



Universidade do Minho
Escola de Engenharia

Omid Abrishambaf

MRTS - A Flexible System for Microgrids
Real-Time Digital Simulation Using
Hardware-in-the-Loop



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Submitted Thesis at University of Minho
For Master Degree in Mechatronic Engineering

Supervisors
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Prof. Doctor Zita Vale

DECLARATION

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MRTS - A Flexible System for Microgrids Real-Time Digital Simulation Using Hardware-in-the-Loop

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Year of Completion: 2015

Submitted Thesis at University of Minho for Master Degree in Mechatronic Engineering

É AUTORIZADA A REPRODUÇÃO INTEGRAL DESTA DISSERTAÇÃO APENAS PARA EFEITOS DE INVESTIGAÇÃO, MEDIANTE DECLARAÇÃO ESCRITA DO INTERESSADO, QUE A TAL SE COMPROMETE.

University of Minho, ____/____/____

Signature:

تقدیم به همه کسانی که علاقه مند به علم هستند

For all those interested in science.

Acknowledgements

I would like to express my special appreciation and thanks to my advisors: Prof. Doctor João Luiz Afonso and Prof. Doctor Zita Vale, you have been a tremendous mentor for me. I would like to thank you for encouraging my research and for allowing me to grow as a research scientist. Your advice on both research as well as on my career have been priceless. It was a pleasure working with you.

The experimental work would not have been finalized so straightforwardly without the enthusiastic dedication of Luis Gomes and Pedro Faria. I am grateful for their help during performing of the experimental test in the GECAD laboratory.

A special thanks to my family. Words cannot express how grateful I am to my father (Mohammad Hossein), mother (Mahin), my brothers (Reza and Amin) and my fiancée (Mahsa) for all of the sacrifices that you have made on my behalf. Your prayer for me was what sustained me thus far. At the end, I would like to express deep appreciation to my friends who supported me in this program, and also for their delightful friendship.

Abstract

The recent changes on the power systems paradigm require the active participation of small and medium players in the electricity network management. With the electricity price flotation, the small and medium players must manage their consumption in order to decrease the economic costs without the degradation of the users' comfort. Additionally, the appearance of new concepts in the power systems, such as smart grids and microgrids, bring several advantages. This includes the use of distributed generation and the execution of demand response programs. However, their implementation on the current power grid can also bring management and stability issues.

The purpose of this dissertation is to simulate, in real-time, a microgrid facility by employing real hardware resources and survey of the consumption and generation profiles of the small and medium consumers. The facility would include small power load, medium power load and a micro-generation unit. This microgrid facility proposes controlling methods of hardware devices that enable the real loads to be integrated as hardware-in-the-loop (HIL) loads for the small and medium simulation players. The implemented system uses real consumption loads and real wind power generator.

The main contribution of this dissertation is the integration of real resources inside the simulation environment. Furthermore, this study describes the hardware and software developed and implemented on the loads built to manual use, outside of the simulation environments. In the case studies, actual consumption and generation profiles of the small and medium consumers has been employed in order to simulate in real-time.

Keywords: Real-Time Simulation, Hardware-in-the-Loop, Microgrid, Distributed Generation.

Resumo

As mudanças recentes no paradigma dos sistemas elétricos de energia requerem uma participação ativa dos participantes de pequeno e médio tamanho na gestão da produção e utilização da eletricidade. Com a flutuação do preço da eletricidade, estes participantes têm de gerir o consumo de modo a diminuir custos sem degradar o conforto dos utilizadores.

Além disso, o aparecimento de novos conceitos de eletrónica de potência, como as redes inteligentes e as micro-redes, traz grandes vantagens. Isto inclui o uso de produção distribuída e a execução de programas de resposta à procura. No entanto, as suas implantações podem trazer complicações de gestão e estabilidade aos atuais sistemas elétricos de energia.

O objetivo desta dissertação é simular, em tempo real, uma micro-rede usando recursos de hardware reais e analisar o consumo e perfis de geração de consumidores pequenos e médios. A micro-rede incluiria uma pequena carga, uma média carga e uma unidade de micro-geração. Esta micro-rede propõe métodos de controlar dispositivos de hardware que permitem integrar cargas reais como cargas *hardware-in-the-loop* (HIL) para simulação de participantes pequenos e médios. O sistema implementado tem cargas com consumos reais e um gerador de energia eólica.

A principal contribuição desta dissertação é a integração de dispositivos reais dentro do ambiente de simulação. Além disso, este estudo descreve o hardware e o software desenvolvidos e implementados nas cargas desenhadas para utilização manual, fora dos ambientes de simulação. Nos casos de estudo, o consumo real e os perfis de geração dos consumidores pequenos e médios foram utilizados para realizar as simulações em tempo-real.

Palavras-Chave: Simulação em Tempo Real, Hardware-in-the-Loop, Micro-Rede, Produção Distribuída.

Abstract (Persian)

تغییرات اخیر در سیستم های توزیع قدرت ، شرکت کردن فعال مصرف کنندگان و تولید کنندگان برق را بیش از پیش مورد اهمیت قرار داده است. همچنین با توجه به متغیر بودن قیمت برق ، این واحدها باید مدیریت کافی را بر روی مصرف خود داشته ، تا بتوانند هزینه های ماهیانه انرژی را کاهش دهند. علاوه بر این، پیدایش مفاهیم جدیدی در سیستم های قدرت ، مانند شبکه های هوشمند ، فواید بسیاری را برای این سیستم ها ایجاد کرده اند. این فواید شامل استفاده از تکنولوژی تولید پراکنده و یا اجرای برنامه های پاسخ به بخش تقاضا می باشند. البته در کنار این فواید، این مفاهیم جدید مشکلاتی مدیریتی و پایداری را برای شبکه ایجاد می کنند.

هدف از این پایان نامه ، شبیه سازی زمان واقعی یک شبکه برق کوچک می باشد که از مصرف کنندگان و تولید کنندگان واقعی استفاده می کند. این شبکه برق کوچک با استفاده از سناریو HIL ، روش های کنترلی را ارائه می دهد که اپراتور را قادر می سازد تا با ادغام سخت افزار های واقعی در محیط شبیه سازی ، به نتایج واقعی و قابل قبول تری دست یابد. همچنین این پایان نامه ، نرم افزار ها و سخت افزار هایی را توضیح می دهد که با اجرای آنها بر روی وسایلی که برای استفاده های معمولی و خارج از محیط شبیه سازی ساخته شده اند ، به صورت سخت افزار های واقعی در محیط شبیه سازی ایفای نقش کنند. در موارد بررسی شده در این پایان نامه ، یک دوره دو ساعته از این شبیه سازی زمان واقعی برای مصرف کنندگان خانگی و تجاری بیان می شود.

کلمات کلیدی: شبیه سازی زمان واقعی ، HIL ، شبکه های کوچک برق ، تولید پراکنده.

Index

Acknowledgements	vii
Abstract	ix
Resumo	xi
Abstract (Persian)	xiii
List of Figures	xvii
List of Tables	xix
List of Abbreviations and Acronyms	xxi
Chapter 1 – Introduction	1
1.1. Power Network Management Issues	1
1.2. Motivations	1
1.3. Objectives	2
1.4. Contributions	2
1.5. Thesis Organization	3
Chapter 2 – Survey of the Power Systems	5
2.1. Current Power Grids	5
2.2. Smart Grids	8
2.3. Microgrids	13
2.4. Conclusion	16
Chapter 3 – Demand Side Management in the Smart Grid Context	17
3.1. Smart Home in Demand Side Management	17
3.1.1. Description of Smart Home	17
3.1.2. Application of Smart Appliance in Demand Side Management	20
3.2. Distributed Generation in Demand Side Management	22
3.2.1. Overview and Key Issues of Distributed Generation	23
3.2.2. Micro-Generation Systems	25
3.3. Conclusion	28
Chapter 4 – Microgrid Real-Time Simulator	29
4.1. Overview of the MRTS	29
4.2. Real-Time Digital Simulator	31
4.3. Integration of MRTS Players	36
4.3.1. Low Power Consumer	37
4.3.2. Medium Power Consumer	47
4.3.3. Micro-Generation Unit	52
4.4. MRTS Power Lines	55
4.5. Conclusion	57
Chapter 5 – Simulated Scenarios and Case Studies	59
5.1. Simulation of Residential Consumption Profile	59
5.2. Simulation of Small Commerce Facility Consumption Profile	63
5.3. Simulation of Residential Consumption and Generation Profiles	67
5.4. Conclusion	73
Chapter 6 – Conclusion	75
6.1. Conclusion	75
6.2. Suggestions for Future Works	77
References	79

List of Figures

Figure 2.1 – Structure of the current power distribution networks.	5
Figure 2.2 – Influence of natural disasters on power distribution network.	8
Figure 2.3 – Smart meter.	11
Figure 2.4 – Plug-In Electric Vehicle.	13
Figure 2.5 – Overview of the microgrids [14].	14
Figure 2.6 – Home-scale microgrid.	15
Figure 2.7 – HAN and NAN networks [16].	16
Figure 3.1 – Various components of a smart home.	18
Figure 3.2 – Schematic of a real smart home [20].	19
Figure 3.3 – Load shifting technique in DSM [22].	21
Figure 3.4 – Consumption of different kinds of domestic appliance [22].	22
Figure 3.5 – Inputs and outputs of the central controller unit [26, 29].	27
Figure 3.6 – Flowchart of management algorithm in grid-connected mode [28].	28
Figure 4.1 – Overview of the MRTS.	30
Figure 4.2 – Effect of the step size in the precision [32].	32
Figure 4.3 – OP5600-OPAL-RT simulator.	32
Figure 4.4 – Documents of the output boards, (a) Analog output (b) Digital output.	33
Figure 4.5 – Controlling process of the real resources by the real-time simulator (i.e. OPAL).	34
Figure 4.6 – RT-LAB home windows.	35
Figure 4.7 – Two main subsystems of a Simulink model for executing on OPAL.	35
Figure 4.8 – MRTS Simulink model.	36
Figure 4.9 – Hardware of the 4 kVA Load.	38
Figure 4.10 – Arduino Mega 2560 equipped with Ethernet shield.	39
Figure 4.11 – Arduino management scenario.	39
Figure 4.12 – Flowchart of Arduino program.	40
Figure 4.13 – Modbus RTU message in RS-485 communication.	41
Figure 4.14 – RS-485 interface between Arduino Mega 2560 and energy meter.	42
Figure 4.15 – Modbus TCP/IP message in Ethernet communication network.	43
Figure 4.16 – MATLAB Simulink model of 4 kVA load.	44
Figure 4.17 – An example of IEEE 754 conversion (decimal number to 4-bytes hexadecimal message).	45
Figure 4.18 – IEEE 754 conversion (4-bytes hexadecimal message to decimal).	47
Figure 4.19 – Front view of the 30 kVA load.	48
Figure 4.20 – Simulink model for controlling 30 kVA hardware resource.	49
Figure 4.21 – Block parameters (a) OpCtrl OP5142EX1 (b) OP514EX1 DigitalOut.	49
Figure 4.22 – Flowchart of implemented function for 30 kVA load.	51
Figure 4.23 – EOLYP 1.2 kW wind turbine emulator.	52
Figure 4.24 – Equipment of the wind turbine emulator.	53
Figure 4.25 – Controlling diagram of wind turbine emulator by the OPAL.	53
Figure 4.26 – MATLAB Simulink model for controlling wind turbine emulator.	54

Figure 4.27 – MRTS power lines architecture.	55
Figure 4.28 – MATLAB Simulink model for TCP/IP communication.	56
Figure 4.29 – MRTS configuration for case studies.	57
Figure 5.1 – Consumption profile of the private house 1 from 9:20 AM to 11:20 AM [41].	61
Figure 5.2 – Proposed system for case study 1.	61
Figure 5.3 – Configuration of MRTS power lines for case study 1.	62
Figure 5.4 – Real-time simulation of residential consumption by 4 kVA load in period of two hours.	62
Figure 5.5 – Controlling decision of 4 kVA load.	63
Figure 5.6 – Consumption profile of the small commerce facility from 22:00 PM to 00:00 AM [41].	64
Figure 5.7 – Implemented scenario for case study 2.	65
Figure 5.8 – Configuration of MRTS power lines for case study 2.	66
Figure 5.9 – Simulink model used in the case study 2.	66
Figure 5.10 – Real-time simulation of consumption in case study 2.	67
Figure 5.11 – Consumption profile of private house 1 for case study 3 [41].	68
Figure 5.12 – MRTS power lines configuration for case study 3.	69
Figure 5.13 – Two probable situations of case study 3.	70
Figure 5.14 – MATLAB Simulink model of case study 3.	71
Figure 5.15 – Simulated generation and consumption profiles of the private house 1.	71
Figure 5.16 – Energy sold to the utility grid by MRTS system.	72
Figure 5.17 – Energy purchased from the utility grid by MRTS system.	72
Figure 5.18 – Merging the purchased energy profile with generation and consumption profiles.	72
Figure 5.19 – Integration of sold energy profile with generation and consumption profiles.	73

List of Tables

Table 4.1 – Function codes of Modbus protocol [36].	42
Table 5.1 – Measured data of active power consumption in period of two hours on private house [41]....	60
Table 5.2 – Measured data (active power) of the private house 1 for case study 3 [41].	68
Table 5.3 – Wind speed data for case study 3 [42].	69

List of Abbreviations and Acronyms

AC	Alternating Current
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
DA	Distribution Automation
DC	Direct Current
DER	Distributed Energy Resource
DG	Distributed Generation
DR	Demand Response
DSM	Demand Side Management
EPRI	Electric Power Research Institute
ESS	Energy Storage System
EV	Electric Vehicle
FIT	Feed-In Tariffs
HAN	Home Area Network
HIL	Hardware-In-the-Loop
HMI	Human Machine Interface
IEA	International Energy Agency
ISO	Independent System Operator
LAN	Local Area Network
MAN	Metropolitan Area Network
MRTS	Microgrid Real-Time Simulator
NAN	Neighborhood Area Network
PEV	Plug-in Electric Vehicle
PLC	Programmable Logic Controller
PMU	Phasor Measurement Unit
PV	Photovoltaic
RER	Renewable Energy Resource
RPM	Revolutions Per Minute
RTO	Regional Transmission Organization
SCADA	Supervisory Control And Data Acquisition
SOC	State-Of-Charge
UPS	Uninterruptible Power Supply

Chapter 1

Introduction

1.1. Power Network Management Issues

In the last years, we witness a change in the electrical distribution networks [1]. The paradigm of smart grid is becoming a reality in today electrical networks [2]. The participation of small and medium players in the smart grid context is a difficult task that must be overcome.

The use of Distributed Generation (DG) in small and medium players makes the network management more difficult and instable [3]. In order to solve this problem, new concepts have been implemented, such as, microgrids [4]. This type of aggregator can manage and control a small or medium geographic area in order to change the electrical network to a distributed system.

The participation of small and medium players inside the smart grid context could be made by the execution of Demand Response (DR) programs [3]. These programs can be executed by any aggregator, geographic or contractual. The small and medium players have the option to participate in DR programs. There are two main DR programs [5]: incentive-based and price-based.

Therefore, it is necessary to have an autonomous system in order to promote the DR participation among the small and medium players. This will give autonomy to the players and reduce the user interaction with the system.

Additionally, it is essential to produce substantial reliable simulations before the massive execution of DR programs [6]. The simulation of an electrical distribution network can be very difficult. The use of computational resources can be very expensive and, in some cases, are incapable of producing reliable results.

1.2. Motivations

The real-time simulation using real resources helps the scientific community to achieve reliable simulation results. Therefore, the integration of consumer and generator

units into the microgrids context, leads to improve the execution of DR programs. Moreover, real-time simulation of a microgrid by real facilities enables analysts of the electricity market to investigate their implementation programs and prototypes.

1.3. Objectives

The main goal of this dissertation is to present controlling methods of the hardware devices that enable them to be integrated as hardware-in-the-loop (HIL) in the real-time digital simulator for microgrids simulation. Therefore, the principal objectives for this purpose include:

- Implementing an algorithm to control the hardware resources from the real-time simulator: Executing the hardware and software methods for integrating the real resources into the real-time simulator as HIL;
- Developing a MATLAB Simulink model for merging resources into the real-time simulator: Designing and developing a Simulink model for employing the real resources on the simulation environment;
- Connecting the real resources to the real-time simulator via standard communication protocols: Using several standard communication protocols, such as IEEE 754, for integrating the hardware resources into the real-time simulator.

The implementation of objectives was possible only after an exhaustive study mentioned in the state of the art (chapter 2 and 3), which allowed the author to acquire knowledge in this area.

1.4. Contributions

Integration of real hardware resources in the simulation environment brings a possibility for the experts to investigate their prototype. This dissertation provides a flexible system for microgrids real-time digital simulation using hardware-in-the-loop that can be used for investigating different concepts of the power grids such as demand response. There are already technical papers submitted in this topic:

- Omid Abrishambaf, Luis Gomes, Pedro Faria, and Zita Vale, “Simulation and Control of Consumption and Generation of Hardware Resources in Microgrid Real-Time Digital Simulator,” in *Innovative Smart Grid Technologies Latin America (ISGT LA), 2015 IEEE PES Conference On*, Montevideo, Uruguay, 5-7 Oct. 2015. (Abstract accepted)

- Omid Abrishambaf, Luis Gomes, Pedro Faria, Joao L. Afonso , and Zita Vale, “Real-Time Simulation of Renewable Energy Transactions in the Microgrid Context Using Real Hardware Resources,” in *Transmission and Distribution Conference and Exposition (PES T&D), 2016 IEEE PES*, Kay Bailey Hutchinson Convention Center, Dallas, Texas, USA, 2-5 May 2016. (Submitted)

In addition to these mentioned papers, the proposed system in this dissertation contributes to development of the following research projects:

- *DREAM-GO*: This project Concerns about Demand Response (DR) programs with adequate business models for leverage demand flexibility both on centralized and distributed models, as renewable energy generation that is highly depend-able of uncontrolled factors (as wind and solar radiation) for which hardly trustful anticipated forecasts. This project is financed by Horizon 2020 European Commission.
- *GID-Microrede*: GID project proposes a distributed approach to manage the energy resources of a microgrid. The use of microgrids has been gaining strength in the respective literature and academic community, providing numerous benefits to the electric distribution network. The microgrids increase the electrical network reliability and reduce the impact caused by network faults. This project is financed by QREN and is part a of SEAS project.
- *SEAS – Smart Energy Aware Systems*: SEAS project addresses the problem of inefficient and unsustainable energy consumption, which is due to a lack of sufficient means to control, monitor, estimate and adapt energy usage of systems versus the dynamic usage situations and circumstances influencing the energy usage. SEAS project objective is to enable interworking of energy, ICT and automation systems at consumption sites, and to introduce dynamic and fine grained ICT-based solutions to control, monitor and estimate energy consumption. This project is under the European ITEA2 program and the reference number is 12004.

1.5. Thesis Organization

This dissertation has been organized into six main chapters. After the introduction, mentioned in chapter 1, all of the theoretical concepts of this project are addressed in the chapters 2 and 3. These chapters are related to state of the art.

Chapter 4 presents the technical and scientific aspects of the work. In this chapter all of the specifications of hardware resources (small consumer, medium consumer and micro-generation unit) and implemented scenarios for merging these resources into the simulation environment are described.

Chapter 5 presents several case studies that employed the developed system in this dissertation in order to simulate real consumption and generation profiles of small and medium consumers.

Finally, chapter 6 proposes the conclusions reached by this dissertation. Furthermore, it provides suggestions for future works in order to continue the goals of this thesis.

Chapter 2

Survey of the Power Systems

Electric power system, in simple way, is related to a set of equipment that generates electricity and transmits it to the consumers by transmission lines. A network consists of this set of equipment, called power grid. Power system depending on the demand side, categorizes in three parts of household consumers, commercial consumers and industrial consumers. In this chapter, the actual power grid will be explained, and then smart grids and microgrids will be described.

2.1. Current Power Grids

Current power grid is a power distribution network that we see in our life for a long time without any changes. Current power grid after passing an order dispatches electricity from a power plant (where electricity produces) to the consumers. The hierarchical structure of current power grids has been illustrated in Figure 2.1.

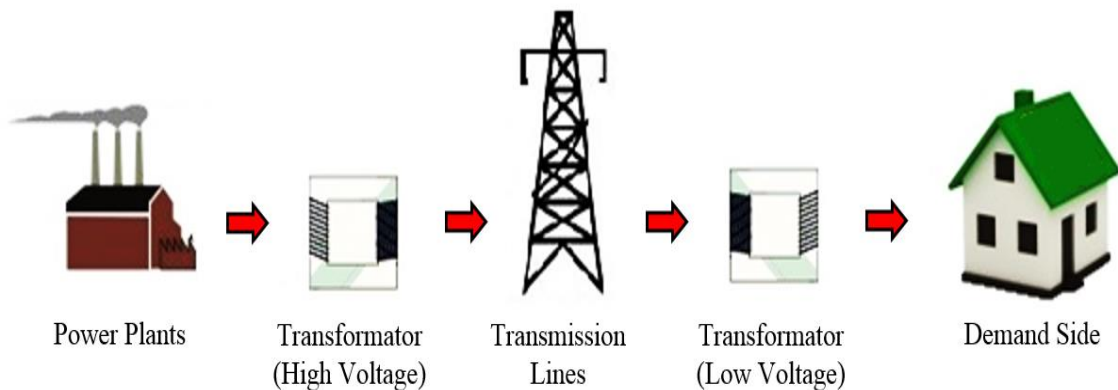


Figure 2.1 – Structure of the current power distribution networks.

As it can be seen in the Figure 2.1, power plants (which can be coal-fired power plants, natural gas, nuclear and hydropower) are situated on the first level of this structure and consumers have been located on lower level of that. Generally, these power grids have one-way distribution lines that deliver produced electricity to the clients [2].

Difficulties and Limitations

Inefficiency in Management of Peak Demand

Generally, power distribution networks are designed for a bigger value of the peak demand. Peak demand occurs rarely more than a period of short time and it means that the power grid should be always ready for this phenomenon and it would be a reason for the inefficiency of the normal power grid. Moreover, power network should be able to produce an additional amount of electricity for compensation of this demand that has primarily related to fossil power plant. It has implications such as lower productivity, increasing production costs, producing much more greenhouse gases and thereupon will lead to have air pollution and global warming [2].

Additionally, for compensation of this demand, power distribution companies should increase and develop their production capacity. This increased capacity is associated with a rapid increment in the fossil fuel consumption and can be lead to have some additional costs. By constructing more power plants, this phenomenon approximately can be solved but it is not wisely approach and pleasant from an environmental and natural perspective [2].

Inability of Exchanging Reliable Data

In order to troubleshooting, repairing, and maintenance of power equipment, which are generally expensive, several levels of controlling and maintenance approaches such as Supervisory Control And Data Acquisition (SCADA) are created. Because of some limitations (for instance, one-way communication), which are impose by upstream companies to distribution companies, they are not able to have real-time control on the grid. This deficiency feels clearly in demand side. It causes that electricity consumers have no information about the price of electricity and/or amount of energy consumption in real-time. Hence, current power grids are not accountable for customers demand [2].

Limited Functionality of Power Grid in Utilization of Renewable Energy Resources

For supplying the consumers in the peak times, other energy resources such Renewable Energy Resource (RER) can be used. RERs categorize as Distributed Energy Resources (DERs), which are developing significantly, but current power distribution networks are not able to support and integrate this kind of resources. The reason of this inefficiency can be the hierarchical structure and central controlling of the networks that they did not design for two-way flow of the energy [2].

Ineffectiveness of Grid for Development of Electric Vehicles and Plug-in Electric Vehicles

Electric Vehicles (EVs) and Plug-in Electric Vehicles (PEVs) are categorized as Green vehicles. Less greenhouse gas emissions and absence of production of other pollutants are the most important advantages of EVs and PEVs rather than gasoline vehicles with internal combustion engine. By using EVs, lots of air pollution will decrease and global warming can be prevented [7].

By mass production of EVs in the near future, significant losses and damages will occur on the current power network, because EVs can face the grid with overload, and users of EVs may have no information about the optimal time of charging the batteries of their vehicle [7].

Susceptibility of the Grid for Cutting the Power and Power Quality Disorder

Increasing the demand rate of electrical energy, which is associated with weakness of investment in electricity infrastructure, stability of the system has been reduced. Unpredicted increment in demand side or any errors on the power distribution system leads to damage the equipment and interrupt the power. It can have some economic damages for household and industrial users as well [8].

Manufacturers, which have high technology and critical infrastructure, namely communication networks that rely on the high quality of power, in absence of that, their performance would be impaired. Hence, this kind of manufacturers should take some strategies to collate with this issue. This uncertainty of power quality can have irrecoverable damages for consumers of electricity [8].

Vulnerability of Current Power Networks by Natural Disasters

Current power networks are vulnerable by natural disasters such as earthquake or storm. Designing of power distribution networks is such that after facing to natural disasters it cannot retrieve without cutting the power. Only a short circuit of one phase in the network is enough to lose lots of energy.



Figure 2.2 – Influence of natural disasters on power distribution network.

