Miguel Santos Cavaleiro

Automatic Control of a Resilient Microgrid

Master's Dissertation in Electrical and Computer Engineering, supervised by
Professor António Paulo Mendes Breda Dias Coimbra and Professor Manuel Marques Crisóstomo
and presented to the Faculty of Science and Technology of the University of Coimbra

September of 2023

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Resumo

O desenvolvimento de uma micro-rede resiliente representa um passo importante para aumentar a fiabilidade e resiliência dos circuitos elétricos da garagem do DEEC, especialmente em cenários caracterizados por cortes de energia ao nível da rede principal. Este projeto tem como objetivo criar uma fonte de energia sustentável e fiável, mesmo nos momentos mais desafiadores, como desastres naturais ou interrupções de energia em larga escala. Como base, a arquitetura da micro-rede integra painéis fotovoltáicos, soluções de armazenamento de energia e unidades de controlo de modo a fornecer energia de forma contínua.

Um dos pilares da funcionalidade desta micro-rede é a sua capacidade de gerir eficientemente os recursos energéticos disponíveis, garantindo alocação e utilização ótimas. Isso é alcançado por meio da implementação de algoritmos de controlo específicos, projetados para servir a função pretendida. Esses algoritmos permitem que a micro-rede responda dinamicamente à situação, considerando fatores como a duração do corte de energia, desde o seu início. A estratégia de *load shedding* desempenha um papel fundamental nesse sentido.

O *load shedding* é um processo dinâmico que identifica e prioriza automaticamente as cargas conectadas, cortando o fornecimento de energia para aquelas menos críticas durante períodos de escassez de energia. Este processo de tomada de decisão inteligente é suportado pela compreensão abrangente da micro-rede, tal como das configurações de prioridade associadas a cada carga conectada. Dessa forma, a micro-rede garante que os serviços essenciais continuem a receber um fornecimento contínuo de energia, mitigando potenciais interrupções causadas por extensos cortes de energia.

O uso de energia solar por meio de painéis fotovoltaicos é uma componente fundamental das fontes energéticas desta micro-rede. Os painéis captam a energia do sol, convertendo-a em eletricidade que pode ser armazenada para uso posterior ou imediatamente utilizada para alimentar a infraestrutura crítica dentro da garagem do DEEC. Essa fonte de energia renovável garante alguma independência energética, reduzindo a dependência da rede principal.

Os sistemas de armazenamento de energia são outro componente fundamental do design desta micro-rede. Com estes, o excesso de energia gerado durante períodos de oferta abundante pode ser armazenado para uso durante picos de demanda ou situações de emergência.

A unidade de controlo, equipada com algoritmos de controlo de carga, adaptados às necessidades específicas da micro-rede, desempenha um papel fundamental na organização da interação entre fontes de energia e cargas. Esta unidade de controlo é o cérebro da micro-rede, tomando decisões em tempo real que otimizam a alocação e distribuição de energia. A adaptabilidade desses algoritmos garante que a micro-rede se adapta a vários cenários, como cortes de energia prolongados ou aumentos súbitos na demanda de energia.

Durante a realização desta dissertação foram alcançados vários objetivos definidos inicialmente, tais como a realização de simulações que permitem confirmar a viabilidade da micro-rede, funcionando em modo isolado. O outro objetivo principal alcançado foi a implementação prática de um autómato que controla algumas das cargas presentes na garagem de um modo eficaz.

Palavras-chave: micro-rede resiliente; painéis fotovoltaicos; *load shedding*; corte de energia; algoritmos de controlo de carga.

Abstract

The development of a resilient microgrid represents a step in enhancing the reliability and resilience of the DEEC's garage electrical circuits, particularly in scenarios characterized by main grid level power outages. This project aims to create a sustainable and dependable source of power, even during the most challenging times, such as natural disasters or large-scale power disruptions. At its core, the microgrid's architecture seamlessly integrates solar energy harnessed through PV (photovoltaic panels), energy storage solutions, and control units.

One of the pillars of this microgrid's functionality is its capacity to efficiently manage the available energy resources, ensuring optimal allocation and utilization. This is achieved through the implementation of specific control algorithms designed to serve the intended purposes. These algorithms enable the microgrid to dynamically respond to the situation, considering factors like the duration of the power outage, since it occurred. The strategy of load shedding plays a pivotal role in this regard.

Load shedding is a dynamic process that automatically identifies and prioritizes connected loads, effectively cutting power supply to the less critical ones during periods of energy scarcity. This intelligent decision-making process is supported by the microgrid's comprehensive understanding of the priority settings associated with each connected load. By doing so, the microgrid ensures that essential services continue to receive an uninterrupted power supply, mitigating potential disruptions caused by extensive power outages.

The use of solar energy through photovoltaic panels is a key component of this microgrid's sustainable energy mix. These panels harness the sun's energy, converting it into electricity that can be stored for later use or immediately utilized to power critical infrastructure within the DEEC's garage. This renewable energy source not only reduces the carbon footprint but also ensures a degree of energy independence, reducing dependence on the main grid.

Energy storage systems are another critical aspect of this microgrid's design. By incorporating them, excess energy generated during periods of ample supply can be stored for use during peak demand or emergency situations. These energy storage systems provide a critical buffer that ensures a continuous power supply during fluctuations in energy generation, contributing significantly to the overall reliability of the microgrid.

The control unit, equipped with load control algorithms tailored to the specific needs of the microgrid, play a pivotal role in organizing the interaction of energy sources and loads. These control unit is the brain of the microgrid, making real-time decisions that optimize energy allocation and distribution. The adaptability of these algorithms ensures that the microgrid can adapt to various scenarios, such as prolonged power outages or sudden increases in energy demand.

During the completion of this dissertation, several initially defined goals were achieved, such as conducting simulations that confirm the feasibility of the microgrid, working in islanded mode. Another main objective that was achieved was the practical implementation of an automaton that effectively controls some of the loads in the garage.

Keywords: resilient microgrid; photovoltaic panels; load shedding; power outage; load control algorithms.

"The greatest glory in living lies not in never falling, but in rising every time we fall."

— Nelson Mandela, Long Walk To Freedom

Contents

List of Acronyms

List of Acronyms

AC Alternate Current

DC Direct Current

DEEC Departamento de Engenharia Eletrotécnica e de Computadores

ESS Energy Storage System

FBD Function Block Diagram

h Hour

ISR Instituto de Sistemas e Robótica

kW Kilowatt

kWh Kilowatt-hour

LCD Liquid Crystal Display

GVL Global Variable List

MG Microgrid

PLC Programmable Logic Controller

PO Power Outage

PV Photovoltaic

SOC State Of Charge

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1 Introduction

Portugal has endured a significant number of wildfires in recent years, as a result, entire villages, power grid areas and communication methods have been destroyed in some situations. With the use of microgrids, some of the problems created by natural disasters, not only wildfires, can be fixed or mitigated.

Ever since the start of the project, it's goal has been to provide a microgrid capable of ensuring a resilient response to any power outage, mainly if it represents a state of emergency, such as natural disasters.

With the use of solar panels, a sustainable energy generation, the microgrid reduces it's reliance on the main grid power. Energy storage systems have also been installed in the microgrid, ensuring a continuous power supply. A control unit, with specialized programming, optimizes energy distribution and adapts to different scenarios.

In the following sections of this chapter, the structure of the dissertation, the preexisting electrical installation and the previously developed work within the project are presented.

1.1 Dissertation Structure

This dissertation is structured in the following way:

- **Chapter 1**: Introduction, previous works and dissertation goals;
- **Chapter 2**: Introduction to the concept of Microgrid and State of the Art;
- **Chapter 3**: Microgrid architecture explanation, mode of operation's logic breakdown and developed algorithm;
- **Chapter 4**: Simulation results and on site tests' results;
- **Chapter 5**: Discussion of the obtained results;
- **Chapter 6**: Conclusion and Future Work.

1.2 Preexisting Electrical Installation

The preexisting electrical installation was the basis for the developed ResiMicrogrid pilot. This installation consists of:

1. two single-phase plug circuits;
2. two three-phase plug circuits;
3. eleven lighting circuits;
4. lighting controls, a garage door control;
5. a ventilation system;
6. an energy storage system incorporating three batteries and three DC/AC inverters.

The energy storage system comprises three LG RESU10H lithium-ion batteries, 10 kWh each, along with three DC/AC inverters, possessing a combined power of 15 kW. The batteries are charged from the grid during non-peak hours, from 2:00 AM to 6:00 AM, taking advantage of lower energy costs, and discharged during morning peak periods, from 9:15 AM to 12:15 PM.

The lighting circuit consists of 66 lamps, divided into 11 circuit breakers. Four control commands govern seven of the circuit breakers. Each lamp consumes 42W (Watt), resulting in a total power consumption of 2.772 kW (Kilowatt). The two single-phase plugs have a maximum consumption of 3.68 kW each, yielding a total of 7.36 kW.

1.3 Previous Works

The project in which this dissertation is included began in 2021 [3], therefore, this document represents a continuation of previously developed work, such as a master's dissertation by José Miguel Lopes, in 2022 [10]. The microgrid's design planning and simulation programming development were created before this dissertation, and have been updated and changed during the course of this dissertation, as, after further discussion, the ResiMicrogrid project's team realized that in order to implement a working microgrid there were some necessary features not thought of before, such as required electrical components, design decisions and programming logic changes.

2 State Of The Art

This chapter provides an overview of the State of the Art of Microgrids, as this dissertation's focus is the islanded mode operation of a microgrid.

2.1 Introduction to Microgrids

Microgrids are a relatively new technology that has been gaining popularity in recent years as a way to improve the resilience and reliability of the electrical grid. A microgrid is a small-scale electricity generation and distribution system that can operate independently from the main electrical grid. This allows it to provide power to a specific geographic area, such as a single building, a neighborhood or a campus [12], during times when the main grid is unavailable.

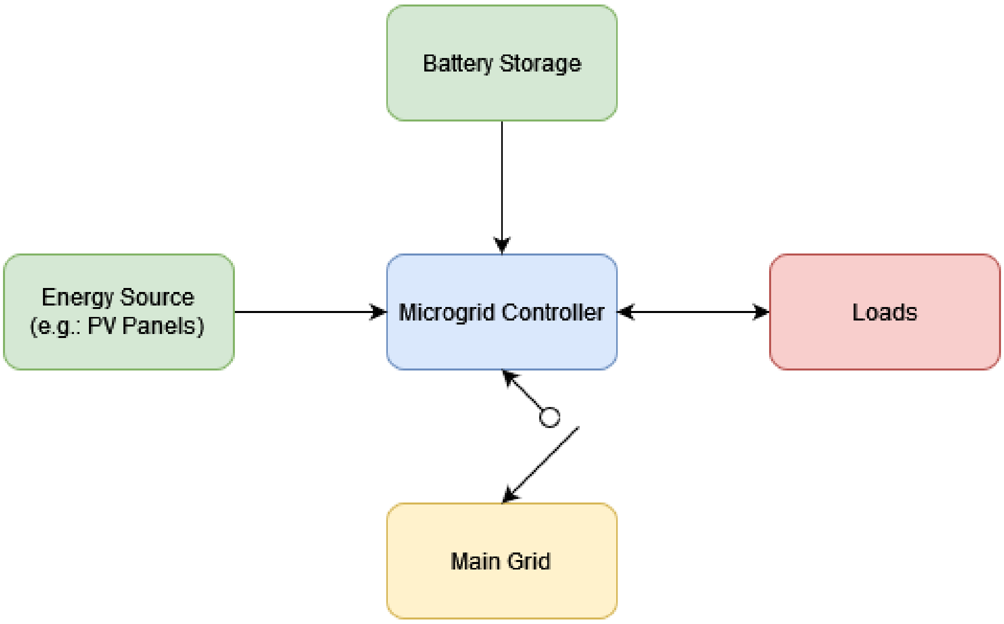


Figure 2.1: Simplified Microgrid Architecture.

The state of the art of microgrids is rapidly advancing, with new technologies and approaches being developed all the time. The increase in the share of renewable energy production has also made it necessary to control both existing loads and local generation devices.

Thus, it is now essential to manage these resources in a smarter way in order to enhance their existence and availability through various tools.

Another important development in the field of microgrids has been the use of intelligent control systems. These systems use advanced algorithms to automatically monitor and control the flow of electricity within a microgrid, ensuring that power is distributed efficiently and effectively. This allows microgrids to operate smoothly and reliably and can also help to reduce the overall cost of providing power to a community.

