerate the heat transfer – extra dissipating surface in the form of tubes or radiators connected to the transformer tank is installed, a part that is known as the radiator of transformer or radiator bank of the transformer [127] [128].

#### 2.2.2.2 Oil Natural Air Forced (ONAF)

The heat dissipation can be increased through the expansion of the dissipating surface but when natural convection is not enough – applying forced air flow on that dissipating surface the transformer is cooled more rapidly. For this purpose, fans that dissipate air on the cooling surface are employed, the forced air removes the heat from the surface of radiator and provides an improved cooling when compared to natural air. Since heat dissipation rate is faster by employing the ONAF method instead of ONAN, the transformer can tolerate extra loads without crossing the accepted temperature limits [107].

#### 2.2.2.3 Oil Forced Air Forced (OFAF)

By employing OFAF cooling system the oil is forced to circulate within the closed loop of transformer tank through the use of oil pumps. The main advantage is that it is a compact system and for the same cooling capacity of the former two systems of transformer cooling OFAF occupies considerable less space. Forcing the oil circulation and removing the air over the radiators will usually achieve a smaller, economical transformer than either ONAF or ONAN. However, the maintenance burden is increased due to the required oil pumps, motors and radiator fans. The application of such transformers in attended sites must be with good maintenance procedures. OFAF cooling is used usually by both generator and power station interbus transformers [107] [127].

#### 2.2.2.4 Oil Forced Water Forced (OFWF)

Since the water is better heat conductor than the air, in the OFWF cooling system of transformer, the hot oil is transferred to an oil-to-water heat exchanger by means of oil pump where the oil is cooled when in contact with cold water on oil pipes of the heat exchanger [127] [129].

#### 2.2.2.5 Oil Directed Air Forced (ODAF)

ODAF which is mainly utilised in very high rating transformers is an improved version of OFAF where forced circulation of oil is directed to flow through predetermined conduits in transformer winding. The cooled oil enters the transformer tank from the radiator or cooler and flows through the winding where predetermined oil flowing paths crossing the insulated conductor are provided for ensuring faster rate of heat transfer [107] [130].

#### 2.2.2.6 Oil Directed Water Forced (ODWF)

ODWF or is similar cooling method to ODAF and the only difference is that the hot oil temperature is decreased in the cooler through the use of forced water instead of air [107].

### 2.2.3 Transformer thermal diagrams

Since the power transformer it is an essential element of the distribution network, an appropriate preservation of mineral-oil-tilled distribution transformers is very important in power systems, consequently a need is generated to adopt a protective approach regarding transformer loading, with the purpose of benefiting as much as possible from their availability and long term service [116].

The insulation system of a distribution transformer is fundamentally made of paper and oil which suffers from ageing. An unexpected increase in the load results in a rise of the $\Theta_h$ and consequently affects the thermal decomposition of the paper [6] [115] [116] [131] [132].

Due to the reason of the temperature distribution not being uniform, the hottest section of the transformer will subsequently be the most damaged. As a consequence, $\Theta_h$ directly affects the life duration of transformers [133] [134].

A basic thermal diagram is created in [116], as shown in Figure 2.1, on the understanding that such a diagram is the simplification of a far more complex distribution. The assumptions made in this simplification are as follows [116]:

- The oil temperature inside the tank suffers a linear increase from bottom to top, regardless of the cooling method.
- It is also estimated that the temperature rise of the conductor at any position up the winding is presumed to increase linearly, parallel to the oil temperature rise, with a constant difference $g_r$ among the both straight lines, where $g_r$ is considered to be the difference between the winding average temperature rise by resistance and the average oil temperature rise in the tank.
- The $\Theta_h$ rise is higher than the temperature rise of the conductor at the top of the winding, due to an allowance that has to be made for the increase in stray losses, for possible additional paper on the conductor and for differences in local oil flows. To take into consideration such non-linearities, the difference in temperature between the $\Theta_h$ and the top-oil ($\Theta_o$) in tank is made equal to $H \times g_r$, namely, $\Delta\Theta_{h,r} = H \times g_r$.

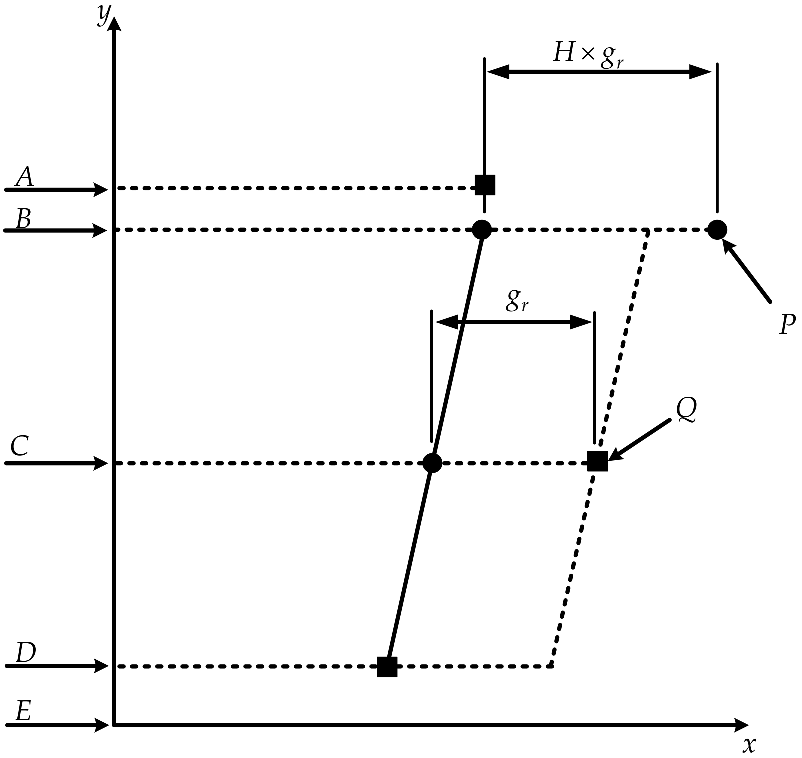

Figure 2.1 - Thermal diagram of the transformer.

The description of Figure 2.1 concerning the transformer sections is made as follows: $A$ is the $\Theta_o$ temperature derived as the average of the tank outlet oil temperature and the tank oil pocket temperature, $B$ is the mixed oil temperature in the tank at the top of the winding (often assumed to be the same temperature as $A$), $C$ is the temperature of the average oil in the tank, $D$ is the oil temperature at the bottom of the winding and $E$ is the bottom of the tank.

As for the variables, $g_r$ is considered to be the average winding to average oil (in tank) temperature gradient at rated current, $H$ the Hot-spot factor, $P$ is the $\Theta_h$, $Q$ is the average winding temperature determined by resistance measurement, while in the $y$ axis are situated the relative positions and in the $x$ axis the temperature values. The symbol (●) means a measured point and (■) signifies a calculated point.

As has been mentioned before, the $\Theta_h$ should be referred to the adjacent oil temperature as it is assumed to be the $\Theta_o$ inside the winding. Measurements have shown that the $\Theta_o$ inside a winding might be, depending on the cooling method, up to 15 K higher than the mixed $\Theta_o$ inside the tank [116].

For many transformers in service, the $\Theta_o$ inside a winding is not accurately known. On the other hand, for most of these units, the $\Theta_o$ at the top of the tank is well identified, either by measurement or by calculation.

The calculation rules in this part of IEC 60076 [116] are based on the following:

- $\Delta\Theta_{o,r}$ the $\Theta_o$ rise in the tank above $\Theta_a$ at rated losses [K];
- $\Delta\Theta_{h,r}$ the $\Theta_h$ rise above $\Theta_o$ in the tank at rated current ($I_r$) [K].

The parameter $\Delta\Theta_{h,r}$ can be determined either by direct measurement during a heat-run test or by a calculation model validated by direct measurements.

In Figure 2.2 is represented an alternative basic thermal diagram of oil transformers, as proposed in [135], where a cross section of an oil transformer is shown.

In Figure 2.2, $\Theta_b$ is the bottom oil temperature rise in cooler and winding in K, $\Delta\Theta_r$ is the average winding temperature rise in winding in K, $\Delta\Theta_w$ is the top oil temperature rise in winding in K, $\Delta\Theta_c$ is the top oil temperature rise in the cooler and winding in K.

For instance part of the winding at the bottom of the leg is in cool oil and part at the top of the leg will be encircled by the hottest oil. To measure these two values a thermometer has to be inserted in the oil at the top of the tank close to the outlet to the coolers and another at the bottom of the tank.

The average oil temperature will be midway between both values and the average gradient of the windings is the difference between average oil temperature-rise and average winding temperature-rise, namely, the temperature-rise determined from the change of winding resistance [105]. The hot-spot factor is one of reasons why there will be such difference between maximum gradient and average gradient as can be seen in Figure 2.3 which represents an assembly of conductors surrounded by horizontal and vertical cooling ducts. The conductors at the corners are cooled directly on two faces, whilst the remaining ones are cooled on a single face only. In addition, except in the case of the oil flow being forced and directed, the heat transfer will be poorer on the horizontal surfaces, as a result of the poorer oil flow rate. Thus, the oil in these regions could well be hotter than the general mass of oil in the vertical ducts [105].

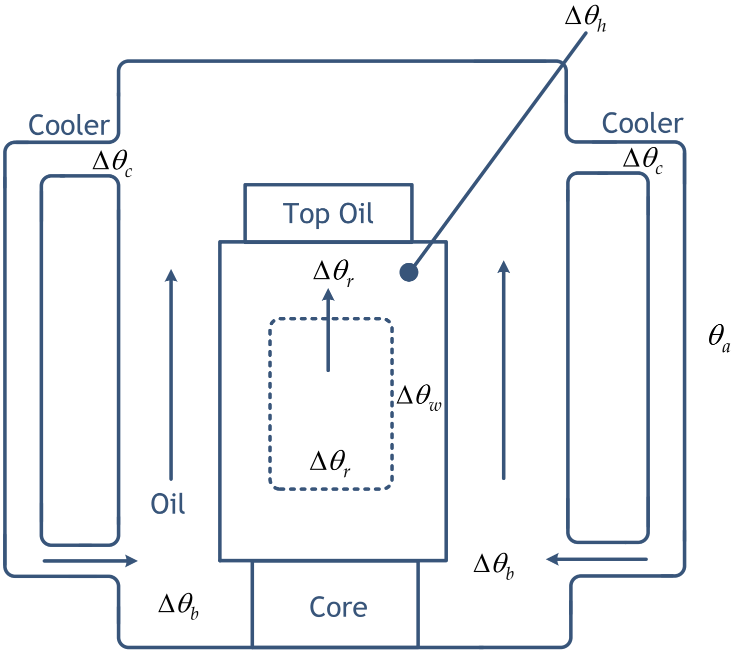

Figure 2.2 - Basic thermal diagram of oil transformers.

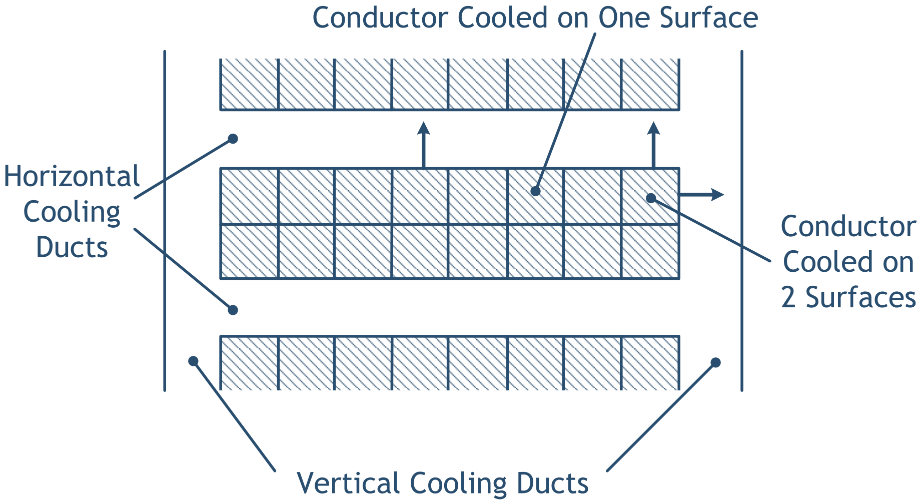

Figure 2.3 - Winding hot spots.

## 2.2.4 Transformer Manufacturing Process

In the current competitive market background there has been an urgent necessity for the transformer manufacturing industry to increase transformer efficiency and to reduce costs ever since low cost products, high quality, and processes have become the key to survival in a global economy. By reducing load and no-load (iron) losses, an improved transformer efficiency can be reached [136]. However, in order to maximise economy, the costs of the production of the transformer, its installation, maintenance and losses have to embody the minimum long-term cost to the transformer user [137]. Minimum no-load losses are for the most part important considering the fact that since a transformer is continuously energised, i.e., 24 h per day, every day, then considerable energy is consumed in the core (no-load losses), while load losses occur only when a transformer is on load. Consequently, the transformer design should be based on the given specification, utilising the economically available materials with the intention of reaching lower costs, reduced size, lower weight, and a greater operating performance [138].

In the classic liquid-immersed transformers the cellulose-based paper and pressboard materials are utilised mainly as insulation in the windings and within the core/coil assembly – the active part. The winding conductors can be insulated with enamel as well. The whole active part assembly is then dried, closed in a steel tank and immersed in mineral oil – the dielectric and cooling medium [105].

Contemporary compact designs of distributed power generation systems might require transformer designs where a focus on the limited size and weight of the design is essential. For instance, in wind turbine construction it is usual to utilise liquid-immersed transformers using alternative insulation materials. Cellulose-based paper and board can then be substituted with aramid insulation and mineral oil can be exchanged with ester fluids or silicone. The higher operating temperature permitted by such kinds of materials allows for the reduction of the cooling systems of transformers. Consequently, the active part and overall dimensions of the equipment are much more compact. This means less material is utilised for such designs [139].

For the core the high-grade grain-oriented silicon steel is automatically cut to length and tightly wound on modern equipment. Afterwards, accurately formed lap joints promote lower losses. In a computer-controlled continuous annealing furnace each core is annealed after forming to eliminate stress. In order to guarantee the lowest possible core losses the atmosphere within the furnace is continuously purged with 100% nitrogen to assure an oxygen-free environment [140].

The copper or aluminium wire utilised in the high-voltage section of the coils is precisely placed between the cuffed edges of the thermally set diamond paper insulation. Hard pressboard cooling ducts make possible an even flow of oil throughout the coil intended for cool efficient operation [141]. Accurately slit, and edge-conditioned aluminium strip is utilised in the low voltage section for improved short circuit strength and also to eliminate hot spots. Winding tensions are carefully monitored and controlled throughout the winding processes to ensure a strong, tight coil assembly [142] [143]. By having a diamond pattern heat-set epoxy coating on both sides of the paper, the thermally upgraded electrical insulation grade Kraft paper can be utilised all over the coil in order to maximise the short circuit strength [144].

After the core and coil are combined, it is fortified by proper frames and banding. Afterwards, leads and accessories are added, and the finished assembly is overheated with the intention of removing any moisture that may have been absorbed during the course of the manufacturing process. In order to add superior strength, the completed unit is retained in the tank by a three-point mounting system [145]. A brief presentation of a manufacturing process [146] flowchart can be observed in Figure 4.

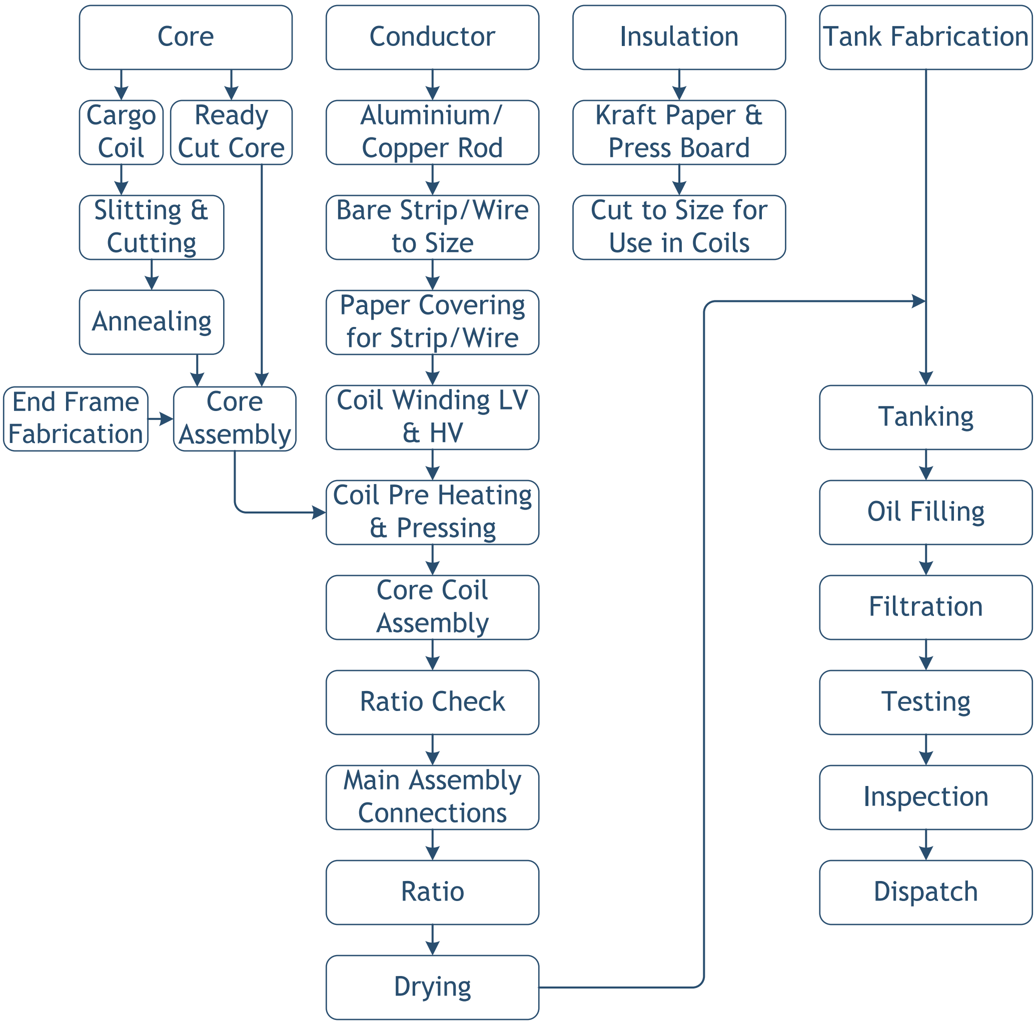

Figure 2.4 – The distribution transformer manufacturing process flowchart.

## 2.2.5 Transformer Ageing Mathematical Formulation

### 2.2.5.1 Transformer ageing characteristics

The degradation of the paper can make the transformer to fold regarding a few mechanisms: the frail paper can be separated from the transformer windings and obstruct ducts; the water is a product of degradation and builds up in the paper, decreasing its resistivity; at the limit, local carbonising of the paper rises the conductivity thus overheat and as a consequence the conductor fails [105].

Due to motives mentioned above it is essential to know the state of the transformer and the operating condition. The Montsinger law dictates that rising the average lifetime temperature 8 degrees over the maximum permissible operating temperature the expected lifetime of the paper oil insulation system is reduced by half [147]. The law is represented by the expression (2.1):

$$Thermal\ Aging = 2 \times \frac{\upsilon - 90^{\circ}\mathrm{C}}{8^{\circ}\mathrm{C}} \tag{2.1}$$

The average lifetime temperature can be assessed with the load duration curve of the transformer as in Figure 2.5. With this average lifetime temperature the LOL can be determined with the Montsinger curve of Figure 2.6. For instance, if the maximum permissible operating temperature is 90 °C and the average lifetime temperature is 98 °C, the total lifetime reduction is 50%. This signifies that the expected lifetime for a transformer of 50 years is reduced to 25 years if the maximum permissible operating temperature is surpassed in average by 8°C. In circumstances of LOL the condition curve of Figure 2.6 has to be revised satisfactorily. Such curve defines the condition of the equipment beginning with 100% (new) and going down to 0% (LOL being 0).

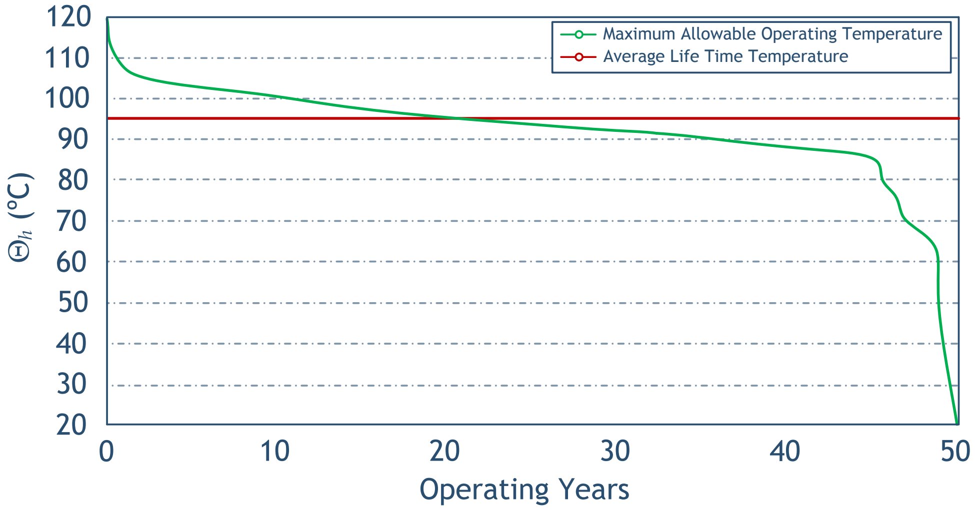

Figure 2.5 - Load duration curve.

Overloads superior to those aforementioned above may be carried in emergencies; however, some LOL beyond normal will occur. The rate of deterioration is a function of time and temperature and is commonly expressed as a percentage LOL. Figure 2.7 shows that LOL for 65°C transformer insulation could be 1% for one 24-hour emergency operation at 145°C, one 8-hour operation at 155°C, or ten 2-hour operations at 145°C, and so on when the emergency operation is preceded by operation at an average continuous $\Theta_h$ not above 110°C [111].

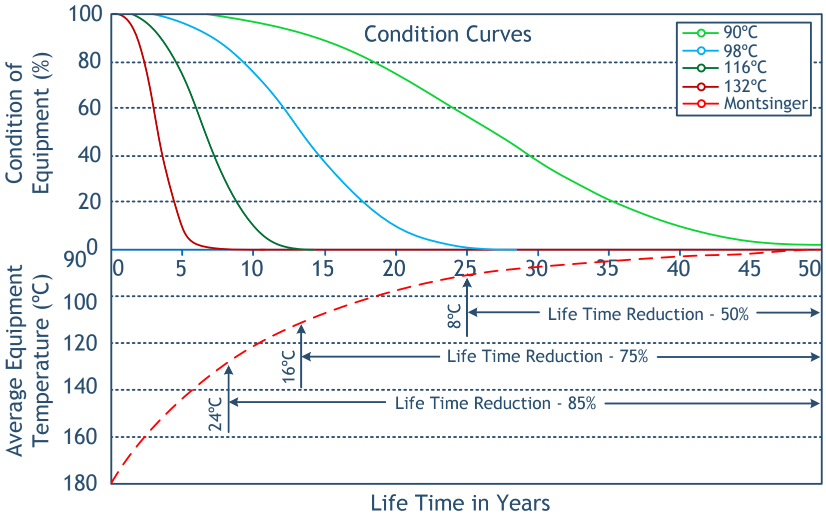

Figure 2.6 – Temperature - lifetime phase diagram and the Montsinger law.

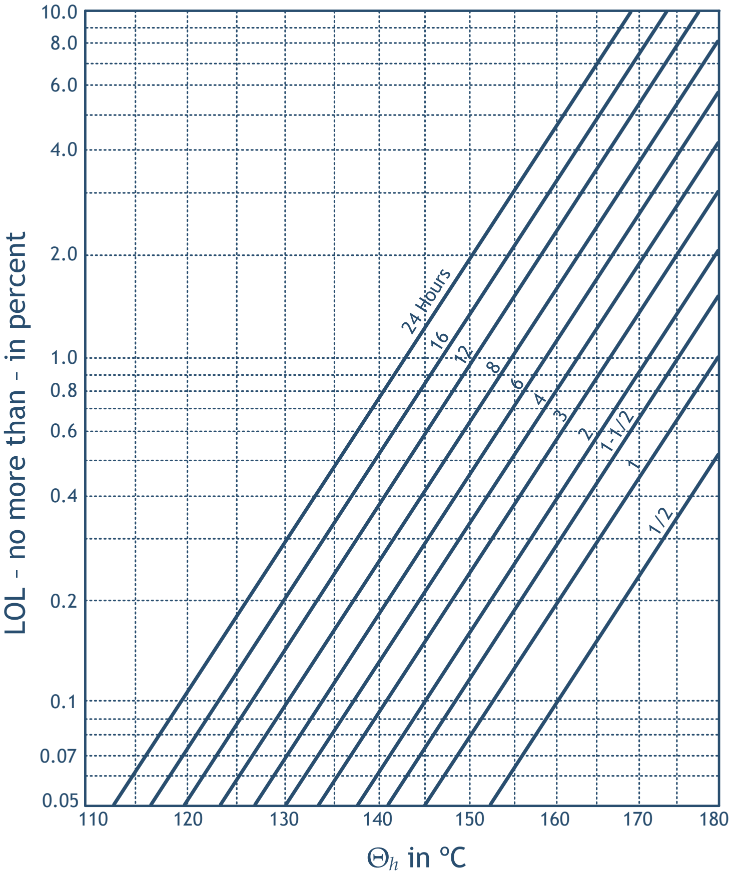

Figure 2.7 - LOL versus $\Theta_h$ for different time periods.

### 2.2.5.2 Transformer ageing equations

The rate as a result of which the ageing of paper insulation for a $\Theta_h$ is increased or decreased when compared with the ageing rate at a reference $\Theta_h$ (110ºC) [116] is the relative ageing rate $V$ [115]. The relative ageing rate meant for the thermally upgraded paper is above one for $\Theta_h$ greater than 110ºC and means that the insulation ages faster compared to the ageing rate at a reference $\Theta_h$, and it is lower than one for $\Theta_h$ less than 110ºC [117].

For the thermally upgraded paper, that is chemically modified with the aim of improving the stability of the cellulose structure, the relative ageing rate $V$ is expressed by (2.2) for thermally upgraded paper and by (2.3) for non-thermally upgraded paper [115]:

$$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\Theta_h+273}\right)} \tag{2.2}$$

$$V = e^{\frac{(\Theta_h - 98)}{6}} \tag{2.3}$$

After a certain period of time, the loss of life $L$ during the time interval $t_n$ is as follows (2.4):

$$L = \int_{t_1}^{t_2} V dt \quad \text{or} \quad L \approx \sum_{n=1}^{N} V_n \times t_n \tag{2.4}$$

According to [115] experimental evidence point out that the relation of insulation deterioration to time and temperature follows an adaptation of the Arrhenius reaction rate theory that displays the following form (2.5):

$$Per\ unit\ life = Ae^{\left(\frac{B}{\Theta_h+273}\right)} \tag{2.5}$$

where $A$ and $B$ are constants.

The transformer per unit insulation life relates per unit transformer insulation life to winding hottest spot temperature and it is presented in expression (2.6) which should be used for both distribution and power transformers since both are manufactured using the same cellulose conductor insulation. The use of this expression isolates temperature as the principal variable affecting thermal life. It also indicates the degree to which the rate of ageing is accelerated beyond normal for temperature above a reference temperature of 110°C and is reduced below normal for temperature below 110°C. The equation is as follows (2.6):

$$Per\ unit\ life = 9.80 \times 10^{-18} e^{\left(\frac{1500}{\Theta_h+273}\right)} \tag{2.6}$$

The per unit transformer insulation life expression can be used in the following two ways. It is the basis for calculation of an ageing acceleration factor (FAA) for a given load and temperature or for a varying load and temperature profile over a 24 h period. FAA has a value greater than 1 for winding $\Theta_h$ greater than the reference temperature 110°C and less than 1 for temperatures below 110°C. The equation for FAA is as follows (2.7) [115]:

$$FAA = e^{\left(\frac{1500}{383} - \frac{1500}{\Theta_h + 273}\right)} \tag{2.7}$$

Equation (2.7) can therefore be used to calculate equivalent ageing of the transformer. The equivalent life (in hours or days) at the reference temperature that will be consumed in a particular time period for the given temperature cycle is the following (2.8):

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \tag{2.8}$$

where $F_{EQA}$ is the equivalent ageing factor for the total time period and $n$ is index of the time interval, $t$ while $N$ is total number of time intervals, $F_{AA,n}$ is the ageing acceleration factor for the temperature which exists during the time interval $\Delta t_n$.

The insulation per unit life equation can be used to calculate percent of total LOL as well, as has been the practice in earlier editions of the referenced transformer loading guides [115]. To do so, it is essential to arbitrarily determine the normal insulation life at the reference temperature in hours or years. Then the hours of life lost in the total time period is calculated by multiplying the equivalent ageing determined in Equation (2.5) by the time period ($t$) in hours. This gives equivalent hours of life at the reference temperature which is consumed in the time period and typically the total time period used is 24 h. The equation is given as follows (2.9):

$$\%\, Loss\ of\ Life = \frac{F_{EQA} \times t \times 100}{Normal\ insulation\ life} \tag{2.9}$$

### 2.2.5.3 Temperature rise equations for linear loads

The simple idea of the $\Theta_o$ rise model is that an increase in the losses is a consequence of an increase in the loading of the transformer and subsequently of the overall temperature in the transformer. The temperature fluctuations are dependent on the global thermal time constant of the transformer which consequently depends on the rate of heat transfer to the environment and the thermal capacity of the transformer [6] [132].

In steady state, the total transformer losses are proportional to the top-oil temperature rise ($\Delta\Theta_o$). As a result, $\Delta\Theta_o$ is mathematically presented as follows (2.10):

$$\Delta\Theta_o = \Delta\Theta_{o,r} \times \left( \frac{P}{P_R} \right)^x = \Delta\Theta_{o,r} \times \left[ \frac{1 + R \times K^2}{1 + R} \right]^x \tag{2.10}$$

where, $P$ is the total losses in W, $P_R$ is the total losses at rated load in W, $\Delta\Theta_{o,r}$ is top-oil temperature rise at rated current in K, $R$ is the ratio of load loss to no-load loss at rated load ($K$=1), $K$ is the load in [per unit] or [%], and $x$ is the oil exponent.

The hot-spot temperature rise over top-oil temperature ($\Delta\Theta_h$) is proportional to the transformer winding loss considering the winding exponent and the hot-spot temperature rise at rated loss. Thus, the $\Delta\Theta_h$ can be expressed as follows (2.11):

$$\Delta\Theta_h = \Delta\Theta_{h,r} \times K^y \tag{2.11}$$

where, superscript $y$ stands for the winding exponent. Therefore, in steady state, the $\Theta_h$ is calculated as follows (2.12):

$$\Theta_h = \Theta_a + \Delta\Theta_o + \Delta\Theta_h \tag{2.12}$$

By inserting Equations 2.10 and 2.11 into Equation 2.12, the following equation represents the $\Theta_h$ in steady state (2.13):

$$\Theta_h = \Theta_a + \Delta\Theta_{o,r} \times \left[ \frac{1 + R \times K^2}{1 + R} \right]^x + \Delta\Theta_{h,r} \times K^y \tag{2.13}$$

On the other hand, in transient conditions, the $\Theta_h$ is described as a function of time, for varying load current and ambient temperature [116]. The oil insulation of a transformer under working conditions is exposed to different types of stress, such as thermal, mechanical, environmental, and electrical. The outcome of each stress factors or the interaction effects of them affect the ageing of the insulating system [132].

In an occurrence of increasing steps of loads, the top-oil and winding hot-spot temperatures escalate to a level corresponding to a load factor $K$. The top-oil $\Theta_o(t)$ temperature is expressed as follows (2.14):

$$\Theta_o(t) = \Delta\Theta_{o,i} + \left\{ \Delta\Theta_{o,r} \times \left[ \frac{1 + R \times K^2}{1 + R} \right]^x - \Delta\Theta_{o,i} \right\} \times \left( 1 - e^{-t/(k_{11} \times \tau_o)} \right) \tag{2.14}$$

where $\Delta\Theta_{o,i}$ represents the top-oil (in tank) temperature rise at start in K, $\Delta\Theta_{o,r}$ signifies the top-oil temperature rise at rated current in K, $R$ is the ratio of load loss to no-load loss at rated current, $K$ is the load factor (load current/rated current), $x$ is the oil exponent, $k_{11}$ is a thermal model constant and $\tau_0$ is average oil time constant.

The hot-spot temperature rise $\Delta\Theta_h(t)$ is as follows (2.15):

$$\Delta\Theta_h(t) = \Delta\Theta_{h,i} + \left\{H \times g_r \times K^y - \Delta\Theta_{h,i}\right\} \times \left[k_{21} \times \left(1 - e^{-t/(k_{22} \times \tau_w)}\right) - (k_{21} - 1) \times \left(1 - e^{-(t \times k_{22})/\tau_o}\right)\right] \tag{2.15}$$

where $\Delta\Theta_{h,i}$ represents the hot-spot-to-top-oil (in tank) gradient at start in K, $H$ is the hot-spot factor, $g_r$ is the average winding to average oil (in tank), $y$ is the winding exponent, both $k_{21}$ and $k_{22}$ are thermal model constants and $\tau_w$ symbolises a winding time constant.

In case of decreasing step of loads, the $\Theta_o$ and winding hot-spot temperatures decrease to a level equal to a $K$ [116]. The top-oil temperature $\Theta_o$ $(t)$ can be calculated using (2.16):

$$\Theta_o(t) = \Delta\Theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x + \left\{\Delta\Theta_{o,i} - \Delta\Theta_{o,r} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x\right\} \times \left(e^{-t/(k_{11} \times \tau_o)}\right) \tag{2.16}$$

The hot-spot temperature rise is given by (2.17):

$$\Delta\Theta_h(t) = H \times g_r \times K^y \tag{2.17}$$

Finally, with $\Theta_o$ $(t)$ and $\Delta\Theta_h(t)$ from Equations (2.14) and (2.15) for increasing load steps, and Equations (2.16) and (2.17) for decreasing load steps and considering $\Theta_a$ the overall hot-spot temperature $\Theta_h$ $(t)$ equation is calculated by (2.18):

$$\Theta_h(t) = \Theta_a + \Theta_o(t) + \Delta\Theta_h(t) \tag{2.18}$$

### 2.2.5.4 Differential equations solution for linear loads

The following subsection describes the use of heat transfer differential equations, applicable for arbitrarily time-varying load factor $K$ and time-varying $\Theta_a$. The purpose of the heat transfer differential equations is to be the basis for software that could to process data in order to define $\Theta_h$ as a function of time and subsequently the corresponding insulation life consumption and LOL. The differential equations are represented in block diagram form in Figure 2.8 [116].

As it can be seen in Figure 2.8, the inputs are the load factor $K$, the ambient temperature $\Theta_a$ on the left and the output is the desired $\Theta_h$, on the right. The Laplace variable $s$ is in essence the derivative operator $d/dt$.

In Figure 2.8 [116], the second block in the upper most itinerary symbolises the $\Theta_h$ rise dynamics. The first term (with numerator $k_{21}$) represents the fundamental hot-spot temperature rise, previously to the effect of changing oil flow past the hot-spot to be taken into consideration. The second term (with numerator $k_{21}$ - 1) represents the varying rate of oil flow past the hot-spot, a phenomenon which changes in a slower mode. The combined effect of these two terms is to justify for the fact that a sudden rise in load current could cause an otherwise unexpectedly high peak in the hot-spot temperature rise, immediately after the sudden load change.

If the $\Theta_o$ can be measured as an electrical signal into a computing device, then an alternative formulation is the dashed line path, with the switch in its right position; the $\Theta_o$ calculation path (switch to the left) is not required. The time step will be less than one-half of the smallest time constant $\tau_w$ to obtain a reasonable accuracy. Additionally, $\tau_w$ and $\tau_0$ must not be set to zero.

When heat-transfer principles are applied to the distribution transformer situation, the differential equations for $\Theta_o$ (inputs $K$, $\Theta_a$ and output $\Theta_o$) is:

$$\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\Theta_{o,r}) = k_{11}\tau_o \times \frac{d\Theta_o}{dt} + \left[\Theta_o - \Theta_a\right] \tag{2.19}$$

The differential equation for $\Theta_h$ rise (inputs $K$ and output $\Delta\Theta_h$) is most easily solved as the sum of two differential equations where:

$$\Delta\Theta_h = \Delta\Theta_{h1} - \Delta\Theta_{h2} \tag{2.20}$$

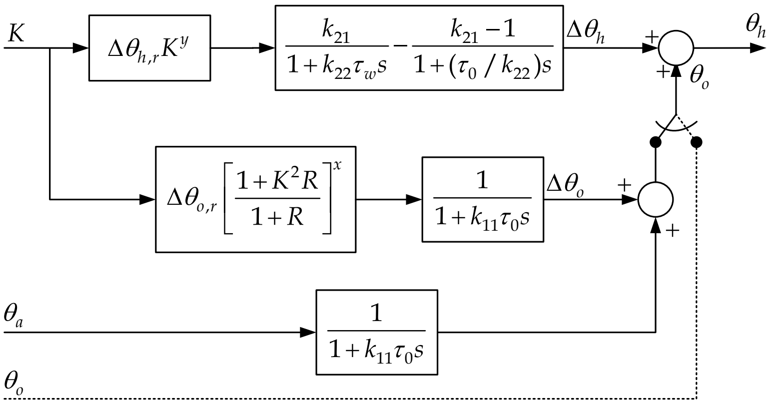

Figure 2.8 - Block diagram representation of the heat transfer differential equations.

The two equations are:

$$k_{21} \times K^{y} \times (\Delta\Theta_{h,r}) = k_{22} \times \tau_{w} \times \frac{d\Delta\Theta_{h1}}{dt} + \Delta\Theta_{h1} \tag{2.21}$$

and

$$(k_{21} - 1) \times K^{y} \times (\Delta\Theta_{h,r}) = (\tau_{o} / k_{22}) \times \frac{d\Delta\Theta_{h2}}{dt} + \Delta\Theta_{h2} \tag{2.22}$$

the solutions of which are combined in accordance with equation (2.18). The final equation for the $\Theta_h$ is:

$$\Theta_{h} = \Theta_{o} + \Delta\Theta_{h} \tag{2.23}$$

If the differential equations are converted to difference equations, then the solution is quite straightforward, even on a simple spreadsheet. The differential equations (2.18-2.22) can be written as the following difference equations, where $D$ stands for a difference over a small time step. Equation (2.19) becomes:

$$D\Theta_{o} = {Dt}/{k_{11}\tau_{o}} \left[ \left[ \frac{1 + K^{2}R}{1 + R} \right]^{x} \times (\Delta\Theta_{o,r}) - \left[ \Theta_{o} - \Theta_{a} \right] \right] \tag{2.24}$$

The $D$ operator implies a difference in the associated variable that corresponds to each time step $Dt$. At each time step, the $n^{th}$ value of $D\Theta_o$ is calculated from the $(n-1)^{th}$ value using:

$$\Theta_{o(n)} = \Theta_{o(n-1)} + D\Theta_{o(n)} \tag{2.25}$$

Equations (2.21) and (2.22) become:

$$D\Delta\Theta_{h1} = \frac{Dt}{k_{22}\tau_{w}} \times \left[ k_{21} \times \Delta\Theta_{h,r} K^{y} - \Delta\Theta_{h1} \right] \tag{2.26}$$

and

$$D\Delta\Theta_{h2} = \frac{Dt}{{1}/{k_{22}}\, \tau_{o}} \times \left[ (k_{21} - 1) \times \Delta\Theta_{h,r} K^{y} - \Delta\Theta_{h2} \right] \tag{2.27}$$

The $n^{th}$ values of each of $\Delta\Theta_{h1}$ and $\Delta\Theta_{h2}$ are calculated in a way similar to equation (2.23). The total $\Theta_h$ rise at the $n^{th}$ time step is given by:

$$\Delta\Theta_{h(n)} = \Delta\Theta_{h1(n)} + \Delta\Theta_{h2(n)} \tag{2.28}$$

Finally, the $\Theta_h$ temperature at the nth time step is given by:

$$\Theta_{h(n)} = \Theta_{o(n)} + \Delta\Theta_{h(n)} \tag{2.29}$$

### 2.2.5.5 Transformer ageing equations for non-linear loads

In general, winding eddy losses, stray losses in other structural parts and, in general, potential regions of excessive heating can be inflated by the presence of harmonic currents. Ohmic losses divide into no load or core losses and load losses expressed as (2.30):

$$P_G = P_{NL} + P_{LL} \tag{2.30}$$

where $P_G$ is the global losses, $P_{NL}$ is the no load losses and $P_{LL}$ gathers the losses related to primary and secondary currents flowing through the windings ($I^2R_t$) and stray losses that are classified into winding eddy losses and structural part stray losses.

Winding eddy losses covers eddy current losses and circulating current losses between strands or parallel winding circuits. Therefore the total load loss is given by (2.31):

$$P_{LL} = P_L + P_{EC} + P_{OSL} \tag{2.31}$$

where $P_L$ is the losses due to load $I^2R_t$, $P_{EC}$ is the winding eddy losses and $P_{OSL}$ is the other stray losses.

Other aspect to be take into account when estimating internal losses derived from harmonic load currents is the presence of a dc value in the load current which increase the magnetizing current and audible sound level without strongly penalizing the transformer core loss.

As a result, liquid-filled power transformer $\Theta_o$ rises as well as the total load losses with the increase of harmonic loading. Guidelines for power transformer derating considering the harmonic load impact on the top-oil rise due to the additional power losses can be found on [148]. The eddy-current loss $P_{EC}$ generated by a harmonic load current is given by (2.32):

$$P_{EC} = P_{EC\text{-}0} \times \sum_{h=1}^{h=h_{\max}} \left(\frac{I_h}{I}\right)^2 h^2 \tag{2.32}$$

where $P_{EC\text{-}0}$ is the winding eddy-current loss at the measured current and the power frequency, $h$ is the harmonic order, $h_{max}$ is the highest significant harmonic number, $I_h$ is the root mean square (RMS) current at harmonic of order $h$ and $I$ is the RMS load current.

Load current RMS calculation is obtained by (2.33):

$$I = \sqrt{\sum_{h=1}^{h=h_{\max}} I_h^2} \tag{2.33}$$

where $h_{max}$ is the highest significant harmonic number. In practical terms, transformer power supply capability can be described in terms of a proportional facto as a form of (2.34):

$$F_{HL} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2 h^2}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2} \tag{2.34}$$

It defines an RMS heating value as function of the harmonic load current. In other words it establish a ratio of the total winding eddy current losses due to the harmonics to the winding eddy current losses at the fundamental frequency.

A relationship similar to the harmonic loss factor for other stray losses that have to do with bus bar connections, structural parts, tank is expressed as (2.35):

$$P_{OSL} = P_{OSL-R} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_R}\right)^2 h^{0.8} \tag{2.35}$$

where $P_{OSL-R}$ is the other stray loss under rated conditions and $I_R$ is the RMS fundamental current under rated frequency and rated load conditions. A harmonic loss factor $F_{HL-STR}$ normalised to the RMS current and to RMS fundamental current is (2.36):

$$F_{HL-STR} = \frac{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2 h^{0.8}}{\sum_{h=1}^{h=h_{max}} \left[\frac{I_h}{I}\right]^2} \tag{2.36}$$

Based on the knowledge of internal power losses sources the top-oil rise is calculated as [115] (2.37):

$$\Delta\Theta_o = \Delta\Theta_{o,r} \left(\frac{P_{LL} + P_{NL}}{P_{LL-R} + P_{NL}}\right)^{0.8} \tag{2.37}$$

where $\Delta\Theta_o$ is the top-oil-rise over ambient temperature (ºC), $\Delta\Theta_{o,r}$ is the top-oil-rise over ambient temperature under rated conditions (ºC), and $P_{LL-R}$ *i*s the load loss under rated conditions. In turn, the load loss $P_{LL}$ is calculated by (2.38):

$$P_{LL} = P_G + F_{HL} \times P_{EC} + F_{HL-STR} \times P_{OSL} \tag{2.38}$$

where $F_{HL}$ is the harmonic loss factor for winding eddy currents and $F_{HL-STR}$ is the harmonic loss factor for other stray losses.

Then, hottest spot conductor rise is estimated by (2.39):

$$\Delta\Theta_g = \Delta\Theta_{g,r} \left( \frac{P_{LL}(pu)}{P_{LL-R}(pu)} \right)^{0.8} \tag{2.39}$$

where $\Delta\Theta_g$ is the hottest-spot conductor rise over top-oil temperature, $\Delta\Theta_{g,r}$ is the hottest-spot conductor rise over top-oil temperature under rated conditions, $P_{LL}\ (pu)$ is the per-unit load loss and $P_{LL-R}\ (pu)$ is the per-unit load loss under rated conditions.

## 2.2.6 Limitations of IEEE and IEC standards

### 2.2.6.1 IEEE Standard

The traditional IEEE Standard $\Theta_h$ calculation technique utilises a number of assumptions that are not correct, such as: the variation of ambient temperature is assumed to have an instantaneous effect on oil temperature, the oil temperature in the cooling duct is assumed to be identical to the top oil temperature, the change in winding resistance with temperature is neglected, the change in oil viscosity with temperature is neglected and the effect of tap position is also neglected [149].

Furthermore, experimental work has shown that at the onset of an abrupt overload, oil inertia induces a quick increase of oil temperature in the winding cooling ducts that is not reflected by the $\Theta_o$ in the tank. Therefore alternate sets of equations are being developed which take into account the recent improvements and all the aforementioned factors [149].

Another important development is the withdrawal of the guide on definition of transformer “Thermal Duplicate” that was frequently utilised to provide default values for winding temperature rise at rated load [150]. This reference will not be available to provide support to the $\Theta_h$ rise assessed by the manufacturer any longer which could reduce the credibility of transformer manufacturer in providing the above-mentioned critical thermal parameter [149].

### 2.2.6.2 IEC Standard

A new edition on the loading guide has been published in 2005 [116]. It is now clearer that the hot-spot factor $H$ that links the average winding to oil gradient to the hotspot to top oil gradient can vary over an extensive range depending on transformer design and size impedance.

In the IEC Standard the correct calculation of the critical temperature difference between winding hottest spot and top oil will also depend on manufacturer capability to correctly model the oil flow within the winding ducts, the heat transfer characteristics of the various insulation thickness utilised throughout the winding, the distribution of losses along the winding, and the impact of local format restricting the oil flow [149].

The IEC standard also recognised that the dynamic response of the previous calculation technique was not suitable as a sudden increase in load current could cause an unpredicted high peak in the winding $\Theta_h$. To address all type of load variations, a comprehensive set of differential equations is given. Such equation takes into account the oil time constant, the winding thermal time constant and three new constants to characterise the oil flow [149].

## 2.3 Influencing factors of the transformer ageing

Several factors, according to the literature, have an impact on the insulating paper and oil ageing, such as the EVs, harmonics, $\Theta_a$, DR, DG and experimental loads created explicitly to study the impact on the LOL of the transformer. In Table 2.1 a survey is made of the available literature regarding the loads and other key factors that influence the ageing of the transformer.

Table 2.1 - Factors/Types of Load that influence the transformer LOL.

| **Factor affecting the transformer** | **Description** | **Reference** |
|---|---|---|
| EV/PHEV | Studies that have been carried out to evaluate if the transformer insulation temperature could or not withstand the widespread adoption of EVs. | [6] [117] [132] [133] [134] [151] [152] [153] [154] [155] [156] [157] [158] [159] [160] [161] [162] [163] [164] [165] [166] [167] [168] [169] [170] [171] [172] [173] [174] [175] [176] [177] [178] [179] [180] [181] [182] [183] [184] [185] [186] [187] [188] [189] [190] |
| DG/PV | The operation of DG units may lead to reductions in the time evolution of transformers' LOL rate. | [131] [165] [191] [192] [193] [194] [195] [196] [197] [198] [199] [200] [201] |
| DR | DR can be utilised during contingencies to mitigate the LOL. | [119] [120] [202] |
| $\Theta_a$ | The possibility that $\Theta_a$ rise may impact distribution transformer life through dielectric degradation. | [203] [204] [205] [206] [207] [208] |
| Experimental Load | Study of different loads that might impact the $\Theta_h$ and LOL of the transformer. They are of experimental nature or recorded in a specific moment and place. | [112] [113] [206] [209] [210] [211] [212] [213] [214] [215] [216] [217] [218] [219] [220] [221] [222] [223] [224] [225] [226] [227] [135] [228] [229] [230] [231] [232] [233] [234] [235] [236] [237] [238] [239] [240] |
| Harmonics | Studies focusing on the effect of harmonics on the transformer's LOL. | [164] [167] [195] [199] [241] [242] [243] [244] [245] [246] |

### 2.3.1 Demand Response

The concept of DR is related to the eminent alteration of the electricity consumption pattern by final user customers, as a reaction to incentives or price signals, for technical or economic reasons when called or scheduled by the network or market operator. DR has been in recent times largely and intensely explored in order to take full advantage of the power system's operation [247].

