Energy Management for Enhanced Microgrid Operation

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Abstract

This thesis proposes energy management system controllers for enhancing microgrid operations. This involves the design and testing of energy and load management systems of microgrids. The main microgrid topology features a wind turbine generator, controllable loads, and a battery energy storage system. Depending on the test system, the topology can consist of a diesel generator that can act in both isolated and grid-connected mode. Real data has been obtained from trusted sources. This data is then used in the microgrid controller algorithms.

The first microgrid controller proposal schedules the charging and discharging times of the battery energy management system, while it minimizes the amount of diesel that is consumed. This controller operates in grid-connected mode with an import constraint limit. The algorithm proceeds to curtail load when the diesel generator is not available. The islanded mode corresponds to a second microgrid controller proposal that removes the connection to the power utility. The last case situates the microgrid controller as a seller of electricity back to the grid. Using a microgrid controller topology, this scenario explores power quality improvement and an increase in the hosting capacity of renewables.

In each scenario, an offline optimization for a twenty-four hour window is used to validate the results. The microgrid controller algorithms are implemented in real-time hardware in the loop co-simulation platform. This implementation allows for the acquisition of real-time results and it tests different scenarios through a general algorithm. A group of metrics is proposed for each scenario to quantitatively validate the results.

Résumé

Ce mémoire propose des contrôleurs de système de gestion de l'énergie pour améliorer les opérations de micro-réseau. Cela implique la conception et l'essai de systèmes de gestion de l'énergie et de la charge du micro-réseau. La topologie principale du micro-réseau peut avoir la présence d'un générateur d'éolienne, des charges contrôlables et un système de stockage d'énergie à batterie. Selon le système d'essai, la topologie peut consister en un générateur diesel qui peut agir en mode isolé et relié au réseau. Les données réelles ont été obtenues à partir de sources fiables. Ces données sont ensuite utilisées dans les algorithmes de contrôleur de micro-réseau.

La première proposition de contrôleur de micro-réseau planifie les temps de chargement et de déchargement du système de gestion de l'énergie à batterie, tout en minimisant la quantité de diesel consommée. Ce contrôleur fonctionne en mode connecté en réseau avec une limite de contrainte d'importation. L'algorithme continue à réduire la charge lorsque le générateur diesel n'est pas disponible. Le mode *Islanded* correspond à une deuxième proposition de contrôleur de micro-réseau qui supprime la connexion à l'utilitaire électrique. Le dernier cas situe le contrôleur du micro-réseau en tant que vendeur d'électricité vers le réseau. En utilisant une topologie de contrôleur de micro-réseau, ce scénario explore l'amélioration de la qualité de l'alimentation et une augmentation de la capacité d'accueil des énergies renouvelables.

Dans chaque scénario, une optimisation hors ligne pour jour est utilisée pour valider les résultats. Les algorithmes de contrôleur de micro-réseau sont implémentés en temps réel dans la plate-forme de co-simulation en boucle. Cette implémentation permet l'acquisition de résultats en temps réel et teste différents scénarios via un algorithme général. Un groupe de métriques est proposé pour chaque scénario pour valider quantitativement les résultats.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

ANN	*Artificial Neural Network*
BESS	*Battery Energy Storage System*
CRIO	*CompactRIO*
DER	*Distributed Energy Resource*
DG	*Distributed Generator*
EPS	*Electric Power System*
EMS	*Energy Management System*
ESS	*Energy Storage System*
HIL	*Hardware in the loop*
IPP	*Independent Power Producer*
MPPT	*Maximum Power Point Tracking*
NI	*National Instruments*
PI	*Proportional Integral*
RTDS	*Real Time Digital Simulator*
SITL	*System In the Loop*
SOC	*State of Charge*
VPP	*Virtual Power Plant*
WTG	*Wind Turbine Generator*

List of Symbols

a, b, c, d	*Constant parameters from the diesel generator technology*
$C_{DieselGen}$	*Total cost of diesel generation*
C_{Hourly}	*Associated cost in one hour of importing energy from the utility*
$C_{ImportedEnergy}^{Total}$	*Total cost of importing energy from the utility*
E_{Grid}	*Imported energy*
$E_{Violation}^{Grid}$	*Imported energy upper than the maximum limit allowed*
$\mathrm{E_{minESS}}, \mathrm{E_{maxESS}}$	*SOC power energy constraints BESS*
$\mathrm{E_{SOC}}, SOC$	*BESS state of charge*
L	*Load profile*
$Load_{Curtailed}$	*Set point of load curtailed*
$L_{Profile}$	*Real maximum load profile*
m	*Slope*
$P_{Curtailed}, P_{dr}$	*Power curtailed*
$P_{Curtailedmin}, P_{Curtailedmax}$	*Control load power constraints*
P_{DG}, P_{Diesel}	*Diesel power dispatched*
$\mathrm{P_{diesel/Curtailed}}$	*Power dispatch point for diesel generator or controllable loads*
P_{ESS}, P_{BESS}	*Power dispatch point for the BESS*
$\mathrm{P_{Grid}}$	*Power imported from grid utility*
$P_{PeakViolation}^{Grid}$	*Peak imported power upper than the maximum allowed value.*
$\mathrm{P_{load}}$	*Load Power dispatch*
$\mathrm{P_{minDiesel}}, \mathrm{P_{maxDiesel}}$	*Diesel power constraints*
$\mathrm{P_{minESS}}, P_{maxESS}$	*BESS power constraints*
$\mathrm{P_{minGrid}}, \mathrm{P_{maxGrid}}$	*Import power constraints*
$\mathrm{P_{Residual}}$	*Residual power from the power balance constraint*
P_W	*Active power from the WTG*
$\mathrm{P_{WTG}}$	*WTG power produced*
SOC_{min}	*Minimum BESS state of charge*
T	*Total period time of simulation*
$T_{Violation}^{Grid}$	*Total time of power violation imported from the grid*
U_D	*Diesel unit commitment*
W	*Real WTG power data*
$W_{Power}(i)$	*Vector power produced by the WTG*
$Wp_{Profile}$	*Wind speed real maximum profile*
$W_{speed}^{xmeters}$	*Wind speed normalized to a desired height*
$\delta t, \Delta\mathrm{t}$	*Delta time*

Chapter 1: Introduction

Electric utility providers have recently been making efforts to modify the current distribution network. One of the biggest modifications is the incorporation of microgrids in the electrical system. A microgrid is defined as “a group of loads and distributed energy resources that act as a single entity with respect to the grid” [1]. In this document, a microgrid is a system that takes power from sources of electrical power generation and delivers it to users. The system accounts for different types of sources that are close to the energetic demand. This includes renewable generation and diesel generators. These systems are expected to operate independently which means that they can get connected or disconnected from the electric utilities. Most importantly, a microgrid controller has several functions such as for ancillary service, energy and load management, and the transition from getting connected or disconnected from the utility.

The main reasons for incorporating microgrids are to guarantee the resiliency of the power delivery system and to increase the penetration level of renewable resources [2, 3]. We need to quantify the economic and environmental benefits that are derived from these.

Currently, the IEEE, with other entities, are developing the standards P230.7 and P230.8 for the specifications and testing of microgrid controllers. When the standards and specifications are finalized, it is going to be necessary to have a set of tools and platforms to test and validate the functionality of industrial controllers. These platforms require a set of real-time tools, which allow the user to test the controllers, emulate a realistic network and perform constant communication dispatch. Even though the dispatches are done in minutes, the acquisition of data, while the simulation and the optimization algorithm are running without interruptions, creates the need to have a real-time controller platform.

The microgrid controller can perform the functions of energy and load management for the system. Depending on the topology that is established, if the microgrid is connected to the grid, it can sell or buy energy from the electrical utilities through the grid. Therefore, it is necessary to design and differentiate the energy management system algorithm depending on the optimization objectives and electricity generation sources that are available. The various energy management system algorithms create the necessity for a general platform, which allows there to be a general interface with the option to change the objective function and constraints.

The research objective is to study the incorporation of microgrid controllers. From a seller's perspective, the controller is expected to be able to regulate the power fluctuations that are caused by renewables, in order to increase their participation in the energy market. The controller can also reduce the costs of operation and fuel consumption. This is done by optimally dispatching all of the generation resources with a pertaining schedule.

1.1 Literature review

1.1.1 Microgrid

A microgrid is defined as an independent electrical system that is capable of operating without a connection to an electrical utility (islanded mode) [4]. It contains electrical sources of energy and electrical power consumers. It is a small distributed system that can be connected to an electrical utility or a grid arrange. In both cases, the energy that is supplied is expected to be by local distributed resources mostly. Those sources are also expected to be a combination of renewable energies, small fossil fuel-fired generators and storage systems. In [5], four requirements to consider a system as a microgrid are defined: the system is originally designed as an islanded electrical system, it must have loads and distributed resources, it can be connected or disconnected from the grid arrange and it can send or receive electrical energy.

A point of common coupling is considered to be the point of connection between a microgrid and an electrical power system. The connection refers to the "grid-connected" mode of the small electrical system. By acting in this mode, the voltage and frequency references of the distributed system are controlled by the network. It can be seen as an infinite bus that absorbs or gives the necessary power required by the elements on the grid [6]. In exchange, distributed resources such as PV arrays, wind turbine generators and energy storage systems can operate with low power losses through PID control loop strategies [7] that control the active power references.

This islanded distributed system is projected to be self-sustainable, which means that power balance constraints can be met by avoiding the use of external energy [8]. Islanded mode is when the microgrid is no longer connected to the network. As previously mentioned, this feature is accounted for and expected in the design of the distributed system. In this case, the system has no connection to the grid and it must reach stability by selecting one generator to set the voltage and frequency reference [9]. One option is to set this generator to react and supply all of the power demand changes by regulating the speed set-point. This mode of operation is called isochronous.

Distributed resources can act in either droop or isochronous mode [10]. Both modes can control the speed and voltage reference of the system. By controlling these two parameters, the active and reactive power operation points are also controlled. When a determined DER is acting in isochronous mode, the voltage and frequency operating points are maintained at a defined reference, even after there is a load change on the system. By acting in droop mode, the DER such as a diesel generator or combined heat and power only supply a certain percentage of the load change. Renewable resources always supply the maximum amount of power that is available. The changes in active power against the frequency, and the changes in reactive power against voltage for isochronous mode remain constant, while there is a slope in droop mode [11].

Both configurations of a microgrid are expected to have economic and environmental impacts. One goal is to increase the penetration depth of renewable resources. By reducing the use of fossil fuel generation, the pollution decreases and the costs of energy production are reduced. Therefore, the first important point to design these systems is to work with renewable energy and use fuel generation and electrical power from the grid (in that order) in cases of contingencies or power imbalances.

Certain amount of energy reserved can be used as a backup power, it's a good alternative method that ensures reliability and improves the participation of renewable energy [12,13]. This method is necessary because certain energy resources cannot be controlled, such as the wind and solar irradiance. The amount of energy that is reserved is independent of the BESS. It is expected to operate only when the available resources cannot meet the power balance constraints.

1.1.2 Power Dispatch Calculations

An economic dispatch is the process of optimally determining the amount of power that each electrical source must produce in order to meet an energetic demand constraint. Depending on the technology of the electrical power source, the relation between the cost and power that is produced changes. In this document, the costly source of energy is the diesel generator. For this type of generation, the relationship between power that is produced versus cost is fit to a quadratic function. In [14], it can be seen the cost can be increased or decreased by controlling the amount of fuel that is used. Figure 1-1 shows the relation between the cost and generated power.

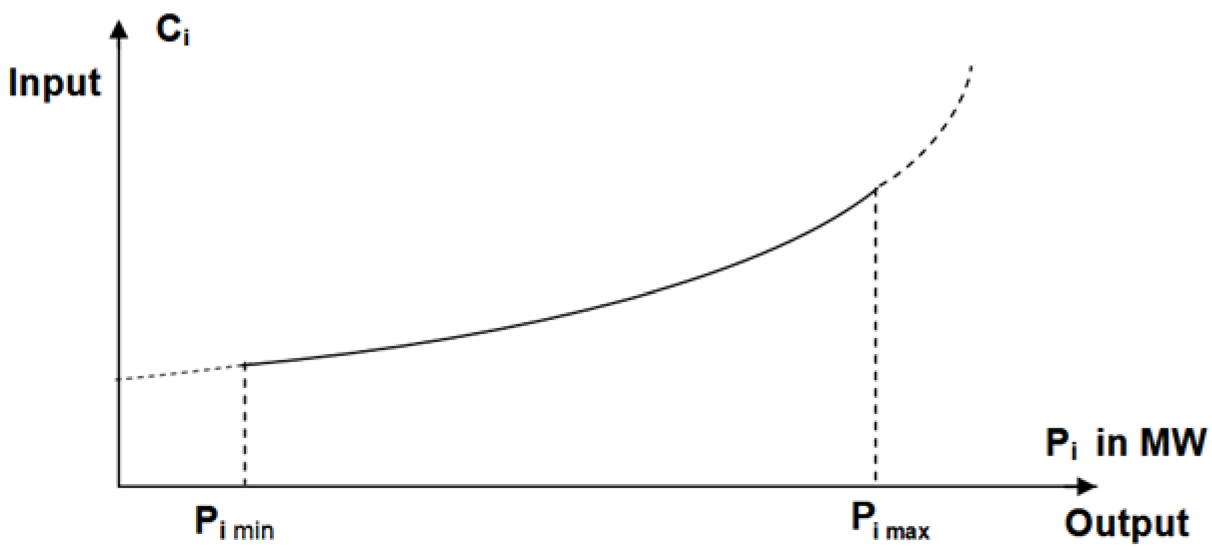


Figure 1-1 Quadratic cost function [14]

The cost function will be minimized here in order to reduce the fuel consumption. The quantitative results section will include both the power that is produced and the cost of operating the generator.

1.1.3 Power Fluctuations

Incorporating renewables in distribution networks requires modifying the current electric transmission system. The deregulated energy market allows the presence of independent power producers (IPPs) in the electric structure. The energy market evolved to differentiate regulated and competitive players in the power industry [15]. Due to uncontrollable fluctuations nature, the renewables are classified as competitive players.

From an economic perspective, the competitive industry is more risky because prices also fluctuate [16]. In the future, it will be expected that the electric utilities imposed a maximum percentage of power fluctuations. It could increase the amount of green energy and create a positive impact on the environment. It could also create an economic impact by reducing the costs of energy production.

To control the market, there are some penalties that are imposed on producers when the agreed energy is not dispatched [17,18]. In order to avoid these penalties, [19] has proposed an approach that is based on the utilization of wind power and pumped-storage units [19]. In order to be more competitive in the market, some studies have been conducted to increase the efficiency of renewable energies. One clear example is the wind turbine generators that increase range efficiency from 5% to 35% [20-22]. In spite of all of these efforts, wind and solar energy, among other resources, remain uncontrollable.

In order to increase the hosting capacity of renewables sources, certain attempts have been made [23]. One example is the use of virtual power plants (VPPs). These plants are defined by [24] as the connection of many DERs into one big cluster and they are controlled through an information network. In [25], VPPs are formulated to be used for load and congestion management, voltage control and short-circuit protection. Certain vendors have focused their attention on developing energy management software using the concept of VPP [26,27]. A sequential algorithm is used in [28] to incorporate the use of DER in the market, to act as a system management and to explore the concept of VPP.

Renewable energies such as wind turbine generators (WTGs) and PVs can benefit from energy storage systems. Control strategies and information on how to size batteries can be found in [29,30]. Examples that use the control of energy storage systems for the applications of microgrids are examined in [31-33] and their benefits are also discussed.

In the literature, different strategies to help the IPPs bid a price in the market are related to the implementation of unit commitment [34,35]. In order to maximize wind power utilization while minimizing risks, a method that is conducted is to implement price based unit commitment (PBUC), chance constraints and sample average approximations (SAA), in which the IPP operates and schedules thermal generators, wind farms and pumped-storage units [36]. The chance constrain will be used to model the uncertainty factor of the renewables. Contrary to the objective of this work, in [21], the chance constraint is used in a unit commitment problem with an uncertain wind power output from the system operator's perspective. In order to solve the problems, stochastic SAA algorithms are described in [37-39].

Currently, Hydro-Quebec has a balancing agreement. It uses hydropower generators to guarantee a delivery rate that balances the wind power contracts [40]. This document proposes to incorporate a microgrid in order to smoothen the maximum power fluctuations that are produced by renewables. Also, by smoothening the power, the hosting capacity of wind turbine generators in a distribution network is also expected to increase. The aim is to create a real-time platform that can validate the results. Certain metrics are going to be proposed in order to quantify the results. The microgrid is going to be set up from the point of view of an IPP to minimize the delivery of power fluctuations. The system is going to be composed of WTGs, an energy storage system and controllable loads. The controller's function is to have an energy management system and primary control loops.

1.1.4 Real-Time Hardware in the Loop Concept

Different entities in the market have developed an interest in having an optimal way to test power systems and their controls, among other features, before their installation. Real-time simulations are a recent concept in the last decade, in which a power system is emulated and tested. The final goal of the interface is to have accurate results that are as close as possible to reality.

Real-time emulators are the point of connection between software and hardware tools and these tools allow simulating a desired network. According to the global, leading designer of real-time digital simulators [41], real-time emulators guarantee an economic benefit by decreasing the time of testing and avoiding any damages to real equipment. According to [42], the most common technique for these simulations is to have a control system with analog channels. This feature enables external hardware interaction.

