STATE OF THE ART OF HYBRID AC-DC MICROGRIDS

STAREA ACTUALĂ A MICROREŢELELOR HIBRID AC-DC

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Abstract: *In this article, the authors set out to address the issue of current stage of research-development-implementation and industrial projects, as two categories of investments in microgrids field. Important aspects of the differences between microgrids on AC, DC or hybrid technologies have been shown. In order to align the work with the stage in Romania, a case study based on a microgrid was described, allowing observations based on components, chosen control strategies, future development visions and the benefits of an intelligent control solution.*

Keywords: AC-DC, Microgrids, Control Strategies, Distributed Energy Resources, Power grid

Rezumat: *In acest articol autorii şi-au propus să abordeze tematica stadiului actual al proiectelor de cercetare-dezvoltare-implementare şi a celor industriale, ca două categorii de investiţii în microreţele. S-au evidenţiat aspectele importante ale diferenţelor dintre microretelele în funcţie de cele trei tehnologii: de AC, DC sau hibrid. Pentru a alinia lucrarea cu stadiul din România, s-a descris un studiu de caz care are la bază o microreţea care permite observaţii pe baza componentelor, a strategiilor de control alese, a viziunilor de dezvoltare viitoare şi care evidenţiază beneficiile aduse de o soluţie de control inteligent.*

Cuvinte cheie: AC-DC, Microreţele, Strategii de Control, Surse Distribuite de Energie, Reţea eletrică

1. Introduction

In recent years, energy demand, especially electricity and thus energy consumption has increased significant and with a very high impact on the environment. The Microgrid (MG) concept is one of the most important technologies for efficient, flexible and reliable use of distributed energy resources. [1]

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First power distribution systems, small and islanded, can be also considered microgrids. This is the reason microgrid can't be considered as a new development. But lately environmental concerns and limited reserves of conventional fuel (as coal, petroleum) lead to the need to find alternative resources [2]. Thus, microgrid concept was reintroduced as low voltage distribution [3] system to integrate distributed generation to the main grid. It was a big interest in the research of alternative current microgrids (AC MG), because of the familiarity with the AC power systems [4]. But the development of operational technology sector, along with advances in power electronics made possible modern loads such as notebooks, tablets, phones, TV's, energy storage devices, made direct current (DC) systems a popular solution for many applications. This is the reason why DC MG and hybrid solutions have been proposed nowadays [1], [5]. Hybrid AC-DC MGs main characteristic is that the two networks (AC and DC) are combined in the same distribution grid [6].

A complete definition for microgrids can be found in reference [7]: "a localized group of electricity sources and loads that it normally operates connected to, that acts as a single controllable entity and in a synchronized way with the conventional utility grid, but can be disconnected and independently operated according to physical and/or economic conditions".

An increasing interest in the control of microgrids can be observed, due to the recent changes in the structure of power generation, which nowadays may include renewable sources. In a simple definition, microgrids are small-scale power systems that facilitate the effective integration of distributed generation and storage devices [8]. Figure 1 shows their structure.

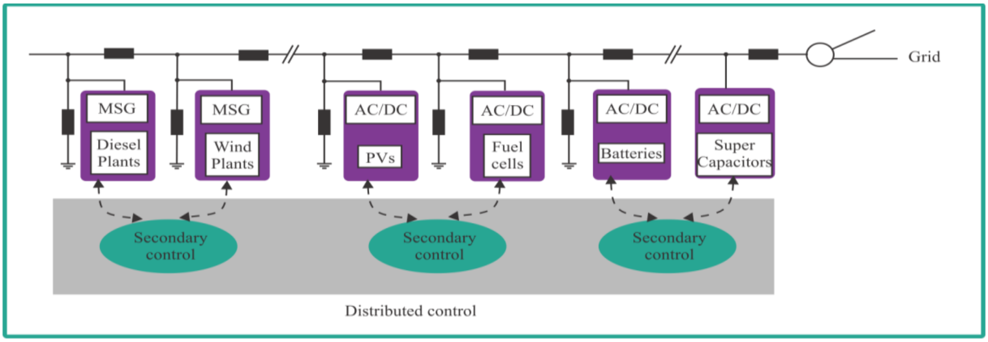

Figure 1. Structure of hybrid MG [9].