One of the challenges facing the development of microgrids is the lack of standardization in the industry. Currently, there is no single, widely accepted set of technical standards for microgrids, which can make it difficult for different microgrids to interoperate and share power. This is an issue that is being addressed by organizations such as the Institute of Electrical and Electronics Engineers (IEEE), which is working on developing industry-wide standards for this technology.

Overall, the state of the art of microgrids is one of accelerating innovation and growth. As more and more communities and organizations seek to improve the resilience and reliability of their power systems, the use of microgrids is likely to continue to increase. With advances in renewable energy technologies and intelligent control systems, the future of microgrids looks bright, and they are likely to play an increasingly important role in the electricity industry.

2.2 Microgrids' Advantages

The implementation of microgrids yields a multitude of benefits. Firstly, they enable a seamless integration of distributed generation, especially renewable energy sources like wind and solar, thereby reducing reliance on fossil fuels and substantially reducing carbon emission.

An increasing energy dependence is being observed in all sectors of society, which implies a need for more generation, distribution, and storage of electricity. Therefore, the efficiency and sustainability of distribution networks are key factors for better resource preservation and environmental protection [5].

The creation of microgrids, which primarily rely on renewable generation sources, allows a building or cluster of buildings to achieve economic savings, reduce greenhouse gas emissions, and make various improvements to operational conditions.

Microgrids offer an effective solution for integrating small-scale Distributed Energy Resources close to local loads within low-voltage distribution networks. Their versatile capabilities make microgrids a valuable power supply option for a diverse range of customers. Microgrid technology ensures uninterrupted power supply [9], making it particularly valuable for remote areas lacking access to the main utility grid or regions prone to severe power outages, such as areas that experience frequent wildfires [6], which cause stress in the transmission and distribution systems

From the perspective of utilities, microgrids can be regarded as controllable loads that contribute to peak shaving during high-demand periods by reducing their own consumption through the shedding of non-critical loads and by delivering surplus power to the main grid utility. Microgrids also reduce overall distribution system losses by deploying distributed generation at the point of demand, eliminating the need for extensive transmission lines and deferring costly infrastructure investments. This approach enhances energy efficiency while simultaneously reducing fuel costs, especially when leveraging renewable energy sources like wind and solar.

Furthermore, microgrids open up several economic opportunities [4] when participating in local electricity markets. They can provide various additional services to the main grid, including active power support through frequency regulation, system restoration support, and load balancing services. These contributions can be compensated through fixed payments, service availability payments or frequency-based payments.

2.3 Types of Microgrids

Microgrids come in several types, each with its unique characteristics and applications. Here's a brief introduction to three types of microgrids: DC (Direct Current), AC (Alternating Current), and Hybrid.

2.3.1 DC Microgrids

A DC microgrid is a localized and self-contained electrical network that operates on DC power rather than the more common AC power used in traditional electrical grids. DC microgrids have gained attention and significance [1] due to their ability to offer specific advantages in certain applications, particularly in scenarios where DC power sources are abundant or where DC loads dominate. Some key characteristics and features of DC microgrids are:

- **Direct Current:** Unlike traditional AC grids, where electricity frequently changes direction in the form of sine waves, DC microgrids operate with a consistent flow of electrical current in one direction. This makes them well-suited for certain types of power sources and loads, such as solar panels, batteries, and some electronic devices that inherently use DC power.

- **Energy Sources:** DC microgrids often incorporate renewable energy sources like PV panels and wind turbines. These sources generate DC electricity natively, eliminating the need for DC-AC conversion and increasing overall system efficiency.
- **Efficiency:** DC systems generally experience lower energy losses during transmission and distribution compared to AC systems. This efficiency advantage can be particularly important in remote or off-grid applications.
- **Energy Storage:** DC microgrids frequently employ DC-based energy storage systems, such as lithium-ion batteries. This allows for efficient energy storage and retrieval, reducing energy losses during charging and discharging cycles.
- **Load Compatibility:** Certain loads, such as LED lighting, electronic devices, and electric vehicles, naturally use DC power. DC microgrids are well-suited for locations where these types of loads are prevalent.

In summary, DC microgrids offer an innovative approach to electrical power distribution, leveraging the advantages of direct current for specific applications and environments. They have the potential to enhance energy efficiency, reliability, and sustainability in various settings, while also serving as a valuable component of future smart grid systems.

2.3.2 AC Microgrids

An AC microgrid is a localized and self-contained electrical network that operates on AC power, similar to the conventional power grid. AC microgrids have gained prominence due to their versatility and compatibility with a wide range of power sources and loads [11]. Here are key characteristics and features of AC microgrids:

- **Alternating Current:** AC microgrids use the same type of electrical current as the traditional grid, where the direction of electrical flow alternates back and forth in a sinusoidal waveform. This standardization ensures compatibility with a wide array of electrical devices and equipment.

- **Energy Sources:** AC microgrids can incorporate various energy sources, including renewable energy sources, such as solar panels and wind turbines, and combined heat and power (CHP) systems. These sources often generate AC electricity, which aligns with the grid's format.
- **Interconnection:** AC microgrids can seamlessly connect to the main AC grid when available, allowing for the import or export of electricity as needed. This grid interconnection provides flexibility and access to backup power during emergencies.
- **Energy Storage:** Energy storage systems, such as lithium-ion batteries, are compatible with AC microgrids. These systems store excess energy generated during periods of low demand and release it when demand is high, contributing to grid stability.
- **Load Diversity:** AC microgrids accommodate a wide range of electrical loads, including lighting, heating, cooling, industrial machinery, and electronic devices. This makes them suitable for diverse applications, from residential areas to industrial facilities.

In summary, AC microgrids offer a versatile and adaptable approach to localized power distribution, making them well-suited for various applications and environments. They leverage the familiar AC format and are compatible with a wide array of energy sources and loads, providing reliability, efficiency, and the potential for cleaner and more sustainable energy solutions. AC microgrids are a significant component in the development of modern smart grid systems.

2.3.3 Hybrid Microgrids

A hybrid microgrid is a localized and self-contained electrical network that combines both AC and DC power sources, loads, and energy storage systems [7]. Hybrid microgrids are designed to harness the advantages of both AC and DC systems, offering flexibility, efficiency, and reliability in diverse applications. Here are key characteristics and features of hybrid microgrids:

- **AC and DC Integration:** Hybrid microgrids seamlessly integrate both AC and DC power sources and loads within a single, unified system. This integration allows for versatile energy generation and distribution.
- **Energy Sources:** Hybrid microgrids can incorporate a variety of energy sources, including fossil fuels, renewable sources, such as solar panels and wind turbines, and

combined heat and power (CHP) systems. These sources can generate both AC and DC electricity as needed.

- **Energy Storage:** Energy storage systems, such as batteries, are a crucial component of hybrid microgrids. They store excess energy from both AC and DC sources and release it when demand is high or during grid outages, enhancing grid stability.
- **Load Compatibility:** Hybrid microgrids accommodate a wide range of electrical loads, including lighting, heating, cooling, electronic devices, and electric vehicles, whether they operate on AC or DC power. This adaptability suits various applications, from residential areas to industrial facilities.
- **Grid Interconnection:** Many hybrid microgrids can connect to the main AC grid when available. This interconnection allows for importing or exporting electricity and can serve as a backup power source during emergencies.
- **Scalability:** Hybrid microgrids are designed to be scalable, enabling the addition of new power sources, loads, or energy storage units as energy requirements evolve. This flexibility makes them adaptable to changing conditions.
- **Energy Conversion:** Hybrid microgrids may include devices for converting between AC and DC power, ensuring compatibility between various sources and loads. These converters optimize energy flow within the microgrid.

In summary, hybrid microgrids offer a comprehensive solution for localized power distribution by integrating both AC and DC components. Their versatility, adaptability, and capacity to leverage renewable energy sources make them suitable for various applications and environments. Hybrid microgrids play a crucial role in modern energy systems, contributing to reliability, efficiency, and sustainability while enhancing grid resilience.

2.4 Microgrid Modes

Microgrids can operate in two modes: islanded mode and grid-connected mode.

- **Islanded mode**

  The microgrid is completely independent of the main grid. This means that it must generate all of its own power and have its own energy storage system to provide power during peak loads or outages. Islanded microgrids are more resilient to outages and other disruptions, but they are also more expensive to build and operate.

- **Grid-connected mode**

  The microgrid is connected to the main grid. This means that it can draw power from the main grid when needed and sell excess power back to the main grid. Grid-connected microgrids are less resilient to outages and other disruptions, but they are less expensive to build and operate.

  In this mode, microgrids enable better control over energy generation and consumption within a localized area, also helping to manage peak demand and reduce stress on the grid during periods of high electricity consumption. This control can lead to optimized energy use, reduced losses during transmission, and overall higher energy efficiency.

  Microgrids can also facilitate the integration of electric vehicle charging infrastructure, enabling efficient charging and discharging of EV batteries while managing their impact on the grid.

Load Shedding in Islanded Mode

Load shedding in the context of local islanded microgrids refers to the controlled and temporary reduction or disconnection of electrical loads within the microgrid to match the available power generation capacity [2]. When a microgrid operates in islanded mode, it relies solely on its local energy resources, such as solar panels, wind turbines, and batteries, to meet the demand of its connected users. In some situations, the demand for electricity may exceed the microgrid's generation capacity, leading to an energy deficit. [6]

Load shedding is managed through a control system that continuously monitors the microgrid's energy supply and demand and triggers specific load shedding strategies if needed. Here's how load shedding works in the context of local islanded microgrids:

1. **Real-Time Monitoring:**
    - The microgrid's control system continuously monitors the power generation from local sources and the electricity demand from connected loads in real-time.
2. **Identifying Energy Deficit:**
    - If the demand for electricity exceeds the available local generation capacity, an energy deficit occurs. This may happen during periods of high energy consumption or when renewable energy generation is temporarily low due to weather conditions, such as cloudy skies or calm winds.
3. **Load Shedding Decision:**
    - To maintain the stability and resilience of the microgrid, the control system decides which non-critical electrical loads to shed or reduce temporarily. Non-critical loads are typically considered less essential for maintaining essential services or safety.
4. **Load Shedding Execution:**
    - The control system sends signals to disconnect or reduce the power to selected non-critical loads. This shedding of load helps to bring the demand back in line with the available generation capacity.
5. **Prioritization of Critical Loads:**
    - During load shedding, critical loads like hospitals, emergency services, and communication centers are prioritized to ensure they receive uninterrupted power supply.
6. **Load Restoration:**
    - Once the microgrid's energy supply and demand balance is restored or improved, the control system may gradually restore the disconnected or reduced non-critical loads.

Load shedding is a critical strategy in islanded microgrids to ensure energy stability, prevent blackouts, and protect the overall integrity of the system during periods of energy scarcity. Proper load shedding management requires careful planning, effective communication, and consideration of the needs of critical facilities to minimize the impact on users while maintaining the microgrid's functionality and reliability.

The best mode for a microgrid depends on the specific needs of the community or facility it serves. For example, an islanded microgrid may be a good choice for a remote community that is not well-connected to the main grid. A grid-connected microgrid may be a good choice for a community or facility that wants to take advantage of the benefits of renewable energy, but also wants to be able to draw power from the main grid when needed.

2.4.1 Mode Transition

The microgrid can switch between two primary modes: Grid-Connected Mode and Islanded Mode. The ability to transition between these modes relies on a control and management system integrated into the microgrid. Here's an overview of the switching process:

1. **Grid-Connected Mode:**
    - In this mode, the microgrid is connected to the main power grid, drawing electricity from it to meet its demand.
    - The control system continuously monitors the grid status for stability and quality. As long as the grid is operational and within acceptable parameters, the microgrid remains in grid-connected mode.
2. **Transition to Islanded Mode:**
    - If the control system detects an issue with the main grid, such as a blackout, voltage instability, or frequency deviations, it triggers a transition to islanded mode to ensure local power supply.
    - The microgrid control system activates switches that isolate the microgrid from the main grid, therefore using only local energy sources, such as solar panels, wind turbines, or generators to supply power.
3. **Islanded Mode:**
    - In this autonomous mode, the microgrid relies solely on its local energy resources to meet the demand of connected users.

- The control system continuously balances energy generation and consumption, ensuring that critical facilities receive power and the microgrid remains stable.

4. **Transition Back to Grid-Connected Mode:**
    - When the main grid stabilizes and returns to normal operation, the control system monitors its status and verifies its quality.
    - If the main grid meets predefined criteria for stability, the microgrid control system initiates a synchronization process. This process ensures that the microgrid's voltage and frequency match those of the main grid.
    - Once synchronization is successful and safe, the control system reconnects the microgrid to the main grid, and it resumes operating in grid-connected mode.

