Interaction between physical micro-grids

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About ERA-Net Smart Grids Plus

ERA-Net Smart Grids Plus is an initiative of 21 European countries and regions. The vision for Smart Grids in Europe is to create an electric power system that integrates renewable energies and enables flexible consumer and production technologies. This can help to shape an electricity grid with a high security of supply, coupled with low greenhouse gas emissions, at an affordable price. Our aim is to support the development of the technologies, market designs and customer adoptions that are necessary to reach this goal. The initiative is providing a hub for the collaboration of European member-states. It supports the coordination of funding partners, enabling joint funding of RDD projects. Beyond that ERA-Net SG+ builds up a knowledge community, involving key demo projects and experts from all over Europe, to organise the learning between projects and programs from the local level up to the European level.

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List of acronyms

ADMM	Alternating Direction Method of Multipliers
AFRR	Automatic Frequency Restoration Reserves
BESS	Battery Energy Storage System
BTB	Back-To-Back
CSPR	Cost-scaling Push-relabel
DER	Distributed Energy Resource
DG	Distributed Generation
DSO	Distribution System Operator
EI	Energy Internet
e-LAN	energy Local Area Network
EMS	Energy Management System
ER	Energy Router
GOER	Global Optimal Energy Routing
HVAC	High-Voltage Alternating Current
ICT	Information and Communication Technology
LAPPN	Local Area Packetized-Power Network
LOER	Local Optimal Energy Routing
LVDC	Low-Voltage Direct Current
MAS	Multi-Agent System
MG	Micro-grid
MGCC	Micro-grids Central Controller
MMG	Multi–Micro-grid
MV	Medium Voltage
MVDC	Medium-Voltage Direct Current
OPF	Optimal Power Flow
OSPF	Open Shortest Path First
P2P	Peer-to-Peer
PI	Proportional Integral

PLC	Power Line Communication
PLL	Phase Locked Loop
PR	Proportional Resonant
PV	Photovoltaic
PWM	Pulse-width Modulation
RE	Renewable Energy
RES	Renewable Energy Sources
SST	Solid State Transformer
TFEC	Total Final Energy Consumption
TRL	Technology Readiness Level
TSO	Transmission System Operator
VSCs	Voltage Source Converters
WAMC	Wide Area Monitoring and Control system

1. INTRODUCTION

This report is a part of the project m2M-Grid (micro-to-MegaGrid), established by the ERA-Net Smart Grid Plus initiative, with support from the European Union's Horizon 2020 research and innovation programme.

Adoption of bottom-up technologies such as micro-grids (MGs) in a mega scale in distribution grids is facing challenges from coexistence of top-down grid control systems and market models. This project focuses on accelerating the deployment of MGs by:

(i) Enhancing the distribution grid planning process to take into account technical and market impacts of micro-grid integration,

(ii) Developing control functions for effective coordination with distribution grids,

(iii) Developing a tool-box to exploit potential flexibility of MGs.

The developed solutions will be validated in a range of test environments e.g., cross-platform software and power hardware-in-the-loop experiments. Especially, three dedicated demonstrations in Sweden and France will be used to facilitate validation and replicability analyses based on real environments. This project demonstrates market opportunities for involved stakeholders, thus helping to accelerate the adoption process of developed MG technologies. The overall objective of the project is to facilitate the coordinated operation of MGs (both physical and commercial) and distribution systems, and thereby advance overall benefits for end-users as well as distribution system operators (DSOs). The project aims to develop:

(i) A physical interface, with advanced set of control functionalities, to create effective communication and coordination among MGs and between MGs and the distribution grid.

(ii) An interface for commercial MGs to enable flexibility and energy transactions for securing local network operation and promote self-power balancing. This project aims also to develop optimal clustering algorithms for such MG solutions in the mega-scale distribution grid, which can be integrated into and upgrade the future network planning. Developed solutions from this project will be justified in a whole range of test environments, including software platforms and three dedicated demonstration sites.

To accomplish the above-mentioned objectives of the project, the following four main goals have been defined:

1. Development of a new physical test site and specification of functional requirements for MG interoperability: Since the project will develop solutions in a relatively high technology readiness level (TRL) to be tested in three demonstration facilities, involvement of stakeholders is critical to mention in functional requirements and to determine communication interoperability protocols.

2. Development of interfaces to ensure interoperability of physical micro-grids: While the existing distribution network relies on the top-down control methodology, development of MGs initiate opportunities for bottom-up control functionalities to deal effectively with local network issues. Interoperability between them, therefore, is crucial to avoid undesired impacts on grid operation.

3. Development of interfaces to enable commercial MGs: The management of these MGs needs to be aligned with the existing and future market models via a commercial interface to maximize system benefit, thus stimulating active participation from end-users in a larger market volume.

4. Enhancement of network planning process considering multiple MGs: Deployment of MGs can be based on either geographical or market operational boundary conditions. Future network planning process needs to take into account various decentralized control and operation modes of MGs as well as their potential flexibility.

Especially, the Working Package 4 (WP4) of m2M project considers control and coordination methodologies to enable the physical MG interface according to functional requirements specified in WP2, followed by validation in laboratory environments and facility preparation for on-site demonstrations. The work of task 4.2 in WP4 promotes a peer-to-peer (P2P) interaction between physical MGs based on smart power routers or energy router to re-route information and power flows to handle network congestion and other local MG issues. The strategies for load sharing, curtailment, synchronization, and coordination will be developed in this task.

1.1 Aim and scope of the report

The report aims to introduce an overview of the physical multi-micro-grid (MMG) system from the point of view of Energy Internet (EI). In this work, MGs in the MMG system are able to interact directly with each other through the energy router (ER). Therefore, the scope of the deliverable is:

- To introduce key-concepts (MMG system, EI and ER).
- To develop the ER as an interface between physical MGs.
- To develop algorithms for load sharing, synchronization and coordination in P2P interaction between physical MGs.
- To validate the algorithms with a simulation environment.

1.2 Outline of the report

This section continues by giving an overview of global situation and introducing the background.

The remainder of this report is organized as follows:

- Sections 2 presents the concept of a MMG system with the controlling approaches.
- Section 3 demonstrates the role of ERs in the vision of smart grid.
- Section 4 introduces the state of the art of ERs.
- Cooperation strategies between physical MGs are developed in section 5.
- The synchronization between MMG system and the main grid is considered in section 6.
- Section 7 presents a methodology for frequency coordination in MMG system.
- Graph theory based load sharing algorithms are proposed in section 8.
- Finally, section 9 concludes the report with summarizing remarks.

1.3 Global situation

The year 2018 witnessed a comparatively steady market for renewable energy (RE) technologies. Total renewable power generation capacity increased at a constant pace compared to 2017, and the number of countries integrating high shares of variable RE continued to raise. Corporate sourcing of renewables more than doubled compared to 2017, and renewables have expanded in considerable amounts all around the world.

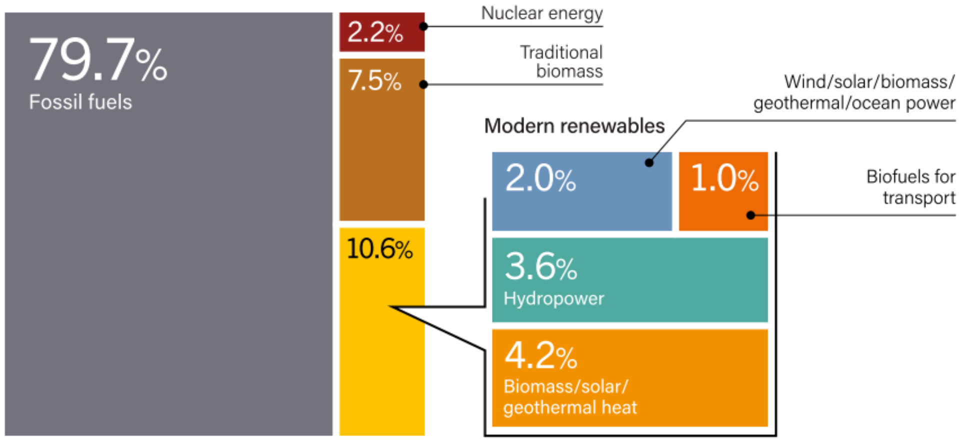


Figure 1.1 – Estimated renewable share of total final energy consumption, 2017 [1].

In 2018, global energy demand grew an estimated 2.3%, the greatest growth in a decade. This was due to strong global economic rise (3.7%) and to higher heating and cooling need in some regions. China, the United States and India together counted for nearly 70% of the total addition in demand. Due to an increase in fossil fuel consumption, global energy-related carbon dioxide (CO_2) emissions increased approximately 1.7% during the year. As of 2017, RE accounted for an estimated 18.1% of total final energy consumption (TFEC). Modern renewables supplied 10.6% of TFEC, with an estimated 4.4% growth in demand compared to 2016. Conventional use of biomass for cooking and heating in developing countries accounted for the remaining share. The highest portion of the modern renewable share was renewable thermal energy (an estimated 4.2% of TFEC), followed by hydro-power (3.6%), other renewable energy sources (RES) including wind and solar energy (2%), and transport biofuels (about 1%) [1] (Figure 1.1).

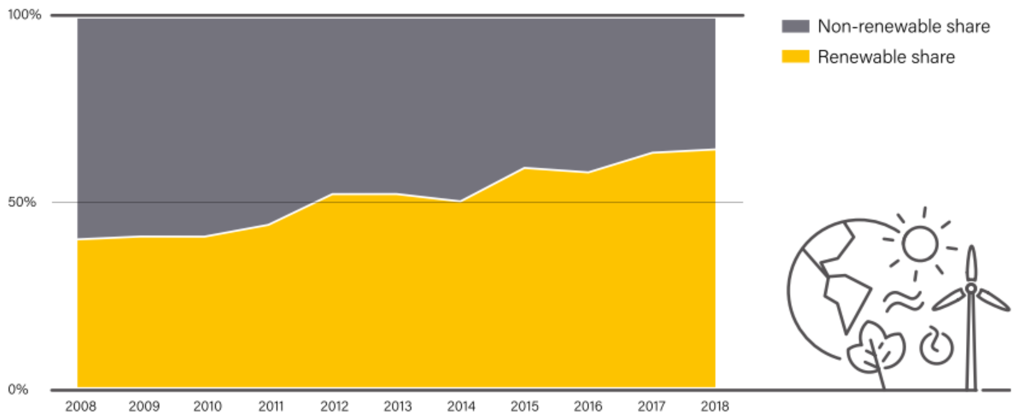


Figure 1.2 – Share of renewables in net annual additions of power generating capacity [1].

In the power sector, RE is more and more preferred for new electricity generation. Around 181 GW of renewable power generation capacity was added in 2018 – setting a new record just above that of the previous year. In general, renewable power generation capacity now accounts for almost one-third of the totally installed power generation capacity worldwide. Approximately two-thirds (64%) of net installations in 2018 were from RES, marking the fourth year in a row that net additions of renewable power generation capacity were higher than 50% [1] (Figure 1.2).