Reference [42] also specifies that a real-time simulator must have a computational process that is very fast in order to ensure for synchronization with the real world. Another important aspect from the reference is that the simulation must run without overruns. This means that the computational process has to be at least less than the time step. Depending on the application, a range for the time step or sampling can be selected. Figure 1-2 shows that a microgrid involving average converter models with power systems will require 50 μ s of simulation. This computational speed is required for the simulation of the grid and its components, such as the DERs. The optimization dispatch that sets the points of operation of each component can take several minutes, as it is in the real world. Throughout this document, the interaction for a real-time simulation of the elements on a microgrid and the control of this components is developed by doing a set of optimization dispatches at regular intervals separated by a few minutes.

The needs for a real-time simulation in this project comes principally, because the testing of a controller algorithm requires several hours of simulation and data acquisition, a non-real-time simulation depending on the application can take large amounts of computational time for this task. Another reason is to allow an interaction with external hardware. The last reason concerns the supervision of the grid from the perspective of an operator of the grid.

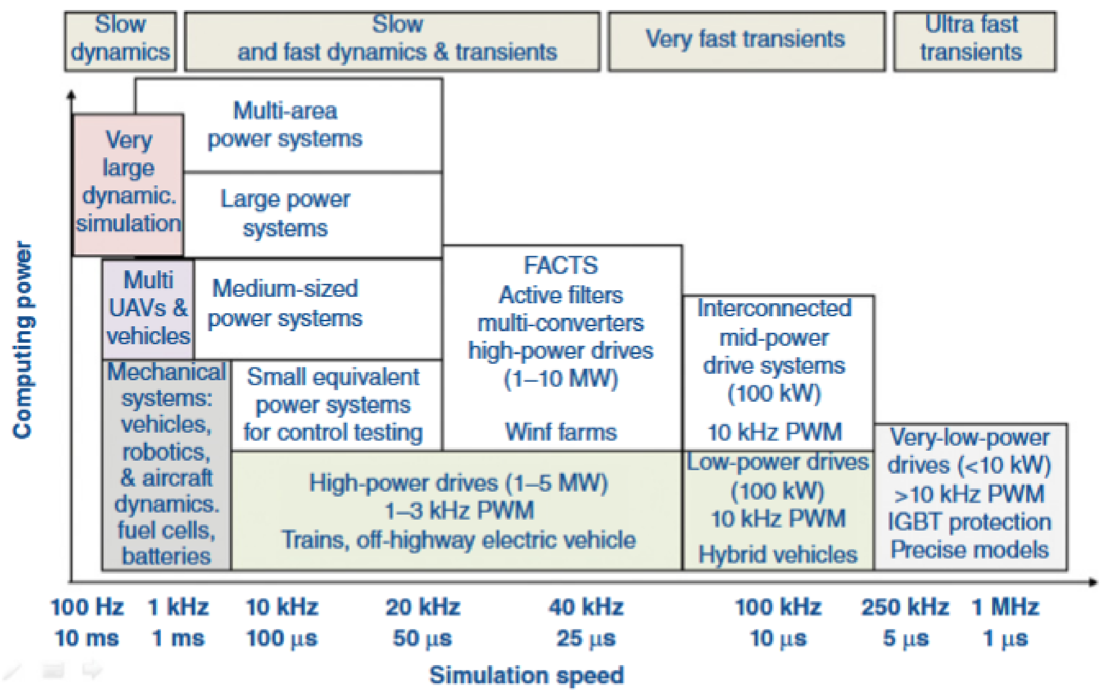


Figure 1-2 Real-time applications and simulation time step [53],[38]

Real time simulations bring up the concept of hardware in the loop. This concept involves incorporating physical hardware that wants to be tested [43]. Therefore, by having an emulated system with a controller and hardware, which are all usually communicated by analog channels, the functionality of a specific application or equipment can be tested [44]. The same document shows that these types of simulations involve 4 layers. The application layer contains the data of the simulation such as the forecast profile. The network layer interfaces the tasks of each component. The link layer establishes how the software and hardware access the data and the physical layer mentions the methods to send and receive information.

One of the main objectives of this research is to design energy management system controllers that can schedule the charging and discharging times of an energy storage system. Also, the management system seeks to meet optimally power balance constraints by doing economic dispatch and load curtailment [45-47]. Based on the aforementioned definition of real-time hardware in the loop, these controllers are part of the last physical layer.

1.2 Problem statement & project description

This research needs to be conducted for the following reasons:

- There is a need for developing a benchmark to test microgrid controllers, this requirement needs a set of performance metrics and objectives to be defined. Also, there is no existent real-time platform that can test algorithms of a microgrid controller, only offline simulations have been developed. In order to meet this, we proposed the use of a grid-connected and islanded microgrid energy management system. This development helps to test different microgrid controller algorithms and topologies. With the development of the microgrid, one defines a set of metrics and objectives to be accomplished by the controller, and it also shows more realistic results of the operation of a microgrid controller.

- By combining the use of energy management systems (or microgrid controller) and microgrid topologies, it is possible to study the enhancement of the participation of renewables selling energy to the grid. This is addressed by smoothing the average power delivered to the grid from a renewable energy. The results of this study are reflected in enhancing the participation of wind generation by smoothing the power at the intertie point of connection. This sections also complements the previous problem statement, by using the real-time platform to benchmark another EMS algorithm.

1.3 Performance requirements

The microgrid algorithm controller and the real-time platform must do the following:

- Reduce the amount of fuel consumed

- Reduce operation costs
- Increase the penetration level of renewable energies
- Allow grid-connected and islanded mode operations
- Reduce the amount of energy that is imported to the grid in grid-connected mode

1.4 Contributions of the Work

1. Formulation of the microgrid DER dispatch problem using sequential quadratic programming to optimize the operating cost of the microgrid. The algorithm is implemented as part of the microgrid controller. The cost optimization also results in reduced fuel emissions. The algorithm is validated through real-time simulations.
2. Formulation of a dispatch function to smooth the average power injected by renewable energy sources that uses battery energy storage and load curtailment as dispatchable units. The dispatch function is integrated as part of the microgrid controller. The algorithm is validated through real-time simulations.

1.5 Thesis Outline

The remainder of the thesis is organized as follows:

Chapter 1: This chapter presents the background of the thesis. A literature review is presented to explain the reason for the research. The objectives, problem description and contributions are described to guide the intention and deliverables of this thesis.

Chapter 2: This chapter details the implementation of microgrid controller algorithms to decrease costs of operation and guarantee power balance. For a utility distribution microgrid two different scenarios connected to the power system are presented. In the first one, the main objective is to reduce diesel use. The second case situates the microgrid without the use of diesel. Instead, it reduces the amount of power that is not delivered to the user (curtailed). The remote microgrid presents the case when the microgrid is disconnected from the grid utility. The diesel generator should dispatch the minimum amount of possible energy. The community microgrid aims to reduce the amount of power fluctuations that are caused by the selling of renewable energy to the grid. By reducing this, the renewables can increase participation in the energy market.

Chapter 3: This chapter presents the design and implementation of the algorithms designed in Chapter 2. The intention of this chapter is to present for each microgrid controller case, the ratings definition for each element presented in each microgrid. Defining objectives depending on the topology of microgrid is part of the design. The hardware and software required to implement the algorithm is equally defined in this Chapter.

Chapter 4: In this chapter all of the scenarios propose metrics to quantify the results and they detail the algorithm procedure. The results are validated through a real-time HIL procedure against an offline optimization. The controller uses a WTG and a BESS as primary resources of energy.

Chapter 5: This chapter presents a summary of the work that has been conducted, the conclusions and an overall analysis of the research. Recommendations for future work are proposed to encourage improvement.

Chapter 2: Microgrid Controller Energy Management Algorithms

2.1 Overview

This chapter provides a description of different microgrid topologies. From these definitions, the chapter defines the study of three energy management system controller algorithms for three microgrid definitions. The intention is to show the mathematical procedure behind a microgrid controller by comparing different topologies and scenarios.

This chapter proposes the use of optimization algorithms to provide economic and environmental benefits on a microgrid. The algorithms have control functions to determine the dispatch points of different energy sources. This means that the controller has a set of constraints and rules that take decisions based on the minimization of the cost of operation.

The algorithm assumes already known forecasted profiles for the wind speed and load.

In the first case, a microgrid that is connected to the transmission system features an algorithm that aims to reduce the amount of consumed diesel. The second case curtails some load to compensate the case in which the diesel generator is out of the system. The last scenario presents a microgrid that is disconnected from the transmission system (acting in stand-alone mode). The diesel generator gives the reference of the voltage and frequency stability of the microgrid. The first two scenarios have a minimum and maximum limit of imported power from the transmission system.

The last subsection of this chapter presents the mathematical procedure to evaluate the performance of the algorithm. The equations are developed to evaluate the results present in chapter 4.

2.2 Microgrid Topologies Definition

[4] defines six different topologies of microgrids. Those are composed by commercial, community, utility distribution, institutional, military and remote. For purposes of this research, there will be studied three types of microgrid topologies. The first topology is situated as an utility distribution microgrid in which the grid is connected. The goal is to reduce costs of operation and give incentives to the community to reduce the demand. The second topology studies the remote microgrid. In this type of topology, the microgrid is expected to operate by itself without the connection to the grid. The last topology called “community” aims to ensure reliability of the system, as it encourages the participation of the community, the research creates the scenario where a user sells big amounts of energy to the grid.

Depending on the test system and the energy sources that are available on the network, the algorithm includes or removes certain rules from the controller. One goal of the controller is that it can be adapted to different topologies. The changes in ratings and addition of new knowledge makes the controller adaptive to any desired energy management system.

2.3 Utility distribution grid-connected microgrid algorithm

Two grid-connected microgrid configurations and control strategies are considered in this section. The control strategies includes as general and specific constraints different DERs, and the objective function is always dependent on the minimization of costs.

The first configuration reduces the liters of diesel fuel consumed for a microgrid featuring wind generation, energy storage and diesel-powered generation. The second configuration avoids the total load that is curtailed for a microgrid featuring wind generation, energy storage and controllable loads, in this scenario the diesel generator is consider to be out of service. For both scenarios, it is assumed that the grid-connected microgrid has a fixed power import limit with the main utility electric power system (EPS).

The general algorithm for each scenario evaluates first the necessary time of use of the energy storage system. In other words, the controller evaluates takes the maximum and minimum ratings available in the ESS, and it evaluates for a defined time line the most efficient way when the ESS needs to be charged or discharged. After scheduling the time of use of the ESS, the objective function for costs is evaluated by applying all the necessary constraints to the other DERs present in each scenario.

2.3.1 Objective functions

Scenario 1

In this scenario, the battery management system's charging and discharging is scheduled and the dispatch is set in order to meet the power balance constraints and minimize the diesel generator participation. The objective function is shown in eqn. (2.1) and it represents the cost function of a diesel generator to be minimized. The function depends on time and unit commitment factors. The cost function evaluates the addition of the total power generated by the diesel generator per step of time.

$$\min \mathrm{C}_{\mathrm{DieselGen}} = \sum_{t=0}^{T} \mathrm{a}\left(\mathrm{b}\mathrm{P}_{\mathrm{Diesel}}^{2}(\mathrm{t}) + \mathrm{c}\mathrm{P}_{\mathrm{Diesel}}(\mathrm{t}) + \mathrm{d}\right)\mathrm{U}_{\mathrm{D}}\Delta\mathrm{t} \tag{2.1}$$

The a, b, c, d constants depend on the cost function of the technology in each diesel generator.

The generation of power from the diesel generator wants to be minimized in order to reduce costs and the environmental impact because this source is most costly and it has the highest polluted energy on the microgrid

Scenario 2

In this scenario, as previously mentioned the diesel generator is assumed to be out of service. With the diesel generator out of service, the microgrid extracts the maximum power in an efficient way in time of all the DERs available. Therefore, by calculating the time of use from the ESS, the residual power depends on the controllable loads and the imported power from the grid. The optimization function in eqn. (2.2) aims to reduce the total amount of load that is curtailed.

The controllable loads are used as an alternative to respect the balance and import power constraints. This cost function is the addition of the total power curtailed per time step.

$$\min Load_{Curtailed} = \sum_{t=0}^{T} P_{Curtailed}(\mathrm{t})\Delta\mathrm{t} \tag{2.2}$$

2.3.2 Constraints

The proposed scheduling algorithm prioritizes wind power generation to supply the microgrid load. In other words, using a previously known wind speed and load profile. The wind speed power produced is firstly used to supply the power demanded by the load profile.

The residual power, shown in eqn. (2.3), is the difference between P_{load} and P_{WTG}. Eqn. (2.4) representing the same residual power is then used to schedule the ESS and the diesel generator or the load curtailed depending on the scenario, considering the import limit from the electric power system (EPS).

Eqns (2.3) and (2.4) are considered as equality constraints. These equations enforce the power balance, requiring equal power produced and consumed.

$$\mathrm{P_{Residual}}(t) = \alpha \mathrm{P_{load}}(\mathrm{t}) - \beta \mathrm{P_{WTG}}(t) \tag{2.3}$$

$$\mathrm{P_{Residual}}(\mathrm{t}) = \mathrm{P_{Grid}}(\mathrm{t}) + \mathrm{P_{ESS}}(\mathrm{t}) + \mathrm{P_{diesel/Curtailed}}(t) \tag{2.4}$$

Where α and β are variables that are used to model the error in the forecasted demand and wind speed, respectively.

The inequality constraints in the following equations represent the maximum and minimum power that each DER is able to deliver. In (2.5), the minimum and maximum exchange power between the grid utility and the DERs are limited. The minimum constraint can be consider a negative value when the microgrid is able to sell power that the ESS cannot absorb.

$$\mathrm{P_{minGrid}} \leq \mathrm{P_{Grid}}(\mathrm{t}) \leq \mathrm{P_{maxGrid}} \tag{2.5}$$

Eqn. (2.6.1) is defined for the first scenario. U_D represents the unit commitment state of the diesel generator, and ϕ represents the minimum amount (percentage) that the diesel generator can dispatch in the on state in order to avoid damage on the generator. U_D can only values between 0 (diesel generator off) and 1 (diesel generator on). For the second scenario, the minimum and maximum amount of power that is allowed to be curtailed is represented by eqn. (2.6.2)

$$\mathrm{U_D P_{maxDiesel}}\phi \le \mathrm{P_{DG}(t)} \le \mathrm{U_D P_{maxDiesel}} \tag{2.6.1}$$

$$P_{Curtailedmin} \le \mathrm{P_{Curtailed}}(t) \le P_{Curtailedmax} \tag{2.6.2}$$

The energy storage system depending on the technology used has maximum and minimum power and energy constraints. These constraints are shown respectively in eqns. (2.7) and (2.8). These constraints must be respected in order to protect the integrity of the ESS. The maximum and minimum power and energy of the BESS depends on its technology.

$$\mathrm{P_{minESS} \le P_{ESS}(t) \le P_{maxESS}} \tag{2.7}$$

$$\mathrm{E_{minESS} \le E_{ESS}(t) \le E_{maxESS}} \tag{2.8}$$

Other constraints:

$$\mathrm{E_{SOC}(0) = 100En_{ESS}(t_{-1})} \tag{2.9}$$

The initial state of charge for the ESS for each iteration is obtained from the previous dispatch and it is defined by eqn. (2.9). It takes a value between 0 and 1. It starts at t-1 because in a non-continuous space the initial state of charge must be known and set.

The relation between the energy and power of the ESS is given by eqn. (2.10). The relation shows that the current state of charge of the ESS depends on the difference between the previous state of charge and the current power supplied. The power supplied is multiplied by the select time step and the efficiency to charge or discharge the battery.

$$\mathrm{E_{ESS}(t) = E_{ESS}(t-1) - \eta P_{ESS}(t)\Delta t} \tag{2.10}$$

Where η represents the efficiency of the battery when charging or discharging.

2.4 Remote islanded microgrid algorithm

This section evaluates the performance of a microgrid operating disconnected from the power system utility. The energy resources inside the system must be able and enough to supply the energetic demand. The goal of the controller in this section is to minimize the cost of operations and incorporate renewable energy to complement diesel generation.

Also, this section complements the equations defined in section 2.3 while running the EMS algorithm for an islanded microgrid. The new topology removes the connection to the utility and does not consider the possibility of load curtailment.

The overall microgrid in islanded mode gets disconnected from the grid utility. This topology introduces two problems. The voltage and frequency synchronization and the DERs have to handle the load demand effectively. In this section, the diesel generator is operated by a synchronous machine that is acting in isochronous mode. With this feature, it sets the reference for the voltage and frequency of the system.

Mathematical Formulation

The optimization function of this subsection is to reduce the total amount of diesel that is consumed, while utilizing the total available energy from the WTG and the BESS. Refer to eqn. (2.1).

The constraints are set equally to eqns. (2.6.1), (2.7-2.10).

Other constraints:

Eqn. (2.11) represents the power balance that must be respected.

$$\mathrm{P}_{\mathrm{Residual}}(\mathrm{t}) = \mathrm{P}_{\mathrm{ESS}}(\mathrm{t}) + \mathrm{P}_{\mathrm{diesel/Curtailed}}(t) \tag{2.11}$$

From eqn. (2.1) in the previous section, α and β are variables that are used to model the error in the forecasted demand and wind speed, respectively. The parameters were selected by trial and error for the convergence of the optimization algorithm. Those variables are a necessary reserve when the WTG is very low and the BESS is not fully charged.