The successful switching between modes relies on robust control algorithms, sensors, and communication systems within the microgrid. Advanced automation and real-time monitoring are essential to ensure seamless switching and to protect the microgrid and its connected devices during the transition process. Additionally, careful planning and testing of the control system are crucial to ensure the microgrid's reliability and safety in various operating scenarios.

3 Microgrid Design

In this chapter, the microgrid components, settings and operation logic are explained.

3.1 Components

In order to develop the microgrid, some software and hardware tools were required. Firstly, the software allows for simulations of the different scenarios without needing the physical grid. After this phase, as the physical electrical grid was built, the software was finally programmed into real hardware.

3.1.1 Software

Before implementing a physical fully operational microgrid, a simulation environment within Schneider Electric's Machine Expert programming software was developed, to recreate possible real world situations. [8]

The load controlling algorithms have been implemented using the computer program EcoStruxure Machine Expert from Schneider Electric. This is the software used to configure and program the PLC, providing comprehensive support for IEC 61131-3 programming languages.

Structured Text, a high-level textual programming language similar to C, was selected for the PLC programming. This language enables the creation of program code using expressions and instructions, offering a wide range of programming loop constructs. Its versatility makes it well-suited for developing intricate algorithms.

Schneider Electric's ZelioSoft2 was also used to create and implement a functional on-site microgrid, utilizing FBD language. [8]

FBD is a graphical representation used in control systems engineering and industrial automation to depict the functional relationships between various components or blocks within a system. It is composed of interconnected blocks that represent specific functions or operations, such as sensors, actuators, controllers, and processes. Lines or arrows between the blocks indicate the flow of signals or data, illustrating how information or control signals move through the system. FBD is a powerful tool for designing and analyzing complex control systems, providing a clear visual representation of the system's functionality and facilitating the understanding of how different components interact to achieve a specific outcome or control task.

3.1.2 Hardware

The following hardware components were necessary to install the microgrid.

Energy Monitoring Devices

Energy monitors acquire data needed for the automation system, where it is processed and utilized for decision-making. Considering the specific requirements of the existing grid and the data needed for the microgrid's optimal functionality, two types of energy monitors were acquired:

- Carlo Gavazzi EM111DINAV81XS1PFA: single-phase energy analyzer with an LCD and a touch keypad; designed for active energy measurement; communication via the RS485 serial port, utilizing the Modbus RTU protocol in slave function mode.

- Carlo Gavazzi EM330DINAV53HS1X: three-phase energy analyzer with an LCD and a touch keypad; designed for active energy measurement; communication via the RS485 serial port, utilizing the Modbus RTU protocol in slave function mode.

Contactors

Contactors play a vital role in load shedding, as they control the activation and deactivation of circuits based on the automation system's output, both single and three-phase contactors will be employed.

PLCs

One chosen PLC is the Schneider Electric's Modicon M241 24 ES Relay Ethernet. This device offers 10 discrete outputs and 14 discrete inputs, having an Ethernet port, enabling communication via the Modbus protocol.

Schneider Electric's Zelio SR3 B261BD was also used to test a functional program on-site.

Photovoltaic and Energy Storage System

The Photovoltaic and Energy Storage System has the following main components:

- 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.

In this setup, the PV system does not inject energy into the grid and has an estimated annual production of around 5100 kWh. All the relevant information pertaining to the photovoltaic system, including batteries' state, generation, and inverter output, is monitored within the Cerbo Gx. This device will establish communication with the automaton. The photovoltaic inverter is responsible for maintaining the microgrid frequency at 50 Hz.

Figure 3.1: Photo of the On-Site Installation.

1. Victron MultiPlus II 3000VA Inverter/Charger
2. Victron SmartSolar MPPT 150/35 Charge Regulator;
3. Victron Cerbo Gx
4. Network Cabinet
5. PLC, Contactors, Energy Monitors
6. Pylontech US3000 Battery, 10.5kWh
7. Fuse Boxes

Another Energy Storage System (ESS) was already installed, three LG RESU10H lithium-ion batteries, part of the existing grid.

Contactor	**5**	**4**	**7**	**2**	**6**	**8**	**3**
Description	Lighting Circuit L9 (Ext)	Lighting Circuits L4, L3	Lighting Circuit L6, L8	Plug Circuit 1	Lighting Circuit L5, L7	Lighting Circuit ISR 1, 2	Plug Circuit 2
Power (W)	252	546	420	0-3680	588	472	0-3680
Priority Level	1	2	3	4	5	6	7

Table 3.1: Load Priority Level Table.

3.2 Load Characterization

Table 3.1 defines the priority level that will be used to decide whether and when to shed the different loads. A higher priority level means it will be shed later, when in island mode. In this table, it is also possible to identify the different circuits, their respective contactor, their absorbed power and priority level.

A priority level classification is used to decide whether and when to shed the different loads. The priority level assigned to each contactor, from 1 (lower priority) to 7 (higher priority), depends on the maximum expected load of each contactor and the relevance of that load to the users.

There are a few more circuits that cannot be switched off and where the critical loads (garage gate, minimum safety lighting, computer network cabinet, PLC) are connected. These circuits have a higher priority than all the others.

3.3 Block Diagram

The architecture of the microgrid was developed considering solar photovoltaic generation, storage, and load management. Because the microgrid is supposed to deliver power during critical and disaster situations, that is, when there is a power outage, it is mandatory to allow its operation in island mode. This is achieved using a contactor controlled by a PLC to disconnect the microgrid from the main grid.

In Figure 3.2, the electrical block diagram of the microgrid that is being implemented as a pilot installation is shown.

3.4 Operation Logic

The microgrid uses one energy monitor to check if there is power on the main grid and determine if it should stay in connected mode or switch to island mode. Two other energy monitors check the power being absorbed at contactors 2 and 3, the microgrid's plug circuits. Contactors 4 to 8 are all connected to different light circuits, while contactor 9 is connected to the 3-phase loads.

The photo-voltaic system is mainly composed of 6 PV panels, a 3 kVA inverter, 10.5 kWh batteries.

When a power outage is detected, contactors 1 (main grid connection), 9 (3-phase loads) and 11 (PV system's batteries charging from the grid) are deactivated. Next, contactor 10 is activated, connecting the PV system's inverter to the three phases of the bus bar. The three phases are now operating as a single-phase system.

When there is power on the main grid, all the loads are supplied.

When a power outage occurs, the microgrid enters in island mode and the following variables are verified: PV generation, battery SOC and time elapsed since the outage. After, the PLC program decides which loads need to be shed and which can keep being supplied, with the goal of keeping the higher priority loads supplied for at least one hour.

When the battery SOC falls below 20% and there is no main grid power, the loads are all shed. If there is enough PV generation and SOC rises above 20%, the loads are gradually supplied again.

When the main grid power returns, an inverse restoration sequence takes place and all the loads are supplied again.

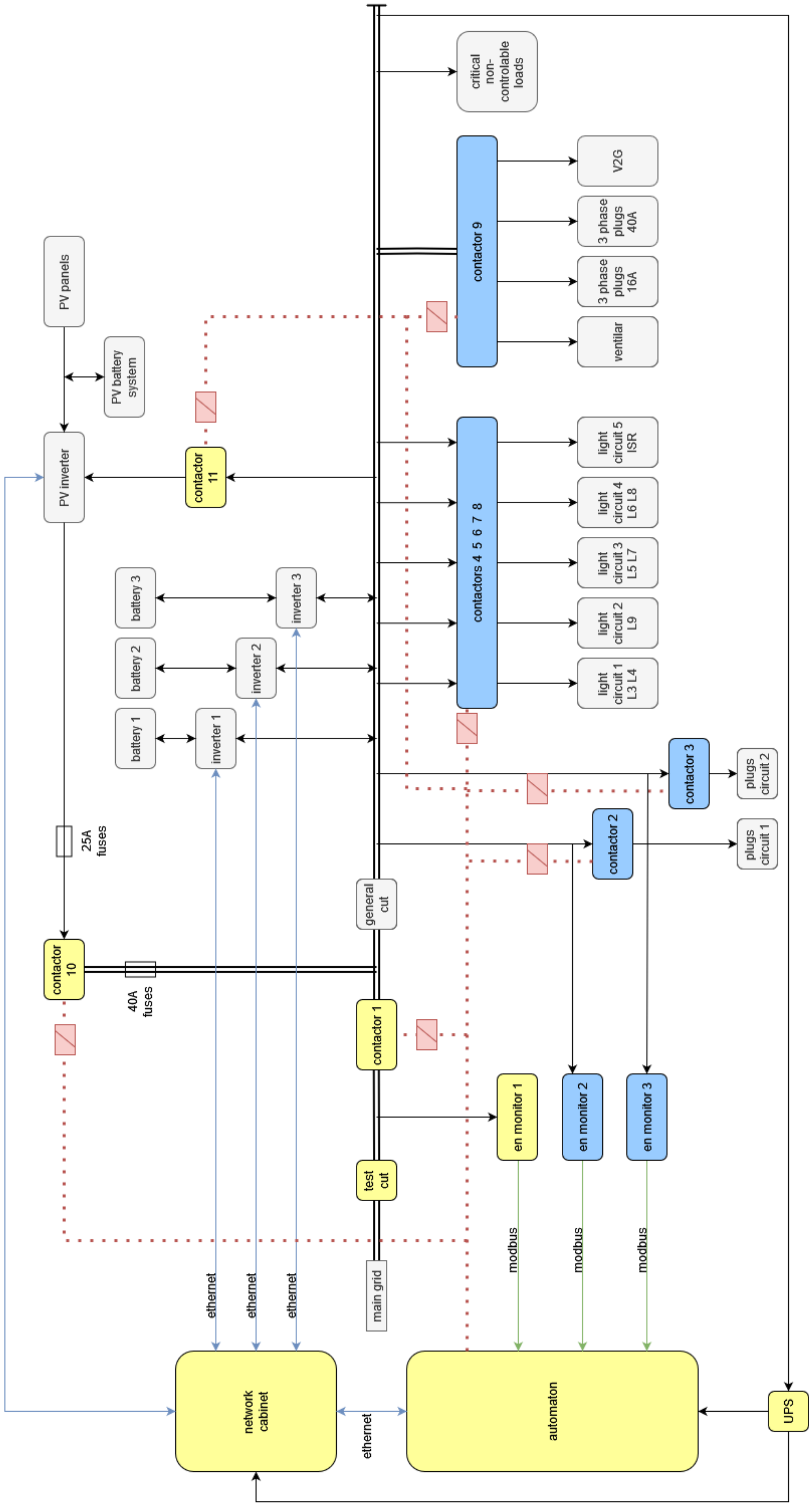


Figure 3.2: Block Diagram of the Microgrid.

4 Microgrid Control

The microgrid operation, for the simulation environment and for the on-site environment are explained during this chapter. The obtained results are presented and described.

4.1 Control Variables

The variables used to control the microgrid are updated in a cyclic manner, in order to ensure the best control possible for every stage of a given situation. These variables have the following values:

PO:

- 0, if at least main grid phase is under 190V.
- 1, if no main grid phase is under 190V.

SOC

- 0, if the battery system has over 20% capacity;
- 1, if the battery system has under 20% capacity.

T:

- 0, if the time since PO is under 1 minute;
- 1, if the time since PO is between 1 minute and 1 hour;
- 2, if the time since PO is over 1 hour;

PMAX:

- 0, if the maximum power that can be supplied for the microgrid to last at least one hour after the PO is under 974W.
- 1, if the maximum power that can be supplied for the microgrid to last at least one hour after the PO is between 974W and 2400W.
- 2, if the maximum power that can be supplied for the microgrid to last at least one hour after the PO is over 2400W.

These values were chosen because 974 W is the necessary power to supply the non-controllable critical loads and 2400 W represents 80% of the PV system's inverter capacity.

The maximum power that can be supplied for the microgrid to last at least one hour is:

$$pmax = PV + \frac{Ebatt}{1 - tpo} \tag{4.1}$$

Given:

$$Ebatt = (soc\% - 20\%).10500Wh \tag{4.2}$$

- PV: power from the PV system (W);
- Ebatt: energy available in the battery system (Wh);
- tpo: elapsed time since the PO (h);
- soc: battery system's SOC (%);
- 10500Wh: maximum battery system energy capacity.