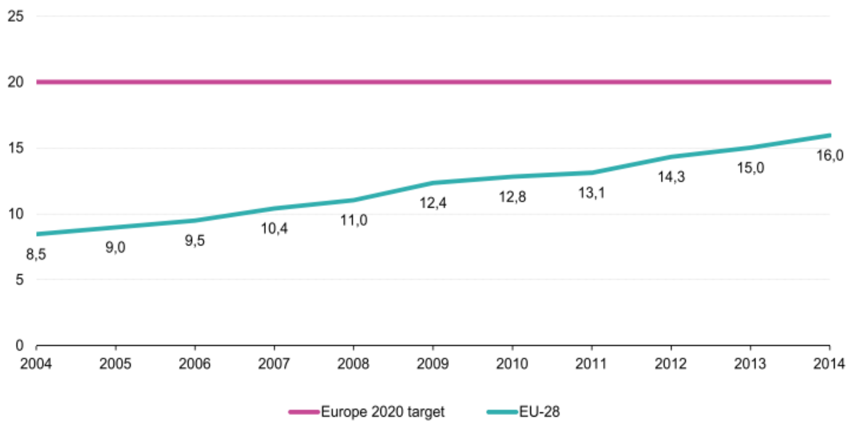


Figure 1.3 – Share of energy from RES in gross final consumption of energy in EU (%) [2].

To meet the Europe 2020 target (Figure 1.3), over the decade 2004–2014, there was a reduction in the primary energy production for fossil fuels and nuclear energy. Production of petroleum products accounted for the highest decline (52.0%), while gas production dropped by 42.9%. Nevertheless, there was a crucial raise (73.1%) in production of RES over the same period [2].

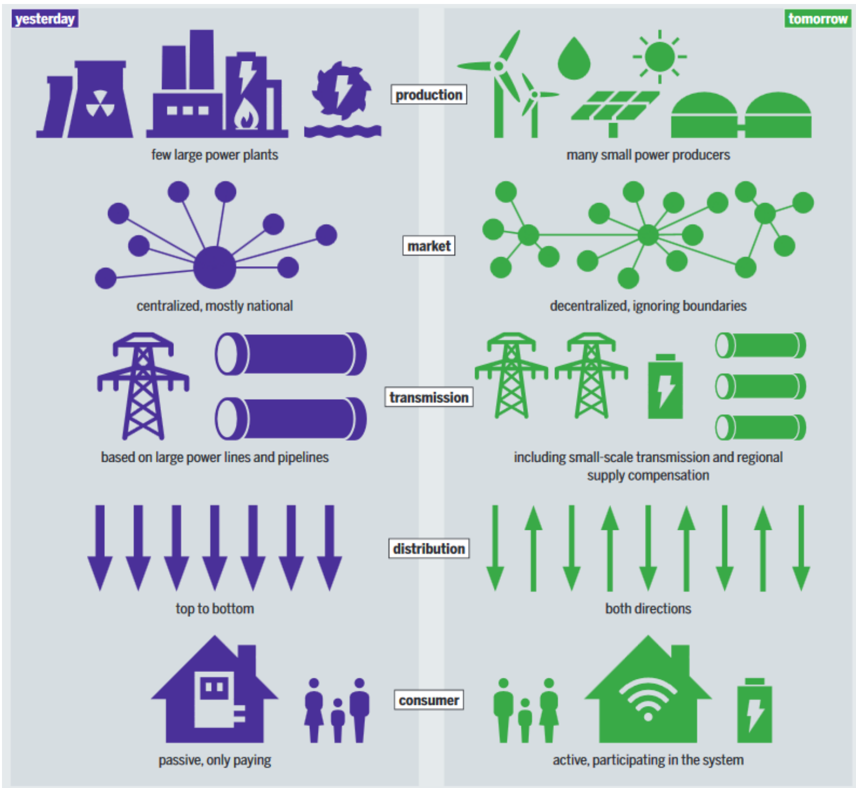


Figure 1.4 – The development of power system [3].

In order to deal with the massive integration of RESs, distribution grids are being transformed from passive to active networks, in the sense that decision-making and control are distributed, and power flows bidirectional (Figure 1.4). This distribution grid system relieves the integration of RES, demand-side management and energy storage systems, and creates opportunities for new types of instruments and services, all of which would require complying with accepted protocols and standards. The main function of an active distribution network is to precisely associate power production with consumer demands, allowing both to decide the best way to operate in real-time [4]. To achieve that, information and communication technology (ICT) plays a key role in this network. The realization of active distribution networks demands the implementation of radically new system idea. MGs, also described as the “building blocks of smart grids”, are maybe the most promising new network structure. The organization of MGs is based on the control capabilities over the network operation offered by the distributed energy resources (DERs) containing micro-generators (such as micro-turbines, fuel cells, and photovoltaic (PV) arrays), together with storage devices (such as flywheels, energy capacitors, and batteries) and controllable loads, at the distribution level [4]. In case of faults or other external disturbances or disasters, these control capabilities allow distribution networks, mainly interconnected to the upstream distribution network, to have the capability to work in stand-alone mode, thus improving the quality of supply. In addition, from the utility point of view, the utilization of micro-sources via a MG system can possibly reduce the need for distribution and transmission facilities. Obviously, DERs located next to loads can lessen power flows in transmission and distribution circuits with two important effects: loss-reduction and the capability to potentially replace the need for more network assets. Moreover, the existence of generation close to demand could improve service quality seen by end-users. MGs can serve network support in times of stress by relieving congestion and aiding restoration after faults. Therefore, all these benefits above will encourage DSOs, consumers, and energy suppliers to establish more MGs.

2. Multi–micro-grid system

2.1 Definition

With the aim to develop smart cities, micro-grids (MG) are being progressively installed in power networks e.g., the MG capacity exceeded 1.8 GW in 2018 in the U.S [5]. Because of the fast expansion of MG technology, more MGs are being set up and connected to distribution networks [6]. An energy management system (EMS) is required for each MG in a power network. An EMS comes with many features, such as day-ahead scheduling combined with a real-time scheduling unit, and a local energy market structure based on the single-side auction that manages a real-time energy cost. Nevertheless, owing to the advancement of the communication and signal processing technology, a MG can be considered as an intelligent node. Therefore, several micro-grids can decrease the limitations in the power transmission network.

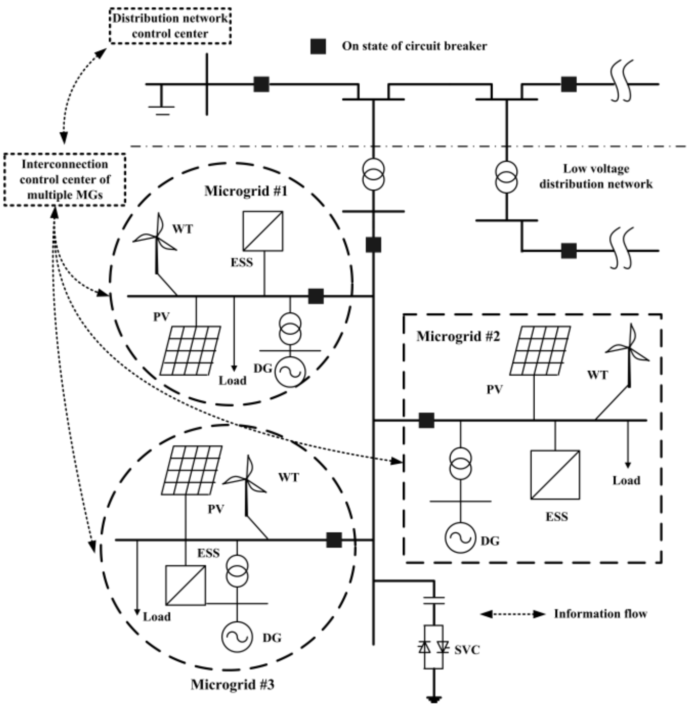


Figure 2.1 – A typical structure of multi-micro-grids system [7].

The first idea about MMG system correlates with a high-level structure, formed at the medium voltage (MV) level, comprising several MGs and distributed generation (DG) units connected to adjacent MV feeders [4]. In a MMG system, it is mostly presumed that the power dispatch of MGs must transmit through the main grid, and a single MG is regarded as a controllable DER. Figure 2.1 describes a typical structure of a MMG system.

In task 4.2 of the m2M project, MGs in MMG system are able to interact directly with each other. The adjacent MGs have the ability to trade energy directly, which is the key motivation for the development of the MMG system and smart grids. For this purpose, the MMG system has become an emergent research topic.

2.2 Controlling approaches

There are several approaches for controlling in MMG system, from fully centralized to fully decentralized strategies. The next section will introduce these approaches with their advantages and disadvantages.

2.2.1 Centralized

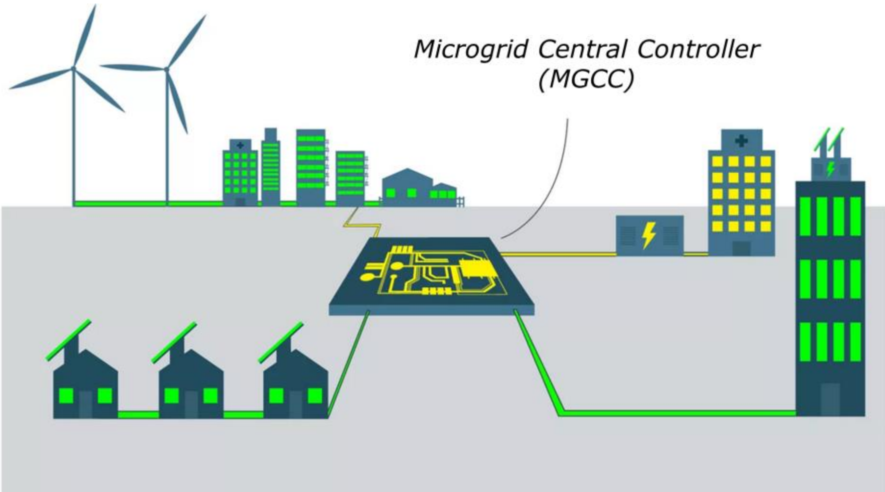


Figure 2.2 – Centralized control architecture.

In fully centralized control scheme as shown in Figure 2.2 [8], all available measurements and information of the integrated MGs are gathered in a micro-grid central controller (MGCC) that imposes the control set points for all units. In [9], the authors introduce an implementation of a centralized controller based on wide area monitoring and control system (WAMC), which can be used to carry out a centralized secondary and tertiary control. In [10], by using WAMC, a centralized secondary voltage controller has been proposed. In addition, authors in [11] implement centralized approach for automatic frequency restoration reserves (AFRR) in the Belgian transmission system, delivered by conventional power plants. There are several advantages and disadvantages of this strategy.

One of the advantages of centralized control system is that the central controller receives all necessary data from the MGs, which allows the multi-objective controller to achieve globally optimum performance. Furthermore, because there is only one controller here, the system has a high controllability.

On the other hand, the computational burden in a single controller can be particularly heavy. This approach requires very high quality of communication from all DERs to the central point of control. Moreover, a centralized controller creates a single point of failure and redundancy of the central controller is costly. Thus, a collapse of the overall system can happen if there is a loss of connection with the central controller. Another drawback of the centralized approach is the privacy as this strategy requires all the information from DERs owners, which must also agree to hand over control of their resources to a third party. MGs might be operated by different utilities and the information on production costs cannot be disclosed. Subsequently, central systems are usually considered less scalable and system maintenance demands complete shutdown.

To tackle the above issues, distributed control architectures are developed, as described in the next sections.

