Sustainable Microgrid Networks: Advances and Applications

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Abstract. *This paper explores the development and implementation of distributed control strategies within AC microgrids, emphasizing their role in renewable energy integration and enhancing environmental sustainability. The research discusses the motivation for integrating renewable energy sources to reduce the carbon footprint and the limitations of conventional distribution networks. Microgrids are introduced as a viable solution to these challenges, offering improved resilience and efficiency in distributed energy systems. The paper classifies microgrids and details their essential components, including energy loads, distributed energy resources, and energy storage systems. The study further delves into various control methods, highlighting the hierarchical control structure with primary, secondary, and tertiary control layers. By examining recent advancements and addressing challenges in microgrid technology, the paper aims to present a comprehensive overview of how modern microgrids can contribute to a more sustainable energy future.*

Keywords. microgrid, energy efficiency, control algorithms, distributed energy sources

1 Introduction

As the world's population continues to grow, and technological progress accelerates with it, the need for energy for humanity to function is increasing at a staggering rate. This growing demand puts great pressure on the existing energy infrastructure and requires, in addition to its modernization, a transition to other, more sustainable and resilient energy systems. According to the International Energy Agency (IEA), global electricity demand is expected to grow by around 3% per year until 2025, which would mean an increase of around 2500TWh. This is more than double Japan's current annual electricity consumption (Electricity Market Report, 2023). The transition to renewable energy sources(RES) is important to mitigate the adverse effects of climate change and reduce greenhouse gas emissions, however, their intermittent and variable nature, such as with solar and wind power, complicates their integration and poses significant technical challenges for traditional distribution systems (Denholm, 2013). Microgrids(MGs), i.e. decentralized energy systems that can operate as a stand-alone energy island or in cooperation with the main distribution grid, have emerged as a possible solution to these challenges. The integration of MGs achieves increased network reliability and efficiency, as well as better opportunities for the integration of RES. By localizing energy production and consumption, line losses are reduced and energy security is increased, especially in isolated or remote areas (Shahbazitabar, 2021) and areas with high risk of natural disasters. Despite their advantages, the complexity of their control algorithms hinders the spread of MGs. Effective MG management requires strategies for balancing power generation and connected load, managing energy storage, and also ensuring synchronization and coordination with the main grid. Continuous refinement of these algorithms is needed to maximize the benefits of MGs and accelerate the transition to RES.

1.1 Legislative motivation for developmentof microgrids

Greenhouse gas(GHG) emissions are a serious problem that needs to be addressed effectively. Within the European Union, this is addressed by the 'European Green Deal' plan, which aims to achieve GHG neutrality by 2050 and to make Europe the first carbon-neutral continent (A European Green Deal, 2019). Although much attention has been paid to reducing emissions in the transport sector, a large part of the emissions is caused by the energy sector, or the production, transport and consumption of energy. In 2012, the European Union adopted Directive 2012/27/EU, which aimed to increase the efficiency of energy use (and thus reduce energy consumption) by 20% compared to 1990, i.e. to a maximum of 959 Mtoe - Million Equivalent Tonnes of Oil - (EU Directive, 2023). The final energy consumption in 2020 was at 907 Mtoe, marking the success of this directive. Also, this success motivated the creation of a new directive, which was recently put into force in October 2023. The EU/2023/1791 Energy Efficiency Directive aims to reduce energy consumption by a further 11.7% by 2030 compared to 2020, i.e. to a maximum of 763 Mtoe of final consumption. This also includes a high promotion of decolonization of heating and cooling systems, maximizing the use of waste heat and RES (Energy Efficiency Directive, 2023). This directive is part of the 'REPowerEU' plan and one of the objectives of this plan is to increase the overall share of RES to 45% by 2030, up from 23% in 2022. The share of electricity consumption in total energy consumption has been fairly stable over the last 11 years, averaging 22.93% with a standard deviation of 0.18% . This sector also shows the most significant progress in the implementation of RES with an average annual increase of 1.405%(Eurostat, 2024). In 2022, up to 41.17% of the electricity in the EU was from RES, while if we consider the share of electricity in total energy consumption and the targets of the "REPowerEU" plan, by 2030 this share should be at 80.55% (REPowerEU, 2023). Such a change will have a major impact on the aforementioned GHG emissions. Emissions due to electricity consumption (in grams of CO2 equivalent emissions per kilowatt-hour [gCO2eq/kWh]) have seen a significant decline over the past decades, which has had a positive impact on the overall reduction of emissions even though total consumption has not seen sharp declines (Eurostat, 2024). This has been a significant motivation in the deployment of RES, and it can be expected that efforts to deploy these technologies will only increase in the coming years.