By running in isochronous mode, it is probable that the BESS will be discharged lower than the minimum that is imposed in order to compensate for the power imbalance. The following equations represent this compensation:

$$if\ \left(E_{minESS} > E_{soc}(t)\right) \rightarrow E_{minESS} = E_{soc}(t) \quad (2.12)$$

The BESS has a minimum value that is imposed by the user and it is called E_{minESS}. Depending on the technology, the system will have a minimum value ($SOC_{minimum}$) to protect the battery. This is shown in eqn. (2.13).

It is remarkable that the compensation is not necessary for the grid-connected case as the grid can account for the convergence of the algorithm.

$$else\ (E_{minESS} < SOC_{minimum}) \rightarrow E_{minESS} = SOC_{minimum} \quad (2.13)$$

2.5 Community grid-connected microgrid algorithm

The goal of this section is to increase the hosting capacity of renewables through the implementation of EMS microgrid controller functions. The distribution network includes a wind farm, which represents the point of view from the independent power producer selling energy to the grid. The hosting capacity is shown under different scenarios with different ratings, and is validated showing a more regulated output power from the WTGs.

The community microgrid topology is used for two purposes supply the energetic demand in a small distribution network and allow the participation in the market of users. In this way the electric utility gives economic incentives to the users that allows the buy of power and load curtailment at peak hours.

2.5.1 Mathematical definition

The main objective function is set to minimize the total amount of load curtailed, which is represented by eqn. (2.14). The principle objective of the EMS is to dispatch a regulated power to the grid as much as possible. In order to complete this task, several constraints are set.

$$\min Load\_Curtailed = \sum_{t=0}^{T} P_{curtailed}(\mathrm{t})\Delta\mathrm{t} \quad (2.14)$$

Where $P_{curtail}$ represents the amount of power that has to be shed from the demand response. Eqns. (2.15) and (2.16) represent the power balance of the system. P_{Grid} is the net power to be sold to the utility. The reference power should approximately equal the power of the grid and the process to obtain this power is explained in the next subsection.

$$P_{Grid}(t) = P_{WTG}(t) + P_{ESS}(t) + P_{curtailed}(t) - P_{Load}(t) \tag{2.15}$$

$$P_{Grid}(t) \triangleq P_{ref}(t) \tag{2.16}$$

The constraints that are associated with the maximum and minimum accepted ratings are similar to the topologies of microgrid previously mentioned, these equations represent the maximum and minimum power available on each models. The equations are as follows:

$$P_{curtailedMin} \leq P_{curtailed}(t) \leq P_{curtailedMax} \tag{2.17}$$

$$P_{minESS} \leq P_{ESS}(t) \leq P_{maxESS} \tag{2.18}$$

$$E_{MinESS} \leq E_{ESS}(t) \leq E_{MaxESS} \tag{2.19}$$

Other additional constraints for the BESS that relates the charging and discharging mechanism for each time step are:

$$E_{ESS}(t) = E(t-1) - \eta P_{ESS}(t)\delta t \tag{2.20}$$

$$E_{SOC}(0) = E\eta_{ESS}(t) * Emax_{ESS} \tag{2.21}$$

In eqn. (2.21), η is the efficiency of the ESS and η is assumed to be the same value when it is charging or discharging. For the initial state of charge of each iteration, this is obtained according to the last dispatch, as show in eqn. (2.21). The values that are received from the dispatch $E\eta_{ESS}(t)$ are in per unit between 0 and 1. Therefore, it is necessary to multiply by the maximum state of charge to obtain the value in kW.

2.5.2 Reference power formulation

The reference power represents the regulated power aimed to be dispatched and sold to the utility. This is added to the optimization program as part of the power balance equality constraint. The correct results depend directly on the size of the ESS. The process to calculate the reference power is described in Figure 2-1. It is necessary to obtain the data as a vector of the forecasted wind power production. The algorithm performs the fit polynomial to the data. The process also requires inputting the degree of the polynomial and it is performed under a least-squares sense. The result is a curve that smoothens the produced power curve from the WTG.

The goal of having a reference power variable is to make this parameter to act as the equality constraint that the DERs must follow. The reference power formulation in other words is obtained by taking the wind speed power profile and limiting the changes of values per step. In this way it is possible to obtain a curve with smooth transitions.

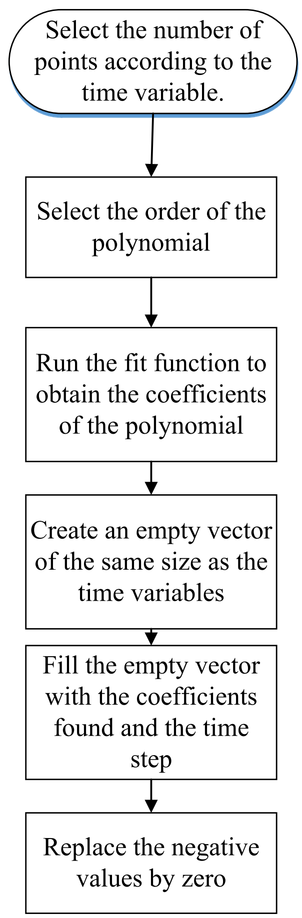


Figure 2-1 Reference power process calculation

Referring to Figure 2-1, an illustration of this process is shown in Figure 2-2. It can be seen that depending on the degree of the polynomial the curve will be adjusted better or worse to the parameters by fitting a smooth transition between each point.

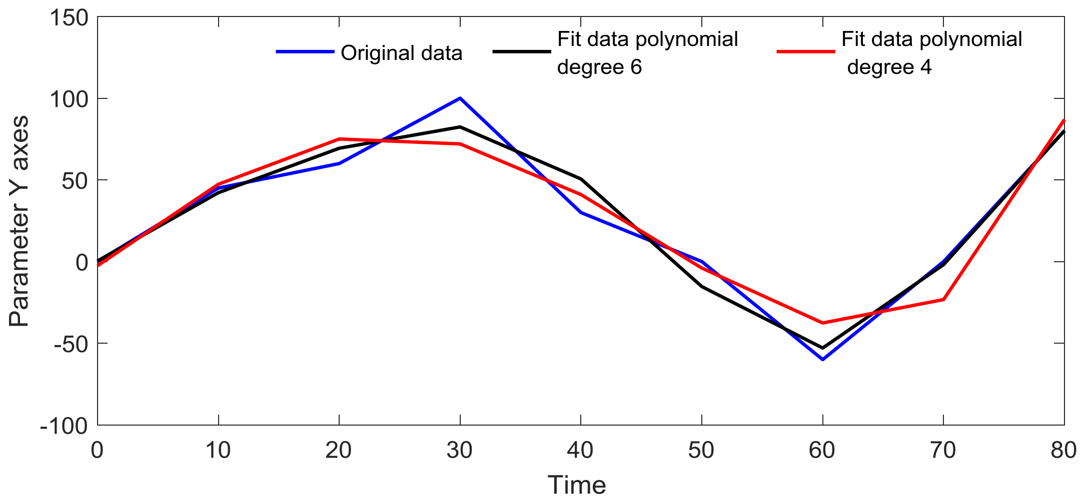


Figure 2-2 Illustration of fit function

2.6 Mathematical considerations to evaluate performance of microgrids

In this section is defined the mathematical procedure to evaluate the performance of any type of microgrid controller. Those parameters will be used later on chapters 3 & 4 of this document.

Eqn. (2.22) is used to calculate the total amount of imported energy. The equations requires to multiply all the power imported from the grid every time with the steps of acquisition, and do the addition over the total amount of time of simulation. As shown in eqn. (2.23), the steps of acquisition are calculated by dividing the total amount of time of simulation by the number of samples per time step. It is important to notice that although the dispatch of power between the controller and the grid is performed in minutes, the acquisition of data and performance of the grid is performed in a scale of 50 μs. This, last requirement ensures the real-time nature of the simulation, by approaching to a real-world continuous time scenario.

$$E_{Grid} = \sum_{t=0}^{T} P_{Grid}(t)\Delta t \tag{2.22}$$

$$Where: \Delta t = \frac{T}{\#\ Samples\ per\ time\ step} \tag{2.23}$$

The total cost of importing power from the grid utility requires the hourly cost each hour. As shown in eqn. (2.24), the hourly cost is multiplied by the time step and the current power imported from the grid. The addition of all the costs gives the total amount of energy imported.

$$C_{ImportedEnergy}^{Total} = \sum_{t=0}^{T} C_{Hourly} P_{Grid}(t)\Delta t \tag{2.24}$$

When the power imported from the grid violates the upper limit, it is desirable to calculate the size of the peak power and energy that has been violated. In eqn. (2.25), in the case of a violation, the first measures the total time of violation by adding the time when the values are higher than the maximum power grid limit. The second metric tallies the total energy overconsumed, by adding all the extra power demanded by the grid and multiplying it by its time step. The last metric measures the peak value of the power grid violation, by calculating over all the time, the maximum power delivered to the grid. All these equations are used to verify and quantify the performance of the controller.

$$if\ P_{Grid}(t) > P_{maxGrid} \ \rightarrow \begin{cases} T_{Violation}^{Grid} = \sum t \\ E_{Violation}^{Grid} = \sum P_{Grid}(t)\Delta t \\ P_{PeakViolation}^{Grid} = Max(P_{Grid}(t)) \end{cases} \tag{2.25}$$

It is desirable to calculate the total amount of load curtailed, as one of the objectives of the controller is to avoid the need of shedding load, because it represents power not supplied to the user. The quantification of this parameter is calculated using eqn. (2.26), this equations adds all the power curtailed obtained per time step, and multiplies it by the selected time step.

$$Load_{Curtailed}^{Total} = \sum_{t=0}^{T} P_{Curtailed}(t)\Delta t \tag{2.26}$$

The total fuel that is consumed in liters depends on the nominal rating power of the machine. Depending on the power that is dispatched, a consumption of diesel is associated, as parametrized in [49]. The proposed table for the quantification of fuel consumed is shown in summarized in eqn. (2.27). It depends on the amount of power supplied.

$$\begin{cases} \frac{1}{4}\, Load = P1\ (kW) \ \rightarrow fuel1\ (L) \\ \frac{1}{2}\, Load = P2\ (kW) \ \rightarrow fuel2\ (L) \\ \frac{3}{4} Load = P3\ (kW) \rightarrow fuel3\ (L) \\ Full\ Load = P4\ (kW) \ \rightarrow fuel4\ (L) \end{cases} \tag{2.27}$$

Each value of $P_{Diesel}(t)$ is classified to the nearest value of load that is consumed. With this classification, a quantity of liters consumed is assigned and multiplied by the delta time.

After obtaining the amount of diesel consumed, it is possible to calculate its cost and the total energy consumed. Eqn. (2.28) shows that the total cost of operating the diesel is calculated by dividing the associated cost of the machine in dollars per liters, divided by the total fuel consumed. Conversely, the total amount of energy produced by the diesel generator in eqn. (2.29) is calculated by diving the total operating cost over its associated cost in dollars per kWh (usually given by the manufacturer).

$$C_{Diesel}^{Total} = \frac{Fuel\ Price\ \$/Liters}{Fuel_{consumed}(Liters)} \tag{2.28}$$

$$E_{Diesel} = \frac{C_{Diesel}^{Total}\ \$}{Price\ \$/kWh} \tag{2.29}$$

In the case of section 2.5 that the controller situates as a community grid-connected microgrid, the quantification of its performance is done by measuring the peak power curtailed and total energy exported to the grid. In eqn. (2.32), it is shown how to calculate the peak power curtailed, by taking the maximum value over all time. Eqn. (2.33) reflects the amount of energy exported or sold to the grid, by adding every point in time of the power balance equation, and multiplying it by its time step. The power balance adds all the generation with the power curtailed and rest the load.

$$P_{curtail}(Peak) = Max\ (P_{curtail}(t)) \tag{2.32}$$

$$E_{Exported}^{Total} = \sum_{t=0}^{T} (P_{wind}(t) + P_{ESS}(t) + P_{curtail}(t) - P_{Load}(t))\Delta t \tag{2.33}$$

2.7 Summary

The microgrid controller algorithm depends on the topology of microgrid studied. In all possible scenarios, the main restriction or constraint is to have a power balance, which means that the total demand is equal to the energy that is produced. The first scenario's main function was to reduce the use of diesel generation. In the second scenario, the algorithm reduces the total load curtailed as the diesel generator was no longer available. This reduction guarantees economic benefits, as the costs of not supplying load are high. The remote microgrid explored the disconnection from the transmission system. Again, the main function was to reduce the use of diesel.

This chapter explored three different topologies of microgrids. For the utility distribution and remote case, it was shown that by removing the power imported from the grid and sizing correctly loads and DERs, the controller can search a possible solution. In both cases, the algorithm has the intention of reliability by maintaining the power balance as an equality constraint. Also, the community microgrid accomplish its purpose of delivering power in a cost-efficient way, by enhancing the power supplied by renewables. In the case of the community microgrid, the general purpose of increasing the participation of the community in the market was accomplished, by allowing the sale of power from a wind farm with low power fluctuations.

Chapter 3: Microgrid Controller Implementation

3.1 Overview

Building on the proposed algorithms of Chapter 2, this chapter proposes the design and implementation of each algorithm and microgrid topology. The chapter is divided in three main sections and one summary. The first section defines the general implementation and software tools involved to model the microgrid controller algorithms. The second section details the ratings and elements involved that characterize the utility distribution and remote microgrid studied. This design, involves the description and assumption of each DER. The implementation details the type of connections to simulate in real-time the proposed microgrids.

The last section proposes the implementation of the community microgrid, as it will be seen the topology in terms of rating and type of connection changes compared to the other microgrids. As the power produced by the WTG is a constant and non-controllable, this section evaluates six different ratings of storage capacity. The BESS rating requires a real solution, which can improve the power quality that is delivered. The power quality is improved by having a smooth transition between each dispatch point of power sold to the grid.

The implementation of each algorithm includes the objectives definition expected from each topology. Also, it involves a description of the sequence of events and general hardware tool requirements.

3.2 General Design

For each case that is presented in the following subsections, an optimization is performed using the Matlab function *fmincon.* An objective function is minimized in all of the cases. The function uses some already known profiles for the energetic demand and the wind turbine. As the function gives the dispatch points at a low operational cost, it is used to compare and validate the real-time simulation on Chapter 4.

The optimization function evaluates the dispatch for twenty four hours. The SOC of charge is assumed to be always known. The real-time controller bases the decisions in the same optimization equations and constraints, but the future SOC is never known. Additionally, some disturbance is added to the WTG for simulation. This disturbance corresponds to a white noise that is passed through a low pass filter and scaled to have a desired turbulence.

3.3 Design & Implementation of utility distribution and Remote Microgrid

3.3.1 Utility distribution grid-connected

The utility distribution microgrid in this document is defined as a group of distributed resources that are connected to the grid. The utility can supply and absorb power from the distributed resources in order to maintain the power balance, it is also the operator of the microgrid. One of the most important features here is that the utility owns the resources of the microgrid, which means that utility operator decides the dispatch operation points for each DER.

Naturally, the utility distribution microgrid will like to maximize its revenue by selling energy to its users at a low production cost from the resources. Implementing this scenario in real life will require a regulatory entity to supervise the energy selling price. For purposes of this study, the dispatch algorithm aims to satisfy the total demand power at the minimum possible production cost, this cost will mean the operational cost of the microgrid for the utility. The algorithm bases its decisions in different constraints, such as the maximum amount power that can be drawn from the utility.

The elements representing this topology and its ratings are shown in this section.

3.3.2 Remote islanded microgrid

The remote microgrid for this document is defined as a group of distributed energy resources that can operate in islanded mode. It means that the demand must be supplied only with present sources, as the connection to the grid is unavailable. In this kind of topology, it is very common to have controllable loads; these loads allow to have power curtailment in the event that the power demanded is higher than the produced power.

For this project, the main goals of the islanded microgrid are to reduce the operational cost, reduce fuel emissions and minimize the amount of load shedding. The last requirement means that the total amount of load curtail has to be minimized.

The elements representing this topology are the same for both utility distribution and remote microgrid. The differences are found in the connection to the grid, the constraint algorithms and certain ratings.

3.3.3 Design

The test system is a grid-connected 25 kV medium voltage microgrid that is composed of a diesel generator, WTG, BESS, and controllable loads. This model is shown in Figure 3-1.

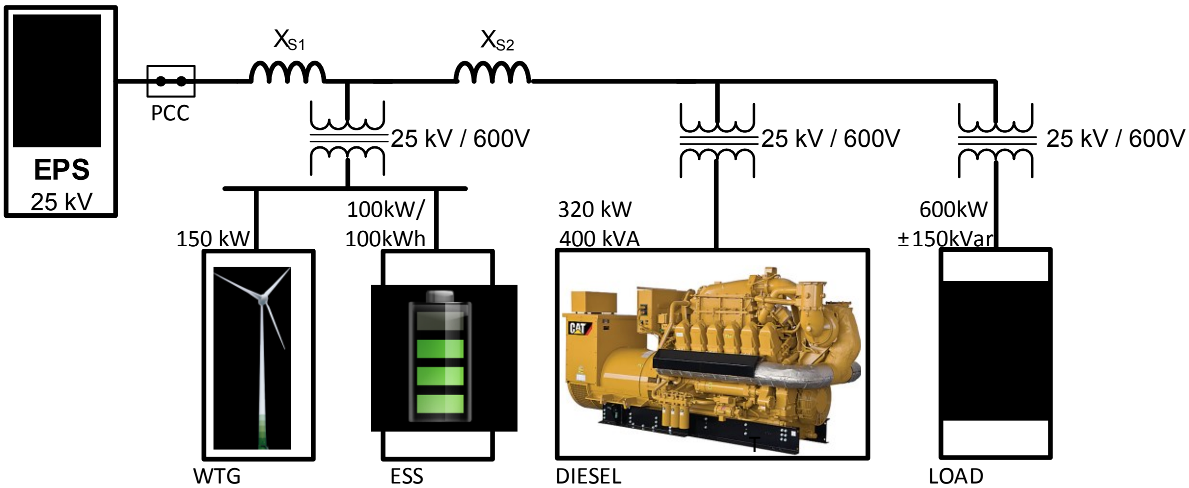


Figure 3-1 Test system 1

Depending on the technology, the diesel generator has a minimum amount of fuel for its operation. In this case, the diesel is operated at a minimum of thirty percent of the total power. The system is modelled with a synchronous machine with the corresponding governor for the active power set points and an exciter to set the field voltage of the machine. The machine is only in an on state when it is strictly necessary. The ramping time to reach steady state is out of the scope of this dissertation. The fuel price is taken from [50].