Energy sources and storage devices generate or reserve variable frequency AC/DC power and are interfaced with a synchronous conventional AC grid, using power electronic DC/AC inverters. Various topologies of hybrid AC/DC MGs based on the interconnection type of the AC and DC networks and on their connection to the main grid are presented in paper [6].

New control strategies are requested in order to preserve the synchronization and proportional power sharing in the network. Thus, a hierarchical control for microgrids has been proposed: primary control (a droop control that maintains voltage and frequency stability of the microgrid subsequent to the islanding process), secondary control (that allows to compensate the voltage and frequency derivations caused by primary control) and tertiary control (that permits an optimal operation in both operating modes and power flow control in grid-connected mode).

The main contributions of this paper are to establish the current state of the art in the field of energy, microgrid installations and their control methods. Thus, a couple of research materials were selected, that have contributed to the innovation of MGs at international level, highlighting industrial projects at global level and identifying a case study for the regional level [10]. It described how a MG works according to the control strategies that will be implemented in a programmable logic controller (PLC).

2. Microgrid international research

An electrical power distribution system can be generally classified in three ways: radial distributions system, loop (or mesh) distribution system and network distribution system, as can be seen in Figure 2.

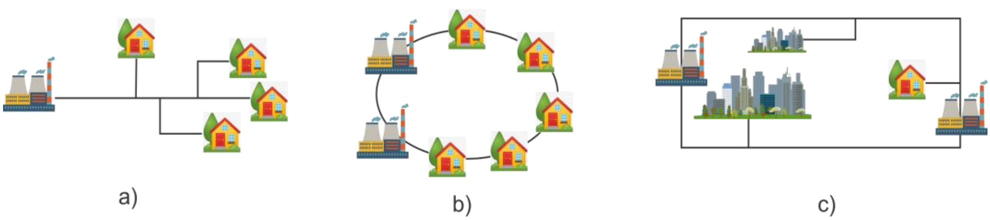

Figure 2. Electrical power distribution system [7]:
a) radial; b) loop and c) network .

The common application of a distribution system is a combination of these three systems, as each one has pros and cons. The radial system is most inexpensive distribution system to construct, and therefore, extensively applied for populated areas. It involves just one power source for a cluster of clients so any failure in the power line will cause a blackout. The loop distribution system is one that crosses all over the consumer area and ends at the generation point and with proper placed switch breakers, the power can be supplied to the consumers in a bidirectional way. This is why this distribution system is considered better than the radial structure for MG applications. It requires additional switches, conductors, and breakers; thus, it is more expensive compared to the radial structure. In a network distribution system, any consumer can be supplied from more than one generation unit, which offers a big advantage in terms of reliability. This system is typically used only in high populated areas or in areas with high power demand, because of excessive expenses.

Based on their integration level into the power utility grid and on their different responsibilities, application areas and relevant key technologies, MGs can be divided in three categories [7]: plant MGs, remote MGs and utility MGs, as presented in Table 1.

Table 1. **Classification of MG**

Classification	**Integrated level**	**Utilities impact**	**Respon-sibility**	**Application area**	**Operational mode**	**Power quality**	**Observation**
Plant MG	Middle	Little	For complement	America (where technology is matured)	Intentional or unintentional island mode	High	– Use of renewable energy – Energy efficient – High power reliability
Remote MG	Low	No impact	Independent system	Distant areas, islands or developing countries	Only islanded mode	Relaxed	– Descentralised control
Utility MG	High	Massive impact	Support of power systems	Europe, Asia (where renewable energy is developing fast)	Connected to grid	Medium	– High power quality & reliability – Contribution to utility stability & robustness

Both plant MG and utility MG have grid connections modes, while remote MG does not have that option. Plant MGs can operate either in planed or unplanned island mode and the sources, loads, network parameters, and control topologies vary in each and every microgrid.