2.2.2 Hierarchical

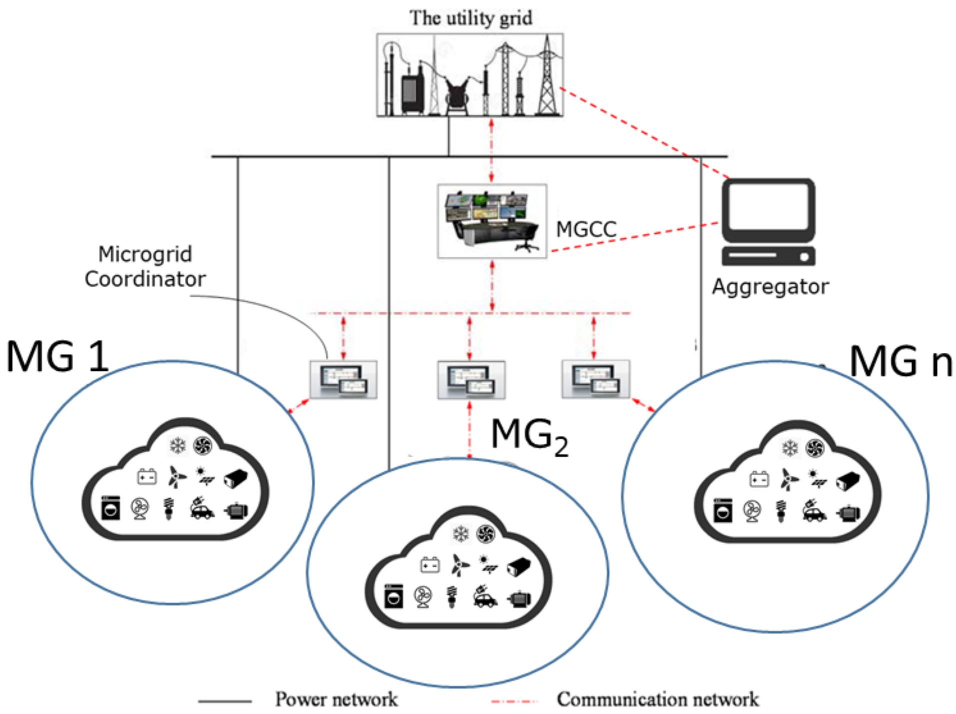


Figure 2.3 – Hierarchical control architecture, inspired from [12].

To overcome the problems of the centralized controller, the hierarchical control strategy is introduced in Figure 2.3. In this strategy, there is an aggregator in communication with the central controller. This aggregator through a hierarchical system, determines which DERs should be used at any moment. Thus, this strategy is also mentioned as the "Aggregate and Dispatch" method. Since the sources are represented to the central optimizer in an aggregated way, there is significantly less information required at the central controller and the system is more scalable. This approach is suitable for utilizing demand response resources. For instance, in [13], the demand response reserves are offered by aggregators to a transmission system operator (TSO) e.g., for automatic or manual frequency restoration reserves.

The coordination of multiple, centrally controlled MGs can also be established in a hierarchical way. In that case, a MG central coordinator organizes multiple MGs, each controlled by a local MGCC. The MGCC of a single MG attempts to obtain an optimal operation point using only its local resources. If the internal resources are not satisfactory, the MGCC shall request the MG central coordinator for external resources from other MGs [14]. Nevertheless, the single point of failure still exists, and the points of aggregation may even turn into new points of failure.

2.2.3 Distributed

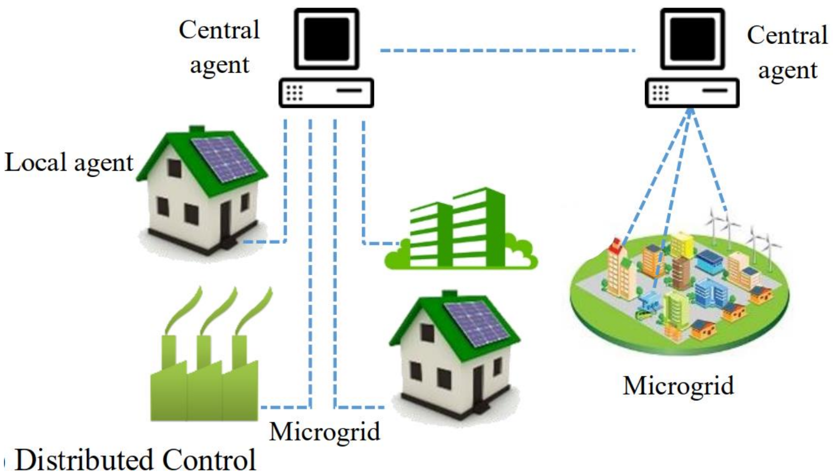


Figure 2.4 – Distributed control architecture [15].

The distributed control method for MMG (shown in the Figure 2.4) consists of local DERs and central agents. In both architectures described before, the DERs are regulated by a third party. Nonetheless, as the owners of the DERs appoint the barrier conditions, it is argued that it might be better to maintain a local control of the DER. In addition, not all DERs owners want to exchange all their data with a third party for privacy reasons. However, to achieve a (near) optimal operation of the system, these DERs should still be coordinated. This is the reason why the concept of distributed control is necessary.

The purpose of distributed control is to break down the centralized problem into a definite number of local controllers or agents. Thus, each agent does not have a global perspective of the problem [16], but they can still work at a globally (near) optimal state with the help of coordination. Coordination is arranged by a central agent which is capable of communicating global constraints, such as the maximum power of a transformer, maximum voltage, and frequency limitations. This task can be achieved by the communication of Lagrange multipliers.

In [17], dual decomposition method or alternating direction method of multipliers (ADMM) are applied successfully for distributed approach. Both of them are based on the dual ascent method, where price vectors are transmitted iteratively from the central controller to the DERs. The DERs optimize their consumption in proportion to these vectors and send back demand vectors to the central agents. Then, the central agents analyze the demand vectors and renew the prices, when operational grid constraints are being violated. This process continues until a steady state solution is achieved.

Distributed approaches have several important advantages. First, the computational requirements are reduced due to the change of global optimization problem into several subproblems. Secondly, the data exchanged between local and central agents is limited, which reduces the requirements of a complex communication system. Finally, the local DERs optimize individually and do not need to send private data to a third party. However, there are still central agents, which potentially form single points of failure.

2.2.4 Fully decentralized (Peer-to-Peer)

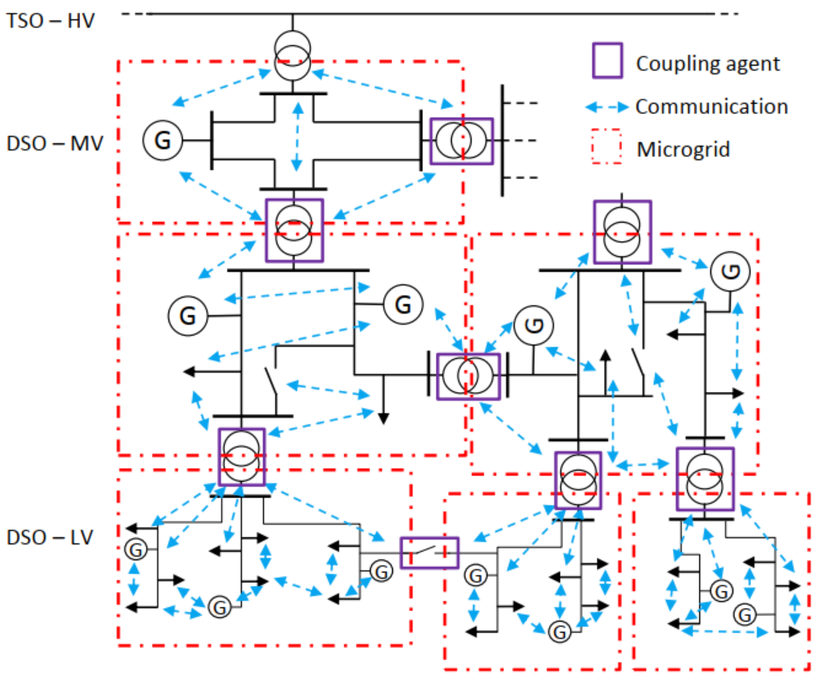


Figure 2.5 – Peer-to-peer control architecture [15].

This methodology is characterized by the complete absence of a central controller, which is inspired by P2P computer networking [18]. In this architecture, a single point of failure is completely eliminated, and the importance of all agents is equal.

Each agent is able to exchange data directly with other agents without the need for a central device [19].

Nowadays, it is preferable to use the control system of a MMG system in a highly decentralized way, because the new DERs are typically distributed in the distribution system, operated by different owners and managed with different goals. Moreover, plug and play property of new resources is crucial to allow for seamless integration over time. In this perspective, P2P control architecture seems to be a good candidate for control of the distribution network.

Still, this architecture may not be applicable to the whole distribution grid, which contains thousands of DERs that are geographically dispersed. To tackle this issue, the grid is usually divided into smaller MGs, containing only a limited amount of DERs. These MGs operate according to the presented P2P control architecture. Points of common coupling are used to connect the different MGs as shown in Figure 2.5.

The elimination of central controller leads to the concept of autonomous MGs. The P2P communication is utilized to send the required information in the MGs. The grid–supporting agents are able to determine the set-points with the help of received data from neighbor agents. In this communication scheme, the agents should be able to reach a (near) optimal operation of the considered MGs. When a single agent fails, the other agents can still manage the system. When a single communication channel fails, the required information can still be transmitted to all necessary participants via other agents. In addition, all data is protected, which eliminates any privacy-related concerns. However, in this control architecture, all agents require significant amount of local intelligence to accomplish the fundamental optimizations. There are two popular algorithms for P2P method in the literature: gossiping algorithm [20] and consensus algorithm [21].

2.3 Connection between physical micro-grids

In most cases, there are two types of interconnection between physical micro-grids. In the first type, the MGs can be connected via the AC line with the use of a breaker [22], [23]. With an appropriate synchronization algorithm, this type of connection has a low investment cost. However, the main drawback of this method is the difficulty of power management between MGs. Also, this method is only suitable for the MMG system that has the same frequency and voltage values in all MGs. In the second type, DC line with back-to-back (BTB) converters can be used as the interface between physical MGs [24]. The topology of the hybrid MG with DC connection at the BTB converter presented in [25] could bring the benefit of multiple AC and DC MGs integration at a common point. In addition, by using BTB converters, each MG can be controlled independently, which leads to flexible voltages and frequencies in MMG system. The Ross Island project in Antarctica [26] introduced a physical dual frequency interlinked system (50 Hz and 60 Hz) by using distributed control system.

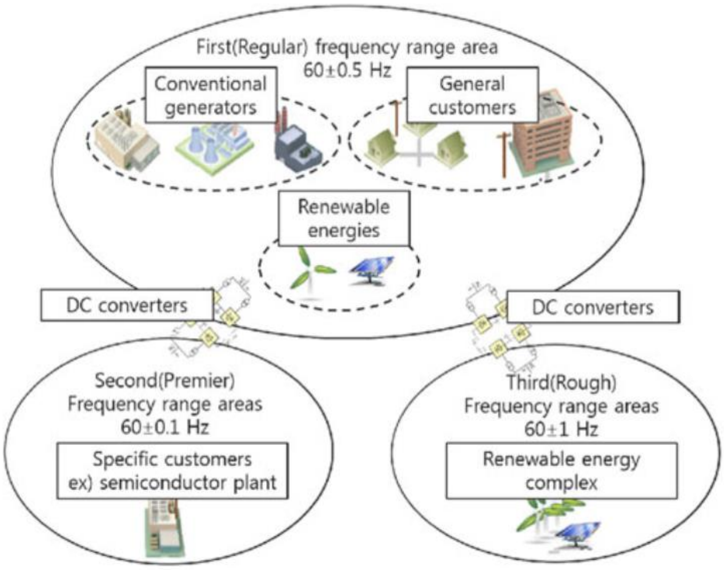


Figure 2.6 – MMG system with the use of BTB converters [27].

In [27], the flexible MMG system can provide some advantages, such as:

- Reduction of the ancillary service cost.
- Improvement of operating efficiency of coal power plants.
- Reasonable pricing system for different customers' needs.