Referring to eqn. 2.27, the generator's size is 320 kW. The data is parametrized according to [51] and it is shown in eqn. 3.1. This equation represents the fuel consumption associated with the power generated by the diesel generator at certain time.

$$\begin{cases} \frac{1}{4}\ Load = 80\ kW \ \rightarrow 23.7\ L \\ \frac{1}{2}\ Load = 160\ kW \ \rightarrow 39.3\ L \\ \frac{3}{4} Load = 240\ kW \ \rightarrow 56\ L \\ Full\ Load = 320\ kW \ \rightarrow 74.9\ L \end{cases} \tag{3.1}$$

The battery storage system is modelled by a lithium-ion battery. The power inverters are average models. The diesel generator and the BESS have a regulation control on the active power dispatch set points that comes from the EMS controller.

The WTG model has a grid-tie converter's controller. It is expected to maintain the voltage on the DC connection while dispatching reactive power. Average models are used for the power converters, similar to the battery. A type 4 is implemented to model the WTG.

The mentioned diesel generator is controlled by an external exciter [52]. The mechanical power of the machine is set by running the machine in frequency mode control. It is fed by a PI control, which minimizes the error of a frequency reference and the feedback of the machine's current frequency.

Table 3-1 lists the maximum and minimum ratings of each component that are modeled in the system for the grid-connected utility distribution topology. Table 3-2 contains the ratings for the islanded case remote microgrid. The power that is supplied by the grid utility has a cost that is associated to each hour. These values are shown in Table 3-3.

Load/Generator	Min Value	Max Value
Load profile	0 kW	600 kW
Demand response	0 kW	450 kW
Diesel generator	96 kW	320 kW
Energy storage system	-100 kW/ 15 kWh	100 kW/100 kWh
Wind turbine generator	0 kW	150 kW
Power import constraint	-300kW	300 kW

Table 3-1 Operation ratings of the entire test system for Grid-Connected microgrid

Load/Generator	Min Value	Max Value
Load profile	0 kW	550 kW
Demand Response	0 kW	450 kW
Diesel generator	96 kW	320 kW
Energy storage system	-100 kW/ 15 kWh	100 kW/90 kWh
Wind turbine generator	0 kW	150 kW

Table 3-2 Operation ratings of the entire test system for islanded microgrid

Hour	Cost $/kWh	Hour	Cost $/kWh
1	0.0474	13	0.0479
2	0.0524	14	0.0470
3	0.0425	15	0.0430
4	0.0458	16	0.0404
5	0.0490	17	0.0403
6	0.0425	18	0.0410
7	0.0444	19	0.0383
8	0.0380	20	0.0428
9	0.0424	21	0.0404
10	0.0509	22	0.0495
11	0.0741	23	0.0418
12	0.1078	24	0.0379

Table 3-3 Hourly cost power imported for one day

The islanded and grid-connected cases have a difference of 50 kW in their load ratings. As the WTG rating is kept constant, the system in islanded mode cannot meet the desired demand. Therefore, the dispatch can reach a solution by curtailing the load. This difference was found by searching empirically the convergence of the islanded system.

The controller is expected to achieve [48,53-56]: a reduction in energy costs, a reduction in the liters of fuel that is consumed by minimizing the amount of energy that is used from the diesel generator, a minimization of the total load curtailed by supplying energy with renewables resources, and an improvement in resiliency by lowering power fluctuations and power violations from the imported power.

	Objectives
1	Reduction of energy cost and liters of fuel consumed
2	Reduction of amount of energy used from the diesel generator
3	Minimization of total load curtailed
4	Increase participation of renewable resources. Reduction of energy and power violations from the imported power.

Table 3-4 Objectives Grid-connected microgrid

The islanded or remote EMS controller must fulfill the following objectives [57,58]: minimize energy costs, reduce the amount of fuel that is consumed and prioritize the energy that is sourced by renewables.

3.3.4 Implementation

Figure 3-3 shows a flow chart of the general process for the controller of an utility distribution and remote microgrid. An explanation of the moving time window optimization process is explained in detail in Figure 3-2. The moving window allows the optimization process to speed up and reduce the minimum amount of energy that is required from the battery. With a correct time in hours selected for the moving window, the optimization algorithm takes a vector in real-time for the initial parameters and calculates the dispatch. As the size of the vectors is reduced, the saving in time and space is increased.

Certain model parameters must be initialized including the ESS state-of-charge (SOC) and the grid import limit among other parameters pertaining to the cost models of the DERs.

The energy management algorithm and sequence is as follows, the algorithm was implemented and published in [48]:

1) Select the time step
2) Create the forecasted profiles
3) Select the moving time window
4) Prepare the wind power forecast vector for two days
5) Prepare the load demand forecast vector for two days
6) Create the reference power vector
7) Create an empty vector to assign the values of the dispatch in the current time

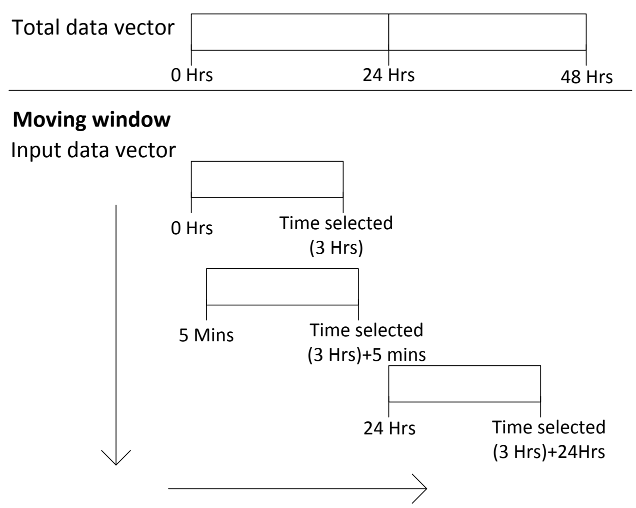


Figure 3-2 Time step simulation forward movement

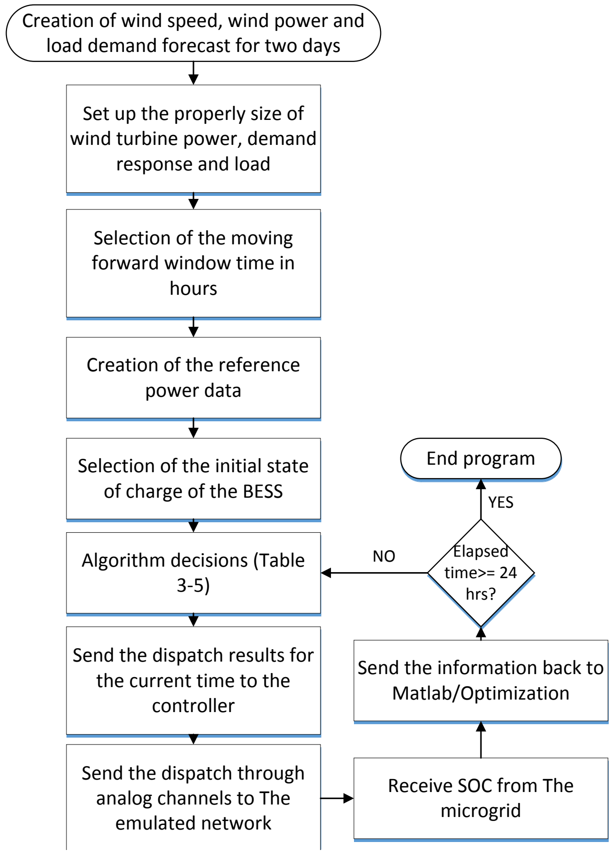


Figure 3-3 General algorithm process for commercial and remote microgrid

Table 3-5 shows the algorithm decisions that are described in Figure 3-3.

Figures 3-4 illustrates the overall platform. The energy management system is separated into optimization and knowledge and a controller that sends the operating points. The optimization and knowledge is modeled into a script in Matlab. The controller receives the operating points from the optimization that is performed. The controller is indicated to send the dispatched power through analog channels and receive the current state of the battery charge. Real-time digital simulators are used to emulate the distribution network and all of the DERs.

The EMS script requires 2 minutes of calculations to perform the optimization and unit commitment and it outputs a DER dispatch set-point for the energy storage system and diesel generator or amount of load to be curtailed every 5 minutes. It is important to mention that the optimization time is fixed and it depends on the computational process of the computer. The dispatch time (5 minutes) can then be adjusted. This type of dispatch does not affect the real-time nature of the simulation, because the emulated microgrid keeps running every 50 μs in the target, this with the purpose of emulate a “continuous real operation”. The 5 minutes dispatch emulates the decisions of a system operator, which is a reasonable time.

Rules	Objectives
1	Power balance: $P_{Remaining} = \alpha P_{load} - \beta P_{WTG}$ $P_{Remaining} = P_{Grid} + P_{ESS} + P_{diesel/Curtailed}$
2	The electric utility can supply or absorb a constraint power: $P_{minGrid} \leq P_{Grid} \leq P_{maxGrid}$
3	The diesel generator when is on must operate at a minimum level: $P_{DG} > P_{MinDG}$
4	The diesel generator must be only turn on when necessary. (For this process is used unit commitment) $U_D P_{maxDiesel}\phi \leq P_{DG} \leq U_D P_{maxDiesel}$
5	There is a maximum allowed load to be curtailed: $P_{curtailed} \leq P_{Curtailedmax}$
6	ESS cannot exceed its maximum and minimum power and energy rated levels: $E_{minESS} \leq E_{ESS} \leq E_{maxESS}$ $P_{minESS} \leq P_{ESS} \leq P_{maxESS}$
7	The current value of the energy depends on the previous value, an efficiency and the power of the ESS $E(t) = E_{ESS}(t-1) - \eta P_{ESS}(t)\Delta t$

Table 3-5 Algorithm decisions of Figure 3-3

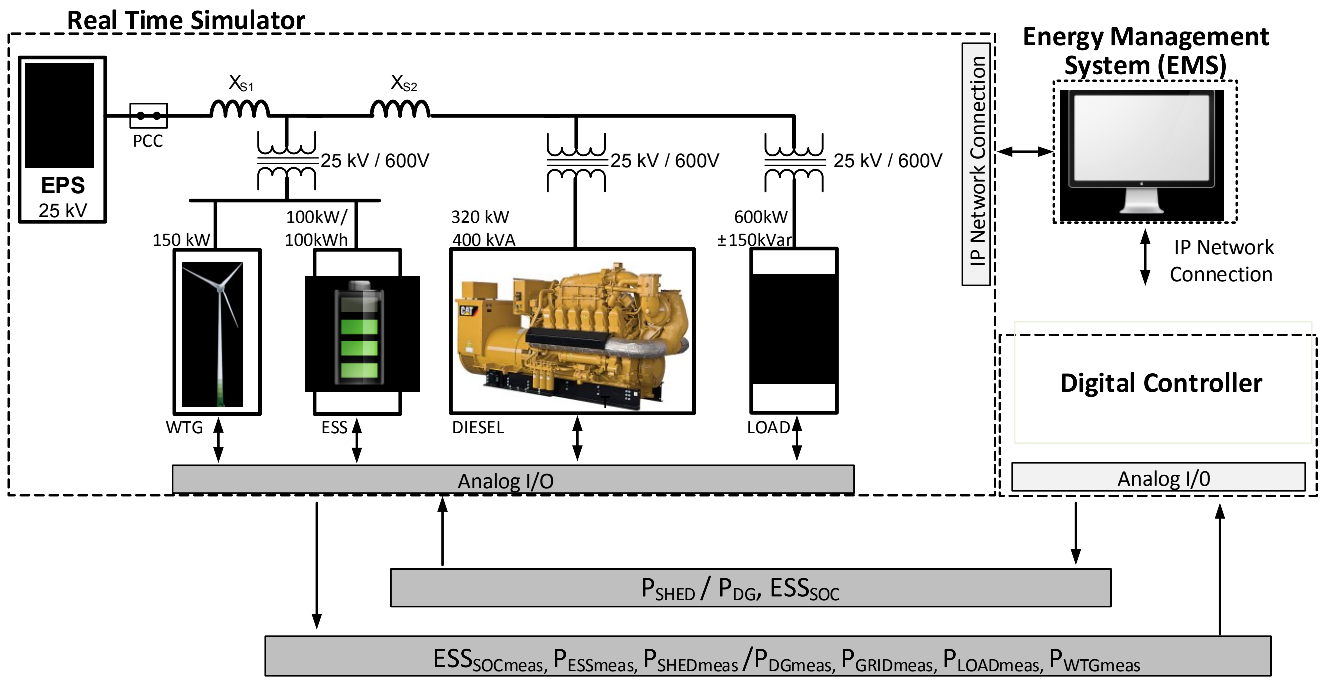


Figure 3-4 Real-time HIL system configuration test system commercial and remote microgrid

3.4 Design & Implementation of Community Microgrid

For this document a community microgrid consist of a small network such as a rural area, these type of microgrids are connected to the utility, but the operation of the distributed sources is handled by the community or certain local power producers. It means that the utility does not own the microgrid. The goal of this topology is to meet the power balance constraints, by supplying all the energetic demand, and if possible selling renewable power to the grid. The focus of this project is to explore the scenario in which the community microgrid can sell energy to the utility with smooth changes of power from renewable sources.

The goal of this section is to increase the hosting capacity of renewables through the implementation of EMS microgrid controller functions. The distribution network includes a wind farm, which represents the point of view from the independent power producer selling energy to the grid. The hosting capacity is shown under different scenarios with different ratings, and is validated showing a more regulated output power from the WTGs.

The wind forecasting helped to schedule the charging and discharging algorithm of the BESS. The test system used in this section was a typical distribution system with different loads and lines. It was connected to a transmission power system and the microgrid topology.

The microgrid topology was integrated by a farm of wind turbine generators, controllable loads and a BESS. With this topology, the controller algorithm had a main objective of increasing the participation of the total power sold by the wind farm. This section shows that by using a microgrid controller topology, power fluctuations are reduced and the total pwoer that is delivered to the grid is a smooth curve for one day.

A second benefit is that power fluctuations can be reduced more depending on the storage capacity but it had the constraint of using existent technology with a low cost of energy storage systems. It can be concluded that power fluctuations due to renewables were reduced and the participation of wind power was increased by using the appropriate battery sizing and algorithm controller.

3.4.1 Design

The model is used to simulate an IPP that is selling renewable energy to the grid utility, using a microgrid topology. The system is shown in Figure 3-5. The DERs operate with the same technology that is mentioned in chapter 2. The topology emulates a 25 kV, distribution-connected wind farm.

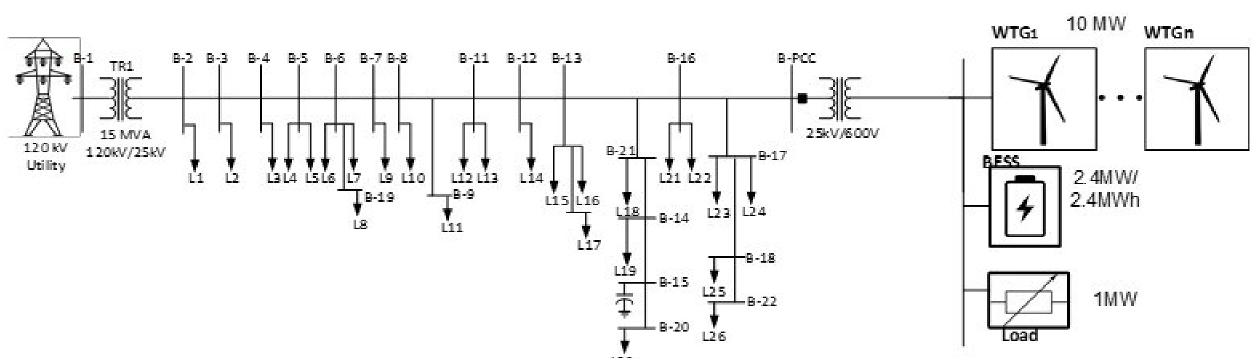


Figure 3-5 Community microgrid

The model of the microgrid distribution network is comprised of an array of wind turbine generators, a battery energy storage system and controllable loads. Table 3-6 displays the ratings for each scenario and component used in the system.

Using the parameters of the installed capacity of a wind farm in [59]. Each wind turbine can have an installed capacity of 2 MW. With a 35% efficiency, each turbine has an average annual energy output of 6132 MWh.