Usually, electric loads have been operated with AC power, thus, an AC distribution system is preferred as standard choice. Among the advantages for its use are the distance capability, the ease of transformation in various outputs for different applications and its natural characteristic inherited from the fossil fuel driven rotating machine.

Nowadays, various communities have implemented renewable-based distribution systems and research has been made in order to optimize their operation and control. Commonly, the distributed generations, storage devices and loads are attached with a common bus base at the distribution networks. The system voltage and frequency are maintained by utility grids when a connection to the main network is possible, while during islanded mode, they are maintained by energy storage devices, nonrenewable DGs and adjustable loads with control techniques. But for AC MGs, drawbacks are also present: the need of the synchronization between each DG and the utility grid, the power quality concern, the three phase possible unbalance.

This is why an interest can be found in DC MGs, where energy storage and a large percentage of the sources and the loads are interconnected through one or more DC busses. But AC buses and DC to AC converters are still necessary due to the fact that some sources and loads cannot be connected directly to DC. Also, as long as AC is going to be used for distribution, the DC MG will need to be connected to the AC grid.

A DC MG has advantages as the lack of synchronization of DGs requirement, the ability to use distributed renewable energy sources that naturally generate DC (PV, wind), no power factor losses, no voltage distortion, like voltage sag, unbalanced voltage, or voltage harmonics, or higher efficiency than AC MGs due to less conversion loss. But, in order to implement a DC MG, a DC distribution network needs to be built. Also, it is harder to implement a protection system for DC MGs compared do AC MGs due to the absence of a zero crossing point.

This is the reason for the interest in hybrid AC-DC MGs, where the AC and DC should be considered as two different parts. MGs have been implemented to supply power or have been installed in laboratories for research reasons.

2.1. MGs international projects

Considering that researchers dedicate their contribution to bringing new standards, that politics seek to regulate for each country has no legal basis, that it takes part in increasing market competitiveness and that it brings before the general public many aspects related to awareness of the positive impact of microgrids, as an integral part of Smart Grid and Smart City, real results must be mentioned.

European Commission also takes part in such initiatives of innovation and increases the level of technology by financially supporting development projects, through support schemes granted at country level through competitive calls, with specific rules and evaluators precisely to make it easier to approach new technologies [11].

For the CONNECT research project, the consortium proposes to provide concepts, technologies and components that support the improved integration of renewable sources and storage, combined with intelligent control of energy flow [12]. The partners believe that primary energy demand and carbon dioxide emissions will be reduced and decentralized energy infrastructure us a point to facilitate these solutions and discover new approaches and technologies for energy conversion.

A Horizon 2020 project [13] will demonstrate the optimal integration of local energy storage in a smart islanded microgrid, fully operated and controlled in an engineering station, which will also communicate with a main power grid. The aim of the project, set by all the partners, will be the development and operation of a prototype, developed in real environment able to scope the challenge of supporting tasks from the consumer from multiple sources.

Five DSO partners (CEZ distribution, ERDF, EON, Enexis and Avacon) associated with in an innovation project [14] retail power system manufacturers and energy systems experts propose a set of six demonstrations over three years to shows in 18 separate use cases involving one or more levers that increase the flexibility of the local energy system.

In line with worldwide innovation, the project described in paper [15] will develop a toolbox with technologies that allow the production renewable energy in a proportion of at least 80% (to cover the consumption) per year, which aims to achieve a reliability performance increased by 50%, decreasing at the same time the network losses by 10%, being in the end an optimized and optimally controlled system.

In the current context of both global economic crisis and remote work, the project presented by paper [16] will develop and demonstrate innovative tools to provide a complete solution for all phases of a microgrid (as energy island) and large-scale applications such as multi microgrids from Europe and India, countries in full growth.

The integration of the oppressive function brings a project into focus [17] with an aims to integrate cutting-edge technologies, solutions and mechanisms in a scalable Cross-Functional Platform connecting energy networks with diverse stakeholders, facilitating optimal and dynamic operation of the Distribution Grid (DG), fostering the stability and coordination of distributed energy resources and enabling collaborative storage schemes within an increasing share of renewables.