2 Microgrids overview

Since the term microgrid was first introduced in 2001, several definitions have been developed for this type of energy network and its functional principle. B. Lasseter (Lasseter, 2001) first defined a MG as a group of micro-energy sources, energy storage systems and loads that represents a single entity that has central control. According to Lasetter, the basis of the MG concept is the idea of a controlled interconnection between the microgrid and the main distribution network. This definition is followed by the generally accepted definition (Shahbazitabar, 2021):" Microgrids are energy distribution systems comprising loads and distributed energy resources (such as distributed generators, batteries or controllable loads) that are controllable and operate in a coordinated manner, whether connected to the main electricity grid and/or as an energy island." MGs have the added economic potential enabled by ancillary services for energy trading between the MG and the main grid. The concept of "energy islands" was explored by Rettig et al. (Rettig, 2023) and laid the foundations of a theoretical framework defining this concept, which is often associated with MGs. The types of energy islands are defined by their boundaries, which can be geographical, as in the case of real islands, political in the case of isolated states or provinces, and technological for the separation of available energy services. While many characteristics are shared with MGs, such as decoupling from larger grids, local energy management, easier integration of renewables, and the use of battery storage units, energy islands are largely isolated on a permanent basis in the context of their geopolitical and physical conditions. This difference shows the adaptability of MGs not only in remote locations but also in the context of easily interconnected grids (e.g. cities, towns, households).

2.1 Microgrid structure

The elements of MGs can be divided into several groups:

Energy loads are all devices that draw electricity from the grid and convert it into other types of energy. We divide loads into two subgroups:

- Non-controllable loads, which include a wide range of appliances that cannot be controlled by the grid. These can be household appliances, production machines, directly controlled electric motors, computing equipment, etc. These devices are a challenge for optimizing control in the MG and their consumption must be monitored.
- Controllable loads whose power draw can be controlled based on the needs of the MG or by external intervention. Examples of these systems include air conditioning units with adjustable target temperature, controllable lighting systems, and frequency-controlled electric motors. This group also includes chargers for electric vehicles, which are a rapidly expanding technology and bring new opportunities and challenges to the MG system. Controllable loads are the basis of supply-demand management strategies and allow control systems to balance demand to some degree to ensure grid stability.

Distributed energy resources (DERs) are small-scale units for local power generation located close to energy loads. They may include (and in most use cases do include) RES. However, fossil fuel consuming generators can also be used as distributed resources, which can be used as a redundant source when renewable energy is scarce. The choice of DERs for use in a MG depends on local resources as well as environmental and economic factors.

Energy storage systems (ESS) are an essential element of the MG and enable the penetration of RES that have intermittent energy supply characteristics. There can be several types of these systems, each with its own advantages and disadvantages of use, as well as specific application cases.

Power electronics layer interfaces are devices that provide conversion between different types of distribution networks (alternating-current(AC) and direct-current(DC)) and also adjust network characteristics (e.g. voltage and frequency). They play a fundamental role in controlling the flow of power within the MG, together with monitoring functions. The basic elements are AC-to-DC converters and vice versa, which allow the connection of different types of sources and loads (Abbasi, 2023).

Control systems, which perform the task of monitoring MG parameters and the status of all elements, communicating with MG elements, and executing control algorithms based on data acquired in real time. They are key to ensure the functionality of the network as they control the power flow within the network and the network mode (grid connected/isolated).

