Energy Management System Designed for the Interconnected or Islanded Operation of a Microgrid Using LabVIEW Software

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Additional information is available at the end of the chapter

Abstract

Integration of distributed generation units and other users within the low and medium voltage distribution grid induces a variety of problems related to the management and control of microgrids. These aspects can be solved by using significantly different Energy Management Systems for the operation of microgrids, comparing to those applied to conventional power systems. The main objective of the Energy Management System is to ensure the rational use of energy, while minimizing its costs. The secondary objectives relate to increasing energy efficiency and reducing energy consumption, but especially to assuring the power facilities security. Moreover, the management of power systems to which renewable sources are connected is one of the main concerns of Distribution System Operators in order to ensure the safe operation, security of power supply, and the operation optimization from the economic side. The chapter regards the LabVIEW design and testing of an Energy Management System for the interconnected or islanded operation of a microgrid to the electric public grid. Furthermore, the chapter leads to the microgrids development in terms of operation and efficiency by achieving an Energy Management System designed for a small mixed microgrid with separate AC and DC rings bidirectionally interconnected by static converters.

Keywords: microgrid, power system, Energy Management System, LabVIEW, operating scenarios

1. Introduction

For the last couple of years, a new solution suitable to local energy distribution within existing power systems has been proposed and developed: microgrids [1].

The two microgrid definitions, which are currently in use, are provided by the US Department of Energy Microgrid Exchange Group and by CIGRÉ C6.22 Working Group, Microgrid Evolution Roadmap, respectively:

> *"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"* [2, 3].

> *"Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded"* [2, 3].

The microgrid concept supports an alternative approach to the integration of distributed energy resources characterized by low installed capacity to distribution grids [4]. When compared to conventional power systems, the main advantage of microgrids consists of the controllable unit feature. Microgrids can be operated as a single load, ensuring easy control and compliance to rules and regulations without impacting the reliability and safety of the user's power supply.

Microgrids are designed to operate semi-independently, usually in grid-connected mode, providing options for isolated or islanded operation, either for economic, reliability, or
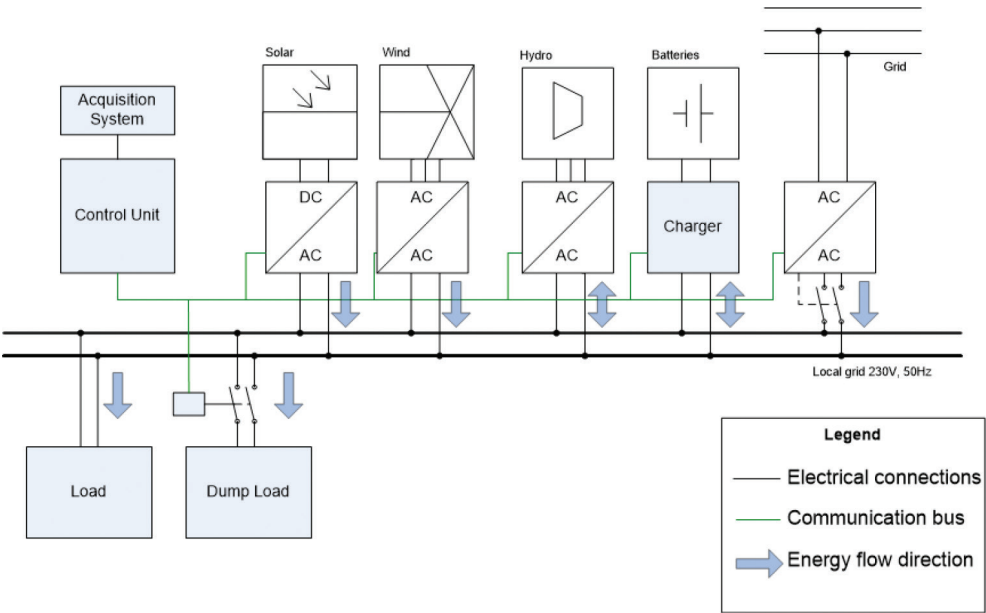

Figure 1. The conceptual model of a typical microgrid configuration [6].

security reasons. Also, the development of new energy sources as well as their integration within microgrids allows the supply of some isolated locations, such as islands or mountain areas, which are not connected to conventional power systems.

Currently, a typical microgrid configuration, **Figure 1**, consists of an open architecture, including electrical, communication, command, and control components, which allow the users and energy sources interconnection. Thanks to the capability of offering higher levels for power quality and reliability, a large number of users will adopt power supply solutions based on advanced technology and power electronics in order to minimize voltage sags, interruptions and other voltage fluctuations, or other power-quality disturbances.

Generic microgrids consist of a number of electric generators with static converters as interface modules, electric loads (to be connected either at DC or AC by inverter modules) as well as a connection (by transformer and conversion modules) to the electric distribution grid.

For an optimal microgrid operation, energy management strategies are necessary, proving their utility by adjusting the generated power for each distributed source [5] and by considering the energy storage which currently represents a main component of the energy sector.

2. Microgrid and Energy Management System configuration

2.1. Architecture of the AC/DC microgrid

The special operating conditions of the power systems require new solutions in order to ensure the continuity of the power supply. Therefore, the chapter proposes and analyzes the integration of renewable energy sources (RESs) (photovoltaic panels and wind turbines) into a mixed microgrid by using the LabVIEW software. Also, the MATLAB environment was used by introducing MATLAB scripts within the developed visual instruments (VI) diagrams.

The designed microgrid takes into account the following requirements:

• mixed microgrid, including various energy sources, which ensures the end user's power supply, by providing a high level of security;

• option to extend the grid infrastructure without achieving any changes in the existing equipment;

• option to connect to the electric public grid and to operate interconnected;

• option to store the generated power in order to establish the energy security and autonomy of the end user [6].

