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Control and Automation of a Resilient Microgrid

Dissertação no âmbito do Mestrado em Engenharia Eletrotécnica e de Computadores, ramo de Robótica, Controlo e Inteligência Artificial orientada pelo Professor Doutor António Paulo Mendes Breda Dias Coimbra e pelo Professor Doutor Aníbal Traça de Carvalho Almeida e apresentada ao Departamento de Engenharia Eletrotécnica e de Computadores da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

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Control and Automation of a Resilient Microgrid

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Abstract

The increasing use of electric vehicles, together with the expansion of low-cost distributed renewable energy generation and technological advancements in energy storage systems, introduced new technologies and altered the paradigm for grid design and administration. Benefits of Microgrids range from increased load flexibility to cope with peak consumption, more efficient integration of intermittent renewable generation, reduced T&D losses, provision of ancillary services as well as economic and environmental benefits. One of the main characteristics of microgrids is that they have the ability to work autonomously in relation to the utility grid using local generation and energy storage resources. The increasing frequency of natural disasters have led to situations where small towns become isolated from the main utility grid. The microgrids' ability to work autonomously from the utility grid present a viable solution to this problem. The objective of this project is to develop innovative strategies and algorithms for the design and management of electric microgrids with a focus on resiliency towards critical and disaster situations and also to use resources to increase its cost-effectiveness. The proposed solutions will be simulated, using a microgrid to be implemented at the DEEC-UC as a pilot. As a result of the work, the study presents an algorithm that efficiently manages the loads of a microgrid in order to ensure its resilience, and an architecture that allows a three-phase system to function as a single-phase system, when the microgrid is isolated from the utility grid.

Keywords: Renewable Energies and Smartgrids; Microgrid, Resiliency, Energy Storage management; Load shedding

Resumo

Com o aumento da utilização de veículos elétricos, juntamente com a expansão da geração de energias renováveis distribuídas a baixo custo e os avanços tecnológicos nos sistemas de armazenamento de energia, introduziram novas tecnologias e alteraram o paradigma para a conceção e administração da rede. Os benefícios da microredes vão desde o aumento da flexibilidade de carga para fazer face a picos de consumo, uma integração mais eficiente da geração renovável intermitente, a redução das perdas de T&D, a prestação de serviços auxiliares, bem como benefícios económicos e ambientais. Uma das principais características das microredes é que têm a capacidade de trabalhar de forma autónoma em relação à rede pública, utilizando recursos de produção local e armazenamento de energia. O aumento da frequência de catástrofes naturais levou a situações em que pequenas aldeias ficaram isoladas da rede de fornecimento de energia. A capacidade das microredes de trabalhar de forma autónoma apresenta uma solução viável para este problema. O objetivo deste projeto é desenvolver estratégias e algoritmos inovadores para a conceção e gestão de microredes elétricos com foco na resiliência para situações críticas e de catástrofes e também utilizar recursos para aumentar a sua relação custo-benefício. As soluções propostas serão simuladas, utilizando uma microrede a implementar no DEEC-UC como piloto. Como resultado do trabalho, o estudo apresenta um algoritmo que gere de forma eficaz as cargas de uma microrede de forma a garantir a sua resiliência, e uma arquitetura que permite que um sistema trifásico funcione como um sistema monofásico, quando a microrede é isolada da rede de fornecimento de energia.

Palavras-Chave: Energias Renováveis e Smartgrids; Microgrid, Resiliência, Gestão de Armazenamento de Energia; Load shedding

Abbreviation

AC	Alternate Current
CFC	Continuous Function Chart
CT	Current Transformer
DC	Direct Current
DEEC	Departamento de Engenharia Eletrotécnica e de Computadores
DG	Distributed Generation
EMS	Energy management system
ESS	Energy Storage System
FBD	Function Block Diagram
h	Hour
IL	Instruction List
ISR	Instituto de Sistemas e Robótica
kW	Kilowatt
kWh	Kilowatt-hour
LCD	Liquid Crystal Display
LD	Ladder Diagram
MG	Microgrid
MGCC	Microgrid Central Controller
MS	Microsource
PCC	Point of common coupling
PLC	Programmable Logic Controller
PV	Photovoltaic

RES Renewable energy sources

ROCOF Rate of change of frequency

RTU Remote Terminal Unit

SFC Sequential Function Chart

SOC State of Charge

ST Structured Text

Dacro:T&DT&D Dacro:T&DTransmission and Distribution

UC Universidade de Coimbra

UFLS Under frequency load shedding

UPS Uninterruptible Power Supply

US United States

UVLS Under voltage load shedding

V2G Vehicle to Grid

W Watts

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1

Introduction

The increasing use of electric vehicles, together with the expansion of low-cost distributed renewable energy generation and technological advancements in energy storage systems, introduced new technologies and altered the paradigm for grid design and administration. Electric microgrids have the potential to revolutionize the utility grid by introducing a new entity with high controllability and autonomous capacity. One of the main characteristics of microgrids is that they can work autonomously in relation to the utility grid using local generation and energy storage resources.

The increasing frequency of natural disasters, particularly forest fires, which have become very common in Portugal and in other areas of the globe, have led to situations where small towns become isolated from the main utility grid. Adding to this, the desertification of the interior of Portugal is a problem that also contributes to the isolation of populations. The microgrids' ability to work autonomously from the utility grid present a viable solution to this problem. By having a well-designed microgrid coupled with a strategic management plan of its resources, it is possible to guarantee the energy supply during extended periods of time or to supply the essential loads during the critical periods when main grid disconnection occurs and maintain operation of critical infrastructures. This will be accomplished through the combination and optimization of several different resources such as local renewable generation, energy storage systems, vehicle-to-grid technology, connection to disaster forecasting systems and demand-side response by using load controllers.

The main contribution of this study is the development of a load management algorithm with the objective of increasing the resilience of the microgrid in the event of a power failure. This algorithm is based on the concepts of load shedding and balance between load demand and power supply.

The developed architecture allows a three-phase system to function as a single-phase system, when the microgrid is isolated from the utility grid.

A characterization of the loads was made, and priorities were assigned to them. These priorities determine the shedding order.

Several operating modes have been defined based on the occurrence of a power outage, the photovoltaic generation, the level of energy available in the batteries and the time that elapses since a failure in the energy supply is detected.

Finally, a simulation environment was developed to test the good functioning of the developed algorithm, having tested all possible scenarios.

This work was developed at the DEEC-UC, in collaboration with the Institute of Systems and Robotics (ISR) and is integrated in the ResiMicrogrid project.

1.1 Thesis Structure

After this chapter, this Thesis is structured in the following manner:

- **Chapter 1:** Presents an Introduction where the motivation and objectives are explained;
- **Chapter 2:** It explains the concept of microgrids, talks about their control and about load shedding, referring to other works already developed;
- **Chapter 3:** This chapter is intended to explain, discuss and detail how the work experiences were developed and conducted, how data was gathered, which hardware and software were used;
- **Chapter 4:** All the developed work is explained. This chapter is divided in several topics. In the first, the changes to the local grid are detailed. The second topic is the architecture of the microgrid. The third topic concerns the classification of loads. Operation modes are defined and explained in the fourth topic. The fifth topic the developed program is explained. Finally, the system is validated through simulations and all the results are explained;
- **Chapter 5:** The final chapter represents a brief discussion about the results obtained in the simulations. Future work, in order to improve the developed system, will be addressed;

2

State of Art

2.1 Microgrids

According to the Microgrid Exchange Group of the US Department of Energy, a microgrid can be described as “[A microgrid is] a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode” [1][2].

To be considered a microgrid, the system must combine local distributed generating sources, inverters, energy storage technologies, a control system and controllable loads to create an energy system that is self-sufficient [3] [4] [5] [6] [7] [8].

The microgrid configuration can be DC, AC, or hybrid. Due to its capacity to function in combination with the main grid, simple structure, and cost effectiveness, the AC microgrid is more focused nowadays [5].

A microgrid has two different modes of operation: grid-connected mode and island mode. In island mode, microgrids can operate autonomously, while in grid-connected they exchange power with the distribution grid [9].

The use of microgrids have many advantages. They help in the integration of distributed generation, which contributes to reduce the carbon emissions and pollution. On the consumer side, they can improve the quality of electricity. Microgrids are viewed by utilities as controllable loads that may help peak shaving during periods of high demand by lowering their own consumption through the shedding of non-critical loads and supplying more power to the main grid utility. By adopting distributed generation at the demand site, microgrids can reduce total distribution system losses by avoiding the need for transmission lines and delaying the building of new transmission lines. Higher energy efficiency is another benefit of this. Fuel expenses can be decreased by utilizing renewable energy sources like wind and solar [10]. Microgrid can also improve the resiliency and reliability of critical facilities [2].

2.1.1 AC Microgrids, DC Microgrids and Hybrid Microgrids

Microgrid can be classified as AC, DC or Hybrid Microgrids. In an AC network, power electronics interfaces are used to directly connect AC sources while DC sources, such as PV and fuel cells, are converted to AC using DC/AC converters. AC/DC converters are used to connect DC loads [11]. Although AC microgrids may be incorporated into the current AC power grid, in order to maintain the stability of the system, synchronization requires more complex control systems [10].

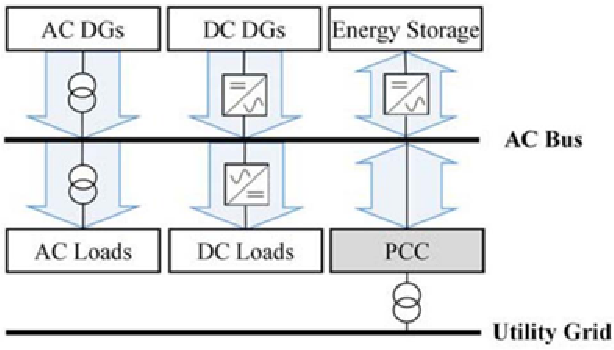

Figure 2.1: General structure of ac microgrids [12]

DC microgrids have the following benefits [6]:

The system efficiency of a dc microgrid is increased by reducing inverter conversion losses between dc output and dc loads.
There are no requirements for reactive power correction or synchronization with the utility grid.
The DC microgrid has the capacity to handle faults on its own. Due to the stored energy in the battery or dc capacitor, a malfunction or voltage sag in the utility grid does not immediately influence the dc bus voltage of the dc microgrid.

However, DC microgrid have some disadvantages [6]:

- Private DC distribution lines must be installed in order to use a DC microgrid.
- DC system protection is more difficult since there is no zero point crossing of current in a DC system.
- The loads in this system have to be adapted for DC power source.

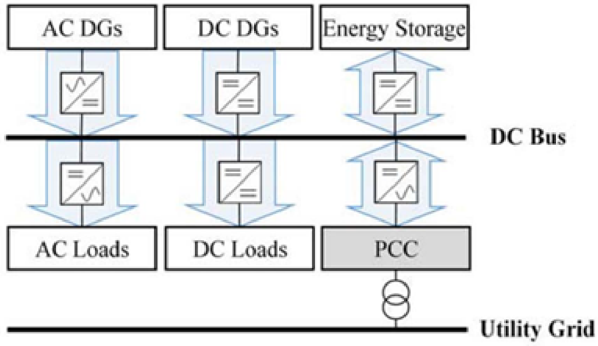

Figure 2.2: General structure of dc microgrids [12]

Hybrid microgrid development is a middle ground option since it can meet some benefits of both AC and DC systems. The fundamental goal is to create networks with the fewest possible converters, hence minimizing conversion losses. In hybrid networks, sources and loads for AC-generation are linked to the AC side of the network, while sources and loads for DC-generation are connected to the DC side. A bidirectional converter, which may function as both an inverter drive and a rectifier depending on the direction of the power flow, connects the AC and DC sides of the network.

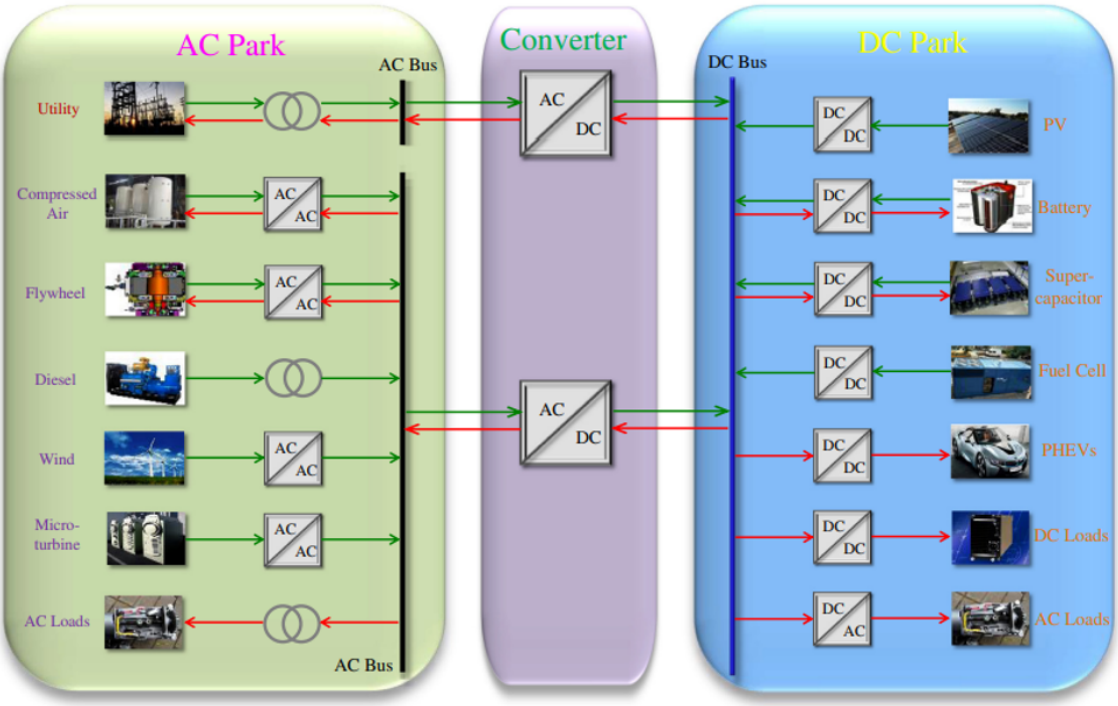

Figure 2.3: Typical system structure for a hybrid microgrid [10]

2.1.2 Modes of operation

Microgrids can operate connected to the main grid or isolated from the grid, in islanded mode.

2.1.2.1 Grid Connected

This is the normal mode of operation of a microgrid. In this mode, the microgrid is connected to the utility grid. The point of connection between the main grid and the microgrid is known as the point of common coupling (PCC) [5]. The microgrid trade power with the utility grid. If the microgrid is in power deficit, the main grid will supply it. On the other hand, if there's excess of power generated by the microgrid, this surplus can be the traded with the main grid [7]. The voltage and frequency are controlled by the main grid [6][13].

2.1.2.2 Islanded Mode

A microgrid can be islanded because of unexpected events but can also be isolated from the main grid due to planned actions, such as maintenance or by considering economic aspects [5][7][14].

In this mode, the resilience and stability of the microgrid are the main objectives.

When it's disconnected from the utility grid the microgrid operates as an independent entity, therefore, since there's no support from the grid, in islanded mode the control of the microgrid is much more complex. The utility grid no longer controls the voltage and the frequency of the microgrid [7].

In the case that the microgrid can't supply all the loads, critical loads have priority over other loads that should be curtailed [12]. There are some issues related with the operation in this mode [6][14][15][16]:

Regulation of Voltage and Frequency:

One or more MSs are needed to keep the MG voltage and frequency constant in islanded mode. Voltage and frequency are kept within reasonable bounds. Loads are shed to return the MG frequency to the nominal value if the frequency falls below the lowest allowable level.

Balance between Demand and Supply

When the MG islands itself, the MG power balance, or the balance between generation and demand, is maintained. This necessitates appropriate demand side management control measures. MG should have enough storage to smooth out any sudden mismatch between generation and load.

Power Quality

In an isolated MG a minor disruption may have an impact on frequency deviation. Real and reactive power component is important to ensure deviation in voltage and frequency values to their nominal values. Disconnection of non-critical loads is one of the action that can be taken to avoid large frequency deviations.

Communication among Microgrid Components

Another factor to take into account is the construction of communication infrastructure linking the microgrid components.

2.1.3 Transition Between Modes

To go from grid-connected to island mode and vice versa, there are some steps that have to be done for the transition to succeed.

The act of reconnecting or disconnecting must be autonomous. The MG needs to have access to sophisticated algorithms that can determine the best time to switch between operating modes [11].

The transition can be planned or can be an unexpected event. It can be non-bumpless, usually when the islanding is unexpected, or bumpless, when the transition from one mode to another is expected [3].

2.2 Control of Microgrids

2.2.1 Control Architecture

Microgrids have two different control modes based on its architecture: centralized control and decentralized control.

2.2.1.1 Centralized Control

The Microgrid Central Controller (MGCC) is the key component in optimizing a microgrid in centralized mode. It's the MGCC that decides how much power needs to be imported from the utility network based on the prices of electricity and gas, and on security information. In critical conditions it also decides how many non-critical loads should be shed [10]. Since there's a need of trading information between the MGCC and the whole MG, it needs a good communication system.

2.2.1.2 Decentralized Control

In this mode the main objective is to increase power production as much as possible to fulfill load demands and export excess electricity to the utility grid [10].

Decentralized control can simplify the optimization with particular constraints by breaking it down into smaller issues and solving them locally, which reduces the quantity of messages [8] and the need of communication.

2.2.2 Control Modes

2.2.2.1 Master-slave

The DG or ESS of the master unit will assume the V/f control function when a microgrid is operating in islanded mode to provide voltage and frequency references for other DGs and ESS within the microgrid. Other DGs are operating in PQ control mode. The master controller is the controller that uses the V/f control mechanism, while the slave controllers are the other controllers. Slave controllers behave in accordance with the master controller's decisions [10].

If the MG is working connected to the grid, all the controllers work in PQ mode. The voltage and frequency references are provided by the main grid [10].

This mode of control is usually applied for small microgrids [17].

2.2.2.2 Peer-to-peer

In a peer-to-peer control system, every DG has equal status in the control of the microgrid. The controllers are not organized in a hierarchy [4][17].

According to [17], only peer-to-peer to control can make the MGs plug-and-play.

In this mode each DG, using a droop control strategy, will be involved in regulating the voltage and frequency in the MG when the MG is in islanding mode [4].

2.2.2.3 Multi-agent control

The focus of the multi-agent technology is the control of frequency, voltage and other aspects. Multi-agent control has autonomy, responsiveness, and spontaneous behaviour. Due to these characteristics it's possible to create a system that can incorporate different types of control without managers and satisfy the demands of distributed control of micro-grids [4].

2.2.3 Control techniques

2.2.3.1 V/f control

This type of control is normally used when operating in islanded mode.