The demand for MGs in the residential sector [18] leads to the need to develop and analyze the system model compared to the above projects and will provide a resilient framework based on the model to reduce the influence of cyber attacks, being in a current context of war. This system model will conduct the hardware-in-the-loop experiment of the controller to validate for advanced simulations and innovative results that can be interpreted in real time.

2.2 Industrial Project in field of microgrids

In response to global challenges and targets to limit climate change, the energy systems around the world need to change. They become more and more dependent on decentralized renewable or low carbon generation resources and in the same time, they face the integration of new types of loads such as electric vehicles, heat pumps, and storage, incorporating digital or "smart" technologies. This is the reason energy systems should be designed, developed, managed, and controlled in concordance with these new requirements [19].

Energy transition implies the digitization of the energy sector, or to point out the importance of the footprint impact, any international plan that contributes to maintaining a high degree of competitiveness in the energy market to propose a business model. Thus, in this paper the research in [20] is referred to, that treats a globalization of the evolution of microgrids, which suffered due to the Covid Pandemic 19, but which followed its growth trend.

The power industry faces today many problems including the rising cost of energy, power quality and stability, an aging infrastructure, mass electrification, climate dynamics and so on. The projected microgrid market growth is shown in Figure 3.

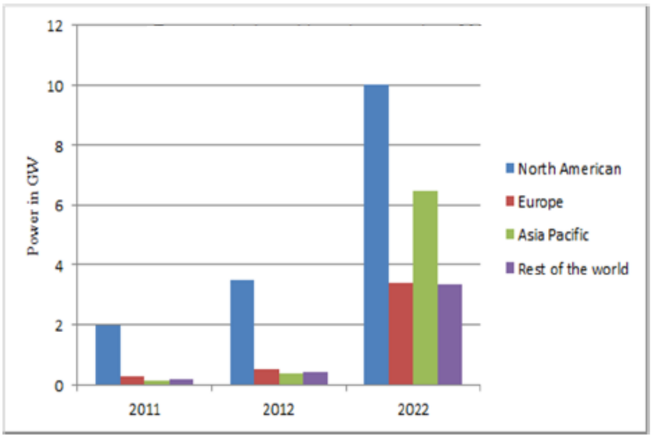

Figure 3. Forecasted Market Growth of MG by 2022 [21].

For this estimation it was a hypothesis the fact that the growth of globally-installed MG capacity has increased dramatically since 2011 and by 2022 it is forecasted to reach a total installed capacity of over 15 GW.

In the research study [20], 236 projects were analyzed, that were classified in 7 main categories, each with examples in Scotland: islanded rural community, remote green village, off grid green town, on grid commuter town, on grid industrial town, large urban and industrial park/campus. This classification is shown in Figure 4.