The developed microgrid model, **Figure 2**, includes the following components: distributed energy sources, distributed storage, backup sources for the generated power, critical or priority energy users (which do not allow any interruptions in the power supply) as well as standard users (which allow power supply interruptions) and one control unit that communicates to all the other components. The standard energy consumers, which can be considered by the
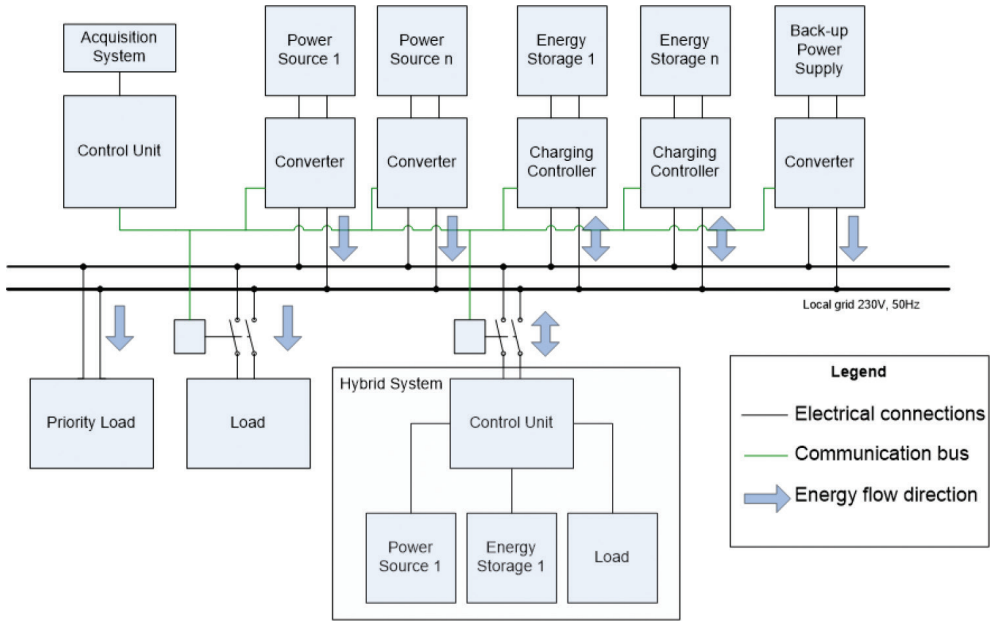
Figure 2. The developed model of mixed microgrid [6].

conceptual microgrid model, include, but are not limited to general lighting, local electrical heating and general electrical outlets. The critical consumers include the following essential services and equipment: technological processes that induce unacceptable interruption costs, safety lighting, or alarm and safety systems [7].

The microgrid model has been implemented by developing LabVIEW models for each component: photovoltaic panels, wind turbine, lead-acid batteries, and end users, all based on load curves and characteristics derived from the client's database.

2.1.1. Mathematical modeling of photovoltaic panels

The description and modeling of the PV panels was achieved by considering the simplified mathematical model based on the single-diode photovoltaic cell which gives the output power P as in Eq. (1):

$$P \ = \ U \cdot I \ = \ U_T \cdot I \cdot \ln\left(\frac{I_{ph} - I + I_0}{I_0}\right) - I^2 \cdot R_s \qquad (1)$$

where

- U—voltage output (V);
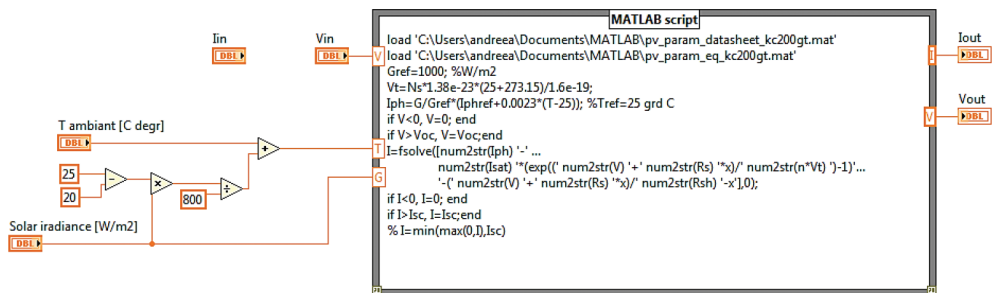- I—electric current generated by the solar cell (A);

- U_T—thermal voltage of the semiconductor (for a 300 K voltage, resulting as $U_T = 0.026$ V) (V);

- I_{ph}—electric current generated according to the values of irradiance and temperature (the theoretical cell current) (A);

- I_0—saturation current (A);

- R_s—series resistor which models the equipment power losses (Ω).

The model related to the external characteristic *I(V)* for a photovoltaic panel has been implemented by using the LabVIEW environment based on Eq. (1). Thus, **Figure 3** shows the diagram developed for a Kyocera photovoltaic panel. The diagram uses the electrical parameters from the technical specification supplied by the producer as well as the parameters suggested by the scientific literature [1, 8].

The photovoltaic panel model was then completed by modeling and implementing a maximum power point tracking (MPPT) controller circuit designed for solar power applications. This additional simulation was necessary given that photovoltaic panels are characterized by an optimization point which provides maximum power. This point generally varies according to the ambient environmental conditions. When adjusting the output voltage of the solar cells in a variable environment, permanent maximum power generation becomes a problem. Under these conditions, tracking the maximum power point for existing photovoltaic systems increases the efficiency in power generation [9].

The MPPT algorithm was implemented by measuring the electrical current for several voltage values at the required time interval. This method removes any possibility for the system to enter an unstable oscillation mode (sometimes affecting other types of algorithms). Also, the algorithm involves the constant pitch scanning of the foreseen operating range. The mentioned MPPT controller model represents a component of the AC/DC microgrid, suitable for the evaluation of the components interconnection mode.

In order to simulate the operation of the photovoltaic cell, the single-diode model with ideal *p-n* junction was used, as suggested by Eq. (1), which avoids complex calculations and leads to increasing the simulator running speed without introducing significant errors to the overall purpose of the microgrid simulator.
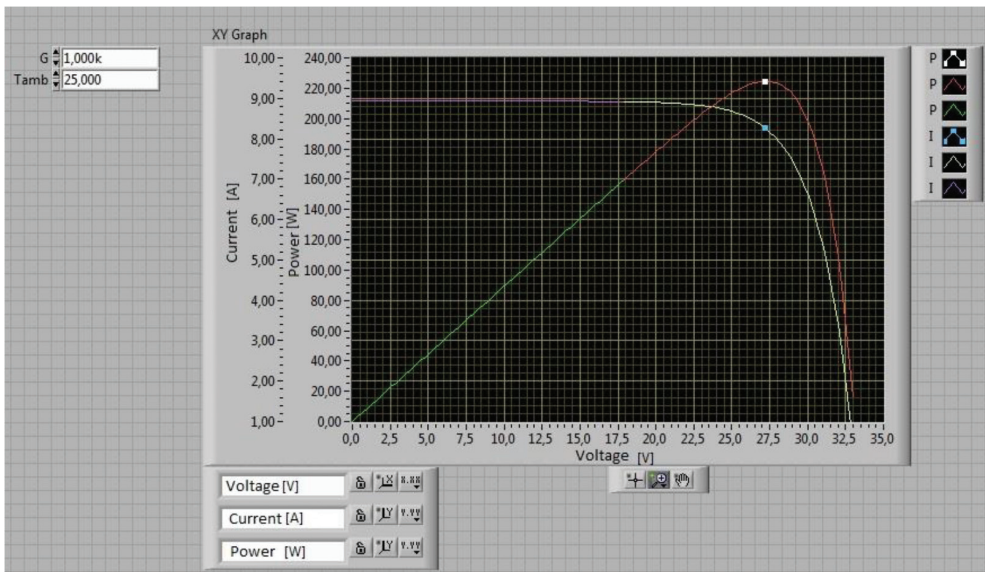