The primary goal of V/f regulation is to keep the system frequency and voltage magnitude constant. In order to keep the frequency at the specified reference value, a frequency controller modifies the active power output. To keep the voltage at the specified reference value, a voltage controller modifies the reactive power output [10].

2.2.3.2 PQ control

The objective of PQ control is to make the microsource's active and reactive power constant [6][10]. This is used when there's no need to provide voltage or frequency support [18]. Due to the inability of the PQ control approach to keep the frequency and voltage constant, an additional distributed generator is required to keep the microgrid's voltage and frequency within a tolerable range. The main power grid is responsible for maintaining the voltage and frequency of the microgrid if it runs in gridconnected mode [10].

2.2.3.3 Droop control

Active Power Control

Because the load in a microgrid is always fluctuating, the generators will adjust their power output in accordance with the frequency deviation [10].

The following equation from [10] can be used to explain how active power output and frequency are related:

$$\Delta P = P_2 - P_1 = S_p (f_1 - f_2) \tag{2.1}$$

Where:

- Power output change of the generator, ΔP
- Reciprocal of slope curve, S_p
- Frequency, f_1

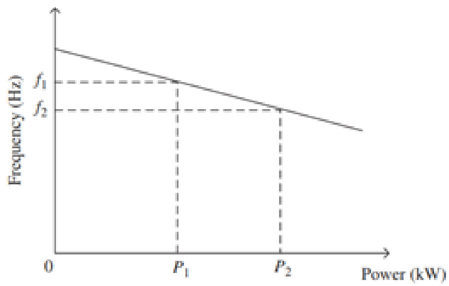

Figure 2.4: Relationship between active power output and frequency [10]

Voltage Control

The relationship between reactive power and terminal voltage is similar to the relationship between active power and frequency. The reactive power output of microsources may be changed to manage the system voltage [10].

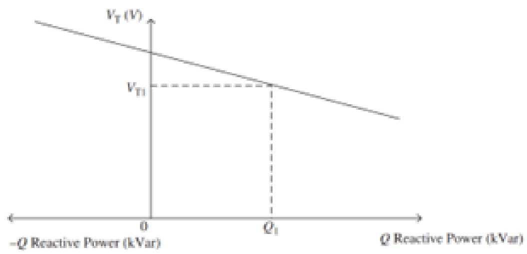

Figure 2.5: Relationship between reactive power output and voltage [10]

2.3 Load shedding in islanded microgrids

The generated power from DG in islanded mode is limited and frequently insufficient to fulfill load demand. Additionally, since renewable energy sources (RES) are intermittent, the quality of the power they provide is uncertain. For this reason, load shedding techniques are frequently used to manage the system in islanded mode. To avoid a total outage, non-critical loads are progressively reduced while the crucial loads are constantly provided [19].

Load shedding consists in the curtailment of loads of a microgrid. This curtailment can be done with several objectives such as control of the microgrid, economic reasons or to increase resiliency. When using load shedding, to achieve successful operation of the microgrid in islanded mode, the management of loads to shed and the state of charge of storage devices are essential [20].

The main principle of load shedding approaches is to identify under-frequency or low voltage in an island microgrid that is brought on by an imbalance between power generation and consumption, and then to plan a load shedding [19].

There are three fundamentals in the process of load shedding [16]:

- Determining when to shed load
- Determining where to shed load
- Determining how much load so shed.

Loads must be classified according to their criticality. The first loads to be shed are the least critical.

The generated electricity from DG in islanded mode is limited and frequently insufficient to fulfill load demand. When the imbalance between power generation and consumption occurs it can cause under-frequency or low-voltage in the microgrid [19].

In [16] and [19] the following characteristics have to be included in a load shedding technique:

- Quick load shedding is necessary to avoid a power system blackout caused by low voltage or under-frequency that would affect the whole island microgrid.
- The load shedding plan needs to be reliable and redundant since if it fails, the entire system will lose electricity.
- The amount of load that needs to be shed should be as little as is required to keep the system stable.

According to [21], load shedding techniques can be categorized in four different groups: conventional, semi-adaptive, adaptive, and computational intelligent.

2.3.1 Traditional Load Shedding

Traditional load shedding is widely utilized by utilities since it is the simplest approach and does not need the use of sophisticated relays. When the system frequency goes below a specified edge, it sheds a specific amount of load. If the first shed is insufficient and the frequency continues to fall to lower limits, more loads need to be shed until the overload is mitigated [16]. Traditional techniques are classified into two types: under frequency load shedding (UFLS) and under voltage load shedding (UVLS).

2.3.1.1 Under Frequency Load Shedding (UFLS)

The UFLS's goal is to detect insufficient generation in any system quickly and automatically shed the least amount of load possible until nominal frequency is restored. Frequency threshold, the amount of load to be shed, and intentional time delays are a few crucial factors that must be considered when developing UFLS approach. UFLS setup frequently uses the frequency deviations (Δf) as parameters. However, the UFLS scheme based on Δf does not have great adaptability since it can't identify the variety of generation losses and the rate of frequency decay. If there is an internal voltage collapse on the island, the UFLS system is ineffective [16].

2.3.1.2 Under Voltage Load Shedding (UVLS)

Electric utilities may effectively address the problems with voltage firmness by using UVLS. Voltage instability is responsible for the majority of power outages in the world. One of the main causes of voltage instability is overloading [16].

The UVLS's goal is to use load shedding to return the voltage to its normal level.

The traditional approach, which includes a moderately longer time delay and a lower frequency threshold, is effective at preventing unintentional load shedding in response to minor disruptions, but it is unable to tell the difference between normal oscillations and the extreme instability of the power system. As a result, during significant disruptions, it has a tendency to shed less significant loads [16].

This strategy's main problem is that it fails to precisely measure the amount of the power imbalance. This situation will either cause over-shedding, which would compromise power quality, or under-shedding, which would cause a trip in the energy supply [16].

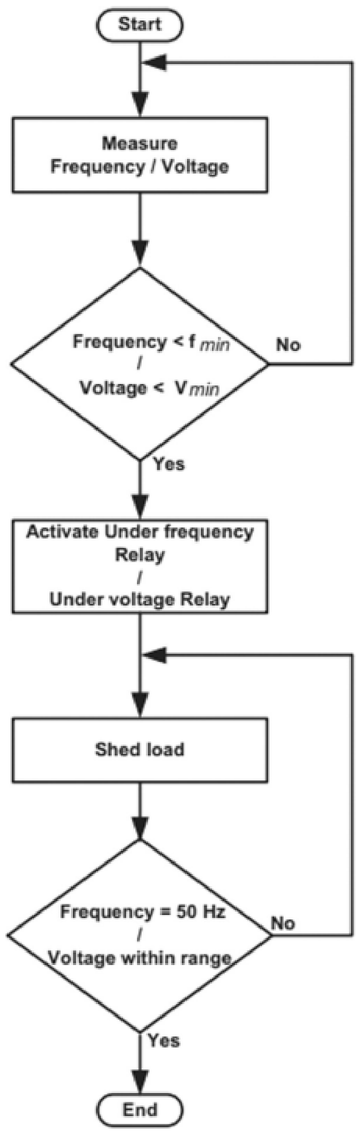

Figure 2.6: Flow chart of traditional UFLS and UVLS techniques [16]

2.3.2 Semi-Adaptive Load Shedding

When there is a lack of generation, a semi-adaptive load shedding strategy uses the frequency decline rate (df/dt) as a measure [16].

The starting point for this technique is the rate of change of frequency (ROCOF) when the system frequency reaches a certain threshold. When (df/dt) is low, the quantity of load shedding is similarly lesser and when (df/dt) is substantial, more load is shed [16].

2.3.3 Adaptive Load Shedding

The adaptive load shedding method is seen as the more sophisticated version of the traditional load shedding plan [21].

The load to be shed is typically accurately determined using an adaptive technique [16].

The sole drawback of this plan is that it cannot carry out the best load shedding because of variation and frequency behavior [21].

2.3.4 Resilience oriented load shedding

In [22] a methodology to maximize the time of energy supply to high priority loads during the power outage as much time as possible.

To accomplish this goal, the proposed energy management requires some control variables to manage demand response actions. The variables of control are the following:

- **ESS's State of Charge:**

  This is the energy available in batteries. It's an important variable since it will influence the microgrid's autonomy in island mode. In the study, the variable that represents the ESS's State of Charge assumes a value according to the percentage of available battery.

- **Renewable-Based Power:**

  It provides details about the primary renewable resources that may be used to produce electricity.

- **Renewable Power Penetration:**

  It's the rate of the loads supplied by renewable energy. It is significant because it demonstrates how much load can be delivered by a less expensive power source.

- **Hour:**

  Since the peak load is greater than the demand at other times, the hour of the day is a significant factor.

- **Load:**

  The system load is the final variable taken into account by the EMS.

  The current load is compared with the mean load of a typical daily demand curve. The control variable assumes a value according to this comparison.

In the study, loads are classified into three different groups according to their priority.

With the five control variables described, it's possible to define 48 operational states that are divided into three different operation modes: emergency, critical and survival. Each of the operation mode has different load shedding actions associated.

3

Methodology

This chapter is intended to explain, discuss and detail how, where and when the work experiences were developed and conducted, how data was gathered, which hardware and software were used.

3.1 The Existent Grid

The development of the project was carried out in the DEEC garage. The existing electrical panel served as a starting point for the pilot that was developed.

The electrical panel is made up of two single-phase plug circuits, two three-phase plug circuits, eleven lighting circuits, controls for lighting, control for the garage door, ventilation system and an energy storage system that includes three batteries and three DC/AC inverters.

In [23] the energy storage system installed in the garage is described. The system is composed with three lithium-ion batteries LG RESU10H [24] that ensure a total storage capacity of about 30 kWh and by three DC/AC inverters [25] with a total power of 15 kW.

Figure 3.1: Energy Storage System [23]

The batteries are being used with economic objectives. The batteries are charged from the grid during off-peak period (2h00 to 6h00), when the energy is cheaper, and are discharged on the morning peak periods (9h15 to 12h15). This way the batteries perform one cycle per day.

The lighting circuit is composed by 66 lamps. The circuit is divided in 11 circuit breakers. There are 4 control commands that control 7 of the circuit breakers.

Each lamp as a consume of 42W, which makes a total consume of 2,772 kW.

The two single-phase plug consume a maximum of 3,68 kW each, making a total of 7,36 kW.

3.2 The Microgrid

In order to build the desired microgrid, several changes had to be made. In the next section a description of the software and hardware that was used on the project is made.

3.2.1 Energy Monitors

Energy monitors are crucial for data acquisition. The information gathered by them will be sent to the automaton, where it will be processed and used for making decisions.

Taking into account the characteristics of the existing grid and the data we need for the proper functioning of the microgrid, two types of energy monitors were acquired:

3.2.1.1 Carlo Gavazzi EM111DINAV81XS1PFA

The EM111DINAV81XS1PFA [26] is a single-phase energy analyzer with LCD display and touch keypad integrated. It is indicated for active energy metering.

The communication is made through the RS485 serial port, using the Modbus RTU (slave function) protocol.

3.2.1.2 Carlo Gavazzi EM330DINAV53HS1X

The EM330DINAV53HS1X [27] is a three-phase energy meter with LCD display and touch keypad integrated. It is indicated for active energy metering.

The communication is made through the RS485 serial port, using the Modbus RTU (slave function) protocol.

3.2.2 Contactors

It will be used single-phase contactors and three-phase contactors. The contactors are extremely important for the load shedding since they are the ones who turn the circuits on or off depending on the automaton output.

3.2.3 Logical Controller

The logical controller used is the Modicon M241 24 ES Relé Ethernet [28]. This logical controller has 10 discrete outputs and 14 discrete inputs. It is important to highlight the ethernet port that allows communication through the Modbus protocol.

Figure 3.2: Modicon M241 ES Relé Ethernet

3.3 PV System

The PV system used does not have energy injection into the grid. Its estimated annual production is 5097 kWh. The system is composed by:

- - 6x 480w polycrystalline panels;
- 1x Victron SmartSolar MPPT 150/35 Charge Regulator;
- 1x Victron MultiPlus II 3000VA Inverter/Charger;
- 1x Victron Cerbo Gx;
- 1x Pylontech US3000 Battery 10.5 kWh.

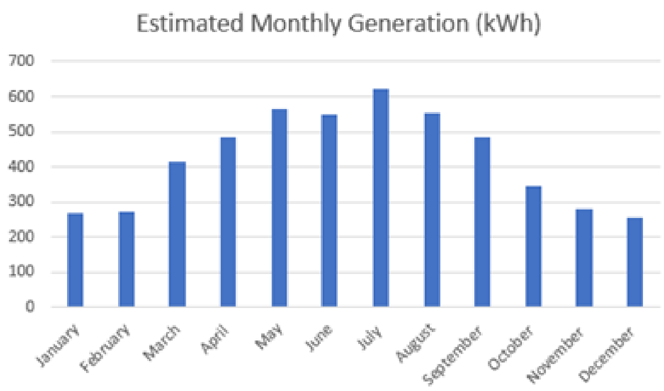

Figure 3.3: PV Estimated Monthly Generation

All the information concerning the photovoltaic system (batteries, generation and inverter) is gathered in Cerbo Gx that will communicate with the automaton. The photovoltaic inverter is responsible for maintaining the microgrid frequency at 50Hz.

3.4 Main Programming languages for the automaton

EcoStruxure Machine Expert is the software for configuring and programming the logic controller. This software supports the following IEC 61131-3 programming languages [29]:

- IL: Instruction List

  It's an assembler-like programming language. An instruction list consists of a series of instructions.

- ST: Structured Text

  Structured Text is a textual high-leves programming language, similar to Pascal or C. The program code is composed of expressions and instructions. In contrast to IL, numerous constructions for programming loops can be used, making this language appropriate for the development of complex algorithms.

- FBD: Function Block Diagram

  It's a graphically oriented programming language. FBD works with a list of networks. Each network contains a graphical structure of boxes and connection lines which represents either a logical or arithmetic expression, the call of a function block, a jump or a return instruction.

- SFC: Sequential Function Chart

  SFC is another graphically oriented language. It describes the chronological order of particular actions within a program. These actions are available as separate programming objects that can be programmed in any available programming language.

- LD: Ladder Diagram

  It's a graphic-oriented programming language. It's suitable for constructing logical switches and also allows to create networks as in FBD.

- CFC: Continuous Function Chart

  It's a graphical programming language based on the FBD language. However, in contrast to the FBD language, there are no networks. CFC allows the free positioning of graphic elements.

The programming language chosen to perform the automaton programming was structured text.

4

Developed Work and Results

4.1 Changes to the local grid

To have the designed microgrid it is necessary to make changes to the existing grid in the garage. These changes are described below.

4.1.1 Changes to the DEEC Garage Electrical Panel:

All contactors mentioned must be connected to the Modicon M241 outputs. Contactor n must be connected to output n – see figure 4.1.

- Install a general circuit breaker for testing the microgrid (63 or 80 A). Necessary if there is no possibility of turning off the power of this board in the general board of the DEEC. When the microgrid is active, disconnecting the supply from the garage board at the general switchboard does not turn off the garage switchboard, which is powered by the resilient microgrid inverters. To turn off the main board it will be necessary to disconnect switch on the garage board to ensure that there is no injection of electrical energy into the garage.
- Install a three-phase energy monitor with CTs (EM330DINAV53HS1X) at the input of the garage electrical panel, upstream of contactor 1 (4x80A contactor LC1DT80AP7) and downstream of the test cut-off circuit breaker if there's one.
- Install a 4x40A modular contactor that will serve to "shunt" (short-circuit) the three phases, feeding them with the PV system inverter. It should serve as a connection point between the PV system inverter and the bus. This injection point must be upstream of the main circuit breaker and downstream of the contactor 1. Install 40 A circuit breakers or fuses (in the cable between the contactor and the busbar) for short-circuit protection.
- Install two 2x20A modular contactors on the two socket circuits (plug circuit 1 plug circuit 2).
- Install two single-phase energy monitors (EM111DINAV81XS1PFA) between the contactors of the plugs circuits and their circuit breakers.
- Change the command connection of contactors 4 to 8, which are connected to lighting circuits 1 (circuit breakers L3 and L4), 2 (circuit breakers L9), 3 (circuit breakers L5 and L7)

and 4 (circuit breakers L6 and L8), so that they are connected to the Modicon M241 outputs of the resilient network. These contactors already exist in the current framework, but they must be controlled by the new automaton of the resilient network.- -Install one 2x20 A modular contactor in the “ISR lighting” circuit. The contactor must act on the two “ISR lighting” circuit breakers.

- Install a 4x40 A modular contactor that must be connected in order to cut all three-phase loads (three-phase sockets, ventilation, V2G). The existing three-phase ventilation contactor must remain controlled by the building’s general automation and downstream of the 4x40 A three-phase contactor to be installed.
- It is necessary to have the possibility to put the automaton of the resilient network out of service, keeping the board operating normally. Need to install command(s) for automaton or manual mode (MA) or relays to achieve the same effect. The objective is to use the automaton outputs only for tests, keeping the network functional in the periods when it is not necessary to carry out tests. In manual mode, the “shunt” contactor (short circuit of the three phases) must be always open. There will be a switch connected to several relays to permute between manual mode or automaton mode (one relay for each automaton output).

4.2 Architecture

The developed architecture is shown in figure 4.1. This solution was chosen for several reasons.

First, because there are no critical or important three-phase loads. Secondly, because there is no three-phase inverter, nor is it expected to acquire one in the near future. Finally, since all the single-phase loads of the three phases of the switchgear are connected to each other, a greater combination of loads to be switched on and off is possible.

With the buses of the three phases connected to each other, it will allow individual control of the circuits to be turned on and off to control in a more precise way the power that is being consumed according to the available power, connecting and disconnecting circuits through the contactors. It is important to point out that any three-phase circuits must be switched off when the power fails.

The alternative would be to place all critical loads on a single phase of the electrical panel, which would be connected to the PV inverter, leaving all other loads that were not connected in this phase off.