In this report, an islanded MMG system with the use of BTB converters for interlinking the adjacent MG systems will be investigated.

3. Functional expectations of smart grid

Energy Router (ER), also known as Intelligent Power Router or Smart Power Router, is a concept of a technological element in the smart grid operations. In order to understand the critical dependence of the smart grid on ER, the functions expected for the smart grid will be outlined and then the support of these functions by the ER is described. The functions of the smart grid can be classified into the following seven domains: generation, transmission, distribution, operation, market, customer, and service provider. An insightful discussion about energy routers will be continued in section 4 of this report.

3.1 Generation domain

The Generation domain is electrically connected to the Transmission domain and shares interfaces with the Operations, Markets and Transmission domains. Communications with the Transmission domain are important to determine the routing of electricity to the transmission system. A lack of adequate supply may be addressed directly (via Operations) or indirectly (via Markets).

As more energy is generated from distributed sources due to DG integration, loads can also be locally supplied, thus reducing the dependency on the Transmission domain. When the local generation exceeds the local load, the excess energy can flow into the main grid via ERs. At the time of local energy shortage, the grid should provide the deficient amount of energy through the ERs.

3.2 Transmission domain

The Transmission domain is responsible for energy transmission from the Generation domain to the consumers. Energy and supporting ancillary services are obtained through the Markets domain, scheduled and operated from the Operations domain, and finally dispatched through the Transmission domain to the distribution system and finally to the Customer domain.

The Transmission domain needs to dynamically dispatch energy from the DERs that have surplus amount after satisfying their local demands. ERs are hence needed to control the dynamic energy flows.

3.3 Distribution domain

The Distribution domain is the electrical interconnection between the Transmission domain, the Customer domain and the metering points for consumption, distributed storage, and DG. The reliability of the distribution system varies based on its structure, the deployed actors, and the extent of communication among actors (including communication with actors in other domains) [28]. In the smart grid concept, the Distribution domain communicates with the Operations domain in real-time to regulate the power flows associated with the dynamic Markets domain and environmental and security constraints.

When the user demands fluctuate over time, the ERs also take the responsibility of tracking the demand changes to comply with the energy distribution dynamically. Therefore, the energy distribution needs to be implemented via ERs.

3.4 Operation domain

Actors in the Operation domain are responsible for the smooth operation of the power system. For optimization of system operation, the information about grid status must be obtained, such as the current energy generation capacities in DERs and the current energy demands from different customers. This information can be acquired from the ERs used in the Transmission domain and Distribution domains.

3.5 Market domain

Actors in the Market domain exchange price and balance supply and demand. The Market domain is interacted with other domains such as the Operations domain, the domains supplying assets (e.g., generation, transmission, etc.) and the Customer domain. Communications for Markets domain interactions must be reliable. They must be traceable and auditable. Moreover, the energy supply and demand information must be collected from various parts of the grid so that the Market domain can operate effectively. The communication and information collection rely on the ERs of the grid.

3.6 Customer domain

The Customer domain is electrically integrated to the Distribution domain. It communicates with the Distribution, Operations, Market, and Service Provider domains.

Customers purchase energy from the grid through ERs. When the customers also generate energy from renewable resources, the ERs regulate the energy demand and supply for their connected customers. If the aggregate amount of energy produced by the customers exceeds their own demand, the excess amount is sold back to the grid through ERs.

3.7 Service Provider domain

Actors in the Service Provider domain implement services to support the business processes of power system producers, distributors and customers. The Service Provider domain have interfaces with the Markets, Operations, and Customer domains. Communications in the Operations domain are crucial for system control and acquisition of information; communications with the Markets and Customer domains are critical for facilitating economic development through the establishment of "smart" services.

The service provider needs to have the current energy supply and demand information to optimize their service. The information acquisition relies on the ERs.

4. Energy Router: an interface between physical micro-grids

4.1 Introduction

4.1.1 Energy Internet (EI) - Towards Smart Grid 2.0

EI or Internet of Energy is a concept that has been regarded as a new evolution stage of the smart grid. EI aims to increase the energy transmission efficiency and optimize the energy dispatching in time and space.

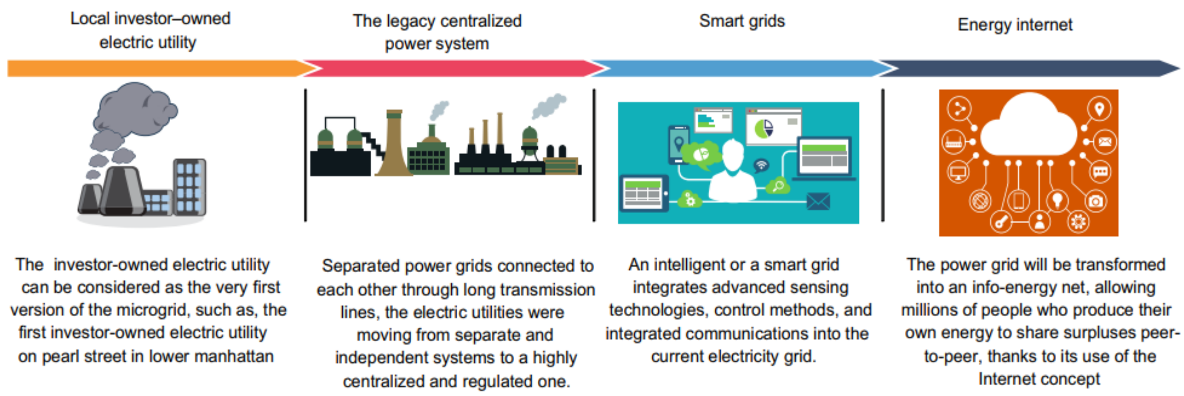


Figure 4.1 – The evolution of grids [29].

In [29], the EI is defined as an Internet-type network of all the elements of a grid system, which closely cooperate with others by sharing both energy and information. Agents or components of this network comprise different prosumers and consumers that have the capability to take and execute decisions individually. MGs, DERs, smart grids, private or governmental energy networks, and any community of prosumers and consumers can be a part of this massive network as agents. The EI is also known as the second generation of the power system because it is provided with advanced sensing and measurement technology, as well as latest control and monitoring technology [30]. The EI also takes advantage of a modern communication network to achieve a higher stage of safety and reliability and enhance the economic and efficient operation of the power system. Moreover, integrating advanced communication network and smart devices into the power system enables system operators to embed plug-and-play feature and intelligent energy management.

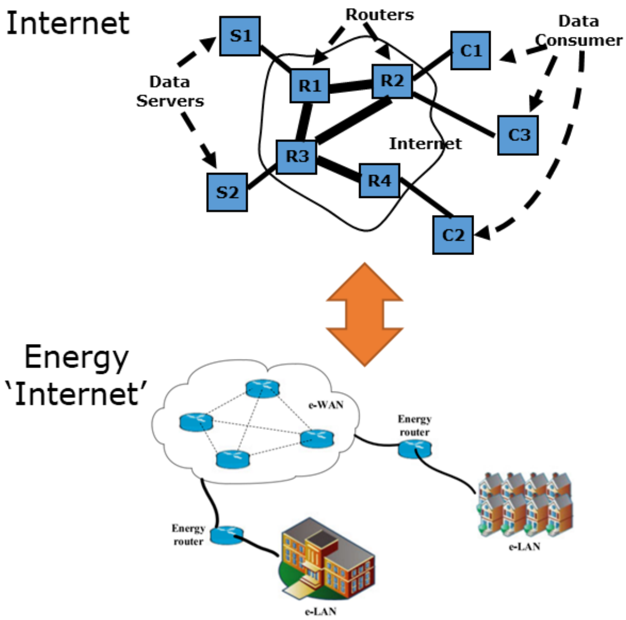


Figure 4.2 – Power system in the vision of Energy Internet [31].

As demonstrated in Figure 4.2, MGs acting as agents are components of the EI network, where they are represented by energy local area networks (e-LANs). MGs have the potential to be the fundamental element of the EI structure, as they are a promising technology that can reinforce the reliability and profitability of energy supply to end consumers [32].

4.1.2 Emerging agent: Energy Routers

ER is an active technological element in smart grids. ERs dynamically adjust the energy distribution in transmission and distribution networks by rerouting energy flows. In other words, ERs take on two major tasks, dynamic adjustments of energy flows and real-time communications between power devices [33].

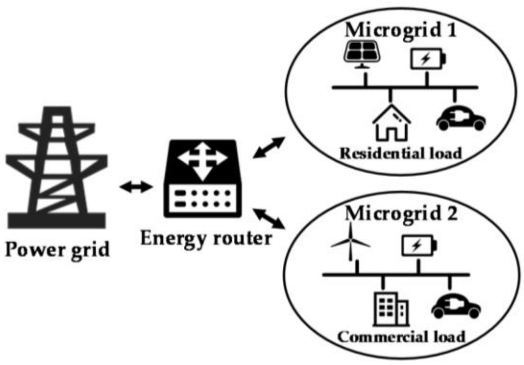


Figure 4.3 – Energy router-based interconnecting framework [34].

An ER-based framework for MG interconnection is demonstrated in Figure 4.3. In fact, as a multi-port conversion device with control and communication functions, the ERs are able to carry out power quality regulation, voltage/frequency conversion, reactive power compensation, renewable energy access and power flow control.

4.2 Benefits of Energy Routers

ERs are associated with the following benefits [34], [35]:

- The issue of instant energy excess or shortage can be solved with "complementary" energy trade between the adjacent MGs.
- Active control of power flow can be used to eliminate congestion problems.
- Shared DC bus and voltage source converters (VSCs) enable electrical isolation between the MGs.
- The capability of electrical isolation improves power quality and can enhance operation reliability.
- The power system architecture shifts from the conventional framework to a scheme, which is cooperative.

As ERs are used widespread in the grid, they handle a broad range of functions. Similar to the Internet routers, the ERs have different location-dependent tasks, which can be generally classified as the user-level functions and the grid-level functions [33].

1) User-level functions: There are three main categories of users: distributed renewable energy resources, distributed energy storage devices, and loads. These users form a MG, where the ER operates as its central coordinator. Each user in the same MG communicates with the ER for all the energy services. We consider below all the user-level functions required at an ER.

- <u>User Attachment:</u> When a user joins the smart grid via the ER, the ER is in charge of discovering new user attachments and configuring them for precise operations.
- <u>Service Request:</u> When there is a need for a service, the connected user sends a "service request" message to the ER. The ER then responds with a "service acceptance" message back to the user and regulates the energy service.
- <u>Status Update:</u> The user delivers the "status update" message to the ER when the user status changes.
- <u>Service Termination:</u> When the users terminate the service, they transmit the "service termination" message to the ER and then disconnect from it. The ER terminates power exchange with these users.
- <u>User Detachment:</u> When the user disconnects from the grid, the ER detects the disconnection and updates their user interfaces accordingly.

2) Grid-level functions: An ER is not only connected to the energy customers, but it also communicates with the other ERs in the grid system to organize smart energy management. Some typical operational scenarios are discussed below:

- When the PV system is ready, it transmits the energy generation request to the ER. The ER examines the power demand, which includes the current load demand and the energy capacity of the distributed energy storage devices, and then accepts the request of the PV system, which then initiates the solar energy conversion.
- When the PV system stops generating energy, it transmits the "service termination" message to the ER. The ER informs the distributed energy storage devices to start energy supply.
- In the case of light load, the ER begins to charge the plug-in electric vehicles and the distributed energy storage devices.
- The ERs are also able to influence the electricity usage dynamically according to the costs. For example, when the price of electricity is the highest for industrial users, their ERs may schedule the non-urgent tasks at a different time.