Figure 3. The diagram developed for the photovoltaic panel [1].

The MPPT simulator, initialized with the photocell parameters provided by the PV manufacturer, estimates the parameters required for the calculation model, receives from the rest of the microgrid simulator the irradiation and temperature values according to the climatic scenario, and performs a constant coverage scanning in order to determine the maximum power point. For further reducing the scaled range, the simulator starts from the maximum possible value of solar irradiation and reaches the null value of the electric current, calculating the value of generated power for each iteration. In a memory cell, only the maximum instantaneous current - power set of values is registered (which at the start of the determination is initialized and starts from 0), respectively, the power and intensity of the electric current. For each new measurement, the value of the regulated current is decremented, and the resulting power is compared to the maximum registered value. The pair of values represented by the electric current—power, which meets the condition of the highest power value, becomes the current stored value. When the instant measured power drops below 70% of the last determined maximum point, the scanning stops and the control value becomes the maximum power value.

The simulation shown in **Figure 4** is provided with a memory for the solar irradiance and temperature indicated by the last iteration climatic scenario. If the new values are different, the determination is resumed.

2.1.2. Mathematical modeling of wind turbines

Figure 5 shows the diagram developed for the evaluation of voltage and current outputs characteristic to a wind turbine. The determination of the wind turbine's output power was achieved by linear interpolation of the power characteristic in relation to the wind velocity.

Figure 4. Simulation and modeling of the maximum power point for variable environmental conditions (G, T_{amb}).
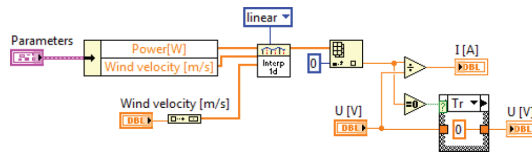
Figure 5. The wind turbine diagram implemented in LabVIEW [1].

The output current was computed by considering the wind turbine's operating voltage equal to the microgrid's voltage U_n = 24 V. Also, the theoretical power of the wind turbine, P (W), was taken into account, expressed in Eq. (2):

$$P = \frac{1}{2}\rho\, AC_p\, v^3 \tag{2}$$

where

- ρ—air density (kg/m^3);
- A—area of the surface described by the turbine rotor, which is perpendicular to the wind direction (m^2);
- C_p—power coefficient;
- v—wind velocity at the turbine entrance (m/s) [1].

2.1.3. Mathematical modeling of battery storage systems

Most power systems with insulated operation, which are designed for consumers' continuous supply, require battery storage systems in order to equalize the irregular nature of meteorological parameters. Currently, the most used batteries for renewable energy sources applications consist of lead-acid (PbA), lithium-ion (Li-ion) or nickel-cadmium batteries [10].

The mathematical models related to battery storage systems are targeting the simulation of real operation characteristics and are used for the behavior estimation related to variable charging and discharging conditions. The mentioned models are also suitable for storage batteries design due to the fact that they allow the analysis of charging and discharging modes independently of the supplied system.

The developed AC/DC microgrid is based on the Shepherd model which describes the electrochemical processes depending on the voltage and electric current values. The Shepherd model also considers the Peukert law, Eq. (3), in order to determine the battery voltage and state of charge.

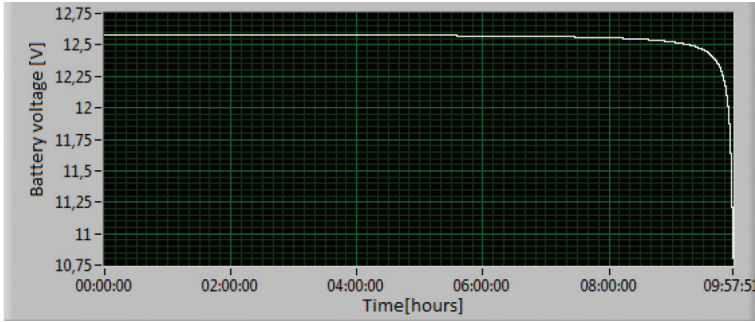$$E_b = E_0 - R_i I - K_i\left(\frac{1}{1-f}\right)I \tag{3}$$

where

- E_b—battery terminals voltage (V);
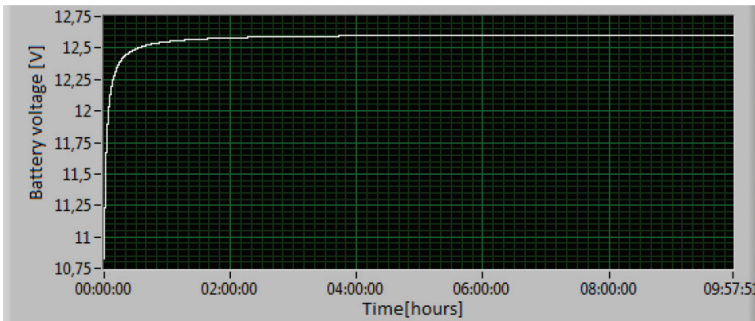- E_0—open-circuit voltage at the battery terminals when the battery is completely discharged (V);

- R_i—internal resistance of the battery (Ω);

- K_i—polarization resistance of the battery (Ω);

- Q—capacity of the battery (Ah);

- I—electric current (A);

- f—fraction extracted from the battery (the capacity extracted from the battery rated to the fully charged battery's capacity Q_0) as suggested by Eq. (4)

$$f = \int_0^t \frac{I \cdot dt}{Q_0} \tag{4}$$

Figures 6 and **7** show an example simulation model of a PbA battery storage system operation when considering a discharging and afterwards a charging current rate of 0.8 A.