Load/Generator	**Min Value**	**Max Value**
Load profile	0	1000 kW
Wind turbine generator	0 kW	10 MW
Demand response	0 kW	500 kW
(scenario 1) Energy storage system	-2400 kW/ 0 kWh	2400 kW/2400 kWh
(scenario 2) Energy storage system	-2400 kW/ 0 kWh	2400 kW/1200 kWh
(scenario 3) Energy storage system	-2400 kW/ 0 kWh	2400 kW/3000 kWh
(scenario 4) Energy storage system	-1200 kW/ 0 kWh	1200 kW/1200 kWh
(scenario 5) Energy storage system	-1200 kW/ 0 kWh	1200 kW/900 kWh
(scenario 6) Energy storage system	-1200 kW/ 0 kWh	1200 kW/1800 kWh

Table 3-6 Ratings of entire test system 2

3.4.2 Implementation

In order to properly run the program from the point of view of the energy management system, the following steps are necessary for the controller:

Init 1 Select the time step

Init 2 Initialize the energetic demand and wind speed profiles based on real or forecast data

Init 3 Power produced for the WTG based on the wind speed profile

Step 1 Residual power calculation

Step 2 Initialize timer with stopping criteria and initialize window moving (Figure 3-2)

Step 3 Knowledge base algorithm calculations for one time step

Step 4 Send results to the FPGA controller with analog channels

Step 5 Receive the information of the current state of charge from the emulated system on a real time digital simulator

Step 6 Update the information for the next step in the knowledge base, increase the variables that are responsible to move forward the time by 1 and check the stop criteria

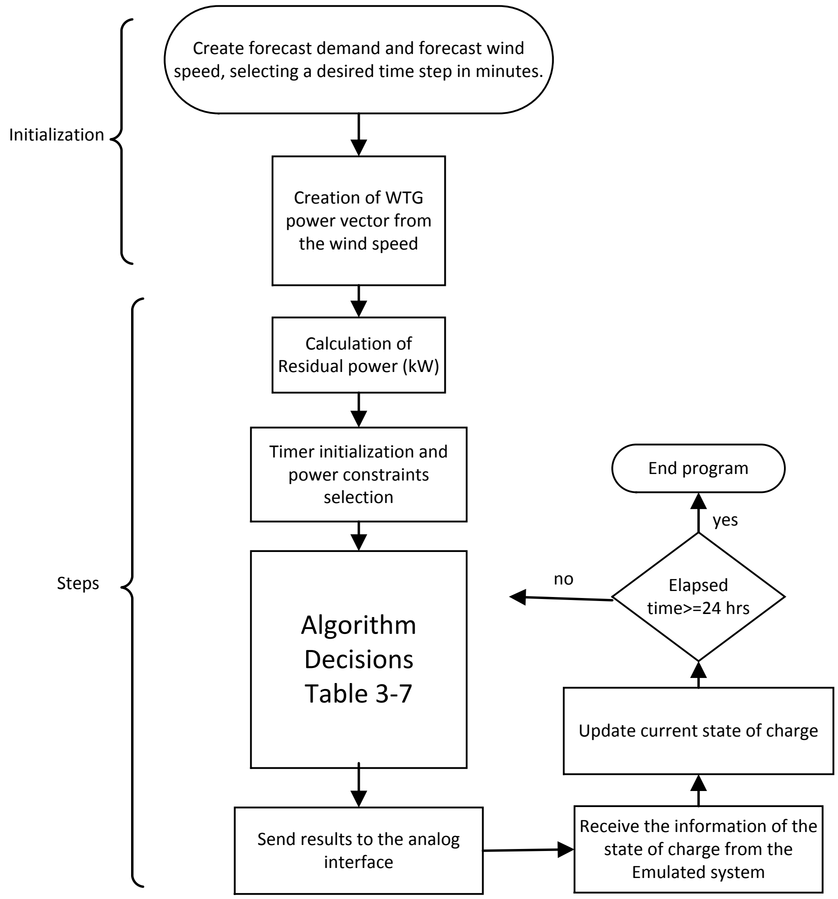


Figure 3-6 General algorithm process for community microgrid

Table 3-7 shows the algorithm decisions that are described in Figure 3-6.

Rules	Objectives
1	Power balance: $$P_{Grid} = P_{WTG} + P_{ESS} + P_{curtail} - P_{Load}$$ $$P_{Grid} \triangleq P_{ref}$$
5	There is a maximum allowed load to be curtailed: $$P_{curtailed} \leq P_{Curtailedmax}$$
6	ESS cannot exceed its maximum and minimum power and energy rated levels: $$\mathrm{E_{minESS} \leq E_{ESS} \leq E_{maxESS}}$$ $$\mathrm{P_{minESS} \leq P_{ESS} \leq P_{maxESS}}$$
7	The current value of the energy depends on the previous value, an efficiency and the power of the ESS $$\mathrm{E(t) = E_{ESS}(t-1) - \eta P_{ESS}(t)\Delta t}$$

Table 3-7 Algorithm decisions of Figure 4-3

The dispatch for the test system in a community microgrid is also every 5 minutes. Fig. 3-7 shows the communication process for the hardware and software of the implemented tools. The optimization process can take between 90-180 seconds, depending on the energy storage capacity that is selected.

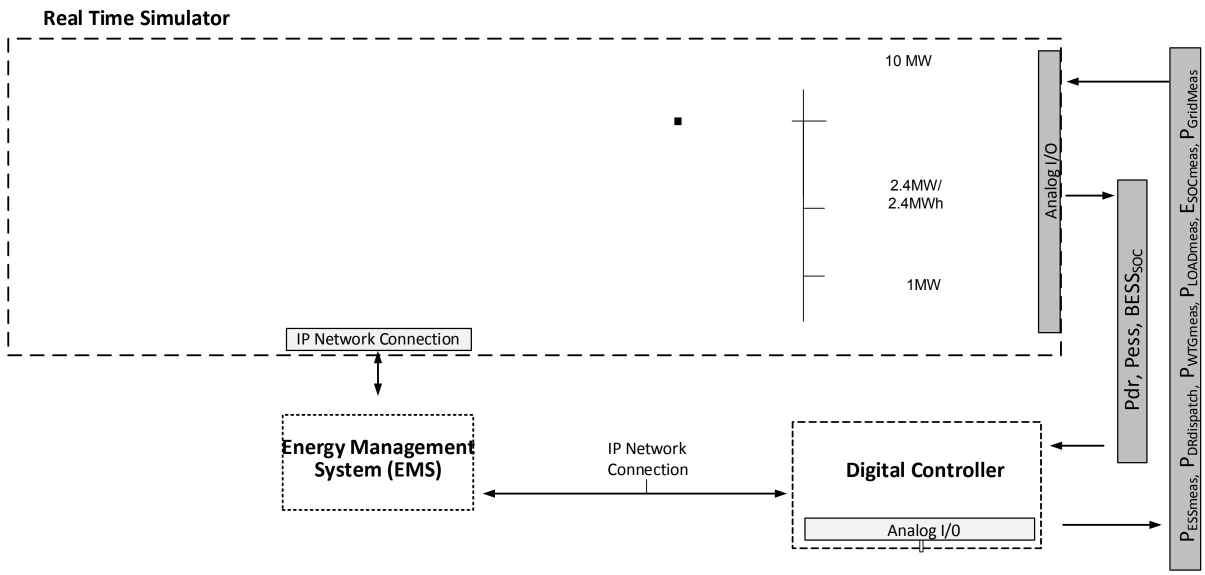


Figure 3-7 Real-time HIL system configuration community microgrid

3.5 Summary

The focus of this chapter was to develop a way to implement the algorithms formulated in Chapter 2. The implementation considered the different type of topologies and challenges that each of them represent. The utility distribution and remote microgrid was developed under the same topology with similar ratings, as the only difference between them is the connection to the grid utility. In the remote case, the ratings for the BESS were adjusted.

For the community microgrid the test system used was a typical distribution system with different loads and lines. It was connected to a transmission power system and the microgrid topology. The microgrid topology was integrated by a farm of wind turbine generators, controllable loads and a BESS. With this topology, the controller algorithm had a main objective of increasing the participation of the total power sold by the wind farm.

The chapter also presents the real-time configuration with a diagram that explained all of the required tools was documented.

The definition of objectives and implemented algorithm allows in the next chapter to evaluate the performance of each microgrid topology.

Chapter 4: Microgrid Controller Testing

4.1 Overview

Using the developed microgrid controller algorithms and proposed implementation from Chapter 2 and Chapter 3, the goal of this chapter is to test the performance in real-time of each microgrid controller. Each scenario has graphical, analytical and quantitative results that compare the theoretical results with real-time implementation. Theoretical results are obtained by running an optimization for the desired time in open-loop, while real-time results are obtained by connecting the controller with a real-time emulator of the network. The chapter proposes a set of metrics to benchmark the theoretical and real-time results.

There are three main subsections and one summary, each subsection corresponds to the aforementioned proposed microgrids. In each section is defined the metrics to be evaluated through conclusions and quantitative results. The quantitative results are presented in tables and are derived from the mathematical equations presented in Chapter 2. The graphical results are presented as figures that reflects the power and energy dispatch for one day depending on the DER.

The utility distribution microgrid case presents two different scenario results, at the end these two scenarios have an individual and joint evaluation. Similarly, the community microgrid presents results for six scenarios that evaluates the performance of different BESS sizing. The remote microgrid results are presented and it only has one scenario.

4.2 Metrics, Results & Validation for utility distribution Microgrid

The grid-connected microgrid EMS is tested under two configurations. In the first configuration, the diesel generator is used as the costly energy source. In the second configuration, the diesel generator is assumed to be inactive, and load curtailed is performed in accordance to the residual power. The maximum active import limit from the grid is set to 300 kW. The 24-hour load profile and 24-hour wind power shown in Figure 4-1 remain constant in both configurations. For each configuration, the offline and real-time results are both compared. The offline results correspond to the optimization function that is defined by the constraints and the objective function from the previous chapter. For the real-time simulation results, the EMS iteratively dispatches DER set-points every 5 minutes based on the data that it receives from the emulated model that is running on the RTDS.

As mentioned in Chapter 3, the wind power profile shown in blue in Figure 4-1 is used to obtain the residual power by calculating the difference with the demand power in black. This wind power profile contains some noise for the real-time simulation case; in the offline case this perturbation was not included. This was because one of the purposes of the controller was to showcase how the system and the EMS were capable to handle unforeseen changes.

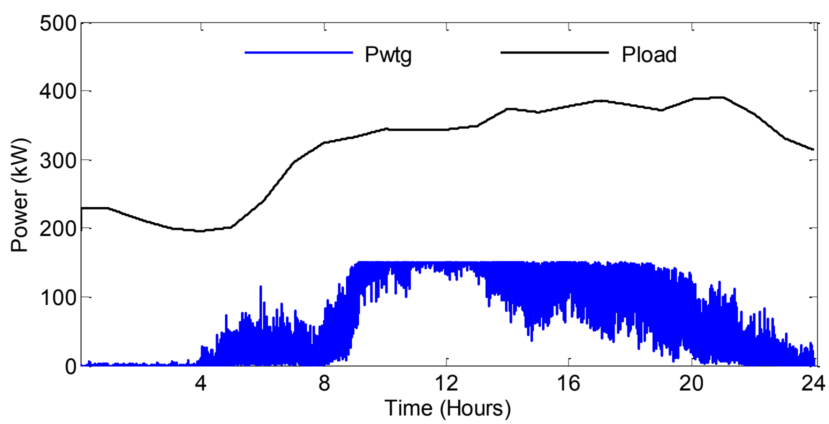


Figure 4-1 24 hours load and WTG profiles

The quantification of results to evaluate the possible need of a real-time simulation and a controller interface for a utility distribution microgrid defined in section 2.3 uses Table 4-1. This table presents all the metrics necessary to compare offline and real-time results. Please refer to Chapter 2 for references on how to compute these metrics.

Parameter	Unit
Net imported power from the grid utility	kWh
Net cost of energy imported from the grid	$
Total time of imported power violations	Hours
Amount of energy above the power import constraint	kWh
Peak power violation	kW
Amount of energy used in demand response	kWh
Total fuel consumed	Liters
Net energy consumed by diesel generator	kWh
Net cost of energy dispatched by diesel generator.	$

Table 4-1 Proposed metrics test system utility distribution microgrid

4.2.1 Fuel consumed minimization

This section of results corresponds to scenario 1 of section 2.3.1. As mentioned in Chapter 2, the goal of this scenario is to minimize the amount of fuel consumed. In this scenario eqn. (2.5) imposed an upper limit for the total amount of power that can be imported from the grid. As mentioned in Table 3-1, the maximum import constraint corresponds to 300 kW. Figure 4-2 presents the real-time and offline results of the power delivered by the grid. The black line corresponds to the offline dispatch and blue line corresponds to the real-time dispatch. In this figure, it can be seen that the constraint is always respected. As the real-time simulation has certain perturbances in its delivered power, it can be seen that the grid compensates for this stochastic generation.

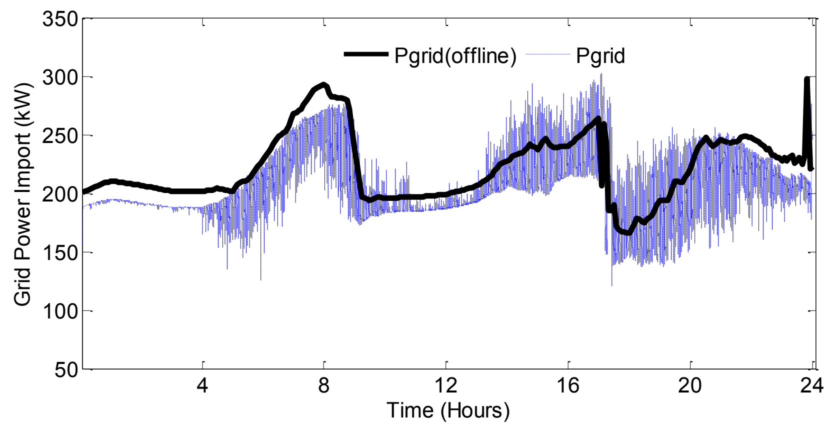


Figure 4-2 Imported power from the Grid

Figure 4-3 presents the power generated by the diesel generator and the BESS. When the power is negative, it means that the BESS is absorbing the residual power. In blue color on a second y-axis is also presented in this figure the state-of-charge of the BESS. The dotted lines present the offline results, while the continuous line shows the real-time dispatches. As it can be seen in the state of charge, the microgrid controller algorithm schedules the BESS to charge or discharge during the day. The algorithm always respects the maximum and minimum limits of the battery. Must important, the algorithm uses only at the end of the day the diesel generator in black color on the figure. The use of the diesel generator at these hours is because all the other DERs are not able to supply the high demand of power.

The high demand of power combined with a low production of wind power creates the need to use the diesel generator. The good result of the algorithm shows that although the diesel generator is being used, it is being operated at its lower rating to minimize operational costs. This operation results from the efficient charge and discharge of the battery throughout the day.

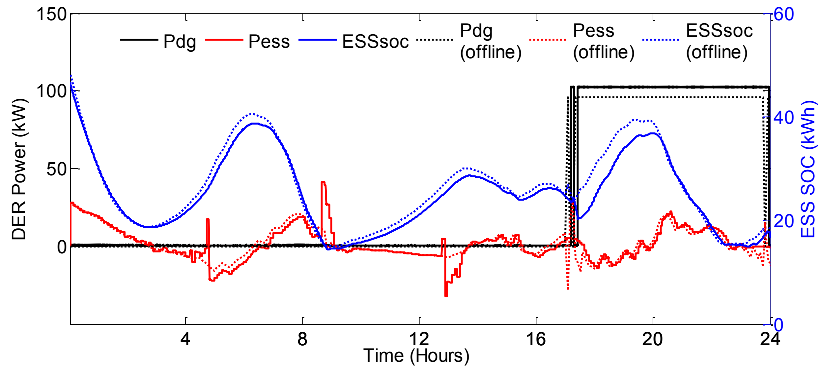


Figure 4-3 Comparison of offline and real-time results

Table 4-2 details and compares the computer real-time and offline metrics. These metrics are important for benchmarking the performance of the microgrid controller and selecting the most suitable one. The table also validates the expected offline results. As it can be seen, the total amount of energy imported from the grid is higher and also costly in the real-time case. Also, the amount of diesel energy consumed and its cost is less for the offline simulation. The difference in results shows that depending on the precision to approximate the emulation to the real world, there is a need for real-time simulations. In this case, as there are not very big differences in the results, it can be concluded that the algorithm is capable of predicting a useful dispatch and it also can account for unpredicted disturbances.

Also, it can be seen from Table 4-2 that all the limits imposed for the imported power of energy are always respected.

Metric	Real-Time	Simulation
Imported energy	5800 kWh	5317 kWh
Total imported energy cost	$475	$447
Import power violation (Time)	0 hours	0 hours
Import power violation (Energy)	0 kWh	0 kWh
Import power violation (Peak power)	0 kW	0 kW
Load curtailed	0 kWh	0 kWh
Diesel consumed	177 L	173.2 L
Diesel energy consumed	601 kWh	588 kWh
Diesel Generator Total cost	$241	$236

Table 4-2 Microgrid controller metrics community microgrid minimization of fuel consumed

4.2.2 Demand response

This section presents the results of the scenario introduced in Chapter 2 in section 2.3.1 scenario 2. This scenario represents the case that the diesel generator is out of operation. The wind power and demand profile are the same shown in Figure 4-1. For this case, the algorithm uses the controllable loads to curtail load in case it is needed to respect the power balance of the system. Ideally all the demand must be supplied, which means the demand response or the total power curtail should be minimized, while respecting the constraints imposed in section 2.3.2.