4.3 Design requirements of Energy Routers

The ER is a technological integration of power electronics, communications and automations. Therefore, its design requirements include these three aspects [33], [36], which are described in the following sections.

4.3.1 Power Electronics

Power electronics are fundamental ER components because they realize automatic energy distribution and management. Therefore, all power electronics elements must be able to operate fast and stable to guarantee the correct execution of the commands issued by the intelligent management module.

4.3.2 Control algorithms

In addition to the power electronics and communications, the ERs must contain the distributed grid intelligence module to participate in decision-making associated with the energy management of the grid. This module utilizes the information collected from the communication module and determines the grid control actions, which are implemented through the ER cooperation.

4.3.3 Real–time communications and information processing

The operations of ER depend on the grid status information it collects. The communications between ERS must satisfy three requirements, which are described below:

- Transmission Latency: The communication latency determines the maximum time in which a specific message should reach its destination through a communication network. The messages communicated between ERs may have different network latency requirements relying on the type of events that trigger the messages. The most time-critical messages in the smart grid need a transfer latency as small as 3 milliseconds. Thus, the ERs must have sufficiently fast processing and communication abilities to assure low latency information exchanges.
- Communication Reliability: The communications between energy routers must be reliable. The energy routers must be designed with the minimum probability of failure. In addition, the ERs must have communication failure detection ability to redeliver the lost messages quickly. In case the interface equipment of an ER fails, the remaining ERs should be able to carry on communications through bypassing paths.
- Information Security: The information exchange between ERs includes among others grid operation information. Falsified or impersonated messages will threaten the grid operations. Thus, the ERs must ensure that communications are protected. Properly designed security mechanisms are needed to hinder unauthorized users from reading and altering information, which is exchanged between ERs.

4.3.4 Plug-and-play features

The plug-and-play characteristic requires that the ERs have a universal standard interface with both energy exchange and communication functions. Particularly, they are expected to quickly analyze different classes of electrical characteristics and monitor the load, energy storage and power generation equipment. The automatic access or disconnection of energy source must match the user's request.

4.4 Topologies

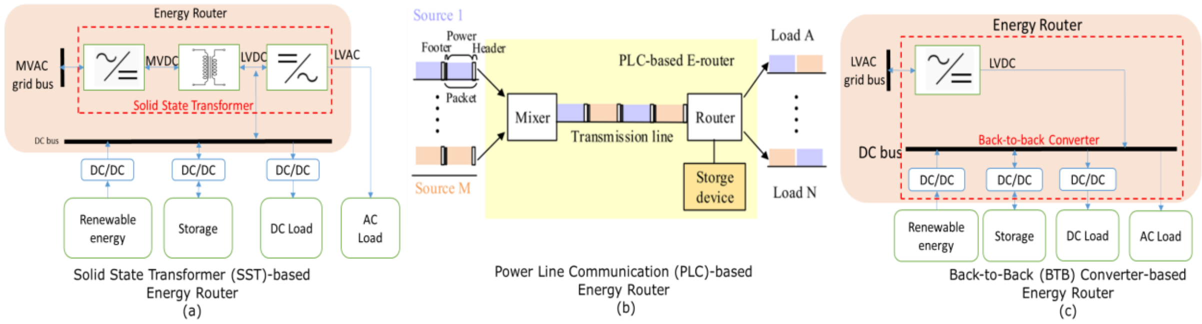


Figure 4.4 – Types of the ERs: (a) SST-based ER, (b) BTB Converter-based ER, (c) PLC-based ER [37].

Figure 4.4 (a) presents a solid state transformer (SST)-based ER with a three stage structure, which has the features of relatively simple control, high functionality and high reliability. Firstly, the high-voltage AC/DC stage rectifies power frequency high-voltage alternating current (HVAC) into medium-voltage direct current (MVDC), which can be used to connect DC grids. Then the middle DC/DC stage adopts dual active bridge topology to transform the MVDC to a regulated low-voltage direct current (LVDC), which is used to facilitate the DC bus or connect DERs. The employment of a high frequency transformer provides the benefit of both electrical isolation and voltage conversion. Finally, the split-phase DC/AC inverter generates an AC output voltage, which can be used to connect AC grids or loads. Thus, the SST-based ER has multiple plug-and-play interfaces for user access. Each interface may connect multiple energy networks or devices, as long as the total power does not exceed the capacity limits of the connected interface [38]. The above technology is appropriate for transmission systems with a high voltage and power level.

In contrast, Figure 4.4 (b) presents the power line communication (PLC)-based ER. The PLC-based ER is able to transmit energy flows and information flows through the same transmission line, which has the benefits of simple wiring, reducing device volume and cost. The development of PLC technologies encourages collinear coupled transmissions of energy and information. Nevertheless, the main disadvantage of the simultaneous power transmission and data communication is that it is difficult to implement the time-division and multi-path transmission of power flows.

Finally, the Back-to-Back (BTB) converter-based ER converter shown in Figure 4.4 (c) is useful for distribution systems, which have a lower voltage and power level. In the literature, BTB converter-based ER proved to have a higher degree of reuse and integration compared to the SST-based ER [37]. Without considering the influence of power grids, the proposed BTB converter can provide energy balance among multiple RESs and loads. In case of simple structure and a small number of loads/sources, the system of energy management and control can be executed directly into the controller of BTB converter itself. Through power electronic converters and ICT, the DERs, storage devices and loads are connected to the DC common bus, which is an intermediate link of the energy forwarding. Among those, the storage device can enable the stability of DC bus by means of absorbing or compensating the imbalance power during a short period [38]. The detailed topology of the ER considered in this task is shown in Figure 4.5.

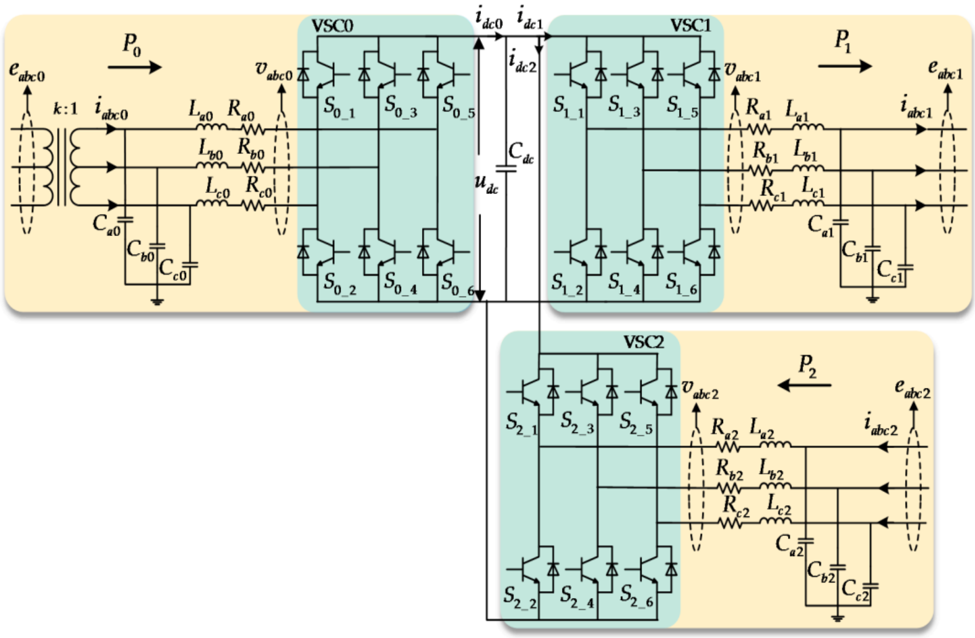


Figure 4.5 – The detailed topology of the ER [34].

4.5 Control of energy routers

4.5.1 Control schematic of the VSCs

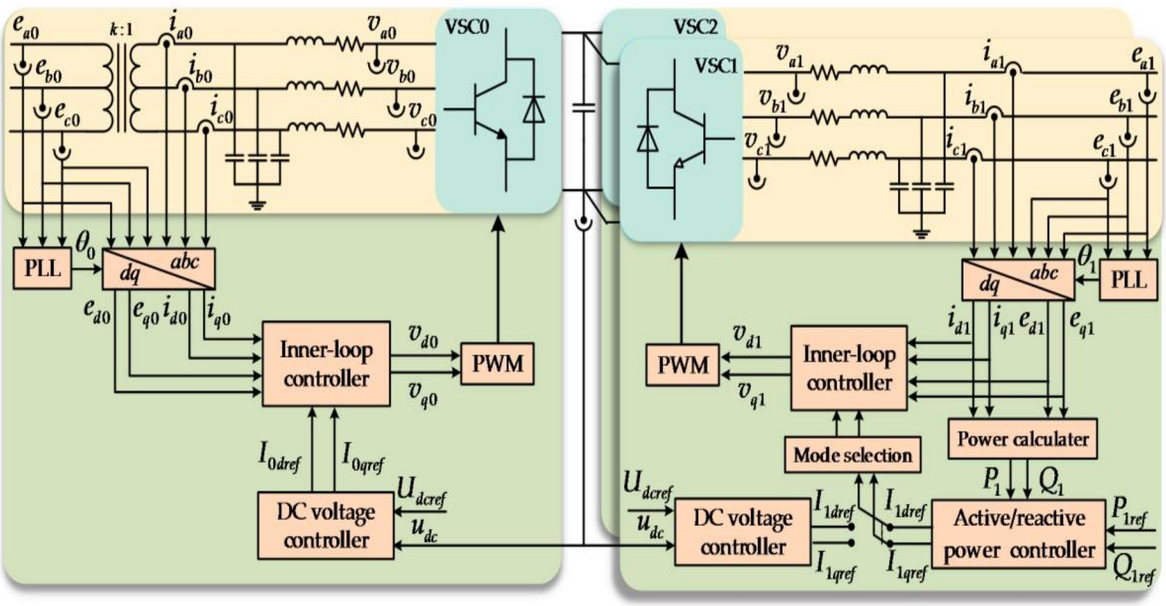


Figure 4.6 – Control schematic of the Voltage Source Converters [34].

The controller structure of the voltage source converters (VSCs) is shown in Figure 4.6. As the VSC_1 and VSC_2 are identical in their structures, the detail of the controller of VSC2 is not shown.

The dual-loop controller consists of two loops: (1) the inner-loop controller, also known as the current feedback loop; (2) the outer-loop controller, which can be either a DC voltage controller or an active/reactive power controller, depending on the control objective of each VSC [34].

A. Inner-loop controller

The voltage control equations of the VSC_i inner-loop controller in rectifier mode can be written as:

$$v_{di} = -\left(K_{Pi} + \frac{K_{Ii}}{s}\right)\left(i_{idref} - i_{di}\right) + \omega_i L_{\Sigma i_{qi}} + e_{di} \tag{1}$$

$$v_{qi} = -\left(K_{Pi} + \frac{K_{Ii}}{s}\right)\left(i_{iqref} - i_{qi}\right) - \omega_i L_{\Sigma i_{di}} + e_{qi} \tag{2}$$

Where K_{Pi} and K_{Ii} are the proportional and integral regulation gain in the inner-loop, respectively.

Similarly, the voltage equations of VSC_i operating in the inverter mode can be written as:

$$v_{di} = \left(K_{Pi} + \frac{K_{Ii}}{s}\right)\left(i_{idref} - i_{di}\right) - \omega_i L_{\Sigma i_{qi}} + e_{di} \tag{3}$$

$$v_{qi} = \left(K_{Pi} + \frac{K_{Ii}}{s}\right)\left(i_{iqref} - i_{qi}\right) + \omega_i L_{\Sigma i_{di}} + e_{qi} \tag{4}$$

B. Outer-loop controller

The outer loop is used to generate the inner-loop current reference signal and input to the inner-loop control. According to different control objectives, the outer-loop controller can be classified as active/reactive power controller or DC voltage controller.