Absence of distributed power sources, namely RER in the global networks leads to have a much more vulnerability by natural disasters that these cases are because of the hierarchical structure and central controlling of the power networks [8].

Old and Outdated of Power Grid

It is more than 100 years that pass from the first designing of the power grid. Energy transmission lines and prevalent power distribution networks are very old and primal and obsolete technologies are applied for designing and construction of them [8].

By using smart grids and microgrids technologies, most of these difficulties and limitations that mentioned above, would be solved. In the next part, smart grids and microgrids will be demonstrated completely.

2.2. Smart Grids

The smart grids are the development and updating of the current power networks and contain advanced monitoring, automation, electricity production controlling, transmission and distribution. The smart grid can be defined from three viewpoints [3]:

- From a consumer viewpoint, smart grid means that they can have intelligent management on their consumption and they can decrease their electricity costs;
- From environment experts viewpoint, smart grid means that using the technology for solving some problems such as adverse changing of climate or avoidance of excessive production of carbon gas and greenhouse gases;
- Moreover, from industry consumers viewpoint, it means removing peak times, intelligent decision and providing detailed information about the network status.

The smart grid is one of the newest technology and it is the result of expert's efforts in order to modernize the distribution networks. The main purpose is to reliable

electricity supply and response to increased demands of the consumers by minimum damages to the environment. Smart grid technology is able to substantial changes on production, transmission, distribution and using the electrical energy, which is associated with economic and environmental benefits, and finally response to the demand side and a reliable and stable power network would be achieved. On the other hand, by using data acquisition on the critical situation, the system is able to decide and prevent undesirable power cut [3].

By increasing the usage of digital information and controlling technologies, power grids are able to have more reliability, security, integration of distributed power resources, responding to the consumer's demand in energy productivity manner.

Features and Applications

In fact, characteristics of the smart grid represent properties of this kind of networks based on their abilities. Smart grids are designed to decrease disadvantages of the current power grid, which mentioned above, and they have the following characteristics and applications:

Consciously and Proactively Participation of Consumers in the Smart Grid

Active participation of consumers in electricity markets has some benefits for both customers and distribution companies. Smart grid provides required information in demand side about their consumption patterns and the price of electricity in order to enable consumers to participate in electricity markets. This feasibility enables consumers to have a reasonable balance between their demand, local power resources and the power grid. The ability of reducing the consumption in the peak times enables electricity manufacturers to decrease investment and operation costs. Simultaneously, environmental benefits, reducing line losses and minimizing the operation time of power plants in low efficiency would be achieved [6].

Modified Production and Storage

Smart grids have the capability of integration DERs located in the place of consumers with concentrated power plants. Although some huge power plants, such as advanced nuclear power plants, have principal and fundamental role in the smart grid, but it is possible for this system to use many small DER units namely photovoltaic cells, wind turbine, advanced batteries, and fuel cells. These small DER units can be connected to the grid and have functionality to use various types of resources with each other by using the ability of Plug and Play [9].

Providing Required Power Quality

Monitoring and surveillance, detection and response to the low power quality lead to decrease losses and provide high quality of power to consumers. Advanced surveillance control methods on principal resources enable experts to diagnosis rapidly and find an approach to collate with the factors, which can decrease the power quality, such as thunderbolt, fluctuations, line faults and harmonic sources. By using smart grids, various levels of power quality with different prices can be achieved [9].

Flexibility of the Grid against Disorders and Natural Disasters

Smart grids are able to deal with unexpected phenomenon by separating the damaged parts from the main grid due to other parts of grid continue working without any problem. This automatic diagnosing and operating cause to decrease the time of power outage and improves management power by electricity companies [9].

New Productions, New Services and New Markets

Smart grids provide a communication between customer and seller, which are consumers and Regional Transmission Organization (RTO). By increasing the energy transmission paths and mounting DER units near of consumers location, contribution of customers in the electricity markets will be increased [9].

Application of Intelligent Networks for Maintenance

Latest technologies have been used in the smart grids in order to have effective utilization of equipment. In addition, they can represent the exact and required time for maintenance. Moreover, this feature of smart grids can lead to decrease the maintenance costs due to prevent unnecessary repairs [9].

Automatic Meter Reading and Advanced Metering Infrastructure

Recently investments are concentrated on smart meters. Most of experimental projects applied Automatic Meter Reading (AMR) on the demand side. One of the reasons of using AMR devices is automatically generation of monthly bill by two-way communication ports, such that it does not require a manual operator for reading the energy meters. In the near future Advanced Metering Infrastructure (AMI) will be launched in order to have two-way communication protocols between customers and distribution companies. By replacing of smart meters instead of current meters, data collection, measurement and intelligence analysis of energy consumption would be achieved for distribution companies in order to have network management, information of power outage and billing through this two-way communication. In some countries,

government obligated distribution companies to change the meters of customers without any expense for them and in some others, government intends to follow this scenario after finishing their pilot projects in smart meter communication protocols [10].



Figure 2.3 – Smart meter.

AMR devices have lots of benefits and advantages for power grids. One of these intelligent benefits is recording the energy consumption of each customer in various range of time in order to compare to other customers. Therefore, by having this information, the system can provide real-time price of energy and proposes several methods to consumers for reducing peak load by showing this information on customers homepage. Finally, in order to have perfect energy management analysis and real-time data feedback, it is necessary to install and setup the AMR devices in demand side [10].

Demand Response and Demand Side Management

Demand response programs can be executed and managed in two branches: *large section*, which is wholesale, that contains the RTO and Independent System Operator (ISO) and *small section*, which is distribution companies.

Demand response on the retail level defines in two ways: active and passive. On the passive section, by notifying the customer from the dynamic price, they are encouraged to reduce their power consumption voluntarily at peak times. On the active section of demand response, customer will agree that smart devices will interrupt automatically at peak times [5].

Distributed Energy Resources

One of the aspects of the smart grids is improving integration of DER such as Photovoltaic (PV) arrays and wind turbines into the power grids. Smart grids enable customers to have multi directional energy current: from power companies to home, home to power companies or even home to home. RERs have already significant growth in DERs. Beyond the RERs, EVs Batteries, cogeneration of electricity and heat

and Uninterruptible Power Supply (UPS), which will be described in below are other cases that can act as DERs [11].

Uninterruptible Power Supply (UPS) is a device that can supply equipment for limited time independent from the input power. This device is suitable for computers, medical devices, security equipment, etc. In addition, it can improve the output power in term of voltage level, voltage variations and sudden mutations. Furthermore, in smart UPS not only it can cover the mentioned features, but also it can interrupt the power of connected devices correctly in appropriate times especially at peak load moments [12].

For the same reason, it is noticeable to have a brief explanation of Feed-In Tariffs (FIT) in the smart grids.

Feed-In Tariffs (FIT) is the cost that paid from electricity companies to customers who inject their excess energy of RERs to the utility grid. This scenario can encourage the consumers to use RERs. It should mention that smart grids are more suitable for implementing this scenario [12].

Distribution Automation

Distribution Automation (DA) is a method that improves the reliability of its distribution power system. By using DA, it would be possible to have remote monitoring and controlling of equipment in distribution power grids. Moreover, automated decision, rapid and efficient troubleshooting and system recovery would be achieved. DA consists of central controlling and monitoring systems such as SCADA or distribution management systems. Additionally, it contains some principal features that are efficient to reduce the number and duration of power outages [12].

Comprehensive Awareness of the Area

Comprehensive monitoring on the region and situational awareness are essential for improving reliability and avoid disruption in energy supplying. Synchrophasors is one of the important technologies on measurement. The most important kind of Synchrophasors is Phasor Measurement Unit (PMU), which is a device that measures electrical waves on a power network [12].

Electrical Transportation

One the most important and fundamental applications of the smart grids is the capability of dealing with the energy required for electrical transportation. EVs greatly increase network loads, however, smart grids provide several facilities that enable them

to communicate with electricity companies to choose the best charging cycle time considering low energy price, less effect on the network and reducing production of greenhouse gases [7].



Figure 2.4 – Plug-In Electric Vehicle.

It should be noticed that huge automobile manufacturers are investigating to supply part of energy required of houses via energy stored on the EVs batteries when the utility grid is outage. It means that not only it would be possible to inject the additional power of vehicle to the grid, but also by implementation of TIF scenarios, customers are able to charge their EVs whenever the electricity price is low and in peak times inject it to the utility grid for decreasing their costs.

2.3. Microgrids

Microgrids are referred to local power grids that are subset of the main grid and can be consist of DG and local loads. Microgrids operate in two modes: independent from the main grid, which is island-mode, and dependent to the main grid, which is grid-connected mode [4]. A succinct and complete description of a microgrid can be defined as:

“A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode” [13].

According to the mentioned definition, microgrids should have the following capabilities [4]:

- Operating dependent or independent from the main grid;

- Ability of integration and management of energy resources (DERs or power plants);
- Synchronous operating with other energy resources available on the main grid or other microgrids;
- Provision of various levels of power quality and reliability for customers.

For better perception of the microgrids and integration with other networks, Figure 2.5 illustrates an overview of microgrid concepts.

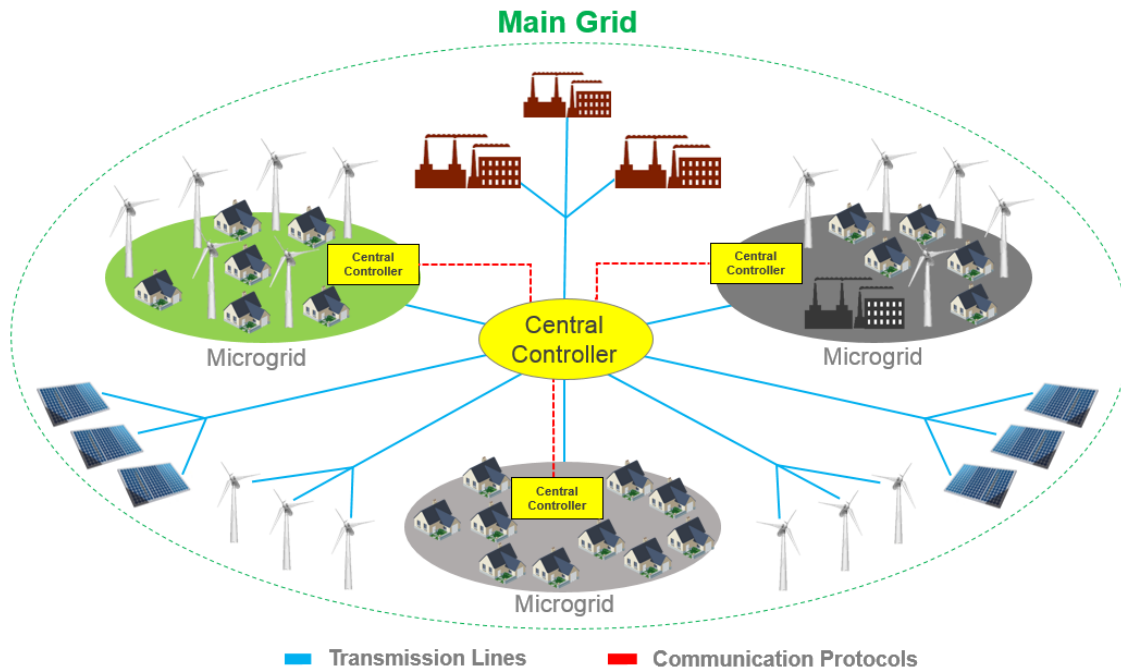


Figure 2.5 – Overview of the microgrids [14].

As it is clear in Figure 2.5, each microgrid is a section of the main power grid and consists of energy resources in order to supply the local loads. In peak demand times, other microgrids or main network can support the local loads and when the generated energy of a microgrid is more than the demand of local loads, excess of generated energy can be transmitted to the other parts of network. Each microgrid, regarding to generated energy on the demand side, can have several DERs while, in the main grid (which can be a smart grid), there are many DERs such as wind farms and PV arrays. On a larger scale, microgrids are able to have their own power plants, which operate synchronous with the main grid. It is noticeable that each microgrid has a central controller unit that will be responsible for diagnosing of operation in grid-connected or island-mode. This unit of all microgrids is connect to each other and they are subset of central controller unit of the main grid. The main controller unit has all of information about the generation of power plants, DERs and energy required of demand side and

based on these data an appropriate decision and functionality will be sent to the controller unit of each microgrid [14].

One of the benefits of microgrid is enabling the main network to operate in multi functionality mode by division of that in several sections. In other words, by using microgrid scenario and expanded use of DGs, the main grid has enough readiness to face with possible events. For instance, if in one part of network some natural disasters damage the transmission lines, the system will be able to interrupt the power in order to repair the damaged parts and simultaneously will supply related local loads with other resources [14].

Microgrids can be categorized according to their components and players. Utility network of a city including thousands of houses, several DERs and a power plant is one category of microgrid. Electricity network of an industrial park without any DERs is other kind of microgrid. The power grid of an island that does not have any power plant and includes hundreds of households and a significant number of DERs, is other type of microgrid. This category is called “off-grid” microgrids [15].

By smart grids and microgrids technologies, installing DER units in the place of consumers would be possible. By this way, each household can have their wind turbines or PV arrays in order to have individual grid. However, this grid should be dependent on the utility grid. Figure 2.6 shows a simple diagram of a home-scale type of microgrids.

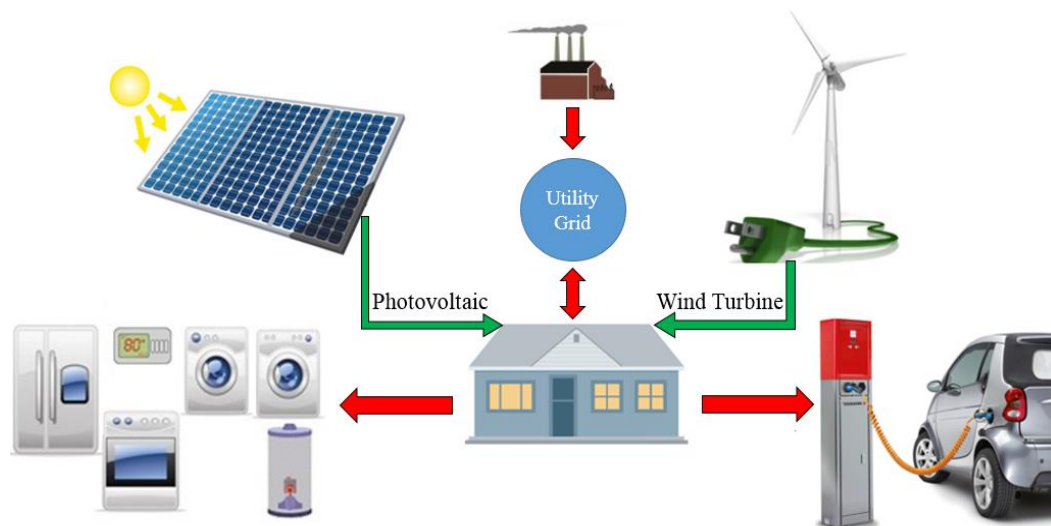


Figure 2.6 – Home-scale microgrid.

Another possibility of a home-scale microgrid is purchasing or selling energy to neighbors. Hence, it will be possible to inform remotely about the conditions of own

node and in the case of more energy required, neighbors networks could be advisable. These two nodes are defined as a Home Area Network (HAN) and Neighborhood Area Network (NAN) [16].

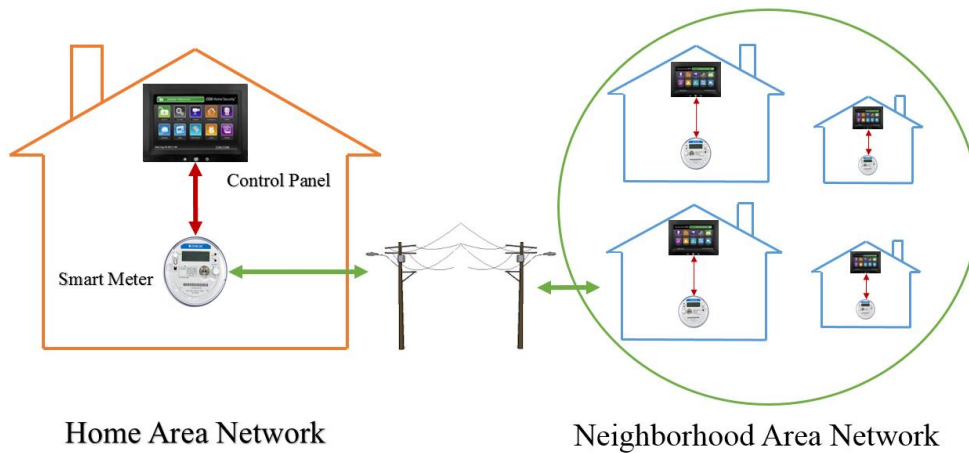


Figure 2.7 – HAN and NAN networks [16].

This characteristic of the microgrids is achievable by employing smart meters, having intelligent monitoring and two-way communication protocols between both HAN and NAN [16].

2.4. Conclusion

In this chapter, smart grids and microgrids technologies were presented as new scenarios for modernization of the current power network. The major objective of the smart power grids can be considered as the increment of reliability, efficiency and participation of consumers in the current power grid. By applying these technologies into the current power grid, it will be possible to remove the hierarchical structure and improve the integration of DERs into the network. Implementation of the smart grid and microgrid projects is not so easy and rapid because cooperation and contribution of domestic consumers, industries and other players would be required [14].

Chapter 3

Demand Side Management in the Smart Grids Context

Demand Side Management (DSM) is one of the major functions of the smart grid. The main objective of DSM is to optimize the consumption of customers by encouraging them to shift their high consumption loads to off-peak times. This scenario not only decreases the electricity costs of customers, but also causes to reduce pressure on the network by having less energy consumption in the peak times [17, 18]. DSM depending on types of load, which are residential, commercial and industrial, has six principal techniques: load shifting, peak clipping, strategic conservation, strategic load growth, valley filling and flexible load shape [17].

Current DSMs by employing some specific techniques and algorithms manage the energy system for limited number of loads. While intelligent DSMs in the smart grids use smart devices and advanced communication protocols in order to collect information about the load curves of consumers, peak times of the network and other useful data. By applying this data, intelligent DSM provides a good approach to realize the optimal management of energy [17, 18].

In this chapter, at first a brief explanation of smart home will be described then, importance of smart appliance for DSM will be investigated and finally, influence of using DG in the DSM will be explained.

3.1. Smart Home in Demand Side Management

According to the definition of DSM, smart home is an essential part of DSM. Real-time monitoring of the consumption and electricity prices is one of the benefits of smart home that improves DSM scenarios [18].

3.1.1. Description of Smart Home

Smart home is defined as a house that involves high technology of communication and computation and equipped with various types of sensors. All of the components such as outlets, TV, refrigerator, air condition, etc. are connected to a database, which

called central controller unit. Additionally, PV arrays or home-scale wind turbines can be employed in order to supply the required energy of house. In the meantime, different technologies have been applied for real-time communication and send/receive the desired data. ZigBee and dash7 are the most common kinds of communication protocols used in smart home [19].

In order to understand the influence of smart home on the quality of life, an individual daily program of people has been compared in two cases: current homes and smart homes. In a typical house, people after returning from their workplace in the afternoon, they turn the heating/cooling system on, take a shower and turn on the coffee machine, drink a coffee and start to watch TV. Then, they start working with computer, check the emails and after spending lots of time with family, they decrease the heating/cooling system and go to bed. However, in a smart home, when they return from their workplace, temperature of the house is on the desired value due to heating/cooling system is working automatically, the lights will be dimmed at specific times such as watching TV or when they are going from one room to another one. New email notifications can be heard and when they go to the bed, lights will be turned off automatically and heating/cooling system reduces to an optimal level. As you can see, smart home has a significant effect on the life quality of people.

The equipment that is employed in the smart home includes smart meters, smart switches, smart sockets, smoke detectors, infrared detectors, etc. Additionally, for supplying the required energy, PV arrays and/or home-scale wind turbine can be used. Figure 3.1 illustrates the equipment of a smart home.

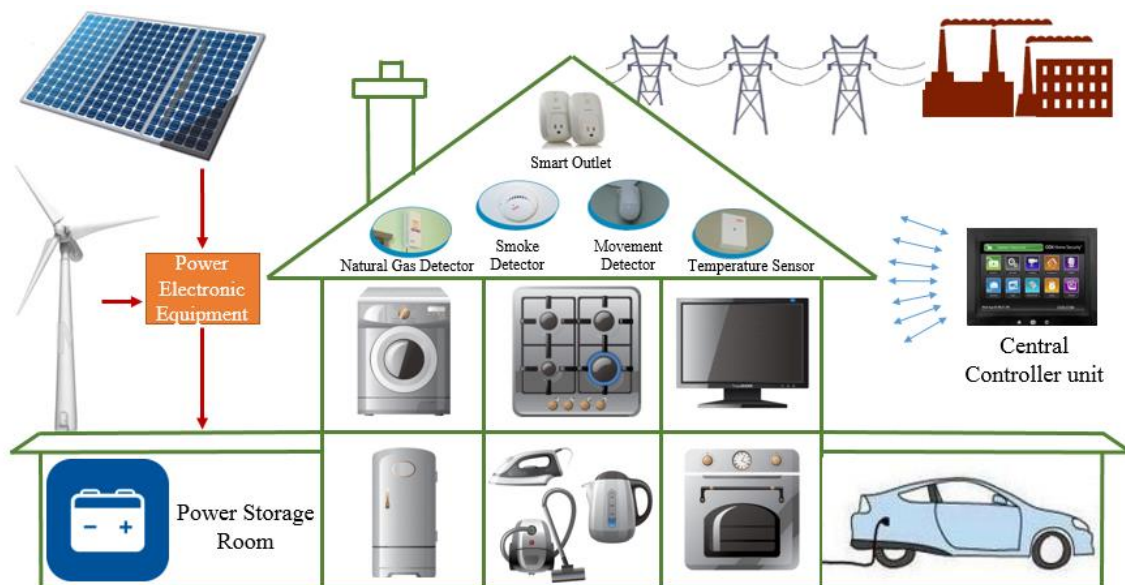


Figure 3.1 – Various components of a smart home.

As Figure 3.1 shows, all of the components in smart home such as wind turbine and PV arrays as power generators, domestic appliances as consumers and smart switches, smart sockets, smoke detectors etc. as controllers, have communication with central controller unit. In addition, Figure 3.2 shows various types of mounted sensors and controlling systems.

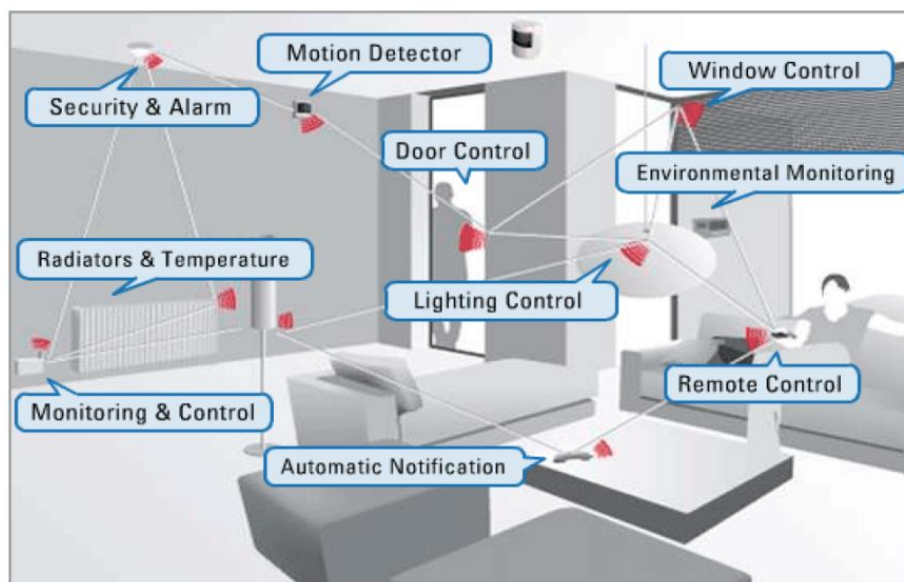


Figure 3.2 – Schematic of a real smart home [20].

The most important advantages of the smart home and smart appliances are convenience, economy and safety. In below a brief explanation of each one is explained.

Convenience

Increasing life quality and convenience can be expressed as the main benefit of smart home. By using of that, people can live modern and systematic. For instance, mounted sensors on the various parts of the home enable the operator to adjust the temperature of environment and intensity of lights automatically or manually from a remote control unit. From a scientific look on this subject, the voltage range in all over the world is variable from 110 V to 240 V. However, most domestic appliances need electricity in the range of 5 V to 24 V such that all of them have an adaptor due to change the level of voltage. By using smart sockets, it will be possible to supply such devices (5 V to 24 V) directly from the outlets and eliminates this huge number of adaptors [20].

Safety

As it was demonstrated, different types of safety sensors such as gas detector, smoke detector, water leak etc. are mounted in the smart home. For instance, in the case of smoke or gas detection, windows will be open and air condition system starts to work. Surely, this scenario increases the safety of users. In other scenarios, smart home reduces the risk of electric shocks by transmitting power only to the outlets that appliance are connected to them and preventing power transmission to free sockets [20].