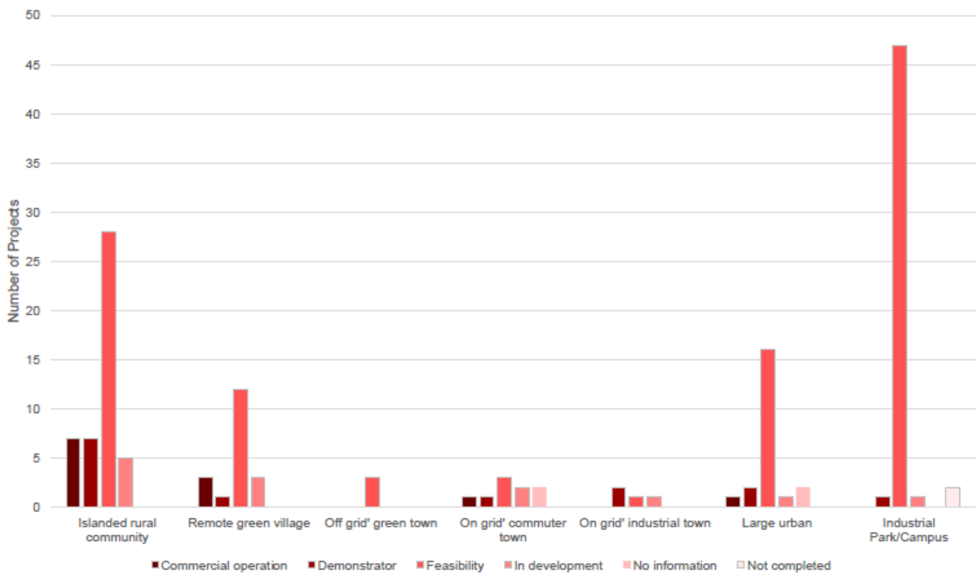

Figure 4. Projects classification [20].

As example, in Canada investment solutions are supported by 250 inhabited islands in many undersea cable connections and 291 remote (off grid) communities - 251 diesel generators. There are 5 examples of Island Energy Systems: Ramea (using wind and diesel to fulfil demand, excess electricity is stored as hydrogen), Lasqueti (uses solar, wind, micro-hydro and diesel generators for power), Prince Edward Island (25% of electricity supplied via wind, proposing new wind projects for 2019), Lasqueti (installed solar, diesel and battery hybrid system with prototype “smart control”) and Wolfe Island (location of 86 2.3MW wind turbines).

Also, China aims for renewable energy to make up 35% of its energy mix by 2030. It is also of real interest that it understands that through 433 uninhabited islands it will ensure a large part of the country's energy independence.

Denmark has pillars of 73 uninhabited islands and smart meter penetration rate of 80% of all households, along with 2 Smart City projects: Frederikshavn aims to be 100% renewable and Aarhus plans to be carbon-neutral by 2030. Neighboring country, Finland shows interest in over 3.5 million smart meter points, 25,000+ island communities although many connected via roads and 1 example Island Energy System: Aland an island with a target to become carbon-neutral by 2051, by introducing wind, smart grids, 40% of heat supply already is delivered through Denmark.

There are many interests for Japan, Latvia, Lithuania, New Zealand, Norway, Sweden, United States of America and others and through this summary it is demonstrated that this paper is of interest and addresses a topic that aligns with global investment.

2.3. Real Operated Case description

It is no longer hidden that Romania has aligned itself both in terms of legislation and regulations with the European conditions and standards imposed, and that it has facilitated investments in this area of renewable and new technology. Thus, it has been shown that it will start investing over 16 billion Euros to ensure Romania’s energy security in 2022 and beyond, and that it shows an interesting market for large European investors. For example, Premier Energy aims to develop capacities with a combined generation capacity of 300-500 MW within five years in Romania and other countries in the region.

Also, of interest is the Monsson group of companies, which has equipped its building with an intelligent micro-network, which–will be analyzed below.

The case study began with the initiative to be energy-independent from the utility network and thus a simulation of equipment and possible control regimes was performed [22]. The MG is presented in Figure 5. It consists of photovoltaic panels with a total installed capacity of 120 kW, two storage units of different capacities (40 kWh and 56.3 kWh, chosen for research purposes), a gas generator of 120 kVA, two geothermal pumps and a charging station for electric vehicle. The microgrid has been designed to cover over 80% of the consumption in the Monsson office building. A controller developed using a redundant hardware platform Siemens S7-1500 was used for data acquisition, monitoring, control of system elements to ensure efficient use of available power supply and energy storage resources. The solution was chosen on the basis of technical specifications to optimize the total energy supplied from the national grid according to a cost constraint, as a basic scenario with which it was compared to.