Figure 6. Voltage variation at the battery terminals during a discharging cycle for a discharge current rate of 0.8 A.

Figure 7. Voltage variation at the battery terminals during a charging cycle for a charge current rate of 0.8 A.

2.2. Configuration and structure of the Energy Management System

The main characteristics of the designed Energy Management System (EMS) consist of the following:

- The option of computing for any practical configuration of the microgrid, providing the possibility of adapting to the needs of each beneficiary.

- The option of implementing energy storage during low-cost periods and injecting it into the electric public grid during high-cost periods; even though this strategy is commonly used, EMS can still not be economically efficient due to limitations imposed by the storage equipment. Also, this involves risks in critical users power supplying.

- Ensuring and maintaining energy backup.

- The option of connecting or disconnecting backup sources that are not generally repre-sented by RES and therefore dispose of limited available power and/or at an inconvenient price cost. In this case, EMS disconnects users according to their associated priority.

- The option of estimating the available power, which, in the absence of storage equip-ment, is achieved by monitoring and registering the primary energy sources like wind and sun.

- The option of implementing the electric public grid within the developed model of AC/DC microgrid as follows: either backup energy source, dump-load consumer or both [6, 11].

The algorithm covers the energy management functions and is based on the developed microgrid model which includes the control unit. Thus, for initializing it, the information about the components must be inserted as follows:

The *energy generation sources* require the following information:

- port—parameter assigned to communication/monitoring/control;

- installed power;

- dependent size and conversion factor—for the estimation of energy generation;

- available power;

- the production cost/kWh.

The *end users* require the following information:

- port—parameter assigned to communication/monitoring/control;

- installed power;

- priority—parameter which allows the end users selection for different operating scenarios;
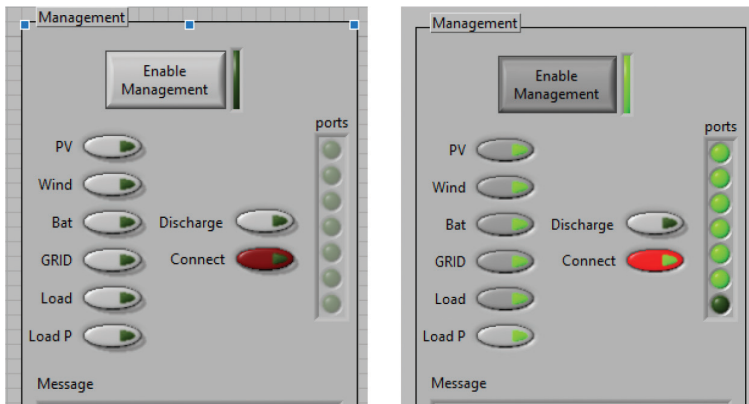
- operation mode (without any interruptions, permanent or continuous, dump load—connection for injecting the production excess of electric power);

- sale price—electricity pricing for the energy which is sold to the end user (if applicable).

The *battery storage systems* require the following information:

- port—parameter assigned to communication/monitoring/control;

- storage capacity;

- storage cost—estimated cost/kWh depending on the limitations of the storage equipment.
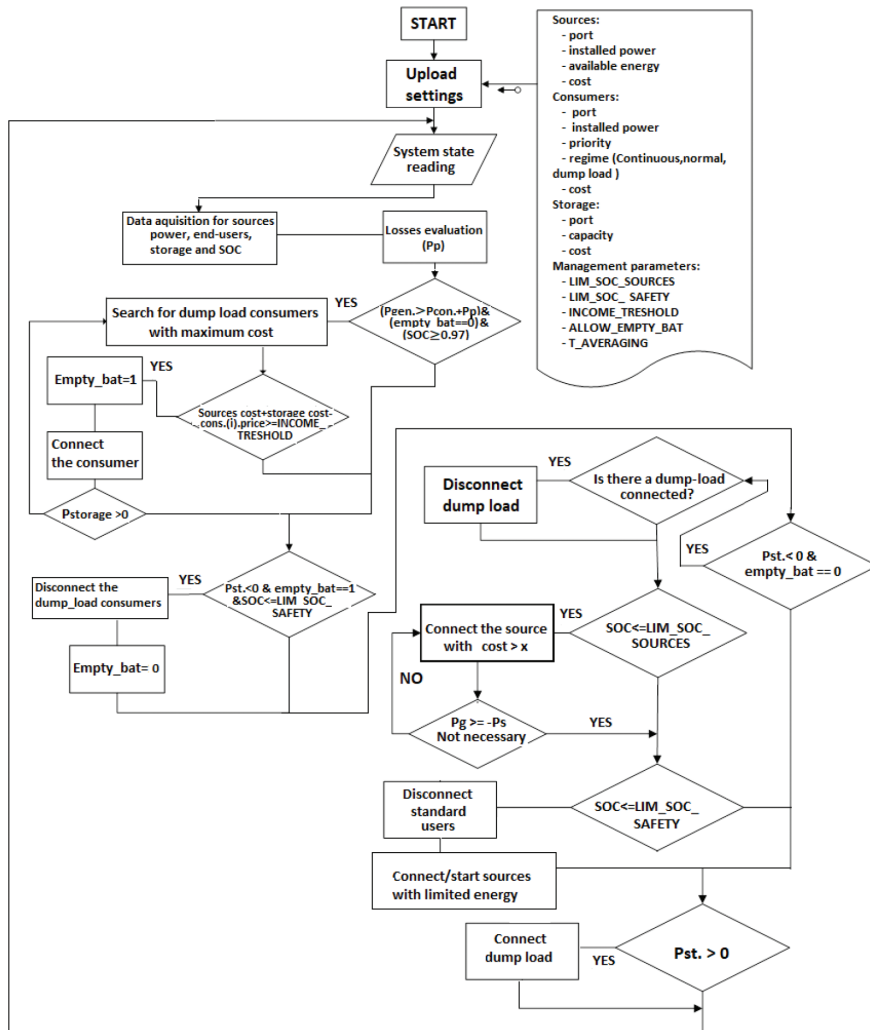
The *Energy Management System* parameters consist of the following:

- LIM_SOC_SOURCES—the limit of storage devices for which the backup sources are connected;

- LIM_SOC_SAFETY—the limit of storage devices for which standard end users are disconnected;

- LIM_COST_SOURCES— the high-priced sources are connected only if necessary;

- INCOME_THRESHOLD—the price threshold for which the energy injection into the public grid begins;

- ALLOW_EMPTY_BAT—it allows the use of the stored energy for a maximum profit;

- T_AVERAGING—the averaging time of the measurements. This parameter influences the values of the reaction time [6, 11].
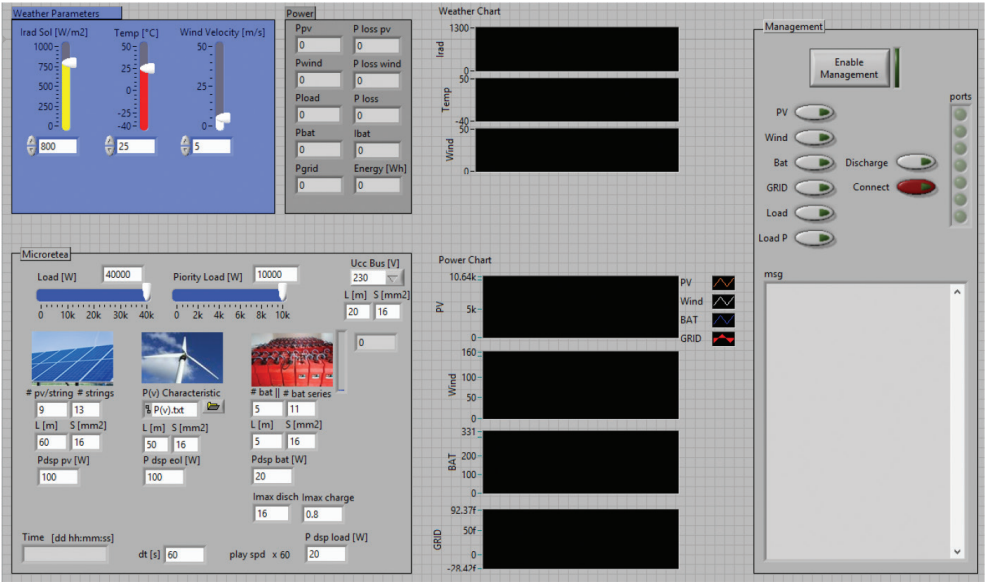

Figure 8. The graphical interface of the developed Energy Management System. The ON/OFF state for the microgrid components and activation/deactivation of the Energy Management System.

Figure 8 shows the graphical interface of the developed Energy Management System. This highlights the connection state (connected or disconnected) related to the considered distributed energy generation sources, battery storage systems, end users as well as the islanded or interconnected operation of the microgrid to the national power system. Also, the connection state regarding the "ports" vector has been envisaged, which has resulted in using the BUILD ARRAY function and thus connecting the communication/command parameters of each element in series [12]. The dependence between the connection state of each component (Boolean and "ports" elements) is shown.
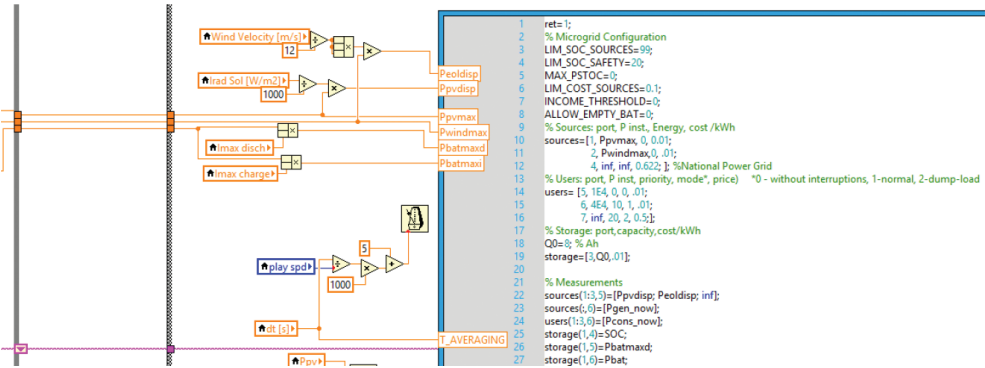

Figure 9. The block diagram of the Energy Management System concept [6, 11].

Figure 10. The graphical interface of the developed application for the modeling and simulation of a small-scale microgrid and the related Energy Management System.

Figure 9 contains the block diagram of the Energy Management System concept designed for the islanded or interconnected operation of the microgrid with the national power system while **Figure 10** shows the graphical interface of the developed application related to the microgrid design and simulation.

In addition to the LabVIEW environment, MATLAB was used as well by introducing a MATLAB script within the developed VI related to the Energy Management System. **Figure 11** shows a section of the main loop management, presenting a MATLAB residue code which was then implemented in the general LabVIEW diagram.
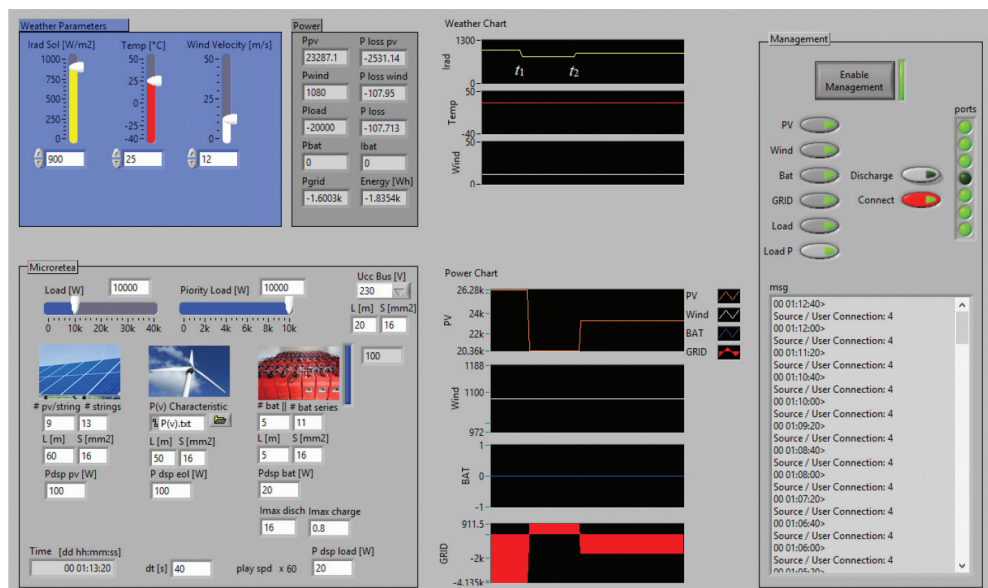

Figure 11. Section of the MATLAB script related to the LabVIEW Energy Management System.