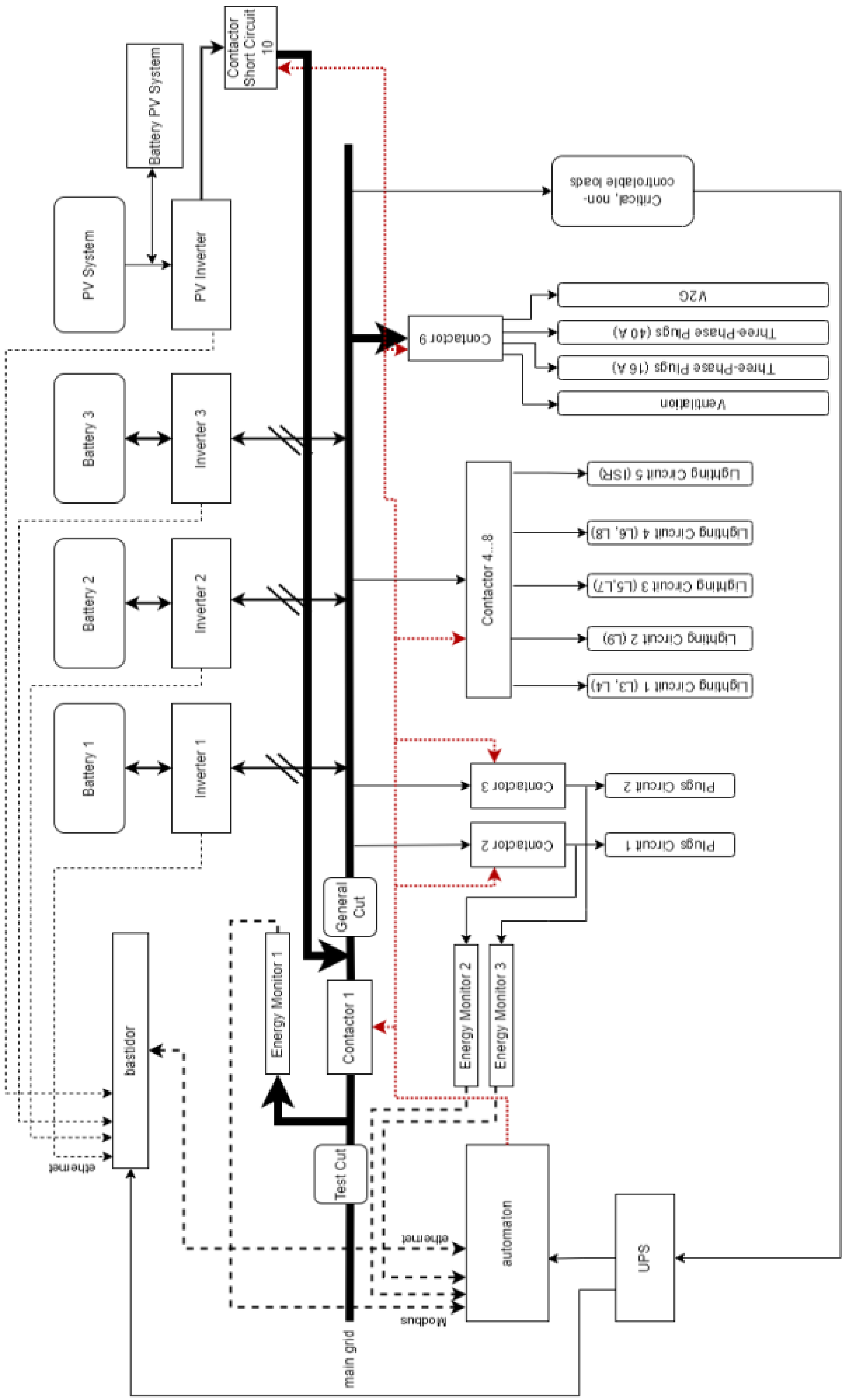

Figure 4.1: Microgrid Architecture

Contactors 1 and 10 can never be switched on at the same time. Whenever the transition from on-grid to islanded or islanded to on-grid is made, it is necessary to ensure that one contactor is off before turning on the other.

It should be noted that for simulation purposes, the three batteries and inverters that already existed in the grid will not be considered. This is because, in a first phase, the microgrid will only work with the photovoltaic system. Furthermore, from the point of view of testing resilience, adding more batteries would not be relevant as it would only result in more power injection.

4.3 Load Classification

In this section, a survey of the single-phase loads of the microgrid is made. Loads are organized by priority levels. Lower priority are the first to being curtailed, while the ones with higher priority are the last to be shed.

Single-phase loads

Load classification is only made for single-phase loads since that it's the loads that we are going to control when the microgrid works in isolated mode. Three-phase loads will be cut off when the transition from on-grid to islanded is made.

	Power	Contactor
Plug Circuit 1	0 – 3680 W	2
Plug Circuit 2	0 – 3680 W	3
Lighting Circuit L1	294 W	–
Lighting Circuit L2	210 W	–
Lighting Circuit L3	294 W	4
Lighting Circuit L4	252 W	4
Lighting Circuit L5	294 W	6
Lighting Circuit L6	252 W	7
Lighting Circuit L7	294 W	6
Lighting Circuit L8	168 W	7
Lighting Circuit L9	252 W	5
Lighting Circuit ISR 1	378 W	8
Lighting Circuit ISR 2	94 W	8
Garage Gate	100 W	–
Automaton	10/20 W	–
Bastidor	250 W	–
UPS	$<$ 100 W	–

Table 4.1: Single-phase loads

The lighting circuits L1 and L2, the garage gate, the automaton, the bastidor and the UPS are the most critical loads and will always be supplied while the microgrid has power. The contactors 1 and 10 are not mentioned in this table because they are used for the transition of the microgrid. They are not used for load shedding. Contactor 9 is also out of the table because it's used to cut off the three-phased loads.

Each plug circuit has a contactor associated, while some lighting circuits are grouped in groups of two.

Organize loads by priority

To know what loads should be shed, loads must be organized by level of criticality. To define the priority of each load, the power of each load was taken into account, as well as its relevance to users.

To better understand the criteria for choosing priorities, it is advisable to visualize table 4.2. In this table, the squares correspond to the lighting circuits while the circles correspond to the plugs circuits.

Priority	Contactor	Power
1	5	252 W
2	4	546 W
3	7	420 W
4	2	0 – 3680 W
5	6	588 W
6	8	472 W
7	3	0 – 3680 W

Table 4.2: Circuit Priority

The first load that should be shed are the loads associated to the contactor 5. The exterior illumination is not important for people using the garage.

Next, the objective was for all the corridors to have some lighting, with some being cut off. Considering the lighting arrangement, it was decided to turn off the lighting circuits L3 and L4, followed by circuits L6 and L8.

Having two plug circuits in the garage it was decided that one should have priority over the other. Plug circuit 2 has an isolation chamber connected, so this circuit is crucial. The next step is to shed the plug circuit 1, since it can have a great impact in the microgrid resiliency considering its power consumption.

At this point we have two lighting circuits and a plug circuit to control.

The next loads to be shed are the ones in contactor 6, since the ISR lighting circuit has greater importance from the user point of view.

Contactor 8 is the next on the list, leaving the garage only with the critical lighting supplied.

The last contactor to be shed is the contactor 3 since the plug circuit 2 is the most important thing in the garage from the user point of view.

4.4 Operation Modes

This section defines the operating modes of the microgrid and what define each mode. There are five main operation modes:

On-Grid Operation

In this mode the microgrid is supplied by the main grid. All loads are supplied. The microgrid will work in this mode until a power outage occurs.

Islanded mode operation

In this mode the microgrid is supplied by the PV system. Only single phase loads are supplied. In this mode there's a power supply limitation. Only 80% of the inverter capacity will be used, so the microgrid has a load limit of 2400 W.

This mode of operation is divided in three different modes.

Since many power outages are very small, the first mode has the objective to supply as many loads as possible during the first minute of the power outage.

In the second mode, loads are managed so that the microgrid survives the failure for at least one hour.

In the third mode, only the critical non-controllable loads are supplied. This is done until the power from the main grid comes back or until it's impossible to supply the critical non-controllable loads.

Stand-by Mode

In this mode the microgrid is disconnected from the main grid and from the PV system. The microgrid enters this mode if there's no power from the main grid and if the batteries from the PV system are discharged.

Transition from On-Grid to Islanded mode

It transitions from on-grid to islanded mode operation. It's a mode that assures that the microgrid disconnects from the main grid and that connects the microgrid to the PV systems when all conditions are assured.

Transition from Islanded Mode to On-Grid

Like the previous mode, it's a transition mode. It transitions from islanded mode to on-grid operation. It's a mode that assures that the microgrid disconnects from the PV system and that connects the microgrid to the main grid when all conditions are assured.

4.4.1 Quantities that define the operation mode

To control the microgrid it is necessary to have some control variables. The variables needed to control this microgrid are as follows.

State of Charge (SOC) of the Energy Storage System

It's the percentage of energy available in batteries for use. It's one of the most important variables to define the operating state of the microgrid.

PV Generation

The level of energy produced by the PV it's important because it directly influences the power that can be supplied to the microgrid.

Time since blackout

It's the time that has passed since the power outage occurred. It's important because the microgrid should work in different modes according to this time.

4.4.2 Control Variables

Considering the mentioned variables, we can now define the control variables that will define the state of the grid.

PO_{VAR}

This variable changes its value according to the values measured from the Energy Monitor 1. It can assume two values (0 and 1) according to these measures.

$$PO_{VAR} = \begin{cases} 0, \text{ if } PO = \text{ false} \\ 1, \text{ if } PO = \text{ true} \end{cases} \tag{4.1}$$

SOC_{VAR} This control variable changes its value according to the energy available in the batteries of the PV system.

$$SOC_{VAR} = \begin{cases} 0, \text{ if } SoC > 20\% \\ 1, \text{ if SoC } \leq 20\% \end{cases} \tag{4.2}$$

T_{VAR} This is the control variable associated to the time that has passed since the power outage.

$$T_{VAR} = \begin{cases} 0, \text{ if } t < 1 \text{ min} \\ 1, \text{ if } 1 \leq t < 60 \text{ min} \\ 2, \text{ if } t \geq 60 \text{ min} \end{cases} \tag{4.3}$$

$PMAX_{VAR}$ This variable is associated to the maximum power that can be supplied for the microgrid last at least one hour since the power outage.

$$PMAX_{VAR} = \begin{cases} 0, \text{ if } P_{Max} < 974W \\ 1, \text{if } 974 \leq P_{Max} < 2400W \\ 2, \text{ if } P_{Max} \geq 2400W \end{cases} \tag{4.4}$$

$$P_{\text{Max}} = PV + \frac{E}{(1-\tau)} \tag{4.5}$$

$$E = (SOC[\%] - 20[\%]) * 10500\text{Wh} \tag{4.6}$$

Where:

- PV = Generated power from PV (W)
- E = Energy available from the battery (Wh)
- τ= Time that has passed since power outage (h)
- 974 W corresponds to the power of the non-controllable critical charges.
- 2400 W is 80% of the power of the inverter.

4.5 Programming

In this section the PLC program, which is based on state machine, is explained. States of the program are defined as well as the transitions between stages.

4.5.1 Program operation

The program has two tasks running simultaneously.

The first task, where the states are defined as well as the actions to be carried out in each state, runs in freewheel. This means that it doesn't have a predefined time to run the task. It's always running. As soon as it ends, it starts again.

The second task, where the variables that define the state are updated is a cyclic task. It has priority over the freewheel task. When this task is called, the freewheel task waits for this task to end and proceeds its actions after this task has concluded.

4.5.2 Fundamentals of load shedding

4.5.2.1 When to shed load

It is necessary to shed loads whenever the load demand is greater than the power supply or whenever a circuit exceeds the maximum defined for it.

4.5.2.2 Determining where to shed load

The load shedding is done in order of priority of the loads. Lower priority loads are the first to be shut down.

4.5.2.3 Determining how much load so shed

The amount of load to be disconnected must be sufficient for the load demand to be lower than the value available for supply.

4.5.3 States of the program

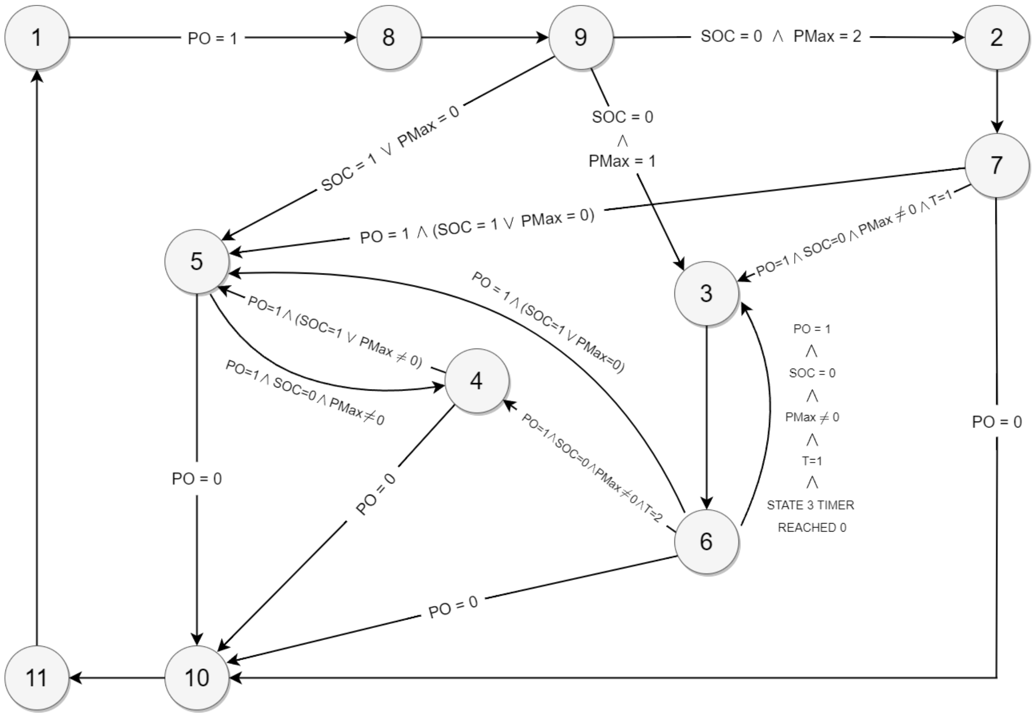

Figure 4.2: State Machine Diagram

State 5 – Stand-by mode:

The program starts in state 5, where the microgrid is not connected to the main grid or the PV system. In this state all contactors are off, i.e., open. In this state, the check is made if there is energy in the main network. If there is power, the program advances to state 10. If there is no power, the battery status and the maximum power to be supplied to the loads are checked. If the percentage of batteries is greater than 20% and the value of the maximum power that can be supplied to the loads is greater than 974 W, the program advances to state 4. If none of these conditions are met, the program remains in state 5 until that any of the conditions change.

State 10 – Transition from Islanded Mode to On-Grid (Phase 1):

If we enter state 10, it means that there is power on the main grid and that we were disconnected from the main grid. State 10 is the first of two states that makes the transition from island mode to grid connected mode.

In this state all contactors are set to off and a timer is set. This timer serves as a protection to ensure that contactor 1 is not turned on until contactor 10 is turned off. The timer must have not less than the contactor response time. After these actions are made it advances to state 11.

State 11 – Transition from Islanded Mode to On-Grid (Phase 2):

State 11 is the second of two states that makes the transition from island mode to grid connected mode.

In this state the program checks if the timer that was set in state 10 has reached 0. If the timer is equal to zero, then contactor 1 is set to on and the state moves to 1. If the timer has not reached zero, it remains in this state until timer equals zero.

State 1 – On-grid operation mode:

In this state we are in grid connected mode. Contactor 10 is off and Contactor 1 is on. All other contactors are set to on. The microgrid works connected to the main grid and all charges are supplied by it.

If a power outage is detected, we advance to state 8. If there's no power outage the consume values are stored in variables to be used in case of a power outage.

State 8 – Transition from on-grid mode to island mode (Phase 1):

If we enter state 8, it means that there is a power outage on the main grid and we want to switch to islanded mode. State 8 is the first of two states that makes the transition from grid connected mode to islanded mode.

In this state all contactors are set to off and a timer is set. This timer serves as a protection to ensure that contactor 10 is not turned on until contactor 1 is turned off. The timer must have not less than the contactor response time.

After these actions are made it advances to state 9.

State 9 – Transition from on-grid mode to island mode (Phase 2) :

State 9 is the second of two states that makes the transition from grid connected mode to island mode.

In this state the program checks if the timer that was set in state 8 has reached 0. If the timer is equal to zero, then contactor 10 is set to on. At this point there are three possibilities:

- it advances to state 2 if battery has more than 20% available storage if the time since the power outage is less than 1 minute and if maximum power that can be supplied is greater or equal to 2400 W (80% of inverter capacity).

- it advances to state 3 if the battery percentage is more than 20% but the maximum power that can be supplied is more than 974 W but less than 2400 W.
- it advances to state 5 if the battery percentage is less than 20% or if the maximum power that can be supplied is less than 974 W.

If the timer has not reached zero, it remains in this state until timer equals zero.

State 2 – Supply maximum possible charges for one minute (Phase 1):

Transition from on-grid to islanded mode has been made. In this state, it turns on the maximum charges that can be supplied. The charges should be supplied for until 1 minute since power failure.

Contactors 4, 5 and 7 must be turned off because of the inverter capacity and will be kept this way in islanded operation. These are the circuits that have fewer priority.

The other contactors are turned on according to their priority and the available power. To know if we should turn on the Contactor 3, we must go to the information that was stored when the grid was on. If the value that is stored is greater than 1426 W, we can't turn on Contactor 3.

After these actions are made, it updates the consume stored values and goes automatically to State 7.

State 7 – Supply maximum possible charges for one minute (Phase 2):

In this state the program checks some conditions to evaluate if it should change state or remain in the same state. It will do this procedure while the time since the failure is less than 1 minute.

During this time, if additional loads are connected to the plug circuits, it turns off that circuit.

If the power is back on the main grid, then it proceeds to State 10.

If the energy available in batteries is less than 20% or if the maximum power that can be supplied is less than 974 W, state changes to State 5.

If the previous conditions are not met, and if more than 1 minute has passed since the power outage, the next state is State 3.

State 3 – Load management so that the microgrid works for at least one hour (Phase 1):

In State 3 the power that is being consumed is calculated and it's compared with the value from the maximum power that can be supplied for the microgrid to last at least 1 hour since the power failure.

If the power consumed is greater than the available power, then some loads need to be shed. This shedding is done by level of priority, and it will be done until the power consumed is less than the power available.

If the power consumed is less than the available power, then the program check if there are loads that can be supplied without exceeding the available power. If there are, they will be switched on according to their priority.

After this is done, a timer is set to this evaluation again.

Next state is State 6.

State 6 – Load management so that the microgrid works for at least one hour (Phase 2):

During this state, a check is made that the power in the plug circuits does not exceed the maximum allowed.

If the power in the main grid is back, state is changed to State 10.

If the energy available in batteries is less than 20% or if the maximum power that can be supplied is less than 974 W, state changes to State 5.

If more than 60 minutes has passed since the power outage and the maximum power that can be supplied is more than 974 W, than next state is State 4.

These conditions will be checked until the timer that was set in state 3 reaches zero or until one of the conditions is met. If the timer reaches zero and none of the conditions are met, then next state is state 3.

State 4 – Supply only critical non-controllable charges:

The microgrid should stay in this state for indefinitely, until the power in the main grid is back or until the batteries reach values lower than 20% or if there's no capacity to In this state all contactors, except for contactor 10, are turned off. Only non-controllable critical loads are being supplied.

If the power in the main grid is back, state is changed to State 10.

If the energy available in batteries is less than 20% or if the maximum power that can be supplied is less than 974 W, state changes to State 5.

The figure 4.3 shows the program flowchart where all those states are presented.