The integration of DR resources can be fully addressed if the available DG resources are also considered. DG and DR can thus be put together through the implementation of smart grids [247].

As stated previously, due to the load growth, upgrade of power transformers is could eventually be required at substations. The usual method of reinforcement for a growing load is expensive. Therefore, utilities tend to increase the utilisation of already installed transformers which results into highly utilised systems. DR, as a solution for load modification in the electricity network, can be utilised during contingencies to mitigate the LOL, while simultaneously the transformer utilisation efficiency can be improved and monetary savings can be achieved in terms of deferred reinforcements [119]. The impacts of DR and other features of smart grids have also been investigated on the ageing of transformers in the literature [119] [120] [202].

M. Humayun *et al.* present a novel DR based optimisation model to limit load on healthy transformers during contingencies. The model selects combination of the best remedial actions among DR, load curtailment and transferring load to a neighbouring substation [119]. M. Humayun *et al.* also propose an optimisation model that quantifies the improvement of transformer utilisation through DR based on transformer $\Theta_h$ and applied to typical Finnish residential primary and secondary distribution transformers [120]. J. Jargstorf *et al.* calculate the effect of DR ageing based on the load of a group of customers and then based on their load being optimised by DR, also in this paper devices are scheduled based on the transformer temperature [202]. In Table 2.2 is made a compilation of transformers on which the ageing is influenced by DR.

Table 2.2 - Transformers on which the ageing is influenced by DR.

| Transformer Capacity kVA | Cooling | Implementation | | Technique | References |
|---|---|---|---|---|---|
| | | Simulation | Field Test | | |
| 20/40/60/80 | ODAF | √ | - | Mixed integer quadratic programming | [202] |
| 1600/40,000 | ONAN | √ | - | Optimisation | [120] |
| 40,000 | OFAF | √ | - | Optimisation | [119] |

Several results point out that the transformers utilisation can be increased considerably by using DR, which can also mitigate the LOL. The magnitude of the use benefit depends on the DR capability of the load and the loading increase can provide monetary benefits by delaying the investments in new equipment [119].

### 2.3.2 Harmonics

Distorted current flow in power systems infrastructure originates two main effects. One of them is a supplementary power losses justified by a higher RMS value of the load. Furthermore, the ac resistance of a cable is raised since the skin and proximity effects depend on current frequency. Therefore conductor ohmic losses have a tendency to grow with an increasing introduction of nonlinear loads. The second consequence effect has to do with harmonic voltage drop across the electrical elements.

As for power transformers the main consequence relates to additional losses and consequently an increase of transformer oil temperature. Furthermore, other possible adverse effects may be revealed as resonances between the transformer inductance and system capacitance and mechanical stress of winding and lamination. The harmonic voltages may also contribute to higher losses with core hysteresis and eddy current.

As a result of the emergent use of modern electronic devices, harmonic currents produced in distribution systems are starting to be a recent problem of ‘power quality’ in power systems. A power quality problem is defined to be any problem discovered in current, voltage or frequency deviations that cause a failure or malfunction of a customer’s equipment. There are a vest range of power quality factors such as: voltage flicker, voltage sag, voltage unbalance, voltage regulation, interruptions, voltage swell and harmonics. An emergent power quality concern is revealed to be harmonics distortion which is created by the non-linearity of customer loads. Harmonics are known to be the currents or voltages with frequencies that are integer multiples of the fundamental power frequency. The non-linearity of the residential and industrial loads is quickly increasing as a consequence of the widespread applications of power electronics [241].

Solid state electronics is utilised to increase the energy efficiency of electrical load devices. The harmonic distortion of current is increasing with a higher utilisation of nonlinear loads i.e. solid state devices. Examples of nonlinear loads are a television set, personal computer, laptop, laser printer, smartphone, compact fluorescent lamp, battery charger, fluorescent tube with electronic ballast, adjustable speed drives, continuous power supply and all the equipment powered by switched-mode power supply units. Such nonlinear loads draw more current than the fundamental current and generate overloading of the distribution system components [241].

The grid harmonics cause destructive impacts on distribution transformers. Increase in the transformer power losses and consequently the resultant temperature rises are the main concern of the impact of harmonics. This could lead to an increase in its insulation $\Theta_h$ and thus, LOL [242]. Due to the initial costs of transformers, and the grid connectivity issues that may appear during their replacements, it is imperative to preserve the transformers and mitigate the lifetime reduction. As a result, researching the effect of current harmonics on the lifetime of distribution transformers is important for the grid design and maintenance [243].

Various studies have been made in literature for modelling the effect of current harmonics on transformer load loss. P. Moses propose a new ageing calculation method for three-phase three-leg power transformers under (un)balanced and (non)sinusoidal operating conditions where the impacts of magnetic saturation, couplings, and hysteresis are accurately included [246]. M. Kazerooni and N. Kar study create an optimal load management of EV battery charging and optimisation of harmonic impacts on the load loss, $\Theta_h$ and life time of distribution transformers [167]. M. Rad *et al.* study the effect of gird harmonics on eddy current loss, other stray losses, $\Theta_h$, and LOL of six 100 kVA distribution transformers [243]. D. Soto *et al.* address the impacts on distribution transformers due to increasing plug-in hybrid electric vehicles (PHEV) loads on the distribution infrastructure, while conducting PV harmonics compensation [164]. S. Taheri *et al.* present the determination of field distribution on the transformer components using finite element method and the calculations of $\Theta_h$ and $\Theta_o$ under harmonic conditions according to two techniques – dynamic thermal model and IEEE guide [245]. A list of literature transformers on which the ageing is influenced by Harmonics are presented in Table 2.3.

Table 2.3 - Transformers on which the ageing is influenced by Harmonics.

| Transformer Capacity kVA | Cooling | Implementation | | Technique | References |
|---|---|---|---|---|---|
| | | Simulation | Field Test | | |
| 1.65/7.5/60/2000 | - | √ | - | Proposed Model | [246] |
| 10 | ONAN | √ | - | Impact analysis | [199] |
| 100 | - | - | √ | Optimisation | [167] |
| 100 | - | √ | - | Impact analysis | [243] |
| 100/500 | - | - | √ | Impact analysis | [241] |
| 200 | ONAF | √ | - | Rapid-prototyping control | [164] |
| 750 | ONAN | - | √ | Impact analysis | [195] |
| 1500/2500 | - | - | √ | Impact analysis | [244] |
| 31,500 | ONAF | √ | - | Impact analysis | [242] |
| 250,000 | ONAF | √ | - | Finite element method | [245] |

Transformers will begin to experience unprecedented loads from EV charging in the future and the battery chargers for EVs have high ratings and employ nonlinear switching devices which could result in significant harmonic voltage and currents injected into the distribution system. Fast charging which is considered to be the preferable technique to attract end users and mitigate the EV average autonomy, implies precisely these types of nonlinear loads [167] [248].

The standards applied to the low-power EV chargers are IEC 61000-3-2 and IEC 61000-3-4, which set limits to the harmonic emissions generated by the charger [248]. The European standard for public power supply is EN 50160 which states that all loads that are connected to the power network have to provide such a low effect on the network that it does not origin a violation of the power supply conditions stated in this standard. This signifies also that the EV chargers, once connected to a public network, must not influence the network operation to a degree in which can cause deviation from the standard [248].

### 2.3.3 Distributed Generation

Electric power systems could turn out to be more heavily loaded in the next decades due to the increasing demand for electricity. The option of utilising DG is a greater challenge for many utilities due to the reason that economic and environmental concerns limit the construction of new transmission infrastructure and large-sized generation units [249]. Furthermore, since DG units are auxiliary modular resources, the output of a DG unit could change over time, especially the output power of several DGs such as photovoltaic systems (PV) and wind turbines which are heavily dependent on the weather, since it cannot be anticipated accurately. Consequently, the uncertainty of DG output needs to be included in the system analysis [250]. The targets of European Union demonstrate noticeably the importance of DG, specifically the fact that the share of renewable DG is expected to be 20% of gross energy consumption at the end of 2020 and 50% of gross energy consumption in 2050 [251] [252].

When devoid of the use of an optimisation process or power flow analysis outcomes, in radial systems the DG units are usually connected to the nodes at the end of the feeders or to the nodes with the highest load on the distribution side. Yet, it is worth noticing that the impacts of DG are strongly dependant on the power network structure and on the output power uncertainties when concerning to renewable DG resources [251]. According to the definition, the size of DG units can vary from several kW to quite a few MW and, in the area of customer locations, can be connected in sub-transmission or even transmission systems. This leads to the transmission and distribution networks being less charged. In the near future, optimal planning of the location and sizing of DG units will become more and more important for the energy suppliers, grid operators and customers in terms of economic and technical aspects [253].

Currently many studies in the literature exist regarding this topic however most of them consider an ideal location of a single-DG unit or the size and location issues in separate due to the fact that the output power of renewable DG units is highly non-dispatchable. Also, the high penetration of DG elevates the level of system uncertainty and the fluctuation of the DG output power is achieved by using different strategies [251].

By not taking suitable measures for allocating and sizing DG units this concept could lose the required functionalities for an efficient system and eventually cause undesirable increases in power losses and electricity costs. Furthermore, at high penetration levels in the existing infrastructure and depending on the network structure and positions of the DG units, the contributing role of DG could reduce the and system reliability and efficiency [253].

The impacts of DG and more specifically the PV have also been investigated on the ageing of transformers in the literature as can be seen in Table 2.4. The incorporation of rooftop PVs in the residential networks at moderate penetration levels is starting to be a reality in many countries. Regardless of the technical challenges in the proper installation of PV units, one of the main benefits is the capacity of PV units to prolong the useful life time of distribution transformers [131] [254].

S. Agah and H. Abyaneh present a novel approach to quantify the economic benefits and the life extension made by the customer-owned DG units of actual distribution transformers installed in five sample cities in Iran [194]. In a [197] novel methodology is presented by M. Hamzeh *et al.* in order to evaluate the micro-grids reliability concerning the dynamic thermal ageing failure of transformers.

A. Masoum *et al.* carry out an analysis into the impacts of rooftop PVs at different penetration levels on the performance of distribution transformers and residential networks [196]. In [195] D. Martin *et al.* present the findings of an analysis of the impact of the new rooftop PV installation at University of Queensland, in Brisbane, on the load profile of three transformers, with IEC thermal models applied to estimate $\Theta_h$. H. Pezeshki *et al.* study the impacts of rooftop PVs at different penetration levels on the performance of distribution transformers and residential networks [131] [191].

M. Awadallah *et al.* present a two-step study on the effects of harmonic distortion of solar panels on distribution transformers via simulation and experiments [199]. H. Jimenez *et al.* show the results obtained after monitoring a distribution transformer during an 18 months period and which attained unusually low power factor levels and where the operating temperature was used as an indicator of the stress on the transformer [200].

In Table 2.4 a compilation is made of transformers on which the ageing is influenced by DG and in some cases, just the PV.

Table 2.4 - Transformers on which the ageing is influenced by DG/PV.

| Transformer Capacity kVA | Type | Cooling | Implementation | | Technique | References |
|---|---|---|---|---|---|---|
| | | | Simulation | Experiment | | |
| 2 | PV | - | √ | - | Power quality impact | [192] |
| 10 | DG/Harmonics | ONAN | √ | - | Impact analysis | [199] |
| 75 | PV | - | - | √ | Test and analysis | [200] |
| 100 | PV | - | √ | - | Impact analysis | [196] |
| 200 | PV/EV | ONAN | √ | - | Impact analysis | [165] |
| 200 | PV | ONAN | √ | - | Impact analysis | [131] [191] |
| 200 | PV/EV Harmonics | ONAF | √ | - | Rapid-prototyping control | [164] |
| 315 | DG | ONAN | √ | - | Economic Benefit | [194] [198] |
| 750 | PV | ONAN | - | √ | Impact analysis | [195] |
| 65,000 | PV | ONAN | √ | - | Sizing tool | [193] |
| 1600/40,000 | DG | - | √ | - | Impact analysis | [201] |
| 750,000 | DG | - | √ | - | Sensitivity analysis | [197] |

As stated above one of the areas where DG units can create significant economic benefits is through the life extension of distribution transformer. It is clear that any life extension is economically beneficial to the distribution network operator, which is usually the entity responsible to replace deteriorated equipment in the distribution network [194]. Concerning DG technologies, it should be noted that wind turbines and microturbines arise as the most promising technologies from the perspective of distribution utility by being capable to generate millions of dollars in benefits for the entire installed distribution transformer population.

### 2.3.4 Ambient Temperature

The impact caused on the power distribution infrastructure through the analysis of the possibility that $\Theta_a$ rise may affect the distribution transformer life through dielectric degradation is studied by several authors. The $\Theta_a$ is one of the most limiting factors that can impact the transformer insulation life. Since increasing the $\Theta_a$, $\Theta_h$ also increases and subsequently, causes the insulation life to decrease [203].

In Figure 2.9 is shown the permissible kVA loading by varying $\Theta_a$ for natural cooled transformers for normal life expectancy. This data does not apply for ambient temperature below 0°C or above 50°C and is based on [111].

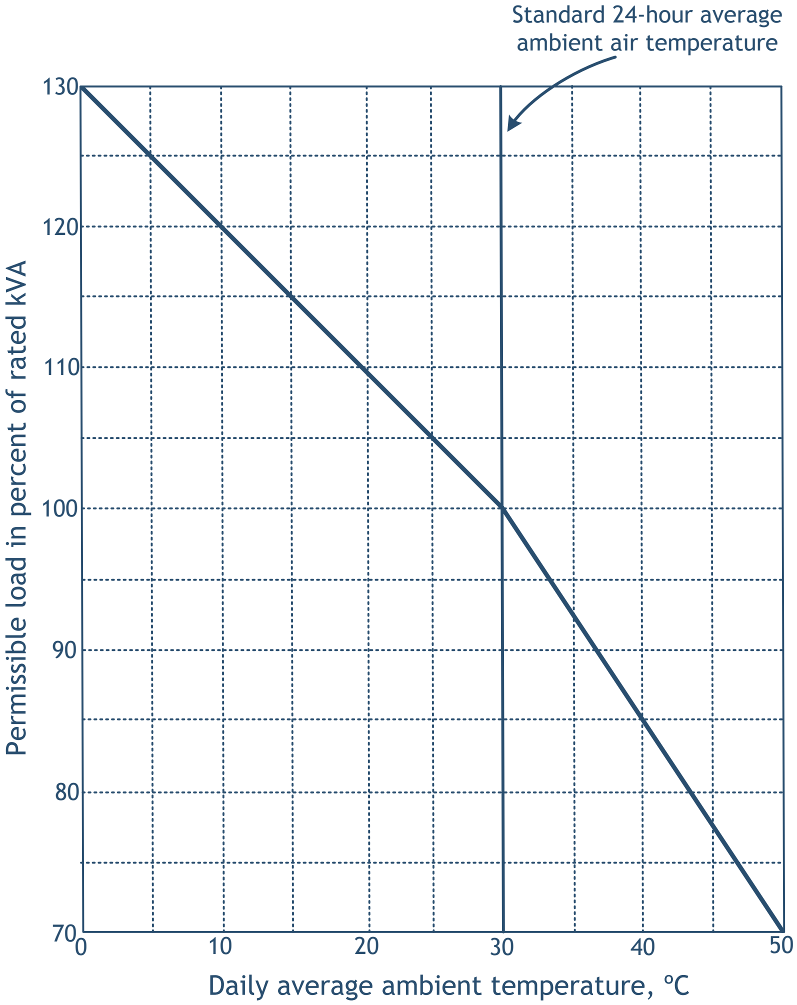

Figure 2.9 - Permissible kVA loading by varying $\Theta_a$ for natural cooled transformers.

Several authors study the impact of the $\Theta_a$ on thee LOL of transformers. J. Stahlhut *et al.* illustrate the possible effects of increased $\Theta_a$ due to various causes, including climate change and urbanisation, on power distribution transformers in service at five locations in the U.S. [207]. B. Sathyanarayana *et al.* study the distribution transformer life assessment with $\Theta_a$ rise projections by using Monte Carlo method [208]. A. Shiri *et al.* investigate a new thermal model for the estimation of $\Theta_h$ in transformers that has been proposed and using this thermal model, the effect of the $\Theta_a$ on $\Theta_h$ and transformer insulation life is also studied [203]. S. Agah and H. Abyaneh present a method for transformer LOL inference by integrating stochastic dependence between non-normal transformer load and $\Theta_a$ into analysis [206]. C. Ravetta *et al.* show results of a study performed to individuate some appropriate thermal models to supervise the performance of oil-immersed distribution transformers installed in the basement of residential buildings, during summertime when temporary severe overload conditions occur [204]. In Table 2.5 is made a compilation of transformers on which the ageing is influenced by $\Theta_a$.

Table 2.5 - Transformers on which the ageing is influenced by $\Theta_a$.

| Transformer Capacity kVA | Cooling | Implementation | | Technique | Reference |
|---|---|---|---|---|---|
| | | Simulation | Field Test | | |
| 25/50/75/100/167 | ODAF<br>ODWF | √ | - | Monte Carlo | [208] |
| 200 | ONAN | - | √ | Comparison | [206] |
| 250/400/630 | ONAN | - | √ | Thermal model | [204] |
| 2000 | AN | √ | - | Thermal model | [205] |
| 180 000 | OFAF | - | √ | Thermal model | [203] |

A study has shown that if two similar transformers are installed in two regions with different climates so that their average temperatures difference would be 11.1°C, the insulation life of the transformer that is installed in the warmer region will be 2.53 times less than the life of the transformer working with lower $\Theta_a$. Regarding the results of several studies, the distribution operator should be cautious when installing and using transformers with similar designs in various regions with different climates [203].

## 2.3.5 Experimental Load

Several studies are made focusing on different loads that might impact the $\Theta_h$ and LOL of the transformer. They are experimental or recorded data in a specific case and are usually conventional or artificial loads created with the purpose to increase the load in order to witness the effect they might have on the transformer $\Theta_h$. V. Galdi *et al.* present a radial basis function network to predict the maximum winding $\Theta_h$ of a power transformer in the presence of overload conditions [240].

M. Lachman *et al.* made a comprehensive approach to dynamic loading of power transformers with nine transformer-months of real-time field data [211]. L. Jauregui-Rivera *et al.* develop a methodology for assessing the reliability of thermal-model parameters for transformers estimated from measured data [238].

T. Weekes *et al.* calculate the level of risk and management of heavily loaded converter transformers for future operation which can be assessed by examining the average rate of LOL of the insulation [223]. A. Elmoudi *et al.* examine a transformer thermal dynamic model for use in an on-line monitoring and diagnostic system [220]. E. Koufakis *et al.* study the measurements of insulating resistance in distribution transformers, at several temperatures, and thereafter proceed to the calculations of the thermal coefficient of the transformers [233].

In Table 2.6 is possible to observe a compilation of several studies that were made focusing on different loads that could impact the $\Theta_h$.

Table 2.6 - Transformers on which the ageing is influenced by unspecified experimental loads.

| Transformer Capacity kVA | Cooling | Implementation | | Technique | Reference |
|---|---|---|---|---|---|
| | | Simulation | Field Test | | |
| 25 | ONAN | √ | - | Fuzzy logic | [232] |
| 25 | ONAN | √ | √ | Neural networks | [240] |
| 25/37.5/50/100 | - | - | √ | Comparison | [218] |
| 50 | ONAN | √ | - | Calculation of ageing | [135] |
| 50/100/250 | - | - | √ | Life cycle prediction | [233] |
| 63 | ONAF | - | √ | Cost-benefit | [225] |
| 100 | - | - | √ | Levenberg-Marquardt | [219] |
| 105 | ONAF | √ | - | Uncertainty analysis | [228] |
| 200 | ONAN | - | √ | Comparison | [206] |
| 300 | ONAN/F | √ | - | Risk assessment | [223] |
| 400 | ONAN | - | √ | Test and analysis | [230] |
| 500 | - | - | √ | Least squares | [224] |
| 630 | ONAN | - | √ | Proposed model | [216] |
| 2500 | ONAN | - | √ | Non-linear least square | [209] |
| 2500 | ONAN | - | √ | Test program | [236] |
| 8 000 | - | √ | - | Monte Carlo | [226] |
| 27 000/36 000 45 000/500 000 | ONAN<br>OFAF | - | √ | Comparison | [211] |
| 40 000 | OFAN/F | - | √ | Non-linear least squares | [220] |
| 167 000 | OFAF | - | √ | Statistical bootstrapping | [238] |
| 250 000 | ONAF | - | √ | Electromagnetic analysis | [222] |
| 250 000 | OFAF | - | √ | Proposed model | [235] |
| 250 000 | ONAF | √ | - | Model assessment | [239] |
| 250 000/273 000 | ODAF | - | √ | Proposed model | [112] |
| 250 000/400 000 605 000 | ONAN/F<br>OFAF | - | √ | Proposed model | [214] |
| 250 000/400 000 605 000 | ONAN/F<br>OFAF | - | √ | Accurate calculations<br>Comparison | [212] |
| 250 000/400 000 605 000/650 000 | ONAN/F<br>OFAF | - | √ | Comparison | [237] |
| 300 000 | ODAF | - | √ | Impact analysis | [217] |
| 400 000 | OFAF | √ | - | Risk assessment | [113] |
| 1 000 000 | - | √ | - | Arrhenius-Weibull | [213] |

## 2.3.6 Electric Vehicles

If widely adopted, the EVs hold the promise of radically reducing carbon emissions derived from the transport section and could, consequently, form a major thrust in the global efforts to meet the reduction of emission targets [255] [256].

The use of EVs is more challenging than PHEV since the first ones are powered only by electricity. Even though the EVs would be primarily utilised for transportation, they could be virtually viewed as a distributed storage resource from the point of view of a System Operator. Accordingly, when EVs are not used to satisfy their intended role, they could provide a variety of ancillary services to the power system such as operating reserves, regulation, back-up power etc. Such use of EVs might also support the peak shifting [155].

By facing an increasing number of EVs connected to power systems for charging, a real concern appears due to the fact that the existing distribution networks might turn out to be more heavily loaded than the expected when they were designed. Low penetration levels of EVs could result in a low impact but, as the number of EVs rises, there could be a real possibility of local distribution networks becoming more congested [132]. An event of simultaneous charging of a large number of EVs can lead to grid inadequacy as regards the available security and capacity. Such occurrences could be avoided, if the EVs are properly integrated within the grid. Incorporating the EV within the grid is a significant opportunity, if they are going to be controlled properly [257]. Without the aforementioned integration, the grid could experience voltage sag, feeder congestions, line overloads, etc.

Distribution networks are intended to supply electricity to the final customers and their sizing is typically based on an estimated electricity demand. Thus, there is a general need to develop modelling techniques in order to support the quantification of the effects on distribution networks in case of high penetration level of EVs charging loads and thus ensure that this environmentally nonthreatening technology is not needlessly constrained. The transformers are vital links in the power and distribution networks and which are to experience unprecedented loads from EV charging [6] [132]. The constant and everyday charging at daytime will add extra load to the distribution system resulting in increases of the power consumption. Since battery chargers are made of solid state electronic devices they produce harmonic currents which also impacts and decreases the lifetime of the transformer [164] [167].

Numerous studies have been carried out to assess whether the existing electricity network and essentially the transformer insulation temperature could withstand the widespread adoption of EVsas can be observed in Table 2.7. S. Weckx *et al.* present a market based multi-agent control mechanism that incorporates distribution transformer and voltage constraints for the charging of a fleet of EVs [166]. K. Qian *et al.* develop a methodology to determine the impacts of high penetration level of EVs charging loads on the thermal ageing of power distribution transformers [133]. A. Hilshey *et al.* describe a method for estimating the impact of EVs charging on overhead distribution transformers, based on detailed travel demand data and under several different schemes for mitigating overloads by shifting EV charging times [117]. G. Razeghi *et al.* study the impacts of PHEV on a residential transformer using stochastic and empirical analysis where the electricity demand of a neighbourhood is modelled based on measured vehicle and household data [179].

R. Vicini *et al.* discuss how increased deployment of EVs acts as a catalyst for development of transformer and home energy management systems in order to reduce the impact of EV battery charging on distribution transformers [157]. H. Turker *et al.* propose a rule-based charging algorithm of EVs and evaluate the consequences and impacts on the ageing rate of low-voltage transformers [162]. In Table 2.7 a compilation of information is created of transformers on which the ageing is influenced by PHEVs, EVs, or both.

Table 2.7 - Transformer Types and Info concerning EV Penetration.

| **Transformer Capacity kVA** | **Type** | **Cooling** | **Implementation** | | **Technique** | **Reference** |
|---|---|---|---|---|---|---|
| | | | **Simulation** | **Experiment** | | |
| 25 | EV | - | √ | - | Genetic program | [152] |
| 25 | EV | - | √ | - | Monte Carlo | [117] |
| 25 | EV/PHEV | - | √ | - | Monte Carlo<br>Impact analysis | [155] [171] [170] [185] |
| 25 | EV/PHEV | - | √ | - | Java-based | [156] |
| 25 | EV | - | √ | - | Binomial probability | [158] [159] |
| 25 | EV | - | - | √ | Control strategies | [160] [184] |
| 25 | PHEV | - | √ | - | Impact analysis | [183] |
| 25 | EV/PHEV | - | √ | - | ARMA | [186] |
| 25 | EV | - | √ | - | Optimisation | [188] |
| 25/37.5 | PHEV | - | √ | - | Monte Carlo | [189] |
| 37.5 | EV/PHEV | | √ | - | Circuit model | [190] |
| 37.5/50 | EV/PHEV | - | √ | - | Monte Carlo | [179] |
| 50 | EV/PHEV | ONAN | √ | - | Impact analysis | [157] |
| 50 | EV | - | √ | - | Probabilistic model | [187] |
| 100 | EV | - | - | √ | Optimisation | [167] [168] |
| 100 | EV | - | √ | - | Smart charging<br>Impact analysis | [173] [174] [176] [178] |
| 160 | EV | - | √ | - | Rule-based algorithm | [162] |
| 160 | PHEV | ONAN | √ | - | Impact analysis | [134] [161] |
| 200 | PV/EV Harmonics | ONAF | √ | - | Rapid-prototyping control | [164] |
| 200 | EV/PV | ONAN | √ | - | Impact analysis | [165] |
| 250 | EV | - | √ | - | Market based multiagent control | [166] |
| 250 | EV | ONAN | √ | - | Impact analysis | [132] |
| 250/300/500/750 | EV | ONAN | √ | - | EV scheduling | [151] |
| 300 | EV | - | √ | - | Circuit model | [172] |
| 315 | PHEV | ONAN | √ | - | Impact analysis | [180] |
| 350 | EV | - | √ | - | Impact analysis | [175] |
| 630 | EV | ONAN | √ | - | Impact analysis | [6] |
| 1000/1500 | EV | - | √ | - | Smart charging | [153] |
| 15 000 | EV | - | √ | - | Smart charging | [133] |
| 36 000 | PHEV | - | √ | - | Impact analysis | [163] |

The current status of EV market share globally can be considered low, not exceeding 7% in leading countries such as Norway [133]. Nevertheless, it is expected that the impact of the penetration of EVs charging loads on thermal ageing of a distribution transformer is going to grow. Additionally, governmental incentive initiatives usually tend to target the penetration of new technologies [258], tax reduction schemes or potential subsidiary programs to promote the purchase and use of EVs are very likely to massively motivate users to replace their conventional car with an EV.

## 2.4 Case Study

The Azores are a Portuguese autonomous region, is an archipelago situated in the North Atlantic and is comprised by 9 islands. São Miguel Island is the key and utmost populated island in the archipelago and covers 760 km$^2$. On the island live circa 140,000 inhabitants.

For this study, a part of São Miguel medium voltage distribution network was utilised as a sample for investigation. A transformer exclusively connected to a private industrial client was selected. Figure 2.10 displays a part of the medium voltage distribution network and the classification of several outputs. For this case study the transformer substation PT1094 was utilised which supplies one private industrial client through a 250kVA, 10kV/0.4kV oil-immersed transformer.

The characteristics of the transformer used in this chapter are drawn from Ravetta et al. [204] that presented the data of a real 250 kVA oil transformer with Oil Natural Air Natural (ONAN) cooling in which a natural convectional flow of hot oil is used for cooling. The properties are presented in Table 2.8.

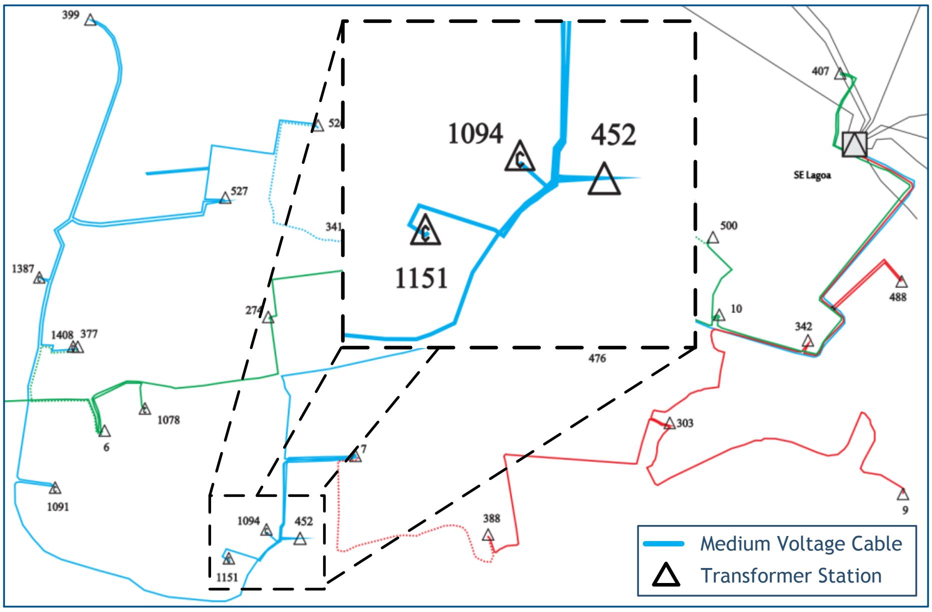

Figure 2.10 - A part of São Miguel medium voltage electric distribution network and the identification of PT1094 transformer station [19].

Table 2.8 - Used Transformer Parameters.

| Symbol | Definition | Value | Units |
|---|---|---|---|
| $g_r$ | Average winding to average oil temperature gradient at rated current | 15.9 | Ws/K |
| $H$ | Hot-spot factor | 1.25 | |
| $k_{11}$ | Thermal model constant. | 0.5 | |
| $k_{21}$ | Thermal model constant. | 2 | |
| $k_{22}$ | Thermal model constant. | 2 | |
| $P_r$ | Distribution Transformer Rated Power | 250/630 | kVA |
| $R$ | Ratio of load loss to no-load loss at rated current | 5.957 | |
| $x$ | Exponential power of total losses versus top-oil temperature rise | 0.8 | |
| $y$ | Exponential power of current versus winding temperature rise | 1.3 | |
| $\Delta\Theta_{o,r}$ | Top-oil temperature rise at rated current | 41.5 | K |
| $\tau_0$ | Average oil time constant | 210 | Minutes |
| $\tau_w$ | Winding time constant | 10 | Minutes |

The private industrial client is a factory that produces sugar out of sugar beet and has many induction motors. It employs around 120 workers and operates in 3 working shifts of 8 hours each. The first working shift starts at 08:00, the second at 16:00 and the third at 00:00. It is presumed in this chapter the workers are evenly distributed throughout the working shifts.

During the month of February 2014 several measurements were realised at the transformer substation PT1094 and the energy consumption of the industrial client was documented, consequently a daily baseline load profile was created as shown in Figure 2.11. It is also given the power factor of the transformer – around 0.95. It can be observed that a 250 kVA transformer is properly designed for a 140 kW of peak in daily load profile, considering that a typical value for an inferior size transformer would be 167 kVA which is not fitting [19].

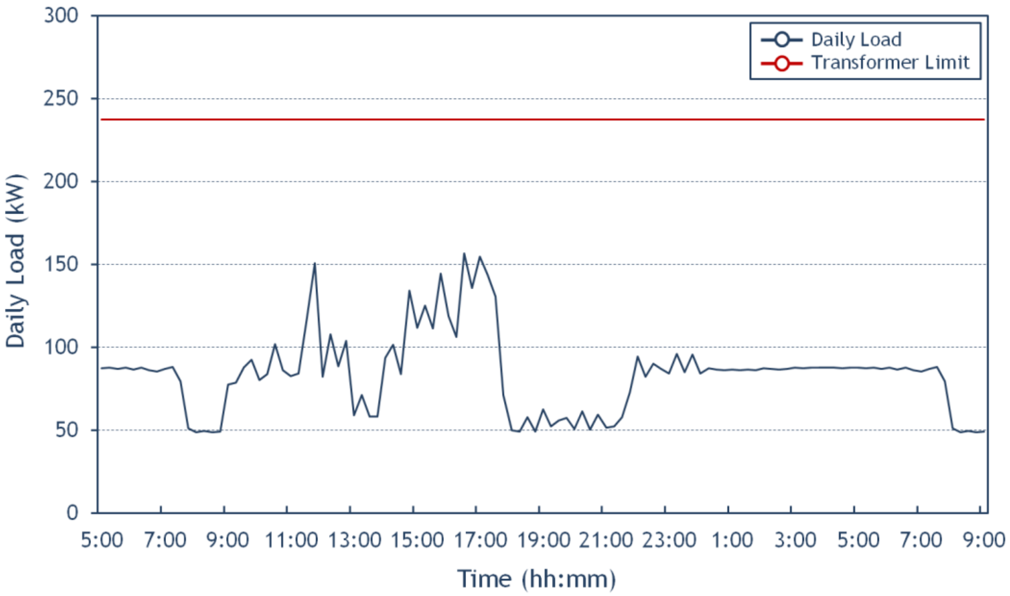

Figure 2.11 - Daily baseline load profile.

During these measurements, in the course of a certain period, the transformer was overloaded due to an abnormal event caused by the induction motors that operate in this factory. The data recorded of such event is presented in Figure 2.12 and by analysing it is possible to apply the transformer thermal model, using the load ratio as an input to acquire the values of $\Theta_h$ and $\Theta_o$ temperatures which can be seen in the Figures 2.13 and 2.14, respectively.

Using the ageing Equations (2.1) and (2.3), transformer LOL can now be determined. The LOL of the transformer is approximately 308 days which means that from the transformer expected life at normal operation (7500 days) is withdrawn the number of days that this transformer lost. Overall, solely for this day of transformer atypical operation the LOL in percentage is 4.21%.

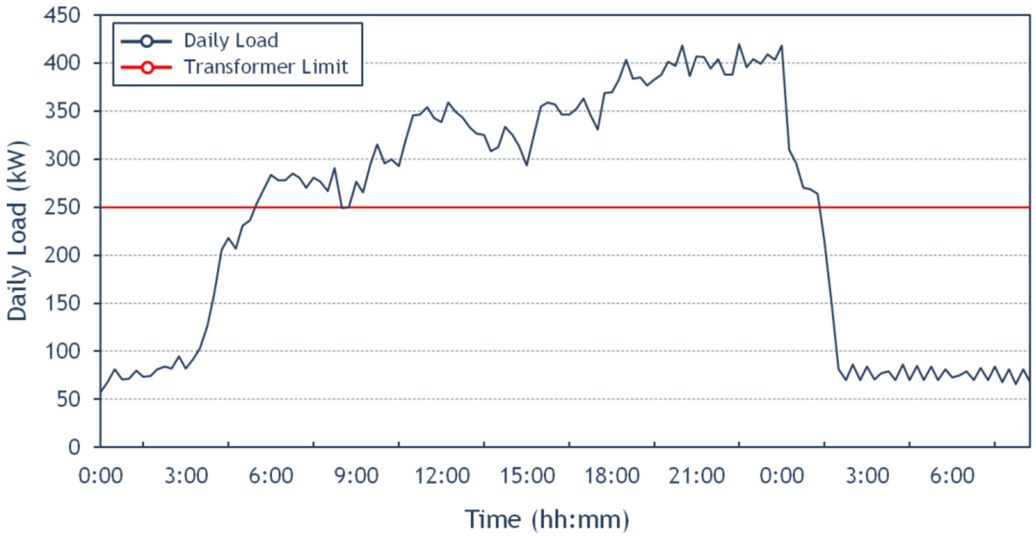

Figure 2.12 - The daily load profile during the anomaly.

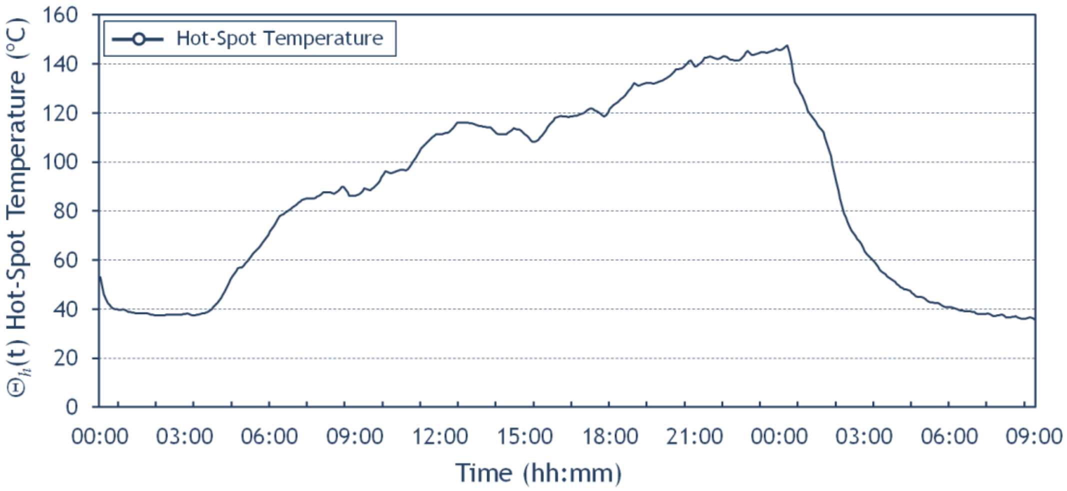

Figure 2.13 - $\Theta_h$ of the distribution transformer.

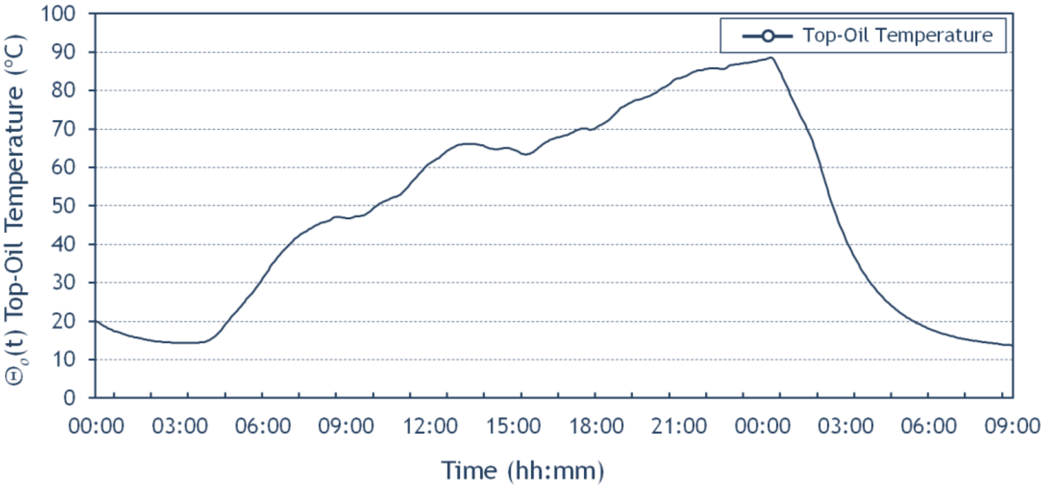

Figure 2.14 - $\Theta_o$ of the distribution transformer.

## 2.5 Aspects of protection and monitoring systems

Transformers are one of the more expensive elements of equipment found in a utility's inventory. The globalisation and the energetic business dynamics unceasingly pressure utilities to do more with less. This leads to an increasing need for tools to support not only transformer protection but the intelligent monitoring of their status, activities, and history – a challenge that could be taken by smart relays. Occasionally overcurrent relays are intended to provide fault protection and also be responsible for some level of overload protection. In many cases, the overload occurrence of transformer operation is performed by Control Centre load dispatchers since this function is too complex for most simple overcurrent relays to successfully handle [240] [259].

In order to keep a reliable protection, it is required to monitor the temperatures. Supplementary prolongation of maximal load after a certain amount induces the ageing as a critical limit. The current thermal digital relays can perform the ageing calculation [259].

Usually, in many practical cases it is not expected that the shape of diagrams would change too much. Particularly it is not expected on small transformer units with fixed consumers. However, it seems too uncertain to protect a transformer only with a simple contact thermometer for $\Theta_o$ measurement and overcurrent protection set-up to a high p. u. current value. According to the experienced staff in power utility companies nobody would accept an extremely risky transformer loading without possessing useful information about the $\Theta_h$ and the ageing [259] [260].

A monitoring system basically gives just additional security, but not fundamentally new content. First of all, an advantage is the possibility for the on-line decisions in circumstances of network faults. For instance, in every moment the monitoring system can provide in a clear form an overloading possibility of the transformer.

A persistent problem in both monitoring systems thermal and digital relays is how to calculate the $\Theta_h$ caused by the complex heat transfer occurrences inside a transformer.

When a fault happens in a transformer, the damage is proportional to the fault time period. Consequently, the transformer has to be disconnected as fast as possible from the network. Quick reliable protective relays are thus utilised for detection of faults. Monitors can similarly detect faults and they can sense irregular conditions which may possibly develop into a fault [261].

The proportions of the transformer and the voltage level does influence on the extent and choice of protective equipment. Monitors avoid faults and protective relays limit the damage in the event of a fault. The cost for the protecting equipment is low when compared to the total cost and the cost involved in case of a transformer fault [262].

There are frequently different opinions about the range of transformer protection. In general, it is more or less standard that transformers with an oil conservator are provided with the following equipment [261]:

Transformers inferior than 5 MVA:

- Gas detector relay (Buchholz relay)
- Ground fault protection
- Overcurrent protection
- Overload protection

Transformers superior than 5 MVA:

- Gas detector relay (Buchholz relay)
- Ground fault protection
- Oil level monitor
- Overcurrent protection
- Differential protection
- Pressure relay for tap-changer compartment
- Overload protection (thermal relays or temperature monitoring systems)

Power transformer protection relays in a power system are required to be able to differentiate internal faults from the remaining operating conditions, and current differential relays have been commonly used for transformer protection. A new scheme for differential protection in which the concept of the Park's instantaneous differential powers was introduced and has also been proposed in the literature [263] [264] [265] [266]. The relays, though, remain susceptible to malfunctioning over-excitation conditions or during magnetic inrush due to the magnetizing current becoming significant [267].

## 2.5.1 Smart Relay

By using the transformer standard [116] IEC 60076-7 which presents the terms that define the transformer $\Theta_h$ calculation and with information from the $\Theta_o$, $\Theta_a$, current and voltage transducers inputs, a smart transformer relay is proposed D. Fedirchuk and Curtis Rebizant in [259].

This relay is able to provide distinctive asset management functionality. This functionality comprises overload tracking with the temperature (adaptive overload), predictive overload early warning and automated load shedding based on temperature and/or current levels. Combined with the LOL estimation, the smart transformer relay delivers protection, monitoring and control for the transformer in one integrated solution.

The basis of the smart transformer relay is the capacity to model the transformer behaviour by a satisfactory process [259]. Such kind of smart transformer relays allows a wide range of unique protection, monitoring and control devices in one integrated platform as proposed in Figure 2.15.

However, another and an enhanced application of the IEEE transformer loading standard with a smart relay developed in [259] by the same authors, is the capacity to monitor both the transformer's current and/or temperature and establish multiple prioritised overload levels for alarm or trip. Such solution allows for the utility to have the ability to offer preferential service to customers and avoid unnecessary full-load transformer trips. Furthermore, the tap changer can be blocked if the current is above a pre-defined setting and prevent load restoration if $\Theta_h$ is greater than a pre-defined level. The functioning of this smart relay is described in Figure 2.16 [259].

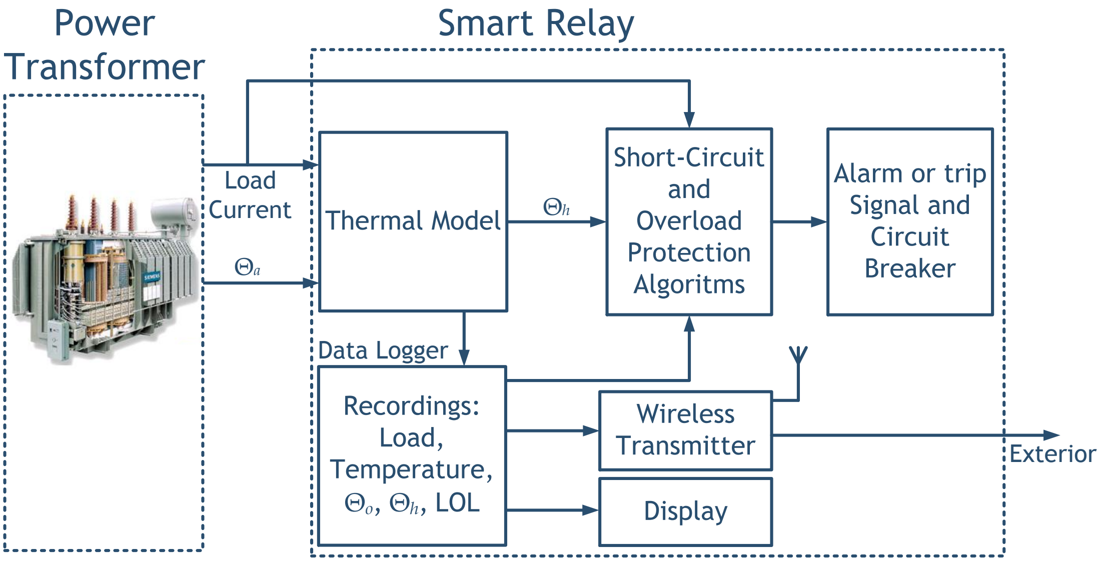

Figure 2.15 - The proposed smart transformer relay.

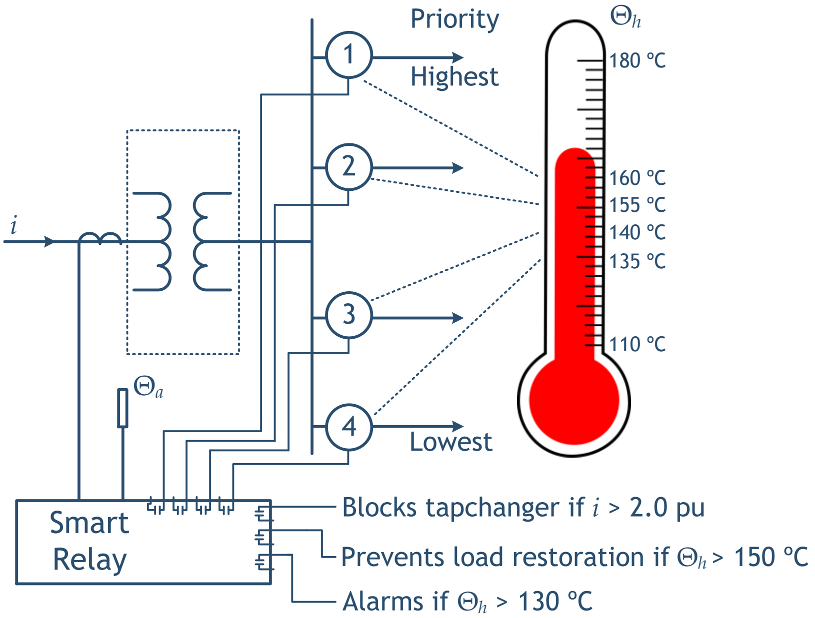

Figure 2.16 - Transformer Relay - Load Shedding Model.

## 2.5.2 Transformer condition on-line Monitoring

It is widely recognised that the risks associated with overloading can be considerably reduced if the transformer conditions are closely monitored during the overload period [268] [269]. The monitoring of winding $\Theta_h$ and dissolved gas-in-oil and furan-in-oil offers a major support to the operator when the transformer experiences overload conditions [149].

### 2.5.2.1 Monitoring of winding temperature

The condition of transformer windings can be assessed by monitoring their equivalent circuit parameters. Modifications in the insulation temperature affect the winding temperature and can be monitored by observing the winding resistance values. Likewise, changes in the short circuit reactance can also provide information on the condition and structure of windings. The equivalent circuit parameters are not influenced by external faults and change only in the presence of an internal factors. Quick and reliable protection could be implemented by monitoring such parameters since inrush current and over-excitation does not affect them. The on-line monitoring of winding temperature can grant a dynamic evaluation of insulation degradation and the respective loss of life can then be transformed into cost. The cost attributed to loss of life has to be subtracted from the apparent benefits achieved from transmitting such extra load [270] [271].

### 2.5.2.2 DGA (Dissolved Gas Analysis)

Dissolved gas analysis is a test utilised as a diagnostic and maintenance tool for oil-filled apparatus. In normal conditions, the dielectric fluid existing in a transformer will not decompose at a fast rate. Nevertheless, thermal and electrical faults can accelerate the decomposition of the dielectric fluid, as well as the solid insulation.