2.2 Classification of microgrids

MGs are a broad concept and therefore further classification is needed to specify their size, purpose, mode of operation and other parameters (Shahbazitabar, 2021). Classification by type:

- **Campus MGs:** usually in schools and on university campuses where they are used for research of energy management, distributed energy resources or controllable loads. Such a grid is also used, for example, by the University of California, San Diego, where it supplies electricity to a 450 hectar campus from two 13.5MW gas turbines, a 3MW steam turbine and 1.2MW of solar panels. Together, these sources cover 85% of the electrical consumption, 95% of the heating and 95% of the cooling within the campus (San Diego Microgrid, 2024).
- **Military MGs:** mainly used for energy security and resilience of military bases. In 2019, a military MG was completed at Kirkland Air Force Base (USA) (Department of Energy, 2020) and is composed of modular parts, each with power conversion, control, protection, and storage functions. These modular parts are interconnected by a single bus with a bipolar DC voltage of ±375 V. The MG connects photovoltaic panels, batteries and gas generators together with controllable loads (electric vehicle chargers).
- **Residential MGs:** These include single households or residential communities and provide them with increased reliability, potential cost savings and increased energy independence. They help reduce the carbon footprint of households and maximize the use of RES. Examples of such energy communities can be found all over the world, one of them is the village of Feldheim in Germany, which covers 100% of its own consumption from RES (Euronews Energy, 2022). Another example is the Isle of Eigg energy island in Scotland, which is completely decoupled from the main energy grid and combines solar, wind and hydro power in its MG, thus reducing the island's dependence on distributed diesel generators and using this energy to heat community centres in case of surplus energy production (Electric, 2024).
- **Commercial MGs:** specialized for use in the commercial sphere to increase the reliability and maintainability of shopping centers, corporate campuses or hospitals. They enable energy management in the hands of businesses and other economic benefits such as reduced energy costs and the ability to sell excess energy to the national grid. As computing capacity moves to the Cloud space, the energy demands of data centers are also increasing, which is why US retailer eBay decided to connect the "Topaz Data Center" in the US state of Utah to the MG to eliminate their dependence on uninterruptible power supplies (UPS). This network is based on a group of biogas generators, which also reduced the energy consumption of local coal-fired power plants (Data Center Knowledge, 2012).
- **Industrial microgrids:** Usually larger than other types of MGs. These grids allow industrial companies to comply with ever-tightening legislation on the energy intensity of production while reducing their own energy costs. Another reason may be insufficient supply capacity from the main grid, as is the case with the Tritax Symmetry Logistics Park in the UK. This MG contains enough renewable energy and energy storage to keep the logistics center running in islanded mode, while at times of low energy consumption the entire center can be powered solely from batteries (Microgrid Knowledge, 2020).

According to their size, MGs are divided into:

- Small networks typically with a capacity in the order of hundreds of kW.
- Large networks with capacity in MW

In terms of use they can be divided into:

- Networks for high quality energy that ensure stable voltage levels without interference and fluctuations. This type of networks is mainly intended for industry and other sectors where even small fluctuations in power quality can lead to service interruptions and financial losses (e.g., data centers) (Azar, 2000).
- Resilience-oriented networks designed to maximize the reliability of power supply even in crisis situations. These networks can operate in grid-connected mode and also in fully isolated mode, and provide rapid restoration of supply during "low frequency, high impact" events such as natural disasters (Chi Xu, 2017).

Division in terms of type of electrical voltage:

- **AC microgrids(ACMGs)** use low and medium AC voltages to transmit power from sources to consumers. The advantage is easier interoperability with the external distribution network and compatibility with appliances operating at traditional low voltage levels. The DC distributed sources and batteries are connected to a common AC bus via DC-to-AC converters, with some of the energy being lost in this conversion and transmission. The AC distribution network can be single-phase, three-phase with a neutral conductor, and three-phase without a neutral conductor. To improve the network parameters and better behavior during faults, it is important to control the loads connected to the MG system by, for example, simply disconnecting them from the power sup-

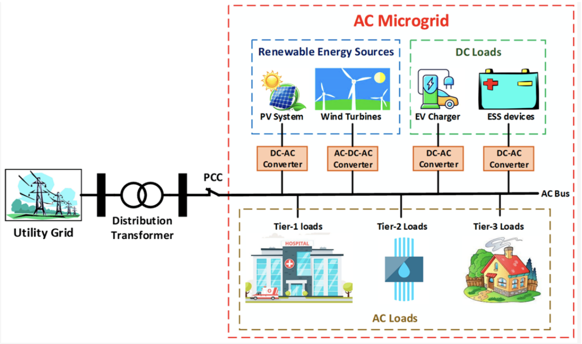

Figure 1: Diagram of a typical ACMG (Abbasi, 2023).