4.5.3.1 Transition Between States

The transition between states is explained in the following table. The first column corresponds to the current state, while the first row represents the next state.

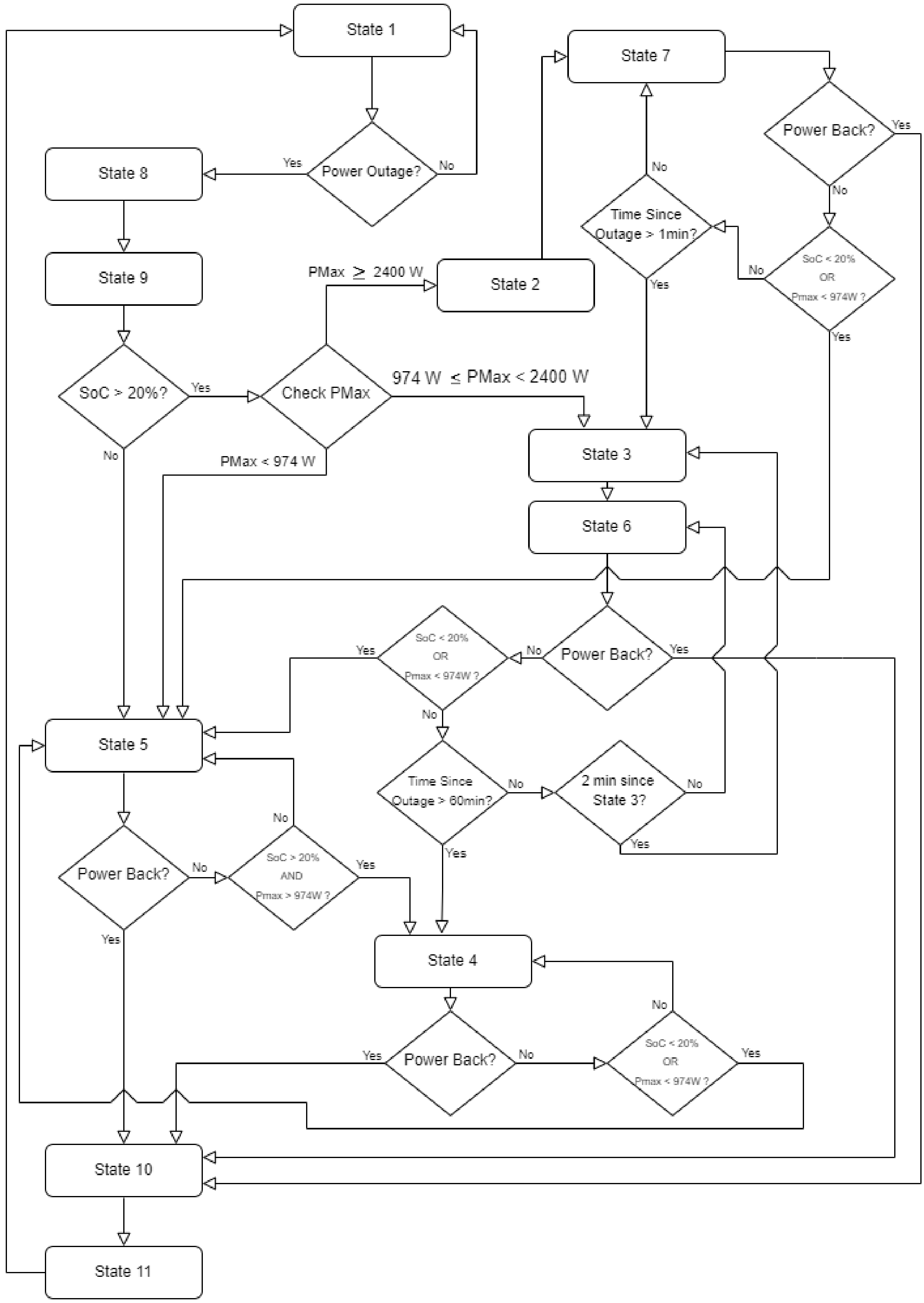

Figure 4.3: Program flowchart

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
S1	---	---	---	---	---	---	---	PO = 1	---	---	---
S2	---	---	---	---	---	---	A	---	---	---	---
S3	---	---	---	---	---	A	---	---	---	---	---
S4	---	---	---	---	PO = 1 ∧ (SOC = 1 ∨ PMax = 0)	---	---	---	---	PO = 0	---
S5	---	---	---	PO = 1 ∧ SOC = 0 ∧ PMax ≠ 0	---	---	---	---	---	PO = 0	---
S6	---	---	PO = 1 ∧ SOC = 0 ∧ PMax ≠ 0 ∧ T = 1 ∧ (State3 timer reached 0)	PO = 1 ∧ SOC = 0 ∧ PMax ≠ 0 ∧ T = 2	PO = 1 ∧ (SOC=1 ∨ PMax=0)	---	---	---	---	PO = 0	---
S7	---	---	PO = 1 ∧ SOC = 0 ∧ PMax ≠ 0 ∧ T = 1	---	PO=1 ∧ (SOC=1∨PMax=0)	---	---	---	---	PO = 0	---
S8	---	---	---	---	---	---	---	---	A	---	---
S9	---	SOC = 0 ∧ PMax = 2	SOC = 0 ∧ PMax = 1	---	SOC = 1 ∨ PMax = 0	---	---	---	---	---	---
S10	---	---	---	---	---	---	---	---	---	---	A
S11	A	---	---	---	---	---	---	---	---	---	---

A - Always

Figure 4.4: State Transition Table

4.5.4 Inputs and Outputs

4.5.4.1 Inputs

The program inputs are measurements from the three-phase energy monitor, single-phase energy monitors, battery percentage information and PV generation information. The voltage values of each phase are received from the three-phase energy monitor. The power information of the circuits is received from the single-phase energy monitors.

4.5.4.2 Outputs

The program outputs correspond to contactors 1 to 10. All outputs are digital (0/1).

4.5.5 Functions of the program

4.5.5.1 Functions to calculate the value of control variables

As mentioned before, there is a task that updates the values of the control variables and the value of P_{MAX}. This task calls five functions that will be described next.

$CALC_{PMAX}$

This function calculates de maximum power that can be supplied so that the microgrid lasts at least one hour since the power outage.

With the values of the battery percentage, the PV generation and the time that has passed since the power outage, it calculates the value of (inserir ligação para a equação do cálculo de $PMAX$).

$PMAX_{VAR}$

This function compares the value that is calculated in $PMAX_{VAR}$ with the values of the non-controllable critical charges and with the maximum power capacity of the PV inverter. If the value of is lower than the value of the non-controllable critical loads, then $PMAX_{VAR}$ is set to 0.

If the value of is greater than or equal to the value of non-controllable critical loads and is less than the value of the maximum power capacity of the inverter, $PMAX_{VAR}$ assumes the value 1.

If the value of is greater than or equal to the value of the maximum power capacity of the inverter, $PMAX_{VAR}$ is set to 2.

PO_{VAR}

It is the variable that indicates whether there is a power outage or not. If any of the phase voltage values is lower than the minimum operating value, the PO_{VAR} variable is set to 1.

SOC_{VAR} In this function the battery percentage of the PV system is compared with the minimum value allowed for the batteries to be connected.

If the battery percentage is higher than that value, SOC_{VAR} is set to 0. If it's lower, SOC_{VAR} is equal to 1.

T_{VAR}

In this function, a comparison is made between the current time and the time when the power failure occurred. If the elapsed time is less than 1 minute, T_{VAR} is equal to 0. If the elapsed time is greater than or equal to 1 minute and less than 1 hour, T_{VAR} is equal to 1. If the elapsed time is greater or equal to 1hour, T_{VAR} is equal to 2.

$POWERCONSUME$

This function is used to know how many power is being consumed. $POWERCONSUME$ initiates with the value of the non-controllable critical loads and then, checks if the contactor 2-8 are on. If they are on, $POWERCONSUME$ adds the power value of that contactor.

$ACTUALIZA - EM2 - EM3$

When this function is called, the values from the energy monitors 2 and 3 are stored in the variables C2.VALUE and C3.VALUE.

4.6 Simulation Environment

To test the developed program, it was necessary to create a simulation environment. The developed simulation environment was created using the software Ecostruxure Machine Expert. On the left, the values that must be read by the automaton are simulated. During the program it is possible to change these values. In the center, the lamps represent the automaton's outputs. When the output is on, the lamp lights up. Finally, on the right, the values assumed by the variables are shown.

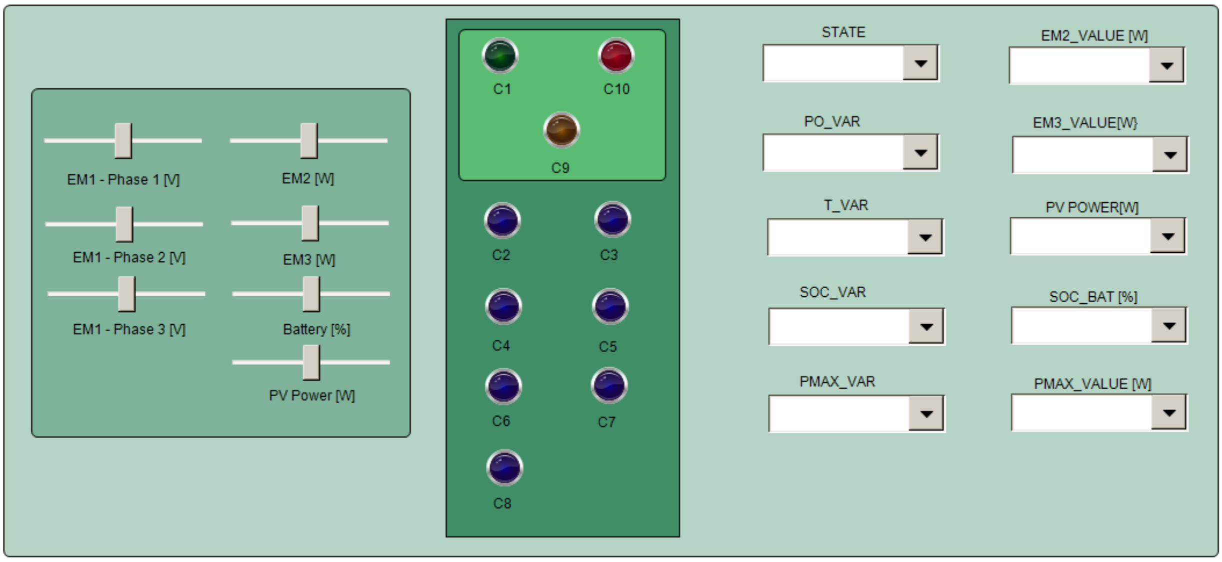

Figure 4.5: Simulation Environment

At the same time, a record of all values is being made which will be used to show the simulation results.

4.7 System Validation and Results

In this section, several scenarios will be simulated to verify the good functioning of the developed program.

4.7.1 Scenario 0: control variables changing according to the measured values

4.7.1.1 Case 1: Battery level falls bellow 20%

In this case, it is possible to observe that, with the decrease of the battery, the $PMAX$ value also decreases. It is possible to observe the moment when $PMAX_{VALUE}$ is lower than 2400 W, with a change in $PMAX$ from 2 to 1 and when the battery goes to values lower than 20%, SOC becomes 1.

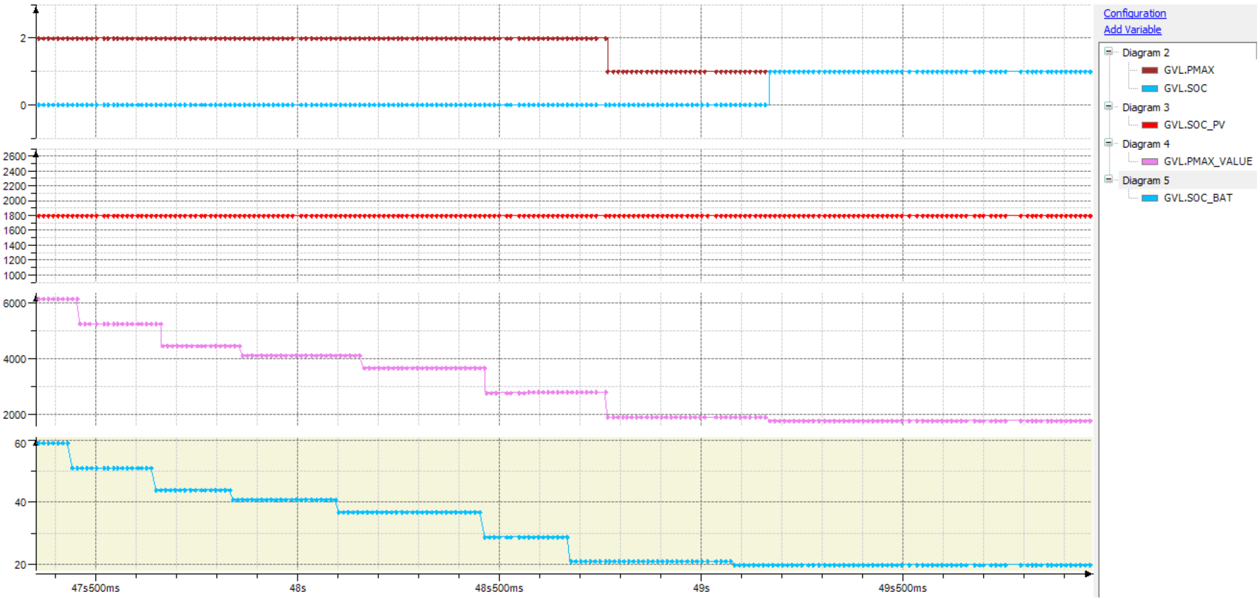

Figure 4.6: Simulation of Scenario 0 Case 1

4.7.1.2 Case 2: Changes in PV generation values

In this case the battery remained constant. It is possible to observe that when the values of the photovoltaic generation (SOC_{PV}) are changed, there are changes in the values of the maximum power that can be supplied ($PMAX_{VALUE}$) and also in the control variable $PMAX$, assuming the value 1 when $PMAX_{VALUE}$ is less than 2400 W and returning to value 2 when it exceeds 2400 W again.

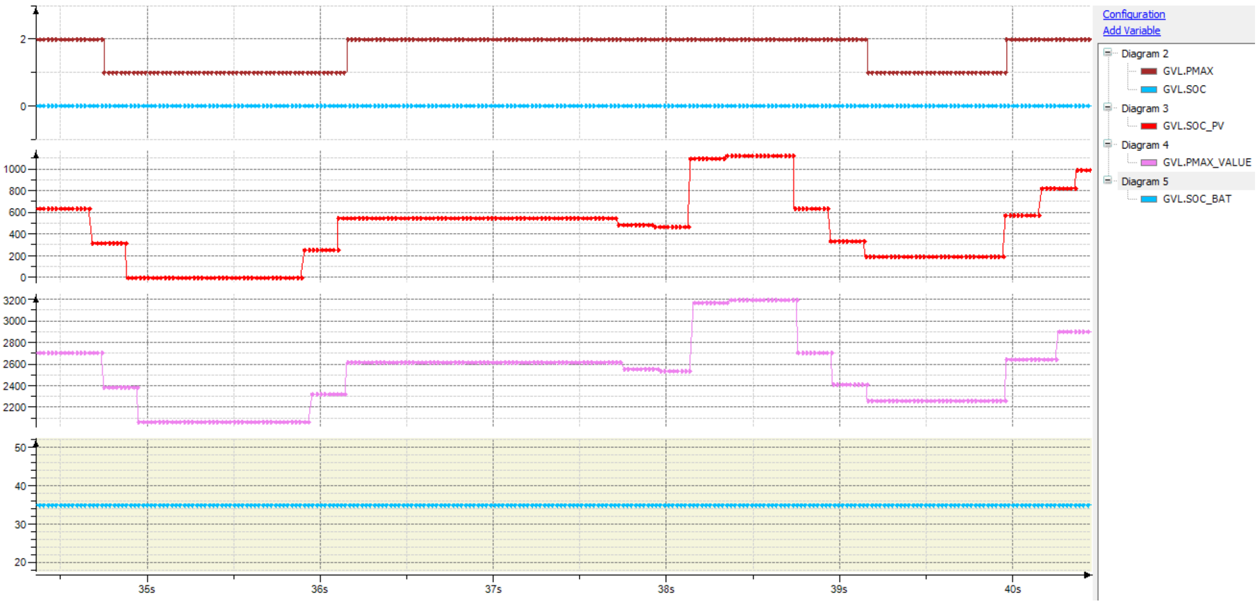

Figure 4.7: Simulation of Scenario 0 Case 2

4.7.1.3 Case 3: Power Outage Detection

It is possible to observe that the three phases can vary, but the power outage is detected only when at least one of them drops to a value below the minimum stipulated operating value. To do this simulation, the stipulated value is 190 V.

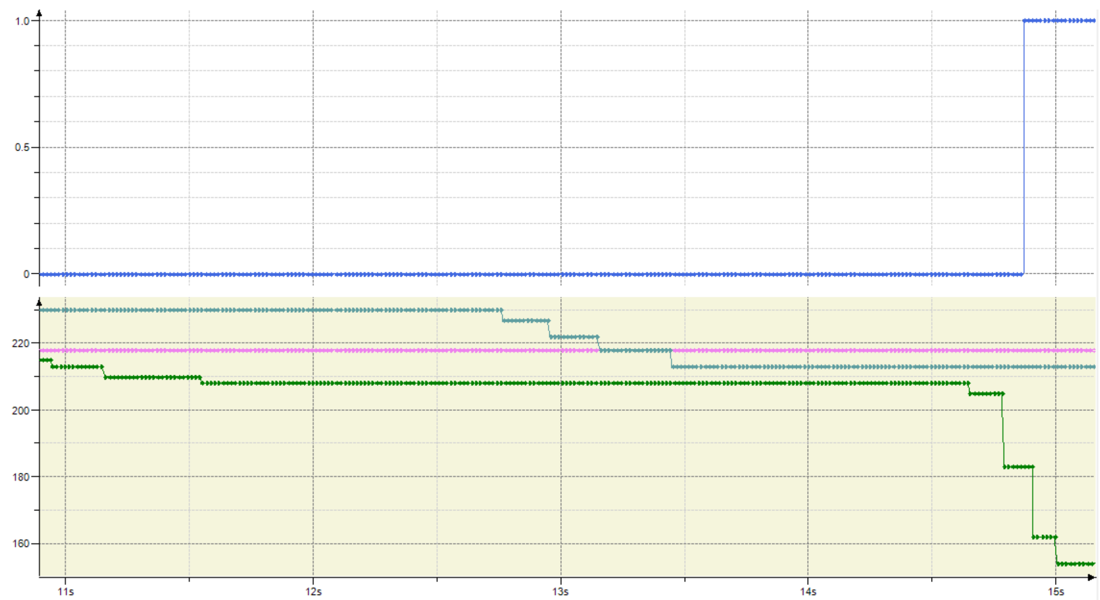

Figure 4.8: Simulation of Scenario 0 Case 3

4.7.2 Scenario 1: the microgrid is in State 1 (grid connected) and there is a power outage

When the microgrid is in state 1 and a power outage occurs (PO=1), there are three possible cases.