Resultant gases by this process are all of low molecular weight and include hydrogen, methane, ethane, acetylene, carbon monoxide, and carbon dioxide, and these gases will dissolve in the dielectric fluid. Anomalous conditions within a transformer can be detected prematurely by analysing the gases that accumulate within it. Analysing the specific proportions of each gas is helpful in identifying faults. Detailed information of such fault types originated from a variety of gases is present in Table 2.9 [271]. Faults detected in this manner may include processes such as sparking, corona, overheating, and arcing. If the right preventive measures are taken early in the detection of these gases, damage to equipment can be mitigated [272], [273].

Numerous methods are existent for the interpretation of laboratory results, for instance as those recommended in IEC Standard 60599 [274] and IEEE Standard C57.104-1991 [275]. Graphical and computational methods using gas ratios and proportions have been formulated for recognizing the characteristic patterns of dissolved gases associated with the main fault types. Such diagnosis procedures have been developed and validated using large data sets for equipment in service, where faults were identified and documented by maintenance experts monitoring the equipment [276].

The present environment of higher loading on ageing transformers, increased service reliability requirements and postponed capital expenditures on new equipment have led the industry to investigate the employment of innovative transformer condition assessment and management tools. As transformers age, they suffer various stresses that can contribute to a multiplicity of failure mechanisms. Proper online DGA monitoring and diagnostic tools could help utilities to avoid unplanned failures, extend transformer useful life and lower maintenance costs [277].

As seen in Table 2.9, all fault types are indicated by a variety of gases and not just one. Consequently, diagnostic approaches that focus on multiple gases take into account the total gassing picture and provide the best diagnostic accuracy [271].

Table 2.9 - Fault types indicated by a variety of gases.

| **Indication/Fault Gas** | CO | $CO_2$ | $CH_4$ | $C_2H_2$ | $C_2H_4$ | $C_2H_6$ | $O_2$ | $H_2$ | $H_2O$ |
|---|---|---|---|---|---|---|---|---|---|
| Cellulose ageing | √ | √ | - | - | - | - | - | - | √ |
| Mineral oil decomposition | - | - | √ | √ | √ | √ | - | √ | - |
| Leaks in oil expansion systems, gaskets, welds, *etc.* | - | √ | - | - | - | - | √ | - | √ |
| Thermal faults—Cellulose | √ | √ | √ | - | - | - | √ | √ | - |
| Thermal faults in Oil 150–300 °C | - | - | √ | - | Trace | √ | - | √ | - |
| Thermal faults in Oil 300–700 °C | - | - | √ | Trace | √ | √ | - | √ | - |
| Thermal faults in Oil >700 °C | - | - | √ | √ | √ | - | - | √ | - |
| Partial Discharge | - | - | √ | Trace | - | - | - | √ | - |
| Arcing | - | - | √ | √ | √ | - | - | √ | - |

The majority of the DGA diagnostic tools utilised today can be found in the IEEE C57.104 or IEC 60599 guides as well as other national or international guides based on them. As indicated in IEC 60599 and 60567 [274], there is constantly some degree of inaccuracy in laboratory dissolved-gas measurements, especially when concerning low gas concentrations. This inaccuracy influence gas ratios and other diagnostic calculations. Consequently, the results based on them might be correspondingly uncertain in a certain number cases [276].

### 2.5.3 Transformer Life Cycle Management

Operating quietly for decades, power transformers usually perform their work without any interruption. Consequently, operators are accustomed to putting their faith in solid transformer capacity, frequently performing only minimal maintenance by means of traditional techniques [278].

In the present day, load requirements, the latest corporate sustainability objectives to monitor closely the operational value of the equipment, and additional environmental constraints have led manufacturers to deliver a comprehensive set of solutions in order to maintain the equipment at peak level under any operational conditions. A new generation of asset managers tend to be more interested in the operational value, including the replacement cost, instead of the depreciated book-value over decades [279].

The power transformer product is a long-lasting capital investment good. Acquisition and replacement require long periods of planning engineering and procurement. Each individual conception is particularly adjusted to several specific requirements, of which the corresponding high replacement value and the important lead time are usually the most important [126].

Several solutions proposed by the manufacturers integrate a broad range of services that are intended to significantly prolong the life of the operating transformers, as can be seen in Figure 2.17. Thus, the manufacturers have developed strategies that integrate all transformers – of any age and any brand – in the plan that is prepared for customers, so making it possible to make the best decision concerning the replacement/extension or equivalent subjects [279].

Overall, such systems permit an accurate and continuous monitoring of power transformers, which are currently far beyond the classic method of performing offline measurements. The experience undoubtedly demonstrates that by utilising online monitoring, improved efficiency in the early detection of faults can be reached [280] [281] [282] so that adequate maintenance actions can be accurately scheduled in advance. It is also possible to utilise spare capacities up to the limits, which results in a higher efficiency, reliability and longer service life of power transformers [283].

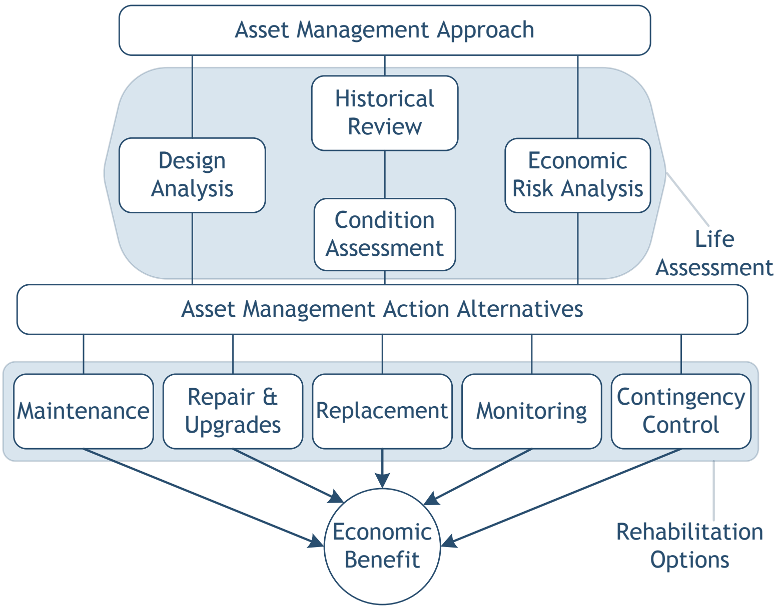

Figure 2.17 - Flowchart of ABB’s approach to asset management.

### 2.5.3.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a tool to estimate the environmental impact of a system or product during its distinctive life cycle phases and the methodology framework according to ISO 14040 [284]. An accurate LCA consists of four iterative steps: goal and scope definition, inventory analysis, impact assessment and interpretation [285].

The current standards [116] [129] are limited to only estimating transformers’ LOL considering the lifetime of the solid insulation transformer, as a simple function of time and the temperatures involved ($\Theta_h$ and $\Theta_a$). Several standards advance further by taking into account other factors [148] [275], such as dissolved gas analysis, polymerisation, harmonics, etc., or are complemented with advanced methods for calculating life through artificial neural networks [240]. On the other hand, such studies always consider only rather limited technical features just for maintenance purposes. Additionally, economic assessment is merely related to the financial costs for transformer replacement. Rather rare is an approach that incorporates real-time O&M data with economic aspects and planning in order to deliver an integrated transformer life management by optimizing its life cycle and amortisation, backing up collaborative work among Operation, Maintenance and Planning departments, to simultaneously optimise grid MVA forecasting, maintenance processes and costs, and operational transformers dispatch for the Utility [286].

The LCA has been performed several times in the literature [286] [287] [288] [289] [290]. The LCA of a generic transformer comprises the raw material manufacturing, operation for 30 years, end of life management and transports, as can be observed in Figure 2.18. In this case, the environmental impact from the assembly and disassembly of the PDTs is minimal and is not included [289].

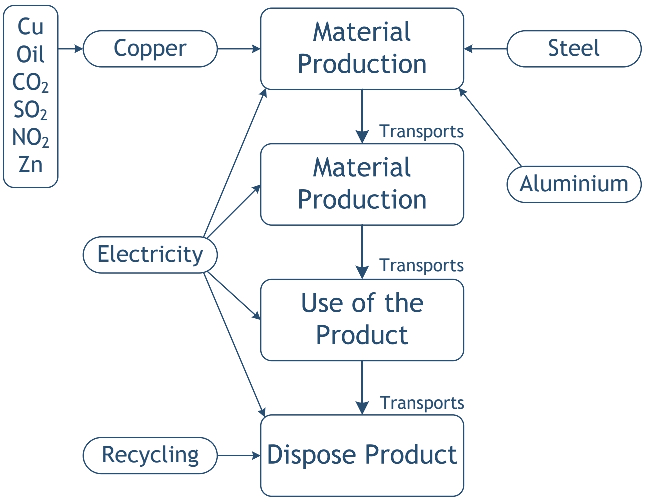

Figure 2.18 - Inventory of material and energy flow for an average transformer.

Also, in such a case, all the transportation in the supply chain has a moderate impact on the LCA. Easy to use tools like openLCA and LCA Light could be very useful in future PDT product development projects [291].

Such studies have an increased importance, so to achieve environmental improvements for the PDT product system it is essential to analyse and consider different types of trade-offs between all the activities in the LCA. An improvement which is positive for the environment at the manufacturing stage might not be so for the environment during the operation phase [290].

## 2.6 Conclusions

In this chapter a comprehensive review was made by analysing and discussing the existing studies in the literature on the effect of loads and other key factors on oil-transformer ageing. The state-of-the-art was extensively reviewed, each factor was analysed in detail, and useful comparative tables were created. The manufacturing process and the life cycle management and assessment of a typical transformer were addressed. A case study was studied of a transformer that was abnormally overloaded due to an anomalous event caused by the induction motors that operate at a factory located on São Miguel Island, Azores. Then, a smart transformer protection was researched in order to address the upcoming challenges. Finally, a monitoring system was considered essential to ensure reliability and sustainability of the transformer. An example is the transformer condition on-line monitoring, either by monitoring the winding temperature or through dissolved gas analysis.

> “You can't build a reputation on what you are going to do.”
> *"Não se pode criar uma reputação sob aquilo que se está por fazer."*
> Henry Ford

# Chapter 3

# Impact of Electric Vehicles Charging on Distribution Transformers: The Case of a Portuguese Island

Wide adoption of electric vehicles (EVs) could bring social and economic benefits. The effort of promoting the use of EVs in road transportation is indispensable to meet the climate change targets and manage the ever unstable prices of diminishing fossil fuels. However, there are still many uncertainties in the market regarding the acceptability of EVs by the final consumer. As a new contribution to earlier studies, this chapter analyses the impact of the EVs charging loads high penetration on the dielectric oil deterioration of two real power distribution transformers, one residential and one industrial, of an isolated electric grid in São Miguel, a Portuguese Island. A power distribution transformer thermal model is used to estimate the hot-spot ($\Theta_h$) temperature given the load ratio. Real data are used for the main inputs of the model, i.e. residential load, private industrial client load, power distribution transformer's parameters, time-of-use rates and EV parameters. Conclusions are finally drawn at the end of the chapter.

## 3.1 Introduction

Preoccupations concerning urban air pollution, the climate change, and the dependency on instable and costly supplies of fossil fuels have compelled policy makers and researchers to explore other possibilities to conventional fossil-fuelled ICO vehicles. One such alternative is the introduction of electric vehicles (EVs) [292] [293]. A broad implementation of such mean of transportation could signify a drastic reduction in greenhouse gases emissions and a compelling argument for our collective attempts of meeting the emission mitigation goals [255] [256] [294]. As a result, during the last few years the electrification of transportation has been increasingly drawing attention and become important.

The wide adoption of EVs is more challenging in comparison with the use of conventional and hybrid vehicles since the main energy source is electricity thus, the electric power systems are required to be qualified to take into account such new challenges and opportunities that are associated with the EVs recharging load [295]. Moderate penetration levels could have a low impact on the grid. On the other hand, as the number of EVs increases, a real possibility of the electric power systems being overloaded can occur –especially the existing electric distribution network [293] [296].

An event of a large number of EVs charging – if occur simultaneously – can lead to grid inadequacy in terms of security and available capacity. This situation can be averted in such cases where the EVs are appropriately incorporated into the electric power system. For the EVs point of view, an occasion of a high number of EVs charging at the same time could eventually be realistic [257]. Without a proper assimilation, the electric power system may possibly suffer excessive voltage drops, feeder congestions, line overloading, etc., especially in the case of an isolated electrical grid such as the one of São Miguel Island, Azores, which lacks suitable integration planning.

The smart grid (SG) is defined as an electricity network that is capable to integrate in a smart way the actions of all users, such as consumers and generators, connected to it with the intention of successfully distribute secure, economic, and sustainable electricity supplies [297]. The SG eases the transition of the renewable energy resources (RES) into the present grid with a higher distributed nature to support the mitigation of carbon emissions.

The latest progress made by researchers in the SG field has led to the prediction of the connection of distributed RES and EVs to the power network and the various technical challenges that come from this new paradigm, thus the overcoming of such obstacles have to be done appropriately [298].

Recently, the implementation of SG paradigm in insular areas has been increasing rapidly with the installation of diverse test systems in other islands around the world. Even though the interconnected power system structure is deemed to be more rigid as regards to stability, isolated areas which could offer an essential foundation for potential islanding operation requirements could be seen as perfect testing grounds for the pre-evaluation of the SG paradigm [299].

The electric distribution network is mainly designed as a passive network intended for energy delivery to the consumers in the traditional electricity network [300]. Thus, there is a broad necessity to create and improve new models and methods in order to assess the impact that high penetration level of EV charging loads could have on the electric distribution network and consequently to make sure that such kind of technology does not overload the grid without reason and helps to reduce the environmental impact of human activity.

Distribution transformers are essential links in the electric distribution networks which could suffer unparalleled charging loads due to the EVs. Several researchers investigated such themes and are aiming to evaluate if the current existing electricity network and the distribution transformer dielectric oil may resist to the penetration of EVs on a large scale [117] [133] [155] [157] [160] [301].

In [301] the authors focus specially on identifying distribution transformers that are most vulnerable in cases of overloading as a result of the implementation of EVs through the employment a binomial probability model that estimates the probability that a specific distribution transformer will suffer overloading. In [155] a study is made in which is assessed the effect of EVs charging on a local residential transformer through the means of an Monte Carlo simulation that was utilised to foresee the final SOC of the daily driving for EV model. In [117] a method is described for assessing the effect of EVs charging on overhead distribution transformers, also presenting a novel smart charging algorithm that regulates EVs charging relying on the assessed distribution transformers temperatures. Other study [157] deliberates how high implementation of EVs will greatly influence the development of home energy management and distribution transformer systems with the intention of decreasing the effect of EV battery charging on distribution transformers by using real load consumption data from Austin, Texas, in the course of a characteristic summer day. In [133] is created a model to define the effect of large implementation rates of additional power to restore the full level of EV battery SOC on the dielectric oil deterioration of distribution transformers through UK generic low voltage electric distribution network model.

One of the most common elements that are found in electric distribution networks are the distribution transformers with an oil-immersed core. The electric distribution network of Azores uses almost exclusively oil-immersed distribution transformers – some of them upgraded very recently [19]. In addition, distribution transformers in their existing form are estimated to keep being operating for numerous years due to its great reliability and extensive use. Thus, the impact of specific SG practices such as EV charging on distribution transformers life and performance considerations must be evaluated in detail.

This chapter presents a model that allows the evaluation of the effect of EVs charging loads on the dielectric oil deterioration of two real distribution transformers, one supplying a residential area and the other a private industrial client, which in turn are part of an isolated electrical grid of São Miguel Island, Azores, Portugal. The method takes into account the uncertainty of EV battery charging loads, for instance the variability of the travel habits of the EV user before recharging – recorded in 2011, the battery SOC at the beginning of the charging process, and different charging styles. The novelty of this study compared to relevant studies in the literature is the real data, the study of a particular case of an island with high penetration of EVs and the EV charging at work during 3 different shifts considering an industrial load.

The remainder of the chapter is organised as follows: in Section 3.2, the employed methodology is developed. In Section 3.3, the electric distribution network of São Miguel, Azores, is presented and discussed and two separated cases are studied, one evaluating the impact of EVs charging on the distribution transformer of a residential area and other on an industrial client. Finally, simulation results are presented and discussed. Finally, the conclusions are summarised in Section 3.4.

# 3.2 Methodology

## 3.2.1 EV battery charging profiles

The charging of EVs is an addition to the existing load. EVs are noticeably distinct when compared with analogous electrical loads as a result of their highly mobile and unpredictable nature. Currently three key factors exist that could affect the influence of EVs on the electric distribution network, specifically the unique nature of the EVs charging process, the driving profile and electrical energy tariff incentives.

With the growth of EV market more and more car manufacturers enter the competition. Hence, a growing supply of EVs with different characteristics is available today [302]. As a result, in order to be more realistic, five different types of EVs are used in this study. The latest models of real existing EVs where used in this study – BMW i3, Renault ZOE, Ford Focus Electric, Nissan Leaf and Kia Soul [303] [304] [305] [306] [307].

In the last few years, EVs are becoming technologically tempting as a result of the progress of Lithium-ion (Li-ion) battery technology that is capable to offer the advantage of higher power as well as higher energy density. Given that Li-ion batteries are becoming generally preferred as the main power source of the current EVs in development [308], in the present study it is implicit that EVs in this case-study employ Li-ion batteries.

Due to the potential of obtaining higher specific energy and energy density, the adoption of Li-ion batteries is estimated to grow fast in EVs. Virtually all EVs that are available in the market today use Li-ion batteries due to its mature technology. The battery capacity for light vehicles in EVs is in the range of 6 kWh to 35 kWh. The charging time varies from 14 hours for slow charging batteries to less than an hour for fast charging batteries [309].

All the EVs utilised in this case study have Li-ion batteries and to understand better effect of charging on the daily baseline load profile the charging profile of a Li-ion battery is briefly described. While the battery SOC is low then the charger functions at rated current, therefore it allows a great quantity of the battery SOC being re-established in the course of the initial charging hours. In practice, the process of charge of a Li-ion battery, despite being represented by simplified characteristics, is described by a relation that reflects the mutually dependent occurrences of battery SOC and charger type [310].

The process pursues until the limit of the battery voltage is reached, at which the current falls while the EV charger preserves a constant voltage. In addition, the EV battery charging process is assumed to be continuous as soon as it is initiated until the full capacity of the battery is reached.

### 3.2.2 Model of EV Charging Load

In this chapter and for both case studies the charging profile of Li-ion EV batteries is utilised, and the stochastic behaviour of the EV battery SOC at the starting point of the charging process is calculated using a probability density function (PDF) associated with the driving range as in [133] [311]. The EV charging demand is given by the initial battery SOC, the charging start time and characteristics. Travel habits of the EV previous to the recharging process define the SOC at the beginning of the charging process of an EV battery and can be perceived as a random variable associated to the driving range. With the basis on a Portuguese study of the general travel information regarding Portuguese drivers of conventional vehicles recorded in 2011 in Lisbon area [312], a PDF of day-to-day driving range can be constructed as expressed by (3.1) and can be observed in Figure 3.1:

$$\left(d;\mu,\sigma\right)=\frac{1}{d\sqrt{2\pi\sigma^{2}}}\times e^{-\frac{(\ln d-\mu)^{2}}{2\sigma^{2}}}\ ,\ d>0 \qquad (3.1)$$

By knowing the average daily driving range, the SOC at the beginning of a recharge cycle that is the residual battery capacity is calculated by utilising (3.2) and by estimating that an EV's SOC descents linearly during the course of the journey (3.2):

$$E_i=\left(1-\frac{d}{d_R}\right)\times 100\ \% \qquad (3.2)$$

by estimating that each trip is initiated with 100% SOC. A typical average value for travel distance is 100 km [154].

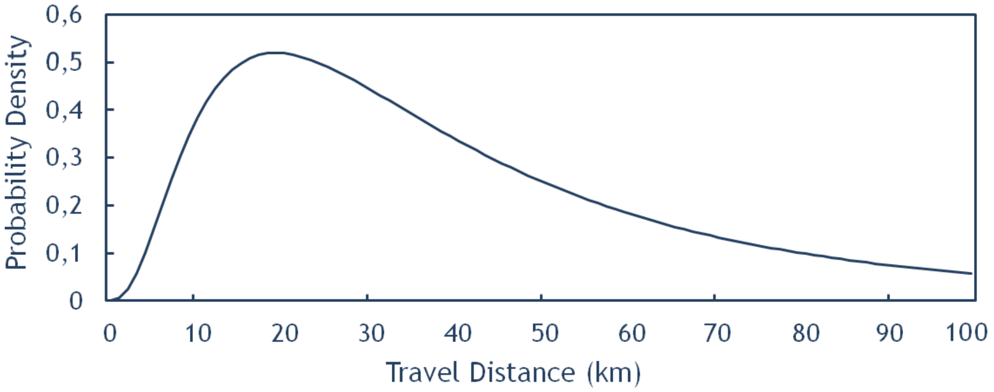

Figure 3.1 - Probability distribution of daily vehicle travel distance.

By replacing (3.2) into (3.1) and switching the variable from *d* to *E*, and by succeeding the journey of one day the PDF of the SOC of the battery is expressed as follows (3.3):

$$h(E;\mu,\sigma)=\frac{1}{d_R\left(1-E\right)\sqrt{2\pi\sigma^2}}\times e^{-\frac{\left[\ln(1-E)-(\mu-\ln d_R)\right]^2}{2\sigma^2}}\ ,\ 0<E<1 \tag{3.3}$$

and truncated at 25% and 95% of battery SOC with parameters as in [313] and can be observed in Figure 3.2.

Based on the information drawn from both PDF, it is feasible to assess the residual battery capacity at the beginning of a recharge cycle. Both electricity tariff rate structure and the objective of the use of the EVs by the users, which is an uncertain factor, influence the initial plug-in instant of the EV and the battery charging process.

### 3.2.3 The Loss of Life of the Distribution Transformer

Since the distribution transformer is a vital part of the electric distribution network, a proper conservation of mineral-oil-tilled distribution transformers is of a high importance in power systems.

Therefore, a necessity is created to implement a caring methodology concerning distribution transformer loading, in order to benefit more from their well-known attributes such as long term service and availability [314].

The distribution transformer's insulation system is essentially created of paper and oil and both experience deterioration. Surprising load intensification has an effect in an increase of the $\Theta_h$ and subsequently the thermal deterioration of the paper is affected [116] [131] [315].

As the distribution of the temperature is uneven, the most deteriorated section of the distribution transformer will as a result be the one with the highest temperature. Thus, the $\Theta_h$ temperature directly affects the life duration of distribution transformers [133].

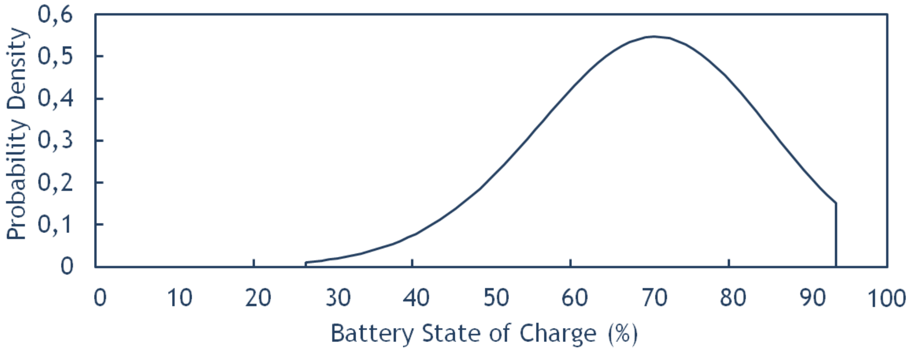

Figure 3.2 - Probability density of battery SOC after one day of driving.

By definition, the $\Theta_h$ is the highest temperature of any spot in the distribution transformer winding. By experiencing elevated electrical loads it originates high core-winding temperatures which in turn cause chemical breakdown of insulating oil and insulating paper [116] [315].

### 3.2.3.1 The distribution transformer calculation of LOL

In case of the thermally upgraded paper the equation of the ageing rate $V$ is expressed as follows [315]:

$$V = e^{\left(\frac{15000}{110+273} - \frac{15000}{\Theta_h + 273}\right)} \tag{3.4}$$

The ageing rate $V$ [316] corresponds to the deterioration of paper isolation for which a $\Theta_h$ is decreased or increased when related with ageing rate at a standard $\Theta_h$ (110ºC) [116].

The LOL of cellulose insulation differential equations can also be expressed with difference equations. The fundamental differential equation is:

$$\frac{dL}{dt} = V \tag{3.5}$$

implying:

$$DL_{(n)} = V_{(n)} \times Dt \tag{3.6}$$

and:

$$L_{(n)} = L_{(n-1)} + DL_{(n)} \tag{3.7}$$

The loss of life (LOL) equation $L$ can also be rewritten and for the duration of the time segment $t_n$ is expressed as following:

$$L = \int_{t_1}^{t_2} V dt \ \text{ or } \ L \approx \sum_{n=1}^{N} V_n \times t_n \tag{3.8}$$

# 3.3 Simulation Results

## 3.3.1 The Proprieties of the Distribution Transformer

In order to determine transient solutions for $\Theta_o$ and $\Theta_h$ a thermal model is developed and proposed for the distribution transformer.

The properties of both distribution transformers used in this chapter are obtained from Ravetta et al. [204] and shown in Table 2.8 in the previous chapter. In corresponds to a real 250 and 630 kVA ($P_r$) oil distribution transformers with Oil Natural Air Natural (ONAN) cooling where a natural convectional flow of hot oil is utilised for cooling. The constants are taken from [116]. Both distribution transformers properties are withdrawn from [6] and [25].

### 3.3.2 Structural Elements of the Insular Grid

The Azores are a Portuguese autonomous region and a 9 islands archipelago located in the North Atlantic circa 3900 km from the east coast of North America. São Miguel Island is the capital and most populated island. The island has around 140,000 inhabitants and covers an area of 760 km$^2$. In this chapter, a part of São Miguel medium voltage electric distribution network is investigated.

The research portrayed in this chapter focuses on two different cases in which the evaluation of the effect of EVs charging loads on the dielectric oil deterioration of two real oil-immersed distribution transformers, one supplying a residential area and the other a private industrial client, which are referred to as case study 1 and 2, respectively. The EVs staring time of charging is selected by taking into account the daily habits of São Miguel's people and the off-peak tariff. In this regard, data are provided under SiNGULAR project [17].

Two different percentages of EVs are used for the two different cases under investigation. The percentage of BMW i3 was chosen in both case studies as high as 40% since it is the fastest selling EV in Portugal according to the ACAP [64]. Renault ZOE and Ford where selected to have a 20% market penetration since these brands already appear to have a significant share in the conventional vehicle market [64]. Data for the charging types and duration of the five EVs are presented in [6] for the first case study and for [25] the second case study.

The present market outlook of EVs can be considered globally low, not exceeding a 7% share in leading countries such as Norway [133]. On the other hand, in this chapter, very high penetration levels are examined. Particularly for an insular area, such as São Miguel, the relatively high transportation cost of fossil fuels, the presence of rich potential of RES, and the opportunities that emerge from the efficient management of an EV fleet [299], are factors that have led to believe that the penetration levels that are likely to be met in such areas in the future will be significantly higher than in continental areas.

In addition, supporting initiatives made by governments frequently have a tendency to aim specific areas such as islands and as a result, potential funding programs or tax reduction schemes to endorse the acquisition and use of EVs are highly expected to significantly encourage customers to exchange their fossil-fuelled ICO vehicles with EVs.

### 3.3.3 Case Study 1

For this case study a distribution transformer that supplies a residential area is chosen. The part of the medium voltage electric distribution network and an identification of several outputs are withdrawn and can be seen in [6]. For this case study the distribution transformer substation PT80 which supplies 292 households through a 630kVA, 10kV/0.4kV oil-immersed distribution transformer is used. A part of São Miguel medium voltage electric distribution network and the identification of PT80 output can be observed in Figure 3.3.

During the summer of 2014 a number of measurements were performed at the distribution transformer substation PT80 and the energy consumption of 292 households was collected and a daily temperature was created as shown in Figure 3.4 and the baseline load profile is withdrawn and can be seen in Figure 3.5. It may be observed that a 630 kVA distribution transformer is oversised for a 140 kW of peak in daily baseline load profile, even if in Azores higher consumption is witnessed during the summer [19].

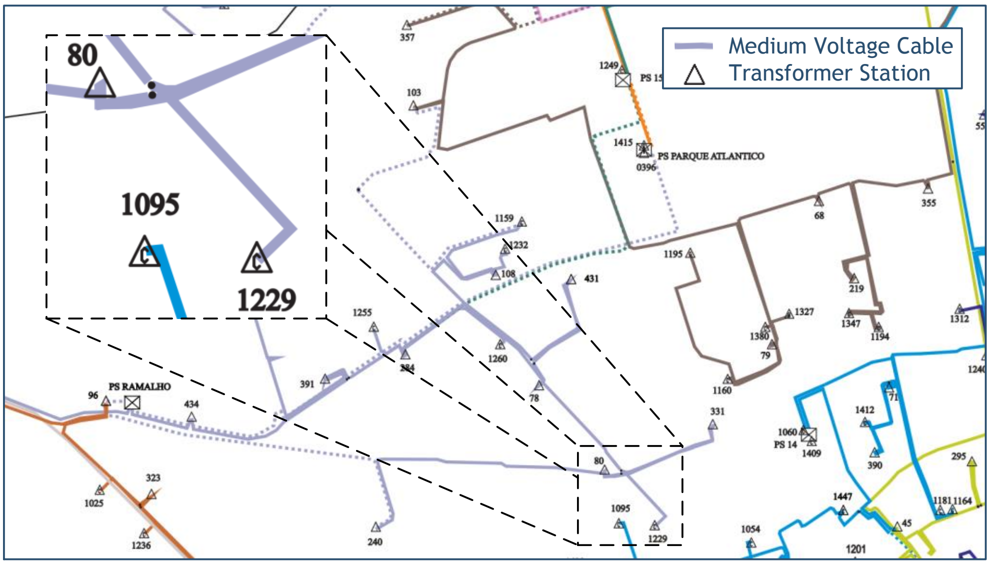

Figure 3.3 - A part of São Miguel medium voltage electric distribution network and the identification of PT80 output.

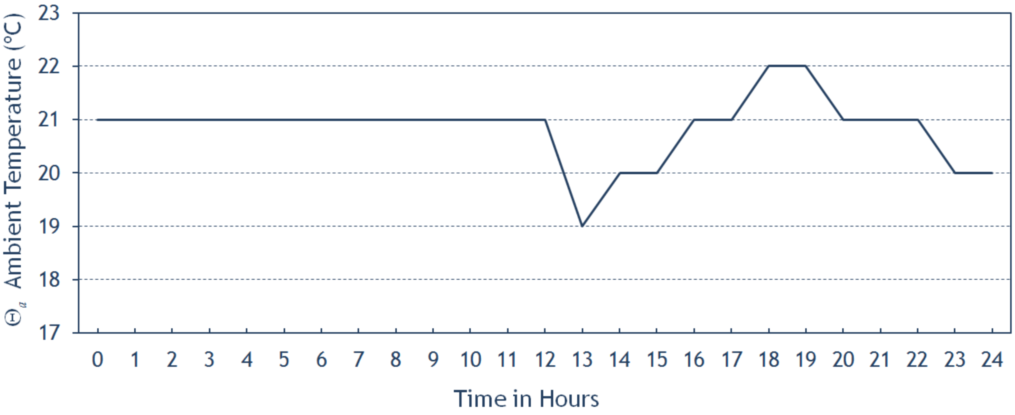

Figure 3.4 – Temperature of a typical day of summer on São Miguel.

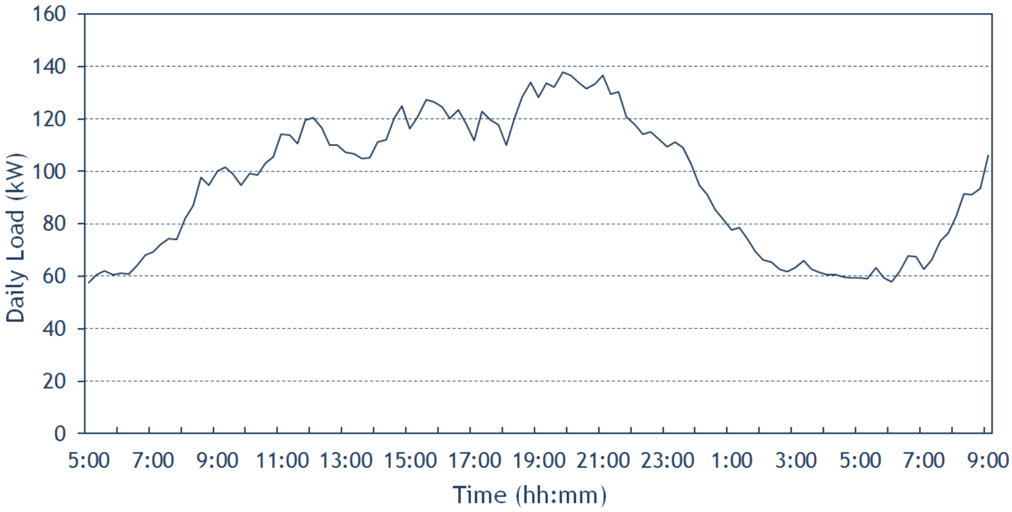

Figure 3.5 - The daily baseline load profile of the transformer substation PT80.

The EV load demand can be affected to some extent by the electricity tariff structure. For this model the current electricity tariff of Azores Islands that entered into force in 2015 is taken into account. Even though a three rate tariff for domestic consumers currently exists in Azores, for this study the two rate tariff is used. The off-peak tariff is 190% lower than the peak tariff and it is initiated instantly after 22:00 [23].

Based on the data collected from the PDF it is possible to apply the distribution transformer thermal model, using the load ratio as an input to obtain the $\Theta_h$ and $\Theta_o$. For this case study one day and a half of the baseline load profile of the summer period of the distribution transformer substation PT80 is used. The total load (in kW) on the distribution transformer is the summation of the $n_d$ domestic loads $P_d$ and loading from $n_{EV}$ randomly selected EVs:

$$P(t) = \left| n_d P_d(t) + \sum_{EV=1}^{n_{EV}} P_{EV}(t) \right| \tag{3.9}$$

A fitting algorithm is applied to determine the impact of EVs charging loads on the dielectric oil deterioration of distribution transformer based on the previously presented methodology. Battery charging of the electric vehicles inflicts an extra load on the distribution transformer. By hypothesizing that a distribution transformer supplies several EVs in a neighbourhood, different charging time and load profiles are obtained for the distribution transformer. The algorithm integrates data obtained from the PDF and calculates the $\Theta_h$ and the distribution transformer's LOL due to EVs charging loads.

Two different scenarios are studied, the first being with different initial SOC of the EVs based on the PDF function, plus different penetration ratios of EVs are considered in this study for the household neighbourhood, beginning with 75% penetration and then with 80%, 85%, 90%, 95% and 100%.

Also, it is considered that 50% of the EV owners charge their cars in slow charging mode and the other 50% in domestic fast charging mode. Finally, it is assumed that 55% of EVs begin charging at 22:00 or are scheduled to do so since as seen before, for Azores the off-peak tariff is 190% lower than peak tariff and it becomes available exactly at 22:00 of each day, as for the remaining 45% of EVs, it is assumed that these users are not very concerned with off-peak tariffs and that the EVs charging are set to begin at 07:00 or are scheduled to do so, when users wake up and go to work and the slow charging mode is used after home arrival, usually after 18:00. These specific percentages are chosen as such due to the reason of being just under and/or above the distribution transformer loading limit, other percentages are redundant.

The second scenario explores a case where during the weekend and at the rule of the same off-peak tariff all the EVs are scheduled or the users chose to charge or the EVs are set to charge at 22:00 and all the owners charge their cars in slow charging mode. The impact on the daily baseline load profile of the distribution transformer substation PT80 made by the energy consumption of the EVs at several penetration ratios from both scenarios is shown in Figure 3.6 and in Figure 3.8, respectively. The starting times of charging for the first scenario is chosen due to the fact that EV users typically do not have a need for fast recharging since they dispose of sufficient time - 3 to 8 h (depending on the charge level) during the non-working period of the day or after 22:00 at the residence with the intention of skipping the drawback of recurring to a public charging station. By analysing Figures 3.6 and 3.8 it can be concluded that for a penetration of EVs of more than 75% the distribution transformer is overloaded. It is then possible to assess the distribution transformer insulation ageing affected by the $\Theta_h$ and the LOL of the distribution transformer which is presented in Figures 3.7 and 3.9, respectively.

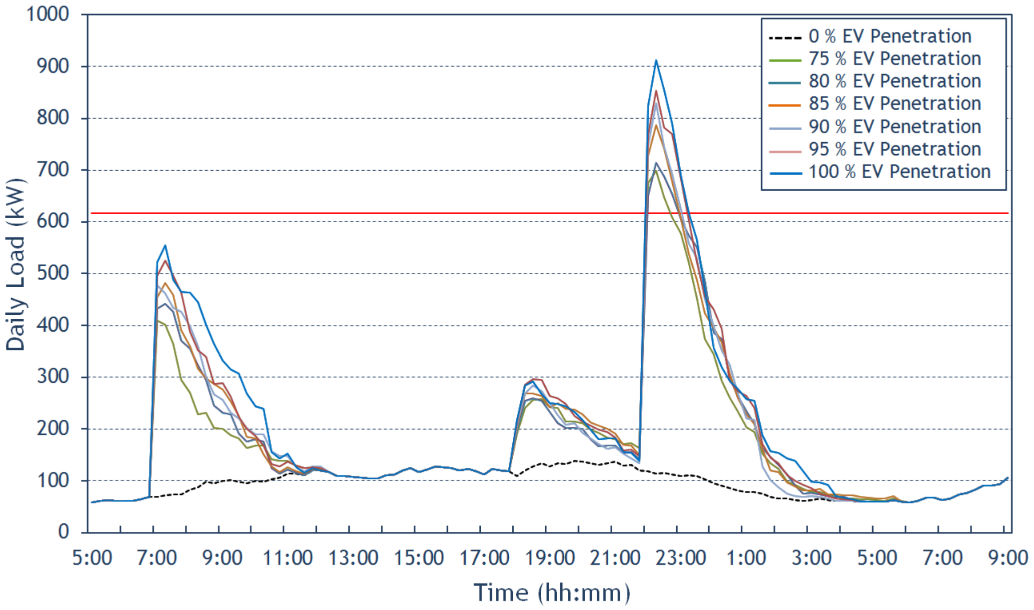

Figure 3.6 – The daily baseline load profile with the studied scenario 1.

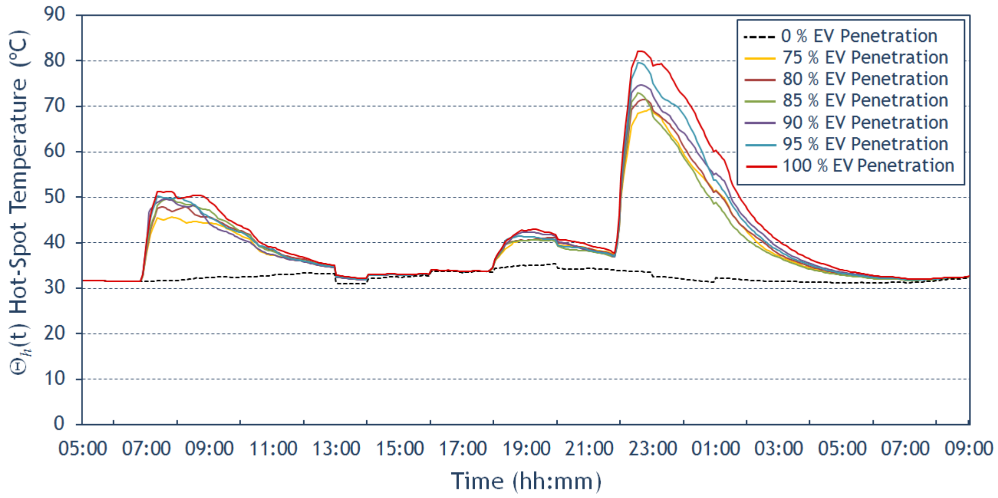

Figure 3.7 – The $\Theta_h$ of the distribution transformer.

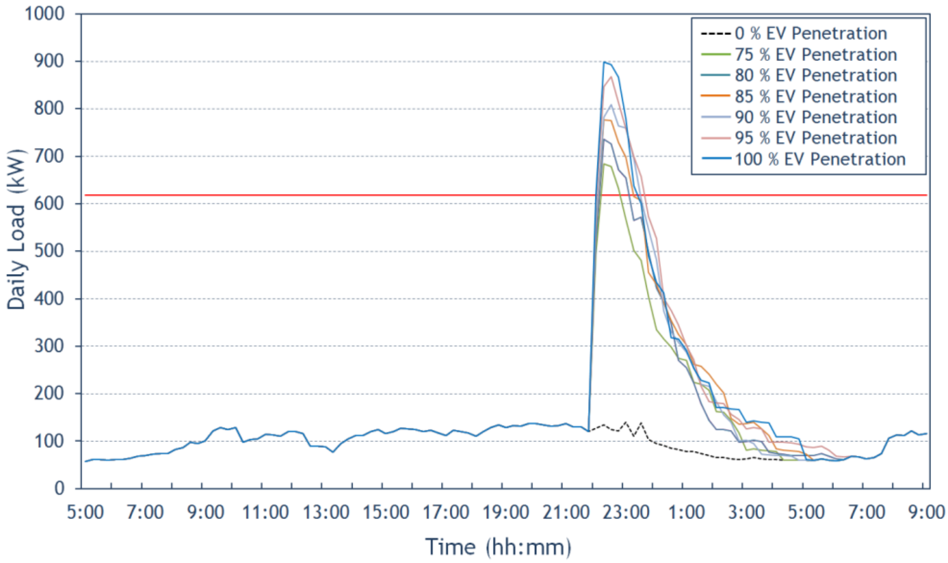

Figure 3.8 – The daily baseline load profile with the 2nd studied scenario.

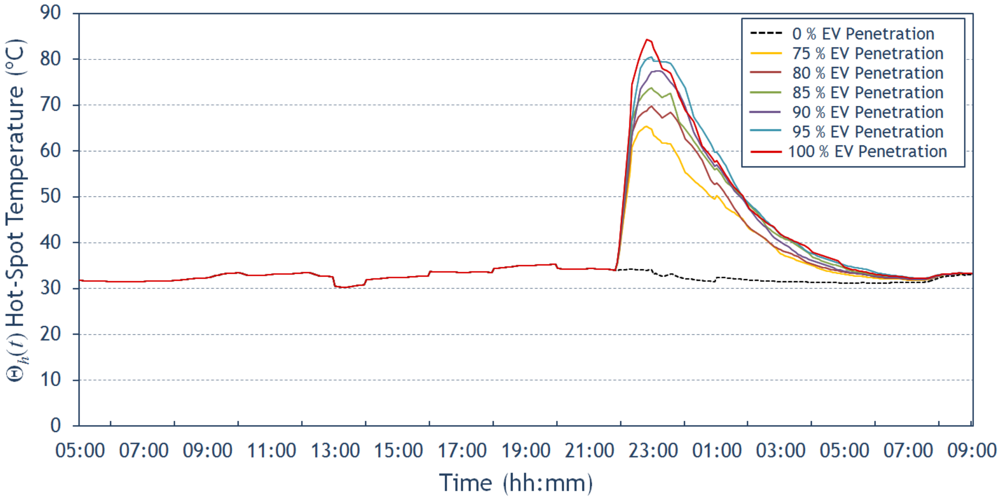

Figure 3.9 – The $\Theta_h$ of the distribution transformer.

Using the ageing equations (2.1) and (2.3), the LOL of the distribution transformer can now be determined. The LOL of the distribution transformer is presented in percentage and also in hours and minutes for each day of EV charging which means that from the distribution transformer expected life at 0% penetration (180000 hours) is withdrawn a number of hours for each day of charging. The results can be seen the Table 3.1.

From Figure 3.6 to 3.9 and from the Table 3.1 it can be concluded that the off peak tariff will encourage users to prefer a certain hour of charging, in this case, 22:00, that will cause a concentration of EVs charging at the same time which in turn will generate an overloading of the distribution transformer, a sudden increase of the $\Theta_h$ and consequently will affect the distribution transformer lifetime.

In both scenarios it can be concluded that for more than 75% of EV penetration the distribution transformer will overloaded resulting in a growth of the $\Theta_h$ of the distribution transformer. The LOL increases with the increase of EV penetration in both scenarios.

By analysing the results obtained from Table 3.1 it can be concluded that the distribution transformer LOL is only affected after a certain amount of EV penetration which is relatively high. If the EV users keep this profile of charging every day the distribution transformer will have a deteriorating LOL after some time.

## 3.3.4 Case Study 2

This case focuses on a distribution transformer that supplies a private industrial client. A part of the medium voltage electric distribution network and an identification of several outputs and can be seen in Figure 2.10 from the previous chapter.

In this case study the distribution transformer substation PT1094 is used which supplies one private industrial client through a 250kVA, 10kV/0.4kV oil-immersed distribution transformer [19].

Table 3.1 – LOL per Day of the Transformer due to EV Charging – Case Study 1.

| ***Level of Penetration*** | **Scenario 1** | | **Scenario 2** | |
|---|---|---|---|---|
| | ***LOL*** | ***% LOL*** | ***LOL*** | ***% LOL*** |
| 0% | 0h 00m | 0 | 0h 00m | 0 |
| 75% | 0h 50m | 0.0005 | 0h 38m | 0.00035 |
| 80% | 1h 09m | 0.0006 | 0h 46m | 0.0004 |
| 85% | 1h 23m | 0.0008 | 0h 54m | 0.0005 |
| 90% | 1h 41m | 0.0009 | 1h 06m | 0.0006 |
| 95% | 2h 17m | 0.0013 | 1h 24m | 0.0008 |
| 100% | 2h 50m | 0.0016 | 2h 46m | 0.0015 |

The private industrial client consists of a factory that produces sugar out of sugar beet. It employs 120 workers and operates in 3 working shifts of 8 hours each. The first working shift starts at 08:00, the second at 16:00 and the third at 00:00. It is assumed in this chapter that the workers are evenly distributed throughout the working shifts.

During February of 2014 several measurements were made at the distribution transformer substation PT1094 and the energy consumption of industrial client was recorded and as a consequence a daily baseline load profile is generated and can be observed in Figure 2.11.

It is also given the power factor of the distribution transformer – approximately 0.95. It may be observed that a 250 kVA distribution transformer is properly sized for a 140 kW of peak in daily baseline load profile, considering that a typical value for an inferior size distribution transformer would be 167 kVA which is not satisfactory [19].

The total load $P(t)$ (in kW) on the distribution transformer is the sum of the factory load $P_f(t)$ and loading from $n_{EV}$ randomly selected EVs:

$$P(t) = \left| P_f(t) + \sum_{EV=1}^{n_{EV}} P_{EV}(t) \right| \tag{3.10}$$

For this case study one day of the baseline load profile of the February period of the distribution transformer substation PT1094 is used and two different scenarios are examined.

### 3.3.4.1 Scenario 1

For the first scenario different penetration ratios of EVs for each working shift are considered for this industrial client, beginning with 35% penetration and then with 40%, 45%, 50%, and 55 %. These specific percentages are chosen as such due to the reason of being just under and/or above the distribution transformer loading limit, other percentages are redundant. Finally it is assumed that the EVs start or are scheduled to charge at the beginning of each working shift.

The effect on the daily baseline load profile of the distribution transformer substation PT1094 created by the energy consumption of the EVs at several penetration ratios from the first scenario is shown in Figure 3.10 the daily baseline load profile is also shown as 0% penetration ratio.

By analysing Figure 3.10 it can be observed that for a penetration of EVs of more than 40% the distribution transformer is overloaded. Also, from the information obtained from the model and presented in Figure 3.10, it is possible to assess the distribution transformer insulation ageing affected by the $\Theta_h$ which is presented in Figure 3.11 and subsequently to calculate LOL at the designated penetration ratios of the distribution transformer.

The LOL of the distribution transformer is presented in percentage and in hours and minutes for each day of EV charging which means that from the distribution transformer expected life at 0% penetration is subtracted the number of minutes or hours for each day of charging. The results can be seen in the Table 3.2.

### 3.3.4.2 Scenario 2

The second scenario is in the following: all EVs are charged with fast charging mode beginning with 15% penetration and then with 20%, 25%, 30%, and 35%. The same percentages are set as the preceding scenario in order to observe the difference between slow and fast charging modes. Just as in the previous scenario, it is assumed that the workers put their EVs to charge at the beginning of each working shift.