Economy

Smart home enables homeowner to specify a program or a schedule, regarding to the real-time prices, to manage the time of using domestic facilities. For instance, high consumption appliances can be supplied when the energy price is low. Therefore, such scenarios can be effective to decrease energy costs and causes smart home becomes affordable [20].

Beside these important benefits, there are some disadvantages, which are not fundamental and by advancement of the technology, they will be eliminated. Three most important disadvantages of a smart home are mentioned in below:

Mounting Costs

Since it is essential for the smart home to apply significant number of sensors and smart devices and due to their high prices, all together can be caused to increase the installation costs of smart home [21].

Training Requirement

It is clear that because of applying advanced technology on the smart home, in order to become easy-to-use for public people, some training documents are essential. This issue is more sensible for older people and may cause to face them with problems. Therefore, smart home should be designed suitable for all ages [21].

Privacy Security

In smart home, all of the equipment and components are connect to each other via wireless local networks. This can provide a suitable condition for hackers and if the networks are not secure enough, the privacy of people may be put in danger [21].

3.1.2. Application of Smart Appliance in Demand Side Management

Execution of DSM scenarios in residential areas will be possible by modification of the consumption pattern and recognition of the best time for using appliances. Load

shifting is widely used as the most effective DSM technique in the current distribution networks especially in residential areas. Smart appliances make this technique more applicable by dealing with real-time electricity price. As it was explained, all of the appliances in the home are connected to a central controller unit. This unit has real-time electricity price and based on this data, it defines a new load schedule for appliances. By this way, central controller unit recognizes that which appliance should be supplied and which should be shifted to other times [17]. Additionally, each domestic appliance can have own controller unit in order to determine the best time of operation by dealing with real-time electricity price and condition of the network. This network can be a home-scale microgrid or utility grid [22]. Figure 3.3 illustrates the technique of load shifting in DSM.

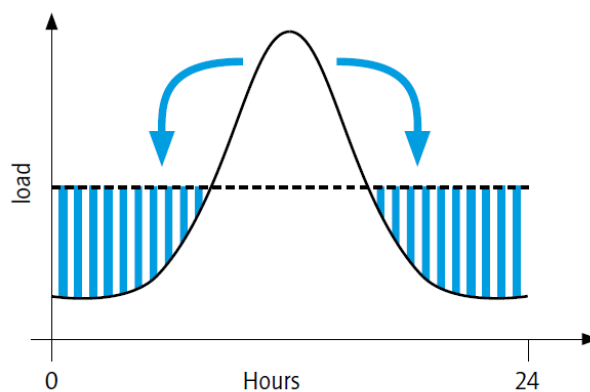


Figure 3.3 – Load shifting technique in DSM [22].

Figure 3.3 presents a symbolic consumption load curve of a house in a period of 24h. Load shifting technique can be achieved by putting delays in activation of some loads such as water heater or dishwasher. Also, this approach can be applied in the refrigerator such that when the network is not on peak, compressor acts and stores energy for cooling and on the peak time it goes completely off and uses that stored energy in order to control the temperature of refrigerator [22].

For this purpose, initially it should be recognized that how much is the consumption of each appliance and it is important to know their capabilities to use them as smart appliance. Figure 3.4 shows the consumption of appliances that normally used in houses.

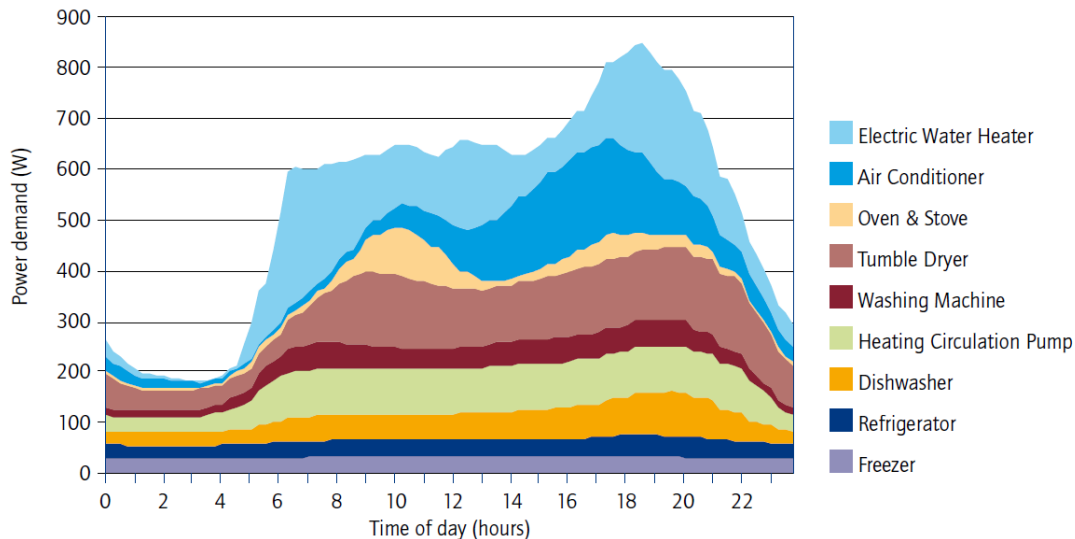


Figure 3.4 – Consumption of different kinds of domestic appliances [22].

As Figure 3.4 demonstrates, the consumption of each appliance in a period of 24 hours has been measured. It can be seen that the highest consumption of power is related to electric water heater such that at the start of evening reaches to the peak consumption, which is 850 W, and during the night reaches to lowest consumption, which is 200 W. In addition, refrigerator and freezer have been located on the bottom of the chart, which require less energy, and their consumption is stable and constantly during the 24 hours. It is clear that by having the information of consumption for each appliance and also by applying some techniques like load shifting, it will be possible to implement DSM scenarios [22].

As a result, it can be said that by using smart appliances, which have capability of turning on and off automatically and dealing with real-time electricity prices, implementation of DSM techniques in home-scale mode would be possible and the costs of electricity consumption can be optimized [22].

3.2. Distributed Generation in Demand Side Management

Distributed Generation (DG) is a technology that has important role on the distribution networks and is defined as small power generations that located near the consumers place. Decentralized configuration of DGs allows the power grid to have more security and reliability. In the meantime, DSM should balance the generated power and energy demand. In a DSM that no DG is exist on the system, DSM is just able to manage the consumption and there is no sufficient management on the generation in the place of consumers. However, by advancing of the technology in DG

and employing in the place of consumers (end-user), DG plays an important role on the advancement, development and efficiency of DSM [23].

By the same token, a brief description of DG, characteristics and importance of that in the smart grid context, are included in this section, and then micro-generation and home-scale DG will be investigated.

3.2.1. Overview and Key Issues of Distributed Generation

DG is referred to the generation of electricity by huge number of generators that are located on the place or near the consumers [24]. According to the different references [25], there are various definitions of DG that three of them are mentioned in below:

- Electric Power Research Institute (EPRI) defines DGs as generators that have capacity of the generation from a few kilowatts up to 50 MW;
- International Energy Agency (IEA) describes DGs as generating plants that provide support to a distribution system connected to the grid;
- International Council on Large Electric System (CIGRE) explains DGs as generators that generally connected to the main grid and not located in a special place.

DGs have several names such as decentralized generation, on-site generation and distributed energy. Generally, it is known as small-scale generation. According to the significant increment of energy requirement in the demand side and inefficiency of long distance transmission lines for this volume of energy, DGs become important for the distribution companies [25].

PV arrays and wind turbines are the most important DGs that their application is increasing on the current power network. The most important applications of DGs consist of providing high level of power quality and reliability, controlling of the voltage and reactive power, optimizing use of produced heat from the generation process and reducing pressure from the transmission lines [24].

Based on the constructional and technological points of view, there are different types of DGs that include:

Micro Gas Turbines

Micro turbines are a new technology of generators that simultaneously produce electricity and heat in small-scale. The output power range is from 25 kW to 500 kW.

This kind of generators became important in DG technologies because of their small-scale, production of electricity and heat simultaneously, high efficiency, low price and flexibility in the loads and the grids [25].

Energy Storage System

In the DGs context, Energy Storage System (ESS) is defined as a storage device that the charging process will be done in low demand times in order to use the stored energy in peak demand times. In fact, the charging process of ESS can be integrated with a DG in order to store the excess of generated power. Some ESSs are able to provide 700 kW in a short period of time (a few minutes) [25].

Renewable Energy Resource

RER is referred to a generator that employs natural energy resources to generate electricity. IEA describes RER as:

Renewable energy resources are defined as resources that are generally not subject to depletion, such as the light and heat from the sun, the force of wind, falling water, and geothermal heat [25].

In the meantime, wind turbines and PV arrays are the most important generators in the RERs. There is a brief description of each of which in below.

As it is clear in the name of wind turbine, is a resource that converts kinetic energy of wind to the electrical energy. Structure of wind turbine consists of a tower, blades and a nacelle. All of the components such as generator, gearboxes, rotor connected to blades and other mechanical and electrical equipment have been mounted on the nacelle located at the top of the tower. The blades should take the kinetic energy of wind in order to spin the rotor of generator to produce electricity. Hence, size of blades and aerodynamics structure of them are consequential. Capability of installation on the remote areas, environmental sustainability, no greenhouse gas emissions and absence of any pollutants are some advantages of the wind turbines [25].

PV arrays are the other types of RERs that are known as solar system. This system by using special panels converts solar radiation to Direct Current (DC) electricity. This process employs many solar cells in each panel and generally each cell regarding to its area, is able to generate 2 to 4 A in 0.5 V. Although, by connecting some of these cell to each other, it will be possible to achieve 12 V on the output in order to store the generated energy in ESS. Another possibility of this system is to use an inverter to

change the level of voltage for various applications. The inverter used for PV arrays, depending on the price and application, can be off-grid or grid-connected. Climate changes are the most effective factor for this kind of DGs, because direct solar radiation is required for an acceptable amount of power generation [25].

Beside the advantages of DGs for the power grid, there are some issues for the integration of them into the current power network. These issues include:

Power Quality

As it mentioned in above, some inverters are required for using the generated energy of RERs. These power electronic devices can produce harmonics. Regarding to the requirement of new equipment to a high rate of power quality, DGs can face the grids with power quality problems in the demand side [24].

Network Balancing

According to the environmental conditions, energy generated by DGs, especially RERs, is variable. Hence, if a microgrid operates on island-mode, the network should be able to have fast reaction and balance the energy between generation and demand side. It means that in energy shortage times, microgrid should purchase the energy from the upstream networks in order to guarantee the local loads from the power fluctuations. From this view of point, integration of DGs in the power grids requires power full management scenarios [24].

Resource Integration

Since huge DG units employ synchronous generators and most of small DG units apply asynchronous generators (induction generators) due to low price, the integration of these two generators can be an issue for the centralized power networks [24].

In total, using DG technologies improve the voltage profiles, voltage stability and power quality and can reduce power losses. However, integration of these technologies into the current power grid makes its analysis more complex [24].

3.2.2. Micro-Generation Systems

According to the high consumption of fossil fuels in the generation of electricity and greenhouse gas emissions in this process, governments and electricity producers became more interest on RERs. Dividing the centralized power grid into the some local networks, small-scale and proximity of them to the consumers place are the factors that make RERs more popular in experts society [26]. PV arrays and wind turbines are two

types of RERs that widely used in the current power grid because they are complement of each other and can give high level of reliability to the consumers. Employing these resources in the houses encourages customers to participate in the electricity markets [26].

Home-scale microgrid is referred to an electricity network of a house that uses PV arrays and/or wind turbines as power sources. This microgrid, like the large-scale microgrids, can be configured to operate in island-mode and grid-connected mode. In the grid-connected mode, not only it can supply the local loads by energy generated from the PV arrays or wind turbines, but also it can inject the excess of power to the utility grid. Since the power sources of this microgrid are connected to the utility grid, they should present high performance in the term of voltage, frequency and harmonics regulation [26].

In the island-mode, using ESS with high capacity is mandatory in order to handle the generated energy. Regarding to the variations of power in PV arrays and wind turbines and lack of utility grid to assist the system in this mode, ESS and other power electronic equipment are responsible to provide an acceptable rate of quality in frequency and voltage [27].

Home-scale microgrid, like other networks, requires a central controller unit. In the grid-connected mode, this unit is responsible for determining and measuring the energy consumed from the utility grid and energy sold back to it. Central controller unit can be a SCADA system equipped with Human Machine Interface (HMI) and other electronic components such as Programmable Logic Controller (PLC), energy meters, relays, circuit breakers, etc. in order to manage the microgrid functionalities [26, 28]. Figure 3.5 illustrates all of the possible inputs and outputs of a central controller unit in a home-scale microgrid.

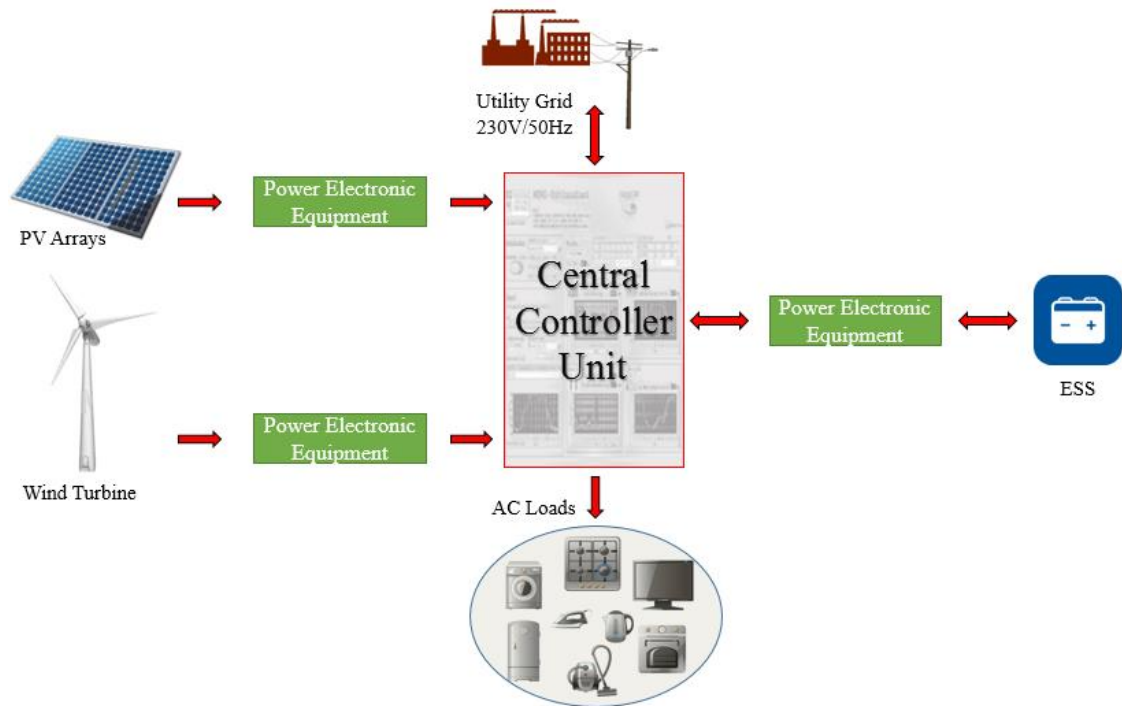


Figure 3.5 – Inputs and outputs of the central controller unit [26, 29].

As Figure 3.5 shows, energy generated by RERs, which are PV arrays and/or home-scale wind turbine, after passing from the power electronic components, is delivered to the central controller unit. Power electronic components in this system include inverters, converters and rectifiers used for PV arrays, ESS and wind turbine. Therefore, the central controller unit would be able to manage this home-scale microgrid by employing these components and using some intelligent algorithms [26]. Figure 3.6 demonstrates one of the management algorithms of the system.

In this algorithm, the system becomes aware from the generation of microgrid power sources by asking data from the energy meters then, according to the comparison of generated power with the loads demand, an intelligent decision will be taken [28].

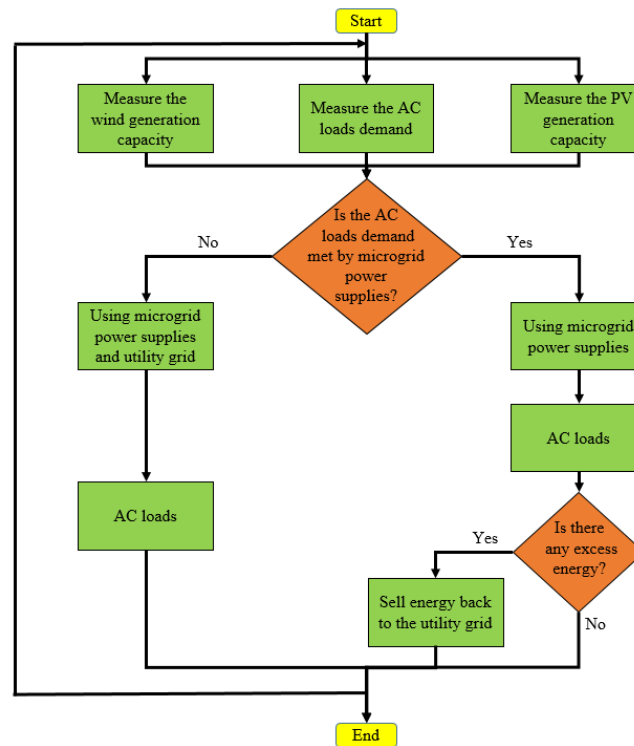


Figure 3.6 – Flowchart of management algorithm in grid-connected mode [28].

The algorithm that mentioned in above was one of the possibilities of the home-scale microgrid. Island-mode is another possible scenario that the system should operate without relying on the utility grid. ESS plays an important role in this mode. Additionally, by integration of ESS on a system that can deal with real-time energy price, the possibility of management and optimization of costs are achievable. This means that if the system is able to have real-time energy price, when the electricity price is low, not only it can supply the local loads from the utility grid, but also it can charge the ESS, and use the stored energy to supply the local loads, or sell energy back to the utility grid when the electricity price is high. All of these scenarios enable consumers to decrease the electricity costs [28].

3.3. Conclusion

As a conclusion for this chapter, DG technologies can change the centralized structure of current power network by dividing large generation units into the some small DG units. These technologies improve some issues of the utility grid and can provide high rate of power quality and reliability to the consumers [25]. In this chapter, advantages and disadvantages of DG were explained and different scenarios of using micro-generation units in home-scale microgrid were demonstrated. In the next chapter, the implemented microgrid prototype using micro-generation unit in a laboratory-scale will be described.

Chapter 4

Microgrid Real-Time Simulator

This chapter describes the experimental part of this dissertation, which is the simulation and control of consumption and generation of hardware resources in the microgrid real-time digital simulator. The proposed system is called Microgrid Real-Time Simulator (MRTS). The main contribution of MRTS is the integration of real resources inside the simulation environment by developing of the hardware and software strategies that implemented on the loads without any automation part and used outside of the simulation environments. Therefore, the MRTS proposes several controlling methods of the hardware devices that enable the real loads to be integrated as hardware-in-the-loop (HIL) loads for the small and medium simulation players.

For this purpose, first an overview of the system is reviewed. Second, the equipment and integration of hardware resources (4 kVA and 30 kVA loads and wind turbine emulator) in the MRTS is explained and finally, MATLAB Simulink models related to the MRTS are proposed.

4.1. Overview of the MRTS

MRTS is referred to simulation of a grid-connected microgrid that implements an actual integration of loads by using real-time digital simulator. The proposed system has been implemented in the laboratory of GECAD research group, located in Institute of Engineering – Polytechnic of Porto (ISEP/IPP), Portugal. The equipment that is used in the MRTS contains:

- OP5600-OPAL-RT, as real-time digital simulator (called OPAL in this system);
- 1.2 kW wind turbine emulator (Three-Phase induction machine);
- Three-Phase 4 kVA variable load in three independent parts of resistive, inductive and capacitive (called 4 kVA load in this system);
- 30 kVA resistive load bank (called 30 kVA load in this system);
- MRTS power lines.

Figure 4.1 illustrates an overview of the MRTS. In this model, OPAL is located at the center of system and consumers and generator are connected to the main unit by standard communication protocols in order to exchange the information.

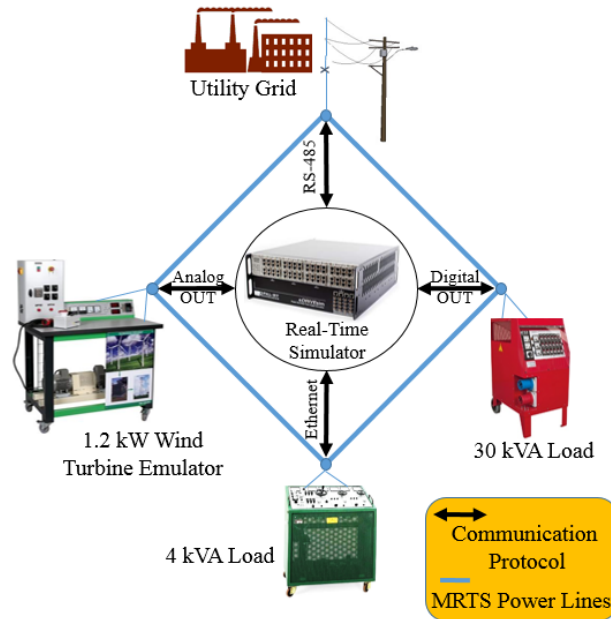


Figure 4.1 – Overview of the MRTS.

MRTS players are connected to the utility grid via MRTS power lines and can be controlled by the OPAL through the communication protocols. According to the specifications of wind turbine emulator, which operates in grid-connected mode, it should connect to the utility grid as well. The OPAL in this model is a central controller unit, 4 kVA and 30 kVA loads are consumers that can simulate the real consumption profiles of a residential house or small commerce facility and wind turbine emulator is a home-scale DG that plays as a micro-generation unit. There are several energy meters mounted on the MRTS players that all are connected to the OPAL in order to have real-time information about consumption and generation.

Various scenarios implement integration of hardware resources of this model. Integration of wind turbine emulator is done by analog output board of the OPAL such that the speed of wind in real-time is sent to the frequency inverter of the motor embedded on the wind turbine emulator in order to control the speed and generation. Simultaneously, the amount of generated energy by the wind turbine is measured by energy meters and will be sent to the OPAL. Communication between the OPAL and energy meters is done through two interfaces: RS-485 interface, with Modbus RTU protocol and Ethernet interface, with Modbus TCP/IP protocol. In both cases, transmitted data follow IEEE 754 format.

For the 4 kVA load integration, an Arduino has been mounted on the hardware that controls a 12 V DC motor for managing the consumption. The communication interface between OPAL and 4 kVA load is Ethernet with Modbus TCP/IP protocol.

In the case of 30 kVA load integration, several relays have been installed on this hardware for controlling the consumption. These relays are controlled by the digital output board of the OPAL.

Therefore, MRTS contains integration of hardware resources and utility grid in order to have a complete simulated system. The proposed system can be a platform to test the demand response programs using real generation and consumption profiles.

4.2. Real-Time Digital Simulator

Nowadays regarding to the high technology applied on various industries and need of using complex model on their applications, simulation techniques play an important role in the researcher's society in order to test and examine their prototypes.

Using the real hardware resources in the simulation environments, takes the advantages of the virtual world in the real world [30]. The use of HIL allows the inclusion of real resources into the simulation environment, minimizes the development time and provides reliable results [31].

OP5600-OPAL-RT is referred to a real-time digital simulator that is a powerful tool for rapid control prototyping and HIL applications. Electronic devices in the OPAL are designed to interface with the real world and provide control, interaction and convenience of some forms. In a real-time simulator system, a predetermined amount of time is given to embedded devices in order to read input signals, perform all necessary calculations such as control algorithms and write all outputs such as hardware devices. This predetermined amount of time is known as step size (T_s), such that by decreasing T_s the accuracy of the results will be increased because it increases the time required to simulate the system. Figure 4.2 provides a better concept of the step size. In this project, the amount of T_s is 0.01 second ($T_s = 0.01$ s).

As you can see in the Figure 4.2, while the amount of the step size is a small value, the precision of the signal processing is much higher comparing with the bigger value of the step size. Therefore, there is a reverse proportion between the value of the step size and the precision of the signal processing.

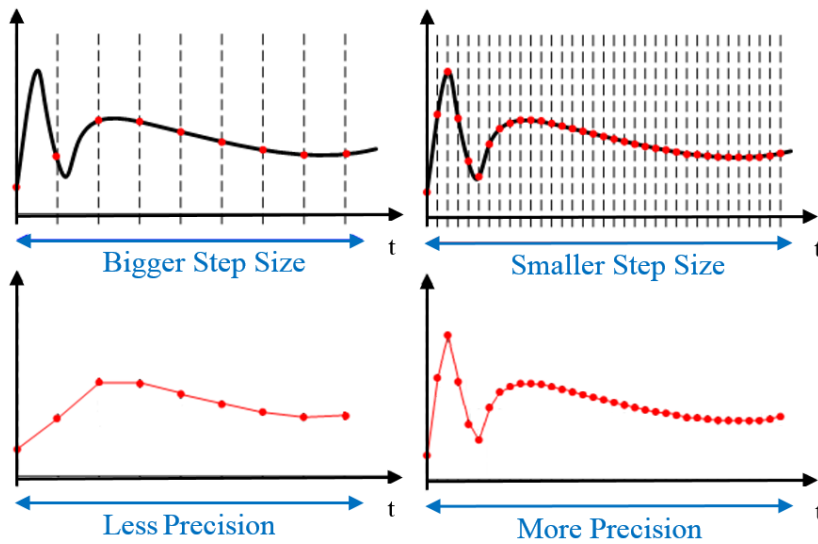


Figure 4.2 – Effect of the step size in the precision [32].