1) Active/Reactive Power Controller: The active/reactive power controller is used to keep the VSC operation in such way that its active/reactive power output on the AC side follows the reference value issued by the MG controller with zero steady-state error.

Classical proportional-integral (PI) regulators are used in the outer-loop control to calculate the current commands to the inner-loop with the power deviations. P_i and Q_i are compared with their reference inputs P_{iref} and Q_{iref}, respectively, and the result of the comparison is used by the PI controller to calculate the current command value.

2) DC Voltage Controller: The DC voltage controller is responsible for keeping the DC-link voltage within an adequate range around the reference value issued by the MG controller. For VSC_i controlled by the DC voltage controller, the active power P_i exchanged with the AC systems is identical to the DC power P_{dc} stored in C_{dc}.

$$P_{dc} = \frac{1}{2} C_{dc} \frac{du_{dc}^2}{dt} = \sum_{i=1,2,3} P_i \tag{5}$$

The current command input to the d-axis of the inner-loop current controller is

$$i_{idref} = \left(K_{Pdc} + \frac{K_{Idc}}{s}\right)\left(u_{dcref}^2 - u_{dc}^2\right) \tag{6}$$

Where K_{Pdc} and K_{Idc} are the proportional and integral regulation gains, respectively. Under this controller, the d-axis current command is derived.

4.5.2 Control patterns for the voltage source converters

The control approach for VSCs in ERs is based on master/slave strategy. The outer-loop controller of the master VSC works as a DC voltage controller to keep the DC-link voltage constant. When the converter dispatches the power, the DC bus voltage must be stable to maintain the energy balance in the system. In contrast, the other VSCs work in slave mode. Their outer-loop controllers work as the active/reactive power controllers, with the aim to manage their power transfer according to the needs of the MGs in connection [34].

The rules to choose the master converter are [34]:

- When main grid is engaged in power transfer, VSC related to the main grid is regarded as the master converter and other VSCs are the slave converters;
- When the main grid does not participate in power exchange, the master converter shall be the VSC in connection with the MG, which supplies energy to its neighbor, while the other VSCs receiving energy shall be the slave converters.

As defined in Table 1, VSCs in the system have three control patterns depending on the operational condition of their inner and outer-loop controllers. The operational conditions of the MGs are determined by choosing the appropriate control patterns for the VSCs and their roles (master or slave). The master converter should be working in control pattern 1. Meanwhile, slave converters can work in either pattern 2 or pattern 3. Finally, eight operational states can be summarized for the ER, as shown in Table 2.

Table 1 - Control patterns for VSCs under different operational conditions [34].

Control Pattern	Inner-Loop Controller	Outer-Loop Controller
Pattern 1 (master control)	Rectifier	DC voltage loop control
Pattern 2	Rectifier	Active/reactive power control
Pattern 3	Inverter	Active/reactive power control

Table 2 - All the states of the ER [34].

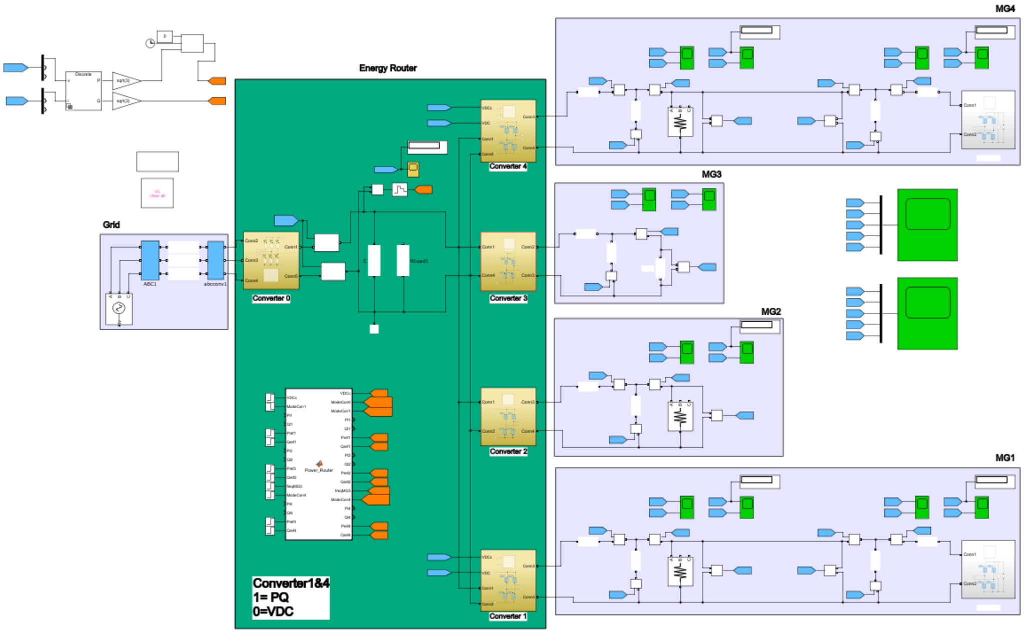
Power Grid	Microgrid 1	Microgrid 2
Include	Grid-connected mode	Grid-connected mode
	Grid-connected mode	Island mode
	Island mode	Grid-connected mode
	Grid-connected mode	Parallel mode
	Parallel mode	Grid-connected mode
Exclude	Parallel mode	Parallel mode
	Parallel mode	Parallel mode
	Island mode	Island mode

5. Cooperation strategies in multi-micro-grid system

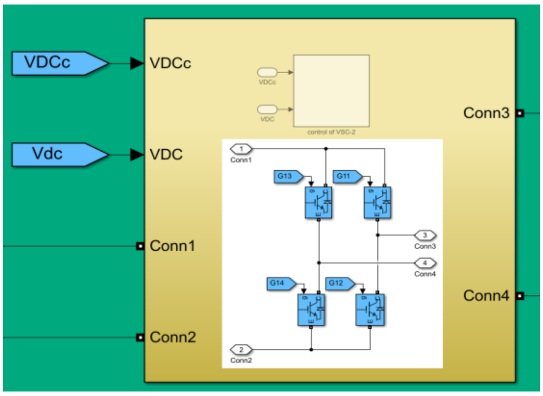
5.1 Modelling

The simulation model of the MMG system is built on the Simulink/MATLAB R2019a software. The configuration of the overall system and the sub-models of VSCs and their controllers are shown in Figure 5.1 (a), (b) and (c), respectively. The model is separated into five areas by an ER. For simplicity, instead of an ER for each MG, one ER is used for all MGs.

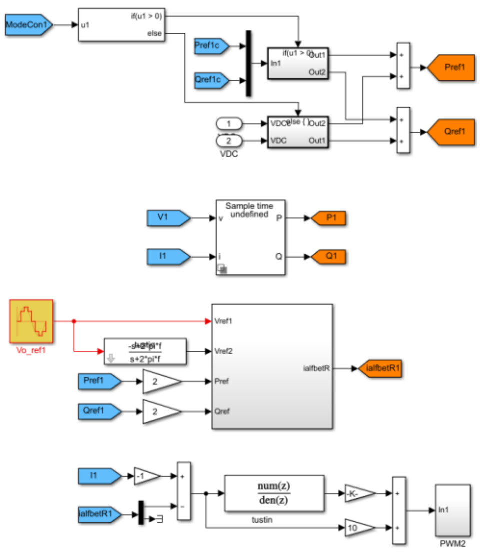
The simulated system consists of 4 MGs, which can be connected to or disconnected from the main grid. The MMG system are interconnected via the ER with a DC-link. MG_1 and MG_4 have a battery energy storage system (BESS) with Lithium-ion batteries.



(a)



(b)



(c)

Figure 5.1 - The simulation model of the multi-micro-grid system: (a) the overall system; (b) VSCs (C) controllers.

Within a MG with active elements controllable sources or loads will be represented by agents that can operate autonomously with local targets or cooperate with others to achieve area tasks. A superior agent is installed for each MG as a moderator to manage autonomous actions as well as to communicate with other areas. In this section, some simulation scenarios are presented to investigate the dynamic characteristics of the MMG system in all the operation modes, and to verify the feasibility of the proposed control strategies. The simulation parameters are listed in Table 3.

Table 3: Simulation parameters.

System parameters	Symbol	Value
LC filter	L / r_L / C	2 mH / 0.1 Ω / 25 μf
DC link voltage	V_{DC}	500 V
DC link capacitor	C_{DC}	6 mf
Operating voltage	v_o	220 V, 50 Hz
Switching frequency	f_s	10 kHz
PR controller gains	k_p / k_i	0.125 / 15
Proportional controller gain	k	36.2
Cut-off frequency	ω_c	5 rad/s
Main grid impedance	Z_L	0.5 Ω, 2 mH

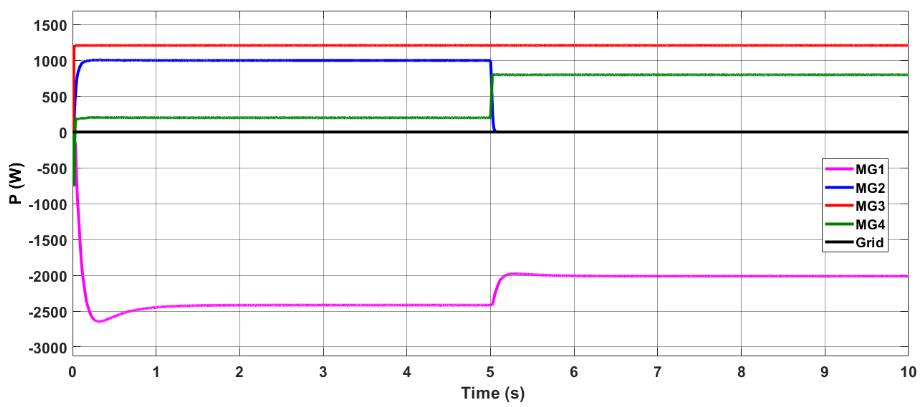
In this section, different simulation scenarios are presented to investigate the dynamic characteristics of the MMG system in all operation modes defined previously, and to verify the feasibility of the proposed control strategies.

5.2 Simulation and results

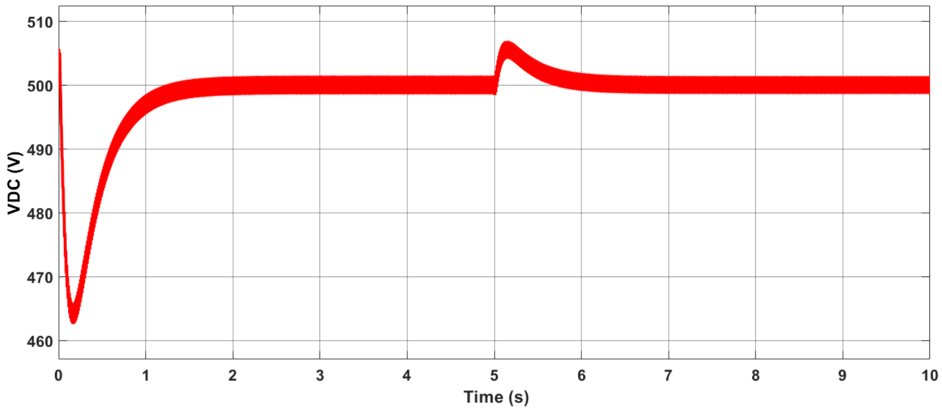
In this part, to take in to account the coordination of MGs' converters, the MMG system in Figure 5.1 works in stand-alone mode.