4.2 Microgrid States

In order to understand the microgrid control, it is necessary to analyze it's state machine diagram.

Table 4.1: State Transitions Table.

STATES	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11
S1	-	-	-	-	-	-	-	PO=1	-	-	-
S2	-	-	-	-	-	-	1	-	-	-	-
S3	-	-	-	-	-	1	-	-	-	-	-
S4	-	-	-	-	PO=1 and SOC=1 or PMAX=0	-	-	-	-	PO=0	-
S5	-	-	-	PO=1 and SOC=0 and PMAX0	-	-	-	-	-	PO=0	-
S6	-	-	PO=1 and SOC=0 and PMAX0 and T=1 and S3 TIMER=0	PO=1 and SOC=0 and PMAX 0 and T=2	PO=1 and SOC=1 or PMAX=0	-	-	-	-	PO=0	-
S7	-	-	PO=1 and SOC=0 and PMAX0 and T=1	-	PO=1 and (SOC=1 or PMAX=0)	-	-	-	-	PO=0	-
S8	-	-	-	-	-	-	-	-	1	-	-
S9	-	SOC=0 and PMAX=2	SOC=0 and PMAX=1	-	SOC=1 or PMAX=0	-	-	-	-	-	-
S10	-	-	-	-	-	-	-	-	-	-	1
S11	1	-	-	-	-	-	-	-	-	-	-

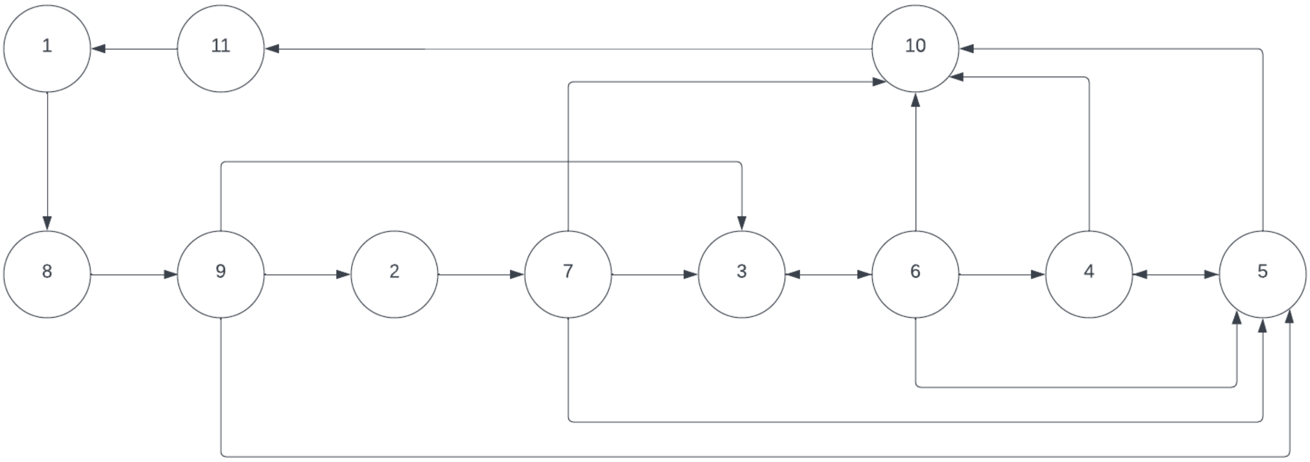


Figure 4.1: State Machine.

The provided table serves as a state transition diagram, depicting transitions between different states within the microgrid. The table utilizes rows and columns to denote the specific states, labeled as S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, and S11.

- Columns (Top Row): The top row of the table showcases the labels for destination states, signifying possible transitions from the current state.
- Rows (Leftmost Column): The leftmost column consists of labels representing the source states, revealing the current state of the system.
- Cells: The cells within the table signify transitions between source and destination states. The "1" in a cell signifies an unconditional transition from the source state to the destination state.

4.2.1 States Description

In this section, the logic of each program state is described.

State 1: On-grid Mode

In this state the microgrid is in grid connected mode. Contactor 10 is off and Contactor 1 and 11 are 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, the program switches 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, the program remains in this state.

State 8: On-grid to Islanded mode (1/2)

There has been a power outage on the main grid and the transition to islanded mode starts, state 8 is the first of two states in this transition.

All contactors are off and a timer is set. This timer ensures that contactor 10 is not turned on until contactors 1 and 11 are turned off. The timer must exceed the contactor response time. After these actions, it advances to state 9.

State 9: On-grid to Islanded mode (2/2)

State 9 is the second of two states that makes the transition from grid connected mode to island mode. The program checks if the timer set in state 8 has reached 0, if so, contactor 10 is turned on. Then:

- if batteries SOC exceeds 20%, 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, it switches to state 2;
- if the batteries SOC exceeds 20% but the maximum power that can be supplied is over 974 W and under 2400 W, it switches to state 3;
- if the batteries SOC is less than 20% or if the maximum power that can be supplied is under 974 W, it switches to state 5.

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

State 2: Supply Maximum Loads for one minute (1/2)

The transition from on-grid to islanded mode is done. In this state, it supplies the maximum loads possible for at least 1 minute since power outage occurs. Contactors 4, 5 and 7 are turned off, because of the inverter capacity, and will be kept this way in islanded mode, as these are the circuits with the lowest level of priority. The remaining contactors are turned on, according to their priority level and the available power. To decide whether to turn on contactor 3 or not, the program evaluates the information recorded prior to the power outage. If the recorded power value is over 1426 W, contactor 3 is not turned on, as that is the maximum power defined for that contactor. After these actions, it updates the power absorbed stored values and switches to state 7.

State 7: Supply Maximum Loads for one minute (2/2)

For the first minute after the power outage, the program checks several conditions to evaluate if it should switch it's state or remain in the same state. During this minute, if additional loads are connected to the plug circuits, it turns off the circuits in which that happened.

- if the power is back on the main grid, it switches to state 10.
- if the batteries SOC is under 20% or if the maximum power that can be supplied is less than 974 W, state switches to state 5.
- if the previous conditions are not met, and if more than 1 minute has passed since the power outage, it switches to state 3.

State 3: Load Management for the Microgrid to last one hour (1/2)

The program calculates the power that is being absorbed and compares it to the maximum power that can be supplied, for the microgrid to last at least 1 hour after the power failure.

- if the absorbed power is over the available power, some loads need to be shed by level of priority, until the absorbed power is less than the power available.
- if the absorbed power is less than the available power, the program checks if there are loads that can be supplied without exceeding the available power, if so, they will be switched on according to their priority. Then, a timer is set to evaluate again. It switches to state 6.

State 5: Stand-by Mode

The microgrid is not connected to the main grid or the PV system, all contactors are off.

- if there is energy on the main grid, the program switches to state 10;
- if there is no energy on the main grid, the battery status and the maximum power to be supplied to the loads are checked;
- if the batteries' SOC exceeds 20% and the value of the maximum power that can be supplied to the loads is greater than 974 W, the program switches to state 4.

If none of these conditions are met, the program remains in state 5 until the conditions change.

State 10: Islanded to On-Grid Mode (1/2)

The first of two states that makes the transition from islanded to grid connected mode. There is power on the main grid and the microgrid is disconnected from the main grid. All contactors are off and a timer is set. This timer serves as a protection to ensure that contactor 1 and 11 are not turned on until contactor 10 is turned off. The timer must exceed than the contactor response time. After these actions, it advances to state 11.

State 11: Islanded to On-Grid Mode (2/2)

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 so, contactor 1 is turned on and it switches to state 1.
- if not, it remains in this state until timer reaches 0.

State 6: Load Management for the Microgrid to last one hour (2/2)

A check is made to ensure that the power in the plug circuits does not exceed the maximum allowed.

- if the power in the main grid is back, it switches to state 10.
- if the batteries SOC is lower than 20%, or if the maximum power that can be supplied is lower than 974 W, it switches to state 5.
- if more than 60 minutes have passed since the power outage and the maximum power that can be supplied is over 974 W, the next state is state 4.

The conditions above are checked until the timer 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, it switches to state 3.

State 4: Supply only critical Non-controllable Loads

The microgrid should stay in this state until the power in the main grid is back, or until the batteries SOC drops under 20%, or if there is no capacity. 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 batteries SOC drops under 20%, or if the maximum power that can be supplied is lower than 974 W, it switches to state 5.

4.3 Simulation Environment

Two videos with specific simulation scenarios were created to demonstrate the microgrid operation when there is a power outage on the main grid. They served as the project's presentation support in May 2023, for I&CPS 2023, in Las Vegas, Nevada, United States of America.

They can be watched through the following links:

- daytime scenario: https://youtu.be/TwyvxQQK-cc
- nighttime scenario: https://youtu.be/QSKp5tBc9Mw

To observe the microgrid's behavior, a monitoring panel was developed, to show the state of inputs (energy monitors' readings, PV generation and battery state), and outputs (contactors ON or OFF and the required variables for the program to work).

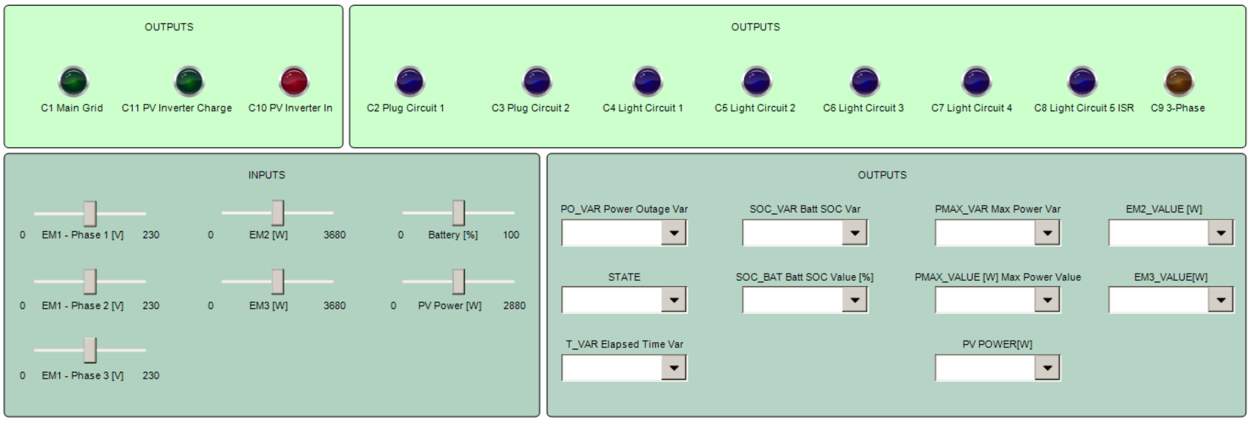


Figure 4.2: Simulation Interface.

To understand how to simulate using this software, follow the instructions given in the Appendix.

4.4 Simulation Results

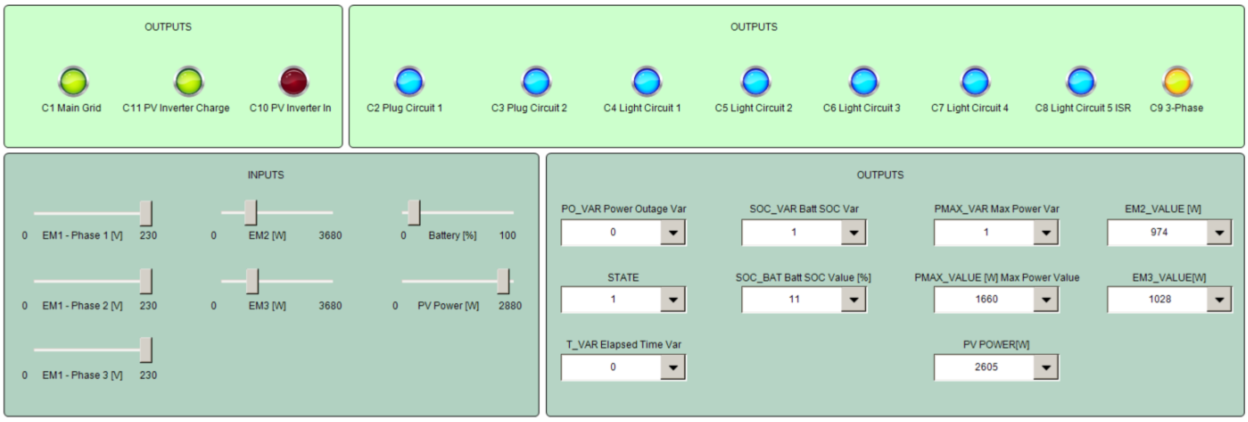
In order to show the operating simulated microgrid, different and common expected situations are represented by the changing variable values, which represent several conditions, that are interpreted by the PLC.