Executing a complex Simulink model with a small amount of the step size brings more accurate and reliable results, however, the simulator machine requires more time for processing.

Generally, the specifications of the OPAL contain:

- Intel Xenon six-cores 3.46 GHz 12 M cache;
- Red Hat Linux operation system;
- Two user-programmable FPGA-based I/O management;
- Up to 128 analog I/O or 256 digital I/O or mix of both;
- TCP/IP communication.

Figure 4.3 shows different views of the OPAL simulator.

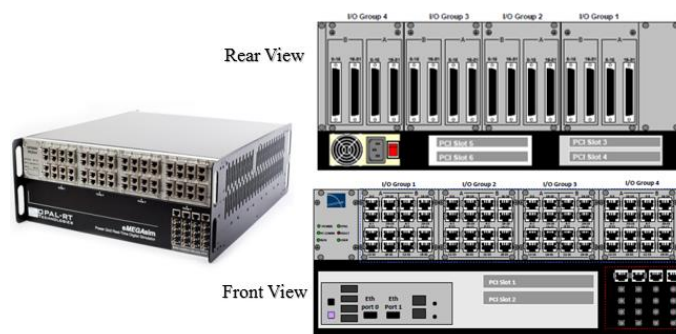


Figure 4.3 – OP5600-OPAL-RT simulator.

Analog and digital I/O boards are mounted inside the OPAL such that in the front view there are many RJ45 connectors that can be used for monitoring the I/O signals. In the rear view, there are DB37 connectors in order to connect the external hardware that

intend to be controlled by the analog or digital I/O. Users of the OPAL, depending on the application, can choose the number of analog and digital I/O boards. One digital output board and one analog output board were selected for the MRTS system. Analog output board has the following features:

- 16 analog output channels;
- Simultaneous output on all of the channels;
- 1 MS/s max. update rate;
- Independent programmable ranges from +/- 100 mV to +/- 17 V;
- 0.01 V resolution in output;
- Outputs short-circuit protected;
- No external power supply required.

Similarly, digital output board has the following characteristics:

- 32 output lines with on-board signal conditioning;
- Short-circuit protection on each output line with opt-isolation;
- +12 V or +5 V output range;
- External power supply required.

For configurations of these boards, a system document describes the actual installation setting in the OPAL for each specific project. This document contains pinout diagram, location of each channel of the board in front view, location of each channel of the board in rear view and related data for configurations of the corresponding blocks in the Simulink model. Figure 4.4 illustrates the documents of analog and digital output boards that have been employed for the MRTS system.

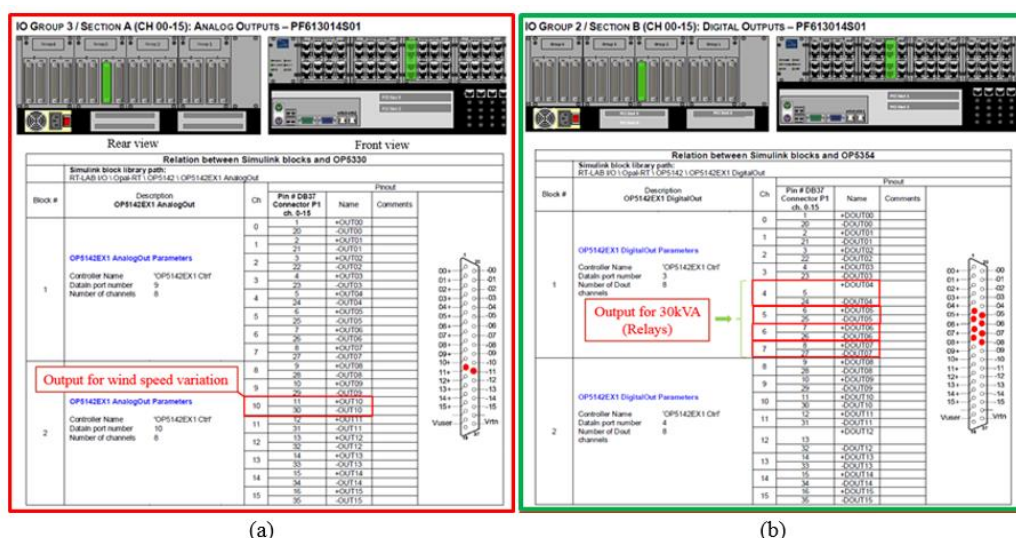


Figure 4.4 – Documents of the output boards, (a) Analog output (b) Digital output.

In these documents, the port number each channel is demonstrated. Additionally, related data that employed for the blocks of the analog and digital boards in the Simulink model exist in these documents. Each channel has two ports: positive port and negative port. All of the positive ports are placed on the left side of DB37 connectors and negative ports are located on the right side of that. As you can see in the Figure 4.4 (a), channel 10 of the analog output board is used for the wind turbine emulator in order to control the wind speed variation by OPAL. In Figure 4.4 (b), four channels of digital output board are applied for four remote switches of 30 kVA load due to integrate it in the MRTS system.

RT-LAB is the main software of the OPAL that can be installed on a host computer. The communication protocol between the OPAL and the host PC is TCP/IP. This software is completely deigned based on MATLAB Simulink environment. By this way, edition of Simulink model and compilation is done via RT-LAB on the host PC and I/O and real-time model execution is implemented by the OPAL. While the Simulink model is executing on the OPAL, a user interface is provided automatically by RT-LAB in the host PC in order to have real-time controlling and data analyzing of the rapid prototype. This scenario has been demonstrated on the Figure 4.5.

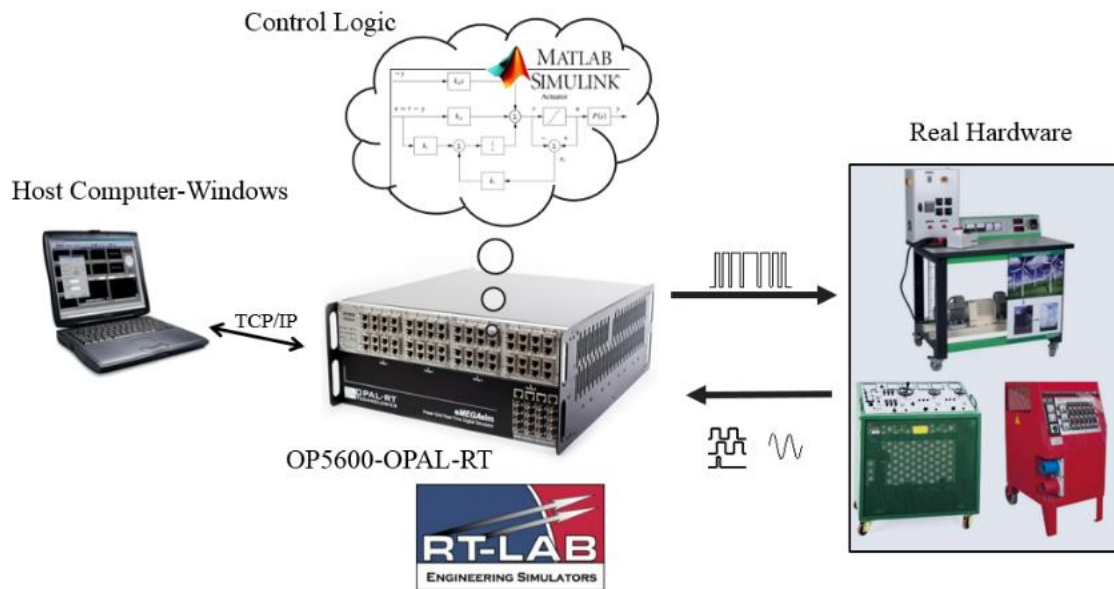


Figure 4.5 – Controlling process of the real resources by the real-time simulator (i.e. OPAL).

Figure 4.6 shows the home windows of the RT-LAB software. By clicking on the edit button, MATLAB Simulink will be open in order to design or edit the diagram of model. After that, the model should be built and executed on the OPAL.

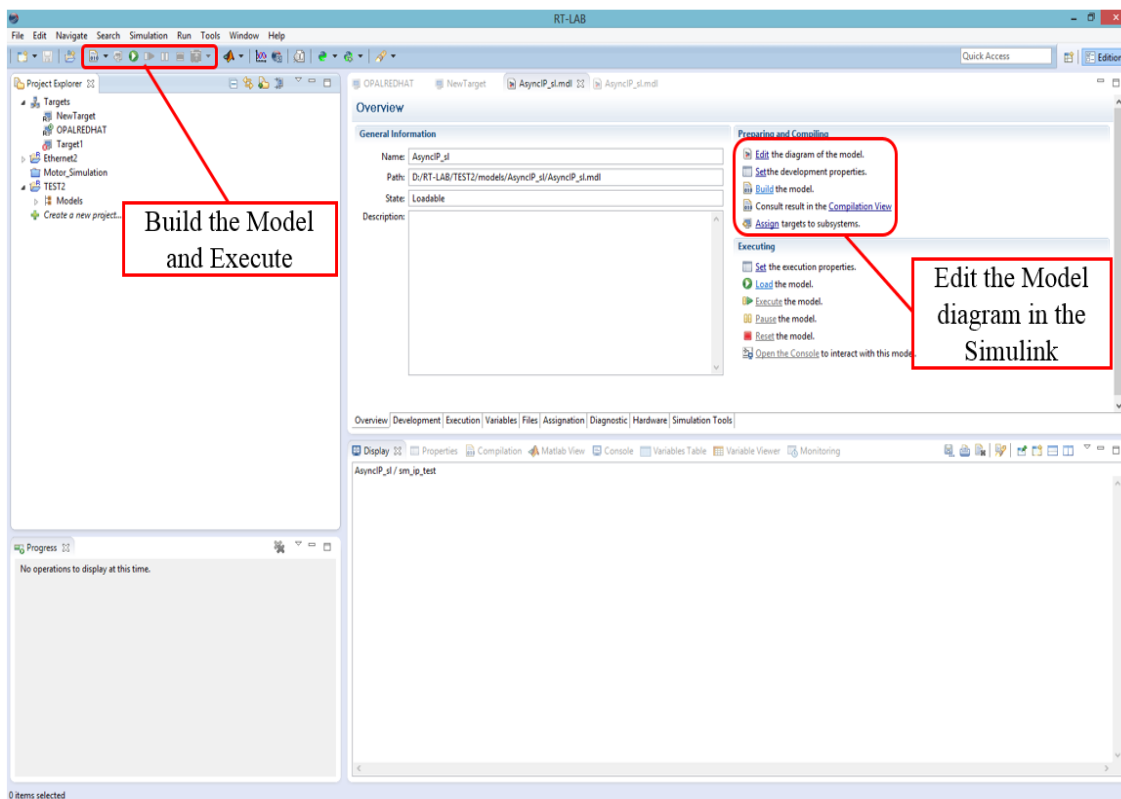


Figure 4.6 – RT-LAB home windows.

In the Simulink environment, the model should be designed in the form of two main subsystems: computation subsystem and console subsystem. Computation subsystem includes all of the computational elements and mathematical operations that will be executed in real-time on the OPAL. Console subsystem contains all user interface blocks such as scopes, displays, constants, switches and other controller blocks. The console subsystem will be displayed on the host PC and allows interaction with the computation subsystem. The data between these two subsystems are transmitted through the TCP/IP link. Figure 4.7 demonstrates the computation and console subsystems.

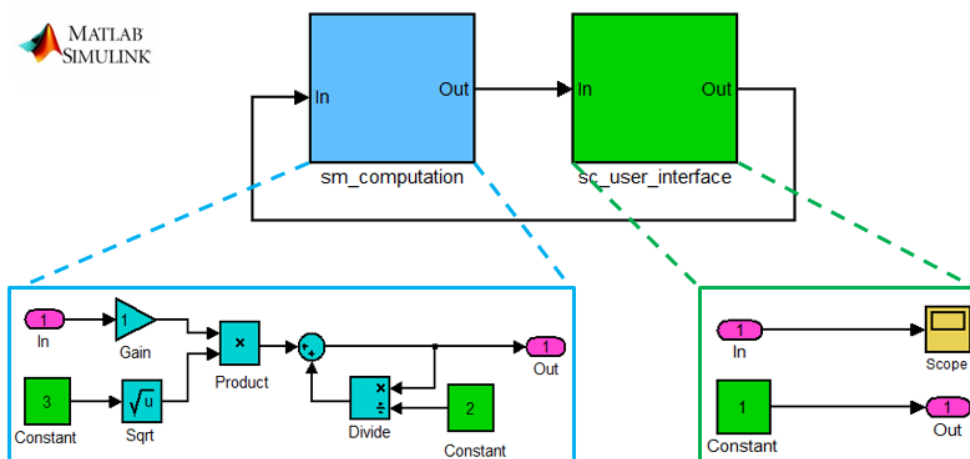


Figure 4.7 – Two main subsystems of a Simulink model for executing on OPAL.

Similarly, the Simulink model of the MRTS system has been illustrated on the Figure 4.8. This model contains all of the scenarios related to integration of real hardware resources in the MRTS system.

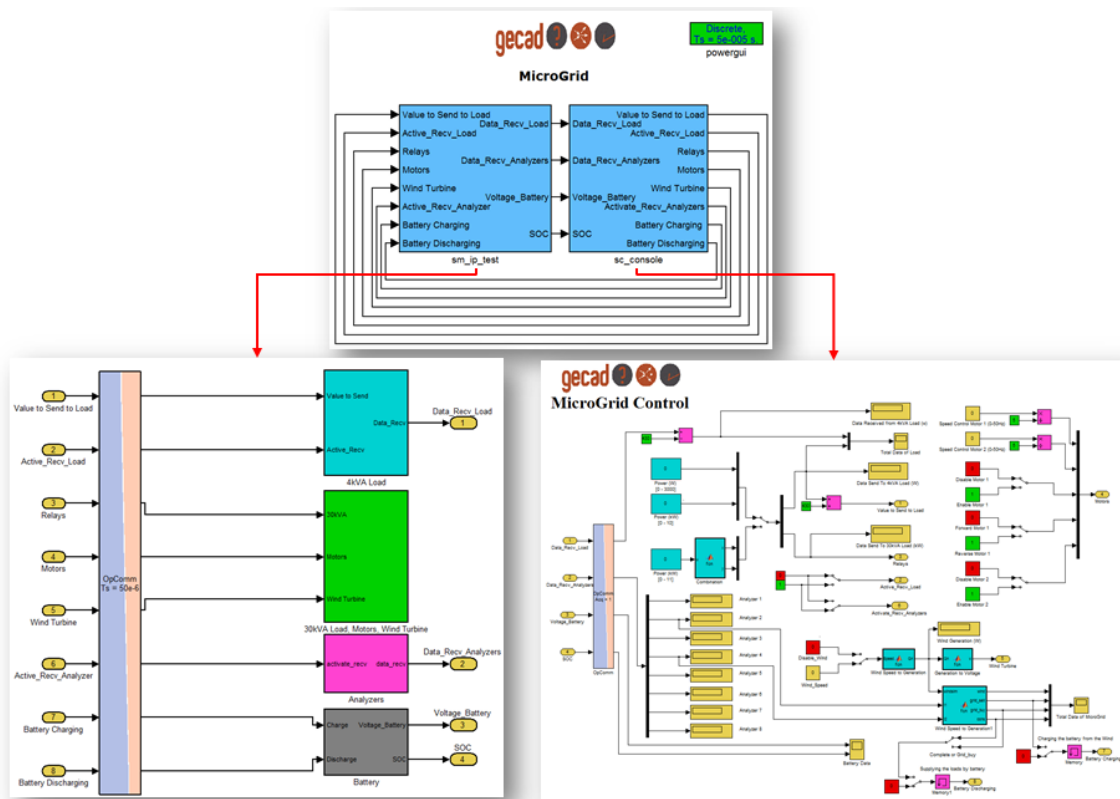


Figure 4.8 – MRTS Simulink model.

In the MRTS Simulink model, all of the computation elements and mathematical operations related to the integration of hardware resources such as 4 kVA load, 30 kVA load and wind turbine emulator are located on the “sm_ip_test” subsystem. Controlling and user interface blocks like switches, scopes and constants are situated on the “sc_console” subsystem. In the next parts, this model will be explained completely.

4.3. Integration of MRTS Players

In this section, implemented scenarios of integration hardware resources in the MRTS system are demonstrated. MRTS players consist of 4 kVA load, 30 kVA load, 1.2 kW wind turbine emulator and MRTS power lines. Ethernet and RS-485 communication interfaces are used for the connection of 4 kVA load and energy meters to the OPAL, digital outputs of the OPAL are applied for the 30 kVA load and analog output of that is used for the wind turbine emulator.

4.3.1. Low Power Consumer

ELETTRONICA VENETA three-phase 4 kVA variable load (called 4 kVA load in this dissertation) is a versatile system that can examine AC or DC generators in single-phase or three-phase mode. This system has the following specifications:

- Three independent modules;
- Resistive, inductive and capacitive sections;
- Maximum active power 3 kW;
- Maximum inductive reactive power 3 kVAR;
- Maximum capacitive reactive power 3 kVAR;
- Maximum apparent power 4.2 kVA;
- Ammeter, voltmeter, wattmeter and power factor meter embedded on the front platform;
- Control circuit with general contactor, protection thermal relay, fuses, signaling lamps and safety terminals.

The system has two power supply inputs: auxiliary 230V/PE – 50-60 Hz and main power 230/400 V – 50 Hz. Figure 4.9 shows a view of the 4 kVA load. Further information about 4 kVA load is available on [33].

As it mentioned in above, this load has three independent sections. Several manual steering mounted on the top of the platform control the power of these sections. In each part, there is a gauge connected to a steering in order to increase or decrease the amount of consumption. The main automatization idea of this load is to have some equipment that can control the gauge of each part automatically and excludes the manual steering. For this purpose, the resistive section was selected in order to implement the automatization idea. It should be mentioned that for the simulation of real consumption profiles, resistive and inductive sections of the 4 kVA load should be integrated in order to have real consumption simulation because in the real consumption profiles there is active and reactive power simultaneously. However, in the MRTS system it is assumed that all of the consumers are resistive and linear.

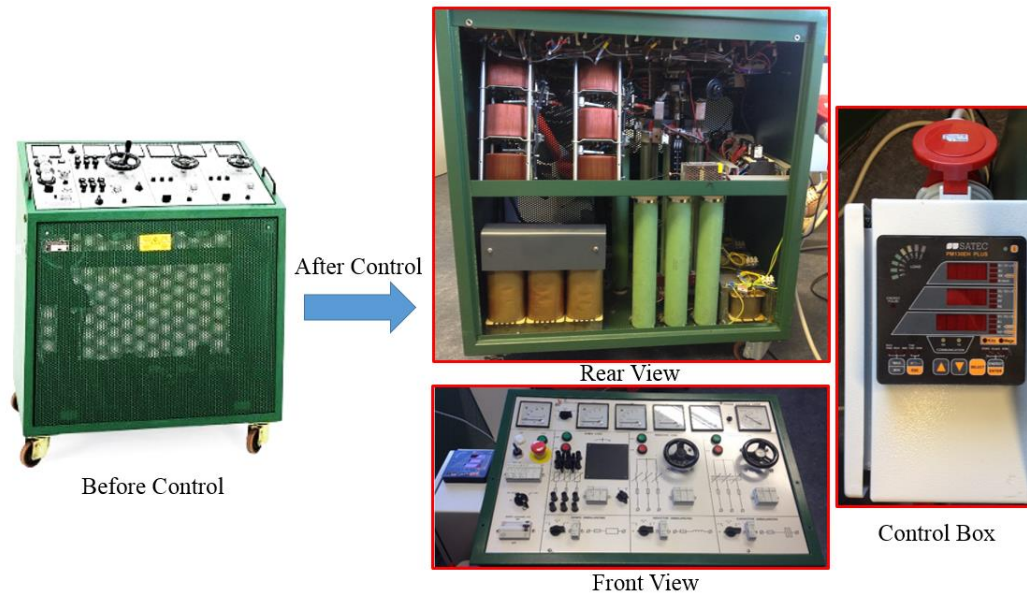


Figure 4.9 – Hardware of the 4 kVA Load.

The first idea of controlling this load is to install a motor on the top of the resistive part in order to move the gauge upward or downward for controlling the consumption. For this reason, a 12 V DC motor was selected to control motion of the gauge. Therefore, by controlling the direction of rotation in this small motor (clockwise and counterclockwise), the gauge can move upward or downward in order to increase or decrease the consumption. Moreover, an energy meter was embedded on the beside of the load for measuring the real-time consumption of the 4 kVA load.

In order to limit the movement range of the motor, two limit switches were used. These switches have been mounted in the maximum and minimum positions of the gauge and can stop the movement of the motor when it reaches to the one of them.

Additionally, an Arduino controls all of these equipment. Arduino is an open-source electronics platform based on easy-to-use hardware and software. The Arduino board includes an AVR microcontroller with complementary components that makes programming easier for user. The complementary components are known as Arduino Shield that can connected directly over various pins. Relay shield is one of these complementary components that employed in this model. This electronic platform has on-board serial interface such as RS-232 and RS-485 interface in order to transmit desired information with other components [34]. Moreover, by equipping the Arduino with an Ethernet shield, it is possible to have Ethernet interface with other equipment. Figure 4.10 shows this electronics platform that has been equipped with an Ethernet shield.

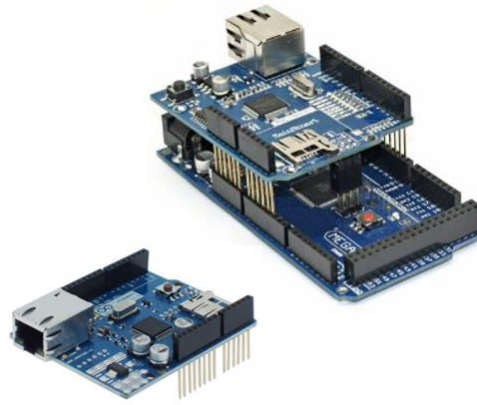


Figure 4.10 – Arduino Mega 2560 equipped with Ethernet shield.

Therefore, these capabilities of the Arduino make it as a good solution for controlling the equipment of 4 kVA load. Hence, an Arduino equipped with Ethernet and relay shields was chosen as controller unit of this system. Various controller components connected to the Arduino have been illustrated on the Figure 4.11.

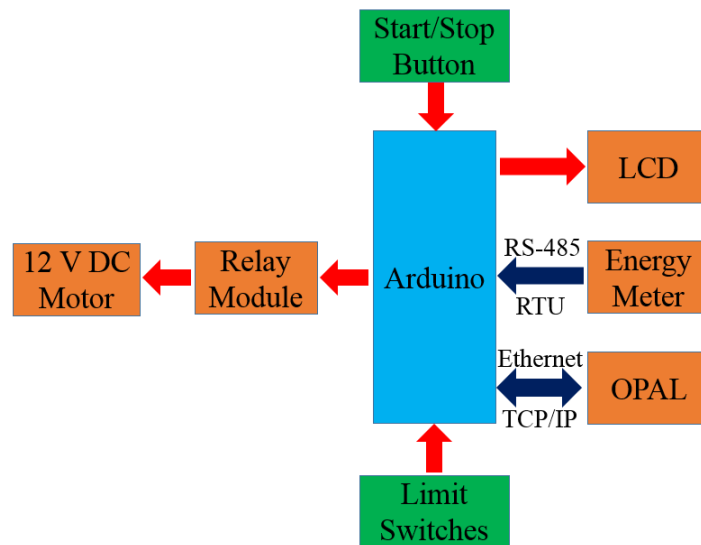


Figure 4.11 – Arduino management scenario.

As Figure 4.11 shows, all of the controller components in 4 kVA load are connected to the Arduino. Start/Stop button are electrically connected to the Arduino such that by pressing this button, Arduino starts to control the equipment. Ethernet shield enables the Arduino to receive the desired power rate that sent from the OPAL and transmit the real-time consumption data to the OPAL through Ethernet interface, with Modbus TCP/IP protocol. The real-time amount of consumption is transmitted from energy meter to the Arduino via RS-485 interface, with Modbus RTU protocol. Moreover, relay shield controls the 12 V DC motor by receiving command from the Arduino and limit switches stop the 12 V DC motor by sending information to the

Arduino. Finally, LCD displays all of the steps of this scenario. These controlling components have been placed on the control box shown on the Figure 4.9. The control box is hardware-developed part of the 4 kVA load and it was not included on the factory setting. This box has a power output socket that is supplied directly from the main power input of 4 kVA load. This socket enables the MRTS system to have series connected loads.