5.2.1 Scenario 1

This scenario demonstrates the dynamic characteristics of the MMG system during the transient load changes, when MG_2 is disconnected from the MMG system, while the power demand (at time t = 5s) of MG_4 increases. The operational mode of all MGs remains unchanged, with MG_1 serving as the master converter and other converters working as the slave converters. The variations in power flows, as well as the DC-link voltage are shown in Figure 5.2.



(a)



(b)

Figure 5.2 - Simulation results of scenario 1: (a) active power; (b) DC link voltage.

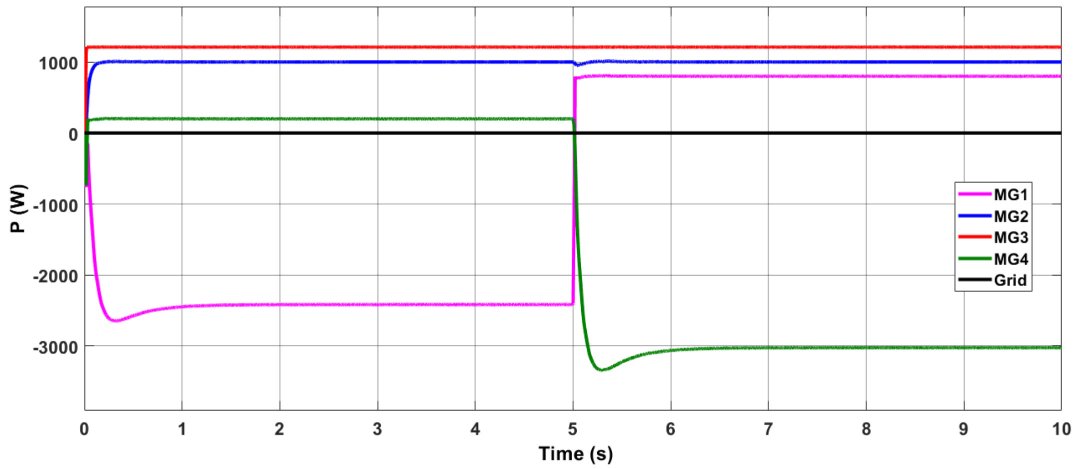
As shown in Figure 5.2 (a), the power flows can track their command value accurately and rapidly after a fluctuation. The power transfer from MG_2 changes to zero when it is not involved in the energy exchange. Also, in Figure 5.2 (b), the fluctuation range of the DC-link voltage at time t = 5s is minor and can be ignored.

5.2.2 Scenario 2

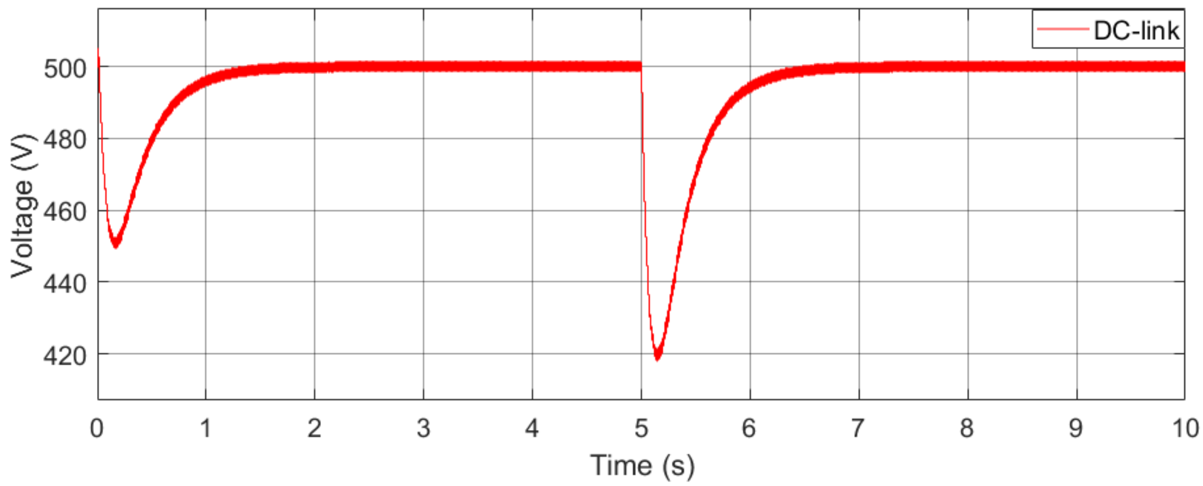
The "master" MG in a MMG system is the MG with the highest surplus of energy. With this strategy, all MGs in the MMG system have the possibility to become a "master", depending on the operation of the network. To preserve a long lifetime of BESS, the maximum and minimum values of SOCs of BESS in the simulation are 80% and 20%, respectively.

In the beginning (from t=0s to t=5s), the BESS of MG_1 acts as master to control the DC-link, so the BESS in MG_1 operates in discharging mode. In addition, during this period, the BESS in MG_4 is allowed to charge as long as the upper limit of SOC is not reached.

At t=5s, the SOC of BESS in MG_1 reaches its lower limit (20%), so the BESS shifts from discharging to charging mode. With that change, the MMG system needs a new master to control the voltage of DC-link. With the SOC of its BESS above 50%, the converter of MG_4 becomes a master converter in place of MG_1. Therefore, the SOC of the BESS in MG_4 decreases rapidly in the last period of the simulation (Figure 5.3 (c)).



(a)



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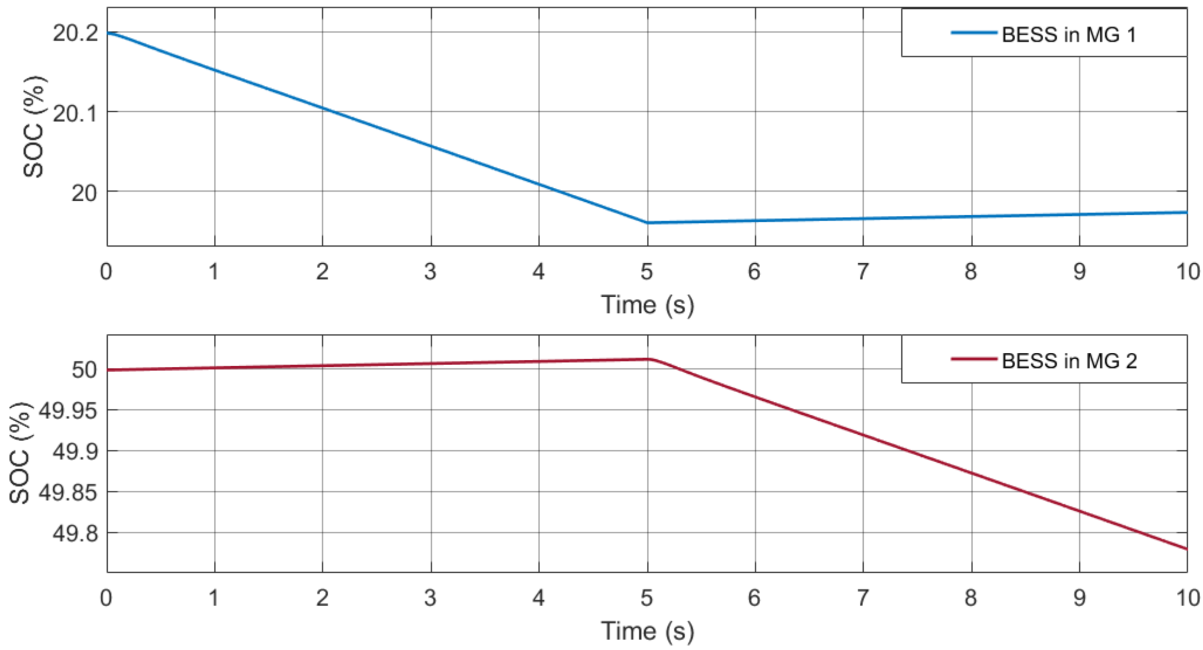


(c)

Figure 5.3 - Simulation results of scenario 2: (a) active power; (b) DC link voltage; (c) State of Charge (SOC) of BESS in MGs

The variations in power and DC-link voltage during the process are shown in Figure 5.3. When the change of master converter occurs at t =5 s, the power flows fluctuate within a narrow range. The DC-link voltage also fluctuates during the change but recovers rapidly.

6. Synchronization

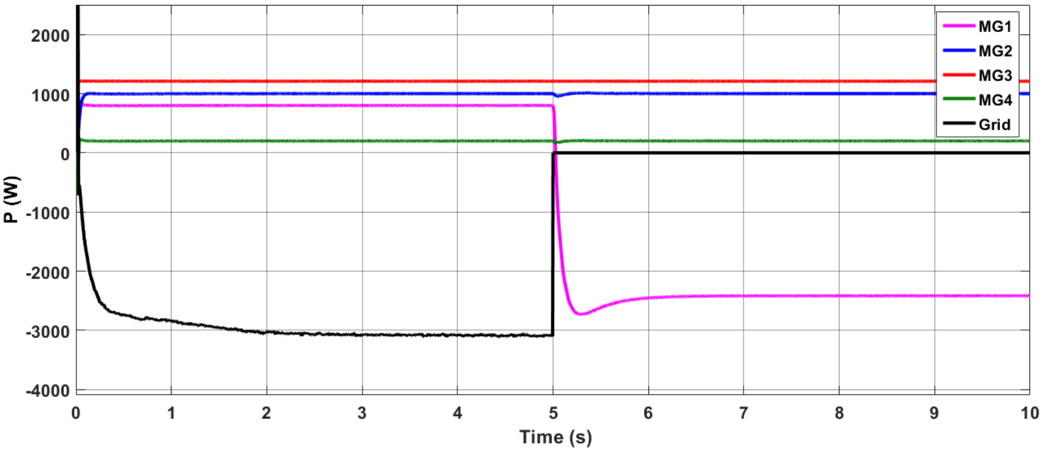
The study and simulations presented in this section use the MMG system models described in section 5.1. The control strategies for synchronizations are based on the master-slave approach, which is discussed in 4.5.2.

6.1 Disconnection from the main grid

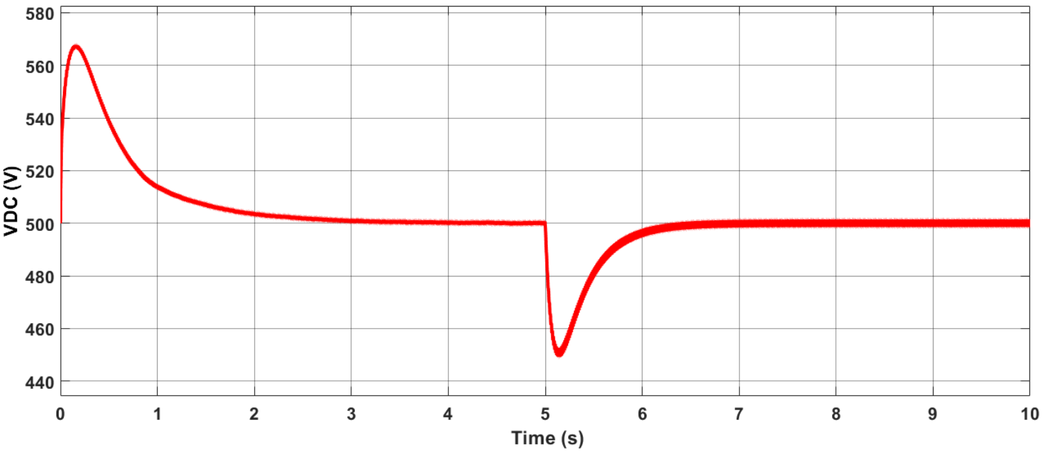
Firstly, the transition state of the MMG system from grid-connected mode to stand-alone mode is considered. In grid-connected mode, the grid converter is in master mode and the rest of the converters are in slave mode. The MMG system is supplied by the main grid.