In the following graphs, the vertical axis represents the variable value and the horizontal axis represents the time.

The variables' names are preceded by GVL, which stands for Global Variable List, in Machine Expert.

4.4.1 Initial On-Grid Operation

In regular circumstances, the microgrid is operating On-Grid, connected to the main grid. Therefore, all the loads are being supplied by the main grid, as seen by the contactors' lights being lit up in figure 4.3.



PO_VAR Power Outage Var
0

SOC_VAR Batt SOC Var
1

PMAX_VAR Max Power Var
1

EM2_VALUE [W]
974

STATE
1

SOC_BAT Batt SOC Value [%]
11

PMAX_VALUE [W] Max Power Value
1660

EM3_VALUE[W]
1028

T_VAR Elapsed Time Var
0

PV POWER[W]
2605

Figure 4.3: On-Grid Operation.

4.4.2 Power Outage Detection

The following graph confirms that the program detects a power outage only when at least one of the three phases of the main grid connection, analyzed by the Energy Monitor number 1, drops below 190 V.

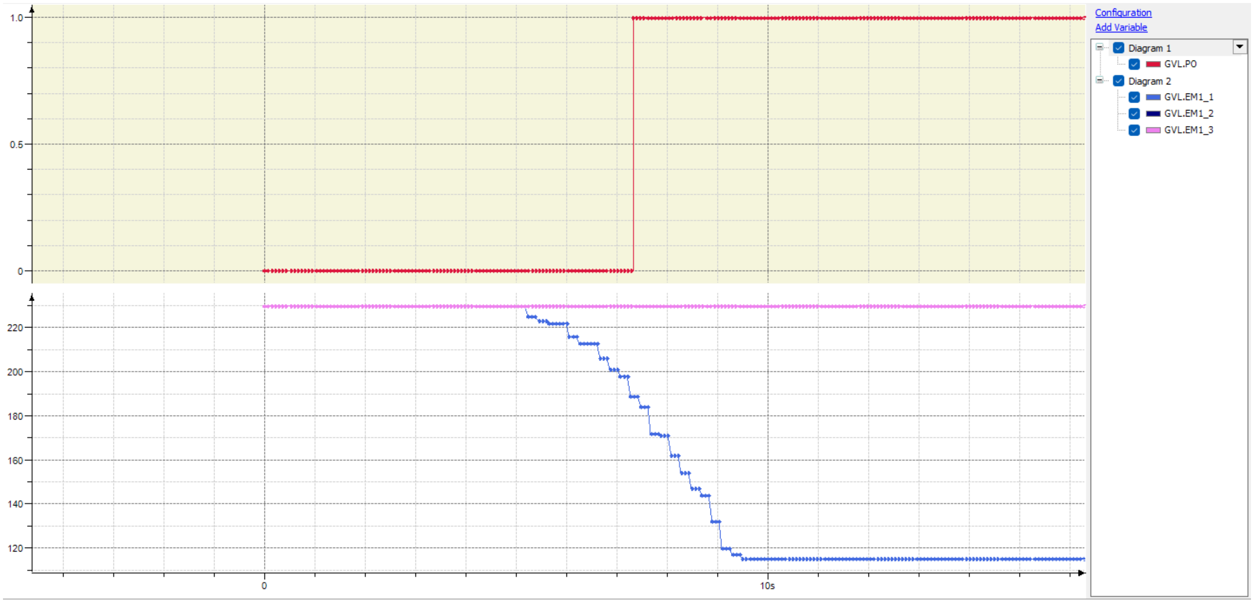


Figure 4.4: Power Outage Detection (One Phase Outage).

As we can see in figure 4.4, at around the 7 seconds mark, the value of one of the three phases, in this case GVL.EM1_1, seen in blue, drops below 190, therefore, the power outage variable value, GVL._PO, rises from 0 to 1, indicating that a power outage has occurred.

4.4.3 On-Grid to Islanded Mode Transition

When the power outage occurs, at around the 4s360ms mark, as the red diagram shows the PO variable value going from 0 to 1, it is possible to see that the Main.STATE variable follows this path:

1. switch from state 1 to state 8, as a power outage has occured;
2. switch from state 8 to state 9, after confirming that contactors 1 and 11 are turned off;
3. switch from state 9 to state 2, after checking that, in this case, the batteries' SOC exceeds 20%, that the time after PO is under 1 minute and maximum power that can be supplied is greater or equal to 2400 W;
4. switch from state 2 to state 7, as, after the first minute since the PO, the main grid power is not back, the batteries' SOC is over 20% and the maximum power that can be supplied is over 974 W.

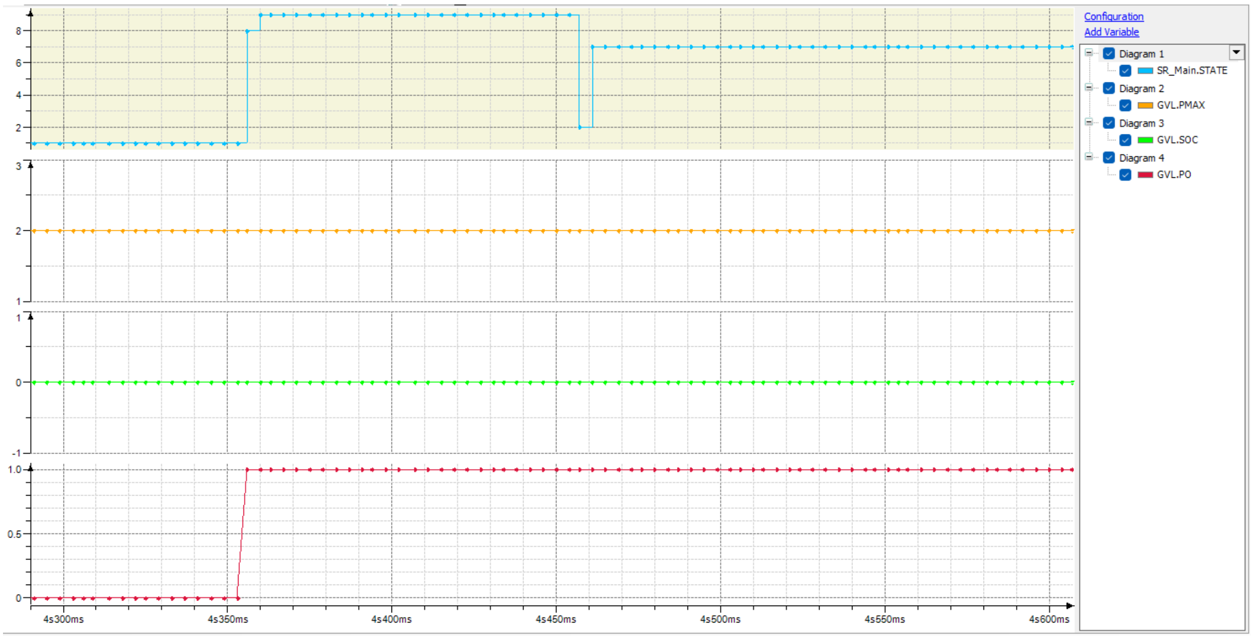
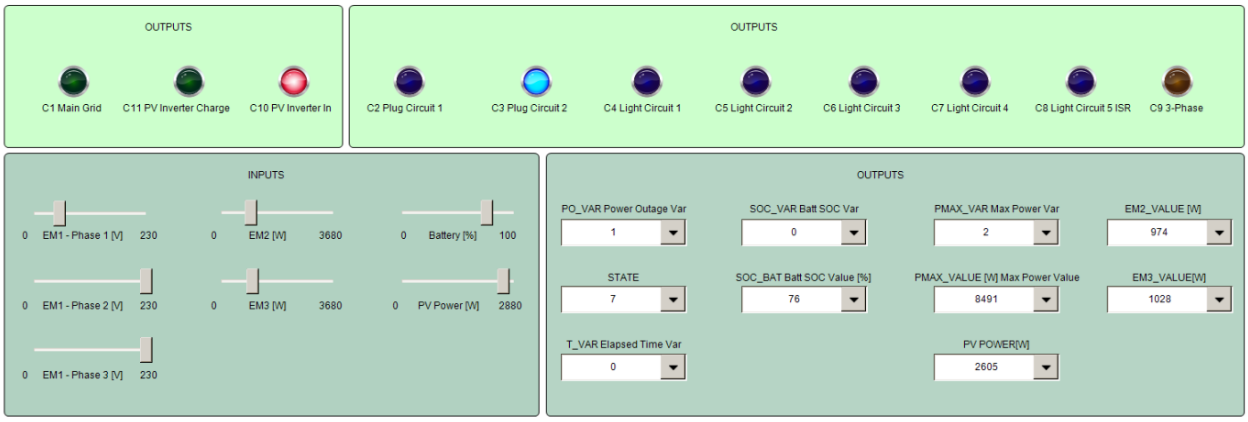


Figure 4.5: Microgrid's reaction to the power outage.

4.4.4 Islanded Mode Operation

As we can defer from figure 4.6, for the first minute after the PO, contactor 3 has been turned on as he recorded power value is under 1426 W and it is the highest priority level contactor.



PO_VAR Power Outage Var
1

SOC_VAR Batt SOC Var
0

PMAX_VAR Max Power Var
2

EM2_VALUE [W]
974

STATE
7

SOC_BAT Batt SOC Value [%]
76

PMAX_VALUE [W] Max Power Value
8491

EM3_VALUE[W]
1028

T_VAR Elapsed Time Var
0

PV POWER[W]
2605

Figure 4.6: Control Panel for the first minute after PO.

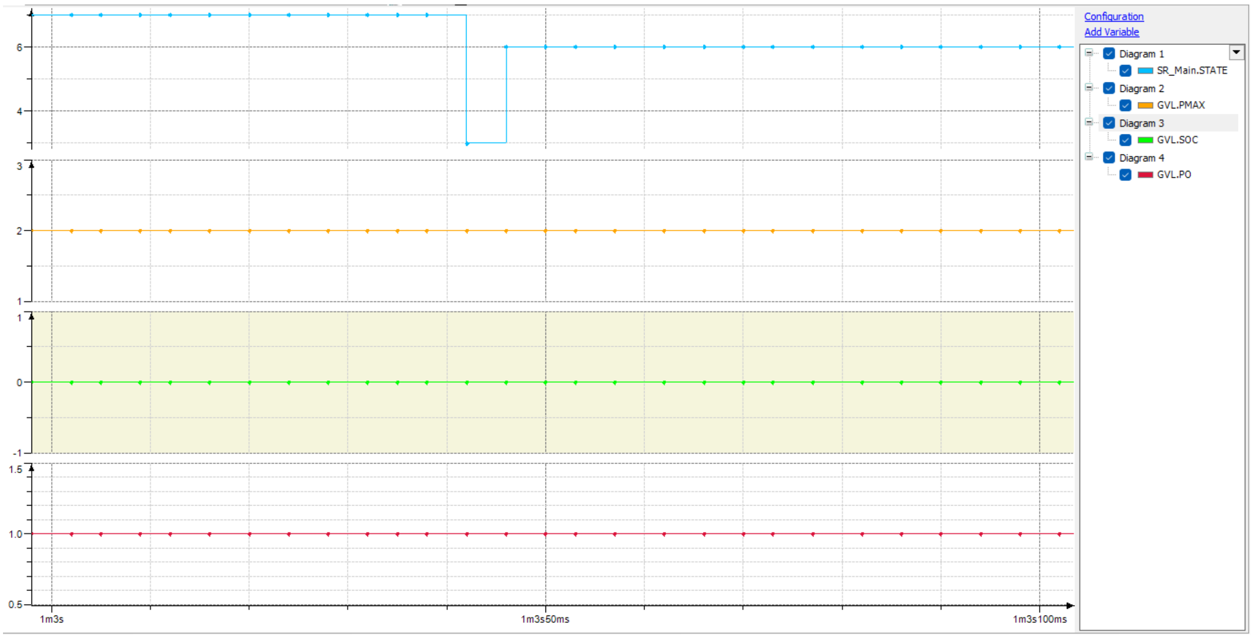


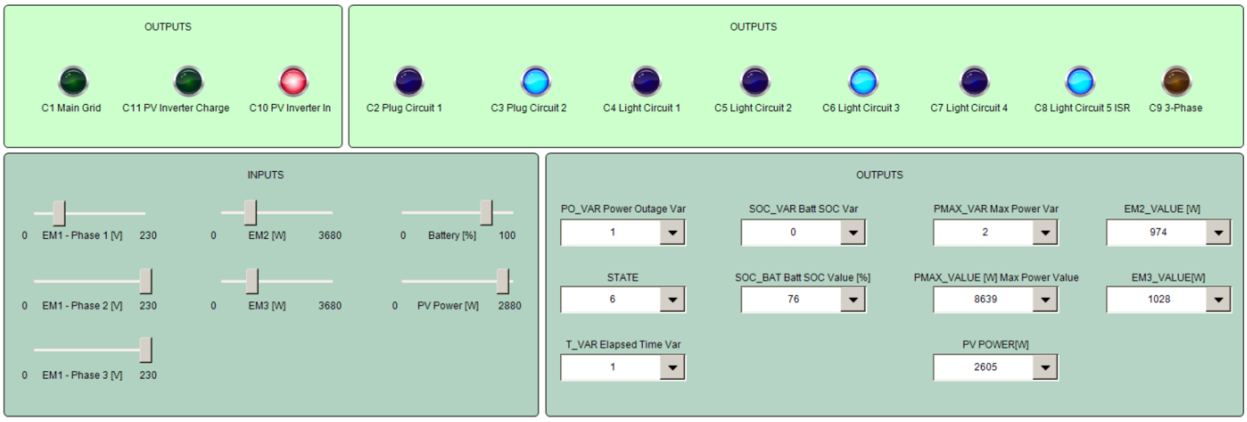
Figure 4.7: After the first minute since the PO.