For integration of 4 kVA load into the MRTS system, Arduino follows an algorithm to control the consumption of 4 kVA load. This algorithm has been illustrated on Figure 4.12. As it is clear in this figure, the algorithm is started by pressing start/stop button on the platform of 4 kVA load. After that, Arduino asks the desired power rate from the OPAL and real-time consumption of the load from the energy meter then, it compares these two values. If the desired power rate is bigger than the real-time consumption, Arduino triggers relay 1, 12 V DC motor moves the gauge to upward and the consumption will increase until the amount of desired power. In the reverse mode, if desired power rate is smaller than the real-time consumption, Arduino triggers relay 2, 12 V DC motor moves the gauge to downward and the consumption will decrease until the amount of desired power. In the last stage, if desired power rate is located on the range of ± 20 W of real-time consumption, Arduino stops the 12 V DC motor.

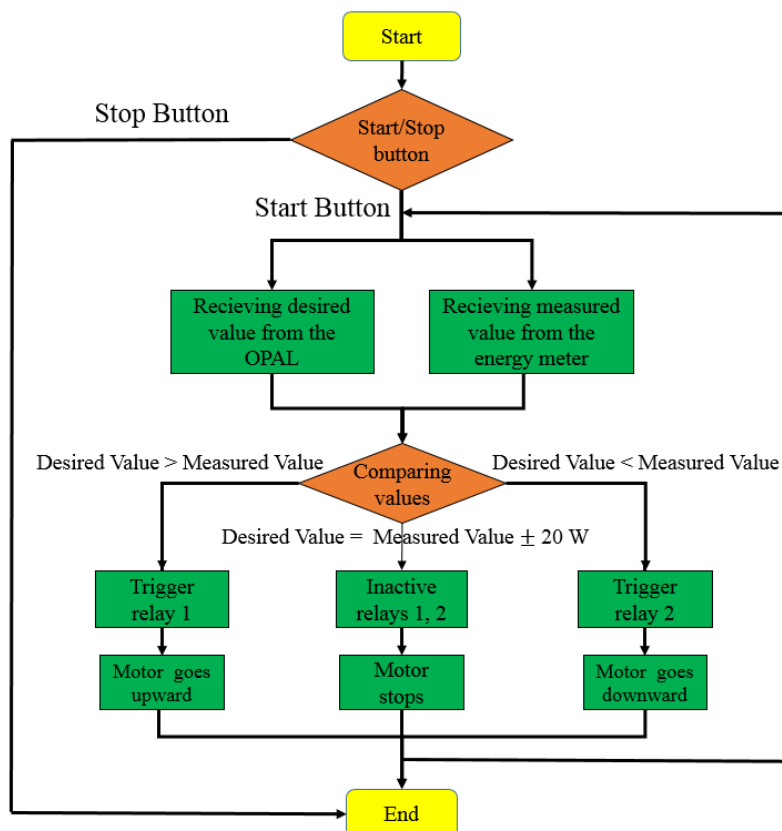


Figure 4.12 – Flowchart of Arduino program.

Additionally, the Arduino transmits the real-time consumption of 4 kVA load to the OPAL. By this way, MRTS system sends the desired power rate to the 4 kVA load and simultaneously receives the real-time consumption data. This scenario enables the MRTS system to have HIL strategy. The explained algorithm has been implemented on the Arduino.

As it mentioned in above, the communication between Arduino and energy meter has done through RS-485 interface, with Modbus RTU protocol. RS-485 is defined as a serial communication between two or more devices that enables the user to create a local network between electrical devices. However, RS-485 can create a short distance network. In this network, one of the devices should be defined as a master unit and others should be slave units. In each devices that have the capability of communication, there is a document called register map. In this document, all of the parameters of device are classified by a specific number. For instance, in the energy meters voltage, current and power of each power line have a specific number, which called register of the parameter. Additionally, each slave device has a specific ID, which called Slave ID. The operator can select this parameter in the slave device configurations. By this way, the master device can ask registers of the desired data from the specific slave device and slave device responds to the master and sends back the desired data. Figure 4.13 shows the message that master device should send to the slave device in order to request the desired information.

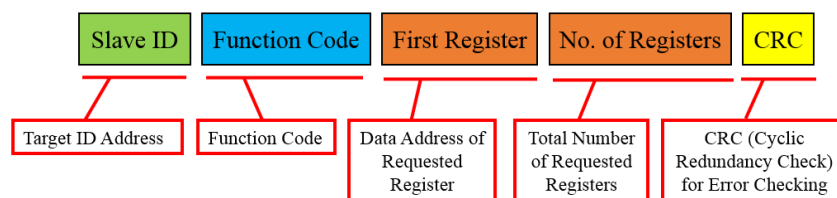


Figure 4.13 – Modbus RTU message in RS-485 communication.

In this message, Slave ID is the address of device that master unit requests the data from that. This address can be selected in the device configurations. Function code is another part of message that indicates the message is for the reading some registers or for writing desired value on these registers. All of the function codes are shown on Table 4.1. First register is a part of message that specifies the address of register that master device requests for it and the next part of message indicates the total number of registers that master device requests for them. In the last section of the message, CRC code is defined. Cyclic Redundancy Check (CRC) is an error-detection code that used

in the communication messages. This code is defined with regard to the other components of the message. The definition process of CRC code is available on [35].

Table 4.1 – Function codes of Modbus protocol [36].

Function Code	Action	Table Name
01 (01 hex)	Read	Read output coils
02 (02 hex)	Read	Read input contacts
03 (03 hex)	Read	Read analog output registers
04 (04 hex)	Read	Read analog input registers
05 (05 hex)	Write single	Write single coil
06 (06 hex)	Write single	Write analog output register
15 (0F hex)	Write multiple	Write several coils
16 (10 hex)	Write multiple	Write analog output registers

In the RS-485 interface, master device defines a CRC code. If the message received from the slave device has exactly the same CRC code, it means that the data have been transmitted correctly and no error happened in this process.

In order to have RS-485 communication between Arduino and other components, MAX485 Integrated Circuit (IC) is required. MAX485 is low-power transceivers for RS-485 communication. Datasheet of this IC is available on [37]. MAX485 is a mandatory component for the Arduino in RS-485 networks. Designed circuit for communication between Arduino and energy meter has been shown in the Figure 4.14.

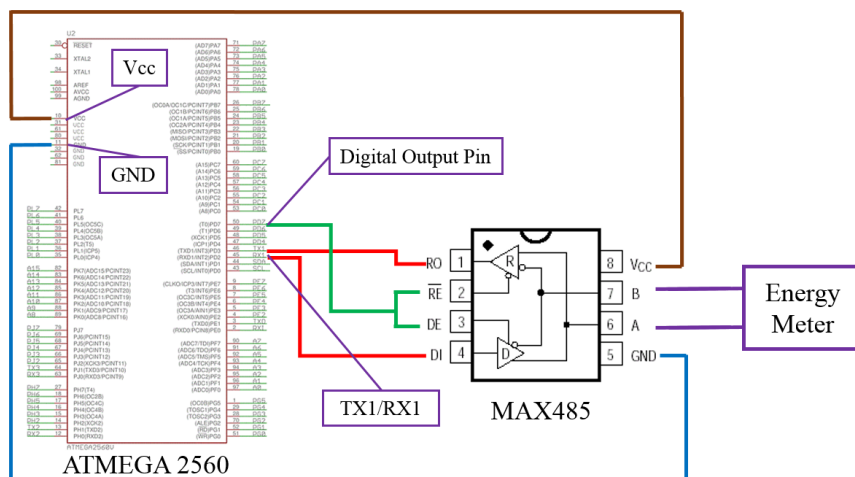


Figure 4.14 – RS-485 interface between Arduino Mega 2560 and energy meter.

By this way, Arduino receives real-time consumption of 4 kVA load by asking the register of total kilowatt from the energy meter. Therefore, these facilities enable MRTS system to be aware from the consumption of real hardware resources.

As it mentioned, Ethernet interface was employed for the communication between Arduino and OPAL. Ethernet interface is defined as computer networking that used for Local Area Networks (LANs) and Metropolitan Area Networks (MANs). This interface is widely used in the private networks to have communication between computers and other electronic devices. Ethernet interface, like other communication protocols, consists of two major parts: server unit and one or several client units. Server unit should define an IP address. If client units intend to connect to the server, they should use the IP address of server. This scenario is exactly same as Slave ID in the RS-485 interface. However, contrary of RS-485 serial communication, Ethernet interface has no distance limitation because it can be a part of internet worldwide network. In the meantime, MRTS system uses Ethernet interface for connecting the OPAL to Arduino. In this network, Arduino is the server unit and OPAL is client unit.

In order to create an Ethernet network in the MRTS system, no special circuit was required. One or more RJ45 connectors were necessary to build the Ethernet network. Therefore, two RJ45 connectors were used for the connection of Arduino and OPAL. By this communication network, Arduino receives the desired power rates of MRTS system from OPAL and sends back the real-time consumption of 4 kVA load to it.

In the Ethernet interface, Modbus TCP/IP protocol is used. This protocol is different from the Modbus RTU. Additionally, in Modbus TCP/IP the message that client unit uses for requesting some registers of the server unit is vary from the message of Modbus RTU. Figure 4.15 shows the components of message that is applied in the Modbus TCP/IP.

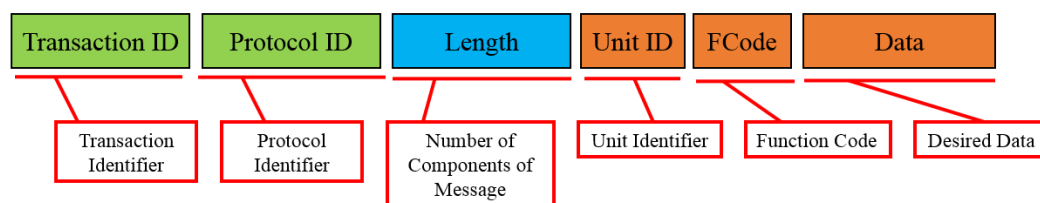


Figure 4.15 – Modbus TCP/IP message in Ethernet communication network.

In this message, transaction ID is used for the synchronization between messages of the server and client. Protocol ID is always zero for the Modbus TCP/IP. Length section provides the number of message components that start from this part. Unit ID can be selected by user (255 if not used). Function codes of Modbus TCP/IP message are exactly same as Modbus RTU, which have been listed in Table 4.1. In the last part, desired data that user intends to transmit to the target, should be placed.

By this way, OPAL can send the desired power rate that intends to be consumed by 4 kVA load, and Arduino can transmit the real-time consumption of 4 kVA load to the OPAL.

In the MATLAB Simulink model of 4 kVA load, communication blocks play an important role due to Ethernet interface between OPAL and the target. Therefore, Modbus TCP/IP send/receive blocks have been placed in the Simulink model. Figure 4.16 shows the Simulink model that loaded on the OPAL. In this model, entire configurations of Modbus TCP/IP have been done.

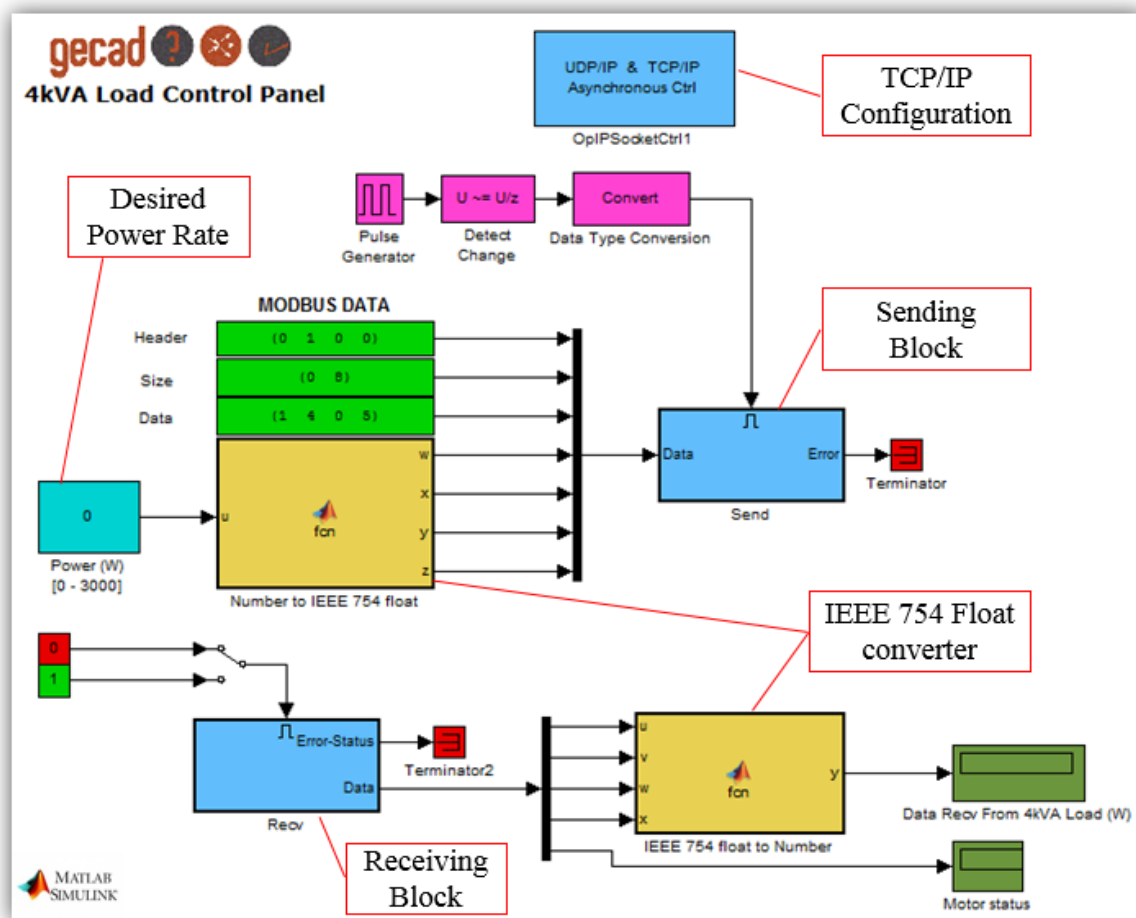


Figure 4.16 – MATLAB Simulink model of 4 kVA load.

In the top of the model, there is “OpIPSocketCtrl1” block. This block is related to the TCP/IP configurations for Ethernet interface such that remote IP address and port number of the target should be defined in this block. Moreover, a controller ID should be specified in this block in order to refer send/receive blocks configurations to this block. In other words, the controller ID of send/receive blocks should be as same as “OpIPSocketCtrl1” block.

According to the Modbus TCP/IP specifications that transmit data in the hexadecimal format, IEEE 754 standard of communication was employed. Implementation of this standard and its converters, are the most important sections of this Simulink model.

IEEE 754 is a technical standard for the float points that converts any decimal number to 4-bytes hexadecimal message. This standard can convert any positive/negative integers or float numbers to hexadecimal format. In the first step of conversion, IEEE 754 converts the decimal number to 32-bit binary string, and then divides this string into the three parts: sign, exponent and mantissa. Finally, it converts this string to four numbers in hexadecimal format.

As it mentioned, the structure of IEEE 754 format includes three parts: sign, exponent and mantissa. The sign bit is the first bit of the IEEE 754 structure that indicates the sign of decimal value. Exponent is referred to the integer part of decimal value and mantissa is dedicated for the float part of that. Figure 4.17 illustrates an example of IEEE 754 conversion between a decimal value and 4-bytes hexadecimal message. In this example, decimal number is “125.4” that is converted to “0x42, 0xFA, 0xCC, 0xCD” in hexadecimal format.

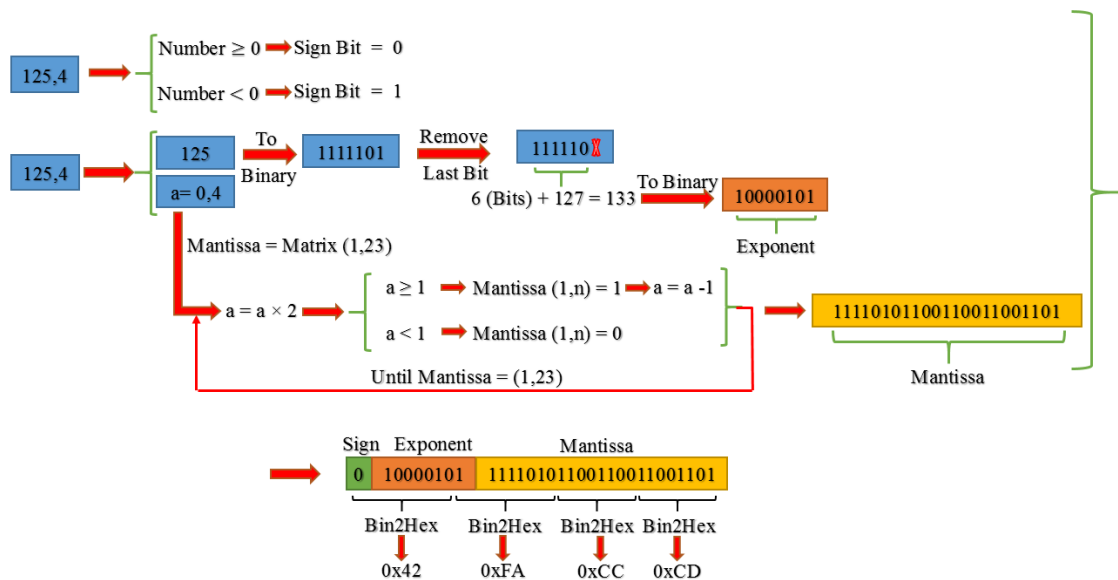


Figure 4.17 – An example of IEEE 754 conversion (decimal number to 4-bytes hexadecimal message).

As you can see in Figure 4.17, in the first step, the sign of decimal number is recognized and placed on the first bit of binary string. Second, the decimal number is divided into the two parts: integer part and float section. Integer part is converted to the binary format and then the last bit of binary string should be removed. Length of this string, which is 6-bit in this example, is the number that should added to the amount of

bias, which is 127 for all binary32 format. By converting the sum of string length and bias value to the binary format, the exponent will be achieved. For the mantissa part, a matrix consists of 1 row and 23 columns should be created and the components of this matrix will be determined from the following process.

The float part of decimal value, which is 0.4 in this example, should be multiplied by 2 and then:

- If the result is bigger than 1, the corresponding array is placed “1”;
- If the result is smaller than 1, the corresponding array is placed “0”.

This process will be continued until the matrix achieves to the array of 23. By this way, the matrix of mantissa is formed such that all of the arrays are 0 or 1.

In the final step, sign bit, exponent and mantissa should be integrated to each other, and thus a 32-bit string is formed. By dividing this string into four parts of 8-bit and converting these four parts to hexadecimal format, the final results is achieved.

These mathematical operations have been done in a MATLAB function block that in the Simulink model called “Number to IEEE 754 float” block. Regarding to Figure 4.16, the message of Modbus TCP/IP is integrated with IEEE 754 conversion block. It means that the desired power rate, which is a decimal value, is converted to a 4-bytes hexadecimal message and will be integrated in the Modbus TCP/IP message in order to be ready for the transmission.

Therefore, the desired power rate will be transmitted to the Arduino in 4-bytes hexadecimal message and Arduino should convert this 4-bytes hexadecimal message into the decimal format.

Additionally, Arduino receives real-time consumption data of 4 kVA load from the energy meter in 4-bytes hexadecimal message thus, Arduino transmits these data of 4 kVA load to the OPAL in 4-bytes hexadecimal message. This means that in the Simulink model of OPAL, another conversion block should be placed in order to convert 4-bytes hexadecimal message into the decimal format. In the Simulink model this block called “IEEE 754 float to Number”, which has been shown on Figure 4.16. This block enables the Simulink model to have the consumption data of 4 kVA load in real-time.

The conversion process of 4-bytes hexadecimal message to the decimal format, has been illustrated by an example on Figure 4.18. In this figure, it is assumed that

“0x42, 0xFA, 0xCC, 0xCD” is a 4-bytes hexadecimal message that received from Arduino and “IEEE 754 float to Number” block intends to convert it to a decimal number.

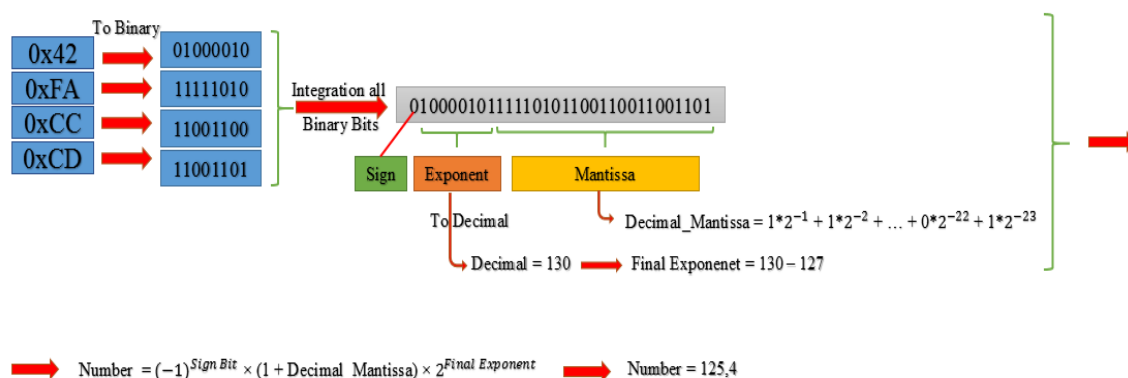


Figure 4.18 – IEEE 754 conversion (4-bytes hexadecimal message to decimal).

The process starts by converting this hexadecimal message to the binary format. By this way, four 8-bit binary strings will be formed. In the next step, these strings should be integrated to each other. Therefore, the main structure of IEEE 754 float, which is 32-bit binary string, is formed. In this string, the first bit indicates the sign of decimal value. If the sign bit is “0” it means that the decimal number is positive and if the sign bit is “1”, the decimal number is negative. The next 8-bit of this string determines the exponent in binary format. Therefore, by converting to decimal system, exponent will be appeared. This value should be subtracted from the bias value, which was 127 thus, the final exponent result will be determined, which is 3 in this example. The next 23-bit are dedicated for the mantissa part. The decimal format of mantissa is calculated by multiplying each bit to the corresponding power of 2. By applying the obtained results into the expression [38] that demonstrated in the bottom of Figure 4.18, the decimal number will be achieved.

As a conclusion, the explained scenarios enable the 4 kVA load to be integrated in MRTS system as HIL. According to the general data of residential power consumption, 4 kVA load is an appropriate facility for simulating the consumption of a residential load. In the next chapter, this simulation will be described.

4.3.2. Medium Power Consumer

CRESSALL AC30 30 kVA portable load bank (called 30 kVA load in this dissertation) is a single or three-phase resistive load that can be used for testing of the different AC systems with the consumption of less than 30 kVA. The capacity of this load is 30 kW at 400 V in three-phase mode and 15 kW at 230 V in the single-phase.

For controlling of the consumption, an integral control panel equipped with single-phase/three-phase selector switch, 18 illuminated switches, voltmeter 0-500 V, ammeter 0-80 A and frequency meter 45-65 Hz, have been mounted on the front view of the load case. In the three-phase mode, the consumption of the load can be controlled in the sections of 1 kW, 2×2 kW, 5 kW and 2×10 kW. In the single-phase mode, the consumption can be controlled in the steps of 333 W.

The resistor elements are mesh and mica card elements that made from the high-grade nickel-chrome stainless steel with 752 V insulation. The cooling system contains of four fans supplied from the test load power. However, the consumption of the fans is not too much and generally not considered on the tests. These fans are embedded under the load bank in order to have more fresh air in the case [39].

This load has two separate input connectors for each single-phase and three-phase mode. Three-phase input connector has five pins consist of three poles, neutral and earth and in single-phase, there is three pins include one pole and earth. Figure 4.19 shows a view of 30 kVA load. Further information about this load bank is available on [39].



Figure 4.19 – Front view of the 30 kVA load.

For controlling this load by the OPAL, four relays have been employed. These relays were connected to the digital output board of the OPAL.

MATLAB Simulink model Developed for controlling the 30 kVA load has been demonstrated on the Figure 4.20.

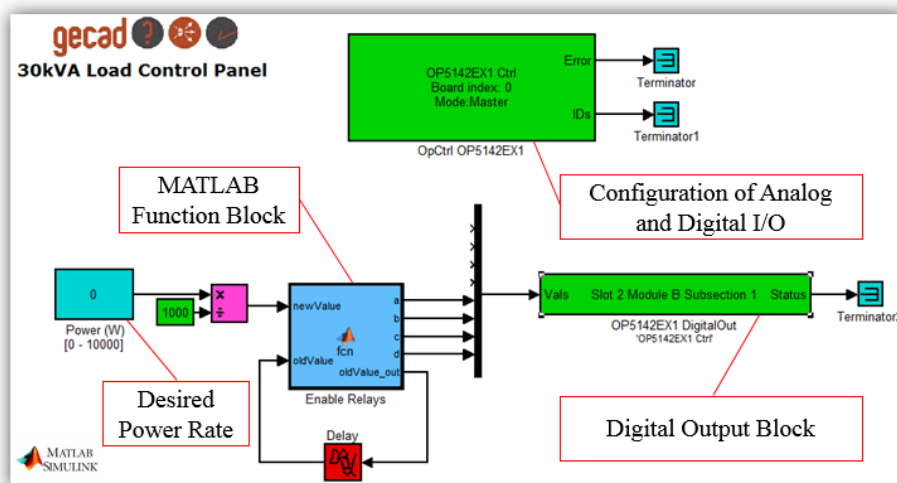


Figure 4.20 –Simulink model for controlling 30 kVA hardware resource.