4.7.2.1 Case 1:

In the first case, the percentage of the battery is greater than 20% ($SOC = 0$) and the maximum power that can be supplied for the microgrid to last at least one hour since the power outage is greater than or equal to 2400 W ($PMAX = 2$).

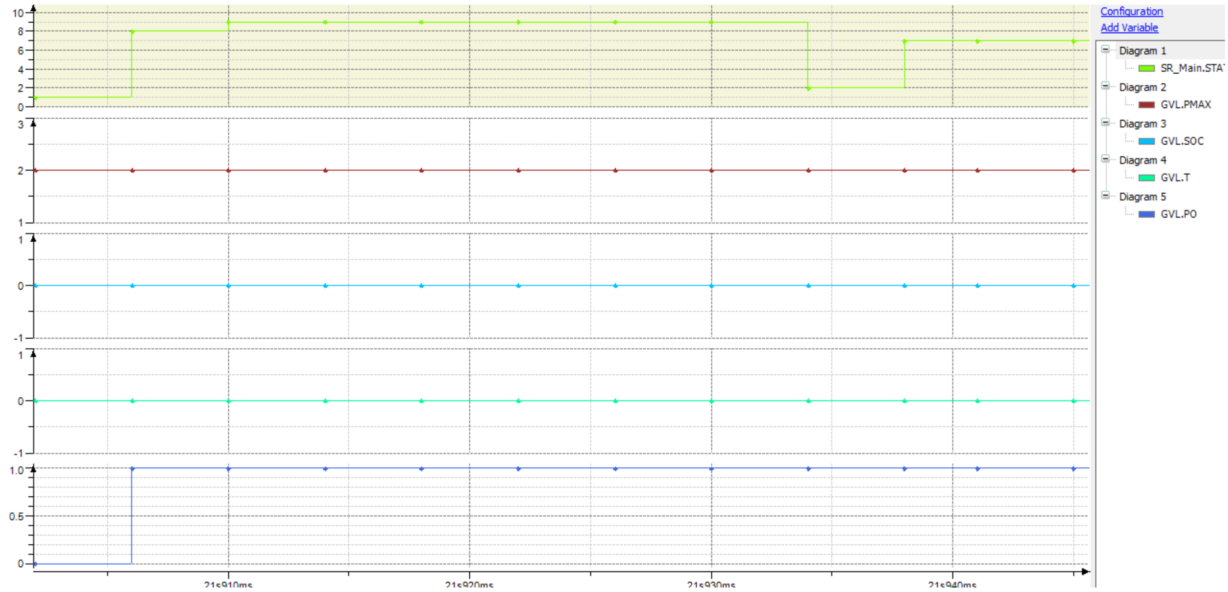

Figure 4.9: Simulation of Scenario 1 Case 1

As expected, when the fault is detected, the microgrid transitions to isolated mode. It's possible to observe this transition by observing the state changes. The state goes from 1 to 8, then it goes to state 9 where it takes a time to ensure that contactor 1 is off before turning on contactor 10 and going into isolated mode. When it reaches this state, it checks the control variables and the next state is defined. As expected, it advances to state 2 and then goes to state 7.

4.7.2.2 Case 2:

In this case, the percentage of the battery is greater than 20% ($SOC = 0$) and the maximum power that can be supplied, for the microgrid to survive at least one hour since the power outage, is greater than or equal to 974 W and less than 2400 W ($SOC = 1$).

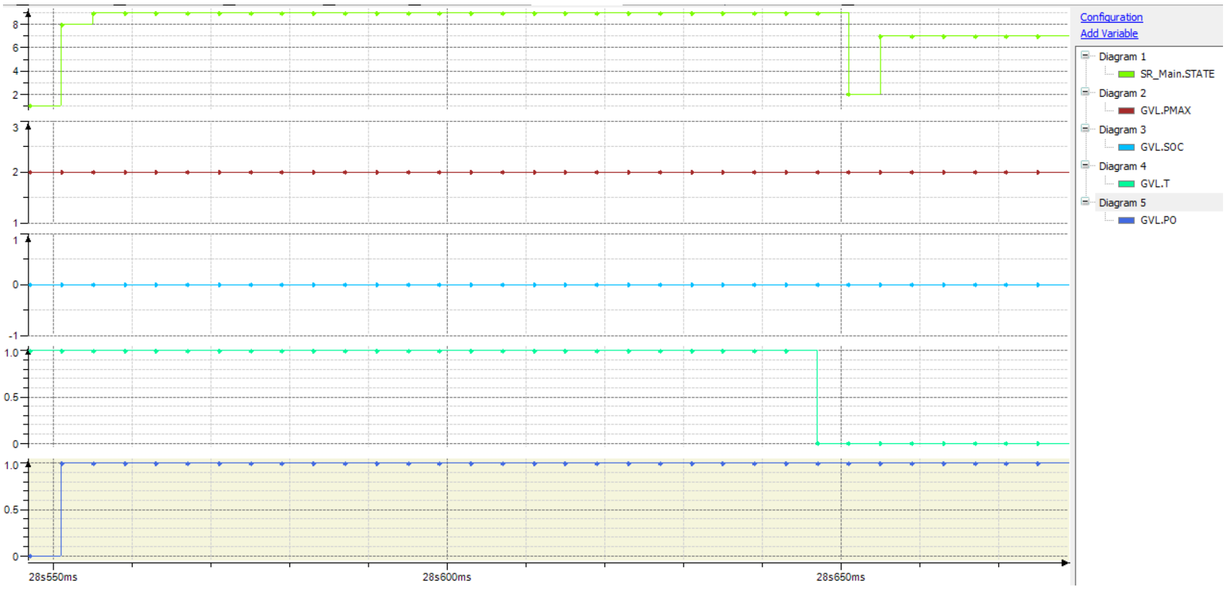

Figure 4.10: Simulation of Scenario 1 Case 2

Again, in state 1 the power outage is detected, and the transition phase starts. The transition phase is carried out in the same way as in the previous case. It goes from state 1 to state 8, immediately going to state 9. When it reaches this state, it checks the control variables and the next state is defined. In this case, it goes to state 3 and then proceeds to state 6.

4.7.2.3 Case 3:

In this case, either the battery percentage is less than or equal to 20% ($SOC = 1$).

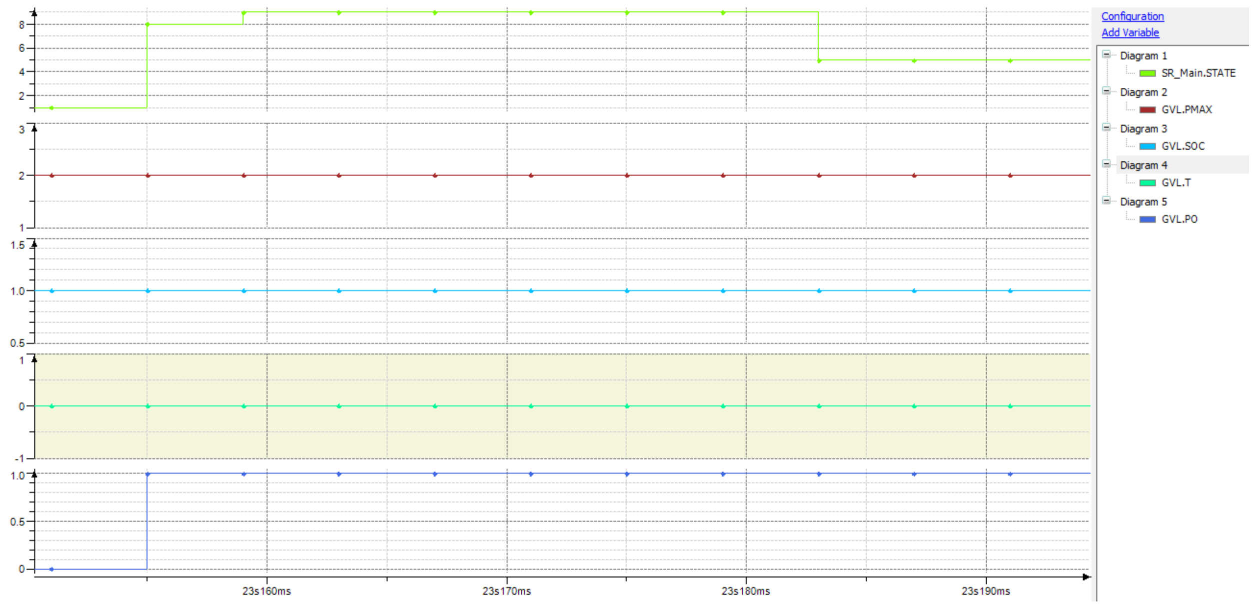

Figure 4.11: Simulation of Scenario 1 Case 3

The transition happens in the same way as in the previous cases. It's possible to observe that the microgrid then transits from state 9 to state 5, just like it was expected, since one of the conditions is met ($SOC = 1$ or $PMAX = 0$).

4.7.3 Scenario 2: microgrid is in State 7

When the microgrid is in stage 7, there are three possible cases.

4.7.3.1 Case 1:

In this case, the microgrid is in state 7 when the power from the main grid is back ($PO = 0$).

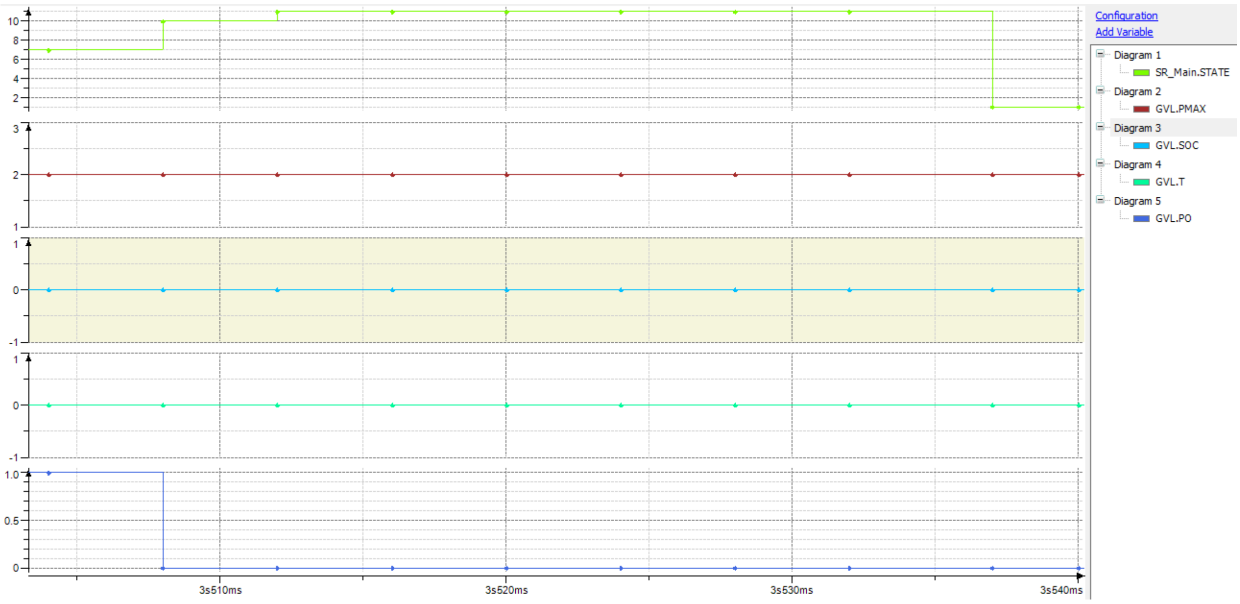

Figure 4.12: Simulation of Scenario 2 Case 1

As expected, the microgrid makes the transition to grid connected mode. It's possible to observe this transition by observing the state changes. The state goes from 7 to 10, then it goes to state 11 where it takes a time to ensure that contactor 10 is off before turning on contactor 1 and going into grid connected mode. After this stage, it advances to state 1 and works on grid connected mode.

4.7.3.2 Case 2:

In this case, there is still a failure in the power supply ($PO = 1$). The microgrid is in state 7 until one minute since the power outage has passed ($T = 1$). The battery percentage is greater than 20% ($SOC = 0$) and the maximum power that can be supplied for the microgrid to last at least one hour since the power outage is greater than or equal to 974 W ($PMAX \neq 0$).

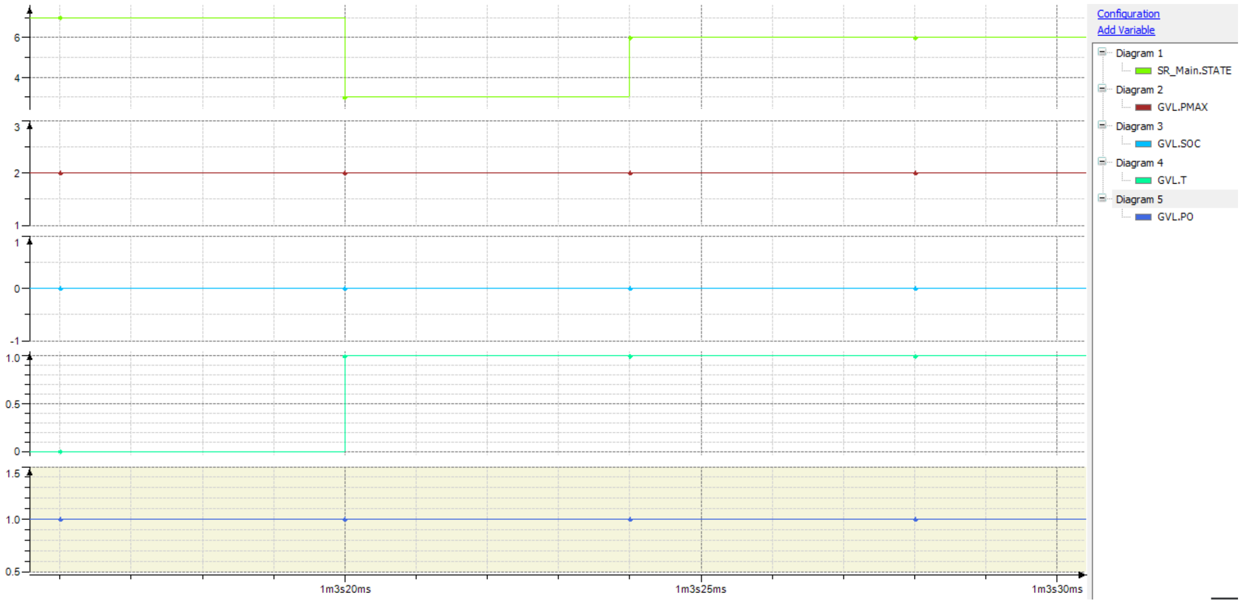

Figure 4.13: Simulation of Scenario 2 Case 2

It's possible to observe that when $T = 1$, the microgrid transits to state 3 and after that it goes to state 6, just like it was expected.

4.7.3.3 Case 3:

In this case, there is still a failure in the power supply ($PO = 1$). The microgrid is in state 7 and it should remain in this state until one minute since the power outage has passed. It's possible to see that the battery percentage falls bellow 20% ($SOC = 1$) and it's also possible to see that the maximum power that can be supplied is falling over the time, ending bellow 974 W ($PMAX = 0$).

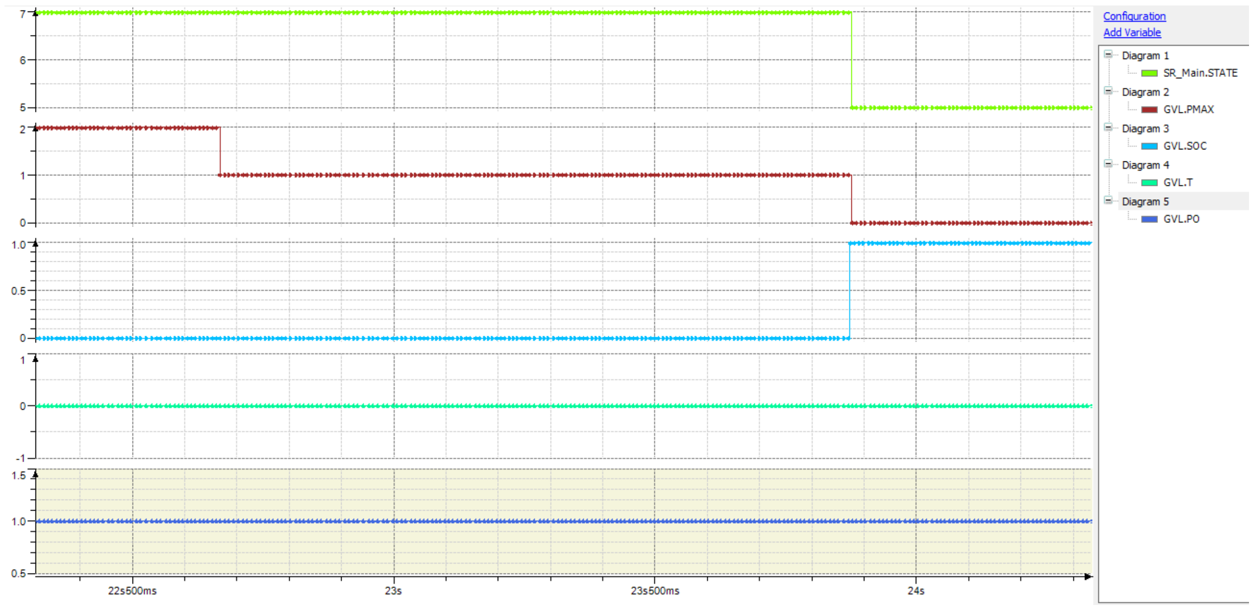

Figure 4.14: Simulation of Scenario 2 Case 3

As it's possible to see, the state changes from 7 to 5 at the moment that the SOC = 1 and $PMAX = 0$, just like expected. In this case, both of conditions happened at the same time, however, it would only be necessary for one of them to occur for the transition be made.

4.7.4 Scenario 3: microgrid is in State 6

Now that the current state is State 6, there are four cases that need to be tested.

4.7.4.1 Case 1:

In the first case, the microgrid is in state 6 when the power from the main grid is back ($PO = 0$).