When the first minute since the power outage has passed, the microgrid reacts in the following manner:

1. switch from state 7 to state 3, as the power is not back in the main grid and the batteries' SOC is still over 20% and the maximum power that can be supplied is over 974 W;

2. switch from state 3 to state 6, as the absorbed power does not exceed the availabe power.

Then, the microgrid switches on the possible loads, without exceeding the available power, this is done according to each load's priority level. In this case, contactors 6 and 8 have been turned on, as shown in figure 4.8, which, after contactor 3, are the second and third highest level contactors.



PO_VAR Power Outage Var: 1
SOC_VAR Batt SOC Var: 0
PMAX_VAR Max Power Var: 2
EM2_VALUE [W]: 974
STATE: 6
SOC_BAT Batt SOC Value [%]: 76
PMAX_VALUE [W] Max Power Value: 8639
EM3_VALUE[W]: 1028
T_VAR Elapsed Time Var: 1
PV POWER[W]: 2605

Figure 4.8: While in state 6, after the first minute.

If, at any time, Energy Monitor 3, reading the Plug Circuit 2, which is connected to contactor 3, reads a value that is over 1426 W, contactor 3 is turned off, as we can see in the following graph.

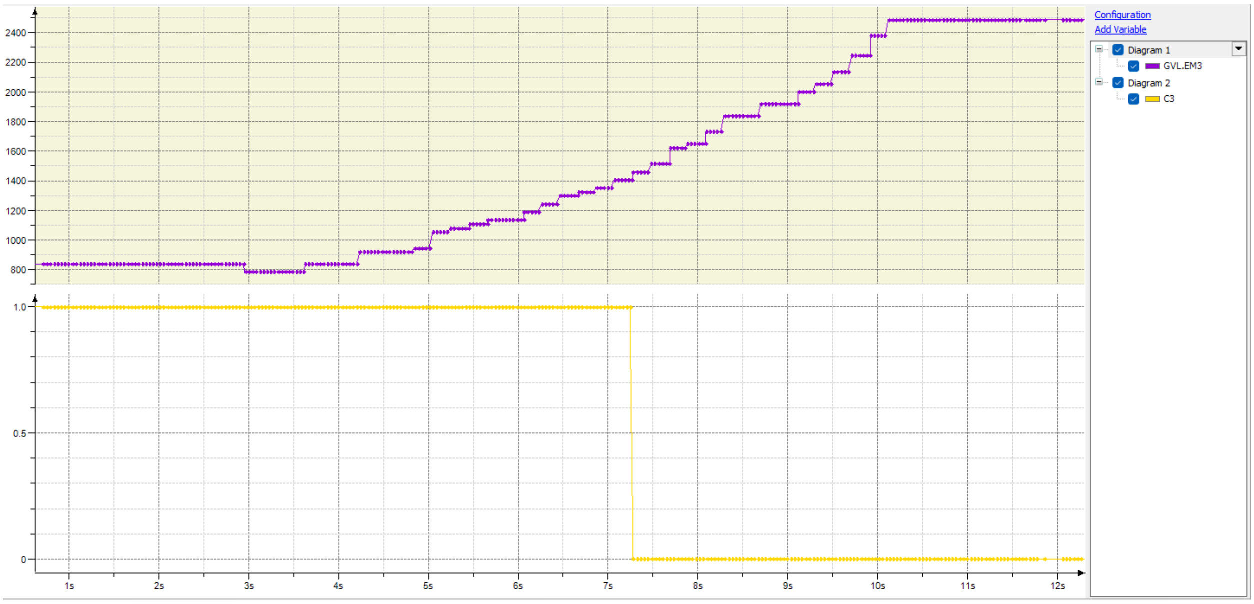
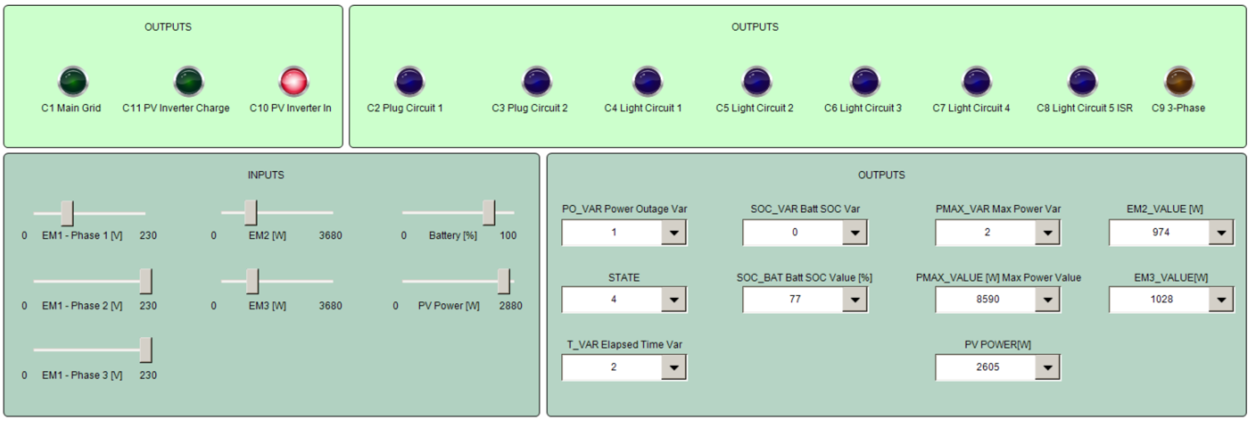


Figure 4.9: Plug Circuit 2 (contactor 3) Power Exceeds 1426 W.

After the first hour since PO, the microgrid switches from state 6 to state 4, supplying only the non-controllable critical loads, as shown in figure 4.10.

It remains there, in this case, because the power is not back in the main grid and the batteries SOC have not dropped under 20%, nor the maximum power that can be supplied is lower than 974 W, as demonstrated in figure 4.11.


OUTPUTS

C1 Main Grid
C11 PV Inverter Charge
C10 PV Inverter In

OUTPUTS

C2 Plug Circuit 1
C3 Plug Circuit 2
C4 Light Circuit 1
C5 Light Circuit 2
C6 Light Circuit 3
C7 Light Circuit 4
C8 Light Circuit 5 ISR
C9 3-Phase

INPUTS

0 EM1 - Phase 1 [V] 230
0 EM2 [W] 3680
0 Battery [%] 100
0 EM1 - Phase 2 [V] 230
0 EM3 [W] 3680
0 PV Power [W] 2880
0 EM1 - Phase 3 [V] 230

OUTPUTS

PO_VAR Power Outage Var: 1
SOC_VAR Batt SOC Var: 0
PMAX_VAR Max Power Var: 2
EM2_VALUE [W]: 974
STATE: 4
SOC_BAT Batt SOC Value [%]: 77
PMAX_VALUE [W] Max Power Value: 8590
EM3_VALUE[W]: 1028
T_VAR Elapsed Time Var: 2
PV POWER[W]: 2605

Figure 4.10: Only the non-controllable critical loads are supplied.

Figure 4.11: After the first hour since PO.

After using the battery until it's SOC drops below 20%, the microgrid switches from state 4 to state, as shown in figure 4.12.

When the SOC variable value switches from 0 to 1, the Main.STATE variable switches from 4 to 5, and the PMAX variable switches from 2 to 1.

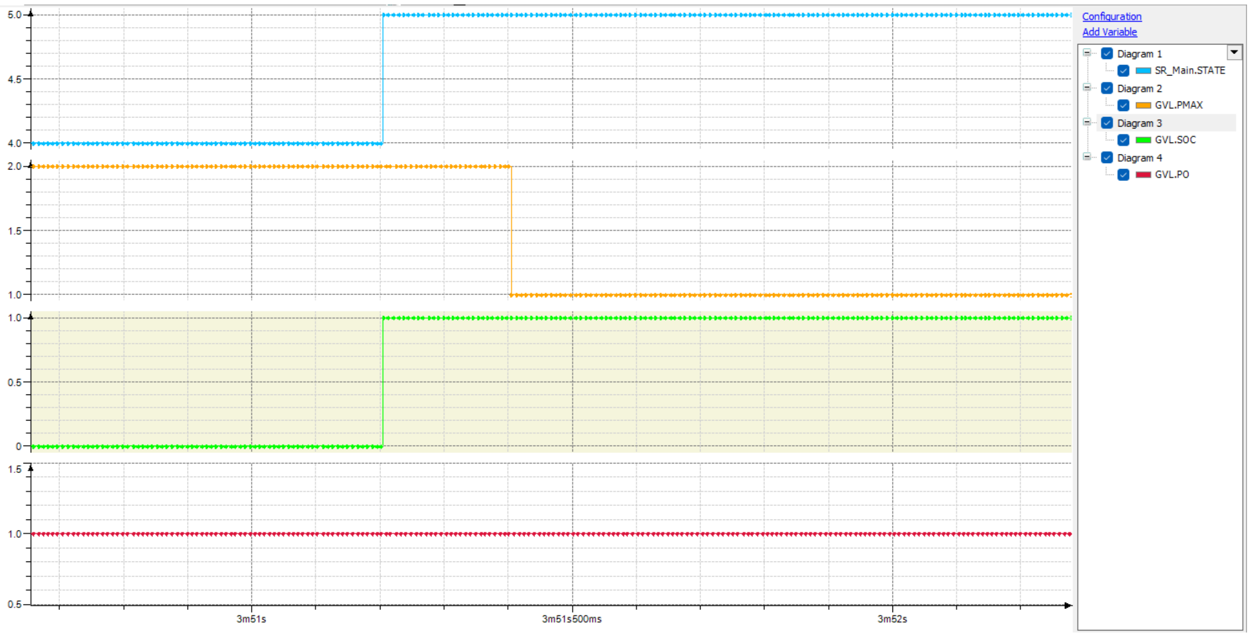


Figure 4.12: Transition from state 4 to state 5.