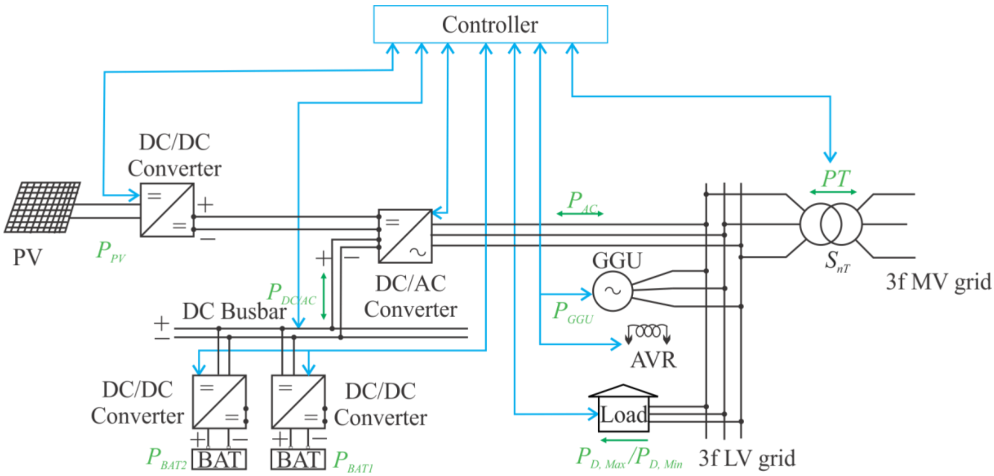

Figure 5. The real case MG structure.

The microgrid aims to maximize the efficiency of conversion modules. Therefore, the PV plant (PV) and batteries (BAT) are located on the DC side, while the load and the synchronous generator are located on the AC side. As usual, AC voltage is used in the three-phase low voltage (3f LV grid) system. The load is fed through a three-phase cabinet. The gas-fired generating unit (GGU) is planned to be connected directly to the LV grid and to be used as a connection buffer and in emergency situations. In addition to the PV plant, the system includes a one-way DC-DC converter (also called a String Booster Box, SBB) and a two-way DC-AC converter, which are integrated into the control system. The exchange of data between the equipment from which it takes information and the PLC was done through different communication protocols. The inverter, which has the role of transforming continuous electricity, from the photovoltaic park through the SBB and later from batteries, into alternative electricity, useful to the consumer of the office building type. The exchange of data between the equipment from which it takes information and the PLC was done through different communication protocols.

The MG takes part in balancing resources to reduce energy consumption costs and even generate additional revenue in the event of a surplus of energy through sales on the electricity market. Therefore, the user becomes a prosumer, an actor active in the energy market, with the possibility to decide how much, when and at what cost it will produce, consume or store this resource. Depending on the user consumption curve, control scenarios were proposed, where the priority given to the different elements, energy cost, gas cost and weather forecast, the use of energy resources can be optimized to ensure optimal decision making.

3. Control strategies

New control strategies are requested in order to preserve the synchronization and proportional power sharing in the network. When microgrid control is taken into discussion, certain tasks should be provided, as voltage control, black start, transition from grid connected to island mode and vice versa, load-shedding, feeding local and critical loads, or producing heat for local installations [23]. As alternatives towards the integration of DG units in the conventional power networks, MGs require more complex control strategies than the ones used for the utility grid. If we deal with a hybrid AC/DC MG, AC and DC sides, and the main power controller need to be correctly managed to obtain an optimal performance [24]. In addition, a MG control system must be flexible so that it allows automatically adjusting to the connection and disconnection of distributed generators.

Thus, a hierarchical control for MGs has been proposed: primary control (a droop control that maintains voltage and frequency stability of the MG subsequent to the islanding process), secondary control (that allows to compensate the voltage and frequency derivations caused by primary control) and tertiary control (that permits an optimal operation in both operating modes and power flow control in grid-connected mode). The hierarchical control scheme can be observed in Figure 6.

Based on studies found in literature, but also on their characteristics, the hierarchical control schemes were detailed in paper [24]. Local control represents the fast, reactive response to a specific situation for voltage and frequency control, which can be performed both from the inverter and from the thresholds fixed in the controller.