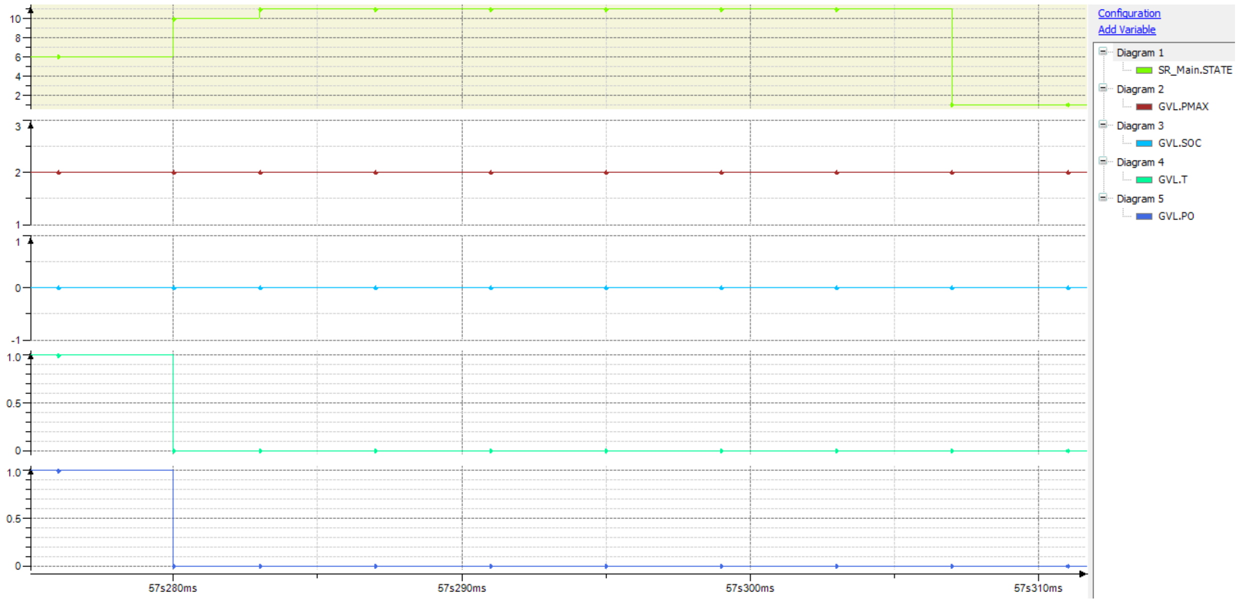

Figure 4.15: Simulation of Scenario 3 Case 1

As expected, and just like in case 1 of scenario 2, the microgrid makes the transition to grid connected mode. It's possible to observe this transition by observing the state changes. The state goes from 6 to 10, then it goes to state 11 where it takes a time to ensure that contactor 10 is off before turning on contactor 1 and going into grid connected mode. After this stage, it advances to state 1 and works on grid connected mode.

4.7.4.2 Case 2:

In this case, there is still a failure in the power supply ($PO = 1$). The microgrid is in state 6 and it should remain in this state until one hour since the power outage has passed. It's possible to see that the battery percentage falls bellow 20% ($SOC = 1$) and it's also possible to see that the maximum power that can be supplied is falls to a value bellow 974 W ($PMAX = 0$).

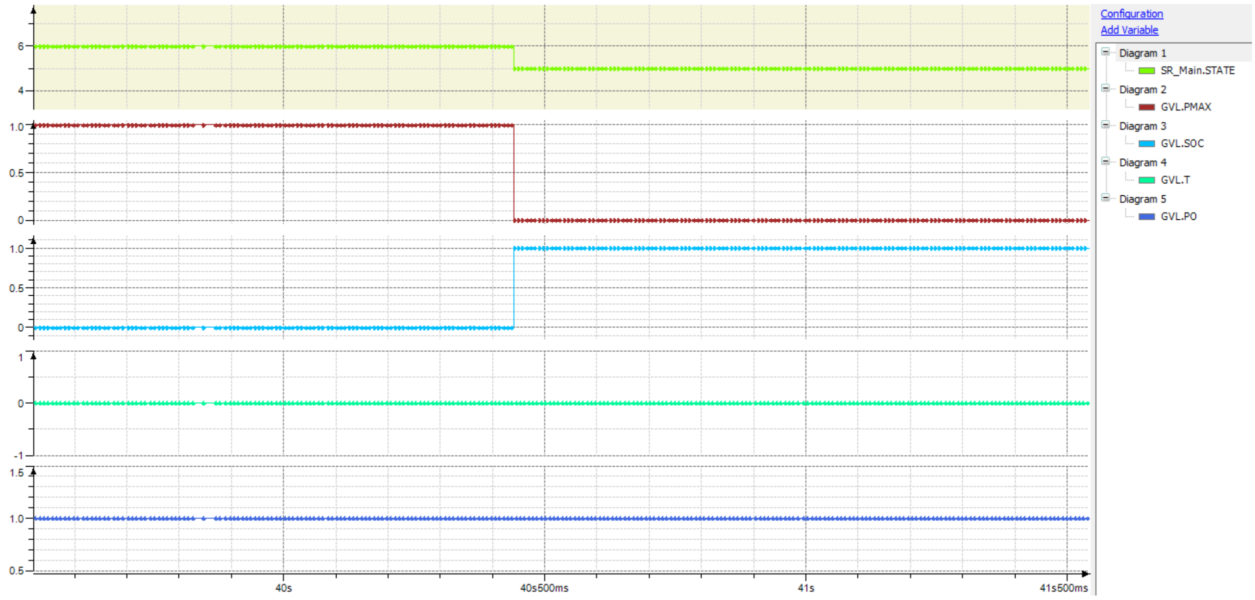

Figure 4.16: Simulation of Scenario 3 Case 2

As it's possible to see, the state changes from 6 to 5 at the moment that SOC = 1 and PMAX=0, just like expected. In this case, both of conditions happened at the same time, however, it would only be necessary for one of them to occur for the transition be made.

4.7.4.3 Case 3:

In this case, there is still a failure in the power supply ($PO = 1$). Battery percentage is greater than 20% ($SOC = 0$) and the maximum power that can be supplied is greater than or equal to 974 W ($PMAX \neq 0$). One hour has passed since the power failure ($T = 2$).

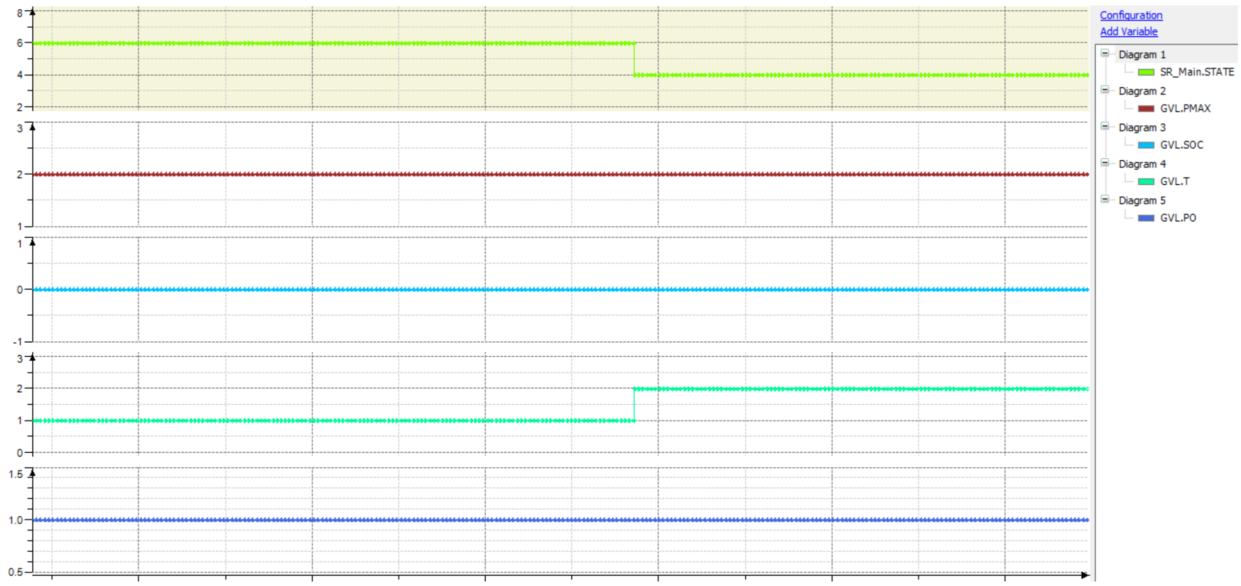

Figure 4.17: Simulation of Scenario 3 Case 3

As expected, when the variable T changes its value from 1 to 2, the state changes from 6 to 4 and stays in that state until $SOC = 1$ or $PMAX = 0$.

4.7.4.4 Case 4:

In this case, there is still a failure in the power supply ($PO = 1$). The microgrid is in state 6 and it should remain in this state until one hour since the power outage has passed. During this time, a check is made whether the timer that was started in state 3 has already expired. If it arrives, the state is supposed to take the value 3 and return to 6

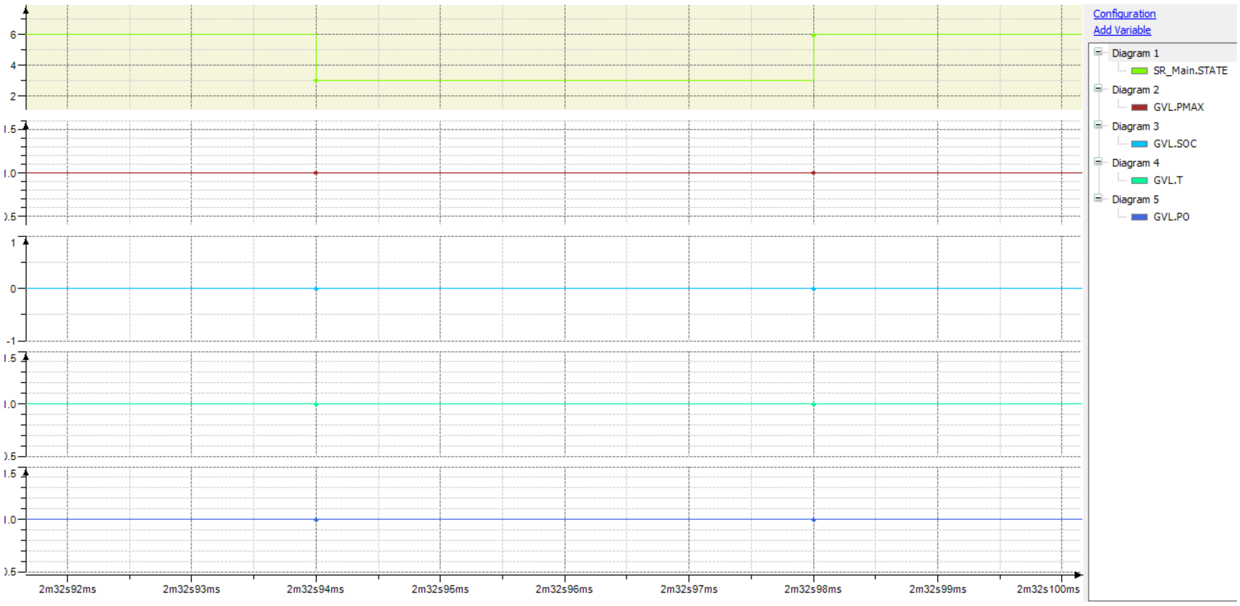

Figure 4.18: Simulation of Scenario 3 Case 4

Since it is not possible to verify in this graph the moment when the timer was set, it is still easy to understand the change of state seen in the graph. Taking into account the control variables ($PO = 1$, $T = 1$, $SOC = 0$ and $PMAX = 2$), the change of state occurs as expected. It is in state 6, changes to state 3 and back again to state 6.

4.7.5 Scenario 4: microgrid is in State 4

If the microgrid is in state four it's because more than one hour since power failure has passed (T=2). In this scenario there only two possible cases. Either the power is back and the microgrid connects to the main grid, or the microgrid runs outs of power and stay in standby mode.

4.7.5.1 Case 1:

Power is back ($PO = 0$).

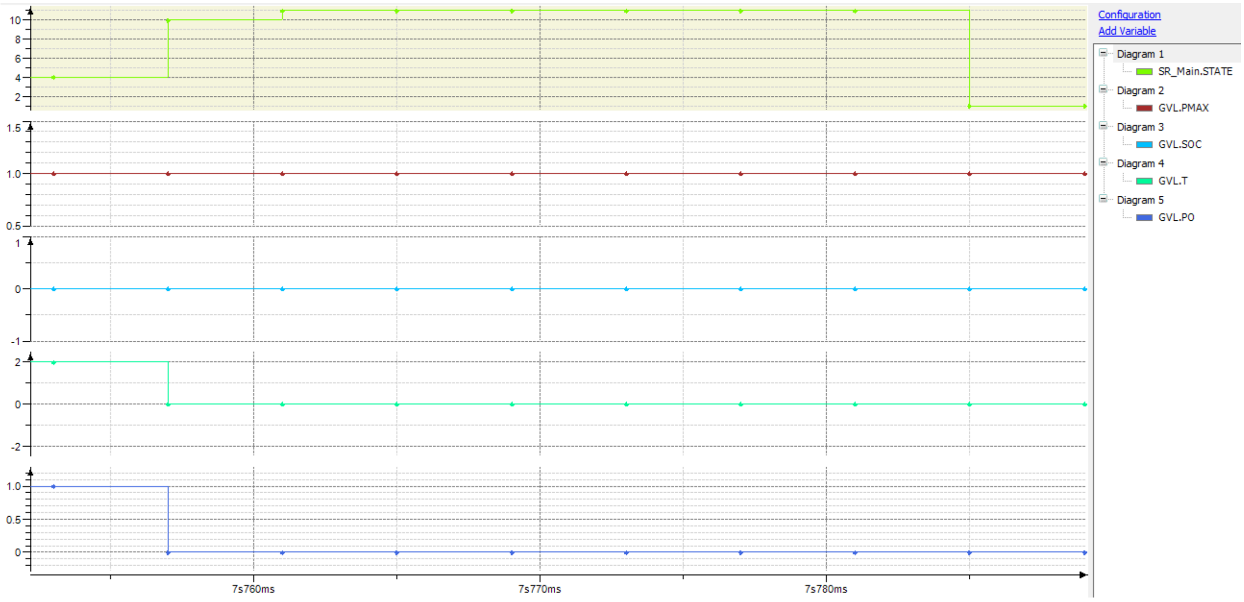

Figure 4.19: Simulation of Scenario 4 Case 1

As expected, and just like in case 1 of scenario 2 and 3, the microgrid makes the transition to grid connected mode. It's possible to observe this transition by observing the state changes. The state goes from 4 to 10, then it goes to state 11 where it takes a time to ensure that contactor 10 is off before turning on contactor 1 and going into grid connected mode. It's possible to observe that when the power comes back, the variable T is set to 0, i.e. the timer that counts the power outage time is reset. After this stage, it advances to state 1 and works on grid connected mode.

4.7.5.2 Case 2:

In this case, there is still a failure in the power supply ($PO = 1$). The microgrid is in state 4 and it should remain in this state until power is back, or battery percentage is less than 20% ($SOC = 1$) or until it's impossible to supply the critical non controllable loads ($PMAX = 0$). It's possible to see that the battery percentage falls bellow 20% ($SOC = 1$) and it's also possible to see that the maximum power that can be supplied falls to a value bellow 974 W ($PMAX = 0$).

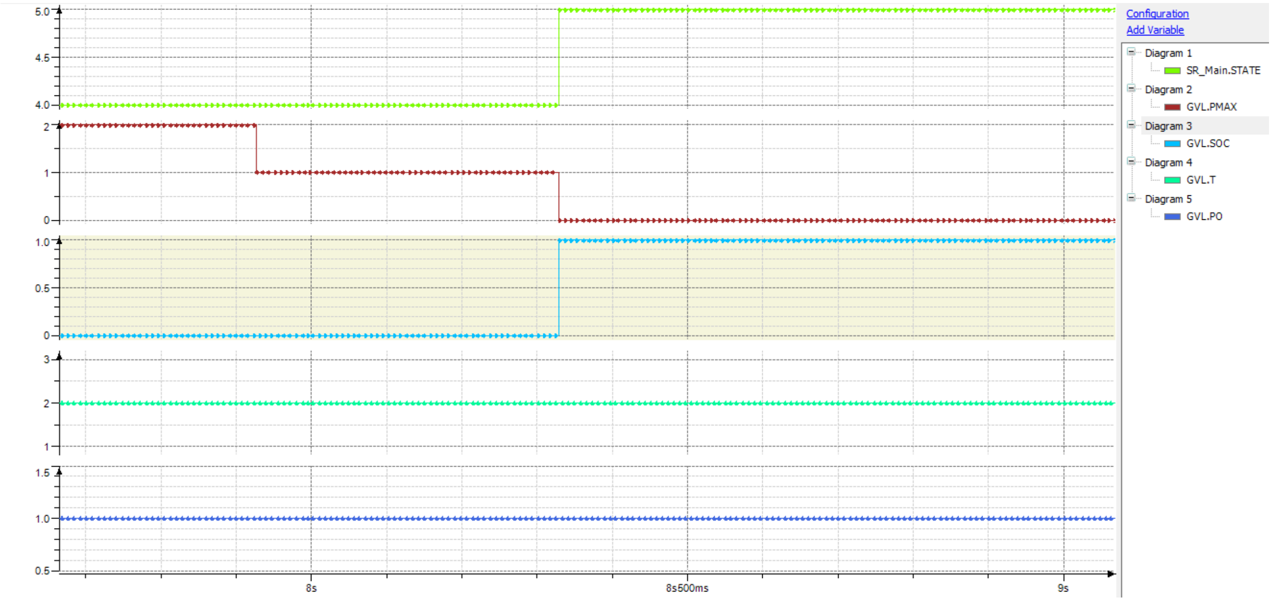

Figure 4.20: Simulation of Scenario 4 Case 2

As it's possible to see, the state changes from 4 to 5 at the moment that $SOC = 1$ and $PMAX = 0$, just like expected. In this case, both of conditions happened at the same time, however, it would only be necessary for one of them to occur for the transition be made.

4.7.6 Scenario 5: microgrid is in State 5

In this scenario, there are only two options. Either the power is back, or the PV system have charged the battery to values above 20% ($SOC = 0$) and there's enough power to supply the critical non-controllable loads ($PMAX \neq 0$).

4.7.6.1 Case 1:

In this case, power is back ($PO = 0$).