3. Experiments and simulation results of the Energy Management System: operation scenarios

The Energy Management System implies independent automatic decisions from a potential user's decisions. The developed microgrid is operational even without an Energy Management System, but it is not provided with automatic decisions which aim the control of the energy flows or connection/disconnection actions of the component elements. Consequently, it results in the energy management for the optimization of both the microgrid operation and beneficiary's income/benefit. Moreover, in order to demonstrate the functionality of this system, the following operating scenarios, available for the "Enable management—ON" state, are suggested.

Operating scenario number I. The distributed energy generation sources (wind energy conversion system, photovoltaic system), the battery storage systems as well as the connection to the low-voltage distribution grid are available. This operating scenario involves the variation of the meteorological parameters during the microgrid functioning. Also, a calculation step $\Delta t = 40$ s is used, during which all the parameter values are maintained constant.

The first operating scenario, represented in **Figure 12**, considers two time moments when the meteorological parameters vary, respectively, t_1—the moment when the solar irradiation drops and t_2—the moment when the solar irradiation increases. These two time moments are established randomly by the user of the LabVIEW application.

Figure 12. The graphical interface of the developed application for the modeling and simulation of a small-scale microgrid and the related EMS. Operating scenario number I.

It is to be noted that at the first moment t_1, the photovoltaic power plant lowers the power output from 26.28 to 20.36 kW due to a decrease of the solar radiation from 1000 to 800 W/m². Until then, there is no need to transfer any energy from the public electric grid. From this moment on, the generated power within the microgrid decreases, and a necessary input from the National Power System is needed (P_{grid} = 911.5 W). At the second considered moment t_2, the solar irradiance increases from 800 to 900 W/m². Therefore, the generated solar power increases from 20.36 to 23.28 kW, and the power input from the National Power System is no longer needed. Contrary to the situation before, after the moment t_2, the excess energy production will be injected into the public grid.
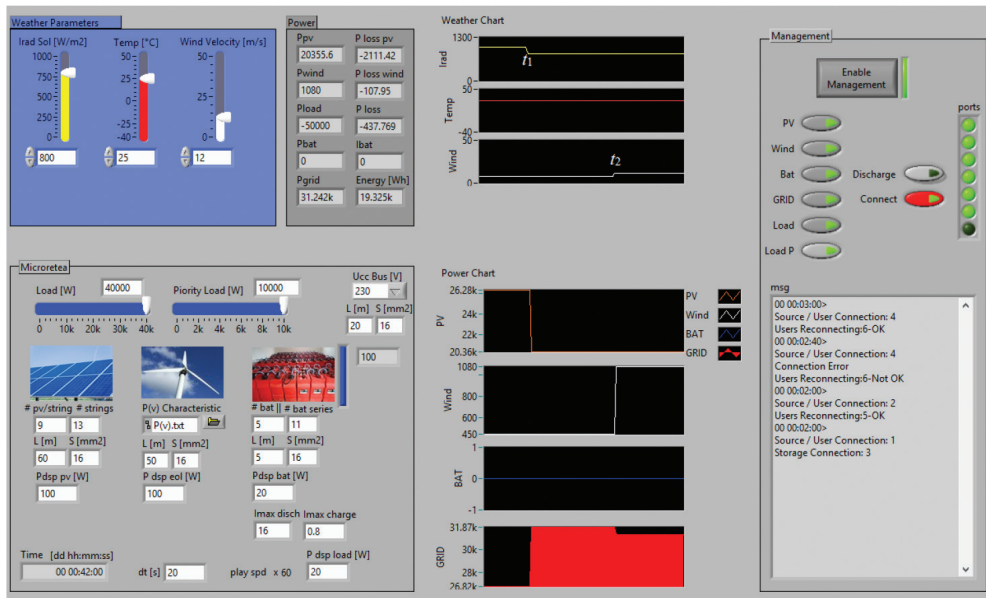
As suggested by **Figure 12**, it is possible to fully ensure the load supply (20 kW) from the production of energy from renewable energy sources during the intervals (0; t_1) and (t_2, end of the simulation), while maintaining the batteries fully charged. Following the supply of the battery storage systems and of the end users, the excess available energy will be injected into the public grid (P_{grid} = 1.6003 kW; *energy* = 1.8354 kWh). The power losses are also considered (related to lines and conductors and to the electronic power devices, respectively). It is noted that the Energy Management System decides to use the National Power System as an energy dump load while the excess energy production is injected into the public grid.

Operating scenario number II. The distributed energy generation sources (wind energy conversion system, photovoltaic system), the battery storage systems as well as the connection to the low-voltage distribution grid are available. In this case, the end users necessary energy is higher than the one considered in the first scenario (P_{load} + $P_{load\ p}$ = 50 kW) and higher than the energy produced from renewable sources. This operating scenario involves the variation of the meteorological parameters during the microgrid functioning. Also, a calculation step Δt = 20 s is used, during which all the parameter values are maintained constant.

The second operating scenario, represented in **Figure 13**, considers two time moments when the meteorological parameters vary, respectively: t_1—the moment when the solar irradiation drops and t_2—the moment when the location wind velocity increases. These two time moments are established randomly by the user of the LabVIEW application.

It is to be noted that at the first moment t_1, the photovoltaic power plant lowers the power output from 26.28 to 20.36 kW due to a decrease of the solar radiation from 1000 to 800 W/m². Until then, the necessary power from the public electric grid for the end users supply was equal to P_{grid} = 26.82 kW. From this moment on, the generated power within the microgrid decreases, and a larger necessary input from the National Power System is needed (P_{grid} = 31.87 kW). At the second considered moment t_2, the location wind velocity increases from 8 to 12 m/s. Therefore, the generated wind power increases from 450 W to 1.08 kW. The microgrid-generated power increases as well and consequently the power input from the National Power System decreases (P_{grid} = 31.242 kW).