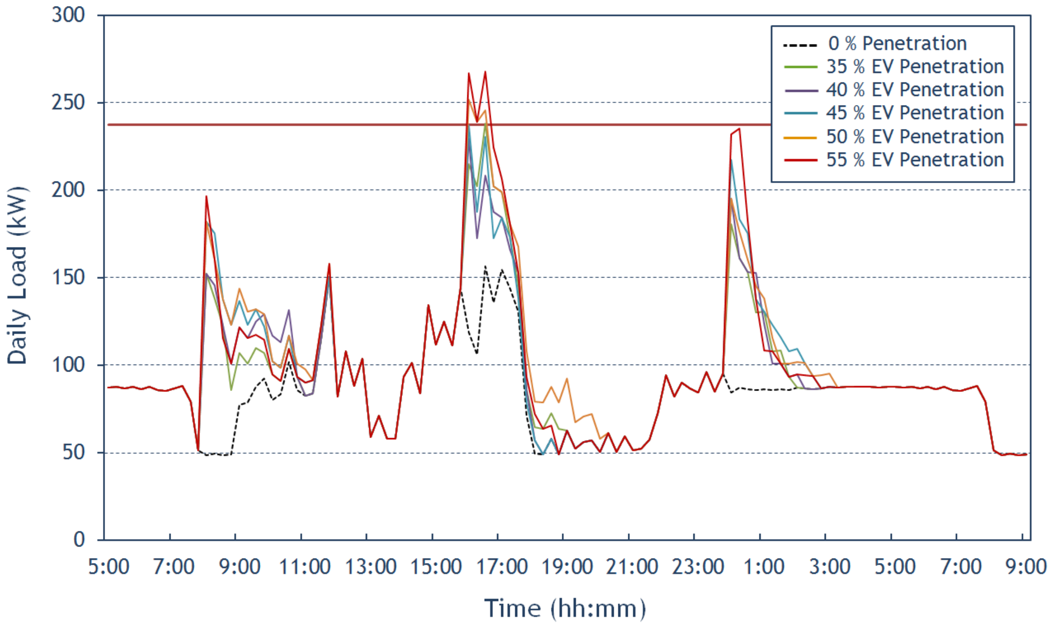

Figure 3.10 – The daily baseline load profile with the first scenario studied.

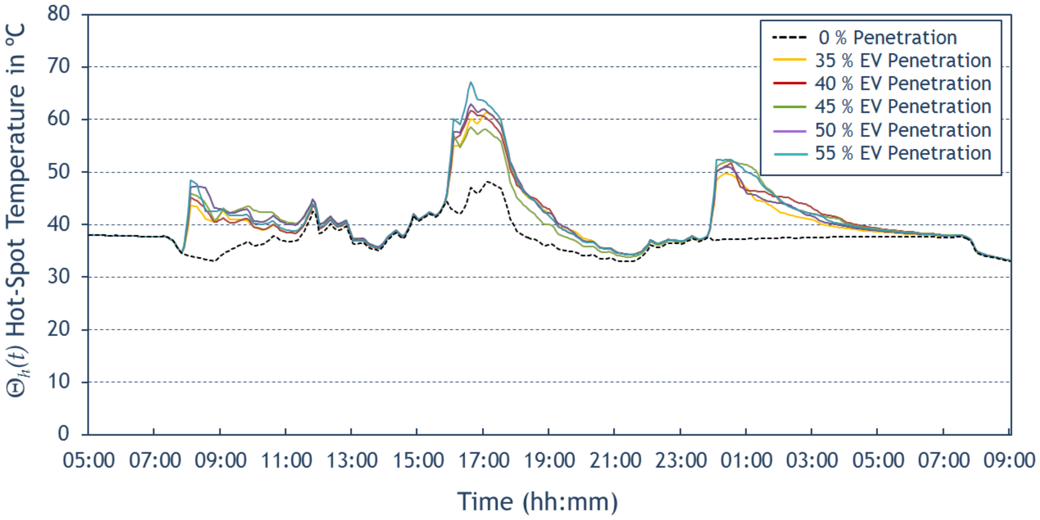

Figure 3.11 – The $\Theta_h$ of the distribution transformer in Scenario 1.

The consequence on the daily baseline load profile of the distribution transformer substation PT1094 made by the energy consumption of the EVs at several penetration ratios from the second scenario is shown in Figure 3.12.

By observing Figure 3.12 it can be noticed that for a penetration of EVs of more than 15% the distribution transformer is profoundly overloaded and even at inferior penetration ratios it is overloaded.

Also, from the information obtained from the model and presented in Figure 3.12, it can be assessed the distribution transformer insulation ageing affected by the $\Theta_h$ which is presented in Figure 3.13. By means of the ageing equations (2.1) and (2.3), the LOL of the distribution transformer can now be determined. The results can also be seen in the Table 3.2.

Table 3.2 – LOL per Day of the Transformer due to EV Charging – Case Study 2.

| Scenario 1 | | | Scenario 2 | | |
|---|---|---|---|---|---|
| ***EV Penetration*** | ***LOL (t)*** | ***LOL %*** | ***EV Penetration*** | ***LOL (t)*** | ***LOL %*** |
| 35% | 36 min | 0.0003 | 15% | 0h 58m | 0.0005 |
| 40% | 40 min | 0.0004 | 20% | 1h 22m | 0.0004 |
| 45% | 45 min | 0.0004 | 25% | 4h 23m | 0.0024 |
| 50% | 58 min | 0.0005 | 30% | 16h 02m | 0.0089 |
| 55% | 77 min | 0.0007 | 35% | 70h 22m | 0.0391 |

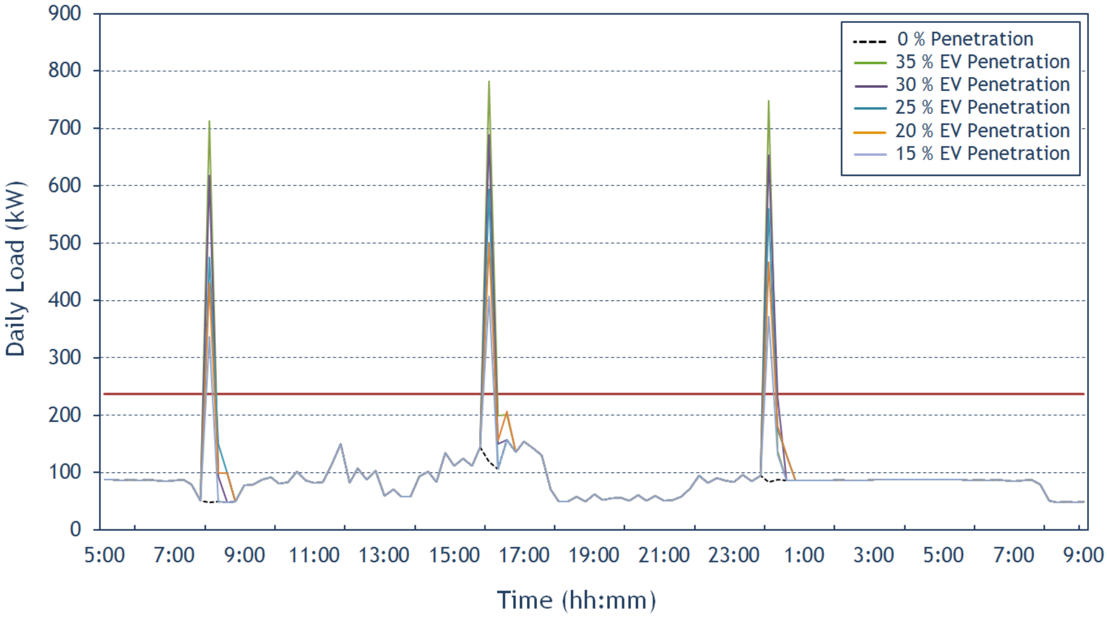

Figure 3.12 – The daily baseline load profile of the second studied scenario.

### 3.3.4.3 Critical Analysis

By analysing the results obtained from Table 3.2 it can be concluded that the distribution transformer LOL is only affected after a certain amount of EV penetration which is relatively high. If the EV users make such profile of charging a routine the distribution transformer will have a deteriorating LOL after some time.

The comparison of both scenarios at 35% EV penetration in the Figures 14 and 15 highlights the level of impact in the distribution transformer ageing by using fast charging over slow charging. By analysing Figures 3.10 to 3.13 and Table 3.2 it can be concluded that each beginning of a shift will influence users to prefer the first hour of charging, that will originate a concentration of EVs charging at the same time which in turn could cause an overloading of the distribution transformer, a sudden increase of the $\Theta_h$ and thus will affect the distribution transformer lifetime.

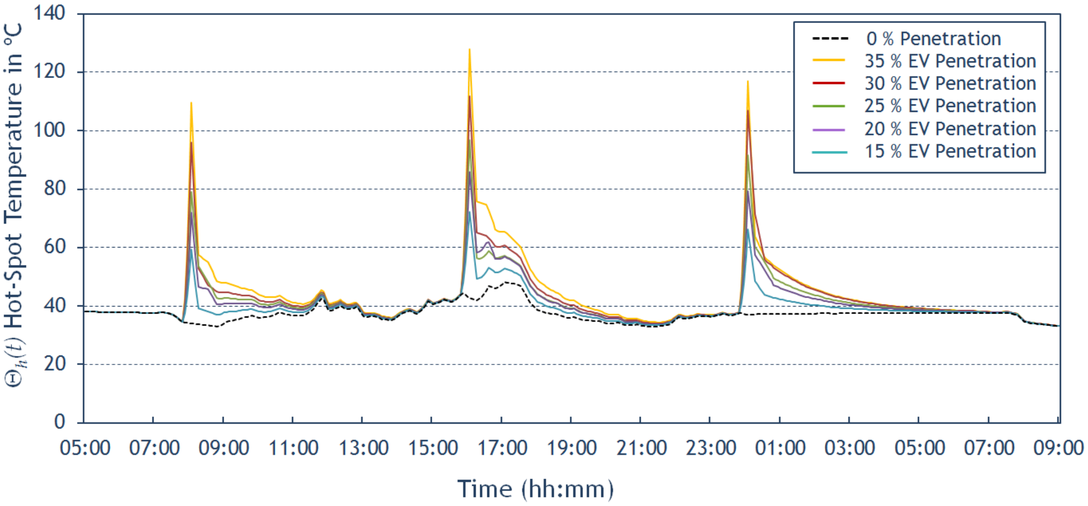

Figure 3.13 – The $\Theta_h$ of the distribution transformer in Scenario 2.

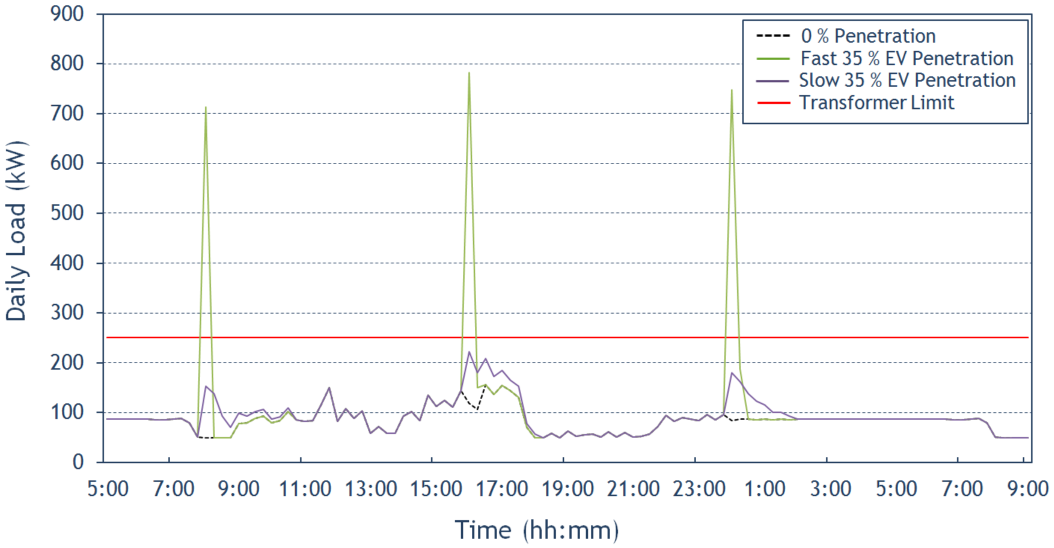

Figure 3.14 – The daily baseline load profile of the second studied scenario.

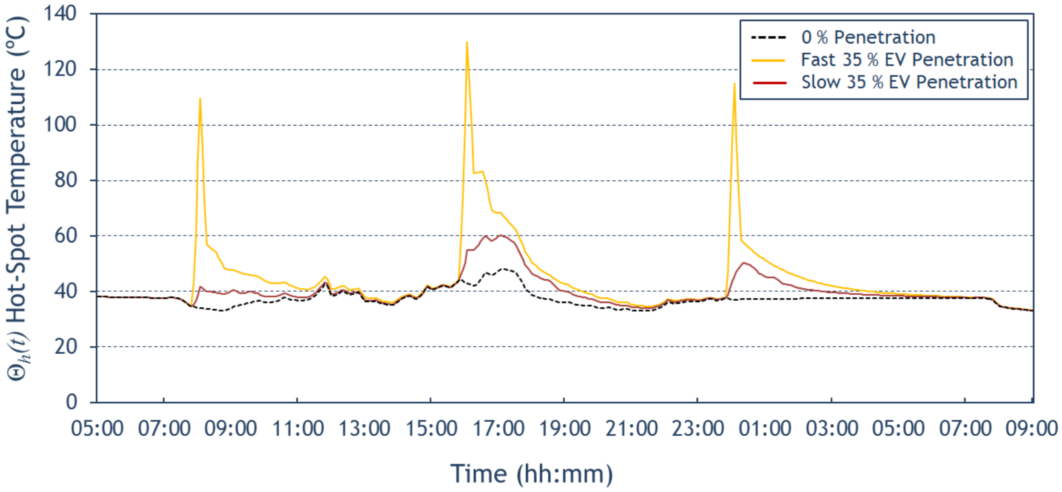

Figure 3.15 – The $\Theta_h$ of the distribution transformer in Scenario 2.

By observing the first scenario it can be concluded that for more than 40% of EV penetration the distribution transformer will be overloaded resulting in an increase of the $\Theta_h$ of the distribution transformer. The LOL slightly increases with the increase of EV penetration in this scenario. In an improbable event of the second scenario occurring, the LOL of the distribution transformer is significantly higher. Thus, it is advised to avoid the fast charging mode since the slow mode takes at maximum 5 hours which is always less than a working shift of 8 hours.

## 3.4 Conclusion

In this chapter a model to estimate the influence of simultaneous EVs charging on the dielectric oil deterioration of two distribution transformers, one at a residential area and other at a private industrial client, was developped. Two different case studies were examined, one focusing on a residential area during working days and weekends and another concerning a private industrial client with several penetration ratios at three different working shifts. Given the fact that the distribution transformer insulation ageing is mainly affected by the $\Theta_h$ a distribution transformer thermal dielectric oil deterioration model was utilised to calculate the $\Theta_h$ given the load ratio. The main inputs to the model, including residential load, distribution transformer parameters, and five different vehicle parameters were taken from real data. Dielectric oil deterioration was then calculated and analysed. Since both distribution transformers have a significant capacity to be used for a side activity – this study showed that even though it has, it still can be overloaded after a specific increase of EV penetration. The developed methodology was applied to assess the impact of multiple EVs charging in the same residential area and it showed that off peak tariff can have an influence over EV users and affect the distribution transformer lifetime. Also, while charging at the workplace, the slow charging mode is recommended over the fast mode since the vehicles will always be 100% charged at the end of each working shift without drastically affecting the distribution transformer lifetime.

“Success is stumbling from failure to failure with no loss of enthusiasm.”
*“O sucesso é um tropeçar de fracasso em fracasso sem perder o entusiasmo.”*
Winston Churchill

# Chapter 4

# Smart Electric Vehicle Charging Scheduler for Overloading Prevention of an Industry Client Power Distribution Transformer

In this chapter an overloading prevention of a private customer distribution transformer in an island in Portugal through the means of a new smart electric vehicle (EV) charging scheduler is proposed. The aim in this chapter is, first, to assess the repercussion of the penetration of additional power to restore the full level of EV battery state of charge (SOC) on the dielectric oil deterioration of the distribution transformer of a private industry client that allows EVs to charge while their owners are at work and at three different working shifts during a day. In addition, the system is part of an isolated electric grid in a Portuguese Island. In the current chapter, a transformer thermal model is utilised to assess the hot-spot temperature by having the information of the load ratio. Real data are used for the main inputs of the model, i.e. private industry client load, distribution transformer parameters, the characteristics of the factory and electric vehicle parameters. In this section it will be demonstrated that the proposed solution allows avoiding the overloading of the distribution transformer, thus mitigating the loss of life, while charging all the EVs plugged-in at the beginning of each working shift.

## 4.1 Introduction

On the other hand, mobility consumes more and more energy and leads to substantial environmental problems. More than 70% of the transport energy consumption in the EU27 (2010) is consequently consumed by road traffic, and more than 90% of such type of energy consumption is based on the use of fossil fuels [317]. Common concerns on the subject of urban air pollution, climate change, and dependence on expensive and unstable supplies of fossil fuels have lead researchers and policy makers to look for alternative choices besides to the traditional internal combustion petroleum-fuelled engine vehicles, such as EVs [318] [319]. Utilising only renewable power sources for charging has the potential to reduce EV lifetime emissions by at least 80% when compared to conventional vehicles [320].

EV could bring various benefits, such as lower emissions of several air pollutants and noise, growing energy efficiency when compared to ICOs, and the substitution of fuel as the main primary energy source for road transport [321]. A substantial widespread penetration of electric vehicles could also have a great effect on the power system. The effects on the system peak load, power plant dispatch, and carbon emissions rely on both the power plant tools and the EVs charging mode [322].

The usual design horizons for power grids are dozens of years as a result of long service life of grid assets. EVs could produce new and unforeseen and sudden load patterns with possibly high simultaneity factors as a result of commuter traffic [296]. Additionally, with a rising number of EVs plugged to power systems for charging, there is also a preoccupation that the distribution networks already installed could turn out to be extra loaded than predicted compared with the time of their conception. Therefore, reduced implementation of EVs may well result in a reduced effect, however if the penetration total amount of EVs increases, a concrete possibility may occur of local electric distribution networks being congested [117] [323]. An occurrence of charging of a great number of EVs at the same time could be the origin grid insufficiencies concerning available capacity and security. Such events can be prevented, if they are correctly incorporated in the grid. If the EVs are operated accordingly – integrating them in the grid could be a substantial and important occasion. Thereupon charging of a high quantity of EVs at the same time turns out to be practical [257]. Devoid of such organised integration, the grid might suffer feeder congestions, excessive voltage drops, line overloads, etc.

Energy systems operation in isolated areas such as islands is often based on the highly costly importation of fossil fuels, which turns out to be a difficult problem with different ramifications including economic, environmental, and confidence of being constantly supplied, with the latest being especially significant for any isolated system such as islands [324]. As a result, insular networks that present weaker structures than the mainland ones could be more seriously affected. It is necessary to supply all or at least the most part of the energy demand on site which usually are renewable energy systems. The penetration of such systems in insular areas are central target of energy policies during the last few years and the design and structure of electric power grids will be forced to change considerably with the recent growing interest in renewable energy systems [1]. On the other hand, the subject of renewable energy sources in island communities has a high complexity owing to many different and difficult factors [325].

A large shift from the traditional to a new smart grid networks was witnessed in the last few years. Such kind of transition is converted into an evolution from a typical radial energy flow to novel and systems with an increased complexity, but with better features such as a higher efficiency, a better incidence of distributed generation, better preservation of the environment, and greater reliability.

The so called new paradigm of Smart Grid is outlining strategies to focus on the energetic needs of this century and afterwards, in order to accomplish such improvements [326]. The notion of smart grid is getting a noticeable role in both energy research and policy in the European Union [327]. The recent progress in smart grid research has predicted the connection of distributed renewable energy sources and EVs to the power network and the numerous technical challenges that come from such a new paradigm and thus have to be approached properly [328].

The implementation of smart grid paradigm in insular areas has been increasing with the installation of diverse test systems in other islands around the world. Albeit the interconnected power system structure is deemed to be more rigid as regards to stability, isolated areas which could offer an essential foundation for potential islanding operation requirements could be seen as perfect testing grounds for the pre-evaluation of the smart grid paradigm [329].

The electric distribution network infrastructure is conceived to provide electricity to final clients and the planning is usually found on the assessed demand of electricity. For the abovementioned reason, there is a broad necessity to elaborate modelling methods to assist the quantification of the impact that a great implementation level of additional power to restore the full level of EV battery SOC could have on the electric distribution networks and consequently guarantee that such ecologically positive technology is not needlessly constrained.

As a result, the distribution transformers by being essential links in electric distribution networks will consequently begin to suffer exceptional loads from EV charging. A significant number of diverse research studies were recently released to evaluate if the current electric distribution network and fundamentally the global adoption of EVs could be tolerated by the transformer insulation temperature [6] [117] [132] [133] [155] [156] [157] [330] [331].

In [330] the control strategies that can eliminate or at least mitigate the hastened ageing of a 25 kVA distribution transformer that might be caused by load peaks instigated by EVs charging are implemented. Other study [157] deliberates how high implementation of EVs will greatly influence the development of home energy management and distribution transformer systems with the intention of decreasing the effect of EV battery charging on distribution transformers by using real load consumption data from Austin, Texas, in the course of a characteristic summer day. In [133] is created a model to define the effect of large implementation rates of additional power to restore the full level of EV battery SOC on the dielectric oil deterioration of distribution transformers through UK generic low voltage electric distribution network model. In [117] a method is described for assessing the effect of EVs charging on overhead distribution transformers, also presenting a novel smart charging algorithm that regulates EVs charging based on assessed transformer temperatures.

In [331] an analysis of the impacts of price-incentive based demand response on a neighbourhood distribution transformer ageing has been performed through a MILP model of a neighbourhood composed of smart households with different end-user profiles. The impact of hybrid EVs on the life duration of the low-voltage/medium-voltage transformer utilising a thermal model to assess the $\Theta_h$ is studied in [134]. In electric distribution networks one of the most common equipment that is found is the oil-immersed distribution transformers. For instance, distribution system of Azores uses almost exclusively oil-immersed distribution transformers with some of them upgraded not long ago [19]. Therefore, transformers in their current form are expected to stay operational for several years to come caused by its boundless utility with intrinsic high reliability and simplicity. As a result, the influence of characteristic smart grid operations for instance EV charging on transformer life and performance considerations must be properly evaluated.

This chapter presents a model based on real data that allows the evaluation of the influence of additional power to restore the full level of EV battery SOC on the dielectric oil decay of an industry client distribution transformer which in turn is a part of an isolated electrical grid of São Miguel Island, Azores, Portugal. The model takes into account the uncertainty of EV battery charging loads such as the predictability of the EVs plug-in starting time, the battery SOC at the beginning and charging modes. Then, given the previously mentioned results to mitigate the effect of the EVs on the loss of life (LOL) of the transformer, an overloading prevention by using the new smart EV charging scheduler is proposed and simulated. Hence, the novelties of this study are threefold: the acquired real data used in the investigation of a specific case of an island with high penetration of EVs, the EV charging at an industrial facility during 3 different shifts considering an industrial load, and finally the new smart EV charging scheduler proposed. This chapter is organised as follows: in Section 4.2 the overloading prevention of the industry client distribution transformer through the means of a model of a new smart EV charging scheduler is proposed and then the simulation results and critical analysis are presented and examined. Finally, the conclusions are drawn in Section 4.3.

## 4.2 The solution of the transformer overloading - new smart EV charging scheduler

Given the overload that the transformer suffers at the beginning of each working shift, a schedule solution is proposed which consists of a model that makes the evaluation of the impact of additional power to restore the full level of EV battery SOC on the dielectric oil deterioration of a real distribution transformer, supplying the private industry client and then schedules the charging of the EV in an optimal manner that turns possible to avoid the overloading of the aforementioned transformer through the development of a new smart EV scheduler.

The rescheduling process purpose is to charge the batteries of all the EVs in a timely manner and meanwhile to avoid the overloading of the transformer.

### 4.2.1 The Smart Charging Scheduler's architecture

Initially, a pre-set limit ($P_{sl}$) of the permissible load has to be introduced in the scheduler in order to limit the sum of the factory loading and the EV batteries. $P_{sl}$ can be less or equal than 95% of the transformer's loading limit so that at least 5% of the transformer capacity remains unused in order to always have a certain reserve.

The operation of such device consists of collecting the data of the transformer parameters, EVs batteries SOC, the industry client load and the $\Theta_a$ and then to reschedule the charging of EVs that surpass the $P_{sl}$ of the scheduler. Such device will also have a data logger and HMI (human-machine interaction) device in order to display all the information related to the made recordings and the modelled data and also to allow an interactive use of the device with functions such as the easy setting of a new $P_{sl}$. Finally the scheduler will have a wireless transmitter in order to send the information to an exterior platform so it could be accessed everywhere by all sorts of portable devices. The operation of the proposed scheduler is displayed in Figure 4.1.

As seen before, $P_T(t)$ is the sum of the loads of the factory and EVs. On the other hand, let the $P_\Omega(t)$ be the remaining EV load that is superior to the $P_{sl}$ in any given instant $t$:

$$P_\Omega(t) = P_T(t) - P_{sl}, \quad \forall\, P_T(t) > P_{sl} \tag{4.1}$$

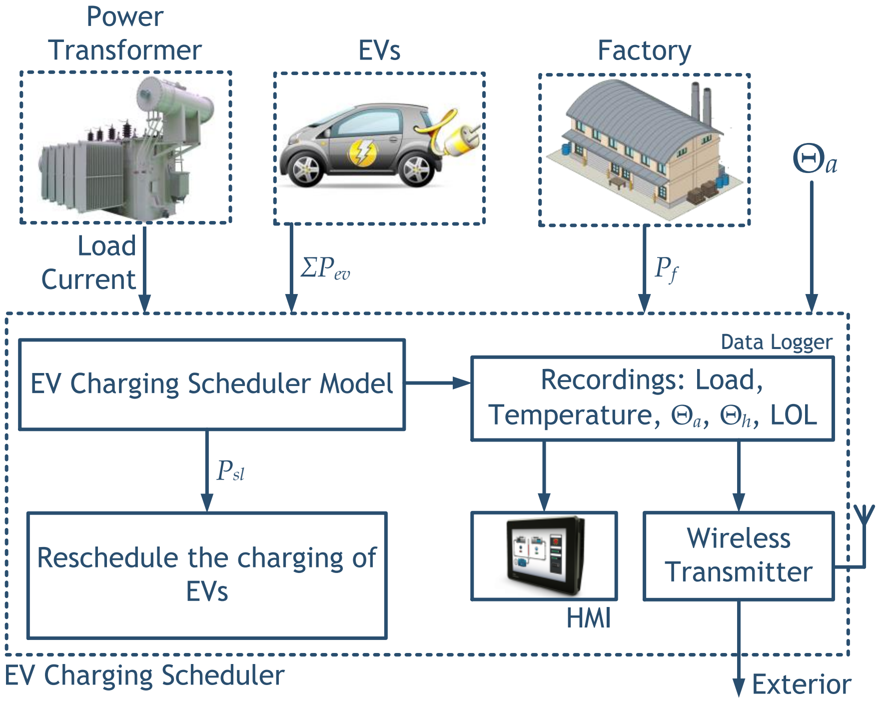

Figure 4.1 – The basic operation schematic of the EV Charging Scheduler.

Thus, the new EV charging scheduler operates in the following mode: at first a charging time frame is established, then effectuates readings of the electric distribution network data, the EV charging data, the factory load and $\Theta_a$, and finally assesses the $\Theta_a$ and LOL. Immediately after this operation it verifies if $P_T$ is equal or higher than $P_{sl}$. If this is the case, then the scheduler is activated and the remaining EV load $P_\Omega$ is rescheduled to the next charging time frame which in this case study is 15 minutes. Finally, if all the EVs are charged then the scheduler is put in stand-by until a new EV connects. The detailed operation of the new EV charging scheduler is shown in Figure 4.2 through the means of a flowchart.

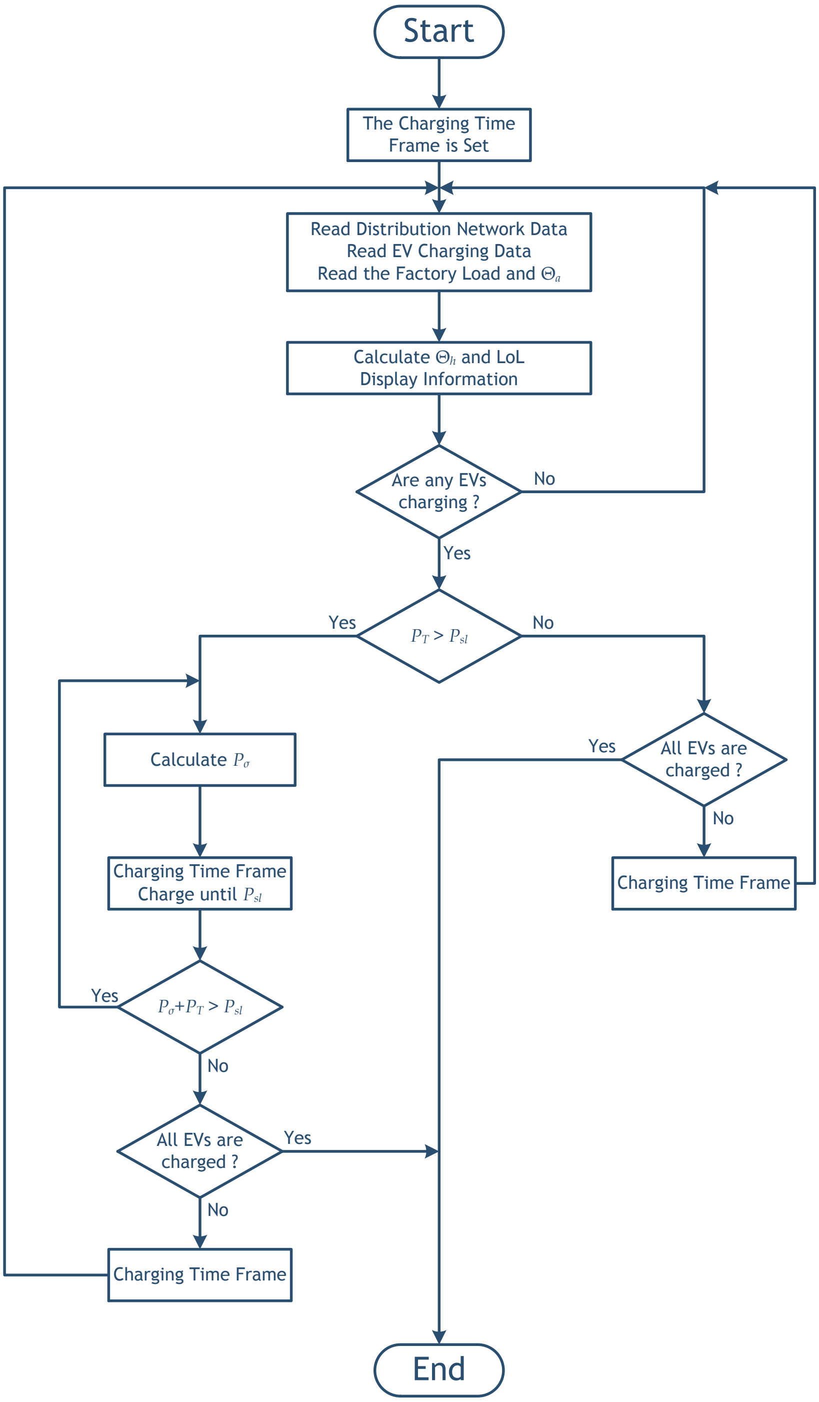

Figure 4.2 – Detailed Scheduler Operation Flowchart.

## 4.2.2 Simulation Results

### 4.2.2.1 Scenario 1

After the implementation of the new EV scheduler model several simulations were performed and results were obtained. In case of a slow charging mode Figure 4.3 shows how the scheduler prevents the overloading of the transformer when compared with Figure 3.12 at several penetration ratios, up to 60%. A small improvement was verified of the $\Theta_h$ in comparison with the first scenario seen in Chapter 3 through the comparison between Figures 3.13 and 4.4. The results in how much LOL was saved in relation with the scenario without the EV charging scheduler is shown in Table 4.1. Juxtaposition between the rescheduled charging of EVs at 60% penetration and non-scheduled charging can be seen in Figure 4.5. The small improvement of $\Theta_h$ verified in this case and presented in Figure 4.6 is of 7.54%.

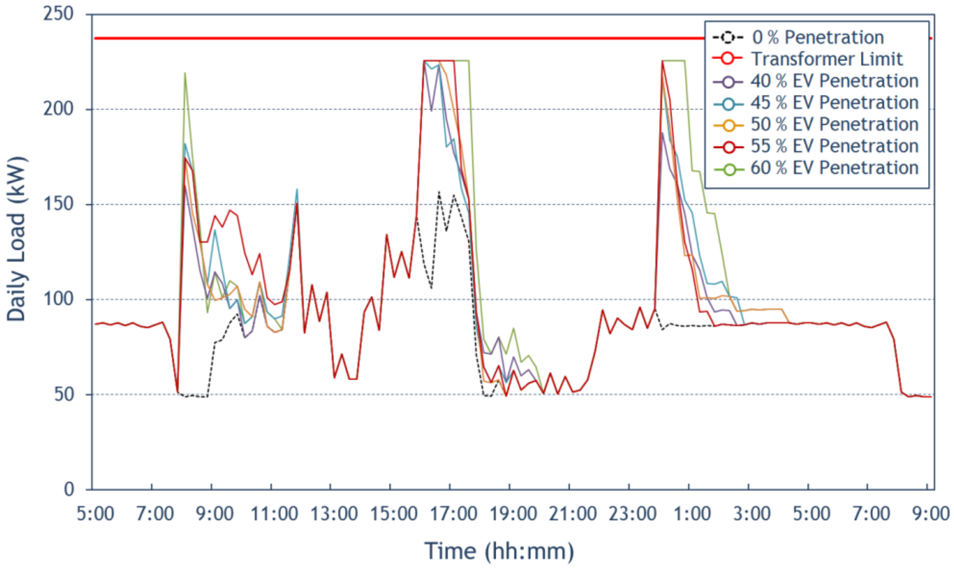

Figure 4.3 – The daily baseline load profile in slow charging mode with the Scheduler in operation.

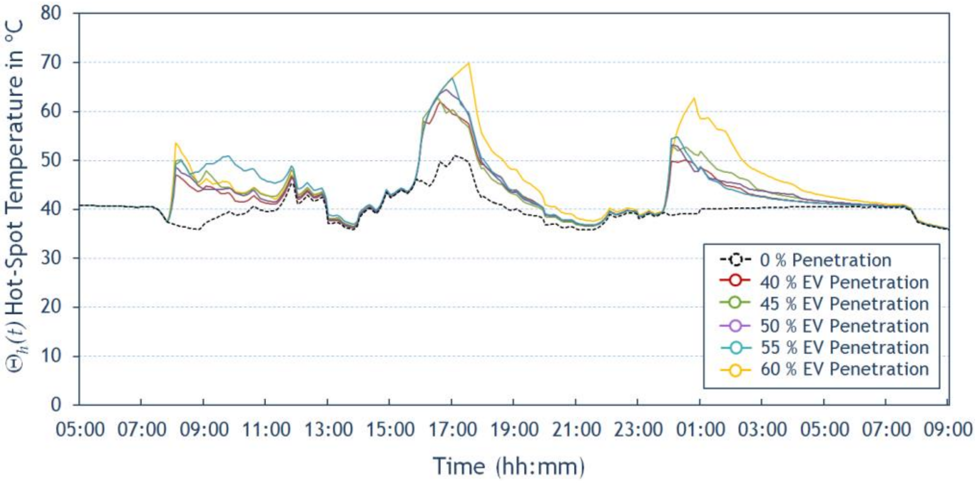

Figure 4.4 – The $\Theta_h$ Temperature in slow charging mode with the Scheduler in operation.

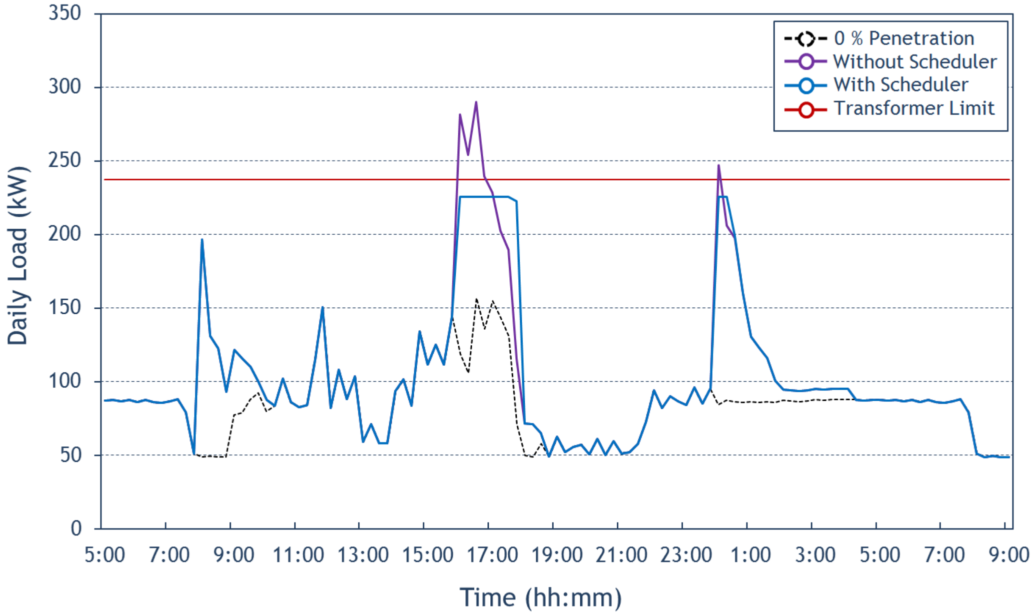

Figure 4.5 – Comparison in slow EV charging mode between the cases with the scheduler and without it at 60% EV penetration.

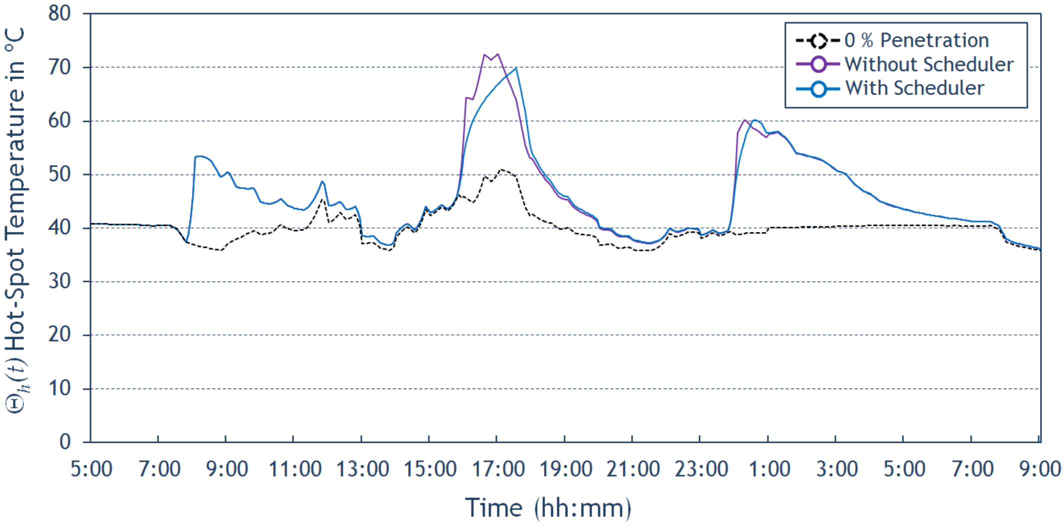

Figure 4.6 – Comparison of $\Theta_h$ between the cases with the scheduler and without it at 60% EV penetration.

Table 4.1 – LOL per Day of the Transformer due to EV Charging

| EV Penetration | LOL (t) | LOL % |
|---|---|---|
| 40% | 39.16 min | 0.0004 |
| 45% | 49.74 min | 0.0005 |
| 50% | 52.12 min | 0.0005 |
| 55% | 53.28 min | 0.0005 |
| 60% | 71.54 min | 0.0006 |

After the aforementioned simulations were concluded many others were made at high penetration of EVs, as much as 60%, and at different pre-set limits. The results show that the EVs are always charged until the end of each working shift, in point of fact nowhere near the end of the shift, but three to four hours earlier. The results can be seen in Figure 4.7 for the daily load profile and Figure 4.8 for the $\Theta_h$. By means of the ageing equations $V$ and $L$, the LOL of the transformer can now be determined. The results show that the LOL decreases each time the $P_{sl}$ is set lower and can be seen in the Table 4.2. With the intention of testing the limits an extreme event was also simulated in order to assess until what point the EV charging scheduler is viable.

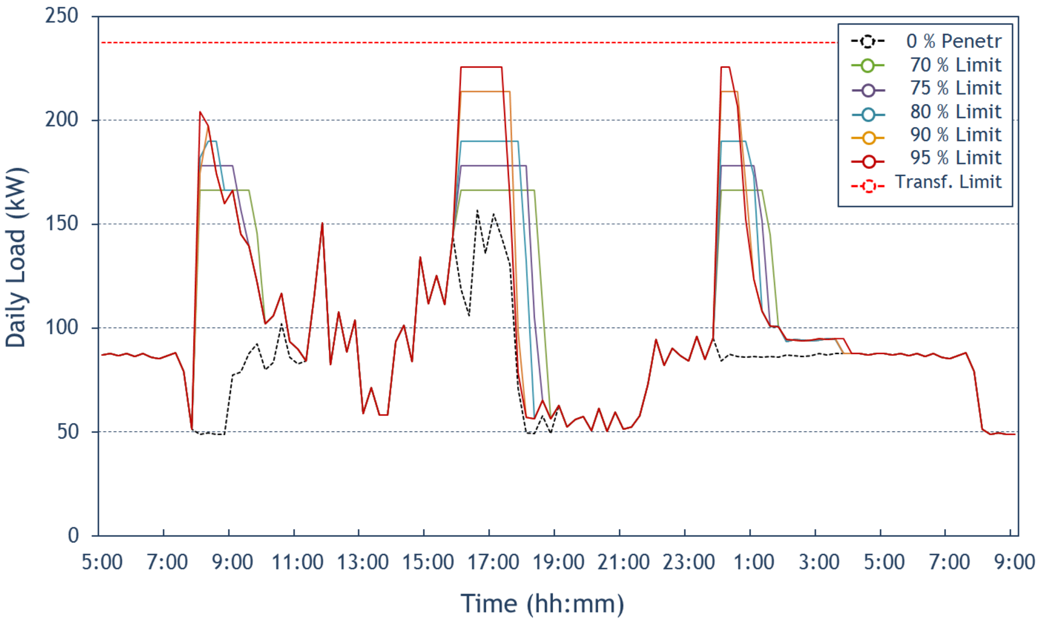

Figure 4.7 – Difference between the operations of the scheduler at several pre-set limits at a 60% penetration.

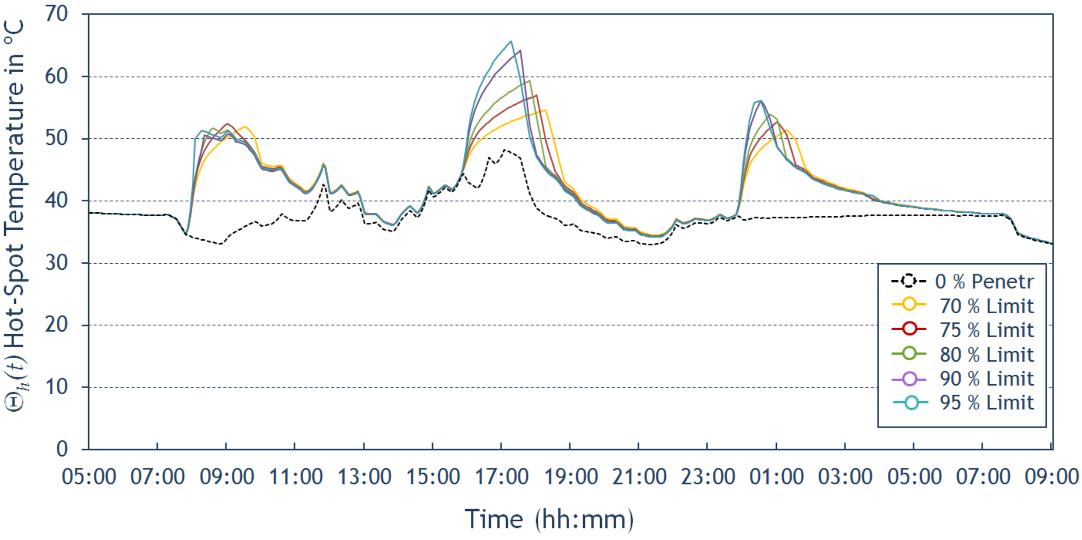

Figure 4.8 – Difference between the $\Theta_h$ at several scheduler pre-set limits at a 60% penetration.

Table 4.2 – The LOL reduction each time the $P_{sl}$ is set lower.

| $P_{sl}$ limits | LOL (t) | LOL % |
|---|---|---|
| 70% | 36.11 min | 0.0003 |
| 75% | 39.91 min | 0.0004 |
| 80% | 44.09 min | 0.0004 |
| 90% | 53.46 min | 0.0005 |
| 95% | 59.64 min | 0.0006 |

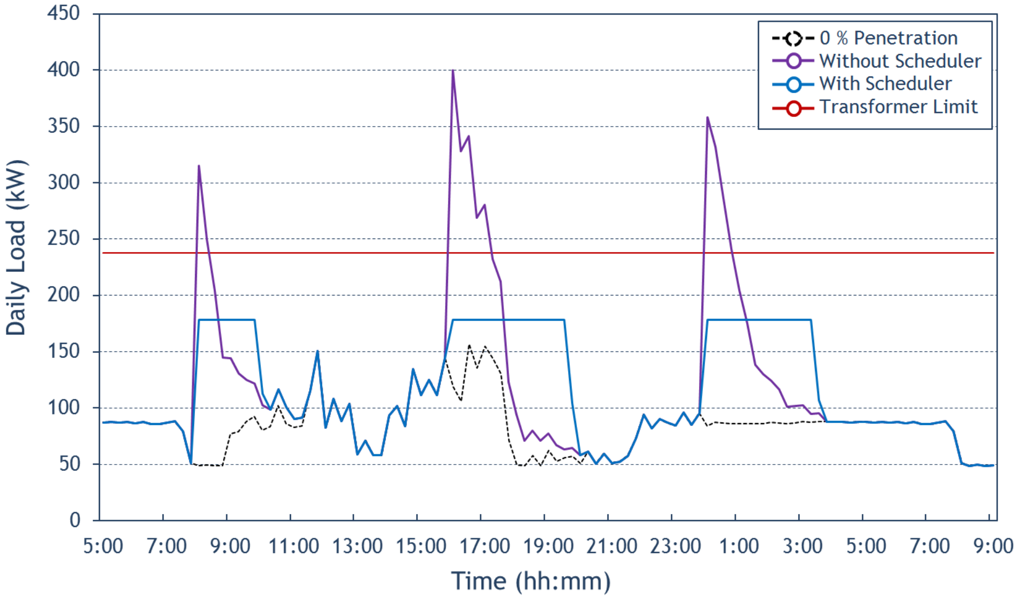

Figure 4.9 – Comparison of an extreme case with 100% EV Penetration with a scheduler at 75% limit or without it.

The results show that at an EV penetration ratio of 100% and a $P_{sl}$ of 75% the EVs are all charged before the working shift ends as it can be observed in Figure 4.9 for the daily load profile. Yet in this case is witnessed a large improvement of LOL, 76.76% of LOL of that day is saved. Such an outcome is presented in Figure 4.10.

### 4.2.2.2 Scenario 2

The second scenario consists in an unlikely event of all EVs being charged with fast charging mode at a 35% penetration. Just as in the previous scenario, it is assumed that the workers plug-in their EVs to charge at the beginning of each working shift. After the implementation of the new EV scheduler model a simulation was performed and results were obtained. A large improvement was verified of the $\Theta_h$ in comparison with the second scenario seen in Chapter 3. A comparison between the rescheduled charging of EVs at 35% penetration and non-scheduled charging can be seen in Figure 4.11. Figure 4.12 shows how much LOL was saved in relation with the scenario without the new EV charging scheduler through means of $\Theta_h$. As much as 98.08% of LOL was saved by using the EV charging scheduler. Even if using the fast changing mode the results demonstrate that the EVs are always charged until the end of each working shift, in actual fact considerably far from the end of each shift.

### 4.2.3 Critical Analysis

By deciding for the new EV charging scheduler the factory employees and personnel can always be assured that their personal EVs will be charged at the ending of each working shift under a plethora of circumstances. Such a solution also allows the charging of all the EVs without crossing the loading limit of the transformer and in the end the solution permits the saving of transformer’s useful life.