Figure 4-4 plots the total power curtailed for 24-hours of operation. The amount of load curtailed increases towards the remaining hours of the day due to the diminishing WTG power output, along with the increasing load demand. Although the EMS is capable of forecasting the load and wind profiles, the lack of generation results in the BESS prematurely reaching its minimum SOC as shown in Figure 4-5. Due to the wind speed gusts and turbulence, the WTG power injection fluctuates significantly, resulting in the EPS supplying a certain amount of power momentarily which is in violation of the power import constraint that is imposed as shown in Figure 4-6. In Table 4-3, the computer performance metrics for the real-time and offline simulation results are compared. The calculations that are performed in Tables 4-2 and 4-3 are in accordance to [60, 61].The real-time and offline results are in accordance too.

The results that are obtained in real-time and offline correspond to each other and the quantitative comparison is summarized in Table 4-3. Those results show that the imported power constraints are violated by a minimum amount of energy for one day. The total amount of load curtailed seen in Figure 4-4 for the whole day shows that its use is minimum and only required at the end of the day. At the beginning of the day, the storage system decreases dramatically to compensate for the wind speed turbulence and the load demand. Also, the fluctuations of WTG in production of power affect the EPS and are mostly compensated by the EPS. The profile is shown in Figure 4-6.

The algorithm has the guarantee to perform a real-time simulation with a local minimum. By comparing sections 4.2.1 and 4.2.2, it can be concluded that load curtailment is compensating similar amounts of energy that was primarily supplied by the diesel generator. The difference between those results changed due to objective function constraints and the presence of EPS.

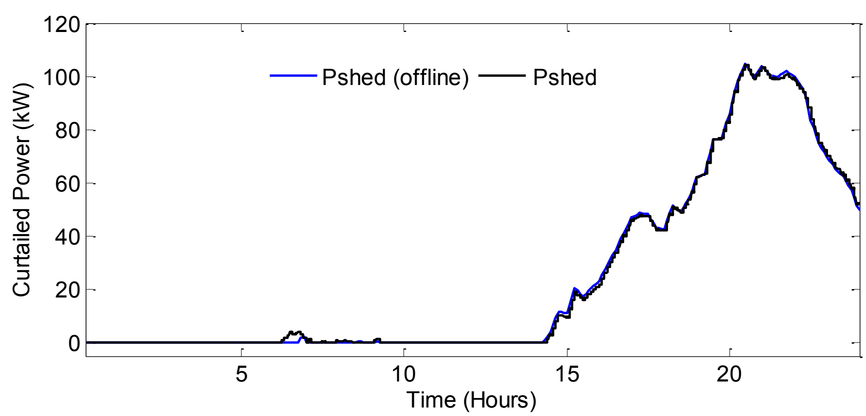


Figure 4-4 Demand response comparison real-time & offline results

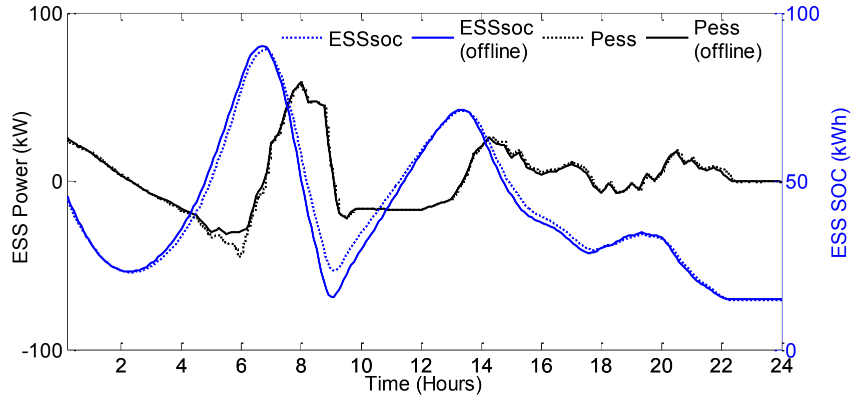


Figure 4-5 Comparison of offline & real-time results for the ESS

Figure 4-5 presents the state of charge of the BESS in blue color, on a second y-axis plot. The results in black represent the power delivered by the BESS. It can be seen that the algorithm schedules the charging and discharging of the battery through all the day to supply the peak power demand and absorb the residual power. The algorithm also respects the maximum limits to charge and discharge the battery. At the end of the day the battery is almost discharged using all the power available to compensate the lack of WTG generation.

Figure 4-6 shows the power supplied by the grid. All the perturbances in the real-time simulation are created to compensate the perturbances on the WTG. In this case for certain periods of time, that are quantified in Table 4-3, the import constraint of the grid power imported in the real-time simulation is violated, and it means that the power produced goes above 300 kW.

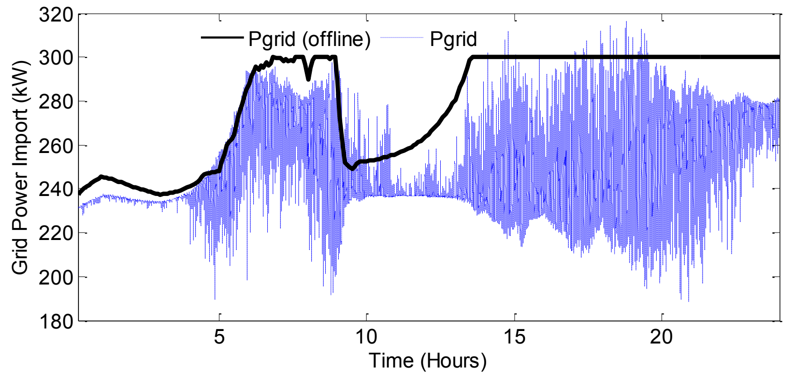


Figure 4-6 Scenario 2- Active power imported from the Grid utility

The metrics shown in Table 4.3 are obtained using the same equations introduce in section 2.6. From this table it is shown first the need of having a real-time simulation. This is because the real-time results shows that the import power constraint is violated by a peak power of 16.5 kW. Although the violation is for a small period of time, in the offline simulation this behavior was not appreciated. The costs and total load curtail are similar, which reflects a correct prediction of the EMS algorithm, but it shows the need to have real-time simulations.

Metric	**Real-Time**	**Simulation**
Imported energy	6966 kWh	6853 kWh
Total imported energy cost	$510	$506
Import power violation (Time)	0.0104 hours	0 hours
Import power violation (Energy)	3.15 kWh	0 kWh
Import power violation (Peak power)	16.5 kW	0 kW
Load curtailed	578 kWh	580 kWh

Table 4-3 Microgrid controller metrics demand response case for community microgrid

4.3 Metrics, Results & Validation for Remote Microgrid

In this section are presented the results for the scenario introduced in Chapter 2 in section 2.4. This section wants to operate an islanded microgrid, without the supply and intertie connection to a grid utility. Table 4-4 establishes the expected parameters to measure and validate the objectives stablished on Chapter 2. The main goal of this type of microgrid is to respect the power balance by supplying all the energetic demand and at the same time minimize the costs of operation. The minimization of cost operation results is savings for the users of the remote microgrid, such as small villages or universities. In this topology, it is necessary to have a strong generator such as a diesel generator to operate as the grid former, it means that this generator has to set the frequency and voltage reference of the system. For this reason, the diesel generator has to be always functioning, but the algorithm can operate to reduce its cost of operation and also decreasing the fuel emission.

Parameter	Unit
Total fuel consumed	Liters
Net energy consumed by diesel generator	kWh
Net cost of energy dispatched by diesel generator.	$
Average Cost of using the diesel generator	$/kWh

Table 4-4 Proposed metrics test system remote microgrid

The forecast profile of the demand and the wind speed power produced is shown in Figure 4-7. In this scenario the turbulence in the wind profile was reduced to allow the algorithm to converge between two minutes of simulation. Also, this perturbance was reduced as the grid is not present to account for higher values of fluctuations.

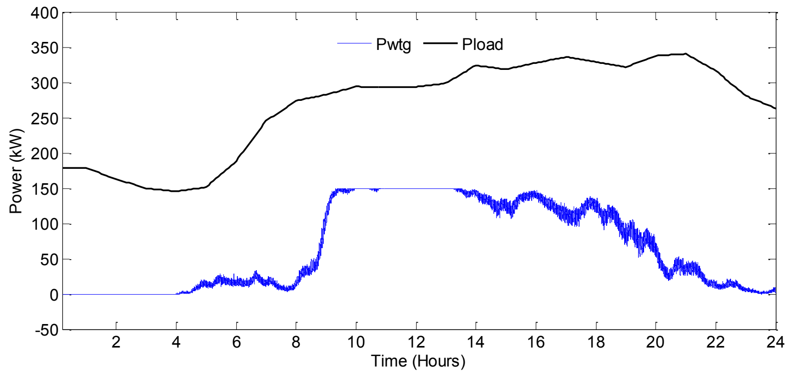


Figure 4-7 24 hours load and WTG profiles remote microgrid

The available resources in the network are the diesel generator acting in isochronous mode, the WTG and the BESS. Figure 4-8 presents the 24 dispatch comparison for the generation of diesel. The offline algorithm goal is to dispatch the minimum amount of diesel power, while respecting the upper and lower limits. As the diesel generator in the real-time case is the point of reference for the voltage and frequency, the prediction between offline and generated power are not exactly the same. The offline algorithm accounts for a reserve, which allows having similar results that can differ by 50 kW maximum. The real-time algorithm is divided into two parts, generated and dispatched. The generated power refers to the measured power that is used in the microgrid and the dispatched plots refer to the set-point that is sent from the EMS controller.

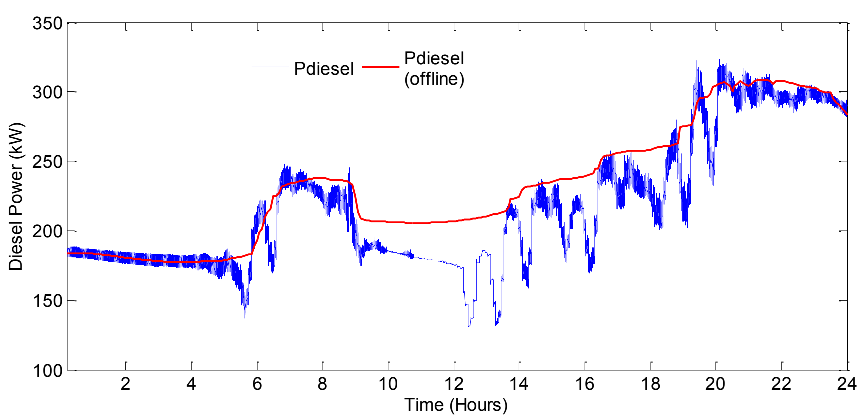


Figure 4-8 Diesel power remote case comparison offline and RT results

Figure 4-9 represents the active power that is generated by the BESS. Similar to the diesel generator, offline and real-time results prove the accuracy in the algorithm. The optimization script guarantees that the 24-hour dispatch for the energy storage system is the maximum power it can deliver for a one day prediction. The dispatched real-time and offline results are slightly different, because the SOC points vary during real-time simulation.

Figure 4-10 presents the SOC. The offline and real-time results show similar behaviors. The upper and lower values are always respected, and the demand response was not necessary. The SOC is fully discharged at hour 9. This is because the load demand reaches its maximum at this point. At the end of the day, the BESS delivers its maximum charge to compensate for the lack of power that is produced by the WTG.

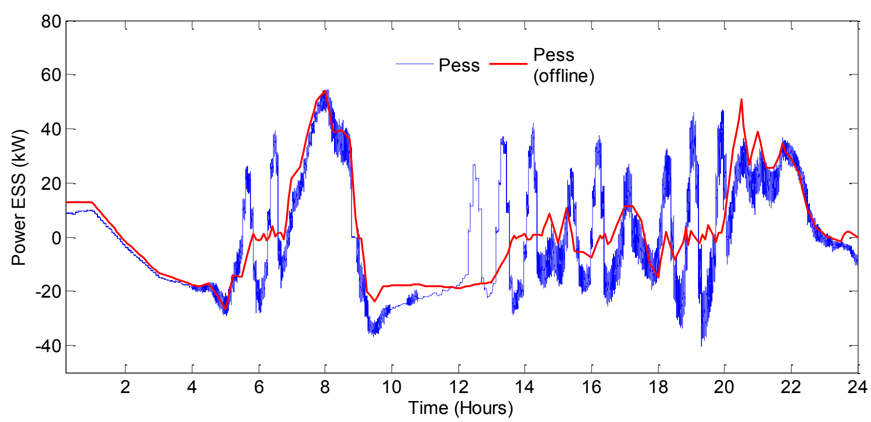


Figure 4-9 BESS power remote case comparison offline and RT results

Figure 4-10 shows that at hour 9 and after hour 22, it is less expensive to operate the BESS at the minimum allowed state of charge point. The total time operating at 15 kWh is 2 hours and 20 minutes. This is an acceptable time that reduces the total cost.

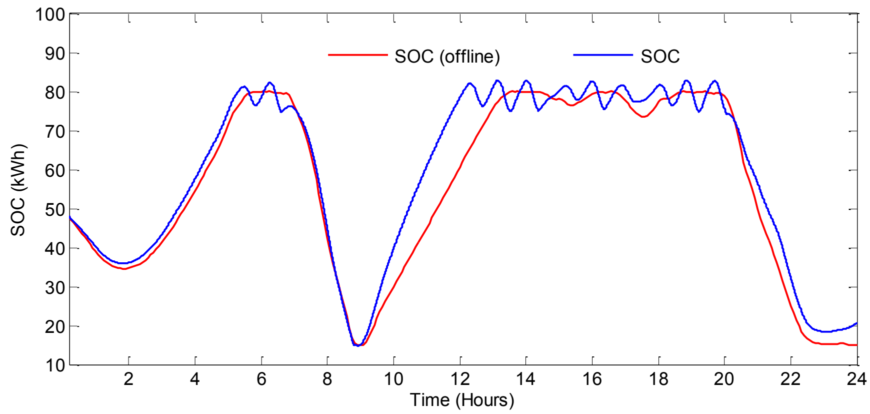


Figure 4-10 SOC islanded case comparison offline and RT results

Table 4-5 displays the metrics for the offline and real-time results. The overall diesel that is consumed in the offline case is higher, as expected from Figure 4-8. The generated power is higher than the dispatched power, but the system does not present any violation in the imposed limits due to the accounted reserve. The machine delivers more than 30% of its nominal power, which justifies the general cost of using this power generation. The results differ by a minimal difference, which validates the results.

The metrics in Table 4-5 are obtained by using eqns. (2.28) and (2.29) to obtain the diesel that is consumed and the total cost.

Metric	Real-Time	Offline
Diesel consumed	1271.9 L	1355.7 L
Diesel energy consumed	5191.5 kWh	5750 kWh
Diesel Generator Total cost	$1729.8	$1815
Diesel Cost	0.3332 $/kWh	0.35 $/kWh

Table 4-5 Microgrid controller metrics remote microgrid case

4.4 Metrics, Results & Validation for Community Microgrid

This section validates the 6 scenarios presented in Chapter 2 in section 2.5. The objective of those scenarios are to present a community microgrid. It means that the grid does not belong to the utility. The objectives here are to supply the energetic demand and enhance the participation of renewable energies. In this type of microgrids there is an incentive for local power producers to sell energy. In the following results will be presented an algorithm that is capable of smoothing the power fluctuations on the change of power sold to the grid per step of time.

The generation of maximum power is normalized to a rating of 10 MW. The process follows the idea of having a farm of wind power generation selling energy to a grid-utility through a microgrid-control topology. Figure 4-11 and Figure 4-12 display the wind power profile and load demand for 24 hours. In Figure 4-11 are presented three different curves, the black line represents the wind power profile for the offline simulation, the blue line shows the forecast wind power profile for the real-time simulation. The red line represents the power reference introduced in Chapter 3 in section 3.4. This power reference is the expected smooth power to be sold to the grid by the offline simulation.

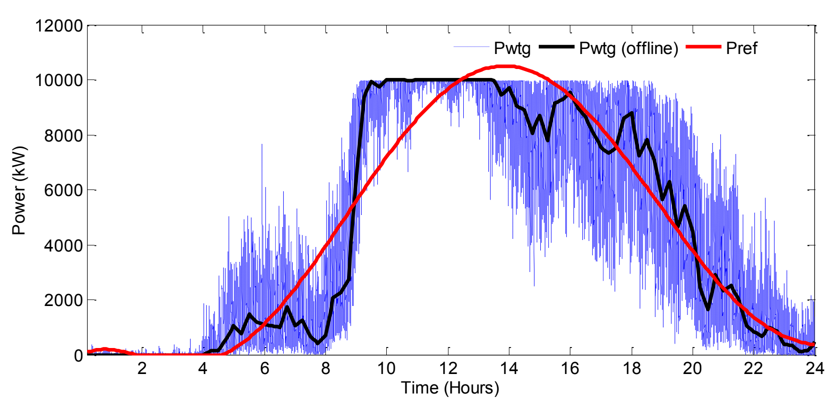


Figure 4-11 Wind power profile for one day

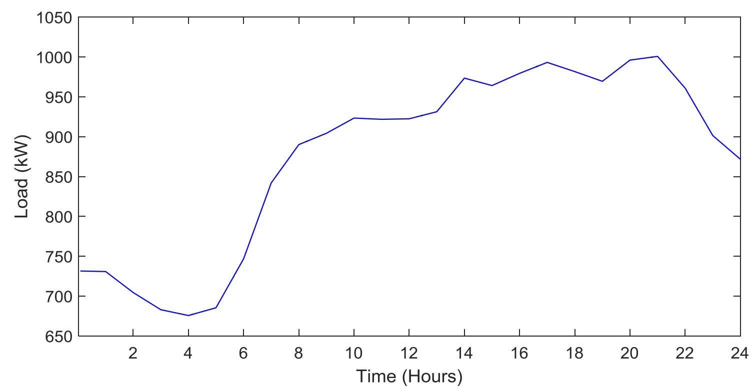


Figure 4-12 Load demand profile for one day

The main objectives and a set of performance metrics are used to evaluate the impact of the optimization algorithm and the microgrid controller platform in order to validate the proper regulation of energy that is sold by independent energy producers [48,62,63].