ply. Moran (Moran, 2016) defines the division of AC loads into three levels according to the possibility of disconnection from the grid:

- Tier-1 loads are the most critical infrastructure that must never be disconnected as part of load shedding. This category includes hospitals, ambulance services, emergency dispatching, and the like.
- Tier-2 system's peak energy load or to shift it over time. These loads may be disconnected for the purpose of starting additional generators during outages. These loads include heating, air conditioners, pool filters, etc.
- Tier-3 loads can only be disconnected in an emergency, for example to prevent a complete failure. Residential and commercial buildings with backup generators are in this category. Some loads in this category can also be used to generate power to the grid to start after a complete outage.

The structure of the AC microgrid is shown in Fig.1

- **DC microgrids(DCMGs** are a new, emerging technology that enables direct connection of DC power supplies, batteries and DC loads. Advantages are lower line losses, easy connection to DC appliances, and fewer synchronization interfaces with AC networks. The DC voltage distribution network can be monopolar (one conductor, the role of the neutral conductor is fulfilled by the earth), unipolar/homopolar (one conductor for the supply, one for the return path of the current) and bipolar (two conductors with opposite voltage polarity, the centre point is grounded). The structure of the DC microgrid is shown in Fig.2

- **Hybrid microgrids(HMGs)** combine the advantages of the two types described above for increased flexibility, efficiency and reliability. They include both AC and DC buses interconnected by rectifiers and inverters. The advantage of this approach is the ability to easily interconnect DC elements with DC elements and greater functional flexibility. The disadvantage is the higher complexity of control systems and algorithms for synchronizing both types of distribution systems (Sinha, 2024) The structure of the hybrid microgrid is shown in Fig.3

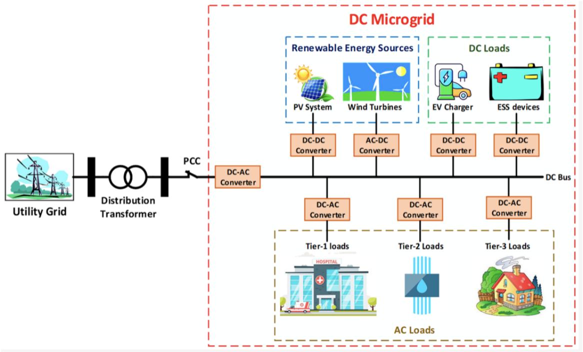

Figure 2: Diagram of a typical DCMG (Abbasi, 2023).

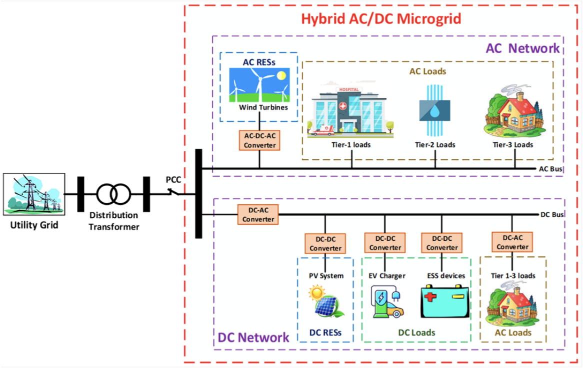

Figure 3: Diagram of a typical HMG (Abbasi, 2023).

3 Control of microgrids

MGs present a cyber-physical system, with the cyber part providing services like inverter control, economical dispatch or power flow management based on measured and collected data (Shan, 2022). Control mechanisms within the MG are usually segmented according to a hierarchical control structure consisting of three layers: primary, secondary and tertiary. Each subsequent layer creates setpoints and references for the layer below. As we go higher in this hierarchical model, the period between control signals (control period) increases as well from the primary control working in miliseconds up to the tertiary control methods generating commands in periods ranging from several minutes up to hours (Abhishek, 2020).