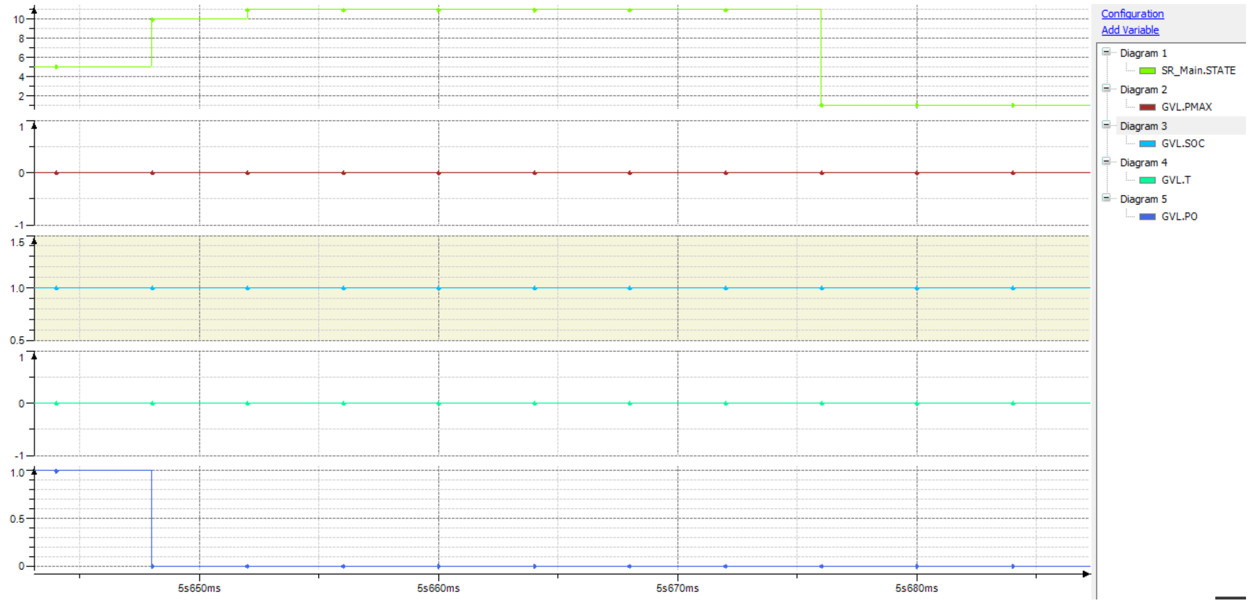

Figure 4.21: Simulation of Scenario 5 Case 1

As expected, and just like in previous scenarios, the microgrid makes the transition to grid connected mode. The state goes from 5 to 10, then it goes to state 11 where it takes a time to ensure that contactor 10 is off before turning on contactor 1 and going into grid connected mode. After this stage, it advances to state 1 and works on grid connected mode.

4.7.6.2 Case 2:

In this case there's still a power outage ($PO = 1$). However, the battery of the PV system has recharged and reached a point where it's possible to supply some loads again, the non-controllable loads ($SOC = 0$ and $PMAX \neq 0$).

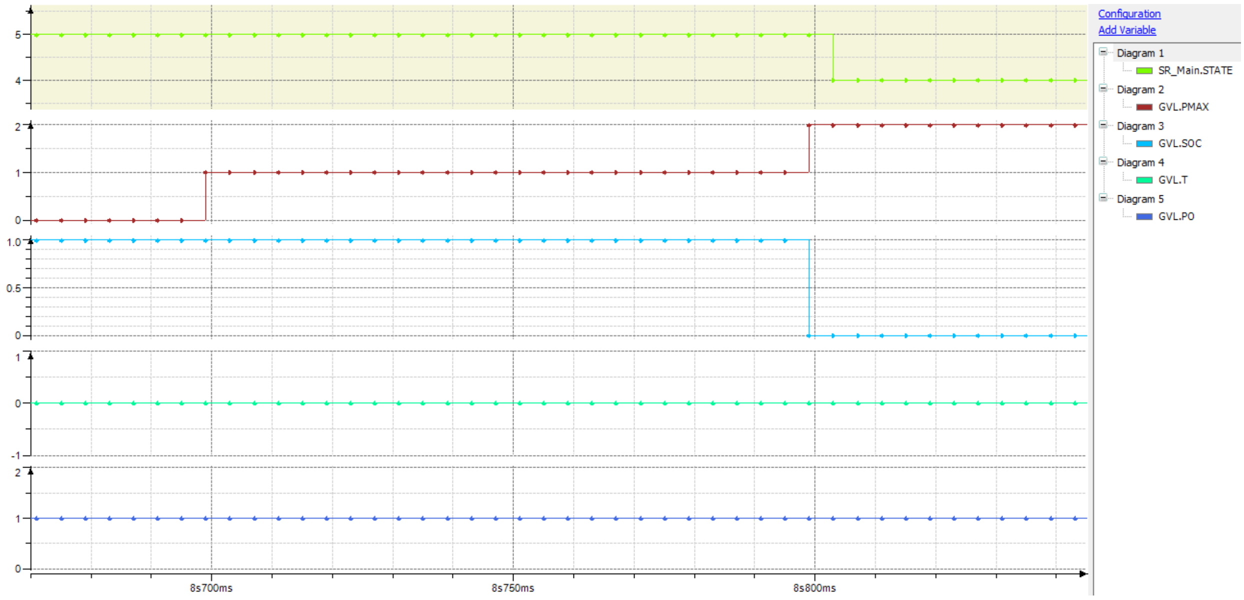

Figure 4.22: Simulation of Scenario 5 Case 2

When this scenario happens, it's possible to see the values from $PMAX$ raising first to 1 and then to 2, which means that the battery percentage is rising, until it reaches more than 20% ($SOC = 0$). At this point, state changes from 5 to 4.

4.7.7 Scenario 6: Prevention regarding plug circuits

Whenever there is an increase in the load on the plug circuits and there is no ability to withstand this increase in load, the circuit is turned off until there is a new balance between load demand and power supply assessment.

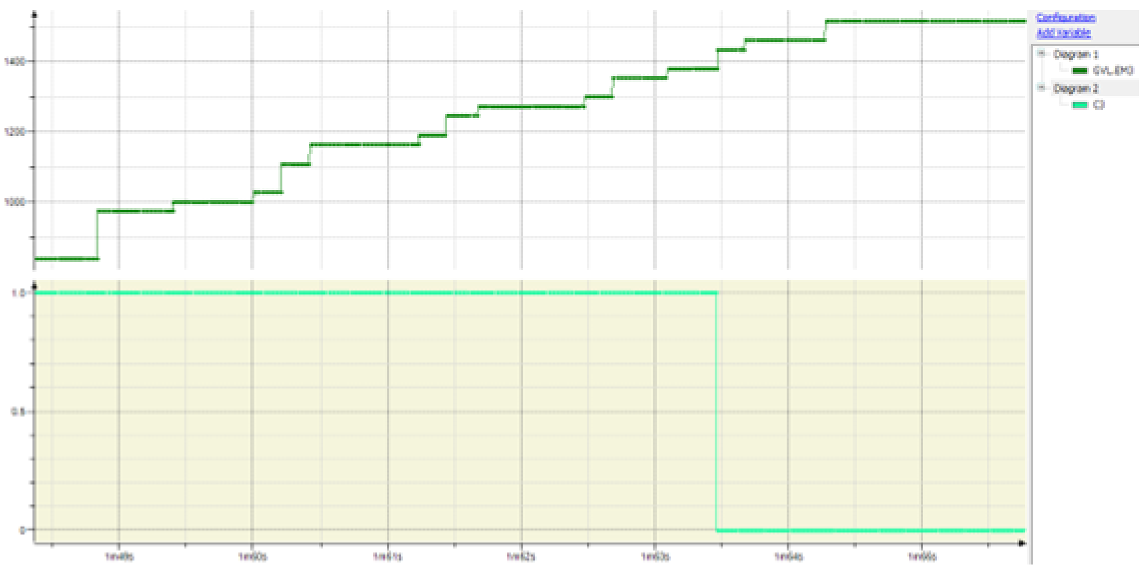

Figure 4.23: Simulation of Scenario 6

It can be seen that the power value of the outlet circuit measured by energy monitor 3 is increasing until it reaches a point where the system switches off output C3.

4.7.8 Visualization of the simulation environment

Next, 4 examples of the simulation environment will be shown.

4.7.8.1 On-grid operation

Figure 4.24: Simulation Environment - On-grid Operation

Despite the battery value being low and the maximum power presenting a value of 1415 W, all loads are being powered once we are connected to the mains.

4.7.8.2 Island mode, State 7

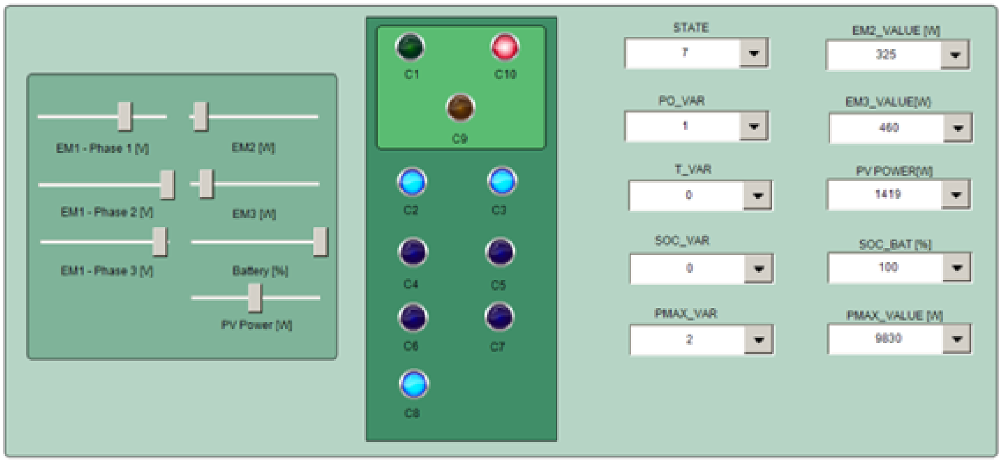

Figure 4.25: Simulation Environment - Islanded Mode, State 7

In this case it is possible to observe that we are operating in island mode, since C1 and C9 are off and C10 is on. Only outputs C2, C3 and C8 are connected.

4.7.8.3 Islanded mode, state 4

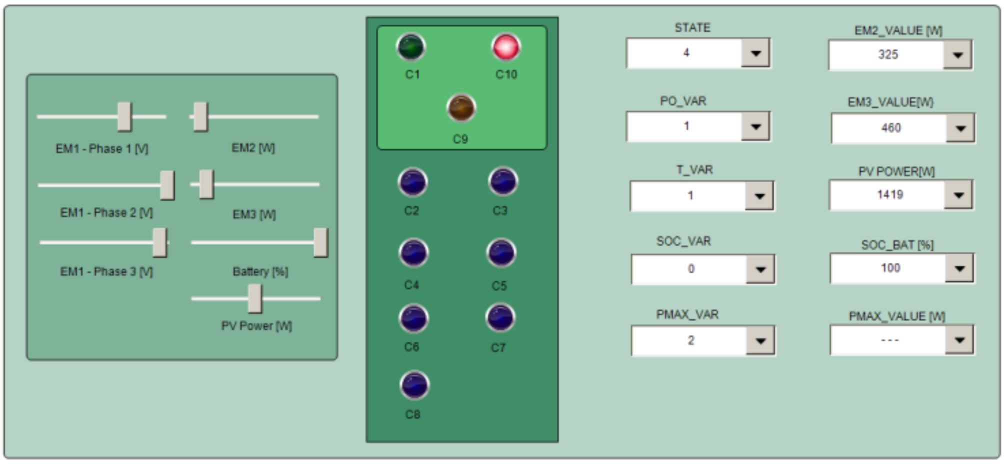

Figure 4.26: Simulation Environment - Islanded Mode, State 4

In state 4, as expected, only critical non-controllable loads are powered, which means that only C10 is on.

4.7.8.4 Stand-by mode

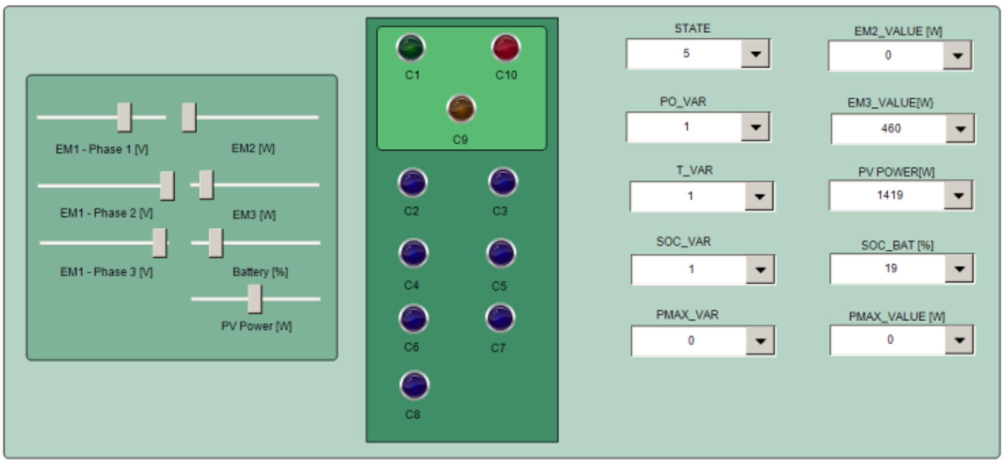

Figure 4.27: Simulation Environment - Stand-by Mode

In stand-by mode all contactors are off, no load is being supplied. The automation is being powered only by the UPS while it waits for the power to come back or for there to be enough battery to go back to state 4. In this case, the microgrid is in state 5 because the battery is at 19% battery.

4.8 Simulation with the three batteries

In this case, we will simulate a scenario where we have not only the PV system to supply the micro-grid, but we also have three batteries and their DC/AC inverters (mentioned in the Methodology).

In this case, there are some changes compared with the previous scenarios. There's no more power limitation on plug circuits and the control variables PMAX and SOC are now as follows.

$$PMAX_{VAR} = \begin{cases} 0, \text{ if } P_{Max} < 974W \\ 1, \text{ if } 974 \leq P_{Max} < 14400W \\ 2, \text{ if } P_{Max} \geq 14400W \end{cases} \tag{4.7}$$

$$P_{\text{Max}} = PV + \frac{E + E_1 + E_2 + E_3}{(1-\tau)} \tag{4.8}$$

$$E = (SOC[\%] - 20[\%]) * 10500\text{Wh} \tag{4.9}$$

$$E_1 = (SOC_{Bat1}[\%] - 20[\%]) * 9800\text{Wh} \tag{4.10}$$

$$E_1 = E_2 = E_3 \tag{4.11}$$

Where:

- PV = Generated power from PV (W)
- E = Energy available from the battery (Wh)
- τ= Time that has passed since power outage (h)
- 974 W corresponds to the power of the non-controllable critical charges.
- 14400 W is 80% of the power of all inverters.

$$SOC_{VAR} = \begin{cases} 0, \text{ if } SoC > 20\% \text{ OR } SoC_{Bat1} > 20\% \text{ OR } SoC_{Bat2} > 20\% \text{ OR } SoC_{Bat3} > 20\% \\ 1, \text{ if } SoC \leq 20\% \text{ AND } SoC_{Bat1} \leq 20\% \text{ AND } SoC_{Bat2} \leq 20\% \text{ AND } SoC_{Bat3} \leq 20\% \end{cases} \tag{4.12}$$

4.8.1 Order of connection of power supply sources

Since we have four different generation sources, the first source that should be connected is the one which battery has higher SoC. This will be the reference for the other sources.

4.8.1.1 Case 1: Battery 2 is the one with more energy

In this case Battery 2 is the battery that has more energy. As expected, it's the first to connect to the microgrid when there's a power failure.

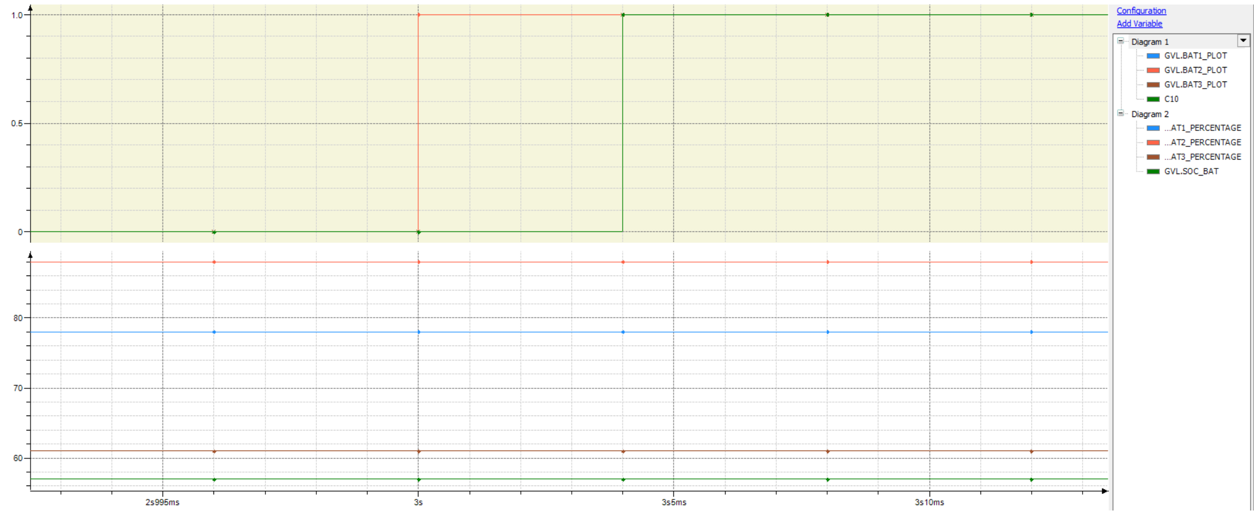

Figure 4.28: Simulation of Connection of Batteries, Case 1

It's possible to observe that Battery 2 is the first to connect, followed by all of the other generation sources.

4.8.1.2 Case 2: Battery 3 is the one with more energy

As in the previous case, Battery 3 is the battery that has more energy. It should be the first to connect.

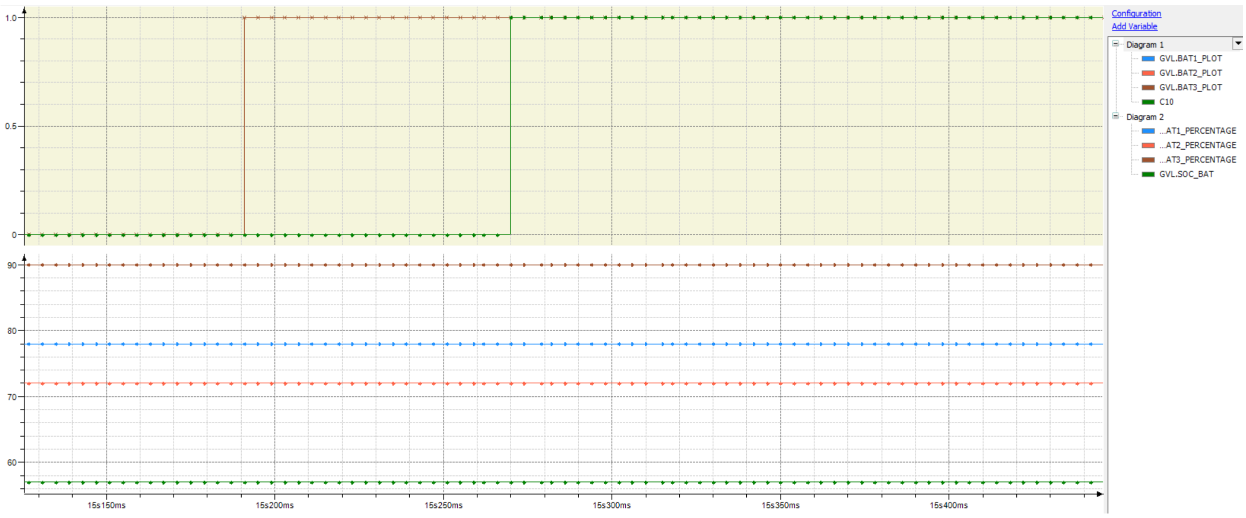

Figure 4.29: Simulation of Connection of Batteries, Case 2

It's possible to observe that Battery 3 is the first to connect, followed by all of the other generation sources.