4.4.1 Objectives

1) Minimization of power curtailed
2) Boost of grid energy exported
3) Comparison of results with different sizes of energy storage
4) Quantification of the maximum load that should be curtailed

4.4.2 Metrics

1) Total load curtailed
2) Peak load curtailed
3) Total exported energy

4.4.3 Results Validation & Comparison

Scenario 1, 2 & 3

Referring to Table 3.6, in Figure 4-13, the first three scenarios with a maximum output power of 2400 kW are shown. The storage capacity is changed for these scenarios to see the impact on the load curtailment algorithm and the available energy that can be sold to the grid. The real-time results include the stochastic generation of wind power produced. The dispatch tends to follow the same pattern as the optimization offline simulation. From Figure 4-13, it can be seen that the three scenarios in both real-time and offline scenarios respect the maximum and minimum constraints of power delivered. The waveform for the 24 hours is similar, but the maximums peaks reached differs. As per example in the case c, when the battery has a higher kWh it can deliver higher peaks of power. This effect will be better quantified in Tables 4-5 to 4-7.

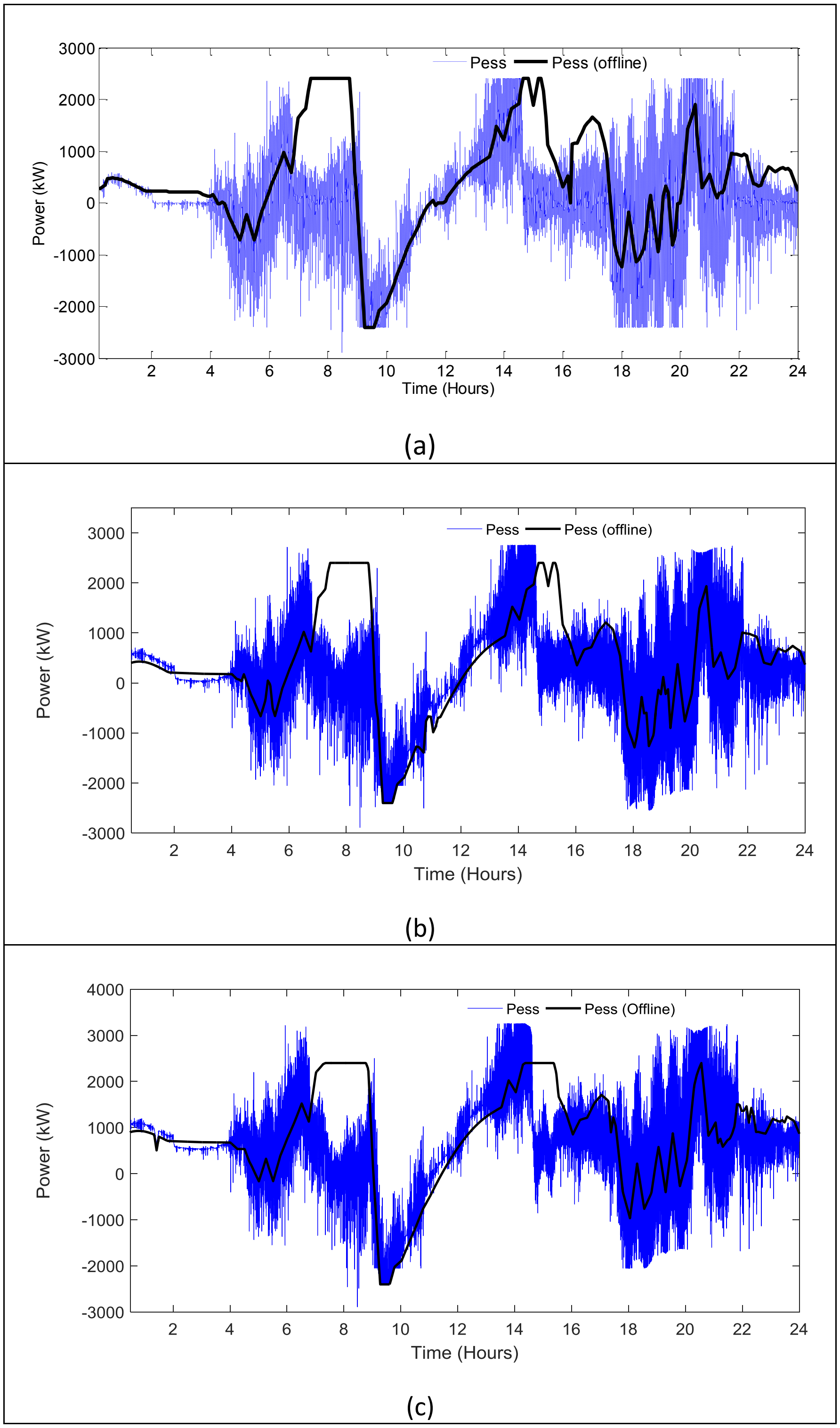


Figure 4-13 BESS power; (a) Pess scenario 1 (2400 kW/2400 kWh); (b) Pess scenario 2 (2400 kW/1200 kWh); (c) Pess scenario 3 (2400 kW/3000 kWh).

Figure 4-14 plots the total amount of power curtailed. The number of periods, where the difference between the reference power and wind power that is produced are higher, reflects the same time where more load shedding is required.

The starting point for the three scenarios of Figure 4-14 is the same, delivering the maximum amount of power that should be curtailed. It can be seen that depending on the sizing of the BESS and the period of time, the demand response should deliver less power. This studied will be corroborated again with Tables 4-5 to 4-7. Observing the plots, it can be seen that at the beginning of the day the battery with higher kWh, in this case c, requires bigger amounts of load to be curtailed. The more interesting analysis is that contrary to the logic expected, the lower BESS in terms of kWh, in this case b, requires also a higher amount of load to be curtailed than case a. This can lead to the conclusion that the correct sizing of the battery for this scenario in terms of minimization of load curtail requires a good balance between the rating of kW and kWh.

Referring to Figure 4-15, these plots represent the actual power that is being sold to the grid. This power is required to be as similar as possible to the power reference introduced in Figure 4-11. The three plots shown that compared to the original power produced by the WTG there is a smooth power being sold to the grid. This means that taking the difference between each point of the profile respect the imposed limit. Although it will be required to use another external source to attenuates the perturbations.

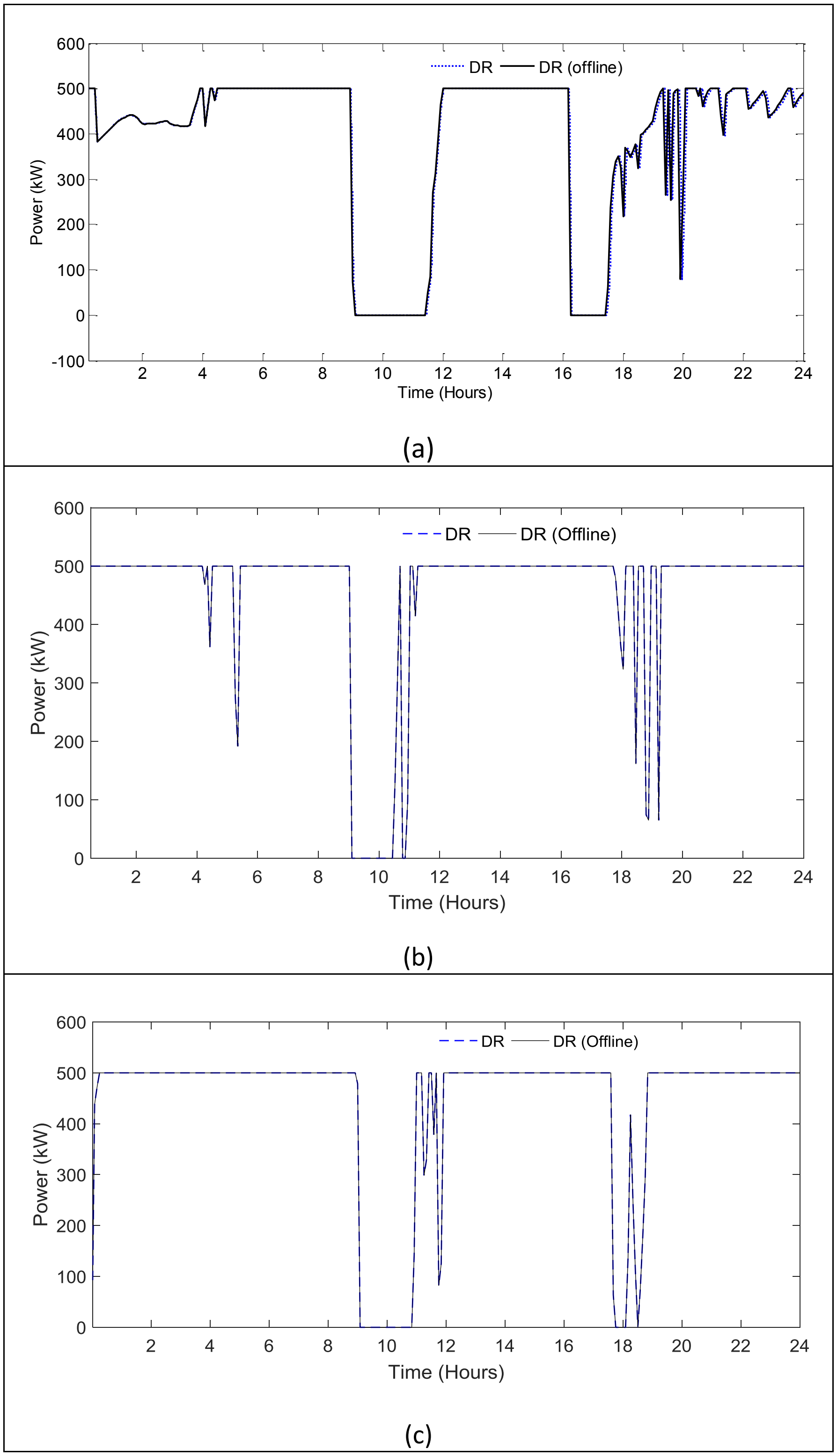


Figure 4-14 Demand response; (a) Pcurtail scenario 1 (2400 kW/2400 kWh); (b) Pcurtail scenario 2 (2400 kW/1200 kWh); (c) Pcurtail scenario 3 (2400 kW/3000 kWh).

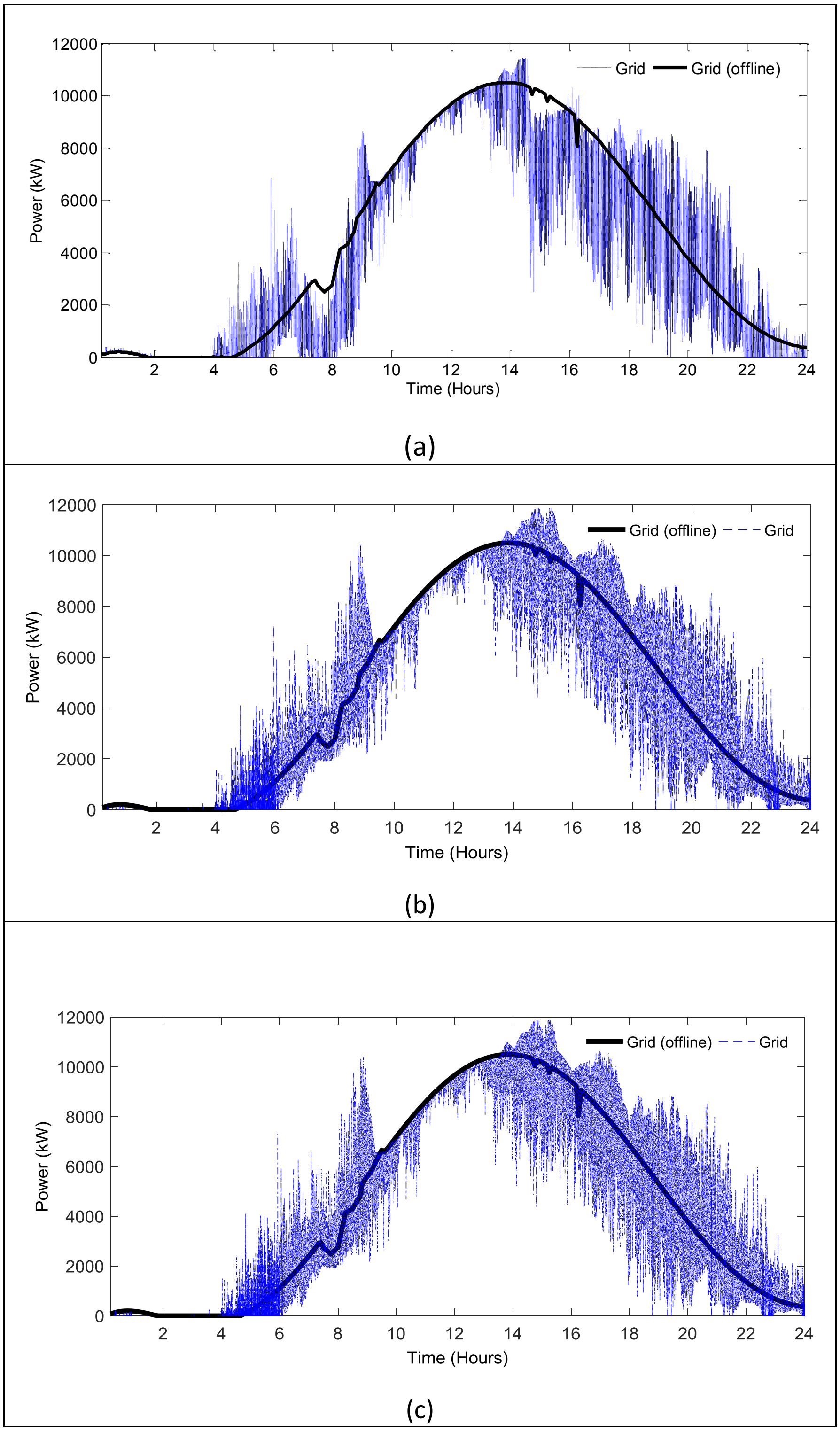


Figure 4-15 Power sold to the grid; (a) Pgrid scenario 1 (2400 kW/2400 kWh); (b) Pgrid scenario 2 (2400 kW/1200 kWh); (c) Pgrid scenario 3 (2400 kW/3000 kWh).

Table 4-6, 4-7 and 4-8 display a mathematical comparison of the real-time and offline results.

Table 4-6, 4-7 and 4-8 corroborates the visual conclusion presented in the previous Figures, which the scenario 1 has the best balance among the three scenarios. This is because in both real-time and offline cases it has the minimal load curtail in kWh. The scenario 3, has the higher amount of energy exported to the grid, this means that this scenario will receive a higher payment for its services. It can be concluded that depending on the goals of the independent power producer, it can size the BESS by exporting more energy or decreasing the amount of power curtailed.