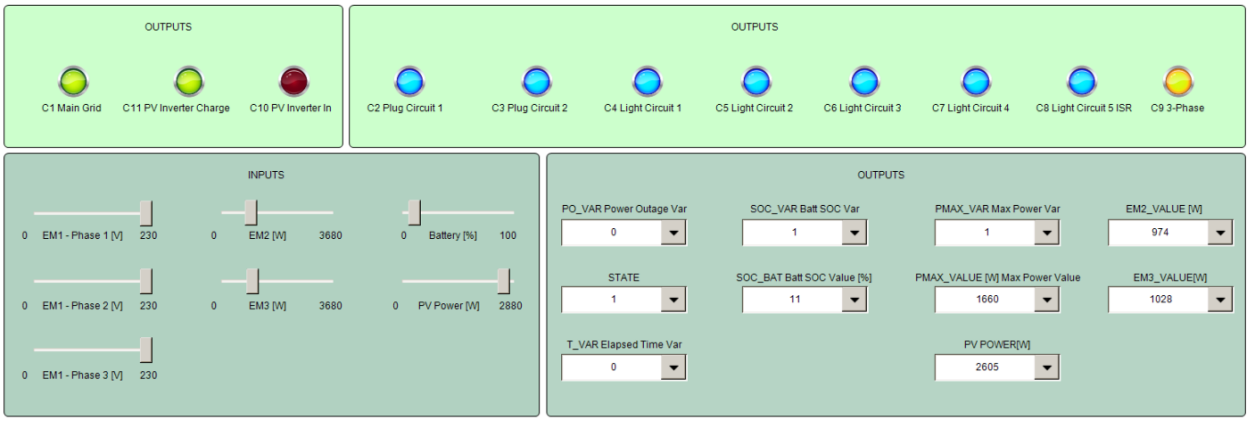
4.4.5 Islanded Mode to On-Grid Transition

As the power is back in the main grid, the microgrid returns to the On-Grid operation, as seen in figure 4.13, by switching states in the following way:

1. switch from state 5 to state 10, as there is energy on the main grid;
2. switch from state 10 to state 11, after a timer is set to serve as a protection to ensure that contactors 1 and 11 are not turned on until contactor 10 is turned off. The timer must exceed than the contactor response time;
3. switch from state 11 to state 1, as the timer that was set in state 10 has reached 0, so contactor 1 is turned on.

Figure 4.13: Transition from state 5 to state 1 (On-Grid).

After this transition is completed we can confirm that the microgrid operates as it did before the PO, by examining figure 4.14.



PO_VAR Power Outage Var: 0
SOC_VAR Batt SOC Var: 1
PMAX_VAR Max Power Var: 1
EM2_VALUE [W]: 974
STATE: 1
SOC_BAT Batt SOC Value [%]: 11
PMAX_VALUE [W] Max Power Value: 1660
EM3_VALUE[W]: 1028
T_VAR Elapsed Time Var: 0
PV POWER[W]: 2605

Figure 4.14: On-Grid Operation.

All the loads are being supplied by the main grid, the way they were before the PO.

4.5 On Site Tests

In this section, the on-site tests' planning and implementation is described.

4.5.1 On Site Tests' Planning

Firstly, the goal was to implement a simple program that would be useful in case of an emergency, to ensure the physical components are correctly integrated, the communication method and protocol are functional and that it is safe to control the grid in the intended way.

In the case of an emergency, turning on lights and opening the garage gate permanently are important safety measures for several reasons:

- **Visibility and Evacuation:** Emergencies often create chaotic and stressful situations. Inadequate lighting can make it difficult for people to see clearly, hindering their ability to navigate safely and quickly. Turning on lights ensures that occupants can easily identify exit routes, obstacles, and potential hazards. It facilitates a smoother and more efficient evacuation process, reducing the risk of accidents or injuries.
- **Access for Emergency Services:** Emergency responders, such as firefighters, paramedics, and law enforcement, may need immediate access to the garage to address the situation. Keeping the garage gate open ensures that these responders can enter the building without delay. Delayed access can impede their ability to provide assistance and may have severe consequences in life-threatening situations.
- **Ventilation:** Some emergencies, such as fires or the release of hazardous gases, can result in poor air quality within the garage. Opening the garage gate helps with ventilation by allowing fresh air to enter and potentially removing toxic fumes. This can be critical for the health and safety of individuals within the building.
- **Communication:** In an emergency, it may be necessary for occupants in the garage to communicate with emergency personnel or building management. Open garage gates make it easier for occupants to signal for help, provide information about the situation, or receive instructions from responders through visual and auditory means.

- **Alternative Exit Routes:** The garage may serve as a primary or secondary exit route for building occupants. In some cases, occupants may be directed to the garage as a safe refuge area during specific emergencies, such as severe weather or building fires. Having the garage gate open allows occupants to access this designated area for safety.
- **Preventing Trapped Individuals:** If the garage gate remains closed during an emergency, it can trap individuals inside the garage, cutting off their means of escape. This can be particularly dangerous if there are no other exit options within the garage. Keeping the gate open ensures that people have a way to exit and seek safety.

To do so, the created program detects a possible power outage and, when it happens, turns on light contactors and opens the garage gate.

4.5.2 On Site Tests' Implementation

To test the created program, a program in FBD was created, using the software ZelioSoft2. This program was uploaded to the PLC via a laptop running the system monitorization, Schneider Electric's Zelio SR3 B261BD.

The PLC’s inputs are:

- **I1:** main grid power outage reading;
- **I2:** battery system connection;
- **I3:** energy monitor 1, 1st phase;
- **I4:** energy monitor 1, 2nd phase;
- **I5:** energy monitor 1, 3rd phase;
- **I7:** CO2 sensor (not functional).

The PLC’s outputs are:

- **Q3:** gate’s contactor;
- **Q4:** gate’s light circuit contactor;
- **Q5:** parking path light circuit contactor;
- **Q8:** ventilation circuits contactors (not functional).

When there is power available in the the battery system and the main grid power runs out the following occurs:

1. the gate’s light circuit contactor and garage parking path’s light circuit contactor are turned on, to ensure there is some visibility, while not draining as much power from the battery system as turning on all the light circuits would;
2. after waiting 20 seconds, in order to ensure the the power outage is not of short duration, the garage gate opens and stays open for as long as there is no power in the main grid.

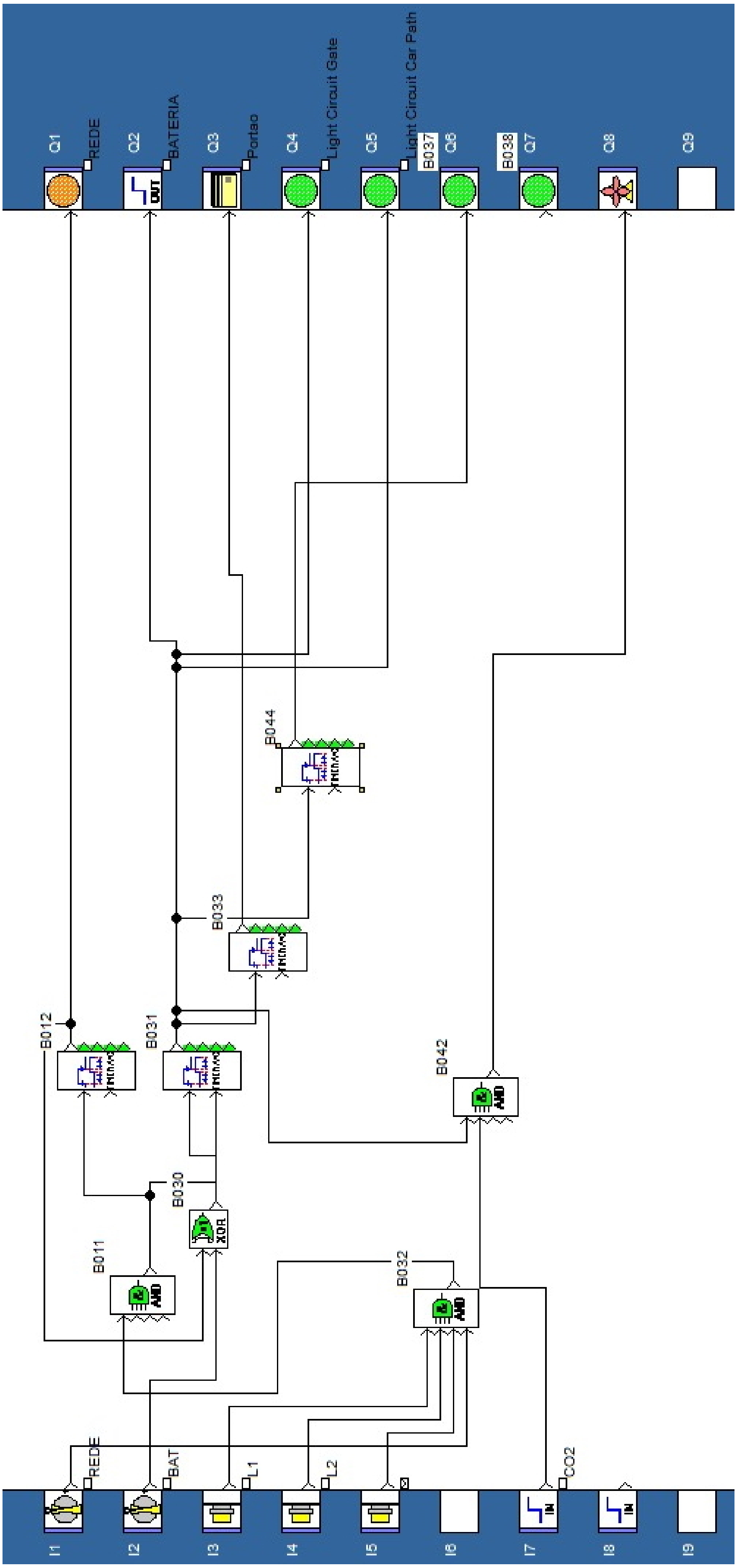


Figure 4.15: FBD Program.

5 Discussion

The results gathered throughout this dissertation are discussed and sumarized below.

5.1 Discussing the Simulated Results

After exploring and analyzing the performance of a microgrid system within a simulated environment. The simulation results presented throughout this research provide evidence that the microgrid functions as intended and effectively manages energy resources to meet various operational states and demands. In particular, the example path through some of the microgrid's states serves as an illustration of its resilience and adaptability.

The key findings and contributions of this study can be summarized as follows:

1. **Effective Microgrid Functionality:** The simulation results clearly demonstrate that the microgrid system is capable of efficiently managing energy resources, responding to changes in demand, and maintaining grid stability. This effectiveness is essential for ensuring uninterrupted power supply and energy management in real-world scenarios.

2. **Adaptability to Varied States:** The example path traversing multiple microgrid states underscores the adaptability and versatility of the system. It showcases how the microgrid seamlessly transitions between different operational states, such as power generation, storage, and distribution, to meet the varying needs of the connected loads.

3. **Resilience and Reliability:** The consistent performance of the microgrid throughout the simulation reinforces its reliability and resilience. These qualities are of paramount importance, especially in scenarios where grid disruptions, renewable energy integration, and load fluctuations are prevalent challenges.

In conclusion, the simulation results validate the functionality and efficacy of the microgrid system in a controlled environment. However, it is essential to acknowledge that on-site implementation may introduce additional complexities and variables that require further investigation and validation. Nevertheless, this research serves as a valuable foundation for future studies and practical applications.

5.2 Discussing the On-Site Results

In this dissertation, the primary objective of implementing a functional microgrid program. This program was designed to ensure the seamless integration of physical components, the robust functionality of communication methods and protocols, and the establishment of a safe mechanism for controlling the microgrid in critical emergency scenarios.

5.2.1 Validation through On-Site Tests

The culmination of our efforts was the execution of on-site tests, a critical phase in confirming the microgrid's functionality during emergency situations. These tests rigorously evaluated the program's ability to detect power outages and trigger the necessary actions.

The on-site tests confirmed that the microgrid operates as anticipated in response to intended emergency cases. The program effectively detects power outages and responds promptly by activating light contactors and opening the garage gate. This successful validation is a testament to the program's reliability and its potential to significantly enhance emergency preparedness and response.

6 Conclusions and Future Work

In conclusion, the culmination of this research and development efforts has yielded promising results. The comprehensive simulation we conducted demonstrates the viability and effectiveness of our microgrid concept. This successful simulation lays the foundation for on-site applications, reaffirming our confidence in the practicality of our approach.

Furthermore, the physical electric installation, designed and implemented based on the simulation's findings, has proven its functionality in a tangible and measurable manner. This achievement underscores our design's potential for scalability and adaptability to a variety of settings and environments.

The on-site tests, conducted under real-world conditions, have provided encouraging outcomes, further validating the potential of our microgrid system.

With the current progress in mind, our microgrid system is developing as expected. As we move forward, it is important to continue refining our concept to meet the project's challenges.

A key factor for future work is advanced testing and optimization, expanding the scope of on-site tests and fine-tuning the system for peak efficiency will be a critical step. This includes exploring various load scenarios and enhancing the microgrid resilience. One example of possible future work is adding a CO2 sensor to, in case of fire, for example, be activated, for the program to turn on all the ventilation systems, therefore circulating fresh air coming in from the garage gate to the whole DEEC building.

In conclusion, our research has demonstrated that the microgrid concept is not only viable but also holds potential for addressing complex energy challenges. The positive outcomes from our simulations and on-site tests provide a strong foundation for further exploration and development. As we continue to evolve and refine our microgrid system, we aim to contribute significantly to the advancement of sustainable and resilient energy solutions.