4.8.1.3 Case 3: PV Battery is the one with more energy

Again, like the previous cases, there's one battery that has more power than the others and it should be the first to connect.

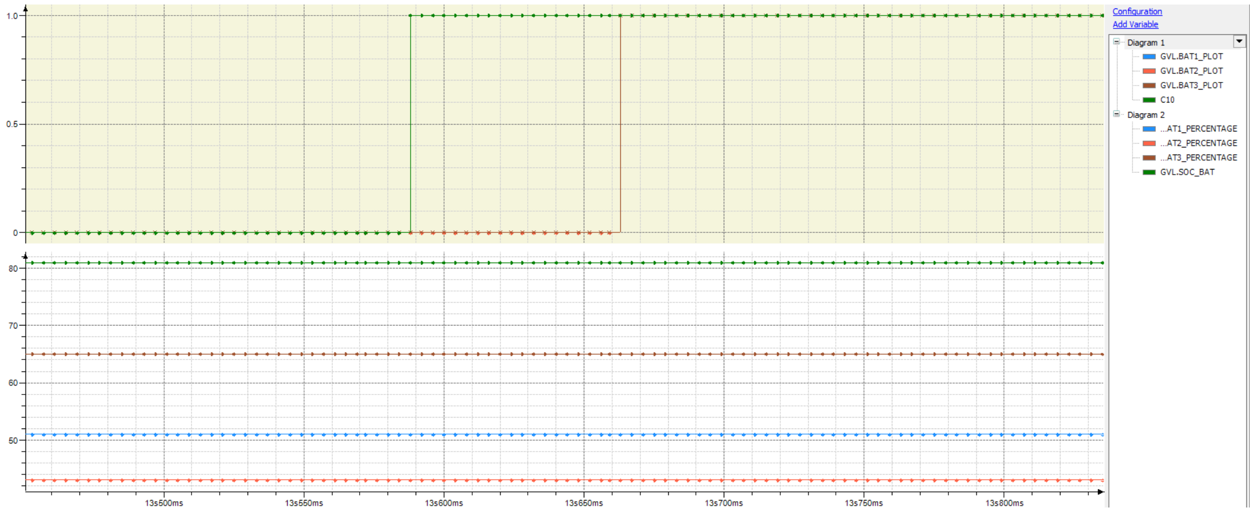

Figure 4.30: Simulation of Connection of Batteries, Case 3

In this case the PV Battery is the one that connects first because it's the one with more battery percentage.

4.8.2 Battery goes bellow 20%

If, at any point, a battery reaches 20%, it should be turned off.

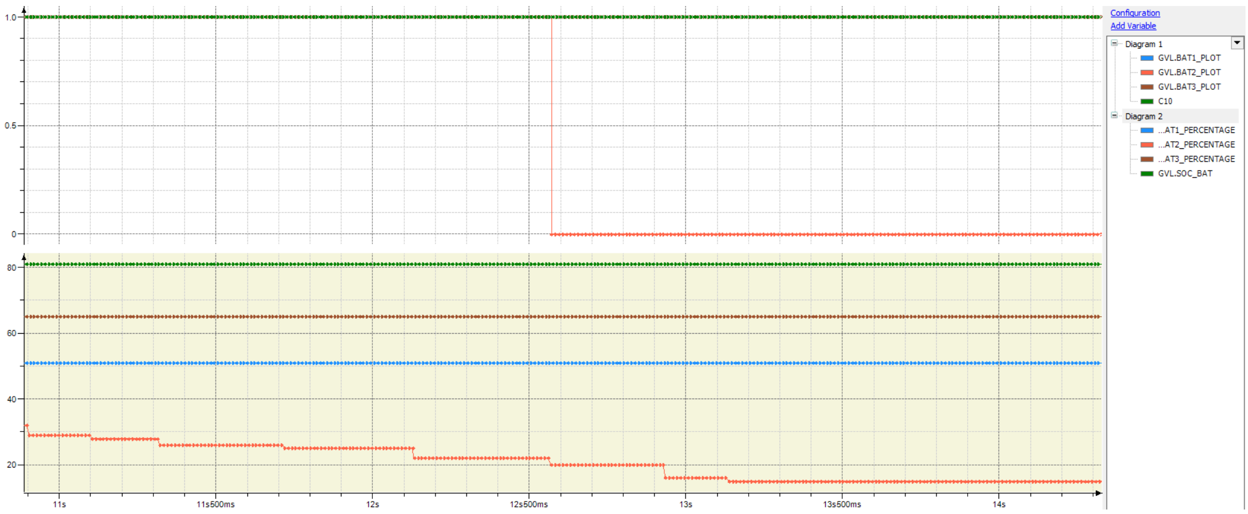

Figure 4.31: Simulation of a battery running out of charge

In this case, Battery 2 is losing charge. When its value is below 20%, it's possible to see that Battery 2 is turned off, just like expected.

4.8.3 Changes in battery levels

In the next case it's possible to see the differences in the $PMAX_{VALUE}$ when the battery values change.

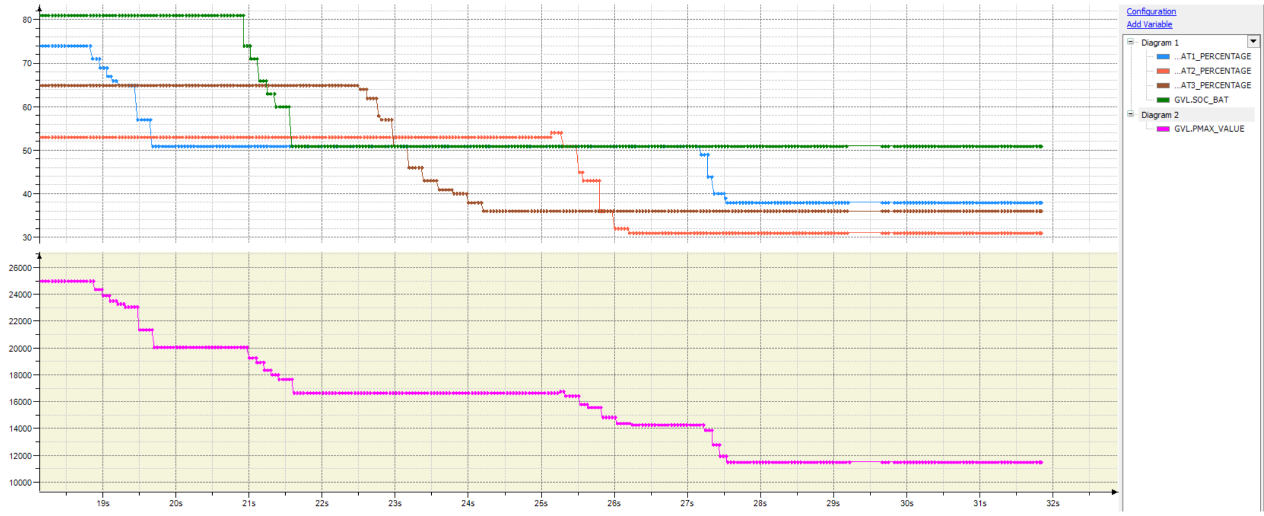

Figure 4.32: Simulation of alterations in battery levels - changes in $PMAX_{VALUE}$

4.8.4 Change in SoC_{VAR}

Like it was explained before, the control variable SoC_{VAR} should only change from 0 to 1 when all bateries are bellow 20%.

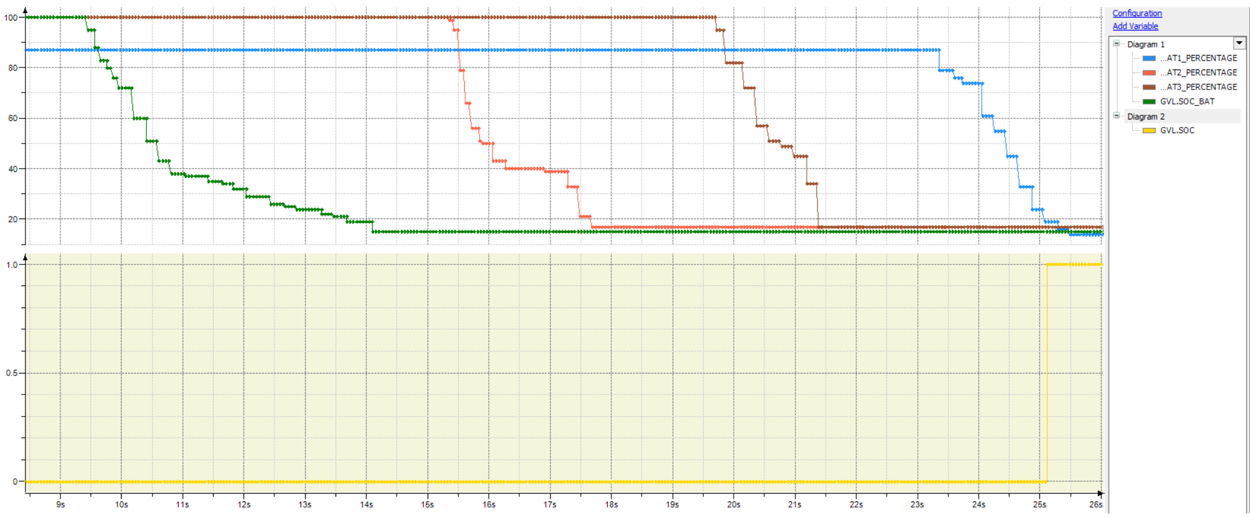

Figure 4.33: Simulation of alterations in battery levels - changes in SoC_{VAR}

As it's possible to observe, SoC_{VAR} only changes value when all batteries are below 20%, as expected.

4.8.5 Simulation Environment

The difference in the simulation environment, regarding the scenarios where only the PV System could supply the microgrid, is that in this case we have three more LEDs that represent the three batteries and three more slide inputs for the batteries values.

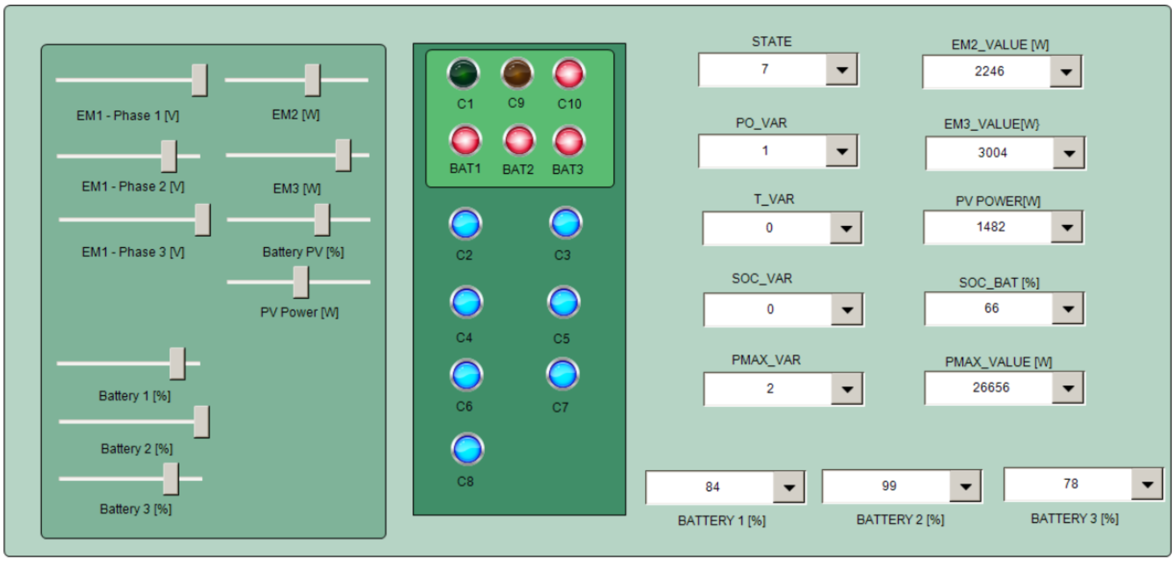

Figure 4.34: Simulation Environment

5

Conclusion and Future Work

The present dissertation had as main objective the development of a solution that would allow the increase of the resilience of a microgrid, having as a starting point and model an existing network in DEEC-UC. For this purpose, it was decided to create a load management algorithm and an architecture that would allow operation connected to the grid or in isolated mode.

In order to achieve the objectives in question, after a careful analysis of the existing network and subsequent study of the fundamentals and theoretical concepts essential and relevant for the present study, we started by identifying the changes that would be necessary to make in the network, in order to reach a micro-network that was according to our needs. The analysis in question allowed us to identify not only the need for changes in the network architecture but also the need to acquire different components. The option for this architecture was related to the fact that, having the buses of the three phases connected to each other, it allows the individual control of the circuits to be turned on and off, to control in a more precise way the power that is being consumed according to the available power, connecting and disconnecting circuits through the contactors. After choosing the architecture, a survey of the single-phase loads was conducted, in order to allow us to know the power of each circuit, with the loads being organized by priority levels.

The next step was to define the operation modes, and, in this case, it was concluded that there are five main operation modes: i) One when the microgrid works connected to the main grid; ii) Another when the microgrid works isolated from the main grid, the islanded mode; iii) Transition from grid-connected to islanded mode; iv) Transition from islanded mode to grid-connected; v) and a stand-by mode, when there is no power remaining in the isolated microgrid.

Regarding the islanded mode, it should also be noted that there are three sub-modes that may occur: i) One where the microgrid powers the maximum possible loads for one minute; ii) and another one where the balance between load demand and power supply is made. The main objective here is that the microgrid lasts for at least one hour since the power outage; iii) and the last mode occurs when one hour has passed and the power hasn't returned. In this stage only the most critical and non-controllable loads are supplied. The present study allowed us to conclude that, with this management, it's possible to maintain the supply to the most critical charges for a long period of time. This time will always vary according to the PV generation.

In addition to all the conclusions mentioned so far, the developed simulation environment allowed us to test all the cases that may occur in a real scenario. The analysis of the results obtained allows us to conclude that the developed proposal presents itself as a viable solution to guarantee the fulfilment of the initial and primordial objective of increasing the resilience of the microgrid. More than a solution for the initial grid that served as the basis for the present thesis, this is a solution that appears to be viable for use in many other situations.

As an example, it can be used and applied in houses or to isolate just some loads considered essential in any building. The only necessary condition for that is to make an initial study of the loads that are intended to be fed and the available generation sources.

5.1 Future Work

Every system presents its own shortcomings. These gaps can be filled with more research and development in order to strengthen, complete and make the product even more resilient. In the future, mainly for economic reasons, it would be interesting to include an option for the grid to disconnect from the main grid when the batteries are fully charged and three-phase loads are not being used. It would also be advantageous to include V2G as it would make the microgrid have more energy resources.

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Appendix

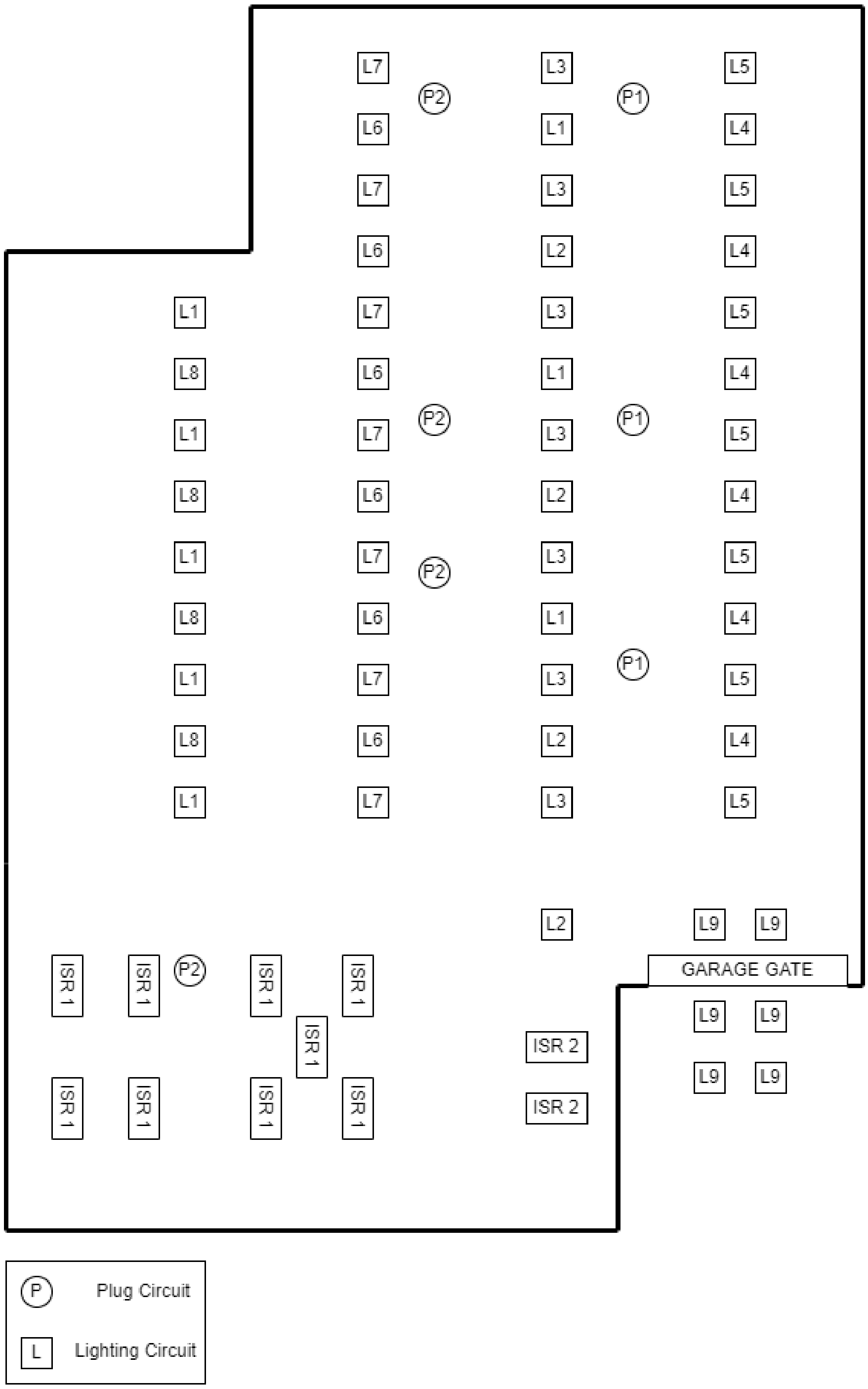

Figure 5.1: Garage Layout