As it mentioned in above, for integration of the 30 kVA load in the MRTS system, four digital output channels were used. For using analog and digital I/O boards of the OPAL, some fundamental configurations are necessary in the Simulink environment. For the same reason, the two green blocks shown on the Figure 4.20 should be placed in the all of Simulink models that tend to use I/O of the OPAL. One of these blocks is “OpCtrl OP5142EX1”, which is equivalent for the all of Simulink models, and the another block can be vary regarding to the digital or analog I/O boards. For the Simulink model of this section, which uses digital output board, “OP514EX1 DigitalOut” block has been placed. The parameters of this block are shown on the Figure 4.21.

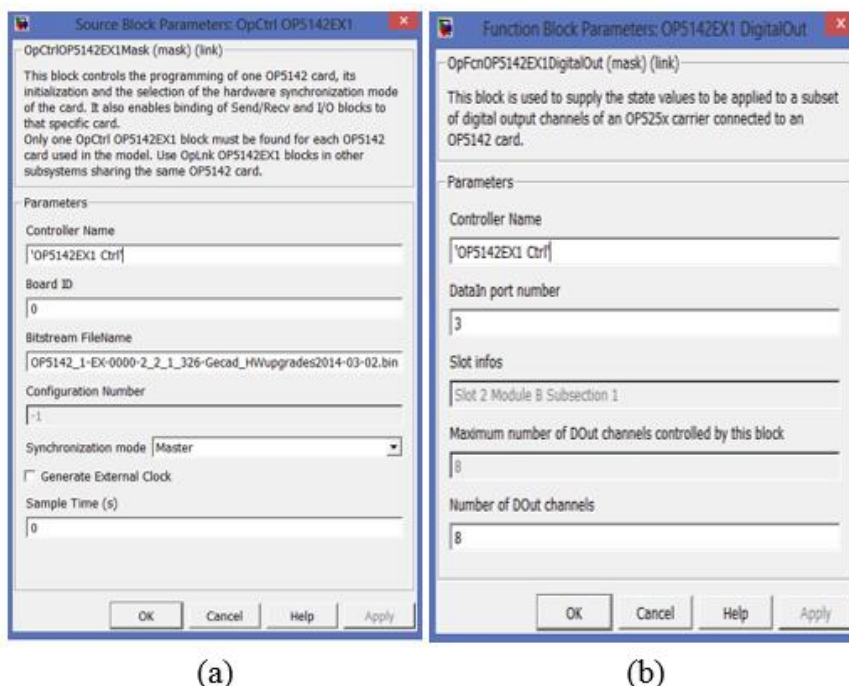


Figure 4.21 – Block parameters (a) OpCtrl OP5142EX1 (b) OP514EX1 DigitalOut.

For the “OpCtrl OP5142EX1” block, there are some basic configurations that are equal for all of Simulink models. This block is the source of other I/O blocks. The configurations include defining a controller name, board ID and bitstream file name. Users can define any controller name, however, board ID and bitstream file name should be defined regarding to the system documents provided by OPAL company.

The parameters of “OP514EX1 DigitalOut” block are controller name, dataIn port number and number of digital output channels. The controller name in this block should be exactly same as the controller name of “OpCtrl OP5142EX1” block. DataIn port number should be defined according to the system documents that shown on Figure 4.4 and the number of digital output channels is defined by the user. The maximum number of digital output channels that can be represented by one I/O board is eight channels.

According to the Figure 4.20, firstly, the desired power rate that MRTS system tends to consume by the 30 kVA load is defined as a constant in the model. Secondly, this power rate converts from watt to kilowatt and enters as an input to a MATLAB function block. The outputs of this block are connected to the last four channels of the digital output board. It should be noted that the relays require a pulse to be activate or deactivate. For this purpose, a delay block has been placed in the Simulink model for activating the corresponding output for a short time. Therefore, the MATLAB function block activates the appropriate relay on the 30 kVA load by regarding to the desired power rate that defined in the constant of the Simulink model.

For this purpose, a MATLAB function was developed in this block due to recognize the amount of input and activate the related output for triggering the corresponding relay. Figure 4.22 demonstrates the flowchart of this function.

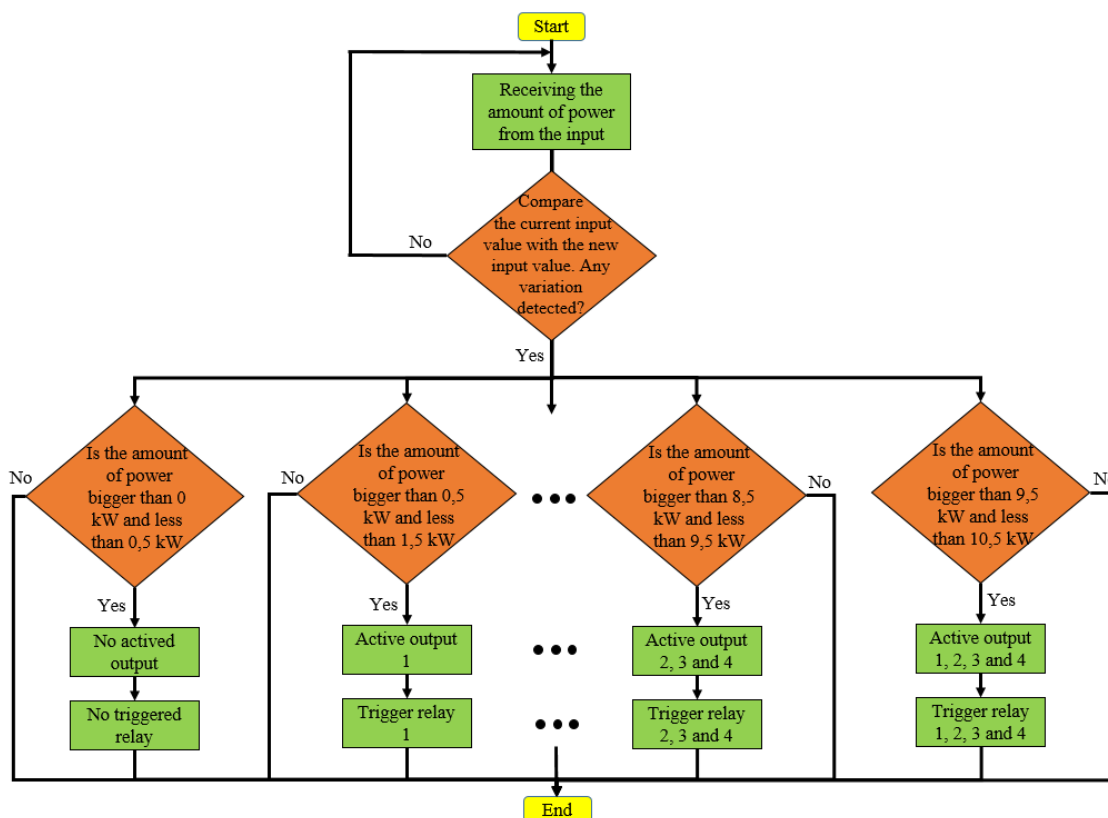


Figure 4.22 – Flowchart of implemented function for 30 kVA load.

In the 30 kVA load, the consumption is adjusted only for the integer values, which are 1, 2, 3 ... 10 kW. It means that by cooperation of these four relays, the amount of consumption is vary from 0 to 10 kW only for the integer values. In the MATLAB function block, a specific range is defined for each integer number. This range is 500 W less and 500 W more than the integer value, namely for 5 kW the specified range is 4.5 kW to 5.5 kW. Therefore, this block should compare the desired power rate with these ranges and recognize this amount of the power is located on which one of these ranges in order to activate the relays related to that range. For instance, 7 kW has a range from 6.5 kW to 7.5 kW. If the desired power rate is 7.2 or 6.8 kW, which is a value between 6.5 kW to 7.5 kW, outputs number two and four of the MATLAB function block should be activated in order to trigger the relays number two and four, because relay number two is for 2 kW and relay number four is for 5 kW switch.

As a conclusion, four remote switches enable the MRTS system to integrate 30 kVA load as a real consumer unit in the simulation environment. This integration required software and hardware development that all of them were described completely. 30 kVA load can be used in the MRTS system as a medium consumer unit. This resource will be employed in the next chapter for simulating the consumption of a small commerce facility.

4.3.3. Micro-Generation Unit

EOLYP 1.2 kW wind turbine emulator is a facility that allows the user to examine the electricity concepts of the wind turbine generator. In this emulator, an inductive three-phase generator has been coupled with a three-phase asynchronous motor with variable speed. This motor simulates the blades of the wind turbine. By this way, the operator can simulate the wind speed by controlling the speed of the motor. Figure 4.23 shows a view of this wind turbine emulator. According to the specifications of this emulator, which should be configured in the grid-connected mode, the generator has been connected to the utility grid in order to inject the produced power. For injecting the generated energy into the utility grid, the emulator should follow the frequency of the grid. If the mechanical frequency of the generated power by the emulator is bigger than the frequency of the utility grid, the generated power is injected into the grid. However, if driving speed is not sufficient, the generator is not able to produce energy.



Figure 4.23 – EOLYP 1.2 kW wind turbine emulator.

The main characteristics of this emulator include:

- Generator: asynchronous machine ($U = 3 \times 400 \text{ V}_{ac}$, $I_{max} = 5 \text{ A}$);
- Active power sent over the network: 0 to 1.2 kW;
- Generator efficiency: 78 % ;
- Speed variation of motor: 0 to 1800 RPM.

Various components of the wind turbine emulator are shown in the Figure 4.24. Start/Stop button is used for turning the emulator on or off. Switches for the capacitors battery are used for compensating of the reactive power and adjusting the power factor

near to 1 by regarding to the speed of the wind and the output power. Each switch has been dedicated for 25% of the capacity of capacitor bank.

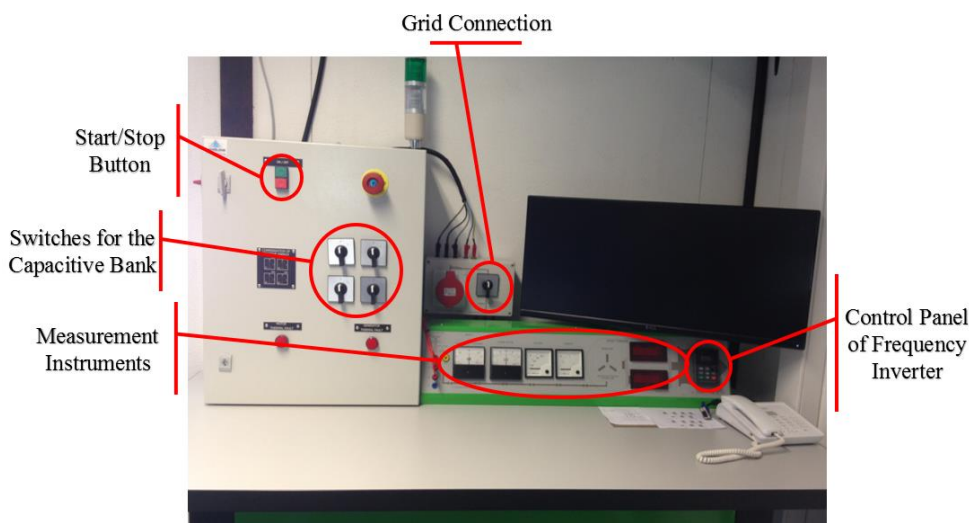


Figure 4.24 – Equipment of the wind turbine emulator.

There is a speed controller unit in the emulator. This unit has the capability of controlling the speed by the related analog input terminal. Therefore, by connecting one of the analog output channels of the OPAL to the analog input terminal of the speed controller unit, the integration of the wind turbine emulator into the MRTS system will be achieved. The wind turbine emulator acts as a micro-generation unit in the MRTS system.

For controlling of this micro-generation unit, one analog output channel of the OPAL was applied. This output channel has the output range of 0 to 10 V with the resolution of 0.01 V. Similarly, the speed controller unit of the wind turbine emulator accepts 0 to 10 V on the analog input terminal. Therefore, the wind speed variation should be converted to the voltage range of the analog output board in the OPAL. The computations of this conversion have been done in the Simulink environment. Figure 4.25 demonstrates the controlling method of this emulator.

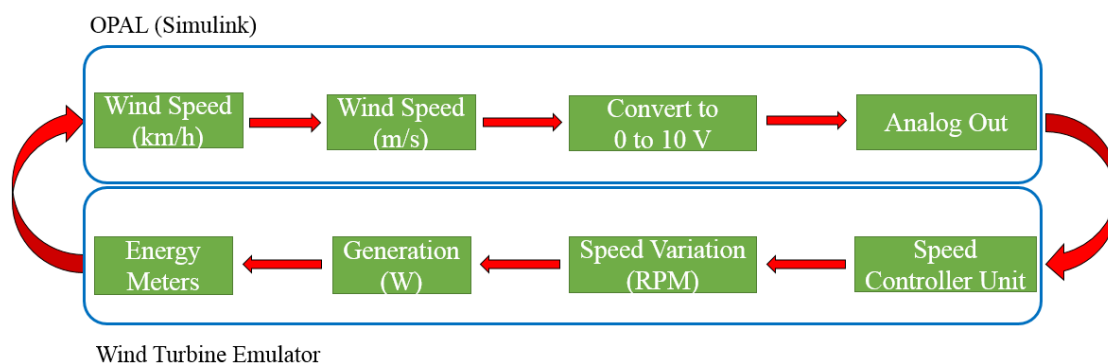


Figure 4.25 – Controlling diagram of wind turbine emulator by the OPAL.

In the first step of this controlling method, wind speed data should be converted from km/h to m/s. In the second step, the wind speed in m/s should be transferred to a reasonable value for the analog output range, which is 0 to 10 V. For this purpose, the proportion between the generated energy and the wind speed data in the Whisper 200 wind turbine was obtained. Whisper 200 wind turbine is a home-scale wind generation facility that can generate 1000 W in the maximum capacity. This proportion was applied to the wind turbine emulator. By this method, the amount of the voltage that analog output should present to the speed controller unit were achieved. In this system, if the wind speed is less than 2.3 m/s and more than 20.3 m/s, the wind turbine will be stopped due to safety and economic reasons. In the next step, the generated power is measured by the energy meters mounted on the MRTS power lines and in the final step, the measured data are transmitted to the OPAL. By this controlling method, it would be possible to put, in the Simulink environment, the wind speed values and get the amounts of the generated energy.

All of these computations have been implemented in MATLAB Simulink environment. Figure 4.26 shows the controlling Simulink model of wind turbine emulator. This model uses one of the analog output channels.

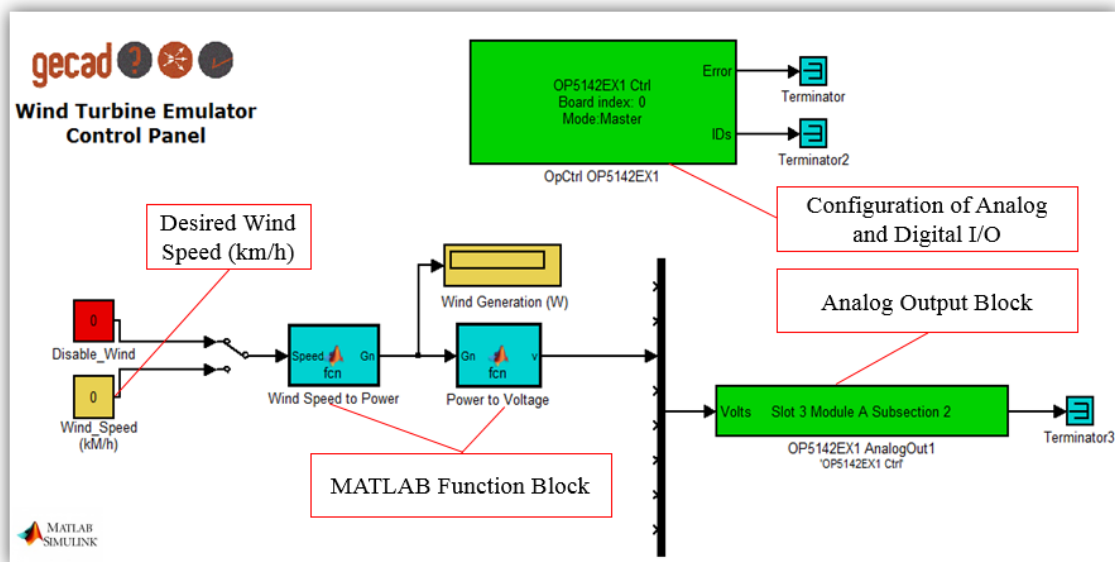


Figure 4.26 – MATLAB Simulink model for controlling wind turbine emulator.

In this model, the configurations of the I/O boards (“OpCtrl OP5142EX1” block) are as same as the configurations that explained in the controlling model of the 30 kVA load. Moreover, the configurations of “OP514EX1 AnalogOut” block are equal to the “OP514EX1 DigitalOut” block, which mentioned on the Figure 4.21.

Two MATLAB function blocks have been placed on this model for converting the wind speed data to a reasonable value for the analog output board of the OPAL. These two blocks are “Wind Speed to Power” and “Power to Voltage” blocks. In the first block, the proportion between the generated energy and the wind speed data of the Whisper 200 wind turbine has been modeled. This proportion was obtained according to the speed-generation chart available on the Whisper 200 manufacturer catalog. In “Power to Voltage” block, the results of an experimental test has have been applied. In this test, the amount of the voltage that OPAL should provide to the analog input terminal of the speed controller unit in order to increase the produced power for 50 W, was acquired. Therefore, by cooperation of these tow MATLAB function blocks, the MRTS system would be able to present the related amounts of the voltage to the speed controller unit of the emulator by regarding to the wind speed data.

As a small brief, the proposed scenario enables wind turbine emulator to be merged into the MRTS system as a micro-generation unit. Furthermore, this system can be used for simulating the real-time generation profiles. In the next chapter, this emulator will be used for simulation of a home-scale wind turbine.

4.4. MRTS Power Lines

Two power transmission lines were employed for the MRTS system. Each line is equipped with two energy meters and several safety components. One of the energy meters has been installed at the beginning and the other has been mounted at the end of the line. Figure 4.27 demonstrates the configurations of the power lines used for the MRTS system.

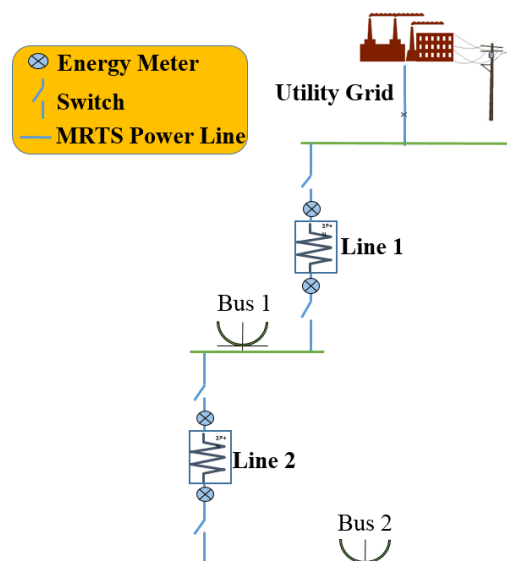


Figure 4.27 – MRTS power lines architecture.

In this system line 1 and line 2 have been employed for the resources used in the MRTS system. The power supply is the input of this system and two buses are the outputs. Although, in the case of wind turbine emulator connected to the one of these buses, it will operate as an input for the system. MRTS players have been connected to the bus 1 and 2.

These power lines are controlled by Cubietruck platform. Cubietruck is a single-board computer that has Linux as operation system and many I/O pins for controlling several devices. Real-time data of the voltage, current, active power, reactive power and other parameters of each line are transmitted from the energy meters to the Cubietruck via RS-485 interface with Modbus/RTU protocol. Then, the OPAL requests the value of the active power in each line from the Cubietruck. The OPAL and Cubietruck are connected to each other through Ethernet interface, with Modbus/TCP protocol. Simulink model designed for this communication has been shown in the Figure 4.28.

In this part, the MRTS system requests the active power parameter from the four energy meters installed on the power lines. Energy meters respond to the OPAL in a 16-bytes hexadecimal message, 4-bytes for each energy meter.

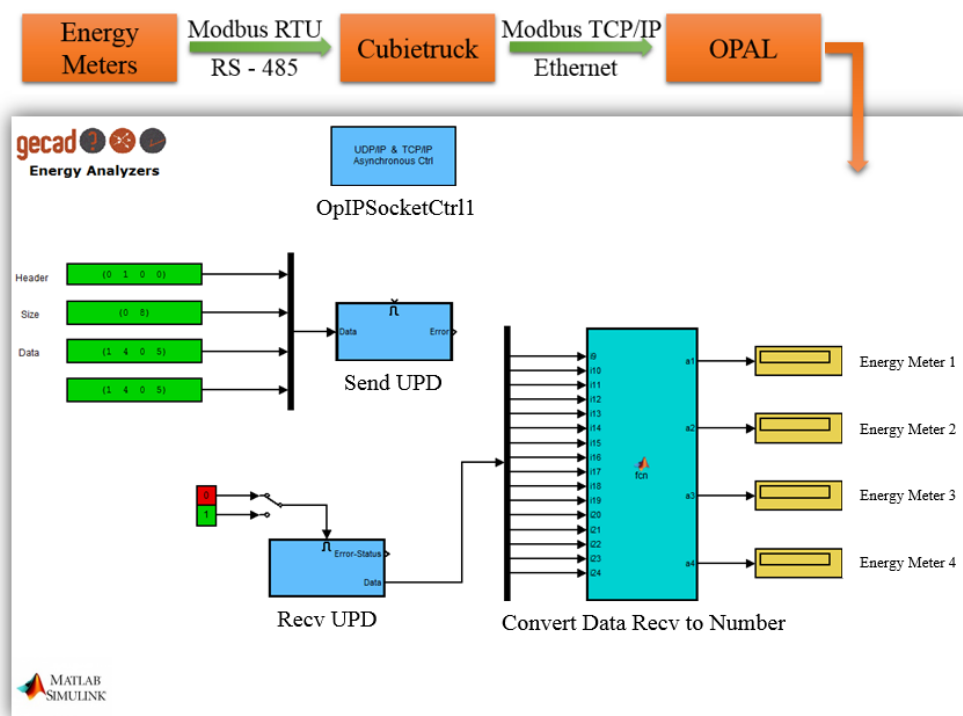


Figure 4.28 – MATLAB Simulink model for TCP/IP communication.

This model is as same as the Simulink model of the 4 kVA load. TCP/IP and controller ID have been configured in the “OpIPSocketCtrl1” block. The only

difference is the format of the received data. In the 4 kVA load, desired data had been transmitted in IEEE 754 format, however, in this model desired data are transmitted in the hexadecimal system and they do not follow the IEEE 754 format. Received data in this model requires merging to each other. This integration has been implemented in the “Convert Data Recv to Number” block. The outputs of this block are four decimal values that indicate the active power of each line. Energy meters 1 and 2 have been dedicated for the line 1, and energy meters 3 and 4 have been assigned for the line 2.

In the MRTS system, wind turbine emulator (micro-generation unit) is connected to the bus 1 because of the grid-connected operation of this emulator and 4 kVA and 30 kVA load (consumers) are connected to the bus 2. This configuration, which is shown in the Figure 4.29, will be used in the next chapter for the case studies.

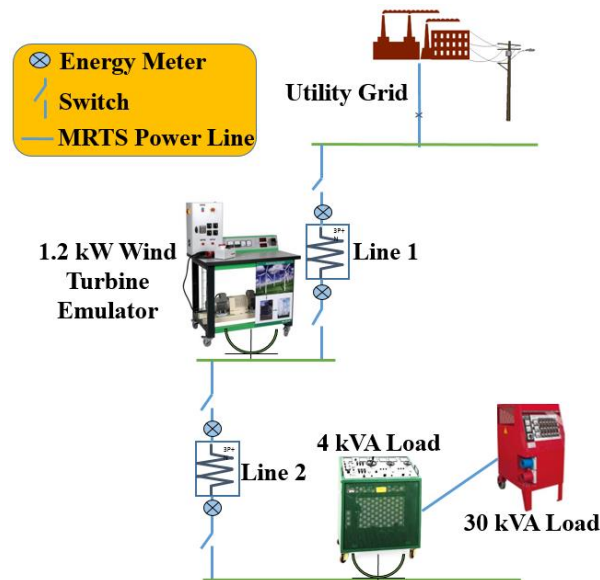


Figure 4.29 – MRTS configuration for case studies.

4.5. Conclusion

In this chapter, hardware and software developed for MRTS system were described. Real resources that built for manual use, were integrated in the MRTS system by implementing several software and hardware scenarios.