3.1 Primary control

Primary control is responsible for regulating each inverter output to ensure power sharing between DGs. For this purpose, droop control is usually used to droop frequency and voltage in relation to active and reactive power, respectively. This control method is decentralized, so it operates locally on the level of a single inverter-interfaced DG using droop method given as:

$$\omega = \omega^* - m_p(P - P^*) \tag{1}$$

$$E = E^* - n_p(Q - Q^*) \tag{2}$$

With ω and E representing the output frequency and voltage command, respectively. ω^* represents the nominal grid frequency, P as measured active power and P^* being the active power reference. The voltage control equation follows the same structure with reactive power measurement Q and reference Q^*. m_p and n_p are droop coefficients which adjust droop characteristic angle. It achieves good results in terms of power sharing between DGs, however with higher droop coefficients power sharing between DGs improves, but it also introduces voltage and frequency deviation from nominal grid values. Droop control outpus serves as a setpoint for inner control voltage(external) and current(internal) control loops. This method can be further augmented with methods for enhancing power stability and compensating power issues like negative sequence currents (Zhao, 2017) or transmission line impedance (Peng, 2019).

3.2 Secondary control

To compensate the primary network output deviation and increase grid stability during transients, secondary control is employed. There are several methods used on this control layer, which we can further divide depending on the system architecture. *Centralized control methods* are computed using a single centralized controller, which collects data from the whole MG and generates references for primary control in DGs. This approach allows to contain the whole control layer in a single device with easier synchronization. However, the main issue is a single point of failure, which can negatively influence primary controllers in case of expected or unexpected power issues (Dadi, 2023). The opposite to this is fully *decentralized system* in which the secondary controllers operate on each DG inverter. Absence of communication makes this design attractive, because of the potential issues that come with packet transfer like communication delay or packet loss. This approach however, is infeasible in case of secondary control because it prevents the controllers to cooperate in reaching a common optimization goal and may cause instability during transients (Singh, 2019). A very promising compromise between these two architectures is *distributed control*, which gained interest of many scientists in the recent years. This communication architecture consists of secondary controllers operating on local DG level, but employing communication links between neighboring nodes (Moradi, 2023). This not only helps distribute computation load between the controllers, it also allows cooperation in optimization problems and converge on nominal values for both voltage and frequency. To describe a distributed communication network, graph theory is commonly used (Liu, 2024). As mentioned before, by introducing communication between nodes, issues associated with packet loss and communication delays are also introduced. Researchers in (Huang, 2024) used a Lyapunov-Krasovskii functional to provide adaptive delay-independent secondary control with stability proved by extensive testing including load variations and plug-and-play scenarios. Another approach presented in (Wu, 2019) employs lead-lag compensation and gain regulation blocks to introduce phase lead and compensate for communication delays with real-time experimental validation.

3.3 Tertiary control

The last control layer in the hierarchical control model is tertiary control. The purpose of this layer is to provide energy management functionalities, control power flow within the MG and optimize the economic dispatch (Shan, 2023). As we go higher in the hierarchical model, the control period lengthens and with tertiary control, the time between commands can be minutes, even hours depending on the optimization goal and prediction horizon. There is a general discussion on whether the tertiary control needs to be employed in islanded MGs as some of the mentioned functionalities can be associated with secondary control as well (Shan, 2022). In grid-connected mode tertiary control also handles electricity market engagement and cooperation in the case of multi-MG networks (Rashidi, 2021). To achieve the stated goals, optimization techniques are used, such as mixed-integer linear or quadratic programming (Vilaisarn, 2022; Jabr, 2021), optimal power flow methods (Brandao, 2020; Chopra, 2022), genetic algorithms (Hernandez, 2023; Kothakotla, 2021) or particle swarm optimization(PSO) (Shan, 2022; Phommixay, 2020).

4 Conclusion

MGs are a technology area with great research and application potential and represent one of the few options for 100% integration of RES, mainly through the use of ESS, which form the core of the MG concept. MGs are based on the separation of services into small, self-managed units, which improves the reliability and flexibility of energy for end consumers. A fundamental prerequisite for proper operation and economic viability is the use of sophisticated algorithms at different levels of MG management, which take into account the instantaneous characteristics of RES, the prediction of energy load, the parameters of energy storage and also the price of energy. The objective of this article is to provide a research platform based on the conducted problem analysis of the studied area.

The follow-up research will be aimed mainly on tertiary control algorithms for MGs with a focus on better utilization of battery storage and improvement of the economic efficiency of MG operation using prediction and optimization algorithms, such as PSO and genetic algorithms.

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