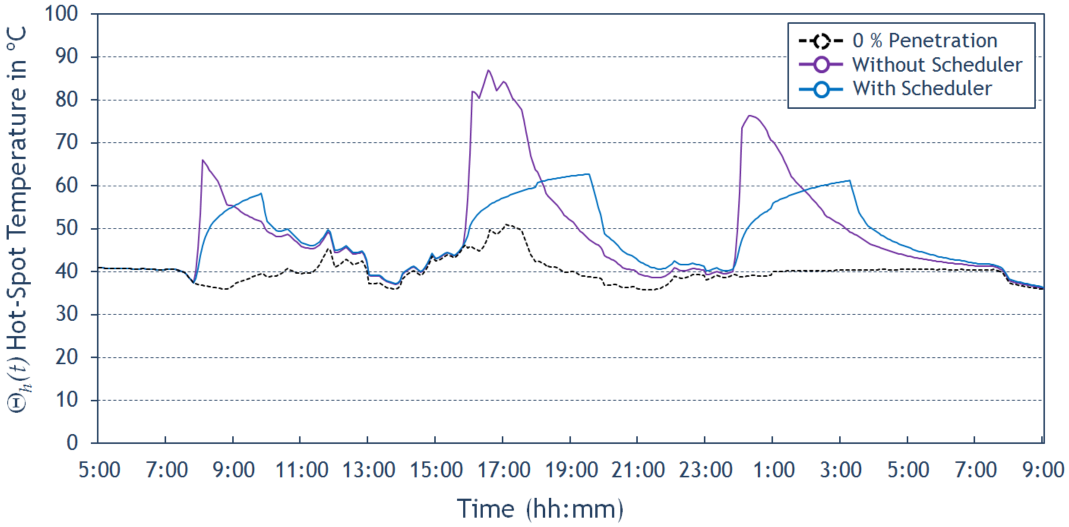

Figure 4.10 – Comparison of $\Theta_h$ of an extreme case with 100% EV Penetration with a scheduler at 75% limit or without it.

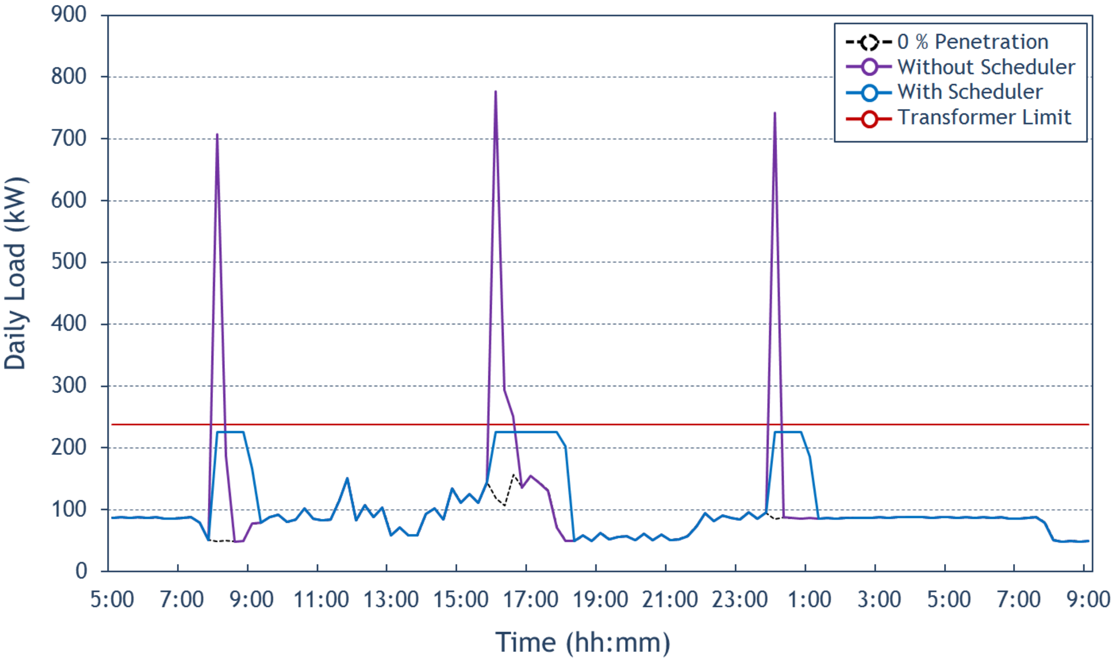

Figure 4.11 – Comparison in fast charging mode of an extreme case with 35% EV Penetration with a scheduler at 95% limit or without it.

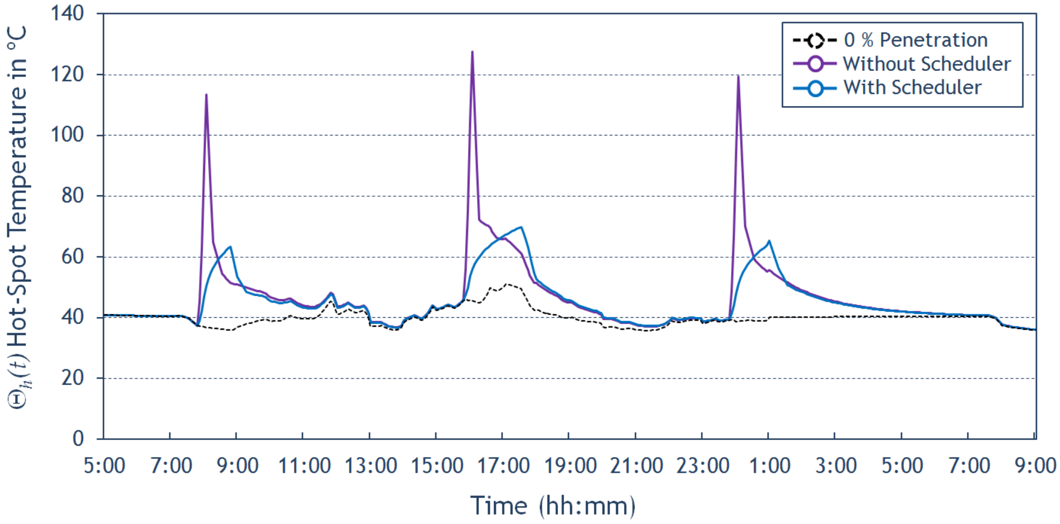

Figure 4.12 – Comparison in fast charging mode of $\Theta_h$ of an extreme case with 35% EV Penetration with a scheduler at 95% limit or without it.

## 4.3 Conclusion

In this chapter a case study of an overloading prevention of an industry client distribution transformer in an island in Portugal employing a new smart EV charging scheduler was proposed. At first, the model that assessed the additional power to restore the full level of EV battery SOC impact on the insulation ageing of a real distribution transformer at a private industry client was applied and described. Different charging scenarios with several penetration ratios were studied at three different working shifts. Since transformer insulation ageing is mainly influenced by the $\Theta_h$, a transformer thermal model was considered in estimating $\Theta_h$ for a specific load ratio. The main model inputs, including factory load, transformer parameters and four different vehicle parameters were taken from real data. Thermal ageing was then calculated and analysed. Given fact that the 250 kVA transformer has a significant capacity to be used for a side activity – this study showed that even though it has, it still can be overloaded after a certain increase of EV penetration. In face of the overload that the transformer suffers at the beginning of each working shift, a novel schedule solution was proposed which consists of a model that makes the evaluation of the influence of additional power to restore the full level of EV battery SOC on the insulation decay of a real distribution transformer, and then scheduled the charging of the EV in an optimal manner that turned possible to avoid the overloading of the studied transformer through the development of the new smart EV scheduler. Such a solution also allowed the charging of all the EVs without crossing the loading limit of the transformer and, in the end, the solution allowed saving of transformer's useful life, which is a very important contribution towards sustainability.

“Science knows only one commandment - contribute to science.”

*“A ciência só conhece um mandamento – contribuir para a ciência.”*

Bertolt Brecht

# Chapter 5

# Consideration of the Impacts of a Smart Neighbourhood Load on Transformer Ageing

Smart grid solutions with enabling technologies such as energy management systems (EMS) and smart meters promote the vision of smart households, which also allow for active demand side in the residential sector. These technologies enable the control of residential consumption, local small-scale generation and energy storage systems to respond to time-varying prices. However, shifting loads simultaneously to lower price periods is likely to put extra stress on distribution system assets such as distribution transformers. Especially, additional new types of loads/appliances such as electric vehicles (EVs) can introduce even more burden on the operation of these assets, which is an issue that needs special attention. Such extra stress can cause accelerated ageing of distribution system assets and significantly affect the reliability of the system. In this chapter, the impact of a smart neighbourhood load on distribution transformer ageing is investigated. The EMS of each household is designed to respond to prices and other signals emitted by the responsive load serving entity within the relevant demand response (DR) strategy. An optimisation framework based on mixed-integer linear programming (MILP) is presented in order to define the EMS structure. Then, the equivalent ageing of the distribution transformer is examined with a thermal model under different scenarios. The case studies that are presented indicate that the integration of EVs in residential premises may indeed cause accelerated ageing of the distribution transformers, while the need to investigate the efficiency of dynamic pricing mechanisms is rendered evident.

## 5.1 Introduction

The Distribution system (DS) that serves as the bridge between transmission system and end-user premises for electric energy transfer is considered as one of the most important points of a power system for the effective and efficient utilisation of electricity.

With the introduction of different kinds of electric loads on the market, the load shapes of end-user premises have started to change significantly, a fact that may lead to compelling circumstances for DS assets such as transformers, lines, etc.

As a new type of end-user appliance/load, electric vehicles (EVs) have recently gained more importance as the electrification of the transport sector, which traditionally is a major fossil fuel consumer, is promoted [332]. EVs differ from the traditional loads, in the sense that they may both consume and provide energy, posing challenges and offering opportunities that should be examined in detail [333], [334]. On the one hand, from the perspective of a load, the energy needs of EVs can reach the levels of new power plant installation requirements. For example, the recommended charging level of a Chevy Volt, a small sized EV, is 3.3 kW, which can even exceed the total installed power of many individual homes in an insular area [335]. On the other hand, EVs can also be employed as a system resource, especially during peak periods through the vehicle-to-home (V2H) and vehicle-to-grid (V2G) options [336], [337].

Apart from EVs, non-dispatchable distributed generation technologies such as photovoltaic systems (PV) and wind energy conversion systems increase the uncertainty in the daily operation of the DS. Herein, transformers, considered as core elements of DS, are given specific importance in industrial applications in order to increase the reliability of DS operation under high penetration levels of the aforementioned technologies in the DS. Transformers are significantly affected by operating conditions such as heavy loading and therefore it is important to evaluate the effects of possible extra loads that can have such impacts on transformer units. The transformer operating lifetime is normally declared by manufacturers under normal operating conditions. However, operating conditions beyond the nominal are likely to cause a decrement in the effective operating lifetime of a transformer unit, especially due to increased thermal load causing insulation ageing (which depends on winding temperature). Thus, it is important to maintain the transformer’s operating conditions within certain limits to ensure longer operation of this pivotal asset of DS. With this aim, “smart grid” solutions that are recently gaining increasing importance are likely to be applied in order to prolong the effective utilisation period of such assets.

The “smartification” grid has been considered to have a prominent position within the new concepts for operating the mature electric power grid in a more efficient and reliable way, that is also supported by high levels of investments from governments of both developed and developing countries. Within the smart grid concept, smart home structures together with smart home energy management systems (EMS) capable of controlling home size distributed energy production facilities, electric vehicle based storage/production options, and controllable new generation smart appliances have also been the specific topic of some research activities in the area of residential demand-side management [338] [339] [340] [341] [342] [343] [344].

Specifically considering smart solutions in the DS areas for the effective utilisation of transformers, the impact of EV charging on the distribution transformers was studied in [155]. Randomised plug-in time, random departure time, and battery charging characteristics as well as the control and optimisation of the EV charging were neglected and presented as the aim of future studies in [155].

Besides, [155] solely considered the impacts of EVs under several scenarios without taking into account any other end-user characteristics. Moreover, [155] neglected the V2G possibility that can raise issues in terms of the magnitude and the duration of transformer overloading. As an extension of the study presented in [155], Ref. [157] also considered the coordination of EV charging activities within a neighbourhood via home EMS, considering incentive based demand response (DR).

However, in [157] no issue related to the minimisation of individual home owner daily electric energy costs was taken into account. Besides, in [157] the V2G possibility is neglected. A method for describing the EV charging effects on overhead distribution transformers and a method for mitigating this impact through a transformer temperature-based smart charging algorithm provided to reduce transformer overloading was proposed in [117]. Moreover, this study neglected the individual home owner cost minimisation.

There are also other studies, not mentioned here, that have provided important insights on the area. However, none of them considered the impact of a time-varying DR scheme on the ageing of a distribution transformer serving a residential neighbourhood. Such considerations are important in order to investigate potential trade-offs between the benefits that emerge from rendering available dynamic tariffs to residential end-users and the inefficient utilisation of the DS infrastructure.

In this study, the impact of the operation of a neighbourhood of smart households contracted under a time-varying pricing scheme on the local distribution transformer ageing is studied, which has not yet been considered in the relevant literature. The investigation of this issue constitutes the major contribution of the chapter.

Furthermore, the effect of the possibility of EVs to cover a portion of the household load through V2H mode is analysed as well. The aim of the numerical simulations is to demonstrate that the integration of EVs may indeed accelerate the ageing of the distribution transformers and to investigate the efficiency of the dynamic pricing scheme.

The remainder of the chapter is organised as follows: in Section 5.2 the proposed methodology is developed. Then, in Section 5.3 a realistic test case is presented and the obtained results are thoroughly discussed. Finally, conclusions are drawn in Section 5.4.

# 5.2 Methodology

The schematic diagram of a transformer serving a neighbourhood composed of multiple smart households is depicted in Figure 5.1.

## 5.2.1 Minimisation of the Cost of Each Individual Household

The equations concerning the smart-household appliances are given below as part of the model of optimizing the cost for electricity usage for each smart household.

The objective of each household $h$ is to minimise the cost of buying energy from the grid. This is expressed by (5.1).

$$h \in H : Minimize Cost_h = \sum_t \left( P_{h,t}^{grid} \times \Delta\mathrm{T} \times \lambda_t^{buy} \right) \tag{5.1}$$

In (5.1), $P_{h,t}^{grid}$ is the power drawn from the grid (kW) from household $h$ in period $t$, $\Delta T$ is the duration of the optimisation interval ($h$) and $\lambda_t^{buy}$ (€/kWh) is the hourly varying price signal. The electricity price is assumed to be the same for all the houses fed by the transformer.

The power balance for each household is:

$$h \in H : P_{h,t}^{grid} + P_{h,t}^{PV,used} + P_{h,t}^{EV,used} + P_{h,t}^{ESS,used} = P_{h,t}^{in} + P_{h,t}^{EV,ch} + P_{h,t}^{ESS,ch}, \ \forall t \tag{5.2}$$

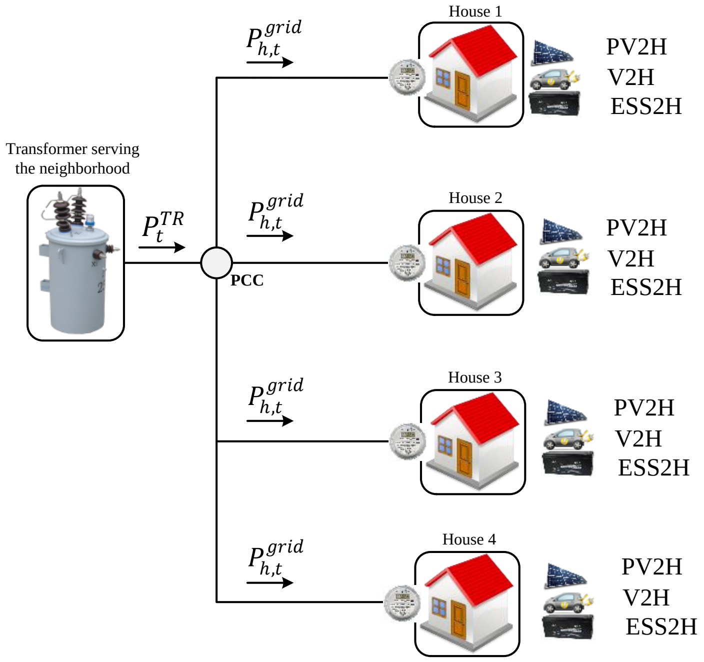

Figure 5.1 - The schematic diagram of a transformer serving a neighbourhood composed of 4 smart households.

The amount of energy consumed to cover the needs of each smart household includes the inelastic load used by all the appliances of the house ( $P_{h,t}^{in}$ ), the charging needs of the ESS of the household ( $P_{h,t}^{ESS,ch}$ ) and also the charging needs of the EV battery ( $P_{h,t}^{EV,ch}$ ). This total amount of electricity consumption is covered, for each household, either by power drawn from the grid through the distribution transformer ( $P_{h,t}^{grid}$ ), or by the power produced by the PV installation ( $P_{h,t}^{PV,used}$ ), or the power stored in the ESS ( $P_{h,t}^{ESS,used}$ ) and the EV ( $P_{h,t}^{EV,used}$ ).

The EV and ESS modelling includes the equations and constraints which have been presented and explained in detail in previous studies of the authors [335], [345]. These constraints are represented by the general expression (5.3) in which $\bar{x}_h$ is the vector of the decision variables pertaining the constraints of each household $h$, while $S_h$ is the set of feasible solutions.

$$h \in H : \bar{\boldsymbol{x}}_h \in S_h \; \forall t \tag{5.3}$$

The optimisation of the smart household is performed through Algorithm 5.1. The EMS of each smart household solves its own appliance scheduling problem in a decentralised fashion. Then, the transformer monitoring unit receives the information regarding the request of power by the neighbourhood and calculates the equivalent ageing.

# 5.3 Tests and Results

## 5.3.1 Input Data

The mathematical model of the smart households described above has been implemented in GAMS v.24.1.3. and was solved using the commercial solver CPLEX v.12. The utilised optimisation interval is 4 minutes (0.066h) and as a result there are 360 periods. The transformer ageing has been calculated following the procedure suggested in the IEC 60076-7 standard and the relevant code has been developed using MATLAB.

**Algorithm 5.1: Cost minimisation for all the households of the neighborhood**

```
5.1: $h \leftarrow 1$
5.2: $P_t^{TR} \leftarrow 0$
5.3: $for\, h = 1 : card(H)$
  Minimise (5.1)
  subject to (5.2)-(5.3)
  $P_t^{TR} \leftarrow P_t^{TR} + P_{h,t}^{grid}$
$end$
5.4: The power that the transformer has to serve is known ( $P_t^{TR,pro}$ ) together with the
individual cost and appliance scheduling of each household.
```

To demonstrate the proposed methodology, a sample neighbourhood consisting of 4 houses that are supplied by a 25kVA single phase pole mounted transformer as a local part of the distribution system is considered the parameters of which are presented in Table 5.1 [189].

It should be noted that the distribution system can use medium or low voltage regarding the consumer type and system configuration. There are also international and regional differences as regards system configurations used for power distribution.

The structure in Figure 5.1 considers a split phase low voltage distribution system which is typical in the US, Japan, Canada, etc. [346], [347].

The total inelastic load profile of the neighbourhood is portrayed in Figure 5.2. Furthermore, each household has a battery based ESS and a rooftop PV installation. Since the households are considered to be close to each other, a PV power curve normalised per 1kW of installed capacity, is used for all the houses, measured in the smart household prototype in Yildiz Technical University, during summer of 2013, assuming random small deviations that could be possibly caused by differences in the efficiency of the PV systems, for example, due to dirty PV panel surfaces etc.

The houses are assumed to host different kinds of consumers with different load profiles. These load profiles are created considering several typical domestic appliances the nominal power which is presented in Table 5.2 [348].

Table 5.1 - Transformer Parameters.

| **Symbol** | **Value** | **Units** |
|---|---|---|
| $g_r$ | 14.5 | Ws/K |
| $H$ | 1.4 | - |
| $k_{11}$ | 1 | - |
| $k_{21}$ | 1 | - |
| $k_{22}$ | 2 | - |
| $P_r$ | 25 | kW |
| $R$ | 8 | - |
| $x$ | 0.8 | - |
| $y$ | 1.6 | - |
| $\Delta\Theta_{o,r}$ | 20.3 | K |
| $\tau_o$ | 180 | min |
| $\tau_w$ | 10 | min |

Table 5.2 - Household Appliances Data.

| *Appliance* | *Rated Power [kW]* |
|---|---|
| Refrigerator | 1.67 |
| Iron | 2.4 |
| Toaster | 0.8 |
| Kettle | 2 |
| Hairdryer | 1.8 |
| Telephone | 0.005 |
| TV | 0.083 |
| Desktop Computer | 0.15 |
| Air Conditioner | 1.14 |
| Hair Straightener | 0.055 |
| Oven | 2.4 |
| Microwave | 1.2 |
| Printer | 0.011 |
| Cooker hood | 0.225 |
| Lighting | 0.1 |
| Other (fixed) | 0.1 |

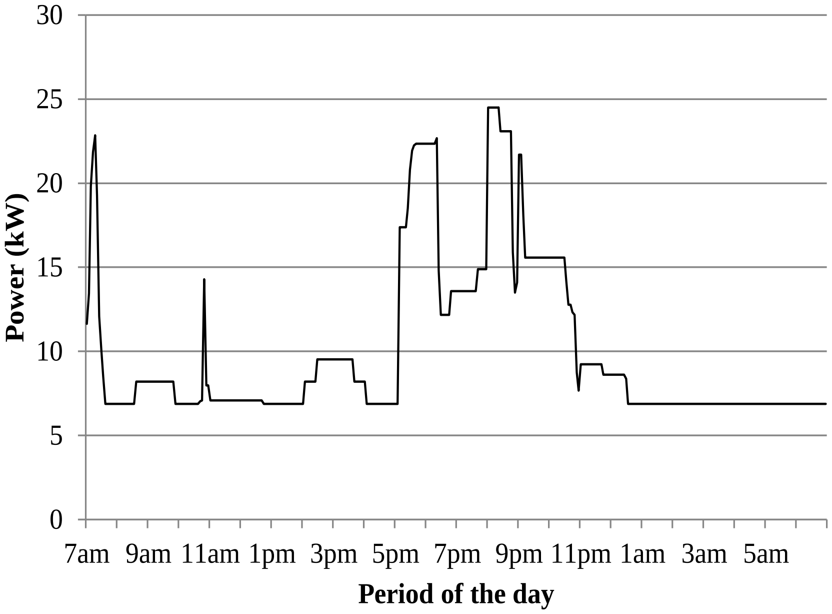

Figure 5.2 - Inelastic load of the neighbourhood.

The PV production for the 4 households is presented in Figure 5.3. Also, the recorded temperature for this day is portrayed in Figure 5.4.

There are already different types of EVs available on the market. Eight different EVs are considered in this study and the relevant EV data are provided in Table 5.3. Besides, three different cases are evaluated with respect to different EV type ownership for each household as presented in Table 5.4.

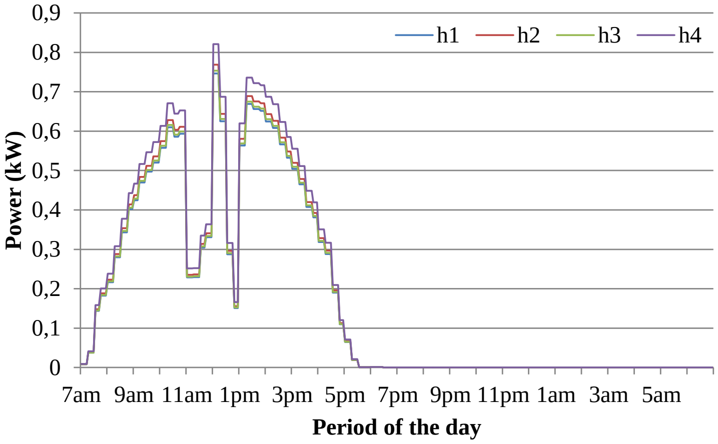

Figure 5.3 - PV power production of the households.

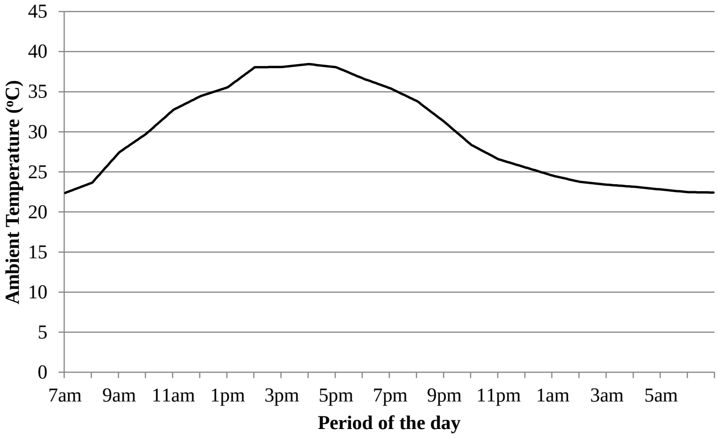

Figure 5.4 - Ambient Temperature.

Table 5.3 - EV Parameters.

| | Battery capacity [kWh] | Charging/discharging rate [kW] |
|---|---|---|
| **BMW i3** | 22 | 6.6 |
| **Chevy Volt** | 17 | 3.3 |
| **Ford Focus Electric** | 23 | 6.6 |
| **Mercedes B-Class** | 28 | 10 |
| **Kia Soul EV** | 27 | 6.6 |
| **Mitsubishi i-MIEV** | 16 | 3.3 |
| **Tesla Model-S** | 85 | 10 |
| **Volkswagen E-Golf** | 24 | 7.2 |

Data concerning the EV, the PV and the ESS of each household are presented in Table 5.5. These assets may be also used to partly or fully cover household energy needs through V2H, energy storage system to home (ESS2H) and PV to home (PV2H) options. The retailer announces a price signal for the 24h of the optimisation horizon as displayed in Figure 5.5.

Table 5.4 - Case Studies.

| | **Case-1** | **Case-2** | **Case-3** |
|---|---|---|---|
| **House 1** | No EV | Chevy Volt | Mercedes B-Class |
| **House 2** | No EV | BMW i3 | Kia Soul EV |
| **House 3** | No EV | Mitsubishi I-MİEV | Volkswagen E-Golf |
| **House 4** | No EV | Ford Focus Electric | Tesla Model-S |

Table 5.5 - Asset Data Of Each Household

| | **House 1** | **House 2** | **House 3** | **House 4** |
|---|---|---|---|---|
| | *Electric Vehicle* | | | |
| Charging/discharging efficiency [%] | 95 | | | |
| Arrival time | 5:08 pm | | | |
| | *PV Installation* | | | |
| Installed capacity [kW] | 1 | | | |
| | *Energy Storage System* | | | |
| Battery capacity [kWh] | 3 | 3 | 2.4 | 2.4 |
| Maximum Charging/Discharging rate [kW] | 0.6 | | | |
| Initial SOE [%] | 50 | 50 | 62.5 | 62.5 |
| Minimum SOE [%] | 25 | 25 | 41.6 | 41.6 |
| Charging/discharging efficiency [%] | 95 | | | |

## 5.3.2 Simulation Results

As mentioned before, in order to evaluate the impacts of incentive-based DR activities on transformer loading, three test cases considering different EV types are presented.

It is to be noted that another issue related to EVs that can be considered in the mentioned case studies, is the time and location based uncertainty of EV integration to distribution system, which is likely to pose a considerable challenge to the distribution system operator in the future together with the expected increase in EV penetration [349]. However, this study follows a deterministic framework in which the impacts of EV based uncertainty are not considered.

Case 1 does not consider EV availability and the relevant results are depicted in Figure 5.6. As it can be observed, no overloading occurs as no extra EV charging load exists. The PV and ESS partly cover the inelastic load of each household. As a result, a reduction in the transformer loading is noticed especially from 9 am to 5 pm during which the electricity prices are relatively high. Furthermore, before 9 am, the ESSs of the households are charging in order to be able to provide this power later, causing a peak to the transformer loading.

In Case 2 each household is considered to possess a relatively small-sized EV. The relevant results are depicted in Figure 5.7. Evidently, an excessive transformer loading occurs, reaching nearly 110% for several late-night periods, especially during the lowest price hours, even if the EV capacities are relatively low in this test case. Another point to be observed is that the inelastic load is partially covered by the V2H option of EVs during the periods after the arrival time of the EVs because of the higher prices the hold during these periods in comparison with the prices in later periods.

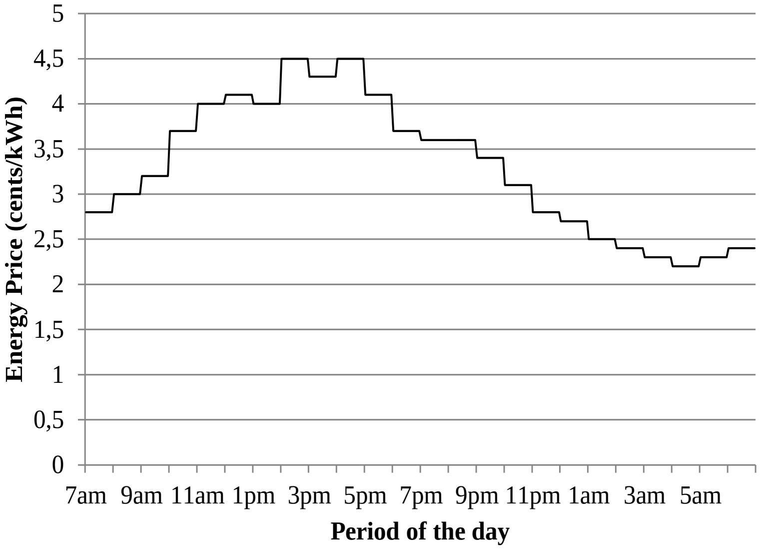

Figure 5.5 - Hourly energy price signal.

Case 3 results in the transformer loading shown in Figure 5.8. This test case is relatively worse in terms of EV capacities that have the capability of being charged with greater power levels than the EVs considered in Case 2.

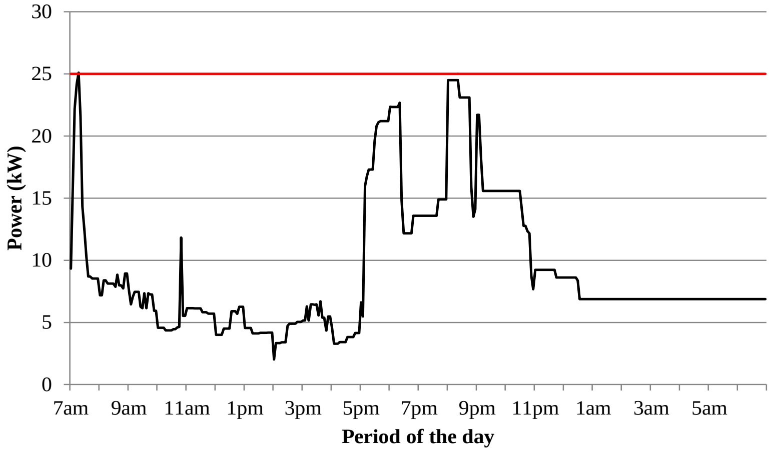

Figure 5.6 - Total transformer load for Case 1.

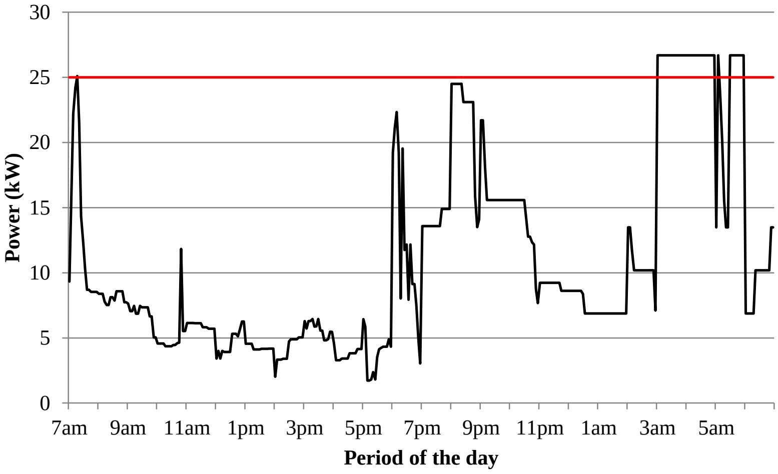

Figure 5.7 - Total transformer load for Case 2.

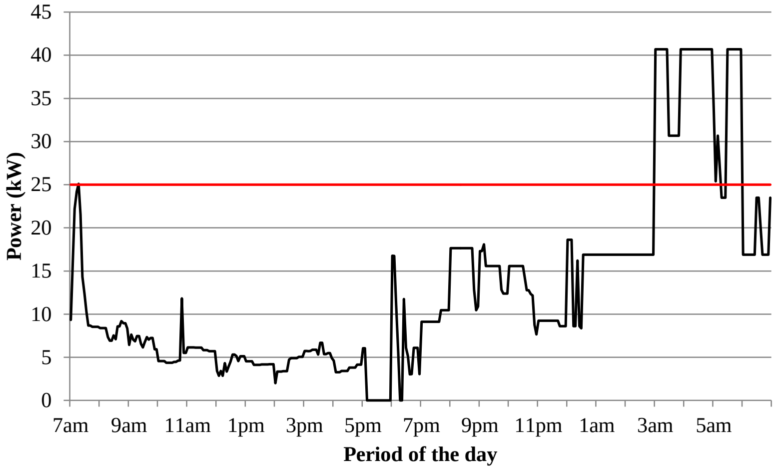

Figure 5.8 - Total transformer load for Case 3.

However, the greater the EV capacity is, the greater the opportunity of covering a more significant portion of the household power requirements by V2H option. This results in lower total transformer loading, especially in higher price periods during which using available EV energy to partly cover the household load and charge later is more profitable than procuring power from the grid. As expected, the capability of greater charging power levels leads to transformer overloading with longer duration and significantly higher levels (exceeding 160%) in comparison with Case 2. This is likely to accelerate the transformer unit ageing, a fact that should be examined further with the analysis of the transformer hot-spot temperature.

In this regard, the hot-spot temperature of the transformer for the three test cases is presented in Figures 5.9 – 5.11, respectively. Case 1 results in acceptable levels of temperature increase in the transformer unit while Case 2 and Case 3 boost the temperature variations due to the increasing requirement of charging power levels, especially due to the choice of EMS to charge the EV batteries after midnight due to the relatively lower prices during these periods. Even if each household owner benefits from such actions of their EMS in terms of total cost, the distribution transformer faces increasing stress that is very likely to cause more rapid ageing of the insulation.

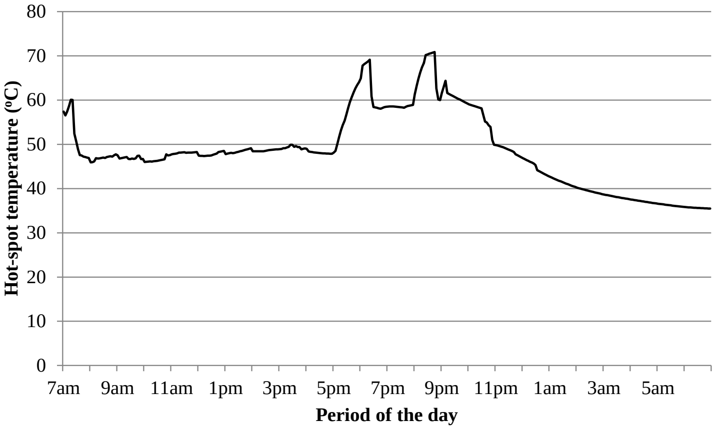

Figure 5.9 - Transformer hot-spot temperature for Case 1.

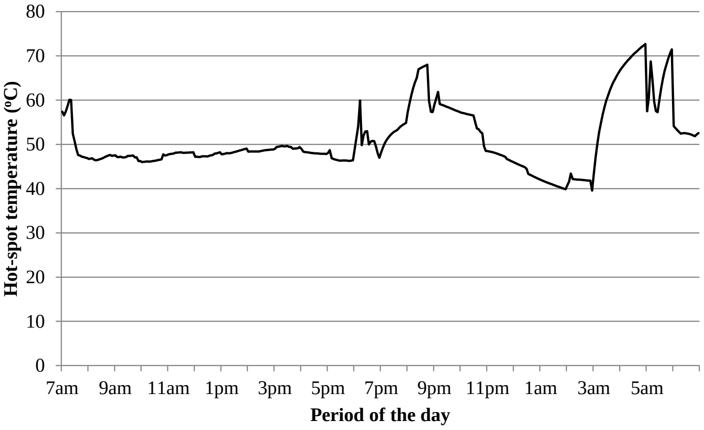

Figure 5.10 - Transformer hot-spot temperature for Case 2.

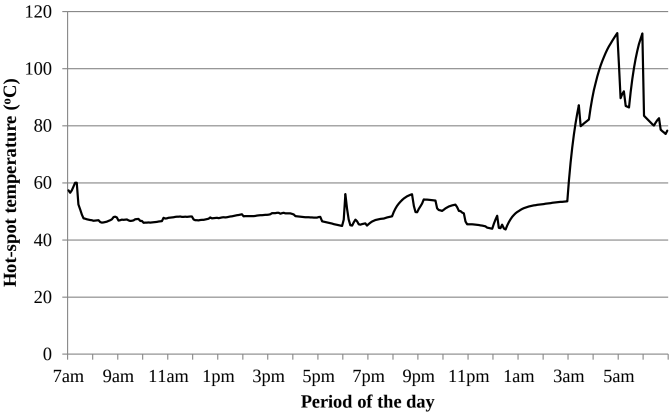

Figure 5.11 - Transformer hot-spot temperature for Case 3.

Table 5.6 - Asset Data of Each Household.

| Ageing in equivalent hours [h] | | |
|---|---|---|
| | With V2H option | Without V2H option |
| Case-1 | 1.68 | 1.68 |
| Case-2 | 2.23 | 2.05 |
| Case-3 | 67.84 | 16.77 |

Table 5.6 presents the relevant equivalent ageing for each test case. As expected, excessive power drawn from the grid through the transformer unit results in a significant increase in transformer ageing in Case 3 in comparison with Cases 1 and 2. It may be also observed that the increase in EV capacities results in an undesired decrease in transformer lifetime that is a main concern for the DS Operators, although it guarantees that EVs can cover longer travelling distances and as a result may promote the electrification of personal transport and the smart grid enabling technologies in general.

As a different analysis, the previous case studies are re-evaluated by considering that the V2H option of the EVs is not available. Normally, the availability of the V2H option allows for higher flexibility for the EMS of the end-user that may also decide to cover a part of the household load requirements from the EV, when the price of procuring power from the grid is high. However, this will in turn result in greater energy requirements to fully charge the EV battery in order to satisfy the comfort conditions of the EV owner, which means a greater peak in the total load of the transformer when the power procurement costs are lower, typically after midnight. Thus, the utilisation of the V2H option is very likely to have a more adverse effect on the loading and the thermal stress of the distribution transformer.

The results regarding the total transformer load and the transformer hot-spot temperature considering that V2H option is not available are presented in Figures 5.12 and 5.13 for Cases 2 and 3, respectively.

As Case 1 does not consider EV availability, the results that were previously depicted in Figures 5.6 and 5.9 do not change and thus are not repeated. It can be seen from the total transformer load for both cases that the observed power peaks are considerably lower and with shorter duration. This is caused by the fact that since no discharge is possible when the EV is at home, less amount of energy is required to charge the EV batteries.

The impact on reduction of power peaks also results in less increase in transformer hot-spot temperature as it can be observed in Figure 5.13. Thus, a significant reduction in the ageing of the transformer is observed as it can be seen in Table 5.6 for both the Cases 2 and 3 when the V2H option is not available. In fact, no ageing acceleration is noticed and therefore, the observed overloading may be considered acceptable.

Furthermore, the total energy procurement cost considering the availability of the V2H option is compared with the corresponding costs for the case in which the V2H option is not available and the relevant results are presented in Table 5.7. End-users benefit from the V2H option due to the possibility of utilizing the energy stored in the EV to cover portion of the household load during higher price periods.

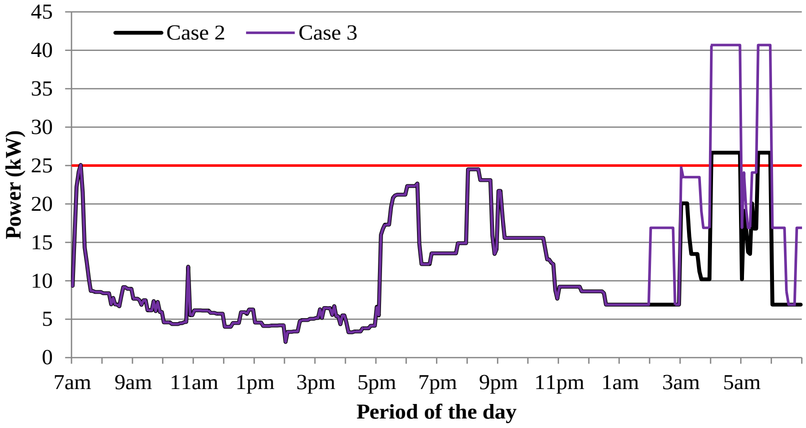

Figure 5.12 - Total transformer load for Cases 2 and 3 without V2H option.

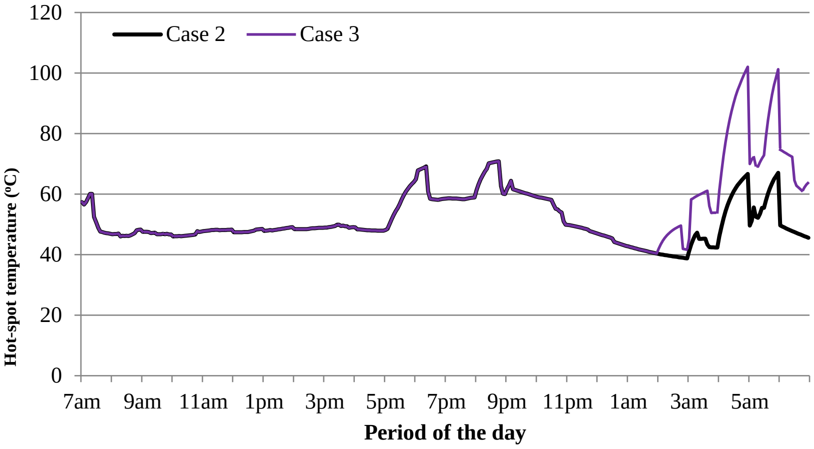

Figure 5.13 - Transformer hot-spot temperature for Cases 2 and 3 without V2H option.

Table 5.7 - Energy Procurement Cost Of Different Households.

| | **With V2H option** | | | | **Without V2H option** | | | |
|---|---|---|---|---|---|---|---|---|
| | **H1** | **H2** | **H3** | **H4** | **H1** | **H2** | **H3** | **H4** |
| **Case 1** | 1.83 | 1.83 | 1.83 | 1.80 | 1.83 | 1.83 | 1.83 | 1.80 |
| **Case 2** | 1.98 | 2.01 | 1.97 | 1.99 | 2.03 | 2.09 | 2.02 | 2.07 |
| **Case 3** | 2.06 | 2.06 | 2.03 | 2.65 | 2.16 | 2.15 | 2.11 | 2.83 |

This comparison indicates that even if the home owners can benefit from the V2H option and increased levels of smart grid enabling technologies, the DS may encounter detrimental results in terms of facing extra stress and ageing of assets, etc., which clearly depicts that the deployment of such new technologies in power system should be carefully planned in order to balance the benefits for both end-users and energy suppliers.

## 5.3.3 On the Efficiency of the Pricing Mechanism

In the pricing mechanism adopted in this study, it is considered that the price of electricity is different during each hour of the day and is known to the consumer before the actual day in which the consumption takes place. Through dynamic pricing consumers are directly exposed to the variability of the cost in the wholesale day-ahead energy market. Currently, two noticeable dynamic pricing programs engaging residential end-users exist in the U.S., one by Pennsylvania New Jersey Maryland Interconnection (PJM) [350] and one by the Midcontinent ISO (MISO) [351]. In both programs the day-ahead market prices are known to the consumer one day before the actual power delivery; however, the way in which they actually price the consumers differs. In the program offered by PJM, the end-users are priced according to the real-time prices that are settled in the end of each hour in the actual dispatch day and are calculated by averaging the 5-minute prices of that hour, while in the program offered by MISO consumers are priced according to the day-ahead prices. In this chapter, the pricing mechanism that is used is similar to the relevant MISO program.

Although dynamic pricing (e.g., real-time pricing) is generally considered to reflect the very short term cost of electricity, the efficiency of this pricing mechanism is often questioned mainly due to two reasons [352]: 1) residential end-users (that are the primary target group of such programs) do not necessarily follow a rational economical model as regards that consumption of electricity, i.e., a consumer may still be willing to consume electricity at peak hours, and 2) the asymmetry between the communication of the prices and the response of the end-user.

Evidently, the very short term costs of electricity are better captured by programs that price the end-user based on the prices produced by real-time markets that are cleared on a very short term basis (e.g. several minutes) rather than by those that price the end user according to the day-ahead market prices; This is the reason why the energy prices in this study, that follow the latter mechanism, do not reflect the power consumption peaks in the early morning hours due to the EV charging; however, the first type of dynamic pricing programs present the disadvantage of exposing consumers to uncertainty, since the electricity price is settled after the consumption interval.

As a result, this type of programs may compromise the incentives provided to the consumers in order to motivate them to enrol, since the rationale behind dynamic pricing is that consumers would exercise price arbitrage, which in turn depends on the differences of the prices within the day, which in this case would not be known a priori. In such cases, uncertainty management techniques would be necessary in order to predict the electricity prices, which may not be justifiable for residential consumers, in terms of complexity and computational burden, because the welfare gain of their participation in dynamic pricing schemes is little.

In order to confront the deficiencies of the pricing mechanism the following are suggested:

1. Development of advanced models that predict the response of the end-users based on exogenous factors such as the weather and the time delay between the communication of the energy prices and the actual response [30].
2. Development of residential consumption coordination strategies that consider distribution system constraints [345], [353] or the interaction of the transformer management unit and the EMS [354] together with dynamic pricing mechanisms.

## 5.3.4 Computational Statistics

The computational statistics of each optimisation sub-problem are provided in Table 5.8. The total solution time, considering an optimality gap of 0%, is 1 sec on a modern laptop computer (i7 at 2.4GHz, 4GB RAM, 64bit Windows).

Note that the separable form of Algorithm 5.1 allows for distributed computing techniques to be applied and as a result the privacy of the end-users is preserved.

As the computational capabilities of embedded systems that are needed to implement EMS and monitoring systems increase, it appears that such complex algorithms will be practically applicable even for large scale systems.

Table 5.8 - Computational Statistics.

| | |
|---|---|
| Equations | 4281 |
| Variables | 4017 |
| Discrete variables | 568 |

## 5.4 Conclusions

In this study, an analysis of the impacts of price-incentive based DR on a neighbourhood distribution transformer ageing has been performed. A MILP model of a neighbourhood composed of smart households with different end-user profiles was developed. The availability of a distributed generation unit, an ESS, and an EV considering also PV2H, ESS2H and V2H capabilities has been modelled. Furthermore, a thermal model of the transformer unit serving this neighbourhood for transformer ageing evaluation has been provided based on existing standards. The main contribution of the study was to combine the impacts of price-responsive residential end-users based DR schemes and relevant impacts on transformer ageing for different case studies based on different capacities of EVs. The availability of V2H option has also been discussed in the comparative analysis. The obtained results for different case studies demonstrated the significant adverse effects of extra EV loads combined with price-based DR activities, which strive to shift as much load as possible to low-price hours. The ageing of the transformer has shown a tremendous intensification with the increase in the capacity of the EV. Besides, the negative impacts of V2H option on the transformer unit extra loading and the relevant increase in ageing have also been comparatively demonstrated. Yet, V2H option availability provided more flexibility for EMS of each household to lower total prices by covering some portion of the household load from EVs. It can be concluded that while greater EV capacities and the availability of V2H option allowed residential end-user EMS to benefit more from price-incentive based DR schemes, these options may adversely affect DS reliability by stressing more DS assets. Thus, DR schemes can also be examined from such a perspective, that is, from DS Operator point of view.

“La liberté commence où l'ignorance finit.”

*"A liberdade começa onde a ignorância acaba."*

Victor Hugo

# Chapter 6

# Model Predictive Control Technique for Energy Optimisation in Residential Sector

Over the years the energy needs have increased dramatically and we have become aware that our needs were and are having implications on the environment in which we live. Increasingly people are aware to saving electricity by turning off the equipment that is not been used, or connect electrical loads just outside the on-peak hours. However, this few efforts are not enough to reduce the global energy consumption, which is increasing. Regarding the field of optimisation, researchers throughout the world have been making an effort in introducing better controls and both in industry and in homes for all types of loads from small lamps to large motors. Much of the reduction was due to mechanical improvements, however with the advancing of the years new types of control arise. All these factors are a motive for the work proposal in this chapter – introducing a new consumption reduction method in residential loads through the implementation of Model Predictive Control (MPC) analysed in two case studies where a single cost function is required to set the reference output near the goal, and consequently through the variation of this cost function by changing the weights, thus, specific control actions have priority over the remaining actions. Therefore, it is possible to have different goals during the day, thus it will be determined the possible savings for each appliance that can be made during off-peak, mid-peak, and on-peak by providing simulations upon 24 hours in the household.

## 6.1 Introduction

Genuine concerns regarding air pollution, climate change, and dependence on unstable and expensive supplies of fossil fuels have lead policy makers and researchers to search for alternatives to conventional petroleum-fuelled combustion power plants with the purpose to reduce greenhouse gas emission [355]. This leads to an urgent need to substitute them with alternate generating capacity or reduce the consumption during peak periods, or both.