The first layer of control in a hierarchical control structure is the **primary level** control. As mentioned before, this control structure is responsible for current and voltage control of the system. Sometimes, in order to achieve proper power management in the system, decentralized load sharing schemes are employed. Some popular primary level control methods are Droop Control method. This type of control allows the correct operation mode of inverter in parallel with the other generators in the microgrid. The current reference for the control of this inverter is derived from the droop characteristic of this inverter, the power management system and the maximum power from the solar panels.

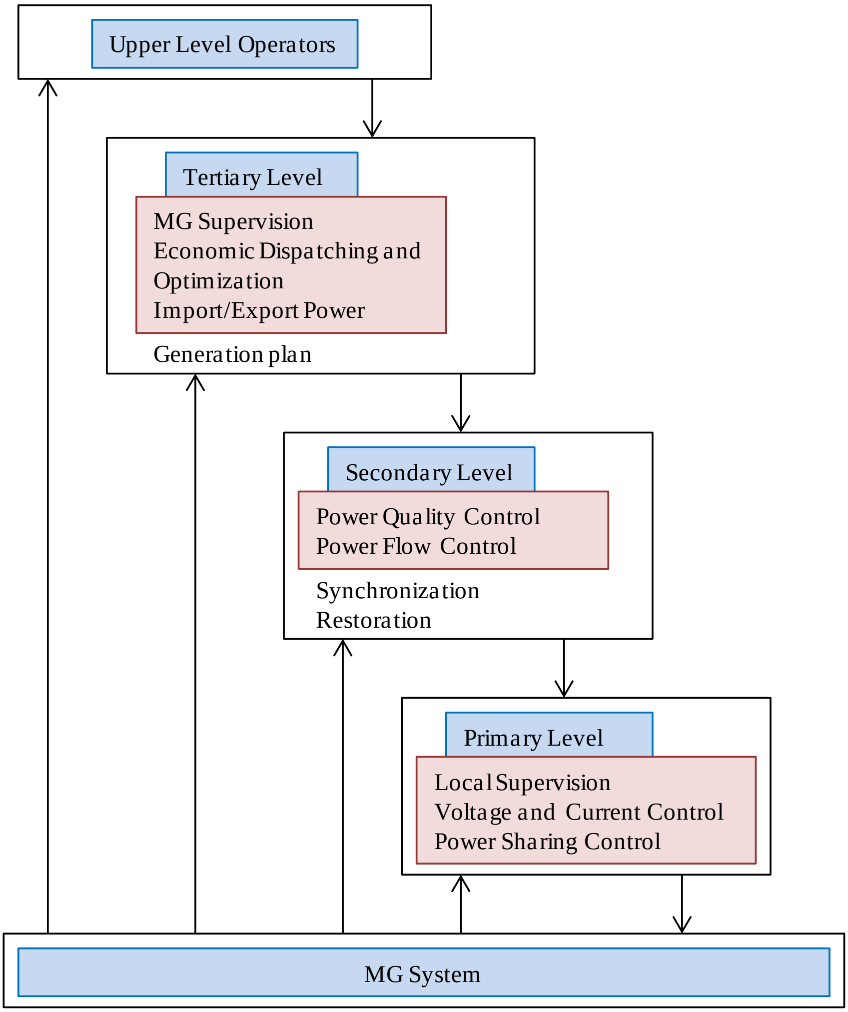

Figure 6. Control scheme - Schematic diagram.

The network remains stable when only one generator operates as a voltage source and the rest as power sources. The battery charger inverter will be the master inverter and will act as a voltage source by setting the mains frequency and voltage. Slave inverters will control their active output power level according to the measured frequency value and their own "P-f droop" characteristic. The master inverter consists of two loops: a current loop and a voltage loop. The reference for the current loop is provided by the external voltage loop and by the power management system. The master inverter will also determine the grid frequency. In this way, the master inverter can control the output power of the slave inverters. Because the interconnected lines are short, the voltage does not vary with the reactive power and a Q-V control doesn't need be used. All the necessary reactive power will be provided by the master inverter and capacitors. The photovoltaic inverter is constantly monitored.