7 Bibliography

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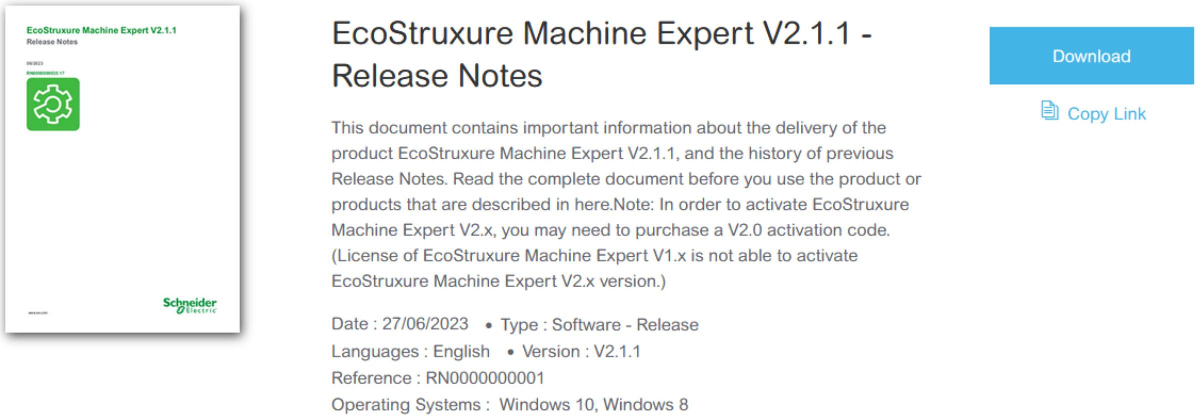
.1 Appendix

.1.1 Installing the software:

Visit https://www.se.com/ww/en/download/document/RN0000000001/?searchSource=guided and download the document.



EcoStruxure Machine Expert V2.1.1 - Release Notes

This document contains important information about the delivery of the product EcoStruxure Machine Expert V2.1.1, and the history of previous Release Notes. Read the complete document before you use the product or products that are described in here.Note: In order to activate EcoStruxure Machine Expert V2.x, you may need to purchase a V2.0 activation code. (License of EcoStruxure Machine Expert V1.x is not able to activate EcoStruxure Machine Expert V2.x version.)

Date : 27/06/2023 • Type : Software - Release
Languages : English • Version : V2.1.1
Reference : RN0000000001
Operating Systems : Windows 10, Windows 8

When inside the document, go to "Installation Instructions".

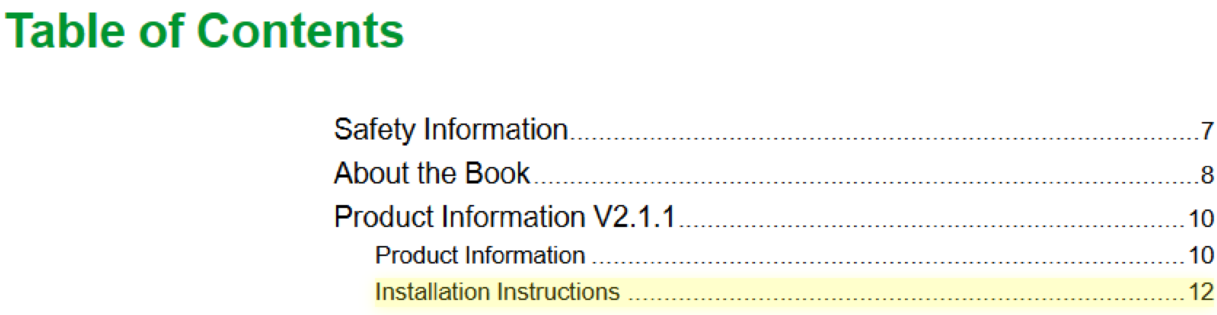
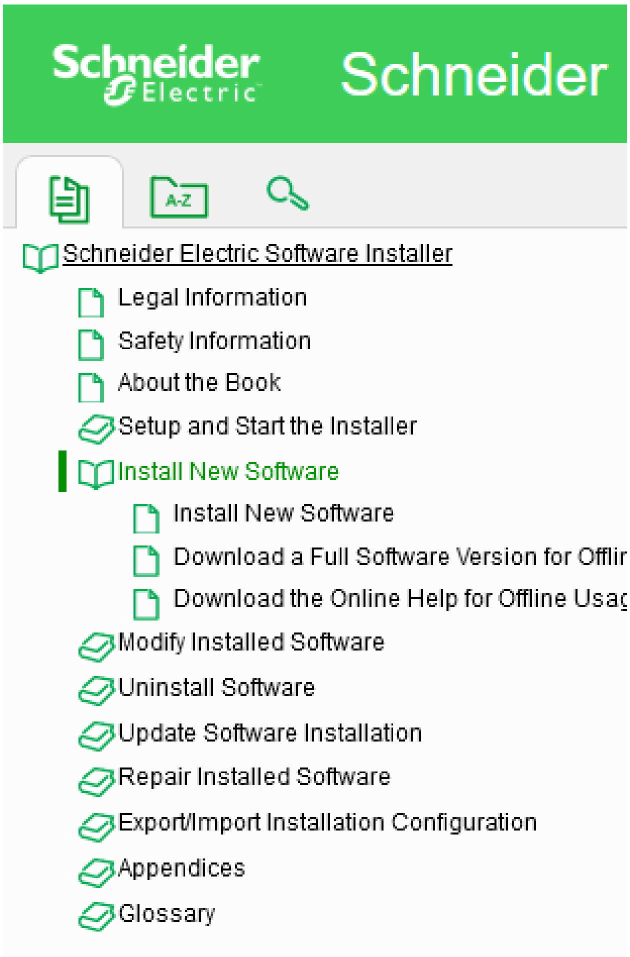
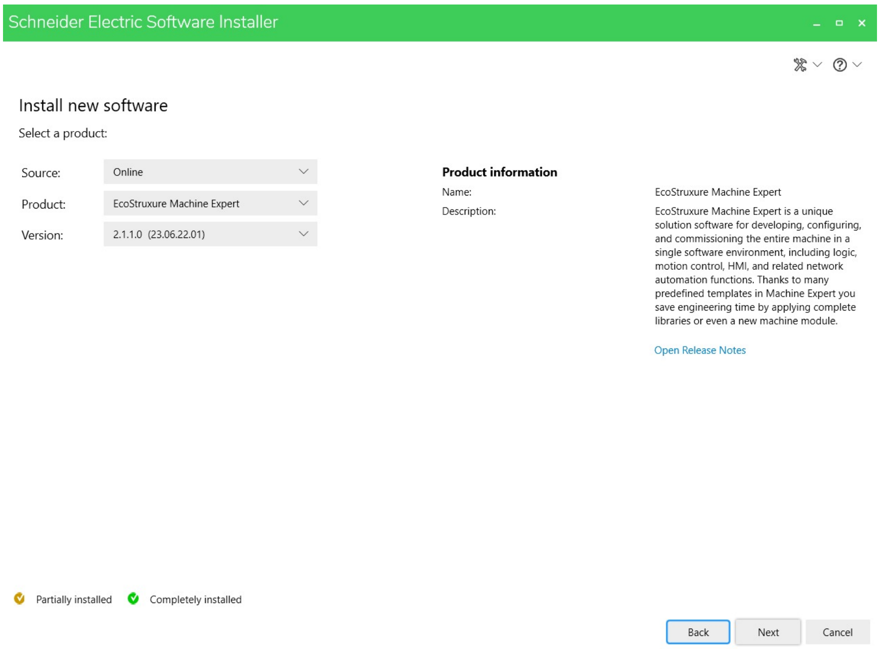


Table of Contents

Then, click “Install New Software” and download the Installer.



After opening the Installer, select each field as shown below:



Install new software

Select a product:

Source: Online

Product: EcoStruxure Machine Expert

Version: 2.1.1.0 (23.06.22.01)

Product information

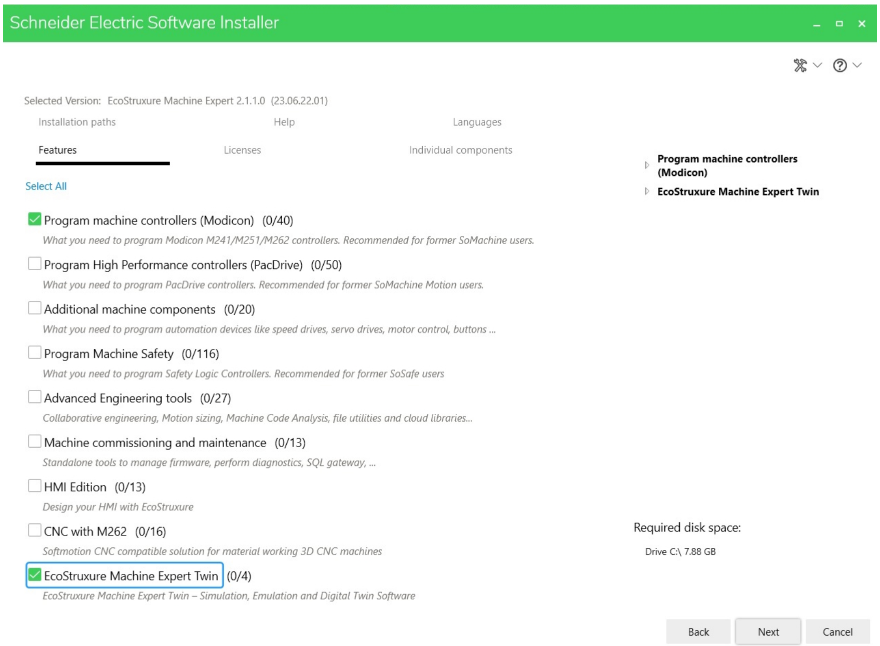
Name: EcoStruxure Machine Expert

Description: EcoStruxure Machine Expert is a unique solution software for developing, configuring, and commissioning the entire machine in a single software environment, including logic, motion control, HMI, and related network automation functions. Thanks to many predefined templates in Machine Expert you save engineering time by applying complete libraries or even a new machine module.

Open Release Notes

Partially installed   Completely installed

Then, select the “Features” as shown and press install.



Selected Version: EcoStruxure Machine Expert 2.1.1.0 (23.06.22.01)

☑ Program machine controllers (Modicon) (0/40)
What you need to program Modicon M241/M251/M262 controllers. Recommended for former SoMachine users.

☐ Program High Performance controllers (PacDrive) (0/50)
What you need to program PacDrive controllers. Recommended for former SoMachine Motion users.

☐ Additional machine components (0/20)
What you need to program automation devices like speed drives, servo drives, motor control, buttons ...

☐ Program Machine Safety (0/116)
What you need to program Safety Logic Controllers. Recommended for former SoSafe users

☐ Advanced Engineering tools (0/27)
Collaborative engineering, Motion sizing, Machine Code Analysis, file utilities and cloud libraries...

☐ Machine commissioning and maintenance (0/13)
Standalone tools to manage firmware, perform diagnostics, SQL gateway, ...

☐ HMI Edition (0/13)
Design your HMI with EcoStruxure

☐ CNC with M262 (0/16)
Softmotion CNC compatible solution for material working 3D CNC machines

☑ EcoStruxure Machine Expert Twin (0/4)
EcoStruxure Machine Expert Twin – Simulation, Emulation and Digital Twin Software

Program machine controllers (Modicon)

EcoStruxure Machine Expert Twin

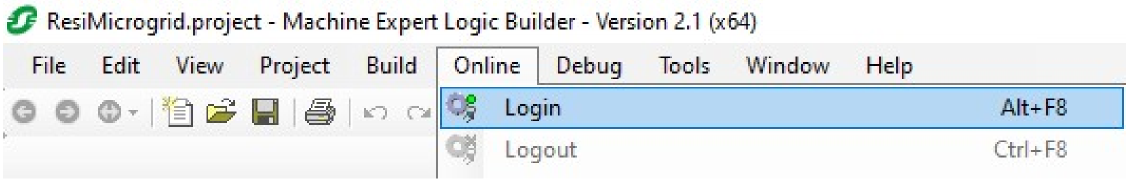
Required disk space:

Drive C:\ 7.88 GB

.1.2 Running the Simulation:

Once the selected project file is opened, inside the software, you can run the simulation by following these steps:

Inside the "Online" menu, press "Login". Internet connection required.



Once the “Login” is done, inside the "Debug" menu, press "Start" to start the simulation and "Stop" to stop it.