One of the options for power generation is the use of renewable energy resources, which can inject power to the grid deprived of greenhouse gas emissions [356]. But, from the load point of view, the renewable energy resources capacity is not sufficient to supply all the required power. These points to the necessity of innovative methods, able to diminish energy consumption in different sectors, but also with the aim of reducing the domestic customer's total energy costs, greenhouse gas emissions and energy demand, especially during on-peak, while always considering the end user preferences [357]. Hence, in this chapter an analysis of the model predictive control (MPC) application in domestic appliances with the purpose of energy optimisation will be made.

In this context, the research theme is focused on the relation between MPC weighting adjustment and the minimisation of energy consumption. Three domestic loads are used for MPC tuning evaluation: water heater (WH), room temperature control by conditioner (AC) and refrigerator (RF).

Present high living standards offered by modern society have been achieved due to abundant energy to relatively low energy prices. This was possible to the large scale exploitation of high carbon coal power over the last decades. However to preserve our economic and social development model substantial changes have to be made to lower greenhouse gas emissions at world scale. The transition from high-carbon coal power to low-carbon electricity from natural gas and mostly on renewables is one solution. However, there are several challenges that inhibit for now, a complete transformation into 100% sustainable energy systems [85].

With increased demand for energy, alternative strategies have to be implemented at different levels of human activity not only at industrial sector to promote efficient use of energy but, also in the residential sector studies reported that it has been responsible for 31% of the worldwide energy needs which includes to a large extent domestic consumers [74]. This means that increasing number of electronics devices and appliances in the average home there are opportunities to obtain efficiency gains on energy usage and concerted actions can be developed to address energy saving in households. One way is introducing innovative tariff schemes based on demand response programs that help the consumer to change their energy consumption habits [358].

By lowering the peak demand, the utilisation of the available grid capacity is improved [79]. Other approach relies on updating control technology namely domestic appliances operated with regulation temperature.

In general, in a typical residential home, the appliances with higher electricity consumption provide heating and cooling services (AC, WH, and in a more reduced scale the RF). Numbers referred to UE-27 reveal that space heating for housing contributes around 70% for household electricity bill while domestic water heating stands at 10% [81].

Effective potential for energy savings as result of adopting efficiency energy measures can reach 30% [82]. In this sense, one of the ways to help reach the objective of reducing energy consumption is trough updating control technology that operates this class of operated domestic appliances. In fact heating and cooling equipment use a conventional ON-OFF device to regulate the temperature. Due to its simplicity and low manufacturing cost this solution has been the main choice by appliance brands for decades.

Alternative control methods have been researched to address energy rational utilisation of electric loads of appliances in a residential home such as residential energy monitoring and management based on fuzzy logic [84], artificial neural networks, PID control, model predictive control (MPC), among others [85].

MPC is a model-based controller concept design. It is defined as an optimal control algorithm that anticipates the future behaviour of control variables based on a process model that optimises the control signal [359]. It is capable to control nonlinearities and at the same time satisfying constraints of the system, it has been gained acceptance in different engineering branches [360]. MPC technique based applications for the residential sector are used with the purpose to decrease peak load, improve building thermal comfort and reduce energy costs [361]. Normally, is proposed for heating, ventilation, cooling and air conditioning (HVAC) systems in order to minimise energy cost beyond a mere reduction of the used energy [362]. Other implementation aims to apply a MPC based appliance scheduling for residential building energy management purposes [363]. In [364] a MPC strategy for energy efficient buildings with thermal storage is proposed.

The formulation of control objectives as a single cost function is required as a part of MPC controller design process. Satisfying all control objectives simultaneously is not feasible since normally specific control actions have priority over other actions. Therefore, performance trade-offs have to be made among the competing control objectives. For this purpose, weight factors are applied to the process input and output variables, thus, enabling individual performance prioritisation to perform the control under process constraints. Consequently, MPC uses different weights on tracking errors [365] and the control variables weight assignment is named MPC tuning.

A previous work regarding domestic loads energy optimisation showed that this type of controller can compete and overpass the thermostat performance by decreasing the energy cost in typical heating and cooling applications [366].

However, the MPC tuning feature that improves the controller performance regarding minimisation of the energy consumption is not explored. Hence, the objective of the research work in case study 1 is to provide insights about MPC weight tuning impact on domestic heating and cooling appliances in order to decrease energy usage and thus the energy bill.

Three domestic loads are used for MPC tuning evaluation: water heater (WH), room temperature control by air conditioner (AC) and refrigerator (RF). A previous work regarding this subject has showed that this type of controller can overpass the thermostat performance with a final lower energy usage cost [366]. In the second case study the objective of the research work is analyse the MPC weight tuning impact on domestic heating and cooling appliances in order to decrease energy usage and therefore the energy bill. Three domestic loads are utilised for MPC tuning evaluation: WH, room temperature control by AC controlled room's temperature and RF. The study follows the path initiated in previous works [366] [367] [368] since a comparison with the thermostat will be made.

The rest of the chapter is organised as follows: Section 6.2 discusses MPC theory followed by the physical models description of the domestic appliances to be simulated. Section 6.3 and 6.4 is dedicated to the case studies and their simulations results. Finally, Section 6.5 provides conclusion inferred from this work.

# 6.2 State of the Art

## 6.2.1 MPC controller design

The MPC is an optimisation tool to solve a series of control objectives. This means the optimisation process produces a sequence of optimal control actions over a finite horizon of future steps, driving the system output towards a known reference and at the same time satisfying system constraints and minimizing a specified performance criterion. MPC formulation in state-space presents several advantages as it facilitates multivariable system representation, analysis of closed-loop properties. Hence, the system to be controlled can be described by linear time-invariant (LTI) equations as a discrete-time state space model:

$$x(k+1) = Ax(k) + Bu(k) \tag{6.1}$$

$$y(k) = Cx(k) \tag{6.2}$$

where $x$ is the system state vector, $u$ is the input vector, $y$ is the output vector, $A$ is the state matrix, $B$ is the input matrix, $C$ is the output matrix.

Bearing in mind that at the current control interval $k$ the model state vector $x(k)$ is known. Then it becomes possible to calculate the new input control vector, to be fed into the system, and at the same time, having process constraints into consideration. For the time $k$ the MPC process predicts the plant output regarding the time $K+P$, where P refers to the number of samples to be estimated in the future - prediction horizon. On the other hand, a sequence of future control actions is also calculated as part of the optimisation process - control horizon. The number of steps ahead is defined by $N$.

Optimal control problem is solved by using a quadratic objective function known as quadratic program (QP). The optimisation cost function combines a set of performance index with regard to different control objectives which are:

$$J(z_k) = J_y(z_k) + J_u(z_k) + J_{\Delta u}(z_k) + J_\varepsilon(z_k) \tag{6.3}$$

where $z_k$ is the QP decision at each control interval, $J_y(z_k)$ minimises output reference tracking error, $J_u(z_k)$ refers to control signal tracking error, $J_{\Delta u}(z_k)$ is applied to regulate control signal increments and $J_\varepsilon(z_k)$ is related with constraint violations. QP decision $z_k$ takes the form as:

$$z_k^T = \left[ u(k|k)^T \; u(k+1|k)^T \ldots u(k+P-1|k)^T \right] \tag{6.4}$$

Assuming the number of process output variables is reduced to one, output reference tracking performance index is described as:

$$J_y(z_k) = \sum_{i=1}^{P} \left\{ \omega_i^y \left[ r(k+i|k) - y(k+i|k) \right] \right\}^2 \tag{6.5}$$

where $r(k+i|k)$ is the set-point signal, $y(k+i|k)$ is the controlled variable and an associated $w_i^y$ - a weighting coefficient that allocates more relevance to the term. $k$ is the current control interval and $k+i$ is the time instant related to the future state prediction.

Control objective related to control signal tracking is:

$$J_u(z_k) = \sum_{i=1}^{P} \left\{ \omega_i^u \left[ u(k+i|k) - u_t(k+i|k) \right] \right\}^2 \tag{6.6}$$

where $u(k+i|k)$ is the manipulate variable or control signal, $u_t(k+i|k)$ is the target for control signal and $w_i^u$ - a weighting coefficient for giving more importance to this term.

The third term in Equation (6.3) minimises abrupt changes between consecutives output control signals into small steps. This means a constraint is imposed on rate of change of control signal. Therefore the performance index is formulated as:

$$J_{\Delta u}(z_k) = \sum_{i=1}^{P} \left\{ \omega_i^{\Delta u} \left[ u(k+i|k) - u_k(k+i-1|k) \right] \right\}^2 \tag{6.7}$$

where $u_k(k+i-1|k)$ is a control signal from the previous control interval and $\omega^{\Delta u}$ a weighting coefficient that penalises changes in the $u_k$.

Finally, the fourth term is related with the constraint violation used for constraint softening and is as follows:

$$J_{\varepsilon}\left(z_k\right)=\rho_{\varepsilon}\,\varepsilon_k^2 \tag{6.8}$$

where $\rho_{\varepsilon}$ is a constraint violation penalty weight and $\varepsilon_k$ is a slack variable at control interval $k$.

A finite control horizon $M$ parameter establishes the number of parameters used to predict future control trajectory. This means given the state variable vector $x\left(k_i\right)$, the future state variables are evaluated for a number of samples $P$ called as the prediction horizon.

By applying $\omega_i^y$ with a higher value than $\omega_i^u$ leads the model output to closely follow the set-point signal. On contrary, if $\omega_i^y$ is reduced the difference from the reference tracking to the plant output will rise.

To stimulate the controller to use smaller increments on control signal the $\omega^{\Delta u}$ must be increased. Therefore, the cost function to be minimised has the following constraints specified as:

$$y_{min}\left(i\right)-\varepsilon_k V_{min}^{y}\left(i\right)\leq y\left(k+i\,|\,k\right)\leq y_{max}\left(i\right)+\varepsilon_k V_{max}^{y}\left(i\right), i=1:P \tag{6.9}$$

$$u_{min}\left(i\right)-\varepsilon_k V_{min}^{u}\left(i\right)\leq u\left(k+i-1\,|\,k\right)\leq u_{max}\left(i\right)+\varepsilon_k V_{max}^{u}\left(i\right), i=1:P \tag{6.10}$$

where $y_{min}$ and $y_{max}$ represents the lower and upper limit of process future outputs respectively. The parameters $V$ are dimensionless controller constants. With a very large $V_{min}$ and $V_{max}$ the constraints are easier to satisfy. The second equation in constraints (10), the $u_{min}$ and the $u_{max}$ are the lower and upper bounds for the control signal.

## 6.2.2 Household

Building material properties dictate thermal response and consequently its energy consumption behaviour. Thus, retention of warm/cold air in the house depends on thermal conductivity characteristics of the materials used on the floor, roof, windows and walls. As a whole, thermal performance is defined by the house geometry and the number of rooms.

In this study, three rooms are modelled, while only one is equipped with a temperature regulation system. Single room dynamic model takes into account the outside environment, $T_{out}$, and the thermal characteristics of the room. The AC power unit is represented as $Q_{ac\_ht}$ thermal source, while the heat to be extracted is represented as $Q_{in}$ thermal source.

Thermal equations are derived from [369] as:

$$\frac{dT_w}{dt}=\frac{Q_s}{C_w}+\frac{T_{out}}{R_wC_w}+\frac{T_{in}}{R_wC_w}-\frac{2T_w}{R_wC_w} \tag{6.11}$$

$$\frac{dT_{in}}{dt}=\frac{(Q_{in}-Q_{ac\_ht})S(t)}{C_{in}}-\frac{T_{in}}{C_{in}}\left(\frac{1}{R_w}+\frac{1}{R_c}\right)-\frac{T_w}{R_wC_{in}} \tag{6.12}$$

where $Q_{ac\_ht}$ is the thermal source due to AC, $Q_{in}$ is the heat to be removed from the room, $T_{out}$ is the ambient temperature, $T_{in}$ is the room's temperature, $T_w$ is the wall temperature, $C_w$ is the thermal capacitance of the wall, $R_w$ is the thermal resistance of the wall, $R_c$ is the thermal resistance of windows, $C_{in}$ is the thermal capacitance of the indoor air and $S(t)$ is a binary variable that emulate the turn-on and turn-off of the thermostat. The AC operation is a power switch block without internal loss.

## 6.2.3 Water heater

Physical description model of the WH takes into account the mass of water - $m$ and where $C_p$ is the water specific heat, $C_w$ is the thermal capacitance of the wall and $UA$ is the fibre glass characteristic, $Q_{eg}$ is the heating element electric rated power and $\eta$ the WH global efficiency. Energy transit equation for WT has the following expression [370]:

$$\frac{dT_w}{dt}=\frac{mC_p}{C_w}T_{in}+\frac{UA}{C_w}T_{out}-\frac{UA+mC_p}{C_w}+Q_{eg}\eta \tag{6.13}$$

## 6.2.3 Air Conditioner

The AC unit model is represented by an input-output power block that receives a certain amount of energy $Q_{out}$ (cooling capacity in terms of BTU) to remove heat $Q_{in}$ from the air inside the room. In the model, AC energy efficiency is equal to one.

# 6.3 Case Study 1

## 6.3.1 Testing Methodology

This section is dedicated to present the main results by adjusting different MPC weights and analyze its effects in order to minimise the energy consumption of the studied household appliances.

For the calculation of energy cost prices charged for the residential market in Canada are used during a 24-hour period. The daily electricity fee is classified in three levels of prices according to different demand periods: off-hours, mid-hours and on-peak hours.

The case studies are comprised of three electrical loads, namely heating and cooling. For each one of them it is measured the energy, the energy cost and temperature variation plotted as function of weight selection relative to the manipulated variable and process output as part of the cost function.

In this case a minor AC 2.61 kWh unit is used to lower the temperature in a residence in a room. The AC operation is externally operated by the MPC system, which includes a temperature sensing device. MPC control specifications are a temperature reference of 23ºC and with a +/- 1º tolerance band.

Such details signify that the control temperature interval is restricted between 22.5ºC and 23.5ºC. Data collection reports to the AC power consumption of the room, room temperature and outdoor temperature – depicted as a disturbance source of the system. An outdoor temperature profile is generated representing a typical summer day. Considerable thermal amplitude is introduced to function as a disturbance source in the temperature equation model of the room.

### 6.3.1.1 Household

A small AC 8900 BTU unit is utilised to lower the temperature in a residence in a room. The AC operation is externally operated by the MPC system, which includes a temperature sensing device. MPC control specifications are a temperature reference of 23ºC and with a +/- 1º tolerance band.

This means that the control temperature interval is restricted between 22.5ºC and 23.5ºC. Data collection reports to the AC power consumption of the room, room temperature and outdoor temperature – depicted as a disturbance source of the system. An outdoor temperature profile is generated representing a typical summer day. Considerable thermal amplitude is introduced to function as a disturbance source in the temperature equation model of the room.

### 6.3.1.2 Water Heater

The WH device has a use pattern related to the residents' daily hygiene since it functions as a hot water tank. Hence, it is expected that during the night the water is heated at a slower rate, while at peak-hour the temperature control system has to react quick enough to compensate the hot water output.

A rated resistive element of 4.5kW is used with the purpose to heat the water. The storage capacity is 184 L in terms of tank net volume.

MPC is initialised with a set point (SP) of 55 ºC with a +/-1.5 ºC band. WH outside air temperature is fixed at 23 ºC.

### 6.3.1.3 Refrigerator

Storing food at low temperature is nowadays common in every household. The RF performs this task using a classic temperature control based on a thermostatic relay. The main disturbance for changing the temperature settings inside of the RF is due to the door opening. That is, the number of times and the time it is kept open increases the temperature inside of the equipment. For simulation purpose the equipment is modelled with a rated power of 0.23kW.

The MPC system is configured to maintain the internal temperature between 3.9ºC and 5.1ºC. Disturbance events for MPC evaluation are generated at 10 pm for 1 hour and at 14 pm for an equal period. Figure 6.1 shows the disturbances sources for the all the 3 cases.

## 6.3.2 Simulation results

### 6.3.2.1 Air conditioner

The Figure 6.2 represents the energy profile with of the MPC operated AC. The different combination between weights leads only to limit values.

On the other hand, since there are three different tariffs during the same day, the objective is to try to lower the energy cost during ON peak hours, as the Figure 6.3 clearly shows that certain combination of weights benefits the home user by reducing the energy consumption in the studied 24 hours period. In Figure 6.4 is shown that the objective of maintaining the temperature between the limits if fulfilled.

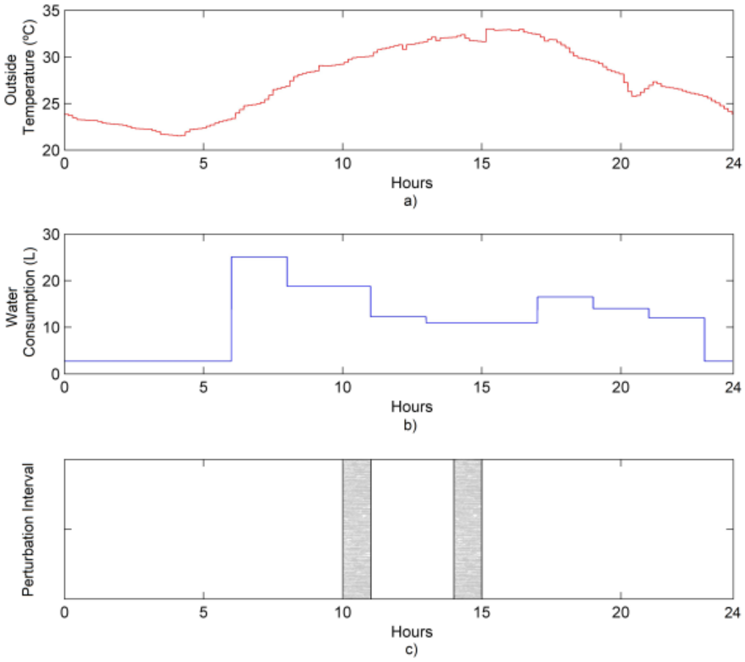

Figure 6.1 - Disturbances sources of a) outside temperature (AC), b) Water consumption (WH) and c) fridge open door event intervals.

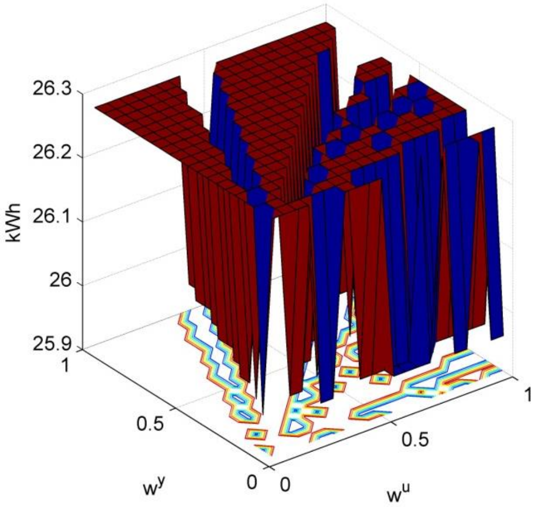

Figure 6.2 - AC: Energy output vs weights tuning.

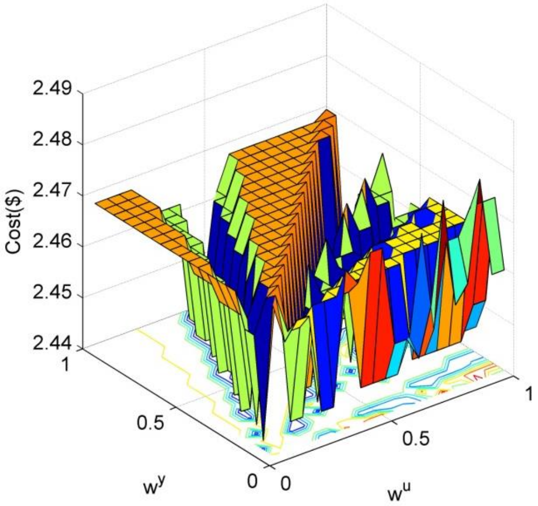

Figure 6.3 - AC: Energy cost vs weights tuning.

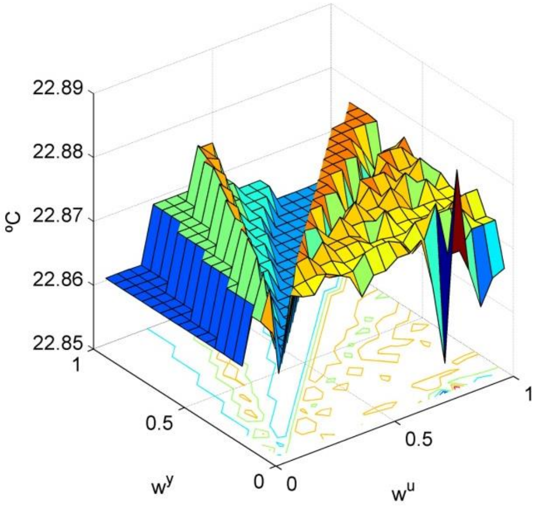

Figure 6.4 - AC: temperature vs weights tuning.

### 6.3.2.2 Water Heater

By observing Figure 6.5 it can be seen that there are four levels of energy consumption. For the lower level of energy consumption the combinations of weights requires that the model output weight tuning has to be calibrated with a reduced value while there are no limits for the manipulated variable weight tuning. In case of Figure 6.6 does not follow the energy profile since it reveals a peak in the cost of energy which is a result of the influence of the price tariff. Figure 6.7 shows that specification of the regulation is satisfied.

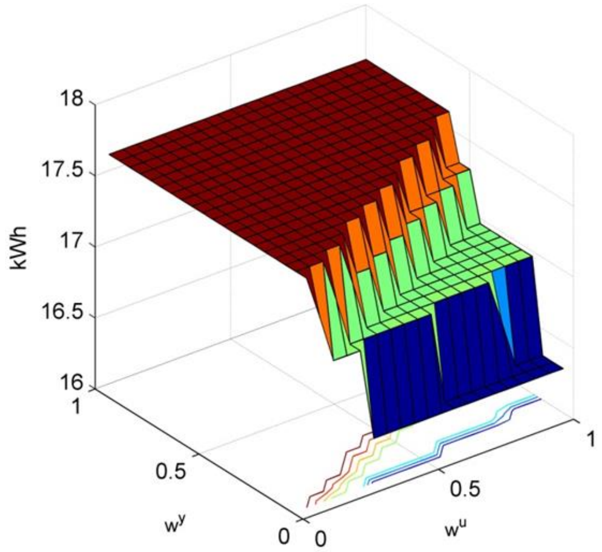

Figure 6.5 - WH: Energy output vs weights tuning.

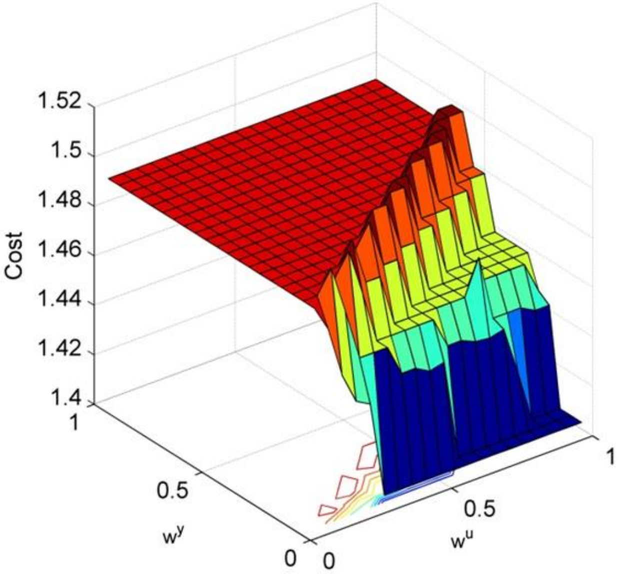

Figure 6.6 - WH: Energy cost vs weights tuning.

### 6.3.2.3 Refrigerator

Unlike the case studies verified previously, the simulation of Figure 6.8 points out that the minimum value of energy is reached with the weight of the system output null when only two weights are admissible on the side of the manipulated value. In Figure 6.9 is shown that the maximum value of the energy cost is coincident with maximum value of the energy output. In the previous cases the implementation of the MPC has shown that the specification limits are followed which does not happens in this case as can be seen in the Figure 6.10.

It becomes evident that in this case aiming the minimum of energy consumption has a penalizing effect in maintaining the temperature in the wanted regulated intervals.

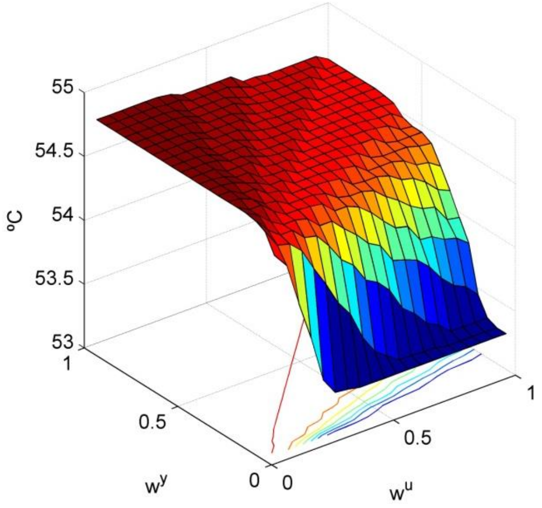

Figure 6.7 - WH: Water temperature vs weights tuning.

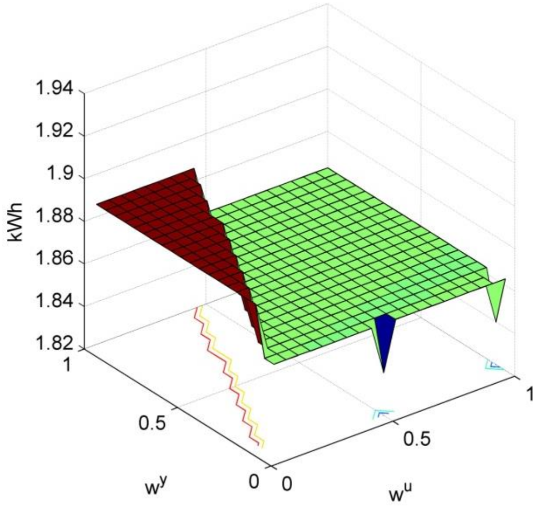

Figure 6.8 - Refrigerator: Energy output vs weights tuning.

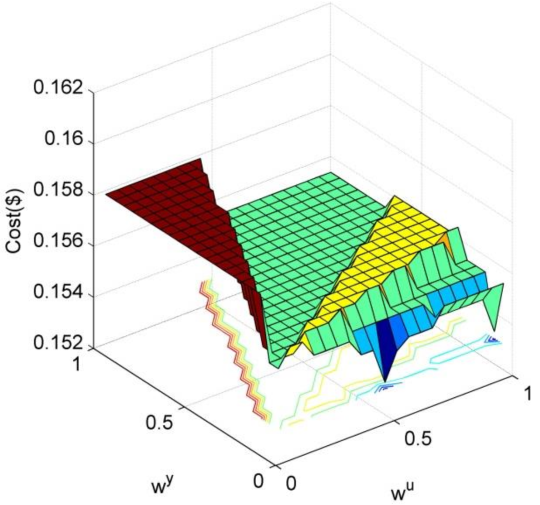

Figure 6.9 - Refrigerator: Energy cost vs weights tuning.

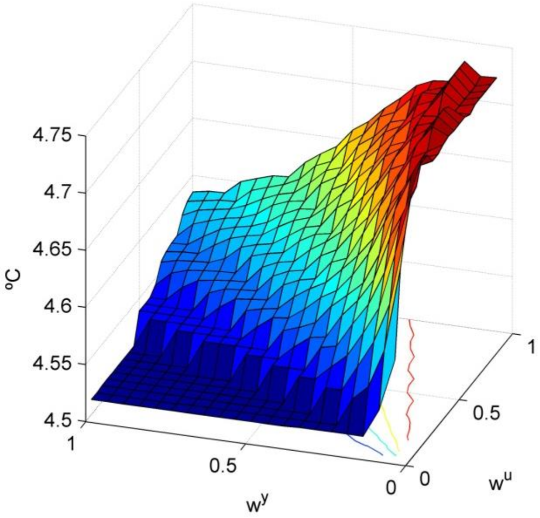

Figure 6.10 - Refrigerator: Inside temperature vs weights tuning.

### 6.3.3 Result Analysis

This chapter has focused on using MPC techniques as an alternative way of improving energy usage of residential households. Three domestic loads were simulated in order to observe the impact of adjusting MPC weights. The simulation outcomes have showed that each domestic appliance requires personalised weights tuning in order to reach the target to reduce at a minimum the energy consumption. On the other hand, it is proven that fact that having a multi-tariff system, the curve of the costs changes significantly when compared with the energy one. However, for the MPC weight tuning calculation it is sufficient to observe the energy curve. Nonetheless, in one of the cases the objective to minimise the energy consumption had a negative effect in maintaining the temperature in the required regulated intervals.

## 6.4 Case Study 2

### 6.4.1 Methodology

The testing framework consists of three domestic appliances commonly found in residences whose function is to provide heating and cooling services: WH, RF and AC.

This set of loads where chosen due to their energy intensive usage and consequently their significant contribution to home electricity bill.

The conventional thermostatic control serves as benchmark against the MPC. In this sense, the energy required to operate the appliances, the cost of using energy spread during off-peak, mid-peak, and on-peak along in conjunction with the temperature variation plotted as function of weight selection relative to the manipulated variable and process output as part of the cost function. For the calculation of energy cost prices charged for the residential market in Canada are used during a 24 hour period.

The MPC controller is explored with two different weighting sets in order to evaluate the impact on electric bill reduction goal. As the calculation time horizon, P control moves number is set to 4 and 12 is the set of N predicted outputs.

### 6.4.2 Case Studies

#### 6.4.2.1 Household

Room's *acclimatisation* is provided by AC system having a cooling capacity of 8900 BTUs (2.608kW). Heat exchange with the external environment through the external wall of the room, it is the main factor of disturbance to maintain the internal temperature in thermal comfort level desired. In order to test both control strategies, the rate of heat loss/generation through the external wall of the room is modelled using a temperature based time series with significant wide thermal amplitude variation upon 24 hours.

The TH device is configured with a setting of +/1° referred to a temperature of 23ºC. MPC cost function is instructed to limit the temperature variations on the same range. That is, between 22.5ºC and 23.5ºC. The values of physical parameters are extracted from [371]. The room's transient thermal model equations are represented by (6.11) and (6.12) [369].

#### 6.4.2.2 Water heater

The WH unit heats the water to be used on personal hygiene activities by the house habitants. Hot water consumption has a peak-hour at early on the morning and at evening before the sleeping period. Thus, temperature regulation system must maintain the water enough hot during those peak-periods.

The heating element inside of WH is rated at 4.5kW and 184 L is the reservoir size of the unit. TH set point (SP) is set to 55ºC with a hysteric range of +/-1.5 ºC. The same temperate fluctuation band is adopted for MPC configuration. WH external wall temperature is fixed at 23 ºC. The modelling of WH follows the equation presented in (6.13) [370].

#### 6.4.2.3 Refrigerator

The temperature of the interior is normally regulated by thermostatic relay. Opening the RF's door increases the energy consumption to recover the previous internal temperature setting. The thermal dynamic behaviour is approximated with the Equations 6.14 and Eq. 6.15. The conventional control is compared to MPC alternative considering a RF simulated with a power rating of 0.23kW (RF's compressor motor nominal power rating).

The MPC system is configured to maintain the internal temperature between 3.9ºC and 5.1ºC. Disturbing events are recreated with two door opening closing sequences, which are simulated at 10-11 pm and at 14-15pm respectively.

### 6.4.3 Results and Discussion

This section presents the main results by comparing two sets of MPC weights on controller performance versus the thermostatic relay response.

#### 6.4.3.1 Transient response characterisation of controllers

##### *Case 1: Air conditioner controlled residential building temperature*

The performance of the MPC technique is presented in Figure 6.11, where two different weights set are employed to tune the controller and compared to the thermostatic approach. Data shown refers to the AC energy consumption, room internal temperature and environment temperature.

As expected the room temperature when regulated by the thermostat shows a maximum and minimum deviation about the set-point, dictated by thermostatic hysteric characteristic. On the other hand, room temperature profile is more erratic with the AC unit actuated by a MPC type controller. By applying different weighting set to the MPC controller, it can be seen that one of MPC weight set overpass the higher limit of the temperature regulation range, although the deviation is very small. In terms of temperature variation the MPC shows lower amplitude.

##### *Case 2: Water heater*

In Figure 6.12 one of the MPC weight set clearly worse the MPC performance since the temperature evolution does not respect the input constraint. In fact, temperature constraint violation can surpass 1ºC. In another period of the day, the same weight set denotes again some visible deviation.

### *Case 3: Refrigerator*

The simulation in Figure 6.13 points out that the TH controller confines easily the successive disturbances impact, due to its hysteric nature. That is, in the first disturbance event which consists of opening the fridge's door several times in a short amount of time, the controller performs a sequence of opening and closing of the switch associated to the TH. As for the next disturbance with the door kept open for a longer time, the refrigerator consumes additional energy to overcome internal cold air loss.

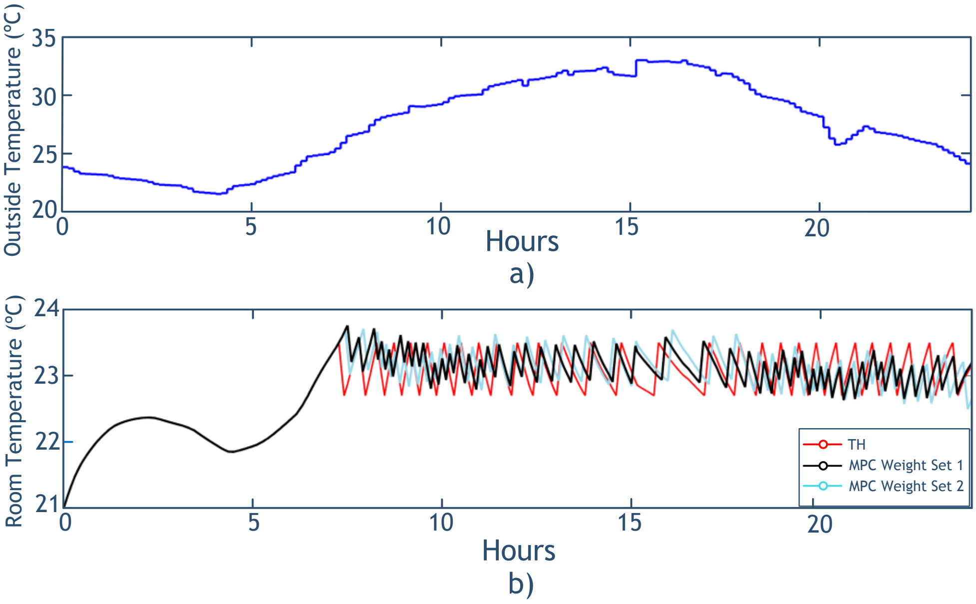

Figure 6.11 - Air conditioner operation: a) Ambient temperature b) TH and MPC responses.

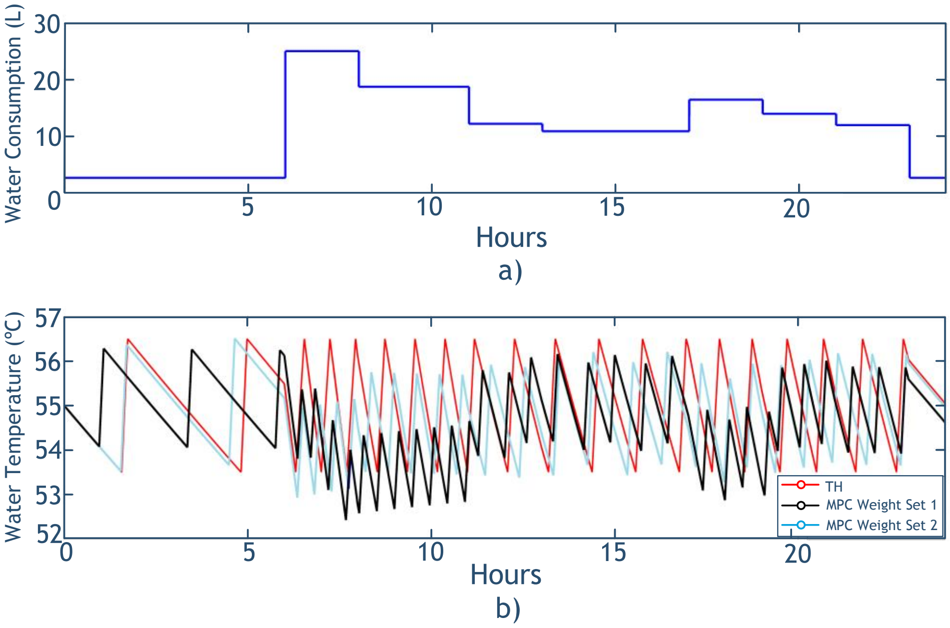

Figure 6.12 - Water heater operation: a) Water consumption b) TH and MPC responses.

In this simulation scenario both MPC weight sets lead to similar regulation responses. In addition, in both tuning sets when the second disturbance arrives, the performance response is insufficient, allowing the temperature rise observed in Figure 6.13.

### 6.4.3.2 Energy consumption and electric bill savings

Tables 6.1, 6.2 and 6.3 gather economic and electric nature data to characterise energy usage efficiency as function of the controller type employed. The energy costs associated to each time frame tariff of the day are also illustrated.

One can see at Table 6.1 and Table 6.2 that MPC weight set 2 enables higher energy consumption reduction in relation to MPC weight set 1, despite its poorer performance in regulating the temperature according to the output constraint. Consequently, the second controller tuning set presents the lowest energy bill. For these two domestic appliances, in both tuning sets loaded on the MPC controller, the cost of the energy consumed is lower than the appliance controlled TH.

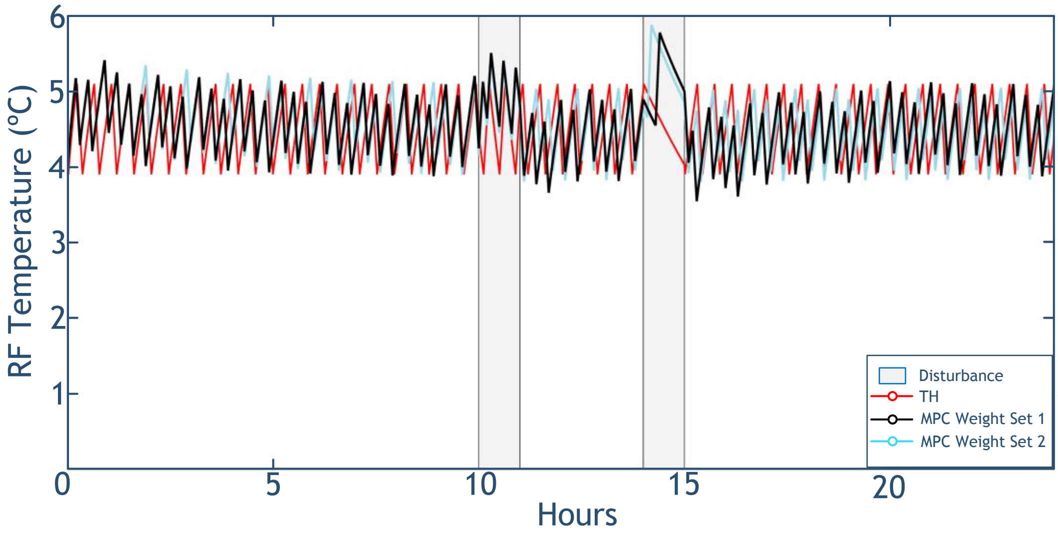

Figure 6.13 - Refrigerator operation: TH and MPC responses.

Table 6.1 - Air Conditioner.

| | **Thermostat** | | **MPC Weight Set 1** | | **MPC Weight Set 2** | |
|---|---|---|---|---|---|---|
| | ***Energy (kWh)*** | ***Cost ($)*** | ***Energy (kWh)*** | ***Cost ($)*** | ***Energy (kWh)*** | ***Cost ($)*** |
| **Off-Peak** | 5.005 | 0.310 | 5.065 | 0.314 | 5.012 | 0.311 |
| **Mid-Peak** | 8.417 | 0.774 | 8.546 | 0.786 | 8.441 | 0.777 |
| **On-Peak** | 12.934 | 1.397 | 12.661 | 1.367 | 12.661 | 1.367 |
| **Total** | 26.356 | 2.482 | 26.272 | 2.468 | 26.114 | 2.455 |

Since there are three distinct tariffs during the 24h time frame, the objective is to lower the energy cost during ON peak hours. This is true to AC and TH appliances.

On the other hand, the same tuning set 2 in the case of the refrigerator the electricity bill is slightly higher, as can be verified in Table 6.3. Anyway, the energy cost computed continues to be lower than the conventional solution based on TH control.

It is now evident that to minimise the energy consumption using a MPC scheme type, the controller parameters values choice must be selected through a tuning procedure to achieve a good performance. However to achieve this goal a penalizing effect may prevent to fulfil the constraint conditions.

Finally, in Figures 6.14, Fig. 6.15 and Fig. 6.16 total energy costs relationship to energy consumption profile are shown for each appliance. For AC and WH equipment electricity bill reduction is aligned with the energy consumption in a linear manner. On a contrary, for the refrigerator is not the case.

Table 6.2 – Water Heater.

| | **Thermostat** | | **MPC Weight Set 1** | | **MPC Weight Set 2** | |
|---|---|---|---|---|---|---|
| | ***Energy (kWh)*** | ***Cost ($)*** | ***Energy (kWh)*** | ***Cost ($)*** | ***Energy (kWh)*** | ***Cost ($)*** |
| **Off-Peak** | 5.919 | 0.367 | 6.278 | 0.389 | 6.480 | 0.402 |
| **Mid-Peak** | 6.740 | 0.620 | 6.975 | 0.642 | 6.480 | 0.596 |
| **On-Peak** | 4.939 | 0.533 | 4.185 | 0.452 | 4.320 | 0.467 |
| **Total** | 17.598 | 1.521 | 17.437 | 1.483 | 17.280 | 1.465 |

Table 6.3 – Refrigerator.

| | **Thermostat** | | **MPC Weight Set 1** | | **MPC Weight Set 2** | |
|---|---|---|---|---|---|---|
| | ***Energy (kWh)*** | ***Cost ($)*** | ***Energy (kWh)*** | ***Cost ($)*** | ***Energy (kWh)*** | ***Cost ($)*** |
| **Off-Peak** | 0.824 | 0.051 | 0.828 | 0.051 | 0.840 | 0.057 |
| **Mid-Peak** | 0.504 | 0.046 | 0.483 | 0.044 | 0.473 | 0.045 |
| **On-Peak** | 0.549 | 0.059 | 0.552 | 0.060 | 0.550 | 0.064 |
| **Total** | 1.878 | 0.157 | 1.863 | 0.155 | 1.863 | 0.156 |

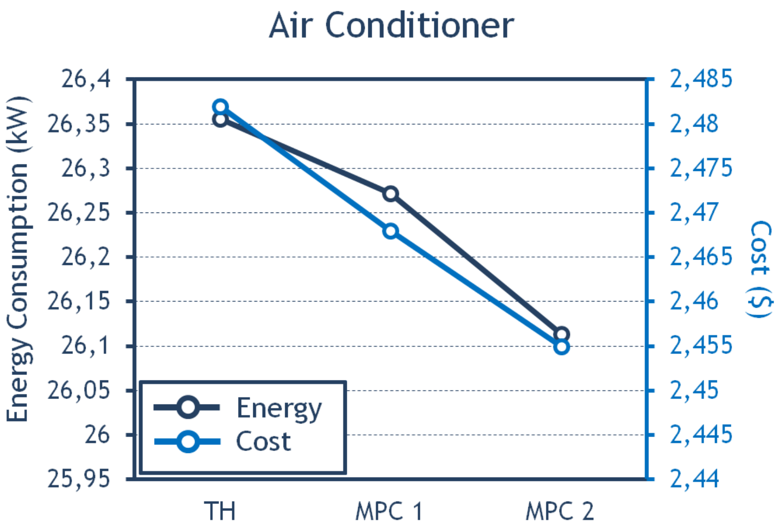

Figure 6.14 - AC: Energy consumption vs energy costs.

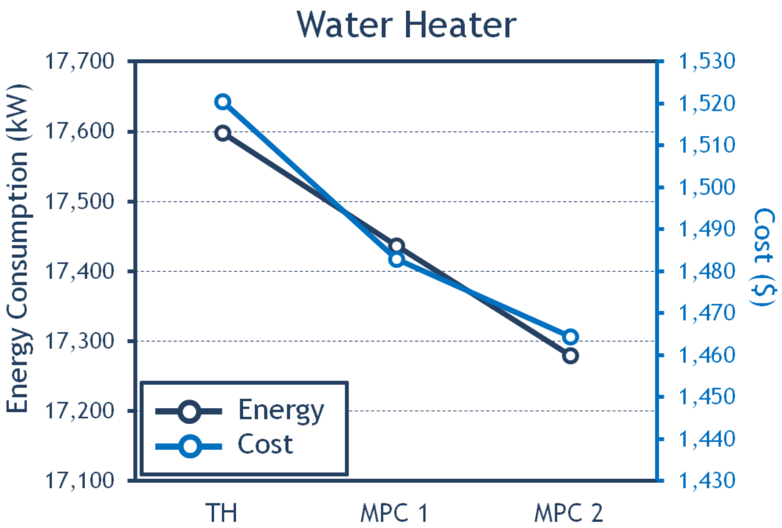

Figure 6.15 - WH: Energy consumption vs energy costs.

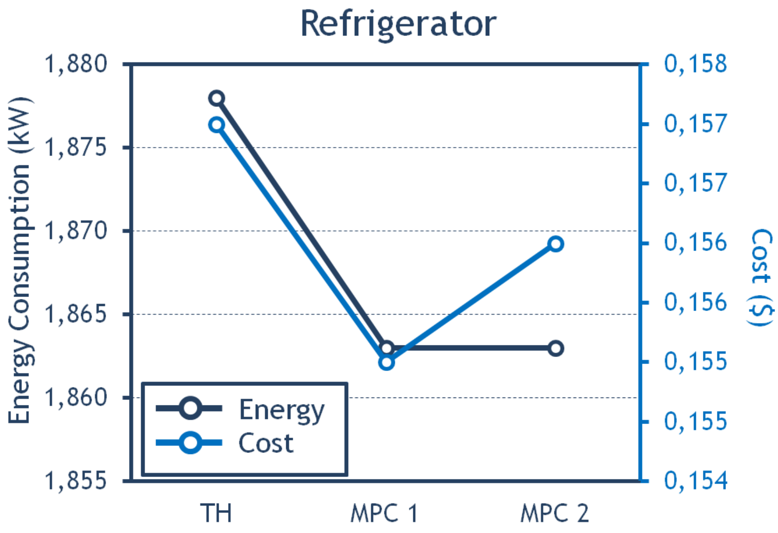

Figure 6.16 - RF: Energy consumption vs energy costs.

## 6.5 Conclusion

In this chapter a study was made concerning the adoption of an alternative control strategy in cooling and heating domestic equipment, normally the highest energy consumers in residential households. In this sense, MPC technique was investigated to assess its capability to improve energy consumption efficiency with the goal of reducing electric bill. In this context, the research theme focused on the relation between MPC weighting adjustment and the minimisation of energy consumption in the first case study. In the second one the MPC performance is further explored tuning the controller with two different weight sets and then compared to a thermostat control. Three typical domestic loads are used as case studies. The simulation outcomes from the first case study have shown that each domestic appliance requires personalised weights tuning in order to reach the target to reduce at a minimum the energy consumption. On the other hand, having a multi-tariff system the curve of the costs changes significantly when compared with the energy curve. The simulation results from the second case study made clear that there was reduction on the energy billed when the thermostatic regulation was replaced by the MPC. The evidence showed that the MPC weight set 2 enabled higher energy consumption reduction in relation to MPC weight set 1, despite its poorer performance in regulating the temperature according to the output constraint. In short, the MPC based thermal regulation had a positive impact of circa 2% on the energy bill reduction. However, the two MPC weight sets have proven that it is necessary to adjust the controller weights in order to maximise the potential of energy cost saving.

“No tengas miedo a la perfección, nunca la alcanzarás.”

*“Não tema a perfeição – pois nunca irá alcança-la.”*

Salvador Dalí

# Chapter 7

# Conclusions

In the following final chapter the main conclusions of the thesis are highlighted on the basis of answering the research questions that constituted the main motivation of the research portrayed in the thesis. Then, several points to guide future research are proposed. Finally, the publications of the author are listed.

## 7.1 Main Conclusions

The results presented in this thesis allow for answers to be given to the research questions that were initially posed in Section 1.6.

- Will the effect of EVs, domestic appliance loads and other key factors on oil-transformer ageing be significant? In order to address the upcoming challenges are the current available transformer protections adequate?