The **second layer of control** in a hierarchical control structure is responsible for restoring the voltages of DC buses to the nominal value. Conventionally, the secondary level control is the MG central controller, but it is considered less reliable because of its well-known drawback of single point failure. It can be implemented by using a PLC, the power line communication technique that uses the existing power lines to transmit high-speed (2–3 Mb/s) data signals from one device to the other [25].

Also, at this level the synchronization of the generators is performed. At the secondary control level, the energy management system measures the power generated and consumed by the loads and considering the droop characteristics of each generator will decide the frequency reference it will send to the master inverter. The secondary control level is implemented in a computer and communicates the data on an RS485 Modbus RTU communication bus. The main task is to provide the necessary power for critical operation mode, to keep the storage system loaded, to implement the protection functions and to predict the most unfavorable cases and to be able to stop the power supply system.

Secondary control is based on predefined rules that set thresholds / limits to determine who becomes a generator and who becomes a consumer, as long as the equipment (inverter and batteries) have allowed bidirectional communication, which allows simultaneous power supply. Its management algorithm has two stages. The first stage implements the start-up function of the microgrid based on renewable resources and the current state of the generators. The second stage continues with the start sequence receiving data from generators and based on the availability of renewable resources and tasks will decide which generators will be used to power the tasks. A first decision can be made based on the state of charge of the batteries taking into account that the master inverter must be able to power the loads if the other generators are turned off. Three cases can occur: 1) the required power exceeds the power produced by the generators, but the critical loads can be sustained, where the non-critical loads should be disconnected from the MG; 2) the consumption due to the loads does not exceed the maximum power produced, in which case the energy demand is divided between the generators; 3) if the critical loads cannot be supported, then it should be decided to switch the generators to a controlled shutdown mode.

A) Connected to the network

When the photovoltaic power generation capacity is greater than the consumer's electricity consumption, a message will be sent to the batteries and the status will be queried, so that if it is discharged, it will start the storage process.
If the battery is charged (standby), switch to the insulated module or inject into the network.

When the fleet of photovoltaic panels will produce less energy than the energy consumed and the battery is discharged, then it is necessary to buy from the national grid a quantity to fill the uncovered peak (so priority will be given to recharging the batteries). If the batteries are charged, the purchased energy will no longer include the required storage. When the power in the panels is zero and the batteries are discharged, the mains batteries are recharged, but only if there is enough power in the batteries.

B) Islanded mode

In this way it is no longer the case to exchange energy with the grid, but it is considered that the microgrid produces energy (from the generator and from the panels) in the following: When the power provided by the park is greater than the power consumed by the building and the batteries are charged, will switch to standby mode. However, if the power is less than the energy consumed and the batteries are discharged, it will be necessary to switch to the mains. When there is no energy produced from the photovoltaic panels, the batteries are used to power the building.

The **tertiary level** of control is considered the last layer of control in a hierarchical control structure, and manages the power flow among the MGs and utility grid. Its fundamental role is the management of power and energy with determined objectives such as coordination of energy storage devices, minimization of operation costs and minimum power flow losses. Tertiary control deals with the import and export of energy in the national grid. During each sampling interval, the dynamic optimal power flow problem is solved based on up to date state-of-charge estimates and predictions of the renewable generation and load. At this level are established the power references for generators. This references generated for the first interval of the time horizon are sent to the lower level control and thus, the time horizon recedes by a step for the next sampling interval. [26].

6. Conclusions

Nowadays, the majority of the electrical power is produced in expansive unified offices, for example, fossil fuel, atomic or hydropower plants. These power plants have great economies of scale, but in fact they transmit power across long separations and contrarily influence nature, because of various monetary, health and security, logistical, natural, land and topographical variables. MG systems facilitate remote applications and allow access to a pollution-free energy by permitting the use of renewable sources of energy. Renewable resources are nowadays world wide spread and because of the intermittent nature of the generated power, such a system can be accompanied by various control means to obtain the maximum potential.

This research paper has been done in order to try to explain the microgrid term and its components are sketched for the different purposes - as research, development or implemented projects, in Romania and worldwide. A hierarchical control of microgrids has also been explained.

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