As suggested in **Figure 13**, it is possible to fully ensure the load supply (50 kW) from the production of energy from renewable sources and the electric public grid. The power losses are also considered (related to lines and conductors and to the electronic power devices, respectively). It is noted that the Energy Management System decides to use the National Power System as an energy generation source, while the microgrid energy production is completed by the public grid.

Figure 13. The graphical interface of the developed application for the modeling and simulation of a small-scale microgrid and the related Energy Management System. Operating scenario number II.

Operating scenario number III. The distributed energy generation sources (wind energy conversion system, photovoltaic system), the battery storage systems as well as the connection to the low-voltage distribution grid are available. This operating scenario does not involve the variation of meteorological parameters during the microgrid functioning. A calculation step $\Delta t = 30$ s is used, during which all the parameter values are maintained constant.

As shown in **Figure 14**, at the first moment t_1, the unwanted discharge of the battery storage system takes place in order to supply the end users. The battery discharges up to a safety limit of 15%, established by the Energy Management System. Until the moment t_1, the necessary power from the public electric grid for the end users supply was equal to $P_{grid} = 27.11$ kW. From this moment on, when the battery discharges, the power input from the National Power System decreases to $P_{grid} = 16.557$ kW due to the energy transfer from the storage systems ($P_{bat} = 10.71$ kW).

The Energy Management System detects the unwanted discharge of the battery storage system and stops its discharging at the moment t_2, when the 15% limit is reached. Thus, **Figure 15** shows a new charging cycle of the considered storage systems and the complete load supply from renewable energy sources as well as from the electric public grid ($P_{grid} = 27.657$ kW, $P_{pv} = 26.284$ kW, $P_{wind} = 160$ W).

These two time moments t_1 and t_2 are established randomly by the user of the LabVIEW application.
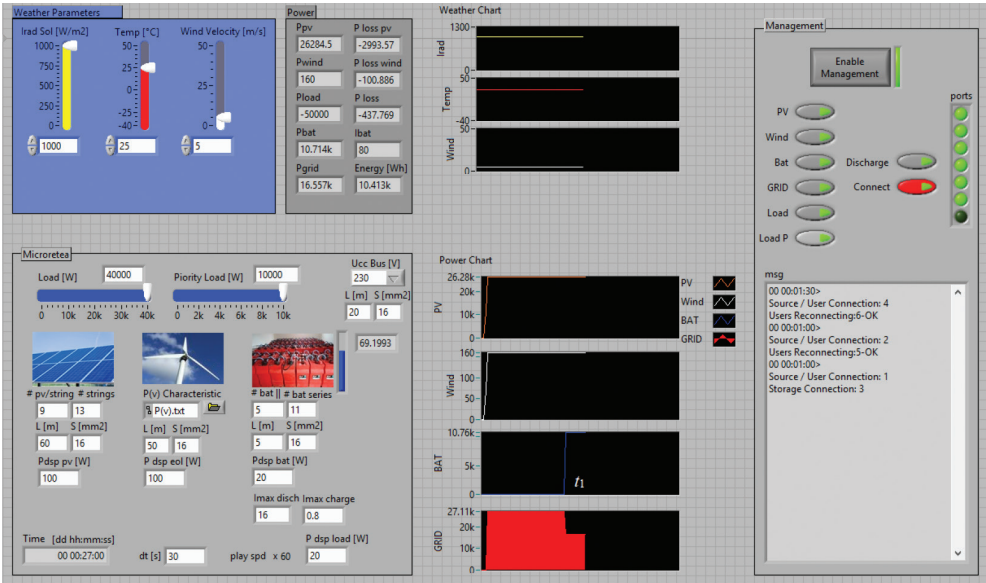
Figure 14. The graphical interface of the developed application for the modeling and simulation of a small-scale microgrid and the related Energy Management System. Operating scenario number III—Section 1.
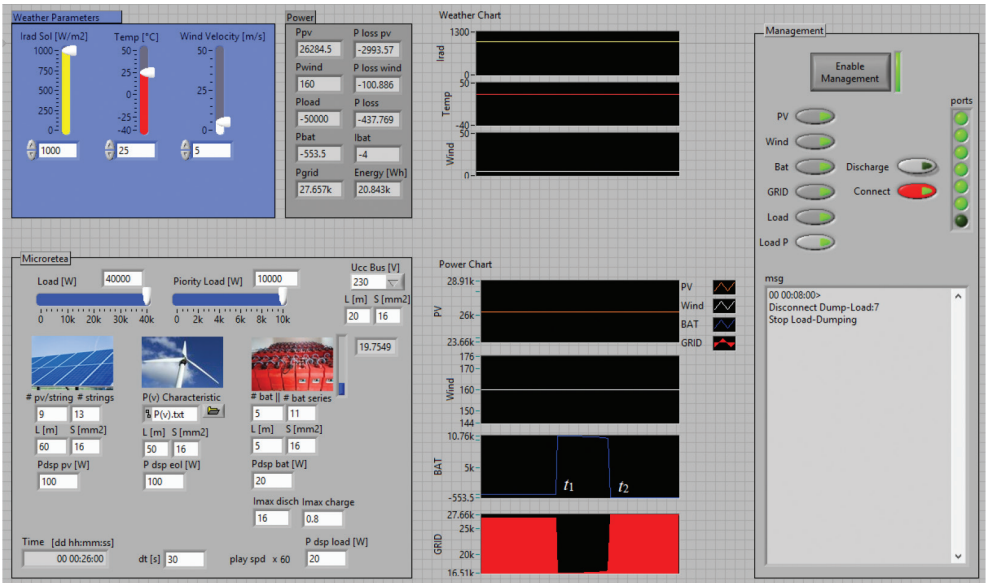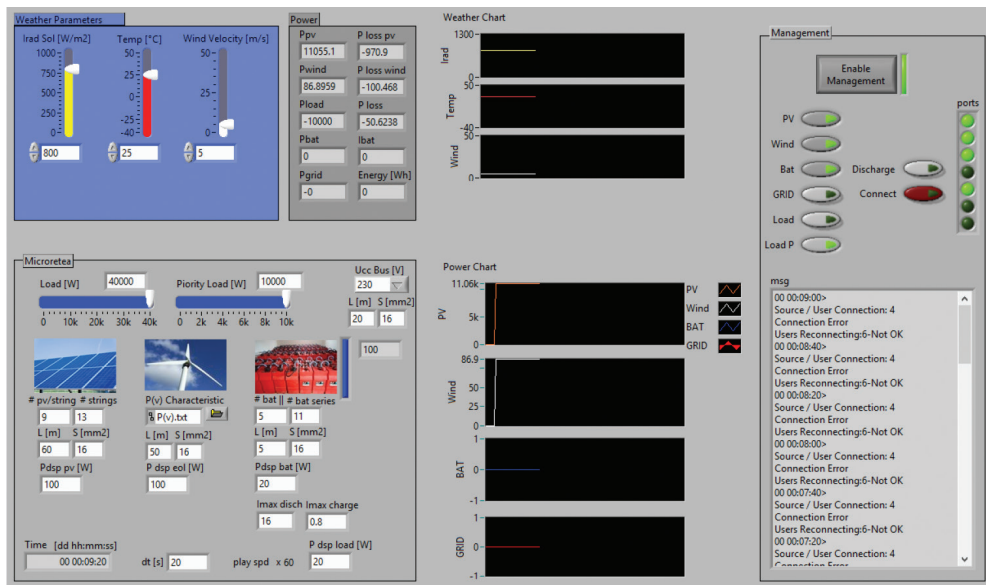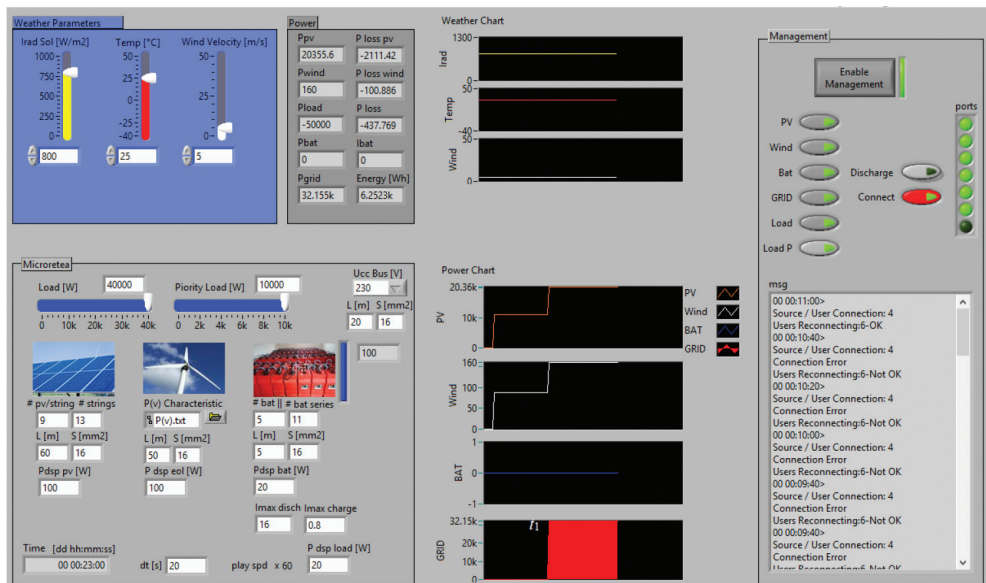