  Transformers are one of the more expensive elements of equipment found in a utility's inventory. The globalisation and the energetic business dynamics unceasingly pressure utilities to do more with less. Several factors, according to the literature, have an impact on the insulating paper and oil ageing, such as the EVs, harmonics, $\Theta_h$, DR, DG and experimental loads created explicitly to study the impact on the LOL of the transformer. Occasionally, overcurrent relays are intended to provide fault protection and also be responsible for some level of overload protection. In many cases, the overload occurrence of transformer operation is performed by Control Centre load dispatchers since this function is too complex for most simple overcurrent relays to successfully handle. Also, in order to keep a reliable protection, it is required to monitor the temperatures. This leads to an increasing need for tools to support not only transformer protection but the intelligent monitoring of their status, activities, and history – a challenge that could be taken by smart relays. Such types of relays are able to provide distinctive asset management functionality. This functionality comprises overload tracking with the temperature also known as adaptive overload, predictive overload early warning and automated load shedding based on temperature and/or current levels. Combined with the LOL estimation, the smart transformer relays deliver protection, monitoring and control for the transformer in one integrated solution. The basis of smart transformer relays is the capacity to model the transformer behaviour by a satisfactory process. Such kind of smart transformer relays allow a wide range of unique protection, monitoring and control devices in one integrated platform.

- Will power distribution transformers situated on islands, both residential and private, be capable to withstand increasing penetration of EVs?

  One of the most common elements that are found in distribution networks are the power distribution transformers with an oil-immersed core. An insular distribution network such as Azorean uses almost exclusively oil-immersed power distribution transformers – some of them upgraded very recently. In addition, power distribution transformers in their existing form are estimated to keep being operating for numerous years due to its great reliability and extensive use. The wide adoption of EVs is more challenging in comparison with the use of conventional and hybrid vehicles since the main energy source is electricity. Thus, the electric power systems are required to be qualified to take into account such new challenges and opportunities that are associated with the EVs recharging load. The impact of specific smart grid practices such as EV charging on power distribution transformers life and performance considerations must be evaluated in detail. Given the fact that the power distribution transformer insulation ageing is mainly affected by the $\Theta_h$, a power distribution transformer thermal dielectric oil deterioration model was utilised in this thesis to calculate the $\Theta_h$ given the load ratio. The developed methodology was applied to assess the impact of multiple EVs charging at a residential area and at work in a factory and it showed that off peak tariff can have an influence over EV users and affect the power distribution transformer lifetime. The study showed that at a certain EV penetration level, the combined charging of EVs can reduce the power distribution transformer LOL. Also, while charging at the workplace, the slow charging mode is recommended over the fast mode since the vehicles will always be 100% charged at the end of each working shift without drastically affecting the power distribution transformer lifetime.

- Can all employees' EVs completely recharge during their working shift at a factory while avoiding at the same time to overload the power distribution transformer?

  In this thesis a case study where a new smart EV charging scheduler was employed in order to prevent the overloading of an industry client power distribution transformer in an island in Portugal. The study showed that it is possible to completely recharge the EVs during their working shift at the factory, regardless of the penetration level. At first, the model that assessed the additional power to restore the full level of EV battery SOC impact on the insulation ageing of a real power distribution transformer at a private industry client was applied and described, and afterwards different charging scenarios with several penetration ratios were studied at three different working shifts making a total of 24 hours. Given the fact that the 250 kVA transformer has a significant capacity to be used for a side activity – this study showed that even though it has, it still can be overloaded after a certain increase of EV penetration. In face of the overload that the transformer suffers at the beginning of each working shift, a novel schedule solution was proposed which consists of a model that makes the evaluation of the influence of additional power to restore the full level of EV battery SOC on the insulation decay of a real power distribution transformer, and then scheduled the charging of the EV in an optimal manner that turned possible to avoid the overloading of the studied transformer through the development of the new smart EV scheduler. Such a solution also allowed the charging of all the EVs without crossing the loading limit of the transformer and, in the end, the solution allows saving of transformer's useful life, which is an important contribution towards sustainability.

- Based on different capacities of EVs will price-incentive based DR have any impact on a neighbourhood distribution transformer ageing?

  To verify this assumption, in the study performed in this thesis, an analysis of the impacts of price-incentive based DR on a neighbourhood distribution transformer ageing has been made. A MILP model of a neighbourhood composed of smart households with different end-user profiles was developed. The availability of a distributed generation unit, an ESS, and an EV considering also PV2H, ESS2H and V2H capabilities has been modelled. Additionally, a thermal model of the transformer unit serving this neighbourhood for transformer ageing evaluation has been provided based on existing standards. The main contribution was to combine the impacts of price-responsive residential end-users based DR schemes and relevant impacts on transformer ageing for different case studies based on different capacities of EVs. The availability of V2H option has also been discussed in the comparative analysis. The obtained results for different case studies demonstrated the significant adverse effects of extra EV loads combined with price-based DR activities, which strive to shift as much load as possible to low-price hours. The ageing of the transformer has shown a tremendous intensification with the increase in the capacity of the EV. Besides, the negative impacts of V2H option on the transformer unit extra loading and the relevant increase in ageing have also been comparatively demonstrated. Yet, V2H option availability provided more flexibility for EMS of each household to lower total prices by covering some portion of the household load from EVs. Thus, in this study it was shown that while greater EV capacities and the availability of V2H option allowed residential end-user EMS to benefit more from price-incentive based DR schemes, such options could adversely affect DS reliability by stressing more DS assets. Thus, DR schemes can also be examined from such a perspective, that is, from DS Operator point of view.

- Does an alternative control strategy in cooling and heating domestic equipment have the capability to improve energy consumption efficiency with the goal of reducing electric bill?

  In this thesis a study was presented concerning the adoption of an alternative control strategy in cooling and heating domestic equipment, normally the highest energy consumers at residential households. The daily electricity fee was classified in three levels of prices according to different demand periods: off-hours, mid-hours and on-peak hours. For the aforementioned purpose, a MPC technique was investigated to assess its capability to improve energy consumption efficiency while also bearing in mind the goal of reducing the electric bill. The MPC performance was further explored through tuning the controller with two different weight sets and compared to a thermostat control. Three typical domestic loads were used as case studies. The simulation outcomes have showed that each domestic appliance requires personalised weights tuning in order to reach the target to reduce at a minimum of energy consumption. Also, the simulation results noticeably showed that there is a tangible reduction on the billed energy when the thermostatic regulation was replaced by the MPC.

## 7.2 Recommendations for Future Work

The following points may be further studied in order to broaden the understanding of the topics treated in this thesis:

- Similar to Chapter 2 of this thesis a comprehensive review of literature can be made regarding the smart transformer and smart relay topics.

- An opportunity of research could be to supply a portion of power consumption of the factory from 3rd and 4th Chapters case studies from the available energy in EV batteries via V2H mode.

- The addition of a local power generation to the factory from 3rd and 4th Chapters case study could be researched, namely the effect of the local power generation in mitigating the power demand of the EVs.

- In a more detailed form the scheduling of the charging of the EVs can be additionally explored. As they are parked on the plant for 8-hours, an opportunity rises to apply several algorithms to determine the charging requirements for each vehicle and scheduling the charging accordingly.

- Finally, a two-side optimisation approach to investigate the appropriate balance between end-user benefits and DS operational considerations could be provided. Besides, the implementation of the proposed structure to study a greater part of the distribution system could be further studied.

## 7.3 Bibliography of the Author

In the following section various publications are displayed in peer-reviewed journals, book chapters and conference proceedings resulting from the research work carried out for this thesis and related research topics.

### 7.3.1 Articles in Journals

• **R. Godina**, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, "Smart electric vehicle charging scheduler for overloading prevention of an industry client power distribution transformer", *Applied Energy* (**ELSEVIER**), Vol. 178, pp. 29-42, September 2016. (Impact Factor of **5.746**, **Q1** Quartile)

• **R. Godina,** E.M.G. Rodrigues, N.G. Paterakis, O. Erdinc, J.P.S. Catalão, "Innovative Impact Assessment of Electric Vehicles Charging Loads on Distribution Transformers using Real Data", *Energy Conversion and Management* (**ELSEVIER**), Vol. 120, pp. 206-216, July 2016. (Impact Factor of **4.801**, **Q1** Quartile)

• E.M.G. Rodrigues, **R. Godina**, J.P.S. Catalão, "Electrochemical Batteries for Balancing the Grid with Renewable Energy Supply: A Novel Comprehensive Study of Two Real Insular Systems", *Applied Energy* (**ELSEVIER**), *submitted.* (Impact Factor of **5.613**, **Q1** Quartile)

• T.D.P. Mendes, E.M.G. Rodrigues, **R. Godina**, J.C.O. Matias, J.P.S. Catalão, "Wireless Wattmeter Development for Integration in Home Energy Management Systems", *Energy Conversion and Management* (**ELSEVIER**), *submitted.* (Impact Factor of **4.380**, **Q1** Quartile)

• N.G. Paterakis, I.N. Pappi, O. Erdinc, **R. Godina**, E.M.G. Rodrigues, J.P.S. Catalão, "Consideration of the impacts of a smart neighborhood load on transformer aging", *IEEE Transactions on Smart Grid*, *in press*, 2016. (Impact Factor of **4.252**, **Q1** Quartile)

• E.M.G. Rodrigues, G.J. Osório, **R. Godina**, A.W. Bizuayehu, J.M. Lujano-Rojas, J.P.S. Catalão, "Grid code reinforcements for deeper renewable generation in insular energy systems", *Renewable and Sustainable Energy Reviews* (**ELSEVIER**), Vol. 53, pp. 163-177, January 2016. (Impact Factor of **5.901**, **Q1** Quartile)

- **R. Godina**, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, "Effect of loads and other key factors on oil-transformers ageing: sustainability benefits and challenges", *Energies*, Vol. 8, No. 10, pp. 12147-12186, October 2015. (Impact Factor of **2.072**, **Q2** Quartile)

- E.M.G. Rodrigues, G.J. Osório, **R. Godina**, A.W. Bizuayehu, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "Modelling and sizing of NaS (sodium sulfur) battery energy storage system for extending wind power performance in Crete island", *Energy* (**ELSEVIER**), Vol. 90, pp. 1606-1617, October 2015. (Impact Factor of **4.844**, **Q1** Quartile)

- T.D.P. Mendes, **R. Godina**, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, "Smart home communication technologies and applications: wireless protocol assessment for home area networks resources", *Energies*, Vol. 8, No. 7, pp. 7279-7311, July 2015. (Impact Factor of **2.072, Q2** Quartile)

- E.M.G. Rodrigues, **R. Godina**, S.F. Santos, A.W. Bizuayehu, J. Contreras, J.P.S. Catalão, "Energy storage systems supporting increased penetration of renewables in islanded systems", *Energy* (**ELSEVIER**), Vol. 75, pp. 265-280, October 2014. (Impact Factor of **4.844**, **Q1** Quartile)

### 7.3.2 Book Chapters

- E.M.G. Rodrigues, **R. Godina**, T.D.P. Mendes, J.C.O. Matias, J.P.S. Catalão, "Influence of large renewable energy integration on insular grid code compliance", in: *Technological Innovation for Cloud-based Engineering Systems*, Eds. L.M. Camarinha-Matos et al., DoCEIS 2015, IFIP AICT 450, **SPRINGER**, Heidelberg, Germany, pp. 296-308, April 2015.

- E.M.G. Rodrigues, T. Caramelo, T.D.P. Mendes, **R. Godina**, J.P.S. Catalão, "Experimental wireless wattmeter for home energy management systems", in: *Technological Innovation for Cloud-based Engineering Systems*, Eds. L.M. Camarinha-Matos et al., DoCEIS 2015, IFIP AICT 450, **SPRINGER**, Heidelberg, Germany, pp. 327-336, April 2015.

### 7.3.3 Articles in Conference Proceedings

- **R. Godina**, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, "EV Charging Scheduler for Overloading Prevention of a Distribution Transformer Supplying a Factory", submitted in: *Proceedings of the IEEE International Universities Power Engineering Conference - UPEC 2016*, Coimbra, Portugal, September 6-9, 2016.

- **R. Godina**, E.M.G. Rodrigues, D. Oliveira, J.P.S. Catalão, E. Pouresmaeil, "Model Predictive Control Technique for Energy Optimization in Residential Sector", submitted in: *Proceedings of the IEEE International Universities Power Engineering Conference - UPEC 2016*, Coimbra, Portugal, September 6-9, 2016.

- **R. Godina**, E.M.G. Rodrigues, M. Shafie-khah, J.C.O. Matias, J.P.S. Catalão, "Overloading Analysis of an Industrial Client Distribution Transformer in a Portuguese Island", in: *Proceedings of the IEEE EnergyCon 2016 Conference*, Leuven, Belgium, April 4-8, 2016.

- M. Shafie-khah, M.H. Shoreh, P. Siano, D.Z. Fitiwi, **R. Godina**, G.J. Osório, J. Lujano-Rojas, J.P.S. Catalão, "Optimal demand response programs for improving the efficiency of day-ahead electricity markets using a multi attribute decision making approach", in: *Proceedings of the IEEE EnergyCon 2016 Conference*, Leuven, Belgium, April 4-8, 2016.

- **R. Godina**, N.G. Paterakis, O. Erdinc, E.M.G. Rodrigues, J.P.S. Catalão, "Impact of EV charging-at-work on an industrial client distribution transformer in a Portuguese island", in: *Proceedings of the 25th Australasian Universities Power Engineering Conference — AUPEC* 2015 (technically co-sponsored by **IEEE**), Wollongong, Australia, 27-30 September, 2015.

- D. Oliveira, E.M.G. Rodrigues, **R. Godina**, T.D.P. Mendes, J.P.S. Catalão, E. Pouresmaeil, "MPC weights tuning role on the energy optimization in residential appliances", in: *Proceedings of the 25th Australasian Universities Power Engineering Conference — AUPEC* 2015 (technically co-sponsored by **IEEE**), Wollongong, Australia, 27-30 September, 2015.

- E.M.G. Rodrigues, **R. Godina**, G.J. Osório, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "Comparison of battery models for energy storage applications on insular grids", in: *Proceedings of the 25th Australasian Universities Power Engineering Conference — AUPEC* 2015 (technically co-sponsored by **IEEE**), Wollongong, Australia, 27-30 September, 2015.

- D. Oliveira, E.M.G. Rodrigues, **R. Godina**, T.D.P. Mendes, J.P.S. Catalão, E. Pouresmaeil, "Enhancing home appliances energy optimization with solar power integration", in: *Proceedings of the IEEE Region 8 International Conference on Computer as a Tool — EUROCON 2015*, Salamanca, Spain, 8-11 September, 2015.

- E.M.G. Rodrigues, **R. Godina**, G.J. Osório, J.M. Lujano-Rojas, J.C.O. Matias, J.P.S. Catalão, "Assessing lead-acid battery design parameters for energy storage applications on insular grids: a case study of Crete and São Miguel islands", in: *Proceedings of the IEEE Region 8 International Conference on Computer as a Tool — EUROCON 2015*, Salamanca, Spain, 8-11 September, 2015.

- **R. Godina**, N.G. Paterakis, O. Erdinc, E.M.G. Rodrigues, J.P.S. Catalão, "Electric vehicles home charging impact on a distribution transformer in a Portuguese island", in: *Proceedings of the 2015 International Symposium on Smart Electric Distribution Systems and Technologies — EDST 2015* (technically co-sponsored by **IEEE**), Vienna, Austria, September 8-11, 2015.

- T.D.P. Mendes, **R. Godina**, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, "Smart and energy-efficient home implementation: wireless communication technologies role", in: *Proceedings of the 5th International Conference on Power Engineering, Energy and Electrical Drives — PowerEng 2015* (technically co-sponsored by **IEEE**), Riga, Latvia, May 11-13, 2015.

- **R. Godina**, E.M.G. Rodrigues, J.C.O. Matias, J.P.S. Catalão, "Sustainable energy system of El Hierro Island", in: *Proceedings of the International Conference on Renewable Energies and Power Quality — ICREPQ'15*, La Coruña, Spain, 25-27 March, 2015.

- E.M.G. Rodrigues, C.A.S. Fernandes, **R. Godina**, A.W. Bizuayehu, J.P.S. Catalão, "NaS battery storage system modeling and sizing for extending wind farms performance in Crete", in: *Proceedings of the 24th Australasian Universities Power Engineering Conference — AUPEC* 2014 (technically co-sponsored by **IEEE**), Perth, Australia, 28 September - 1 October, 2014.

# Bibliography

[1] O. Erdinc, N. G. Paterakis and J. P. Catalão, "Overview of insular power systems under increasing penetration of renewable energy sources: Opportunities and challenges," *Renewable and Sustainable Energy Reviews,* vol. 52, pp. 333-346, 2015.

[2] L. Phillips, "Norway's electric vehicle revolution: Lessons for British Columbia," University of Victoria, Victoria, 2015.

[3] K. Y. Bjerkan, T. E. Nørbech and M. E. Nordtømme, "Incentives for promoting Battery Electric Vehicle (BEV) adoption in Norway," *Transportation Research Part D: Transport and Environment,* vol. 43, pp. 169-180, 2016.

[4] P. C. Baptista, C. M. Silva, J. P. Lopes, F. J. Soares and P. R. Almeida, "Evaluation of the benefits of the introduction of electricity powered vehicles in an island," *Energy Conversion and Management,* vol. 76, pp. 541-553, 2013.

[5] A. Pina, P. Baptista, C. Silva and P. Ferrão, "Energy reduction potential from the shift to electric vehicles: The Flores island case study," *Energy Policy,* vol. 67, pp. 37-47, 2014.

[6] R. Godina, N. Paterakis, O. Erdinc, E. Rodrigues and J. Catalão, "Electric vehicles home charging impact on a distribution transformer in a Portuguese island," in *2015 International Symposium on Smart Electric Distribution Systems and Technologies — EDST 2015*, Vienna, 2015.

[7] D. A. Katsaprakakis, "Hybrid power plants in non-interconnected insular systems," *Applied Energy,* vol. 164, pp. 268-283, 2016.

[8] D. Moro, J. Agard and L. Vicente, "Chapter 23 - Island Systems," in *Ecosystems and Human Well-being: Current State & Trends Assessments, Volume 1*, Washington, DC, Island Press, 2005, pp. 663-680.

[9] O. Erdinc and N. G. Paterakis, "Chapter 1 - Overview of Insular Power Systems: Challenges and Opportunities," in *Smart and Sustainable Power Systems: Operations, Planning and Economics of Insular Electricity Grids*, Boca Raton, Florida, CRC Press (TAYLOR & FRANCIS Group), 2015.

[10] E. Hernández-Delgado, "The emerging threats of climate change on tropical coastal ecosystem services, public health, local economies and livelihood sustainability of small islands: Cumulative impacts and synergies," *Marine Pollution Bulletin,* vol. 101, no. 1, pp. 5-28, 2015.

[11] F. Courchamp, B. D. Hoffmann, J. C. Russell, C. Leclerc and C. Bellard, "Climate change, sea-level rise, and conservation: keeping island biodiversity afloat," *Trends in Ecology & Evolution,* vol. 29, no. 3, pp. 127-130, 2014.

[12] J. Petzold and B. M. Ratter, "Climate change adaptation under a social capital approach – An analytical framework for small islands," *Ocean & Coastal Management,* vol. 112, pp. 36-43, 2015.

[13] C. Betzold, "Adapting to climate change in small island developing states," *Climatic Change,* vol. 133, no. 3, pp. 481-489, 2015.

[14] O. Erdinc, J. Catalao, M. Uzunoglu and A. Rifat Boynuegri, "Smart insular grids: Opportunities and challenges," in *2013 3rd International Conference on Electric Power and Energy Conversion Systems (EPECS)*, Istanbul, 2013.

[15] C. K. Simoglou, E. A. Bakirtzis, P. N. Biskas and A. G. Bakirtzis, "Optimal operation of insular electricity grids under high RES penetration," *Renewable Energy,* vol. 86, pp. 1308-1316, 2016.

[16] E. Rodrigues, G. Osório, R. Godina, A. Bizuayehu, J. Lujano-Rojas and J. Catalão, "Grid code reinforcements for deeper renewable generation in insular energy systems," *Renewable and Sustainable Energy Reviews,* vol. 53, pp. 163-177, 2016.

[17] SiNGULAR, "Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration," Grant Agreement No: 309048, FP7-EU, 2015. [Online]. Available: http://www.singular-fp7.eu/home/. [Accessed 2015].

[18] EDA - Eletricidade dos Açores, "Relatório e Contas 2014," Nova Gráfica, Lda., Ponta

Delgada, 2015.

[19] EDA S.A. - Electricidade dos Açores, “Caracterização Das Redes De Transporte E Distribuição De Energia Eléctrica Da Região Autónoma Dos Açores,” Ponta Delgada, 2014.

[20] R. Bertani, “Geothermal power generation in the world 2010–2014 update report,” *Geothermics,* vol. 60, pp. 31-43, 2016.

[21] Governo Regional dos Açores, “Resolução N.º 181/2000,” Jornal Oficial da Região Autónoma dos Açores, 2000.

[22] ERSE, “Regulamento da Qualidade de Serviço - Região Autónoma dos Açores,” 2004.

[23] EDA S.A. - Electricidade dos Açores , “Preçário 2015 das Tarifas da Região Autónoma dos Açores,” EDA - Electricidade dos Açores, Ponta Delgada, 2015.

[24] SREA, “Anuário Estatístico da Região Autónoma dos Açores,” Serviço Regional de Estatística dos Açores, Angra do Heroísmo, 2013.

[25] R. Godina, N. Paterakis, O. Erdinc, E. Rodrigues and J. Catalão, “Impact of EV charging-at-work on an industrial client distribution transformer in a Portuguese island,” in *Proceedings of the 25th Australasian Universities Power Engineering Conference — AUPEC 2015*, Wollongong, 2015.

[26] EDA - Eletricidade dos Açores, “Procura e Oferta de Energia Elétrica,” Ponta Delgada, 2015.

[27] C. Silvia and R. M. Krause, “Assessing the impact of policy interventions on the adoption of plug-in electric vehicles: An agent-based model,” *Energy Policy,* vol. 96, pp. 105-118, 2016.

[28] G. Wager, J. Whale and T. Braunl, “Driving electric vehicles at highway speeds: The effect of higher driving speeds on energy consumption and driving range for electric vehicles in Australia,” *Renewable and Sustainable Energy Reviews,* vol. 63, pp. 158-165, 2016.

[29] A. Campen, D. Fornahl, N. Iliew and M. Hülsmann, “Introduction,” in *Markets and Policy Measures in the Evolution of Electric Mobility*, Cham, Switzerland, Springer International Publishing, 2016, pp. 1-6.

[30] G. Comodi, F. Caresana, D. Salvi, L. Pelagalli and M. Lorenzetti, “Local promotion of electric mobility in cities: Guidelines and real application case in Italy,” *Energy,* vol. 95, pp. 494-503, 2016.

[31] T. Lieven, “Policy measures to promote electric mobility – A global perspective,” *Transportation Research Part A: Policy and Practice,* vol. 82, pp. 78-93, 2015.

[32] A. M. Haidar, K. M. Muttaqi and D. Sutanto, “Technical challenges for electric power industries due to grid-integrated electric vehicles in low voltage distributions: A review,” *Energy Conversion and Management,* vol. 86, p. 689–700, 2014.

[33] G. Pasaoglu, A. Zubaryeva, D. Fiorello and C. Thiel, “Analysis of European mobility surveys and their potential to support studies on the impact of electric vehicles on energy and infrastructure needs in Europe,” *Technological Forecasting and Social Change,* vol. 87, pp. 41-50, 2014.

[34] W. L. Filho, K. Rath, F. Mannke, J. Vogt, R. Kotter, M. Borgqvist, B. Myklebust and P. v. Deventer, “Fostering Sustainable Mobility in Europe: The Contributions of the Project “E-Mobility North Sea Region”,” in *E-Mobility in Europe - Trends and Good Practice*, Cham, Switzerland, Springer International Publishing, 2015, pp. 3-25.

[35] Amsterdam Roundtable Foundation, “Electric vehicles in Europe: gearing up for a new phase?,” McKinsey & Company, The Netherlands, 2014.

[36] P. Morrissey, P. Weldon and M. O’Mahony, “Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behaviour,” *Energy Policy,* vol. 89, pp. 257-270, 2016.

[37] C. Madina, I. Zamora and E. Zabala, “Methodology for assessing electric vehicle charging infrastructure business models,” *Energy Policy,* vol. 89, pp. 284-293, 2016.

[38] S. Babrowski, H. Heinrichs, P. Jochem and W. Fichtner, “Load shift potential of electric vehicles in Europe,” *Journal of Power Sources,* vol. 255, pp. 283-293, 2014.

[39] F. Carranza, O. Paturet and S. Salera, “Norway, the most successful market for electric vehicles,” in *2013 World Electric Vehicle Symposium and Exhibition (EVS27)*, Barcelona, 2013.

[40] G. Haddadian, M. Khodayar and M. Shahidehpour, “Accelerating the Global Adoption of Electric Vehicles: Barriers and Drivers,” *The Electricity Journal,* vol. 28, no. 10, pp. 53-68, 2015.

[41] B. Nykvist and M. Nilsson, “The EV paradox – A multilevel study of why Stockholm is not a leader in electric vehicles,” *Environmental Innovation and Societal Transitions,* vol. 14, pp. 26-44, 2015.

[42] D. Newbery and G. Strbac, “What is needed for battery electric vehicles to become socially cost competitive?,” *Economics of Transportation,* 2015.

[43] D. Porter, “Consumer priorities crucial to electric vehicle transition,” *Renewable Energy Focus,* vol. 16, no. 5–6, pp. 124-125, 2015.

[44] The Committee on Climate Change, “Pathways to high penetration of electric vehicles,” Element Energy Limited, Cambridge, 2013.

[45] G. Wu, A. Inderbitzin and C. Bening, “Total cost of ownership of electric vehicles compared to conventional vehicles: A probabilistic analysis and projection across market segments,” *Energy Policy,* vol. 80, p. 196–214, 2015.

[46] C. Mazur, M. Contestabile, G. J. Offer and N. Brandon, “Assessing and comparing German and UK transition policies for electric mobility,” *Environmental Innovation and Societal Transitions,* vol. 14, pp. 84-100, 2015.

[47] J. Dumortier, S. Siddiki, S. Carley, J. Cisney, R. M. Krause, B. W. Lane, J. A. Rupp and J. D. Graham, “Effects of providing total cost of ownership information on consumers' intent to purchase a hybrid or plug-in electric vehicle,” *Transportation Research Part A: Policy and Practice,* vol. 72, pp. 71-86, 2015.

[48] I. Rahman, P. M. Vasant, B. S. M. Singh, M. Abdullah-Al-Wadud and N. Adnan, “Review of recent trends in optimization techniques for plug-in hybrid, and electric vehicle charging infrastructures,” *Renewable and Sustainable Energy Reviews,* vol. 58, pp. 1039-1047, 2016.

[49] M. Kuran, A. Viana, L. Iannone, D. Kofman, G. Mermoud and J. Vasseur, “A Smart Parking Lot Management System for Scheduling the Recharging of Electric Vehicles,” *IEEE Transactions on Smart Grid,* vol. 6, no. 6, pp. 2942 - 2953, 2015.

[50] A. Robinson, P. Blythe, M. Bell, Y. Hübner and G. Hill, “Analysis of electric vehicle driver recharging demand profiles and subsequent impacts on the carbon content of electric vehicle trips,” *Energy Policy,* vol. 61, pp. 337-348, 2013.

[51] M. Barth, P. Jugert and I. Fritsche, “Still underdetected – Social norms and collective efficacy predict the acceptance of electric vehicles in Germany,” *Transportation Research Part F: Traffic Psychology and Behaviour,* vol. 37, pp. 64-77, 2016.

[52] Y. Nie, M. Ghamami, A. Zockaie and F. Xiao, “Optimization of incentive polices for plug-in electric vehicles,” *Transportation Research Part B: Methodological,* vol. 84, pp. 103-123, 2016.

[53] M. A. Tamor, P. E. Moraal, B. Reprogle and M. Milačić, “Rapid estimation of electric vehicle acceptance using a general description of driving patterns,” *Transportation Research Part C: Emerging Technologies,* vol. 51, pp. 136-148, 2015.

[54] GEO 2015, “Global EV Outlook 2015,” IEA - International Energy Agency, Paris, France, 2015.

[55] W. Sierzchula, S. Bakker, K. Maat and B. v. Wee, “The influence of financial incentives and other socio-economic factors on electric vehicle adoption,” *Energy Policy,* vol. 68, pp. 183-194, 2014.

[56] A. Poullikkas, “Sustainable options for electric vehicle technologies,” *Renewable and Sustainable Energy Reviews,* vol. 41, pp. 1277-1287, 2015.

[57] S. Weckx and J. Driesen, “Load Balancing With EV Chargers and PV Inverters in Unbalanced Distribution Grids,” *IEEE Transactions on Sustainable Energy,* vol. 6, no. 2, pp. 635-643, 2015.

[58] J. Druitt and W.-G. Früh, “Simulation of demand management and grid balancing with

electric vehicles," *Journal of Power Sources,* vol. 216, pp. 104-116, 2012.

[59] B. Tarroja, J. D. Eichman, L. Zhang, T. M. Brown and S. Samuelsen, "The effectiveness of plug-in hybrid electric vehicles and renewable power in support of holistic environmental goals: Part 2 – Design and operation implications for load-balancing resources on the electric grid," *Journal of Power Sources,* vol. 278, pp. 782-793, 2015.

[60] J. Hu, H. Morais, T. Sousa and M. Lind, "Electric vehicle fleet management in smart grids: A review of services, optimization and control aspects," *Renewable and Sustainable Energy Reviews,* vol. 56, pp. 1207-1226, 2016.

[61] Diário da República, "RCM nº20/2009 - Programa para a Mobilidade Eléctrica.," 2009.

[62] Diário da República, "RCM nº29/2010 - Programa para a Mobilidade Eléctrica.," 2010.

[63] M. B. d. Silva, "Electric vehicle diffusion in the Portuguese automobile market," Instituto Superior Técnico - IST, Lisboa, 2012.

[64] ACAP, "Associação Automóvel de Portugal," [Online]. Available: http://www.acap.pt/pt/home. [Accessed 20 02 2015].

[65] P. Nunes, M. C. Brito and T. Farias, "Synergies between electric vehicles and solar electricity penetrations in Portugal," in *EVS27 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium,* Barcelona, Spain, 2013.

[66] S. P. Mota, "Vendas de carros eléctricos em máximos puxados pela BMW e Nissan," *Diário Económico,* p. 28, 4 February 2015.

[67] R. Galvin and N. Terry, "Selling energy savings in the United Kingdom: A case study of top-down pro-environmental behaviour change in commercial office buildings," *Energy Research & Social Science,* vol. 11, pp. 155-163, 2016.

[68] H. Campaniço, P. M. Soares, P. Hollmuller and R. M. Cardoso, "Climatic cooling potential and building cooling demand savings: High resolution spatiotemporal analysis of direct ventilation and evaporative cooling for the Iberian Peninsula," *Renewable Energy,* vol. 85, pp. 766-776, 2016.

[69] A. Boyanoa, P. Hernandezb and O. Wolfa, "Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations," *Energy and Buildings,* vol. 65, p. 19–28, 2013.

[70] Building Energy Efficiency Task Group, "Building Energy Performance Metrics - Supporting Energy Efficiency Progress in Major Economies," IEA Publications, Paris, France, 2015.

[71] J. I. Levy, M. K. Woo and Y. Tambouret, "Energy savings and emissions reductions associated with increased insulation for new homes in the United States," *Building and Environment,* vol. 96, pp. 72-79, 2016.

[72] C. Ahern and B. Norton, "Energy savings across EU domestic building stock by optimizing hydraulic distribution in domestic space heating systems," *Energy and Buildings,* vol. 91, pp. 199-209, 2015.

[73] International Monetary Fund, "World Economic Outlook Database," IMF, 2014.

[74] International Energy Agency, "Tracking Clean Energy Progress 2014," OECD/IEA, Paris, 2014.

[75] K. M. Roufechaei, A. H. A. Bakar and A. A. Tabassi, "Energy-efficient design for sustainable housing development," *Journal of Cleaner Production,* vol. 65, pp. 380-388, 2014.

[76] M. Beaudin and H. Zareipour, "Home energy management systems: A review of modelling and complexity," *Renewable and Sustainable Energy Reviews,* vol. 45, pp. 318-335, 2015.

[77] S. Berry and K. Davidson, "Zero energy homes – Are they economically viable?," *Energy Policy,* vol. 85, pp. 12-21, 2015.

[78] J. A. Rosas-Flores, D. Rosas-Flores and J. L. F. Zayas, "Potential energy saving in urban and rural households of Mexico by use of solar water heaters, using geographical information system," *Renewable and Sustainable Energy Reviews,* vol. 53, pp. 243-252, 2016.

[79] C. Perfumo, J. Braslavsky and J. Ward, "Model-Based Estimation of Energy Savings in

Load Control Events for Thermostatically Controlled Loads," *IEEE Transactions on Smart Grid,* vol. 5, no. 3, pp. 1410-1420, 2014.

[80] Z. Pan, Q. Guo and H. Sun, "Impacts of optimization interval on home energy scheduling for thermostatically controlled appliances," *CSEE Journal of Power and Energy Systems,* vol. 1, no. 2, pp. 90-100, 2015.

[81] K. Belz, F. Kuznik, K. Werner, T. Schmidt and W. Ruck, "17 - Thermal energy storage systems for heating and hot water in residential buildings," in *Advances in Thermal Energy Storage Systems*, United Kingdom, Woodhead Publishing, 2015, pp. 441-465.

[82] E. Ó. Broin, J. Nässén and F. Johnsson, "The influence of price and non-price effects on demand for heating in the EU residential sector," *Energy,* vol. 81, pp. 146-158, 2015.

[83] A. Khakimova, A. Shamshimova, D. Sharipova, A. Kusatayeva, V. Ten, A. Bemporad, Y. Familiant, A. Shintemirov and M. Rubagotti, "Hybrid model predictive control for optimal energy management of a smart house," in *2015 IEEE 15th International Conference on Environment and Electrical Engineering (EEEIC)*, Rome, 2015.

[84] L. Ciabattoni, M. Grisostomi, G. Ippoliti, D. Pagnotta, G. Foresi and S. Longhi, "Residential energy monitoring and management based on fuzzy logic," in *2015 IEEE International Conference on Consumer Electronics (ICCE)*, Las Vegas, NV, 2015.

[85] P. H. Shaikh, N. B. M. Nor, P. Nallagownden, I. Elamvazuthi and T. Ibrahim, "A review on optimized control systems for building energy and comfort management of smart sustainable buildings," *Renewable and Sustainable Energy Reviews,* vol. 34, pp. 409-429, 2014.

[86] S. Berry, D. Whaley, K. Davidson and W. Saman, "Near zero energy homes – What do users think?," *Energy Policy,* vol. 73, pp. 127-137, 2015.

[87] J. C. Smith and Z. C. Taşkın, "A Tutorial Guide to Mixed-Integer Programming Models and Solution Techniques," University of Florida, Gainesville, 2007.

[88] G. K. D. Saharidis, A. J. Conejo and G. Kozanidis, "Exact Solution Methodologies for Linear and (Mixed) Integer Bilevel Programming," in *Metaheuristics for Bi-level Optimization*, Berlin, Springer Berlin Heidelberg, 2013, pp. 221-245.

[89] J.-M. Réveillac, "8 - Linear Programming," in *Optimization Tools for Logistics*, Kidlington, Oxford, Elsevier Ltd., 2015, pp. 209-237.

[90] S. L. Janak and C. A. Floudas, "Robust Optimization: Mixed-Integer Linear Programs," in *Encyclopedia of Optimization*, Berlin, Springer-Verlag, 2009, pp. 3331-3343.

[91] A. Atamtürk and M. W. P. Savelsbergh, "Integer-Programming Software Systems," *Annals of Operations Research,* vol. 140, no. 1, pp. 67-124, 2005.

[92] Reference Work Entry, "GAMS," in *Encyclopedia of Operations Research and Management Science*, New York, Springer US, 2013, p. 631.

[93] A. I. Kibzun and O. M. Khromova, "On reduction of the multistage problem of stochastic programming with quantile criterion to the problem of mixed integer linear programming," *Automation and Remote Control,* vol. 75, no. 4, pp. 688-699, 2014.

[94] A. Neumaier and O. Shcherbina, "Safe bounds in linear and mixed-integer linear programming," *Mathematical Programming,* vol. 99, no. 2, pp. 283-296, 2004.

[95] O. Kolb, A. Morsi, J. Lang and A. Martin, "Nonlinear and Mixed Integer Linear Programming," in *Mathematical Optimization of Water Networks*, Basel, Springer Basel, 2012, pp. 55-65.

[96] C.-K. Goh and K. C. Tan, Evolutionary Multi-objective Optimization in Uncertain Environments - Issues and Algorithms, Berlin: Springer-Verlag Berlin Heidelberg, 2009.

[97] N. Paterakis, Reserve services provision by demand side resources in systems with high renewables penetration using stochastic optimization, Covilhã: University of Beira Interior, 2015.

[98] B. Kouvaritakis and M. Cannon, Model Predictive Control - Classical, Robust and Stochastic, Cham: Springer International Publishing, 2016.

[99] D. E. Seborg, D. A. Mellichamp, T. F. Edgar and F. J. D. III, "Model Predictive Control," in *Process Dynamics and Control*, Wiley, 2011, pp. 414-438.

[100] S. J. Qin and T. A. Badgwell, "A survey of industrial model predictive control

technology," *Control Engineering Practice,* vol. 11, no. 7, p. 733–764, 2003.

[101] E. F. Camacho and C. Bordons, Model Predictive control, London: Springer-Verlag London Limited, 2007.

[102] B. Huang and R. Kadali, Dynamic Modeling, Predictive Control and Performance Monitoring - A Data-driven Subspace Approach, London: Springer London, 2008.

[103] L. Wang, Model Predictive Control System Design and Implementation Using MATLAB®, London: Springer London, 2009.

[104] J. Love, "Model Predictive Control," in *Process Automation Handbook Part II - A Guide to Theory and Practice*, London, Springer-Verlag London Limited, 2007, pp. 1023-1038.

[105] M. J. Heathcote, J & P Transformer Book, Oxford: Newnes, 2007.

[106] V. Darabad, M. Vakilian, T. Blackburn and B. Phung, "An efficient PD data mining method for power transformer defect models using SOM technique," *International Journal of Electrical Power & Energy Systems,* vol. 71, pp. 373-382, 2015.

[107] C. Bayliss and B. Hardy, "Chapter 14 - Power Transformers," in *Transmission and Distribution Electrical Engineering*, 4th ed., C. Bayliss and B. Hardy, Eds., Oxford, Newnes, 2012, p. 543–614.

[108] N. Cennamo, L. D. Maria, G. D'Agostino, L. Zeni and M. Pesavento, "Monitoring of Low Levels of Furfural in Power Transformer Oil with a Sensor System Based on a POF-MIP Platform," *Sensors,* vol. 15, no. 4, pp. 8499-8511, 2015.

[109] B. C. Degeneff, "3 - Power Transformers," in *The Electrical Engineering Handbook*, W. Chen, Ed., Burlington, Academic Press, 2005, pp. 715-720.

[110] P. Sen and S. Pansuwan, "Overloading and loss-of-life assessment guidelines of oil-cooled transformers," in *2001 Rural Electric Power Conference*, Little Rock, AR, 2001.

[111] United States Department Of The Interior - Bureau Of Reclamation, "Facilities instructions, standards, and techniques - Volume 1-5 - Permissible Loading of Oil-Immersed Transformers and Regulators," Facilities Engineering Branch - Denver Office, Denver, Colorado, 1991.

[112] S. Tenbohlen, T. Stirl and M. Stach, "Assessment of overload capacity of power transformers by on-line monitoring systems," in *IEEE Power Engineering Society Winter Meeting, 2001.*, Columbus, OH, 2001.

[113] W. Fu, J. McCalley and V. Vittal, "Risk assessment for transformer loading," *IEEE Transactions on Power Systems,* vol. 16, no. 3, pp. 346-353, 2001.

[114] N. Rashid, "Short-time Overloading of Power Transformers," Royal Institute of Technology KTH, Stockholm, 2011.

[115] C57.91-1995, "Guide for Loading Mineral-Oil-Immersed," IEEE Standard, 1995.

[116] IEC 60076-7, "Loading Guide for Oil-immersed Power Transformers," 2005.

[117] A. Hilshey, P. Hines, P. Rezaei and J. Dowds, "Estimating the Impact of Electric Vehicle Smart Charging on Distribution Transformer Aging," *IEEE Transactions on Smart Grid,* vol. 4, no. 2, pp. 905-913, 2013.

[118] H. L. Willis, Power Distribution Planning Reference Book, Boca Raton, FL, USA: CRC Press , 2004.

[119] M. Humayun, A. Safdarian, M. Degefa and M. Lehtonen, "Demand Response for Operational Life Extension and Efficient Capacity Utilization of Power Transformers During Contingencies," *IEEE Transactions on Power Systems,* vol. 30, no. 4, pp. 2160-2169, 2015.

[120] M. Humayun, M. Degefa, A. Safdarian and M. Lehtonen, "Utilization Improvement of Transformers Using Demand Response," *IEEE Transactions on Power Delivery,* vol. 30, no. 1, pp. 202-210, 2015.

[121] Power Systems Engineering Research Center, "Transformer Overloading and Assessment of Loss-of-Life for Liquid-Filled Transformers," Colorado School of Mines and Texas A&M University, Tempe, 2011.

[122] W. H. Tang and Q. H. Wu, Condition Monitoring and Assessment of Power Transformers Using Computational Intelligence, London: Springer-Verlag, 2011.

[123] H. Yoshida and T. Suzuki, "Drying Process of Insulating Materials of Transformers," *IEEE*

*Transactions on Electrical Insulation,* Vols. EI-20, no. 3, pp. 609-618, 1985.

[124] ABB Power, “Distribution Transformers,” Cross Advertising, Zürich, 2001.

[125] L. Pierce, “Specifying and loading cast-resin transformers,” *IEEE Transactions on Industry Applications,* vol. 29, no. 3, pp. 590-599, 1993.

[126] Siemens AG, “Transformers - Power Engineering Guide - Edition 7.0,” Siemens Energy Sector, 2015.

[127] Mitsubishi Electric Corporation, “Large Power Transformers,” Mitsubishi Electric Corporation, Tokyo, Japan, 2005.

[128] T. Gradnik and M. Končan-Gradnik, “Cooling system optimization and expected lifetime of large power transformers,” in *Proceedings of the 2006 IASME/WSEAS International Conference on Energy & Environmental Systems*, Chalkida, Greece, 2006.

[129] IEEE Standard Terminology for Power and Distribution Transformers, “IEEE Std C57.12.80-2010 (Revision of IEEE Std C57.12.80-2002),” IEEE, 2010.

[130] “C57.12.80-2010 - IEEE Standard Terminology for Power and Distribution Transformers,” Institute of Electrical and Electronics Engineers, 2010.

[131] H. Pezeshki, P. Wolfs and G. Ledwich, “Impact of High PV Penetration on Distribution Transformer Insulation Life,” *IEEE Transactions on Power Delivery,* vol. 29, no. 3, pp. 1212-1220, 2014.

[132] R. Godina, N. Paterakis, O. Erdinc, E. Rodrigues and J. Catalão, “Impact of EV charging-at-work on an industrial client distribution transformer in a Portuguese island,” in *2015 Australasian Universities Power Engineering Conference (AUPEC)*, Wollongong, Australia, 2015.

[133] K. Qian, C. Zhou and Y. Yuan, “Impacts of high penetration level of fully electric vehicles charging loads on the thermal ageing of power transformers,” *International Journal of Electrical Power & Energy Systems,* vol. 65, pp. 102-112, 2015.

[134] H. Turker, S. Bacha, D. Chatroux and A. Hably, “Low-Voltage Transformer Loss-of-Life Assessments for a High Penetration of Plug-In Hybrid Electric Vehicles (PHEVs),” *IEEE Transactions on Power Delivery,* vol. 27, no. 3, pp. 1323-1331, 2012.

[135] S. C. Tripathy and E. Lakervi, “Evaluation of transformer overloading capability,” *European Transactions on Electrical Power,* vol. 15, no. 5, p. 455–464, 2005.

[136] A. Ashkezari, H. Ma, T. Saha and Y. Cui, “Investigation of feature selection techniques for improving efficiency of power transformer condition assessment,” *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 21, no. 2, pp. 836-844, 2014.

[137] A. J. Trappey, C. V. Trappey, L. Ma and J. C. Chang, “Intelligent engineering asset management system for power transformer maintenance decision supports under various operating conditions,” *Computers & Industrial Engineering,* vol. 84, pp. 3-11, 2015.

[138] P. S. Georgilakis, M. A. Tsili and A. T. Souflaris, “A heuristic solution to the transformer manufacturing cost optimization problem,” *Journal of Materials Processing Technology,* vol. 181, pp. 260-266, 2007.

[139] R. Szewczyk, J.-C. Duart and R. Van Schevensteen, “Comparison of various technologies used for distribution transformers from an ECO standpoint,” in *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, Stockholm, 2013.

[140] Y. Wang, Y.-B. Xu, Y.-X. Zhang, F. Fang, X. Lu, R. Misra and G.-D. Wang, “Effect of annealing after strip casting on texture development in grain oriented silicon steel produced by twin roll casting,” *Materials Characterization,* vol. 107, pp. 79-84, 2015.

[141] V. A. Yatsevsky, “Hydrodynamics and heat transfer in cooling channels of oil-filled power transformers with multicoil windings,” *Applied Thermal Engineering,* vol. 63, no. 1, pp. 347-353, 2014.

[142] P. Marketos, T. Meydan and D. Snell, “Performance of single-phase transformer cores assembled from consolidated stacks of electrical steels,” *Journal of Magnetism and Magnetic Materials,* vol. 254–255, pp. 612-614, 2003.

[143] “Distribution Transformer Manufacturing Tour,” United Utility Supply, [Online]. Available: http://www.uus.org/tour.htm. [Accessed 21 10 2015].

[144] R. Villarroel, D. Garcia, B. Garcia and J. Burgos, “Comparison of the drying times for kraft paper and pressboard in transformer factory drying,” in *2012 XXth International Conference on Electrical Machines (ICEM)*, Marseille, 2012.

[145] D. Li, L. Zhang, G. Li, Z. Lu and S. Zhou, “Reducing the core loss of amorphous cores for distribution transformers,” *Progress in Natural Science: Materials International,* vol. 22, no. 3, pp. 244-249, 2012.

[146] Technical Associates Ltd., “Manufacturing Process,” [Online]. Available: http://www.techasso.com/mpqaplan.htm. [Accessed 25 11 2015].

[147] C. Sumereder, M. Muhr and B. Körbler, “Lifetime management of power transformers,” *e&i Elektrotechnik und Informationstechnik,* vol. 120, no. 12, pp. 420-423, 2003.

[148] C57.110-2008 , “IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents,” IEEE Standard, 2008.

[149] J.-N. Bérubé, J. Aubin and W. McDermid, “Recent development in transformer winding temperature determination,” Neoptix Inc., Québec.

[150] IEEE PC57.145, “Guide for the Definition of Thermal Duplicate Liquid-Immersed Distribution, Power and Regulating Transformer,” 2002.

[151] V. Aravinthan and W. Jewell, “Controlled Electric Vehicle Charging for Mitigating Impacts on Distribution Assets,” *IEEE Transactions on Smart Grid,* vol. 6, no. 2, pp. 999-1009, 2015.

[152] A. Seier, P. Hines and J. Frolik, “Data-Driven Thermal Modeling of Residential Service Transformers,” *IEEE Transactions on Smart Grid,* vol. 6, no. 2, pp. 1019-1025, 2015.

[153] K. Shuaib, L. Zhang, A. Gaouda and M. Abdel-Hafez, “A PEV Charging Service Model for Smart Grids,” *Energies,* vol. 5, no. 11, pp. 4665-4682, 2012.

[154] K. Qian, C. Zhou, M. Allan and Y. Yuan, “Modeling of Load Demand Due to EV Battery Charging in Distribution Systems,” *IEEE Transactions on Power Systems,* vol. 26, no. 2, pp. 802-810, 2011.

[155] Q. Gong, S. Midlam-Mohler, V. Marano and G. Rizzoni, “Study of PEV Charging on Residential Distribution Transformer Life,” *IEEE Transactions on Smart Grid,* vol. 3, no. 1, pp. 404-412, 2012.

[156] M. J. Rutherford and V. Yousefzadeh, “The Impact of Electric Vehicle Battery Charging on Distribution Transformers,” in *2011 Twenty-Sixth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Fort Worth, TX, USA, 2011.

[157] R. Vicini, O. Micheloud, H. Kumar and A. Kwasinski, “Transformer and home energy management systems to lessen electrical vehicle impact on the grid,” *IET Generation, Transmission & Distribution,* vol. 6, no. 12, pp. 1202-1208, 2012.

[158] J. Sexauer, K. McBee and K. Bloch, “Applications of probability model to analyze the effects of electric vehicle chargers on distribution transformers,” *IEEE Transactions on Power Systems,* vol. 28, no. 2, pp. 847-854, 2013.

[159] J. Sexauer, K. McBee and K. Bloch, “Applications of probability model to analyze the effects of electric vehicle chargers on distribution transformers,” in *2011 IEEE Electrical Power and Energy Conference (EPEC)*, Winnipeg, MB, 2011.