For the 4 kVA load integration, 12 V DC motor, two limit switches and one energy meter were mounted on the load. 12 V DC motor increases or decrease the resistive part of load, two limit switches specify the movement range of motor and energy meter measures the real-time consumption of load. An Arduino equipped with Ethernet and relay shields controls the 4 kVA load. In the case of 30 kVA load, several relays that are controlled by the OPAL, manage the consumption of this hardware

resource. For the wind turbine emulator, one analog output channel of the OPAL was applied in order to control the speed variation. Finally, MRTS power lines connected all of these resources to each other and several communication protocols were applied for exchanging information between the main unit (i.e., OPAL) and other resources.

The proposed system can be a platform for executing demand response programs using real generation and/or consumption profiles. Additionally, managing this platform by an intelligent algorithm can examine network management prototypes.

Chapter 5

Simulated Scenarios and Case Studies

This chapter refers the use of the MRTS system for simulating residential consumption profiles and small commerce facility consumption profiles, and for the integration of a micro-generation unit in residential profiles.

Therefore, the wind turbine emulator is used as a micro-generation unit, the 4 kVA load is employed as a consumer for simulating residential consumption profile, and the integration of the 4 kVA and 30 kVA loads is applied for simulating a small commerce facility consumption profile. Additionally, merging the 4 kVA load and wind turbine emulator can be used for simulating the consumption and generation profiles of a house equipped with a home-scale wind turbine. These scenarios have been implemented on three case studies that are mentioned below.

5.1. Simulation of Residential Consumption Profile

In this case study, real consumption data of a private house that have been provided by energy meter mounted on this house, are given to the MRTS system as desired power rate then, by employing hardware resources, which is 4 kVA load in this case study, it attempts to follow the consumption profile of the private house. Therefore, MRTS system would be able to simulate the real-time consumption profile of a private house by 4 kVA hardware resource.

Consumption profiles of several private houses, three offices and one commercial bar are available on IEEE PES Intelligent Data Mining and Analysis [40]. For this case study, private house 1 was selected from the IEEE PES Intelligent Data Mining and Analysis, for the real-time simulation of consumption.

Private house 1 is related to a single-family housing with three adult people. This house consists of three bedrooms, three bathrooms, one living room, one kitchen, one laundry room and corridor. Major charges include one washing machine/dryer, one dishwasher, one electric hob, one electric oven, one fridge, one microwave, one extractor, one vacuum cleaner, one hair dryer, three TVs, one LCD, two laptops, one

router and two electric heaters. This measurement test was begun at 03/06/2011 and finished in 18/06/2011. The measurement instrument was Chauvin Arnoux 8335 and sampling period was each five minutes. Maximum allowable power of this house is single-phase 5.75 kVA.

For this case study, a period of two hours has been selected randomly in the date of 10/06/2011 from 9:20 AM to 11:20 AM. These data are shown in Table 5.1.

Table 5.1 – Measured data of active power consumption in period of two hours on private house [40].

Data	Time	Power(w)
10-06-2011	09:20:00	40,2
10-06-2011	09:25:00	40
10-06-2011	09:30:00	79,74
10-06-2011	09:35:00	102,69
10-06-2011	09:40:00	195,8
10-06-2011	09:45:00	198,7
10-06-2011	09:50:00	209,5
10-06-2011	09:55:00	202,03
10-06-2011	10:00:00	1706,19
10-06-2011	10:05:00	2567,99
10-06-2011	10:10:00	2576,77
10-06-2011	10:15:00	2596,05
10-06-2011	10:20:00	2227,87
10-06-2011	10:25:00	264,36
10-06-2011	10:30:00	282,67
10-06-2011	10:35:00	180,6
10-06-2011	10:40:00	279,62
10-06-2011	10:45:00	328,28
10-06-2011	10:50:00	511,59
10-06-2011	10:55:00	241,41
10-06-2011	11:00:00	198,47
10-06-2011	11:05:00	278,56
10-06-2011	11:10:00	317,27
10-06-2011	11:15:00	273,39
10-06-2011	11:20:00	271,52

Moreover, the consumption profile of this house, regarding to the Table 5.1, is shown on Figure 5.1. As it is clear in this figure, the peak time of this residential load is between 09:55 AM to 10:25 AM, which is related to the time when people wake up and prepare to go to their workplace, and the minimum consumption corresponds to the time when people are sleeping or when they are on the workplace.

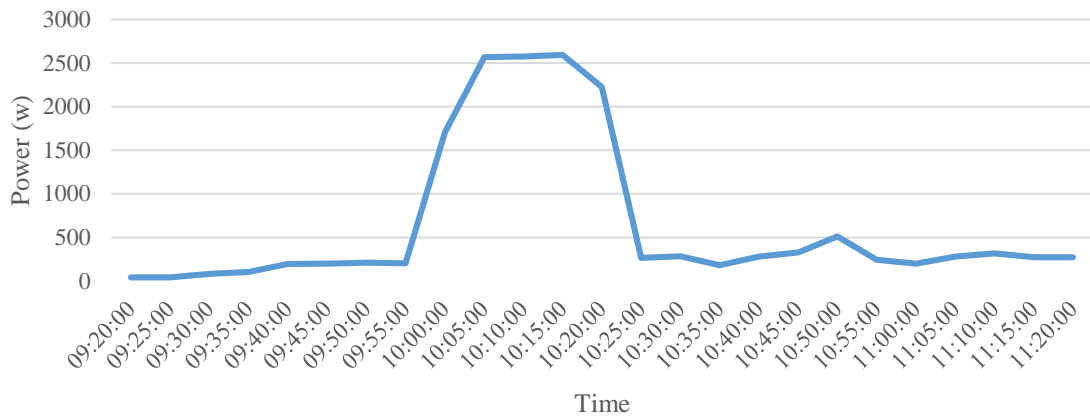


Figure 5.1 – Consumption profile of the private house 1 from 9:20 AM to 11:20 AM [40].

The data shown in Table 5.1 and shown in Figure 5.1 are desired power rates for the MRTS system. It attempts to consume these values by 4 kVA load in order to simulate the consumption of private house 1 in real-time. For this purpose, as Figure 5.2 demonstrates, desired power rates of MRTS system are transferred from OPAL to 4 kVA load each 5 minutes then, according to desired power rates, 12 V DC motor embedded on the 4 kVA load increases or decreases the consumption. Finally, energy meter mounted on 4 kVA load measures the real-time consumption (active power) and sends back to the OPAL.

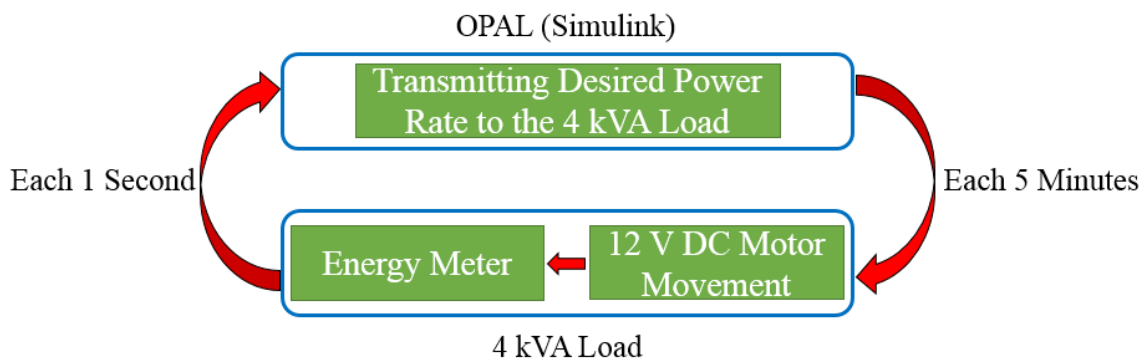


Figure 5.2 – Proposed system for case study 1.

In the context of MRTS power lines, this case study employs power line 1 in order to supply the 4 kVA load. Figure 5.3 illustrates this configuration. It should be noted that energy meters mounted on the power line 1 measure the consumption of the 4 kVA load. By this way, losses on the line and other parameters related to length of the line can be computed.

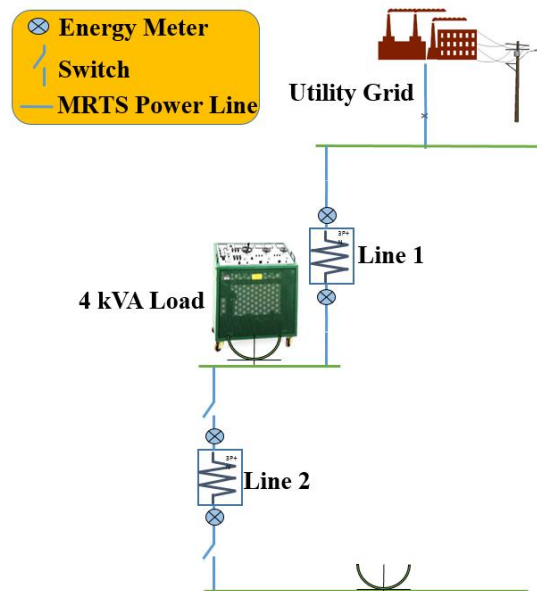


Figure 5.3 – Configuration of MRTS power lines for case study 1.

The Simulink model executed on the OPAL for this case study was shown on Figure 4.16. This Simulink model uses TCP/IP communication protocol for transmitting desired data to the 4 kVA load. In this model, desired power rates after passing from the IEEE 754 conversion blocks, are transmitted to the 4 kVA load and simultaneously the real-time consumption data sent back to the OPAL. The results of this simulation are demonstrated on the Figure 5.4.

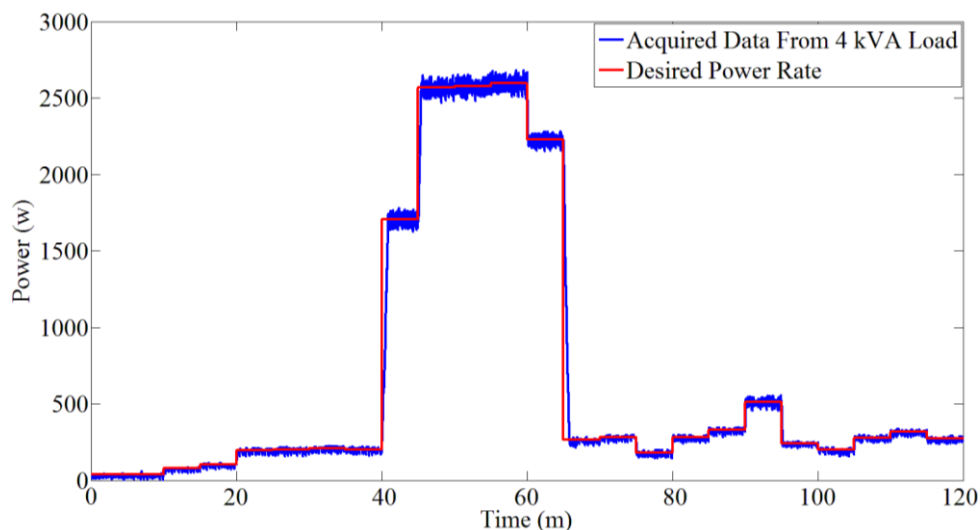


Figure 5.4 – Real-time simulation of residential consumption by 4 kVA load in period of two hours.

In this figure, consumption profile of the private house 1 in the period of 9:20 AM to 11:20 AM has been simulated. The consumption profile of this house has been indicated by red line and simulation data, which acquired from the 4 kVA load, have been specified by blue line. In this simulation, 12 V DC motor attempts to reach to the

desired power rates and according to voltage variations of the utility grid, it tries to be static and equal to the desired power rates, which leads to send back various values to the target. These variations are more sensible on high power rates.

Moreover, state of the 12 V DC motor is shown on Figure 5.5. These results have been adopted in the range of 9 minutes that the profile has high rate of consumption.

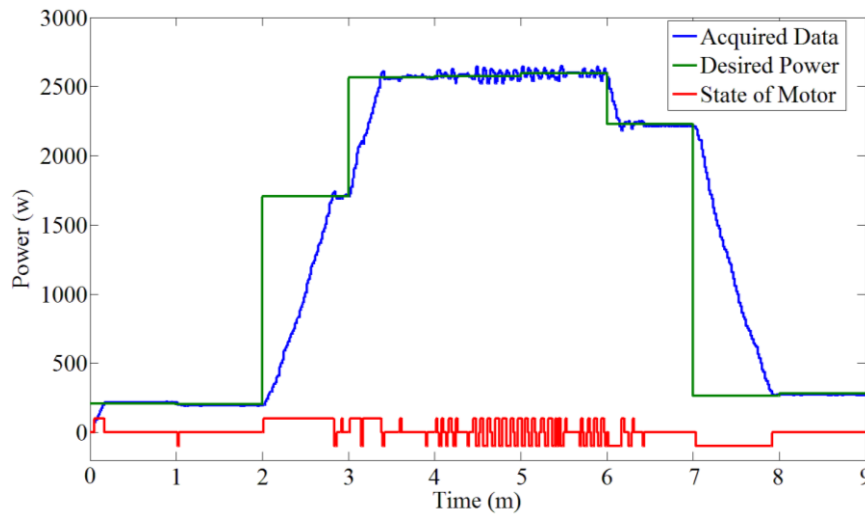


Figure 5.5 – Controlling decision of 4 kVA load.

As you can see in Figure 5.5, while desired power rate (green line) is increasing, the red line that is related to state of 12 V DC motor is located on positive values, which means that motor is moving the resistive gauge to upward in order to reach the desired power rate. In the opposite side, when desired power rate is decreasing, the red line is located on the negative values, which means the resistive gauge is moving to downward.

Therefore, in the case study 1, MRTS system simulated the consumption profile of a house by employing 4 kVA hardware resource. This case study applied HIL scenario for the simulation.

5.2. Simulation of Small Commerce Facility Consumption Profile

In this section, MRTS system employs 4 kVA and 30 kVA loads simultaneously for simulating consumption profile of a small commerce facility.

As it mentioned before, consumption data of various customers are available on [40]. In this case study, consumption profile of commercial bar 1 was chosen from IEEE PES Intelligent Data Mining and Analysis [40].

This commercial bar is related to a small commerce facility with three bathrooms, two floors and one storage room. Major charges consist of two heating, ventilating and air conditioning systems, two air extractors, two large fridges, two fridges, four amplifiers, one speaker, one robot, lighting, one coffee machine, three beer machines, two freezers, one ice machine, one smoke machine, three monitors, one table music, two DJ dishes, eleven surveillance cameras, one security system, decoration lighting, four fans and two cash registers. Maximum allowable power of this small commerce facility is three-phase 13.80 kVA. Business hour is 22:00 PM to 05:00 AM. This measurement experience was begun at 02/07/2014 and finished at 07/07/2014. Measuring instrument was Chauvin Arnoux 8335 and sampling period was each minute.

The period of two hours for this case study has been selected in the date of 06/07/2014 from 22:00 PM to 00:00 AM. These data are demonstrated on Figure 5.6.

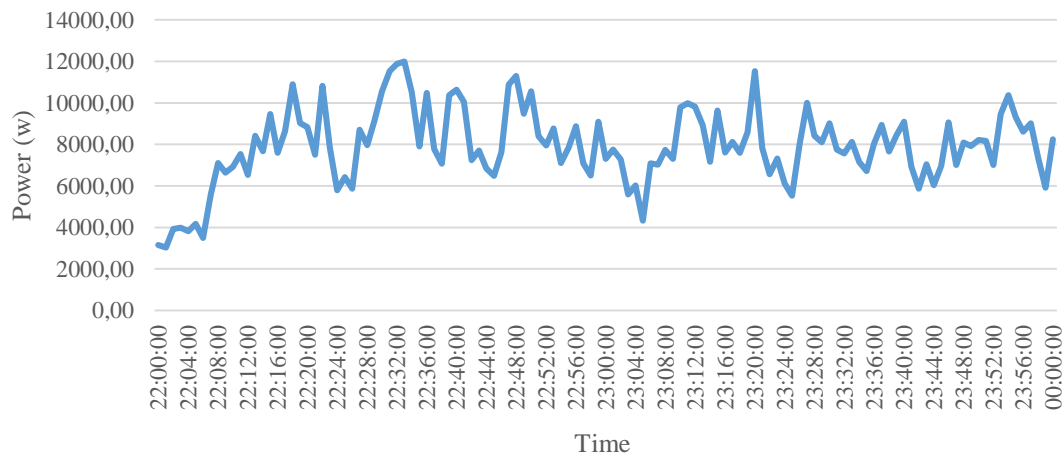


Figure 5.6 – Consumption profile of the small commerce facility from 22:00 PM to 00:00 AM [40].

This profile is started at 22:00 PM, which is minimum consumption in this time, and by passing time to the midnight consumption increases. This profile has many variations in the consumption, thus, MRTS system should be able to support these variations.

According to the previous chapter, the apparent power of the 4 kVA load is around 4 kW and the maximum amount of the power that MRTS system can handle in 30 kVA load is around 10 kW. Therefore, maximum allowable power consumption in the MRTS system is around 14 kW. For simulating the consumption in less than 4 kW values, like case study 1, MRTS system applies 4 kVA load. However, for simulating the consumption in more than 4 kW values, MRTS system should employ 30 kVA load and this hardware resource is able to simulate the consumption only in integer values

such as 1 kW, 2 kW, 5 kW, etc. For this reason, integration of 4 kVA and 30 kVA hardware resources was a solution to solve this problem. By the same token, a scenario has been implemented in the MRTS system that divides desired power rates into the two parts: integer section and float section. The integer section is transmitted to 30 kVA load and the float section is sent to 4 kVA load. For instance, if desired power rate is 6.42 kW, the MRTS system will transmit 6 kW to the 30 kVA load and 420 W will be sent to the 4 kVA load. This scenario has been illustrated in Figure 5.7.

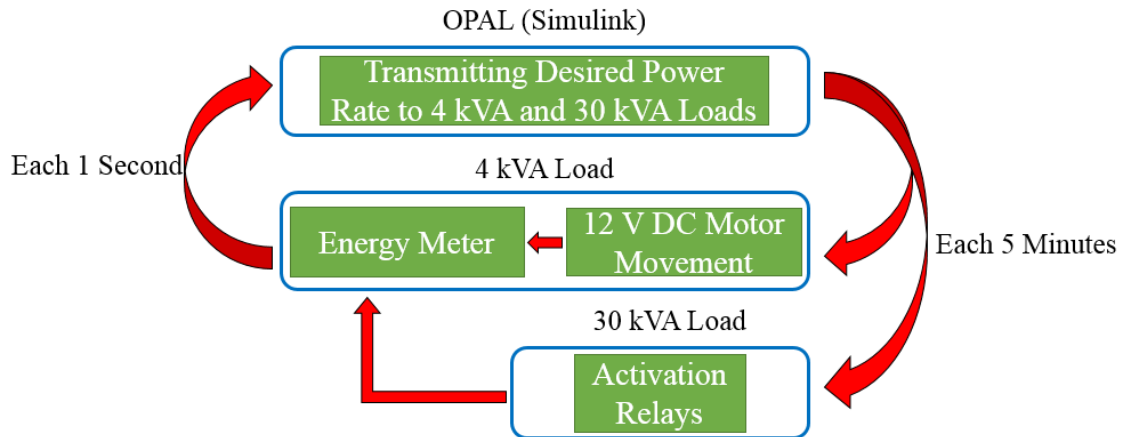


Figure 5.7 – Implemented scenario for case study 2.

In this case study, desired power rate is transmitted from OPAL to 4 kVA and 30 kVA hardware resources each five minutes. The integer section of desired power rate is sent to the 30 kVA load in order to activate the relays mounted on this hardware. Additionally, the float part is sent to 4 kVA load for changing the consumption rate by 12 V DC motor. Moreover, real-time consumption data of these two loads are measured by energy meter installed on the 4 kVA load. They will be sent back to the OPAL each one second.

According to the configurations of 4 kVA load, which mentioned in the previous chapter, it has a power output socket that is supplied directly from the main power input of 4 kVA load. In this case study, 30 kVA load is supplied from this socket. For this reason, the consumption of 30 kVA hardware resource will be measured by energy meter of the 4 kVA load.

MRTS power lines in this case study are similar to the case study 1. The only difference is that 30 kVA load has been attached to the 4 kVA load in series mode. Figure 5.8 shows these configurations.

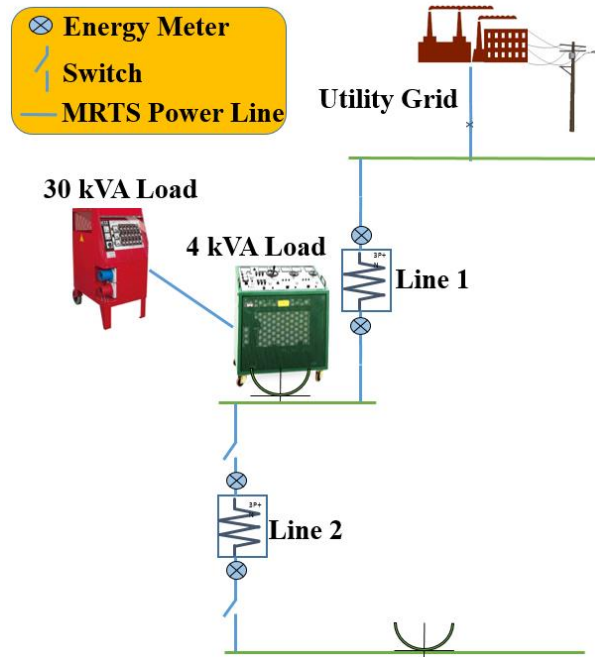


Figure 5.8 – Configuration of MRTS power lines for case study 2.

MATLAB Simulink model for case study 2 is shown on Figure 5.9. This model uses TCP/IP communication protocol for merging 4 kVA hardware resource and employs four channels of digital output board for the 30 kVA load. Real-time consumption data of both loads are transmitted from the energy meter to OPAL.

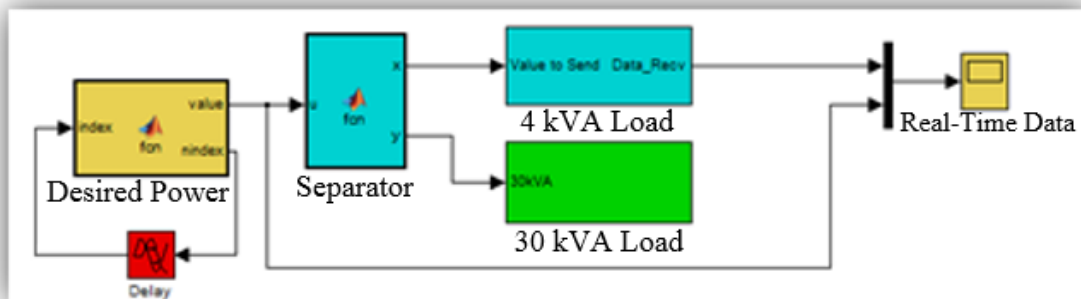


Figure 5.9 – Simulink model used in the case study 2.

In this model, desired power rates, which shown on the Figure 5.6, are passed through a MATLAB function block called “Separator” in order to divide them into the two parts of integer and float. Afterward, they will be sent to the hardware resources by their corresponding blocks. Results of this simulation have been illustrated on the Figure 5.10.

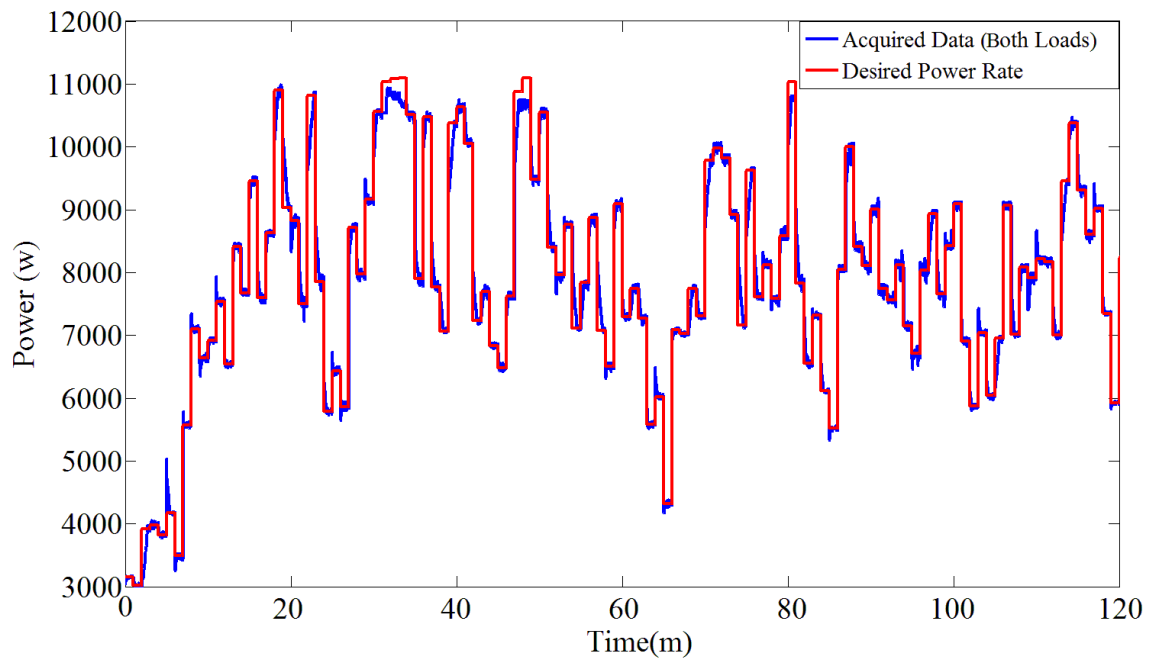


Figure 5.10 – Real-time simulation of consumption in case study 2.