Figure 15. The graphical interface of the developed application for the modeling and simulation of a small-scale microgrid and the related Energy Management System. Operating scenario number III—Section 2.

Figure 16. The graphical interface of the developed application for the modeling and simulation of a small-scale microgrid and the related Energy Management System. Operating scenario number IV—Section 1.

Figure 17. The graphical interface of the developed application for the modeling and simulation of a small-scale microgrid and the related Energy Management System. Operating scenario number IV—Section 2.

Operating scenario number IV. The distributed energy generation sources (wind energy conversion system, photovoltaic system) as well as the battery storage systems are available. This operating scenario does not involve the variation of meteorological parameters during the microgrid functioning. A calculation step $\Delta t = 20$ s is used, during which all the parameter values are maintained constant. **Figure 16** shows the absence of the connection to the low-voltage distribution grid.

The Energy Management System evaluates initially the necessary of the end users' power supply ($P_{load} + P_{load\,p} = 50$ kW), establishes that there is not enough energy for the complete supply and then connects only the priority or critical load (*Load P*) and not the standard one (*Load*). As seen from **Figure 16**, EMS attempts the reconnection, but it fails and supplies only the priority load.

At the moment t_1, when the connection to the low-voltage distribution grid becomes available, EMS decides to use the National Power System as an energy generation source, while the microgrid energy production is completed by the public grid ($P_{grid} = 32.155$ kW). Thus, the other consumers are also reconnected ($P_{load\,p} = 40$ kW) as indicated in **Figure 17**.

The time moment t1 is established randomly by the user of the LabVIEW application.

4. Conclusion

The proposed LabVIEW solution regarded a small mixed microgrid with two separate AC and DC rings bidirectionally interconnected by static converters. In this respect, the mathematical modeling of PV panels, wind turbine, and battery storage systems was achieved, followed by their implementation within the mentioned microgrid by using the LabVIEW environment.

Furthermore, an Energy Management System related to the microgrid model was developed. Thus, the chapter intends to develop an intelligent Energy Management System suitable to the microgrid components (wind energy conversion system, photovoltaic systems, and battery storage systems). The LabVIEW application is provided with a graphical interface, which allows to identify and establish the initial conditions (meteorological parameters, component elements) as well as the microgrid's characteristic parameters.

The diagram corresponding to microgrid LabVIEW modeling and simulation is equipped with Boolean buttons representing the connection status (disconnected or connected) of the distributed generation sources, storage elements, and end users and highlighting the islanded or interconnected operation with the low-voltage distribution grid. To that end, various operating scenarios were proposed, for which the results and operability of the Energy Management System were analyzed. It is to be noted that the developed EMS is suitable to any practical configuration of the microgrid, microgrid that can be adapted to the requirements of each beneficiary.

Acknowledgements

Conflict of interest

The author declares that there is no conflict of interest. Thus, there are no conflicts of interest to disclose.

Appendices and nomenclature

EMS	Energy Management System
MPPT	maximum power point tracking
P_{con}	power consumption
P_{gen}	generated power
P_p	power losses
$P_{storage}$ (P_{st})	stored power
PV	photovoltaic
RES	renewable energy sources
SOC	state of charge

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