[160] Q. Gong, S. Midlam-Mohler, E. Serra, V. Marano and G. Rizzoni, “PEV Charging Control Considering Transformer Life and Experimental Validation of a 25 kVA Distribution Transformer,” *IEEE Transactions on Smart Grid,* vol. 6, no. 2, pp. 648-656, 2015.

[161] H. Turker, S. Bacha, D. Chatroux and A. Hably, “Aging rate of low voltage transformer for a high penetration of Plug-in Hybrid Electric Vehicles (PHEVs),” in *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, Washington, DC, 2012.

[162] H. Turker, S. Bacha and A. Hably, “Rule-Based Charging of Plug-in Electric Vehicles (PEVs): Impacts on the Aging Rate of Low-Voltage Transformers,” *IEEE Transactions on Power Delivery,* vol. 29, no. 3, pp. 1012-1019, 2014.

[163] H. Turker, A. Florescu, S. Bacha and D. Chatroux, “Load rates of low voltage transformers and medium voltage profile assessments on a real distribution electric grid based on average Daily Load Profile (DLP) of a housing for a high penetration of plug-in hybrid electric vehicles (PHEVs),” in *2011 IEEE Vehicle Power and Propulsion*

*Conference (VPPC)*, Chicago, IL, 2011.

[164] D. Soto, S. Balathandayuthapani and C. Edrington, “Mitigation of PHEV charging impact on transformers via a PV-APF harmonic compensation technique: Application to V2G integration,” in *Vehicle Power and Propulsion Conference (VPPC), 2011 IEEE*, Chicago, IL, 2011.

[165] T. Geiles and S. Islam, “Impact of PEV charging and rooftop PV penetration on distribution transformer life,” in *2013 IEEE Power and Energy Society General Meeting (PES)*, Vancouver, BC, 2013.

[166] S. Weckx, R. D'Hulst, B. Claessens and J. Driesensam, “Multiagent Charging of Electric Vehicles Respecting Distribution Transformer Loading and Voltage Limits,” *IEEE Transactions on Smart Grid,* vol. 5, no. 6, pp. 2857-2867, 2014.

[167] M. Kazerooni and N. Kar, “Optimal load management of EV battery charging and optimization of harmonic impacts on distribution transformers,” in *2012 25th IEEE Canadian Conference on Electrical & Computer Engineering (CCECE)*, Montreal, QC, 2012.

[168] M. Kazerooni and N. Kar, “Impact analysis of EV battery charging on the power system distribution transformers,” in *2012 IEEE International Electric Vehicle Conference (IEVC)*, Greenville, SC, 2012.

[169] J. Gomez and M. Morcos, “Impact of EV battery chargers on the power quality of distribution systems,” *IEEE Transactions on Power Delivery,* vol. 18, no. 3, pp. 975-981, 2003.

[170] Q. Gong, S. Midlam-Mohler, V. Marano and G. Rizzoni, “PEV charging impact on residential distribution transformer life,” in *2011 IEEE Energytech*, Cleveland, OH, 2011.

[171] Q. Gong, S. Midlam-Mohler, V. Marano and G. Rizzoni, “Distribution of PEV charging resources to balance transformer life and customer satisfaction,” in *2012 IEEE International Electric Vehicle Conference (IEVC)*, Greenville, SC, 2012.

[172] M. Masoum, P. Moses and K. Smedley, “Distribution transformer losses and performance in smart grids with residential Plug-In Electric Vehicles,” in *2011 IEEE PES Innovative Smart Grid Technologies (ISGT)*, Hilton Anaheim, CA, 2011.

[173] M. Masoum, P. Moses and S. Hajforoosh, “Distribution transformer stress in smart grid with coordinated charging of Plug-In Electric Vehicles,” in *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, Washington, DC, 2012.

[174] A. Masoum, A. Abu-Siada and S. Islam, “Impact of uncoordinated and coordinated charging of plug-in electric vehicles on substation transformer in smart grid with charging stations,” in *2011 IEEE PES Innovative Smart Grid Technologies Asia (ISGT)*, Perth, WA, 2011.

[175] M. Moghbel, M. Masoum, F. Shahnia and P. Moses, “Distribution transformer loading in unbalanced three-phase residential networks with random charging of plug-in electric vehicles,” in *2012 22nd Australasian Universities Power Engineering Conference (AUPEC)*, Bali, 2012.

[176] P. Moses, M. Masoum and S. Hajforoosh, “Overloading of distribution transformers in smart grid due to uncoordinated charging of plug-In electric vehicles,” in *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, Washington, DC, 2012.

[177] P. Moses, M. Masoum and K. Smedley, “Harmonic losses and stresses of nonlinear three-phase distribution transformers serving Plug-In Electric Vehicle charging stations,” in *2011 IEEE PES Innovative Smart Grid Technologies (ISGT)*, Hilton Anaheim, CA, 2011.

[178] A. Masoum, S. Deilami, P. Moses and A. Abu-Siada, “Impacts of battery charging rates of Plug-in Electric Vehicle on smart grid distribution systems,” in *2010 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe)*, Gothenburg, 2010.

[179] G. Razeghi, L. Zhang, T. Brown and S. Samuelsen, “Impacts of plug-in hybrid electric vehicles on a residential transformer using stochastic and empirical analysis,” *Journal of Power Sources,* vol. 252, pp. 277-285, 2014.

[180] S. Agah and A. Abbasi, “The impact of charging plug-in hybrid electric vehicles on residential distribution transformers,” in *2012 2nd Iranian Conference on Smart Grids (ICSG)*, Tehran, 2012.

[181] C. Gerkensmeyer, M. Kintner-Meyer and J. DeSteese, “Technical Challenges of Plug-In Hybrid Electric Vehicles and Impacts to the US Power System: Distribution System Analysis,” Pacific Northwest National Laboratory, Richland, Washington, 2010.

[182] M. Alonso, H. Amaris, J. G. Germain and J. M. Galan, “Optimal Charging Scheduling of Electric Vehicles in Smart Grids by Heuristic Algorithms,” *Energies,* vol. 7, no. 4, pp. 2449-2475, 2014.

[183] S. Shao, Pipattanasomporn, M. and S. Rahman, “Challenges of PHEV penetration to the residential distribution network,” in *PES '09. IEEE Power & Energy Society General Meeting, 2009.*, Calgary, AB, 2009.

[184] Q. Gong, S. Midlam-Mohler, E. Serra, V. Marano and G. Rizzoni, “Distribution transformer tests for PEV smart charging control,” in *2012 IEEE Energytech*, Cleveland, OH, 2012.

[185] V. Marano, P. Tulpule, Q. Gong, A. Martinez, S. Midlam-Mohler and G. Rizzoni, “Vehicle electrification: Implications on generation and distribution network,” in *2011 International Conference on Electrical Machines and Systems (ICEMS)*, Beijing, 2011.

[186] Q. Gong, S. Midlam-Mohler, V. Marano and G. Rizzoni, “Optimal Control of PEV Charging Based on Residential Base Load Prediction,” in *ASME 2011 Dynamic Systems and Control Conference*, Arlington, VA, USA,, 2011.

[187] S. Argade, V. Aravinthan and W. Jewell, “Probabilistic modeling of EV charging and its impact on distribution transformer loss of life,” in *2012 IEEE International Electric Vehicle Conference (IEVC)*, Greenville, SC, 2012.

[188] V. Aravinthan and S. Argade, “Optimal transformer sizing with the presence of electric vehicle charging,” in *2014 IEEE PES T&D Conference and Exposition*, Chicago, IL, USA, 2014.

[189] M. Kuss, T. Markel and W. Kramer, “Application of Distribution Transformer Thermal Life Models to Electrified Vehicle Charging Loads Using Monte-Carlo Method,” in *25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition*, Shenzhen, China, 2010.

[190] J. Taylor, A. Maitra, M. Alexander, D. Brooks and M. Duvall, “Evaluation of the impact of plug-in electric vehicle loading on distribution system operations,” in *IEEE Power & Energy Society General Meeting, 2009. PES '09.*, Calgary, AB, 2009.

[191] H. Pezeshki and P. Wolfs, “Impact of high PV penetration on distribution transformer life time,” in *2013 IEEE Power and Energy Society General Meeting (PES)*, Vancouver, BC, 2013.

[192] A. Hasanzadeh, C. Edrington and T. Bevis, “Comprehensive study of power quality criteria generated by PV converters and their impacts on distribution transformers,” in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, Montreal, QC, 2012.

[193] K. Rajender, K. Rajapandiyan and Vallisaranya, “Transformer rating for solar PV plants based on overloading capability as per guidelines,” in *2014 IEEE Region 10 Humanitarian Technology Conference (R10-HTC)*, Chennai, 2014.

[194] S. Agah and H. Askarian Abyaneh, “Quantification of the Distribution Transformer Life Extension Value of Distributed Generation,” *IEEE Transactions on Power Delivery,* vol. 26, no. 3, pp. 1820-1828, 2011.

[195] D. Martin, S. Goodwin, O. Krause and T. Saha, “The effect of PV on transformer ageing: University of Queensland's experience,” in *2014 Australasian Universities Power Engineering Conference (AUPEC)*, Perth, WA, 2014.

[196] A. Masoum, P. Moses, M. Masoum and A. Abu-Siada, “Impact of rooftop PV generation on distribution transformer and voltage profile of residential and commercial networks,” in *2012 IEEE PES Innovative Smart Grid Technologies (ISGT)*, Washington, DC, 2012.

[197] M. Hamzeh, B. Vahidi and H. Askarian-AbyanehM, “Reliability evaluation of distribution transformers with high penetration of distributed generation,” *International Journal of Electrical Power & Energy Systems,* vol. 73, pp. 163-169, 2015.

[198] S. Agah and H. Abyaneh, “Distribution Transformer Loss-of-Life Reduction by Increasing Penetration of Distributed Generation,” *IEEE Transactions on Power Delivery,* vol. 26,

no. 2, pp. 1128-1136, 2011.

[199] M. Awadallah, T. Xu, B. Venkatesh and B. Singh, “On the Effects of Solar Panels on Distribution Transformers,” *IEEE Transactions on Power Delivery,* vol. PP, no. 99, pp. 1-10, 2015.

[200] H. Jimenez, H. Calleja, R. González, J. Huacuz and J. Lagunas, “The impact of photovoltaic systems on distribution transformer: A case study,” *Energy Conversion and Management,* vol. 47, no. 4, pp. 311-321, 2006.

[201] M. Degefa, M. Humayun, A. Safdarian, M. Koivisto, R. Millar and M. Lehtonen, “Unlocking distribution network capacity through real-time thermal rating for high penetration of DGs,” *Electric Power Systems Research,* vol. 117, pp. 36-46, 2014.

[202] J. Jargstorf, K. Vanthournout, T. De Rybel and D. Van Hertem, “Effect of Demand Response on transformer lifetime expectation,” in *2012 3rd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe)*, Berlin, 2012.

[203] A. Shiri, A. Gholami and A. Shoulaie, “Investigation of the ambient temperature effects on transformer’s insulation life,” *Electrical Engineering,* vol. 93, no. 3, pp. 193-197, 2011.

[204] C. Ravetta, M. Samanna’, A. Stucchi and A. Bossi, “Thermal behavior of distribution transformers in summertime and severe loading conditions,” in *19th International Conference on Electricity Distribution*, Vienna, 2007.

[205] M. Lee, H. A. Abdullah, J. C. Jofriet, D. Patel and M. Fahrioglu, “Air temperature effect on thermal models for ventilated dry-type transformers,” *Electric Power Systems Research,* vol. 81, no. 3, p. 783–789, 2011.

[206] S. Agah and H. Abyaneh, “Effect of Modeling Non-Normality and Stochastic Dependence of Variables on Distribution Transformer Loss of Life Inference,” *IEEE Transactions on Power Delivery,* vol. 27, no. 4, pp. 1700-1709, 2012.

[207] J. Stahlhut, G. Heydt and N. Selover, “A Preliminary Assessment of the Impact of Ambient Temperature Rise on Distribution Transformer Loss of Life,” *IEEE Transactions on Power Delivery,* vol. 23, no. 4, pp. 2000-2007, 2008.

[208] B. R. Sathyanarayana, G. T. Heydt and M. L. Dyer, “Distribution Transformer Life Assessment with Ambient Temperature Rise Projections,” *Electric Power Components and Systems,* vol. 37, no. 9, p. 1005–1013, 2009.

[209] A. Elmoudi, “Thermal modeling and simulation of distribution transformers,” in *5th International Multi-Conference on Systems, Signals and Devices, 2008. IEEE SSD 2008.*, Amman, 2008.

[210] S.-Y. Yun, C.-H. Park and I.-K. Song, “Development of overload evaluation system for distribution transformers using load monitoring data,” *International Journal of Electrical Power & Energy Systems,* vol. 44, no. 1, pp. 60-69, 2013.

[211] M. F. Lachman, P. J. Griffin, W. Walter and A. Wilson, “Real-time dynamic loading and thermal diagnostic of power transformers,” *IEEE Transactions on Power Delivery,* vol. 18, no. 1, pp. 142 - 148, 2003.

[212] D. Susa, M. Lehtonen and H. Nordman, “Dynamic thermal modeling of power transformers,” *IEEE Transactions on Power Delivery,* vol. 20, no. 1, pp. 197 - 204, 2005.

[213] S. Awadallah, J. Milanovic and P. Jarman, “The Influence of Modeling Transformer Age Related Failures on System Reliability,” *IEEE Transactions on Power Systems,* vol. 30, no. 2, pp. 970-979, 2015.

[214] D. Susa and H. Nordman, “A Simple Model for Calculating Transformer Hot-Spot Temperature,” *IEEE Transactions on Power Delivery,* vol. 24, no. 3, pp. 1257-1265, 2009.

[215] J. Jardini, H. Schmidt, C. M. Tahan, C. C. de Oliveira and S. U. Ahn, “Distribution transformer loss of life evaluation: a novel approach based on daily load profiles,” *IEEE Transactions on Power Delivery,* vol. 15, no. 1, pp. 361-366, 2000.

[216] Z. Radakovic and K. Feser, “A new method for the calculation of the hot-spot temperature in power transformers with ONAN cooling,” *IEEE Transactions on Power Delivery,* vol. 18, no. 4, pp. 1284-1292, 2003.

[217] Z. Radakovic, E. Cardillo and K. Feser, "The influence of transformer loading to the ageing of the oil-paper insulation," in *Proc. 13th Int. Symp. High Voltage Engineering*, Rotterdam, The Netherlands, 2003.

[218] J. Jardini, C. Tahan, S. Ahn and E. Ferrari, "Distribution transformer loading evaluation based on load profiles measurements," *IEEE Transactions on Power Delivery,* vol. 12, no. 4, pp. 1766-1770, 1997.

[219] X. Su, W. Chen, C. Pan, Q. Zhou and L. Teng, "A simple thermal model of transformer hot spot temperature based on thermal-electrical analogy," in *2012 International Conference on High Voltage Engineering and Application (ICHVE)*, Shanghai, 2012.

[220] A. Elmoudi, J. Palola and M. Lehtonen, "A Transformer Thermal Model for use in an on-line Monitoring and Diagnostic System," in *PSCE '06. 2006 IEEE PES Power Systems Conference and Exposition, 2006.*, Atlanta, GA, 2006.

[221] M. Khederzadeh, "Transformer Overload Management and Condition Monitoring," in *Conference Record of the 2008 IEEE International Symposium on Electrical Insulation, 2008. ISEI 2008.*, Vancouver, BC, 2008.

[222] A. Elmoudi, M. Lehtonen and H. Nordman, "Thermal model for power transformers dynamic loading," in *Conference Record of the 2006 IEEE International Symposium on Electrical Insulation, 2006.*, Toronto, Ont., 2006.

[223] T. Weekes, T. Molinski, X. Li and G. Swift, "Risk assessment using transformer loss of life data," *IEEE Electrical Insulation Magazine,* vol. 20, no. 2, pp. 27-31, 2004.

[224] X. Zhang and E. Gockenbach, "Determination of the thermal aging factor for life expectancy of 550 kV transformers with a preventive test," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 20, no. 6, pp. 1984-1991, 2013.

[225] M. Martins, M. Fialho, J. Martins, M. Soares, M. Cristina, R. Lopes and H. Campelo, "Power transformer end-of-life assessment-pracana case study," *IEEE Electrical Insulation Magazine,* vol. 27, no. 6, pp. 15-26, 2011.

[226] A. E. Abu-Elanien and M. Salama, "A Monte Carlo approach for calculating the thermal lifetime of transformer insulation," *International Journal of Electrical Power & Energy Systems,* vol. 43, no. 1, pp. 481-487, 2012.

[227] K. Miyagi, E. Oe, N. Yamagata and H. Miyahara, "Thermal aging characteristics of insulation paper in mineral oil in overloaded operation of transformers," *Electrical Engineering in Japan,* vol. 182, no. 2, pp. 1-8, 2013.

[228] P. Wouters, A. van Schijndel and J. Wetzer, "Remaining lifetime modeling of power transformers: individual assets and fleets," *IEEE Electrical Insulation Magazine,* vol. 27, no. 3, pp. 45-51, 2011.

[229] R. Walling and G. B. Shattuck, "Distribution Transformer Thermal Behavior and Aging in Local Delivery Distribution Systems," in *19th International Conference on Electricity Distribution, CIRED* , Vienna, 2007.

[230] B. Suechoey, S. Tadsuan, C. Thammarat and M. Leelajindakrairerk, "An analysis of temperature and pressure on loading oil-immersed distribution transformer," in *The 7th International Power Engineering Conference, 2005. IPEC 2005.*, Singapore, 2005.

[231] W. McNutt, "Insulation thermal life considerations for transformer loading guides," *IEEE Transactions on Power Delivery,* vol. 7, no. 1, pp. 392-401, 1992.

[232] L. Souza, A. Lemos, W. Caminhas and W. Boaventura, "Thermal modeling of power transformers using evolving fuzzy systems," *Engineering Applications of Artificial Intelligence,* vol. 25, no. 5, pp. 980-988, 2012.

[233] E. Koufakis, C. Karagiannopoulos and P. Bourkas, "Thermal coefficient measurements of the insulation in distribution transformers of a 20 kv network," *Measurement,* vol. 41, no. 1, pp. 10-19, 2008.

[234] G. Swift, T. Molinski and W. Lehn, "A fundamental approach to transformer thermal modeling. I. Theory and equivalent circuit," *IEEE Transactions on Power Delivery,* vol. 16, no. 2, pp. 171-175, 2001.

[235] G. Swift, T. Molinski, R. Bray and R. Menzies, "A fundamental approach to transformer thermal modeling. II. Field verification," *IEEE Transactions on Power Delivery,* vol. 16, no. 2, pp. 176-180, 2001.

[236] D. Susa, M. Lehtonen and H. Nordman, “Dynamic thermal modeling of distribution transformers,” *IEEE Transactions on Power Delivery,* vol. 20, no. 3, pp. 1919-1929, 2005.

[237] H. Nordman, N. Rafsback and D. Susa, “Temperature Responses to Step Changes in the Load,” *IEEE Transactions on Power Delivery,* vol. 18, no. 4, pp. 1110-1117, 2003.

[238] L. Jauregui-Rivera, X. Mao and D. Tylavsky, “Improving Reliability Assessment of Transformer Thermal Top-Oil Model Parameters Estimated From Measured Data,” *IEEE Transactions on Power Delivery,* vol. 24, no. 1, pp. 169-176, 2009.

[239] Y. Bicen, Y. Cilliyuz, F. Aras and G. Aydugan, “An assessment on aging model of IEEE/IEC standards for natural and mineral oil-immersed transformer,” in *2011 IEEE International Conference on Dielectric Liquids (ICDL)*, Trondheim, 2011.

[240] V. Galdi, L. lppolito, A. Piccolo and A. Vaccaro, “Neural diagnostic system for transformer thermal overload protection,” *IEE Proceedings - Electric Power Applications,* vol. 147, no. 5, pp. 415-421, 2000.

[241] R. Singh and A. Singh, “Aging of distribution transformers due to harmonics,” in *14th International Conference on Harmonics and Quality of Power (ICHQP), 2010*, Bergamo, 2010.

[242] A. Elmoudi, M. Lehtonen and H. Nordman, “Effect of harmonics on transformers loss of life,” in *Conference Record of the 2006 IEEE International Symposium on Electrical Insulation, 2006.*, Toronto, Ont., 2006.

[243] M. Shafiee Rad, M. Kazerooni, M. Ghorbany and H. Mokhtari, “Analysis of the grid harmonics and their impacts on distribution transformers,” in *2012 IEEE Power and Energy Conference at Illinois (PECI)*, Champaign, IL, 2012.

[244] D. Said and K. Nor, “Effects of harmonics on distribution transformers,” in *Australasian Power Engineering Conference, 2008. AUPEC '08.*, Sydney, NSW, 2008.

[245] S. Taheri, A. Gholami, I. Fofana and H. Taheri, “Modeling and simulation of transformer loading capability and hot spot temperature under harmonic conditions,” *Electric Power Systems Research,* vol. 86, pp. 68-75, 2012.

[246] P. Moses and M. Masoum, “Three-Phase Asymmetric Transformer Aging Considering Voltage-Current Harmonic Interactions, Unbalanced Nonlinear Loading, Magnetic Couplings, and Hysteresis,” *IEEE Transactions on Energy Conversion,* vol. 27, no. 2, pp. 318-327, 2012.

[247] P. Faria, Z. Vale and J. Baptista, “Demand Response Programs Design and Use Considering Intensive Penetration of Distributed Generation,” *Energies,* vol. 8, no. 6, pp. 6230-6246, 2015.

[248] A. Lucas, F. Bonavitacola, E. Kotsakis and G. Fulli, “An experimental approach for assessing the harmonic impact of fast charging electric vehicles on the distribution systems,” SETIS - Publications Office of the European Union, Luxembourg, 2015.

[249] A. J. G. Mena and J. A. M. García, “An efficient approach for the siting and sizing problem of distributed generation,” *International Journal of Electrical Power & Energy Systems,* vol. 69, pp. 167-172, 2015.

[250] A. Bagheri, H. Monsef and H. Lesani, “Integrated distribution network expansion planning incorporating distributed generation considering uncertainties, reliability, and operational conditions,” *International Journal of Electrical Power & Energy Systems,* vol. 73, pp. 56-70, 2015.

[251] E. Karatepe, F. Ugranlı and T. Hiyama, “Comparison of single- and multiple-distributed generation concepts in terms of power loss, voltage profile, and line flows under uncertain scenarios,” *Renewable and Sustainable Energy Reviews,* vol. 48, pp. 317-327, 2015.

[252] K. Groot, “Chapter 6 - The Impact of Distributed Generation on European Power Utilities,” in *Distributed Generation and its Implications for the Utility Industry*, F. P. Sioshansi, Ed., Boston, Academic Press, 2014, pp. 123-139.

[253] C. W. Gellings, “Chapter 5 - As the Role of the Distributor Changes, so Will the Need for New Technology,” in *Distributed Generation and its Implications for the Utility Industry*, F. P. Sioshansi, Ed., Boston, Academic Press, 2014, pp. 97-121.

[254] M. Nissen, “High performance development as distributed generation,” *IEEE Potentials,* vol. 26, no. 6, pp. 25-31, 2009.

[255] P. Jochem, S. Babrowski and W. Fichtner, “Assessing CO2 emissions of electric vehicles in Germany in 2030,” *Transportation Research Part A: Policy and Practice,* vol. 78, pp. 68-83, 2015.

[256] A. Schuller, “Charging Coordination Paradigms of Electric Vehicles,” in *Plug In Electric Vehicles in Smart Grids*, Singapore, Springer, 2015, pp. 1-21.

[257] R. Das, K. Thirugnanam, P. Kumar, R. Lavudiya and M. Singh, “Mathematical Modeling for Economic Evaluation of Electric Vehicle to Smart Grid Interaction,” *IEEE Transactions on Smart Grid,* vol. 5, no. 2, pp. 712-721, 2014.

[258] L. Reggi and S. Scicchitano, “Are EU regional digital strategies evidence-based? An analysis of the allocation of 2007–13 Structural Funds,” *Telecommunications Policy,* vol. 38, no. 5–6, pp. 530-538, 2014.

[259] D. Fedirchuk and C. Rebizant, “Managing Transformer Overload - Smart Relays,” *IEEE Canadian Review,* no. 35, pp. 25-28, 2000.

[260] T. Weekes, T. Molinski and G. Swift, “Transient transformer overload ratings and protection,” *IEEE Electrical Insulation Magazine,* vol. 20, no. 2, pp. 32-35, 2004.

[261] R. Nylén, “Power Transformer Protection - Application Guide,” ABB Relays, Västerås, Sweden, 1988.

[262] “IEEE Std C37.91-2000 IEEE Guide for Protective Relay Applications to Power Transformers,” IEEE , 2000.

[263] L. M. R. Oliveira and A. J. M. Cardoso, “Extended Park's vector approach-based differential protection of three-phase power transformers,” *IET Electric Power Applications,* vol. 6, no. 8, pp. 463-472, 2012.

[264] L. M. Oliveira and A. M. Cardoso, “Application of Park's Power Components to the Differential Protection of Three-Phase Transformers,” *Electric Power Systems Research,* vol. 83, no. 1, pp. 203-211, 2012.

[265] L. M. R. Oliveira and A. J. M. Cardoso, “A Permeance-Based Transformer Model and Its Application to Winding Interturn Arcing Fault Studies,” *IEEE Transactions on Power Delivery,* vol. 25, no. 3, pp. 1589-1598, 2010.

[266] L. M. Oliveira, A. M. Cardoso and S. M. Cruz, “Power transformers winding fault diagnosis by the on-load exciting current Extended Park's Vector Approach,” *Electric Power Systems Research,* vol. 81, no. 6, pp. 1206-1214, 2011.

[267] B. E. Lee, J.-W. Park, P. A. Crossley and Y. C. Kang, “Induced Voltages Ratio-Based Algorithm for Fault Detection, and Faulted Phase and Winding Identification of a Three-Winding Power Transformer,” *Energies,* vol. 7, no. 9, pp. 6031-6049, 2014.

[268] T. Molinski, “Minimizing the Life Cycle Cost of Power Transformers,” in *CIGRE Colloquium,* Dublin, 2001.

[269] W. Bergman, “Equipment Monitoring Selection As A Part Of Substation Automation,” in *IEEE Power Engineering Society 1999 Winter Meeting (Volume 2 ),* New York, 1999.

[270] P. Reddy and B. Rajpurohit, “On-line monitoring of winding parameters for single-phase transformers,” in *2014 IEEE 6th India International Conference on Power Electronics (IICPE),* Kurukshetra, 2014.

[271] Serveron Corporation, “Serveron White Paper: DGA Diagnostic Methods,” Serveron Corporation, A BPL Global Company, Hillsboro, 2007.

[272] S. Singh and M. Bandyopadhyay, “Dissolved gas analysis technique for incipient fault diagnosis in power transformers: A bibliographic survey,” *IEEE Electrical Insulation Magazine,* vol. 26, no. 6, pp. 41-46, 2010.

[273] A. Abu-Siada and S. Islam, “A new approach to identify power transformer criticality and asset management decision based on dissolved gas-in-oil analysis,” *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 19, no. 3, pp. 1007-1012, 2012.

[274] IEC 60599, “Mineral Oil-Impregnated Electrical Equipment in Service—Guide to the Interpretation of Dissolved and Free Gases Analysis,” 1999.

[275] IEEE Std C57.104, “Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers,” 1991.

[276] L. M. Oliveira and A. M. Cardoso, “Condition Monitoring and Diagnostics of Power Transformers,” *International Journal of COMADEM,* vol. 2, no. 3, pp. 5-11, 1999.

[277] L. M. Oliveira and A. M. Cardoso, “Power Transformers Fault Diagnostics by Park’s Vector Approach,” in *Transformers: Analysis, Design, and Measurement*, vol. 26, Boca Raton, Florida, CRC Press, 2012, pp. 287-310.

[278] H. d. F. Jr., J. G. S. Costa and J. L. M. Olivas, “A review of monitoring methods for predictive maintenance of electric power transformers based on dissolved gas analysis,” *Renewable and Sustainable Energy Reviews,* vol. 46, pp. 201-209, 2015.

[279] P. Lorin, “Lifetime decisions - Optimizing lifetime costs for transformers through informed decisions,” Special Report - ABB Review, Geneva.

[280] M. Akhavanhejazi, G. Gharehpetian, R. Faraji-dana, G. Moradi, M. Mohammadi and H. Alehoseini, “A new on-line monitoring method of transformer winding axial displacement based on measurement of scattering parameters and decision tree,” *Expert Systems with Applications,* vol. 38, no. 7, pp. 8886-8893, 2011.

[281] B. Sarkar, C. Koley, N. Roy and P. Kumbhakar, “Condition monitoring of high voltage transformers using Fiber Bragg Grating Sensor,” *Measurement,* vol. 74, pp. 255-267, 2015.

[282] B. Wicaksono, H. Kong, L. V. Markova and H.-G. Han, “Application of fluorescence emission ratio technique for transformer oil monitoring,” *Measurement,* vol. 46, no. 10, pp. 4161-4165, 2013.

[283] C. Yao, Z. Zhao, Y. Mi, C. Li, Y. Liao and G. Qian, “Improved Online Monitoring Method for Transformer Winding Deformations Based on the Lissajous Graphical Analysis of Voltage and Current,” *IEEE Transactions on Power Delivery,* vol. 30, no. 4, pp. 1965-1973, 2015.

[284] “ISO 14040:2006 - Environmental management - Life cycle assessment - Principles and framework,” International Organization for Standardization, 2010.

[285] M. Taylor and A. Taylor, “The technology life cycle: Conceptualization and managerial implications,” *International Journal of Production Economics,* vol. 140, no. 1, pp. 541-553, 2012.

[286] J. Brittes, E. Nunes, J. Jardini, L. Magrini and P. Kayano, “T&ERTTA, technical & economical real time transformer assessmemnt: An innovative approach on power transformer life cycle management,” in *2014 IEEE PES Transmission & Distribution Conference and Exposition - Latin America (PES T&D-LA)*, Medellin, 2014.

[287] W. Wang and J.-L. Bessède, “6 – Life cycle assessment of equipment for electricity transmission and distribution networks,” in *Eco-Friendly Innovation in Electricity Transmission and Distribution Networks*, Oxford, Woodhead Publishing, 2015, pp. 123-133.

[288] X.-p. Deng, Y.-y. Zhang, Y. Tong and B. Liu, “A life cycle cost-effectiveness assessment model for power transformer selection based on grey correlation analysis,” in *2014 China International Conference on Electricity Distribution (CICED)*, Shenzhen, 2014.

[289] M. Carlen, U. Överstam, V. Ramanan, J. Tepper, L. Swanstrom, P. Klys and E. Stryken, “Life cycle assessment of dry-type and oil-immersed distribution transformers with amorphous metal core,” in *CIRED 2011 - The 21st International Conference and exhibition on electricity distribution*, Frankfurt, 2011.

[290] L. Karlson, “LCA study of current transformers,” ABB Corporate Research, 2004.

[291] GreenDelta GmbH, “openLCA.org: Home,” 2014. [Online]. Available: http://www.openlca.org/. [Accessed 13 12 2015].

[292] I. Pavić, T. Capuder and I. Kuzle, “Value of flexible electric vehicles in providing spinning reserve services,” *Applied Energy,* vol. 157, pp. 60-74, 2015.

[293] P. Richardson, D. Flynn and A. Keane, “Optimal Charging of Electric Vehicles in Low-Voltage Distribution Systems,” *IEEE Transactions on Power Systems,* vol. 27, no. 1, pp. 268-279, 2012.

[294] T. Donateo, F. Licci, A. D’Elia, G. Colangelo, D. Laforgia and F. Ciancarelli, “Evaluation

of emissions of CO2 and air pollutants from electric vehicles in Italian cities," *Applied Energy,* vol. 157, pp. 675-687, 2015.

[295] Z. Duan, B. Gutierrez and L. Wang, "Forecasting Plug-In Electric Vehicle Sales and the Diurnal Recharging Load Curve," *IEEE Transactions on Smart Grid,* vol. 5, no. 1, pp. 527-535, 2014.

[296] F. Salah, J. P. Ilg, C. M. Flath, H. Basse and C. v. Dinther, "Impact of electric vehicles on distribution substations: A Swiss case study," *Applied Energy,* vol. 137, pp. 88-96, 2015.

[297] I. Colak, G. Fulli, S. Sagiroglu, M. Yesilbudak and C.-F. Covrig, "Smart grid projects in Europe: Current status, maturity and future scenarios," *Applied Energy,* vol. 152, pp. 58-70, 2015.

[298] F. H. Malik and M. Lehtonen, "A review: Agents in smart grids," *Electric Power Systems Research,* vol. 131, pp. 71-79, 2016.

[299] O. Erdinc, J. Catalao, M. Uzunoglu and A. Rifat Boynuegri, "Smart insular grids: Opportunities and challenges," in *2013 3rd International Conference on Electric Power and Energy Conversion Systems (EPECS)*, Istanbul, 2013.

[300] M. Kabir, Y. Mishra and R. Bansal, "Probabilistic load flow for distribution systems with uncertain PV generation," *Applied Energy,* vol. 163, pp. 343-351, 2016.

[301] J. Sexauer, K. McBee and K. Bloch, "Applications of probability model to analyze the effects of electric vehicle chargers on distribution transformers," *IEEE Transactions on Power Systems,* vol. 28, no. 2, pp. 847-854, 2015.

[302] K. Young, C. Wang, L. Y. Wang and K. Strunz, "Chapter 2 - Electric Vehicle Battery Technologies," in *Electric Vehicle Integration into Modern Power Networks*, New York, Springer New York, 2013, pp. 15-56.

[303] Bayerische Motoren Werke, "The new BMW i3 - Launches November 2013.," BMW UK, Printed in the UK, 2013.

[304] Kia Motors Europe, "The new Kia," Kia Motors Europe, Frankfurt am Main, Germany .

[305] Renault S.A., "Renault ZOE Simply Revolutionary," Renault U.K. Limited Customer Relations, The Rivers Office Park, Denham Way, Maple Cross, Rickmansworth, Hertfordshire, 2013.

[306] ©2014 Nissan North America, Inc. , "2014 Nissan Leaf Brochure," Dealer E-Process, 2014.

[307] Ford Motor Company, "2014 Ford Focus Electric Brochure," Ford Motor Company, 2013.

[308] X. Liu, Z. Chen, C. Zhang and J. Wu, "A novel temperature-compensated model for power Li-ion batteries with dual-particle-filter state of charge estimation," *Applied Energy,* vol. 123, pp. 263-272, 2014.

[309] A. Haidar, K. Muttaqi and M. Haque, "Multistage time-variant electric vehicle load modelling for capturing accurate electric vehicle behaviour and electric vehicle impact on electricity distribution grids," *IET Generation, Transmission & Distribution,* vol. 9, no. 16, pp. 2705-2716, 2015.

[310] F. Pinto, L. Costa, M. F. Dias de Amorini, L. Costa and M. Dias de Amorini, "Modeling spare capacity reuse in EV charging stations based on the Li-ion battery profile," in *2014 International Conference on Connected Vehicles and Expo (ICCVE)*, Vienna, 2014.

[311] P. Zhang, K. Qian, C. Zhou, B. Stewart and D. Hepburn, "A Methodology for Optimization of Power Systems Demand Due to Electric Vehicle Charging Load," *IEEE Transactions on Power Systems,* vol. 27, no. 3, pp. 1628-1636, 2012.

[312] N. B. R. d. C. Pereira, MSc Thesis - Eficiência energética no sector dos transportes rodoviários: metodologia para quantificação do excesso de energia consumida devido ao factor comportamental na condução de veículos automóveis ligeiros, Lisbon: Departamento de Ciências e Tecnologia da Biomassa - Universidade Nova de Lisboa, 2011.

[313] S. I. Vagropoulos and A. G. Bakirtzis, "Optimal Bidding Strategy for Electric Vehicle Aggregators in Electricity Markets," *IEEE Transactions on Power Systems,* vol. 28, no. 4, pp. 4031-4041, 2013.

[314] P. S. Georgilakis, “Environmental cost of distribution transformer losses,” *Applied Energy,* vol. 88, no. 9, pp. 3146-3155, 2011.

[315] C57.91-2011, “IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators,” IEEE Standard, 2012.

[316] C57.91-2011, “IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators,” IEEE Standard, 2012.

[317] H. Helms, C. Kämper and U. Lambrecht, “2 - Carbon dioxide and consumption reduction through electric vehicles,” in *Advances in Battery Technologies for Electric Vehicles*, Woodhead Publishing, 2015, pp. 17-34.

[318] D. Madzharov, E. Delarue and W. D'haeseleer, “Integrating electric vehicles as flexible load in unit commitment modeling,” *Energy,* vol. 65, pp. 285-294, 2014.

[319] Z. Dimitrova and F. Maréchal, “Techno-economic design of hybrid electric vehicles using multi objective optimization techniques,” *Energy,* vol. 91, p. 630–644, 2015.

[320] A. Schuller, C. M. Flath and S. Gottwalt, “Quantifying load flexibility of electric vehicles for renewable energy integration,” *Applied Energy,* vol. 151, pp. 335-344, 2015.

[321] K. Hedegaard, H. Ravn, N. Juul and P. Meibom, “Effects of electric vehicles on power systems in Northern Europe,” *Energy,* vol. 48, no. 1, pp. 356-368, 2012.

[322] C. Weiller and A. Neely, “Using electric vehicles for energy services: Industry perspectives,” *Energy,* vol. 77, pp. 194-200, 2014.

[323] M. Honarmand, A. Zakariazadeh and S. Jadid, “Optimal scheduling of electric vehicles in an intelligent parking lot considering vehicle-to-grid concept and battery condition,” *Energy,* vol. 65, pp. 572-579, 2014.

[324] P. Kadurek, “São Miguel Island as a case study on a possible usage of Electric vehicle to store energy,” *World Electric Vehicle Journal,* vol. 3, no. 4, pp. 756-763, 2009.

[325] B. Möller, K. Sperling, S. Nielsen, C. Smink and S. Kerndrup, “Creating consciousness about the opportunities to integrate sustainable energy on islands,” *Energy,* vol. 48, no. 1, pp. 339-345, 2012.

[326] E. Personal, J. I. Guerrero, A. Garcia, M. Peña and C. Leon, “Key performance indicators: A useful tool to assess Smart Grid goals,” *Energy,* vol. 76, no. 1, pp. 976-988, 2014.

[327] Z. Kovacic and M. Giampietro, “Empty promises or promising futures? The case of smart grids,” *Energy,* vol. 93, no. 1, pp. 67-74, 2015.

[328] A. E. C. Mondragon, E. S. Coronado and C. E. C. Mondragon, “Defining a convergence network platform framework for smart grid and intelligent transport systems,” *Energy,* vol. 89, pp. 402-409, 2015.

[329] O. Erdinc and N. G. Paterakis, “Chapter 1 - Overview of Insular Power Systems: Challenges and Opportunities,” in *Smart and Sustainable Power Systems: Operations, Planning and Economics of Insular Electricity Grids*, J. Catalão, Ed., Boca Raton, Florida, CRC Press (TAYLOR & FRANCIS Group), 2015.

[330] Q. Gong, S. Midlam-Mohler, E. Serra, V. Marano and G. Rizzoni, “PEV Charging Control Considering Transformer Life and Experimental Validation of a 25 kVA Distribution Transformer,” *IEEE Transactions on Smart Grid,* vol. 6, no. 2, pp. 648-656, 2015.

[331] N. Paterakis, I. Pappi, O. Erdinc, R. Godina, E. Rodrigues and J. Catalão, “Consideration of the impacts of a smart neighborhood load on transformer ageing,” *IEEE Transactions on Smart Grid,* 2016.

[332] M. Falahi, C. M. Hung, M. Ehsani, X. Lie and K. L. P. Butler, “Potential Power Quality Benefits of Electric Vehicles,” *IEEE Transactions on Sustainable Energy,* vol. 4, no. 4, pp. 1016-1023, 2013.

[333] Z. Darabi and M. Ferdowsi, “Aggregated Impact of Plug-in Hybrid Electric Vehicles on Electricity Demand Profile,” *IEEE Transactions on Sustainable Energy,* vol. 2, no. 4, pp. 501-508, 2011.

[334] S. Rezaee, E. Farjah and B. Khorramdel, “Probabilistic Analysis of Plug-In Electric Vehicles Impact on Electrical Grid Through Homes and Parking Lots,” *IEEE Transactions on Sustainable Energy,* vol. 4, no. 4, pp. 1024-1033, 2013.

[335] O. Erdinc, N. Paterakis, T. Mendes, A. Bakirtzis and J. Catalao, “Smart Household Operation Considering Bi-Directional EV and ESS Utilization by Real-Time Pricing-Based DR,” *IEEE Transactions on Smart Grid,* vol. 6, no. 3, pp. 1281-1291, 2015.

[336] U. Chukwu and S. Mahajan, “Real-Time Management of Power Systems With V2G Facility for Smart-Grid Applications,” *IEEE Transactions on Sustainable Energy,* vol. 5, no. 2, pp. 558-566, 2014.

[337] A. Alahyari, M. Fotuhi-Firuzabad and M. Rastegar, “Incorporating Customer Reliability Cost in PEV Charge Scheduling Schemes Considering Vehicle-to-Home Capability,” *IEEE Transactions on Vehicular Technology,* vol. 64, no. 7, pp. 2783-2791, 2015.

[338] Z. Chen, L. Wu and Y. Fu, “Real-Time Price-Based Demand Response Management for Residential Appliances via Stochastic Optimization and Robust Optimization,” *IEEE Transactions on Smart Grid,* vol. 3, no. 4, pp. 1822-1831, 2012.

[339] K. Tsui and S. Chan, “Demand Response Optimization for Smart Home Scheduling Under Real-Time Pricing,” *IEEE Transactions on Smart Grid,* vol. 3, no. 4, pp. 1812-1821, 2012.

[340] M. Pipattanasomporn, M. Kuzlu and S. Rahman, “An Algorithm for Intelligent Home Energy Management and Demand Response Analysis,” *IEEE Transactions on Smart Grid,* vol. 3, no. 4, pp. 2166-2173, 2012.

[341] M. Kuzlu, M. Pipattanasomporn and S. Rahman, “Hardware Demonstration of a Home Energy Management System for Demand Response Applications,” *IEEE Transactions on Smart Grid,* vol. 3, no. 4, pp. 1704-1711, 2012.

[342] S. Shao, M. Pipattanasomporn and S. Rahman, “Demand Response as a Load Shaping Tool in an Intelligent Grid With Electric Vehicles,” *IEEE Transactions on Smart Grid,* vol. 2, no. 4, pp. 624-631, 2011.

[343] F. De Angelis, M. Boaro, D. Fuselli, S. Squartini, F. Piazza and Q. Wei, “Optimal Home Energy Management Under Dynamic Electrical and Thermal Constraints,” *IEEE Transactions on Industrial Informatics,* vol. 9, no. 3, pp. 1518-1527, 2013.

[344] X. Chen, T. Wei and S. Hu, “Uncertainty-Aware Household Appliance Scheduling Considering Dynamic Electricity Pricing in Smart Home,” *IEEE Transactions on Smart Grid,* vol. 4, no. 2, pp. 932-941, 2013.

[345] N. Paterakis, S. Santos, J. Catalao, O. Erdinc and A. Bakirtzis, “Coordination of smart-household activities for the efficient operation of intelligent distribution systems,” in *2014 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, Istanbul, 2014.

[346] M. Weigand, S. Bohn, D. Beyer and M. Agsten, “Integration of Electric Vehicle Charging into an International and Environment-friendly Context,” *SAE International Journal of Passenger Cars - Electronic and Electrical Systems,* vol. 7, no. 2, pp. 536-543, 2014.

[347] S. Bohn, M. Agsten, A. Dubey and S. Santoso, “A Comparative Analysis of PEV Charging Impacts - An International Perspective,” in *SAE 2015 World Congress & Exhibition*, 2015.

[348] A. Tascikaraoglu, A. Boynuegri and M. Uzunoglu, “A demand side management strategy based on forecasting of residential renewable sources: A smart home system in Turkey,” *Energy and Buildings,* vol. 80, pp. 309-320, 2014.

[349] S. Bohn, R. Feustel and M. Agsten, “MC-based Risk Analysis on the Capacity of Distribution Grids to Charge PEVs on 3-ph 0.4-kV Distribution Grids Considering Time and Location Uncertainties,” *SAE International Journal of Passenger Cars - Electronic and Electrical Systems,* vol. 8, no. 2, pp. 394-400, 2015.

[350] “ComEd residential real-time pricing program,” [Online]. Available: https://hourlypricing.comed.com/. [Accessed 11 12 2015].

[351] “Power Smart Pricing,” [Online]. Available: https://www.powersmartpricing.org/. [Accessed 15 10 2015].

[352] N. O'Connell, P. Pinson, H. Madsen and M. O'Malley, “Benefits and challenges of electrical demand response: A critical review,” *Renewable and Sustainable Energy Reviews,* vol. 39, pp. 686-699, 2014.

[353] N. Paterakis, M. Medeiros, J. Catalao and O. Erdinc, “Distribution system operation enhancement through household consumption coordination in a dynamic pricing environment,” in *2015 IEEE Eindhoven PowerTech*, Eindhoven, 2015.

[354] N. Paterakis, I. Pappi, J. Catalao and O. Erdinc, "Optimal operational and economical coordination strategy for a smart neighborhood," in *2015 IEEE Eindhoven PowerTech*, Eindhoven, 2015.

[355] J. Salvatore, "World Energy Perspective - Cost of Energy Technologies," World Energy Council, London, 2013.

[356] A. Sapio, "The effects of renewables in space and time: A regime switching model of the Italian power price," *Energy Policy,* vol. 85, pp. 487-499, 2015.

[357] A. Mishra, D. Irwin, P. Shenoy, J. Kurose and T. Zhu, "GreenCharge: Managing Renewable Energy in Smart Buildings," *IEEE Journal on Selected Areas in Communications,* vol. 31, no. 7, pp. 1281-1293, 2013.

[358] Z. Ren, G. Grozev and A. Higgins, "Modelling impact of PV battery systems on energy consumption and bill savings of Australian houses under alternative tariff structures," *Renewable Energy,* vol. 89, pp. 317-330, 2016.

[359] O. Alrumayh and K. Bhattacharya, "Model predictive control based home energy management system in smart grid," in *2015 IEEE Electrical Power and Energy Conference (EPEC)*, London, ON, Canada, 2015.

[360] K. Horváth, E. Galvis, M. G. Valentín and J. Rodellar, "New offset-free method for model predictive control of open channels," *Control Engineering Practice,* vol. 41, pp. 13-25, 2015.

[361] E. Stephens, D. Smith and A. Mahanti, "Game Theoretic Model Predictive Control for Distributed Energy Demand-Side Management," *IEEE Transactions on Smart Grid,* vol. 6, no. 3, pp. 1394-1402, 2015.

[362] G. Mantovani and L. Ferrarini, "Temperature Control of a Commercial Building With Model Predictive Control Techniques," *IEEE Transactions on Industrial Electronics,* vol. 62, no. 4, pp. 2651-2660, 2015.

[363] C. Chen, J. Wang, Y. Heo and S. Kishore, "MPC-Based Appliance Scheduling for Residential Building Energy Management Controller," *IEEE Transactions on Smart Grid,* vol. 4, no. 3, pp. 1401-1410, 2013.

[364] Y. Ma, A. Kelman, A. Daly and F. Borrelli, "Predictive Control for Energy Efficient Buildings with Thermal Storage: Modeling, Stimulation, and Experiments," *IEEE Control Systems,* vol. 32, no. 1, pp. 44-64, 2012.

[365] A. Bemporad, "Model Predictive Control Design: New Trends and Tools," in *IEEE Conference on Decision & Control*, San Diego,USA, 2006.

[366] D. Oliveira, E. Rodrigues, T. Mendes, J. Catalão and E. Pouresmaeil, "Model predictive control technique for energy optimization in residential appliances," in *Proceedings of the IEEE International Conference on Smart Energy Grid Engineering — SEGE'15*, Oshawa, 2015.

[367] D. Oliveira, E. Rodrigues, R. Godina, T. Mendes, J. Catalão and E. Pouresmaeil, "MPC weights tunning role on the energy optimization in residential appliances," in *Proceedings of the 25th Australasian Universities Power Engineering Conference — AUPEC 2015*, Wollongong, Australia, 2015.

[368] D. Oliveira, E. Rodrigues, R. Godina, T. Mendes, J. Catalão and E. Pouresmaeil, "Enhancing home appliances energy optimization with solar power integration," in *Proceedings of the IEEE Region 8 International Conference on Computer as a Tool — EUROCON 2015*, Salamanca, Spain, 2015.

[369] A. Molina, A. Gabeldon, J. Fuentes and C. Alvarez, "Implementation and assessment of physically based electricl load models: application to direct load control residential programmes," *IEE Proc-Gener. Tranm. Distrib,* vol. 150, 2003.

[370] L. L. K. Elamari and R. Tonkoski, "Using electric water heaters (EWHs) for power balancing and frequency control in PV-Diesel Hybrid, mini-grids," in *Proc. World Renewable Energy Energy Congress*, Sweden, 2011.

[371] E. Pouresmaeil, J. M. Gonzalez, C. A. Canizares and K. Bhattacharya, "Development of a Smart Residential Load Simulator for Energy Management in Smart Grids," *IEEE Transactions on Power Systems,* Submited.