This simulation has been done by employing 4 kVA and 30 kVA hardware resources in the period of two hours. Red line is referred to the desired power rates, which transmitted from OPAL, and blue line is consumption data of both loads. As it can be seen in this figure, blue line is following the red line. This means that these two loads are attempting to consume the power rate received from the OPAL.

Therefore, in this case study, the scenario of integration 4 kVA load and 30 kVA load was implemented. This scenario enables MRTS system to simulate float values of the consumption on high rates of power. In the previous cases, MRTS system was able to simulate float values of the consumption by applying 4 kVA hardware resource, however, the power rate was limited to values less than 4 kW. In the case of 30 kVA load, MRTS system was able to consume high rate of power, but only for integer values. For this reason, the scenario of merging these two hardware resources was considered in order to simulate the consumption for float values in high rates of power.

5.3. Simulation of Residential Consumption and Generation Profiles

In this part, wind turbine emulator is merged to the MRTS system. Wind turbine emulator plays the role of a micro-generation unit that can be installed on the demand side. This case study simulates a house equipped with a home-scale wind turbine. Therefore, 4 kVA load simulates the consumption profile and wind turbine emulator follows real-time wind speed data. Results of this case study show the relation between consumption and generation of this house.

For this purpose, consumption profile has been selected from the private house 1 [40] in the date of 10/06/2011, from 12:30 PM to 14:30 PM. Table 5.2 shows these data. The profile of this case study is the next two hours of the profile used in case study 1.

Table 5.2 – Measured data (active power) of the private house 1 for case study 3 [40].

Data	Time	Power(w)
10-06-2011	12:30:00	150,06
10-06-2011	12:35:00	165,57
10-06-2011	12:40:00	163,37
10-06-2011	12:45:00	115,97
10-06-2011	12:50:00	40,98
10-06-2011	12:55:00	41,36
10-06-2011	13:00:00	41,36
10-06-2011	13:05:00	41,22
10-06-2011	13:10:00	41,51
10-06-2011	13:15:00	41,28
10-06-2011	13:20:00	212,84
10-06-2011	13:25:00	2536,99
10-06-2011	13:30:00	2510,39
10-06-2011	13:35:00	1492,63
10-06-2011	13:40:00	879,67
10-06-2011	13:45:00	1224,98
10-06-2011	13:50:00	886,13
10-06-2011	13:55:00	213,81
10-06-2011	14:00:00	220,58
10-06-2011	14:05:00	200,24
10-06-2011	14:10:00	201,91
10-06-2011	14:15:00	281,83
10-06-2011	14:20:00	237,74
10-06-2011	14:25:00	255,56
10-06-2011	14:30:00	246,59

Similarly, Figure 5.11 illustrates the consumption profile related to Table 5.2. This profile is employed as desired power rates for MRTS system.

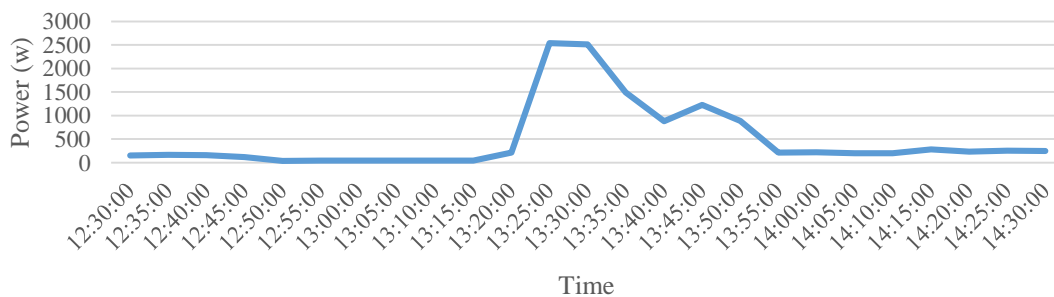


Figure 5.11 – Consumption profile of private house 1 for case study 3 [40].

Wind speed data for generation profile was chosen from ISEP Meteo website [41]. This website is reserved for Institute of Engineering – Polytechnic of Porto (ISEP/IPP). Weather information taken from this website, are stored on respective server each five minutes. A period of two hours was selected from this server. These data have been shown on Table 5.3.

Table 5.3 – Wind speed data for case study 3 [41].

Time (m)	5	10	15	20	25	30	35	40	45	50	55	60
Wind Speed (km/h)	35.4	14.5	29.0	17.7	6.40	22.5	6.40	11.3	16.1	27.4	6.40	6.40
Time (m)	65	70	75	80	85	90	95	100	105	110	115	120
Wind Speed (km/h)	32.3	27.4	24.1	8.00	24.1	16.1	19.3	30.6	17.7	8.00	16.1	22.5

According to features of the wind turbine emulator, while the wind speed is less than 8 km/h (2.22 m/s), it stops the generation due to economic reasons.

MRTS power lines for this case study are shown on Figure 5.12. Wind turbine emulator in this configuration has been connected to the bus 1 and 4 kVA load has been supplied from the bus 2.

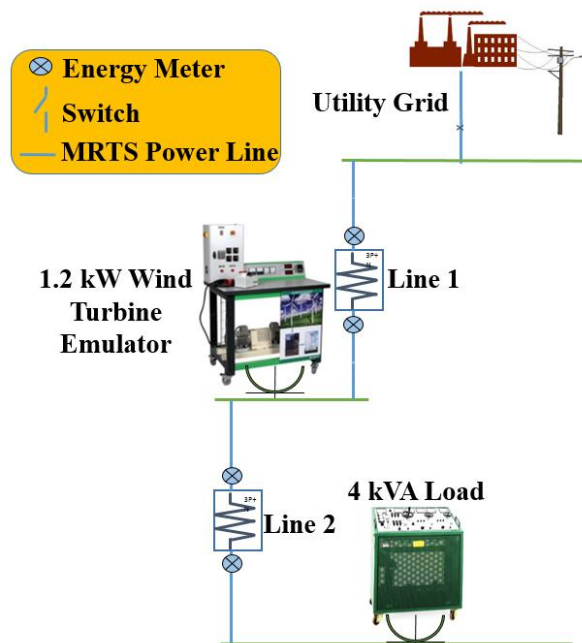


Figure 5.12 – MRTS power lines configuration for case study 3.

In other words, wind turbine emulator can inject the generated power to lines one and two. Additionally, 4 kVA load is supplied from line one. Energy required for this load can be supplied from the wind turbine emulator or from the utility grid. Conditions that may occur in this area are shown in the Figure 5.13.

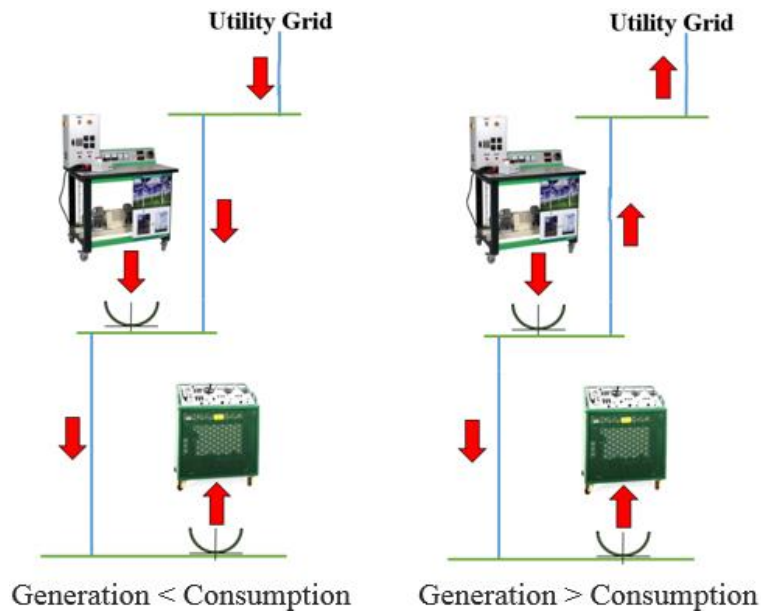


Figure 5.13 – Two probable situations of case study 3.

Wind turbine emulator is able to operate only in grid-connected mode therefore, it can supply the 4 kVA load by relying on utility grid. By this way, if the generated power is more than the energy required of 4 kVA load, excess of produced energy will be injected to the utility grid. This means MRTS system is selling energy to the utility grid. In the opposite side, if generated power is less than the energy required of 4 kVA load, MRTS system should consume energy from the utility grid. In other words, it purchases energy from the utility grid.

In the term of measurement, consumption of the 4 kVA load is measured by energy meter installed on that hardware. Energy generated by wind turbine emulator is computed by energy meters mounted on the power lines such that energy meters of the power line 2 measure the purchased energy from the utility grid or sold energy to it. Moreover, energy meters of the power line 1 measure the consumption of 4 kVA load. Therefore, by subtracting or collecting the measured power of these two lines, energy produced by wind turbine emulator will be achieved.

As it mentioned, main goal of this case study is to simulate a house equipped with home-scale wind turbine. Therefore, MRTS system can propose a platform for operator to inform about the consumption, generation, power sold to the utility grid and power purchased from it. The OPAL provides this platform in MATLAB Simulink environment.

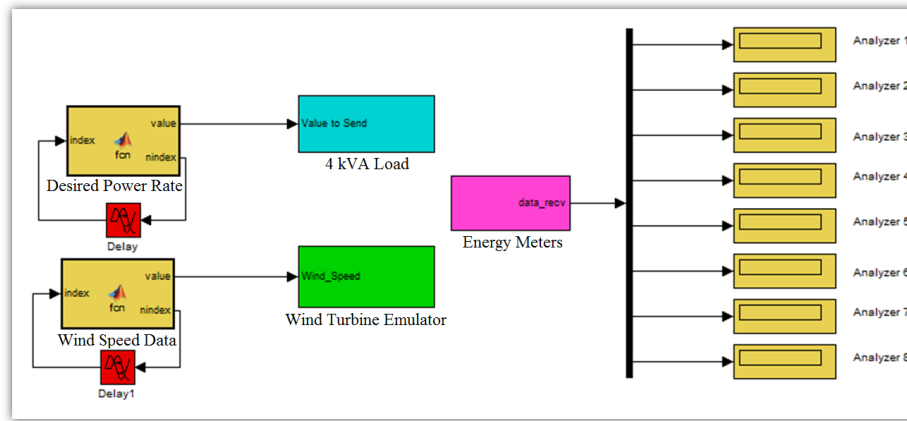


Figure 5.14 – MATLAB Simulink model of case study 3.

In this model, desired power rates and wind speed data are transmitted to 4 kVA load and wind turbine emulator each five minutes. On the other side, energy meters send back active power data to the OPAL each second. Results of this simulation, which has been done in the period of two hours, are shown on Figure 5.15.

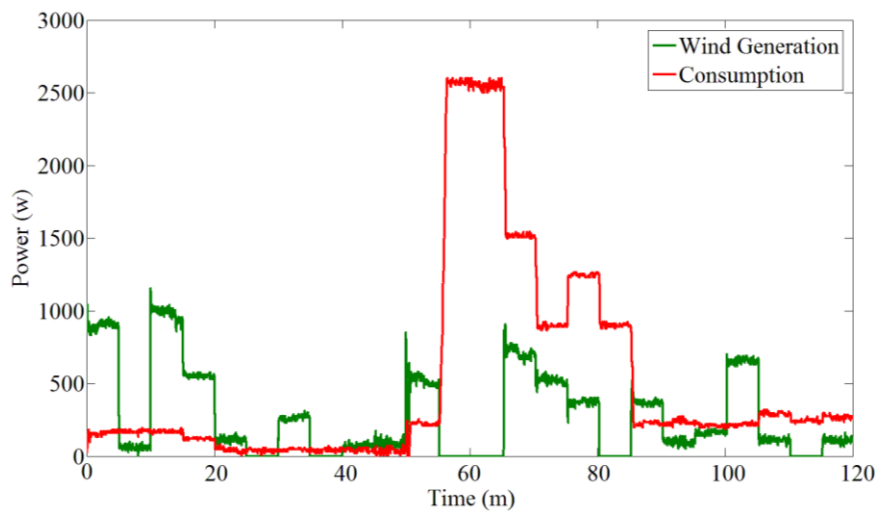


Figure 5.15 – Simulated generation and consumption profiles of the private house 1.

As it can be seen in Figure 5.15, green line indicates the generation profile of wind turbine emulator and red line is the consumption profile of 4 kVA load. In some sections, wind generation profile is situated on the zero value, which means wind speed in that time is less than 8 km/h. In other words, green line shows the generated power by home-scale wind turbine and red line indicates consumption of the house.

The proposed system operates in grid-connected mode therefore, whenever the generated power is more than the consumption of the house, excess of energy can be injected to the utility grid. The following figures are expressed information related to purchased power from the utility grid or sold back to it.

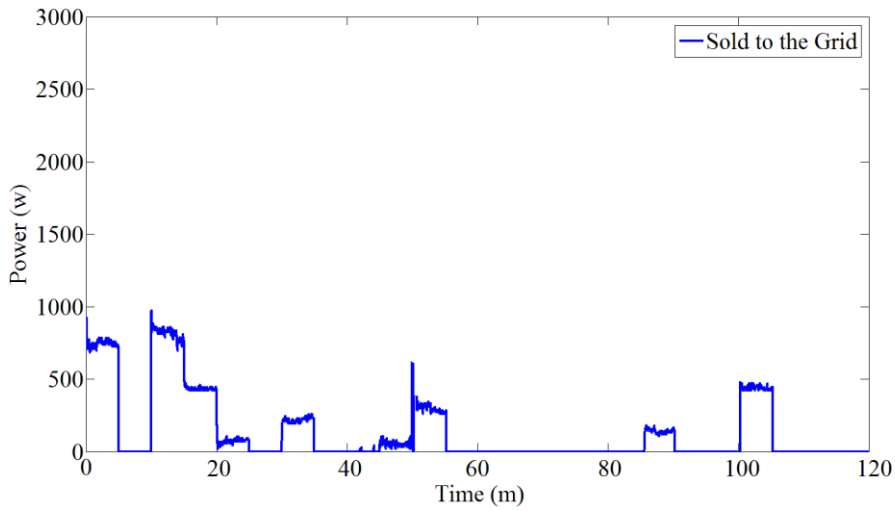


Figure 5.16 – Energy sold to the utility grid by MRTS system.

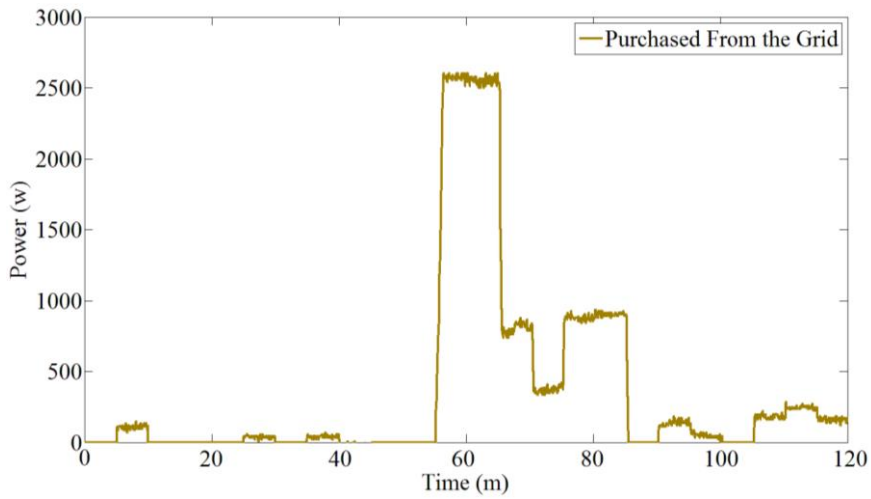


Figure 5.17 – Energy purchased from the utility grid by MRTS system.

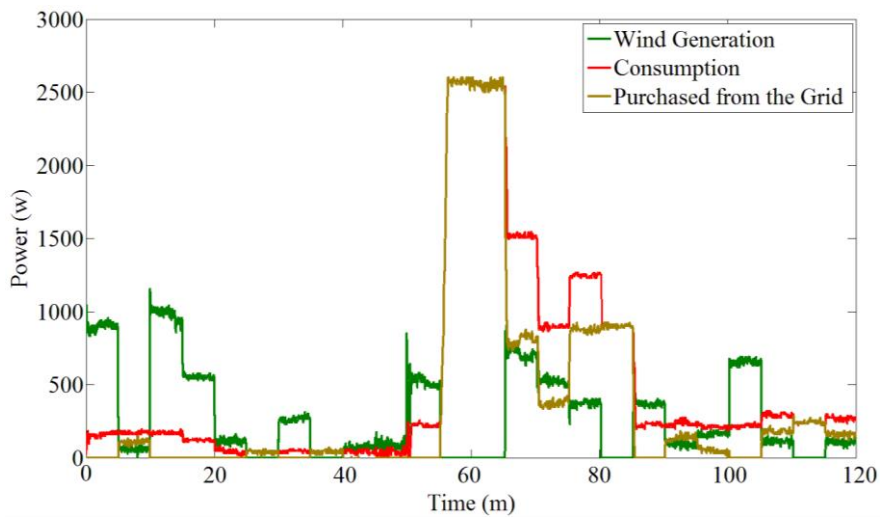


Figure 5.18 – Merging the purchased energy profile with generation and consumption profiles.

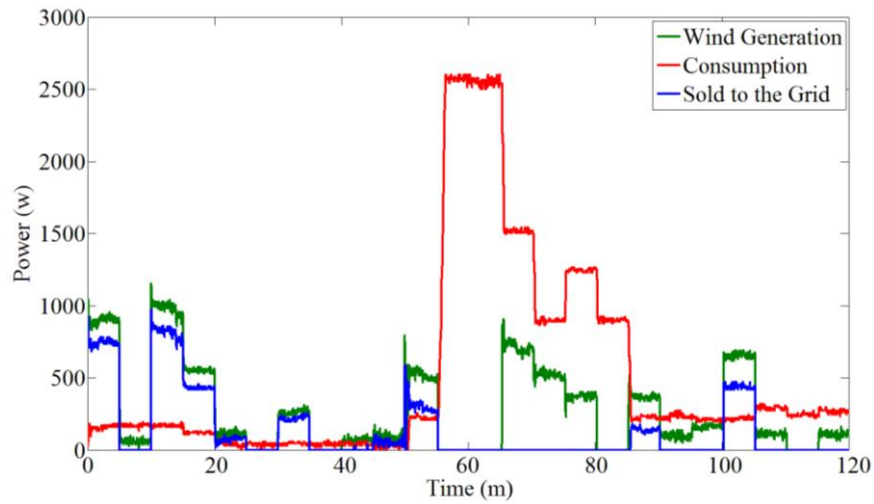


Figure 5.19 – Integration of sold energy profile with generation and consumption profiles.

As it can be seen in Figure 5.17 and Figure 5.18, while there is no generated power, energy purchased from the utility grid is exactly equal to the consumption profile. This means energy required of the residential load is supplied directly from the utility grid. Moreover, when the wind turbine is generating and this produced power is insufficient for residential load, the lack of energy is purchased from the utility grid. During the middle of this simulation, the wind turbine is stopped while the consumption profile is situated on the maximum demand. For this reason, the consumption profile is exactly equal to purchased energy from the utility grid.

Additionally, Figure 5.16 and Figure 5.19 show the amount of power that MRTS system sold to the utility grid. In these figures, blue line indicates power sold to the grid, which is subtract of energy generated and consumed.

Therefore, case study 3 simulated a platform for houses equipped with home-scale wind turbine. In this platform, consumed and generated energy, power purchased from the utility grid and power sold back are indicated.

5.4. Conclusion

As a conclusion for this chapter, three case studies of MRTS system were reviewed. In the first case study, MRTS system simulated the consumption profile of a private house by employing 4 kVA hardware resource. In the second case study, consumption profile of a small commerce facility was simulated by integration of 4 kVA and 30 kVA load and in the case study 3, generation and consumption profiles of a house equipped with home-scale wind turbine were simulated. The main objective of this chapter was using MRTS system in several HIL scenarios.

Chapter 6

Conclusion

6.1. Conclusion

Daily increment of the electricity energy demand on the one hand and excessive consumption of fossil fuels in the huge power plants on the other hand, face the current power grid with serious issues. Inefficiency in management of peak demand, inability of exchanging reliable data and limited functionality in utilization of RERs, are some of these issues. Additionally, because of advanced technology employed in new equipment, delivering high rate of power quality and reliability became important factors for the electricity grids and power distribution companies. Hence, using the smart grids and microgrids technology and integration of them into the current power grid became an interesting context for the electricity expert's society. However, before implementation of their projects, it is necessary to examine and test their prototypes. For the same reason, real-time digital simulator machines can satisfy this requirement.

This dissertation presented a flexible system for microgrids real-time digital simulation using hardware-in-the-loop. The system included of OP5600-OPAL-RT as real-time digital simulator and microgrid players, which were 4 kVA load as low power consumer and 30 kVA load as medium power consumer. Moreover, 1.2 kW wind turbine emulator was integrated as micro-generation unit (home-scale wind turbine). The real-time simulation using hardware-in-the-loop helps the scientific community to achieve reliable simulation results. Additionally, the use of IEEE 754 standard communication in the Simulink environment enabled the system to integrate and employ the results of such resources that follow the IEEE 754 format in their communication protocols.

For the 4 kVA load integration, one 12 V DC motor, two limit switches and one energy meter were mounted on hardware of the load. This 12 V DC motor increases or decrease the resistive part of the load, two limit switches specify the movement range of the motor and energy meter measures real-time consumption of the load. An Arduino

equipped with Ethernet and relay shields manages this controlling process of 4 kVA load. In this system, desired power rate is transmitted from the OPAL to 4kVA load through Modbus TCP/IP protocol in IEEE 754 format. Two MATLAB function blocks have been placed in the Simulink model for implementing the conversion between IEEE 754 format, using 4-bytes, and decimal values. This system was used in the case study 1 in order to simulate the consumption profile of a residential house.

In the case of 30 kVA load, several relays have been installed on the platform of the hardware in order to control the rate of consumption. The digital output board of the OPAL was employed for controlling these relays. According to the specifications of this hardware resource, it operates only in the integer values of the consumption.

For simulating high rate of consumption, merging of these two loads (4 kVA load and 30 kVA load) were considered. In this scenario, desired power rates were divided into the two parts of integer section and float section. Integer section of desired power rate was dedicated to the 30 kVA load and the float section was allocated for 4 kVA load. This scenario enabled MRTS system to simulate the profiles with high rate of consumption. Case study 2 applied this scenario for simulating the consumption profile of a small commerce facility.

Additionally, MRTS system used 1.2 kW wind turbine emulator as a micro-generation unit. For this purpose, one analog output of the OPAL was employed. In the case study 3, this unit has been considered as a home-scale wind turbine. Therefore, consumption and generation profiles of a private house were simulated by this hardware resources. Energy sold to the utility grid and purchased from that, were indicated in this case study.

The results of these simulations demonstrate that using a home-scale renewable energy resource such as wind turbine, cause to reduce electricity costs for the consumers and enable them to have active participation in the electricity markets. This contribution of the customers in the electricity markets has some benefits for the distribution power network. On the other hand, it may lead to face the power grid with several issues. From the electricity producers' viewpoint, this scenario causes to decrease the pressure of network on peak demand times by removing the hierarchical structure of the power grid. From the power quality viewpoint, this scenario has some serious disadvantages for the utility grid. Inverters, rectifiers and other power electronic

devices, which are used on the home-scale renewable energy resource, can face the utility grid with the power quality difficulties.

Additionally, MRTS system can be used for executing demand response programs using real generation and/or consumption profiles. Moreover, if an intelligent algorithm that can deal with real-time electricity prices manages the MRTS system, it would be possible to examine and test the retail electricity prototypes in the term of electricity markets.

6.2. Suggestions for Future Works

As suggestion for a future work, an Energy Storage System (ESS) can be integrated into the MRTS system. This Integration of ESS provides many management cases in the MRTS system. It can store the excess of produced energy by the wind turbine emulator and supplies the loads by presenting the stored energy. In addition, if the MRTS system is able to deal with the real-time electricity price, it will be possible to optimize the costs. For this purpose, the ESS can be charged from the utility grid when the electricity price is low and uses this stored energy for supplying the loads when the electricity price is high. Another scenario is to store energy while the electricity price is low and sells back this stored energy to the utility grid when the electricity price is high. These scenarios can be implemented on a house equipped with ESS. In this house, homeowner can see the real-time operation of the home-scale microgrid.

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