Metric	Real-Time	Offline
Total load curtailed	9278 kWh	9305 kWh
Peak load curtailed	500 kW	500 kW
Total exported energy	97484 kWh	107230 kWh

Table 4-6 Microgrid controller metric scenario 1

Metric	Real-Time	Offline
Total load curtailed	10481 kWh	10470 kWh
Peak load curtailed	500 kW	500 kW
Total exported energy	98687 kWh	108395 kWh

Table 4-7 Microgrid controller metric scenario 2

Metric	Real-Time	Offline
Total load curtailed	13182 kWh	13150 kWh
Peak load curtailed	500 kW	500 kW
Total exported energy	101388 kWh	111075 kWh

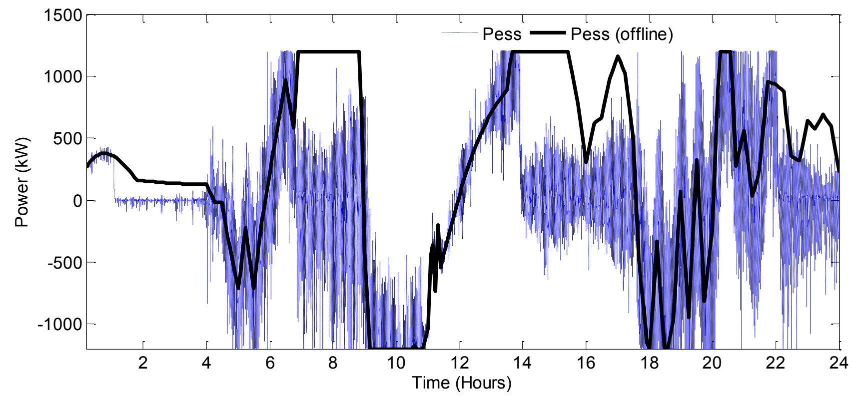
Table 4-8 Microgrid controller metric scenario 3

Scenario 4, 5 & 6

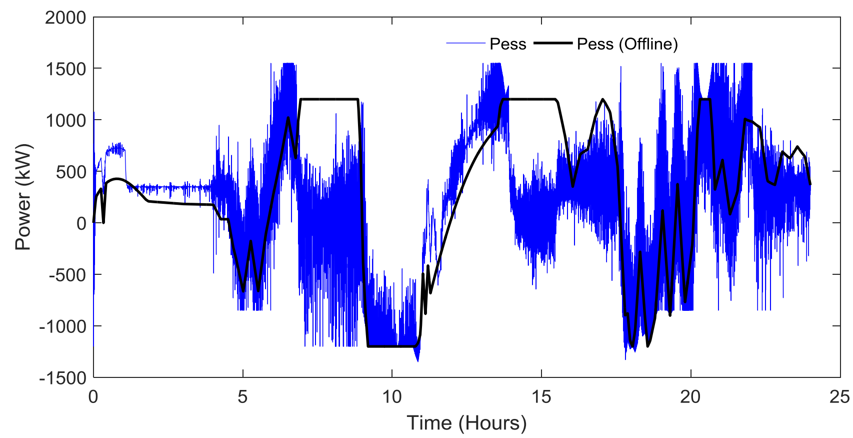
This section corresponds to the scenarios 4, 5 and 6 presented in section 2.5. Figure 4-16 plots the total power that is charged and discharged from the energy management system for scenarios with a maximum output power of 1200 kW. That corresponds to half the capacity of scenarios 1, 2 and 3.

The metrics for both scenarios in offline and real-time are tabulated in Tables 4-6 to 4-11. Figure 4-17 shows that the overall waveform of the three scenarios does not present high changes. Although the scenario that changes more is the scenario 4, that has a combination rating of 1200kW- 1200kWh.

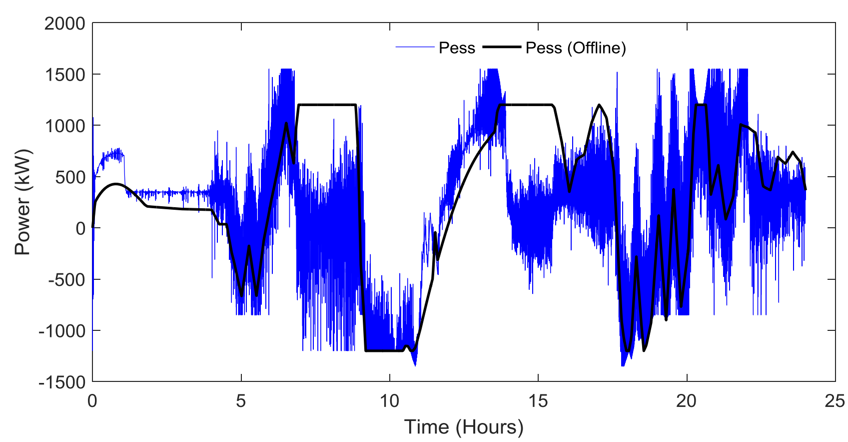
Figure 4-18 show that for the hours 6 to 8 and 11 to 12, the load curatilment with the storage is not enough to mitigate the fluctuations. It leads to the conclusion that a lack of half capacity in the storage leads to higher fluctuations in the intended regulated power. The three scenarios of Figure 4-18 compared with the expected reference in Figure 4-11 presentes biggest differences than the power sold in Figure 4-15. It means that the capacity of 1200 kW is not enough storage sizing to smooth the power sold.



(a)



(b)



(c)

Figure 4-16 BESS power; (a) Pess scenario 4 (1200 kW/1200 kWh); (b) Pess scenario 5 (1200 kW/900 kWh); (c) Pess scenario 6 (1200 kW/1800 kWh).

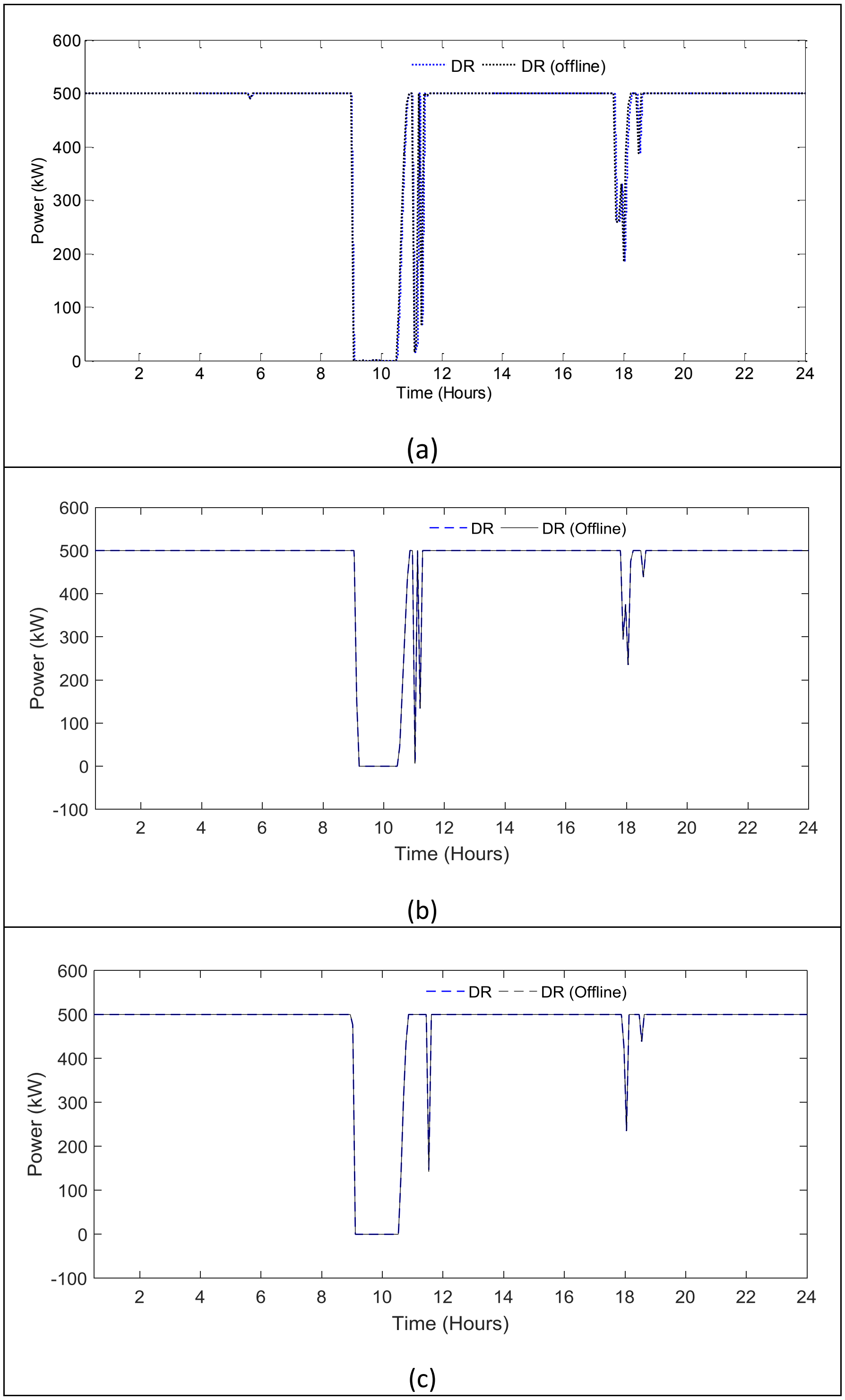


Figure 4-17 Demand response (a) Pcurtail scenario 4 (1200 kW/1200 kWh); (b) Pcurtail scenario 5 (1200 kW/900 kWh); (c) Pcurtail scenario 6 (1200 kW/1800 kWh).

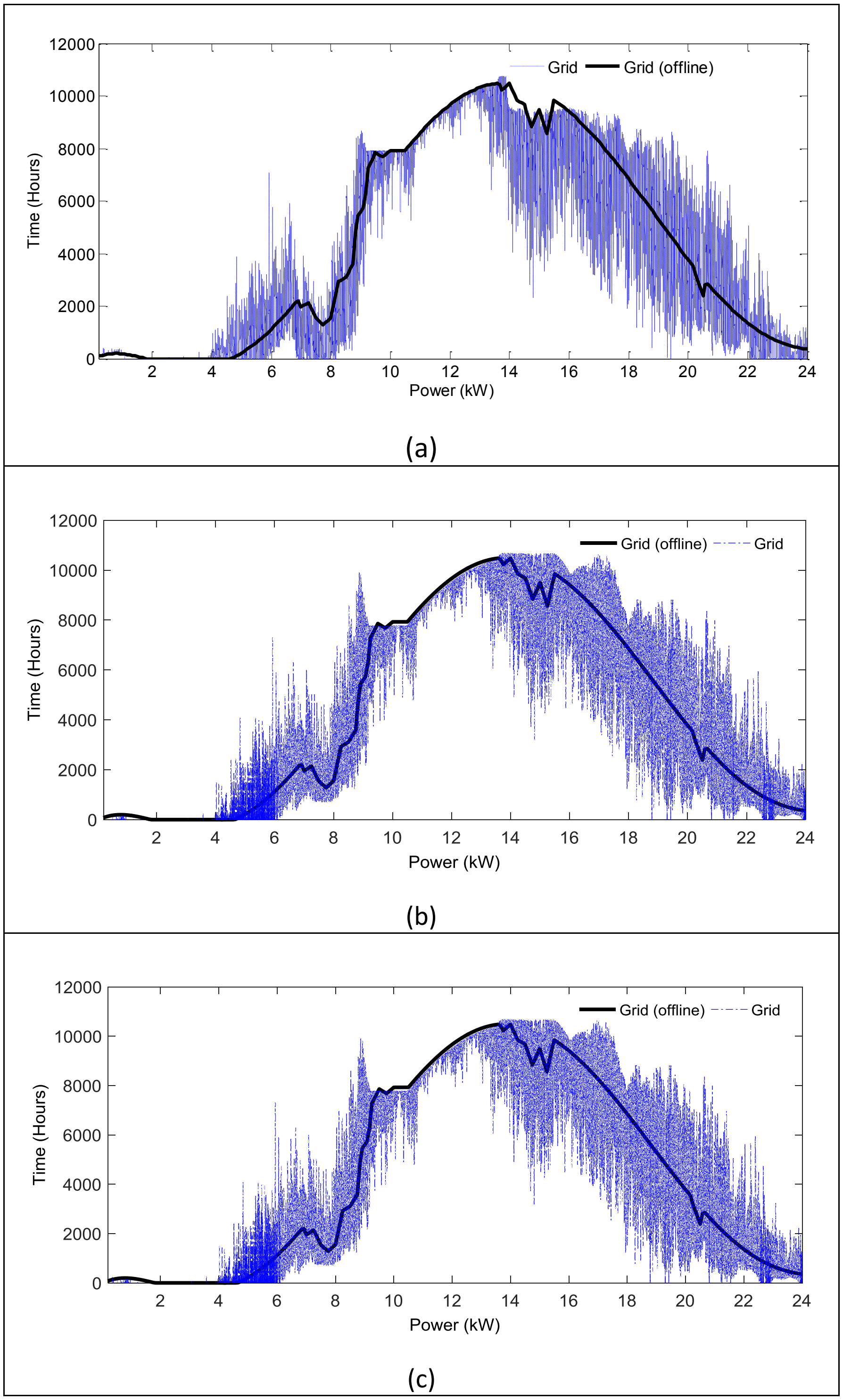


Figure 4-18 Power sold to the grid; (a) Pgrid scenario 4 (1200 kW/1200 kWh); (b) Pgrid scenario 5 (1200 kW/900 kWh); (c) Pgrid scenario 3 (1200 kW/1800 kWh).

Eqns. (2.36), (2.32), (2.33) are used to calculate the values in Table 4-9 to 4-11. Table 4-9, 4-10 and 4-11 and Figure 4-17 show that the total amount of load curtailed for the scenarios with lower output power capacity is higher.

Metric	Real-Time	Offline
Total load curtailed	10911 kWh	10967 kWh
Peak load curtailed	500 kW	500 kW
Total exported energy	99335 kWh	104950 kWh

Table 4-9 Microgrid controller metric scenario 4

Metric	Real-Time	Offline
Total load curtailed	11025 kWh	11045 kWh
Peak load curtailed	500 kW	500 kW
Total exported energy	99449 kWh	105028 kWh

Table 4-10 Microgrid controller metric scenario 5

Metric	Real-Time	Offline
Total load curtailed	10673 kWh	10610 kWh
Peak load curtailed	500 kW	500 kW
Total exported energy	99097 kWh	104593 kWh

Table 4-11 Microgrid controller metric scenario 6

From the results obtained in this section and Table 4-6 to 4-11, it can be concluded that real-time results and offline calculations are very similar in the overall results. Also, no pattern was found that indicates that the real-time results are always lower or higher than the offline results.

By comparing figures for the first three scenarios, it is better to have a battery with equal energy capacity and output power. Figure 4-15 shows that with a higher capacity, the system can deliver a power to the grid with less fluctuations although it will require more load curtailment. The same conclusion can be derived by comparing the last three scenarios

As shown in Figure 4-15 and Figure 4-18, it is important to not oversize the capacity of the battery. Otherwise, the algorithm will incur more costs by curtailing more load. For this study, the best case found in terms of a good power sell to the grid with a low power fluctuations is the first scenario with a rating of 2400 kW/ 2400 kWh.

4.5 Summary

In all the three microgrid topologies were defined metrics to benchmark the performance of each algorithm. The graphical and quantitative results for the utility distribution microgrid shows that when the diesel generator is in service, the overall operation of the system reduces both costs and environmental impact. In the case when the diesel generator is not available, the reduction of load curtailment reflects reliability and economic benefits. The imported power constraint is never violated.

In the case of a remote microgrid, the results showed that the microgrid topology is able to work in stand-alone mode. The results for this topology shows that operating the microgrid without connection to the grid utility and without the possibility to curtail load, the BESS has to compensate all the demand changes by being charged and discharged fast. One way to protect the battery will be to implement new renewable sources and allow the presence of interruptible loads.

This chapter showed that by using a microgrid controller for a community microgrid topology, power fluctuations are reduced and the total power that is delivered to the grid is a smooth curve for one day. A second benefit is that power fluctuations can be reduced more depending on the storage capacity but it had the constraint of using existent technology with a low cost of energy storage systems. It can be concluded that power fluctuations due to renewables were reduced and the participation of wind power was increased by using the appropriate battery sizing and algorithm controller.

Chapter 5: Conclusions & Recommendations for Future Work

5.1 Summary

In this dissertation are defined three types of microgrid controller topologies. The first topology is used to validate energy management system controller algorithms for grid-connected microgrid. The second topology is used to evaluate the controller in an islanded microgrids. The last topology is used to validate a microgrid controller selling renewable energy to a grid utility. The load and wind speed profiles used for each scenario present the same waveform but the rating is scaled in accordance to each implementation.

The first controller aims to reduce the amount of diesel that is used while efficiently scheduling the charging and discharging times of the BESS. The topology is in grid-connected mode and has an imported power constraint. In the eventual case that the diesel generator is out of service, the controller is able to curtail load. The second controller uses an islanded topology. The diesel generator acts in isochronous mode and has the same minimization objective function as the first one. The last controller aims to minimize the power fluctuation due to producing power with renewable resources while increasing the penetration level of these resources.

Also, a real-time hardware in the loop platform is implemented to emulate the microgrid topologies and justify the functionality of each microgrid controller. An offline minimization algorithm is performed to quantify and support the real-time platform results. The explanation and procedure to have the modular platform is detailed for each controller. The equations for each scenario create the rules that are necessary to integrate an adaptive inference system.

5.2 Conclusion

It was shown that implementing a microgrid topology in grid-connected and islanded mode, with a low operational cost energy and load management system controller, has several benefits. A microgrid featuring a BESS, WTGs, diesel generators and controllable loads can be scheduled to have low fuel consumption and low cost by minimizing the diesel generator power production. Those reductions translate into economic and environmental impacts.

It was also demonstrated that by properly sizing the capacity of storage in the BESS, the penetration level of renewables in the energy selling market could be improved. The improvement is reflected by selling more regulated energy with less power fluctuations.

A real-time platform and its sequence of events was developed to validate the functionality of each algorithm and also to emulate the microgrid scenarios. The offline optimization reflects the correct functioning of each controller.

5.3 Recommendations for further work

Despite that this research covered an extensive area of microgrid studies, the project can be extended and improved.

The forecasting methods in this research required several trials to obtain the good results. It will be necessary to incorporate a method that can achieve similar results with few attempts of calculation.

By improving the forecasting methods, a new algorithm that involved this technique can be developed for microgrid controllers. Also, there are many different approaches to optimize the dispatch and schedule DERs on a power system.

The multifunctional real-time platform allows a good number of projects. One possible scenario is to have a microgrid topology with fault cases and protection analysis. Another idea is to incorporate more renewable resources such as PVs and combine heat and power (CHP). With these elements, the microgrid controller can be extended.

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