At t =5s, the MMG system is disconnected from the main grid via a DC switch. At this moment, MG_1 has the highest surplus energy among the four MGs due to the energy stored in its BESS, so the converter of MG_1 becomes the master converter. MG_1 is responsible for supplying its own load and the loads from other MGs in the system until MG_1 reaches its limitation (SOC limit). The converter of MG_1 works in DC-link control mode and the others work in P/Q control mode.

The details of the active power flows and the DC-link voltage variation of the transient process are shown in Figure 6.1.



(a)



(b)

Figure 6.1 - Simulation results of disconnection scenario: (a) Power flow; (b) DC link voltage.

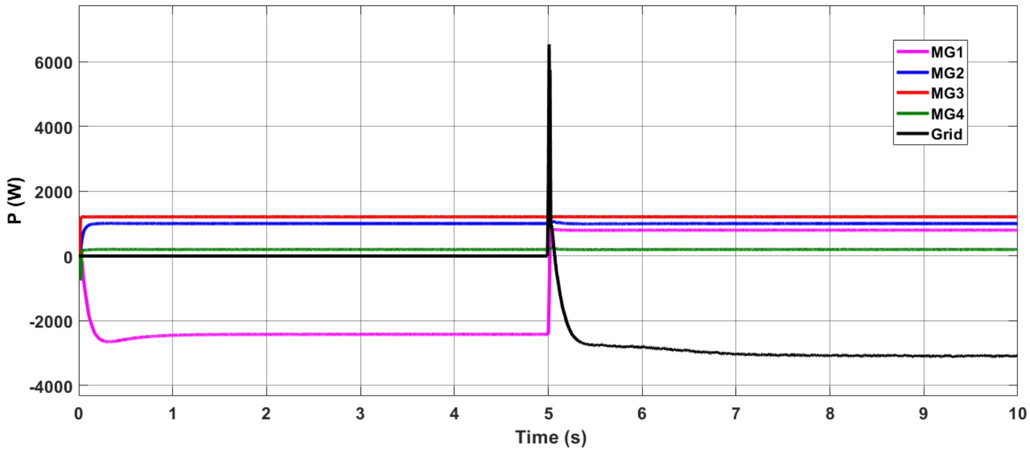
The active power flows within the MMG system are as follows: At t = 0*s*, the total load of MMG system (MG_1=800 W, MG_2=1000 W, MG_3=1210 W, MG_4=200 W) is supplied by the main grid. At t = 5*s*, the MMG system is disconnected from the main grid and MG_1 becomes the master converter. MG_1 is responsible for supplying all the MGs in the system (Figure 6.1 (a)).

The value of the active power of MG_1 changes from 800 W to -2410 W. As shown in Figure 6.1 (a), when the system mode changes abruptly, there are only slight fluctuations in the output power curves, and the stable state is restored quickly. Moreover, Figure 6.1 (b) shows that fluctuation of the DC-link voltage is compensated.

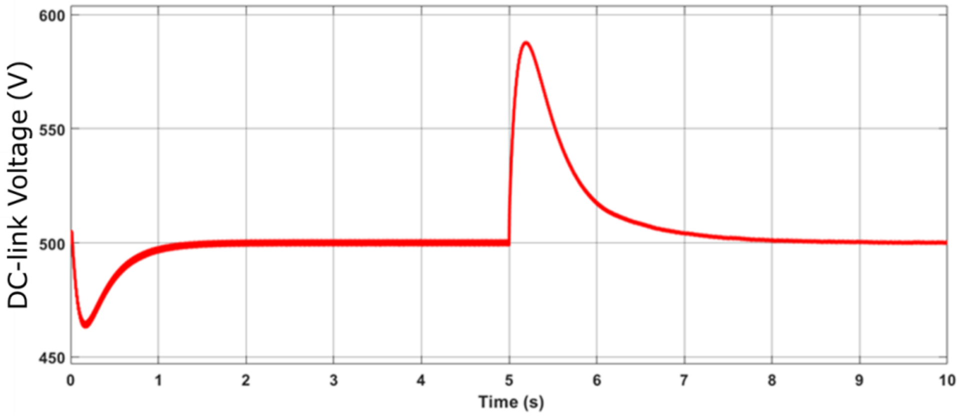
6.2 Reconnection with the main grid

This section studies the transition state from islanded mode to grid-connected mode. As discussed earlier, the ERs, i.e. the BTB converters, also provide isolation between both sides with DC link. Therefore, the only requirements it that the converters in inverter mode are synchronized by phase locked loop (PLL).

At first, MG_1 is in master mode and the rest of inverters are in slave mode. At t = 5s, the MMG system connects to the main grid and MG_1 returns to slave mode. The active power flows and the DC-link voltage variation of the transient process are given in Figure 6.2.



(a)



(b)

Figure 6.2 - Simulation results of reconnection scenario: (a) active power; (b) DC link voltage.

As shown in Figure 6.2, when the system is resynchronized, there are only slight fluctuations in the output power curves. The fluctuation range of the DC-link voltage at the moment of power transfer is significant; however, the stable state is restored quickly.

7. Frequency coordination between micro-grids

7.1 Methodology

The frequency performance of the MMG system can be improved by designing a suitable controller of the ERs with BTB converter [39]. A MMG system is shown in Figure 7.1, where a BTB converter is used for interconnecting two adjacent MGs.

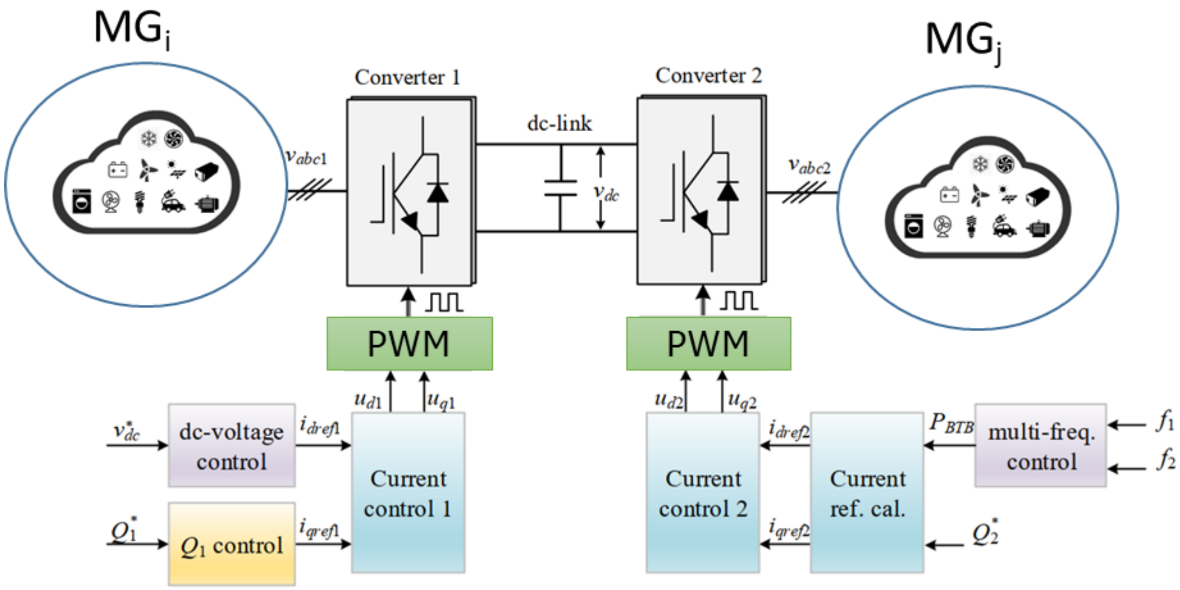


Figure 7.1 – Typical MMG system using BTB converter [39].

It is assumed that converter 1 is responsible for the regulation of the dc-link voltage whereas converter 2 is used for regulating the frequencies of two adjacent MGs. In each MG, the inverter-based DG with the conventional droop control scheme is used. The control diagram of converter 2 is shown in Figure 7.2, which includes the current control 2, reactive power control (Q_2), and the multi-frequency control loop.

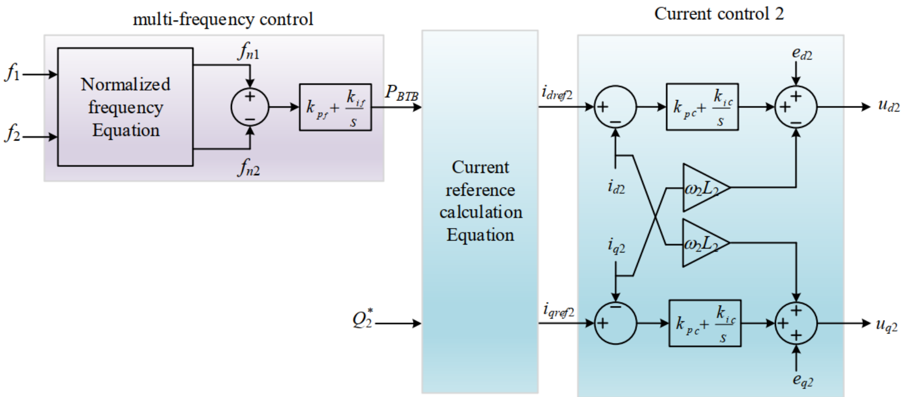


Figure 7.2 – The control diagram of converter 2 [39].

The reference real power (P_{BTB}) is given by the outer multi-frequency controller, as in Equation (7):

$$P_{BTB} = k_{pf}(f_{n1} - f_{n2}) + k_{if}\int (f_{n1} - f_{n2})dt \tag{7}$$

where f_{n1} and f_{n2} are the normalized frequencies of MGs 1 and 2, respectively and k_{pf} and k_{if} are the parameters of PI controllers of the multi-frequency controller. The frequency of each MG is normalized to achieve the unique value of frequency deviation. Equation (8) shows the normalized frequency of MG$_i$

$$f_{ni} = \begin{cases} \dfrac{(f_i - f_{i,rated})}{(f_{i,max} - f_{i,rated})}, (f_i > f_{i,rated}) \\ \dfrac{(f_i - f_{i,rated})}{f_{i,rated} - f_{i,min})}, (f_{i,rated} > f_i) \end{cases} \tag{8}$$

where, f_i represents the measured frequency of MG_i; $f_{i,rated}$ is the rated frequency of MG_i; $f_{i,max}$ and $f_{i,min}$ are the maximum and minimum frequency deviations, respectively; f_{ni} is the normalized frequency of MG_i.

The operation principle of the multi-frequency control is explained in Figure 7.3. Initially, the normal operation points of the two MGs are A_1 and A_2. It is assumed that the load in MG_1 increases suddenly, which results in the reduction of MG_1 frequency from f_{01} to $f_{1'}$. The operation point of MG_1 is changed from A_1 to B_1. With the use of the proposed multi-frequency control, the power through the BTB converter (P_{BTB}) calculated by Equation (7) is transferred to MG_1 to compensate for the load disturbance. As a result, the MG_1 frequency is recovered gradually whereas the MG_2 frequency decreases slightly. The system frequencies of two MGs are stable at new steady state values (C_1 and C_2), when the normalized frequencies of the two MGs are equal.

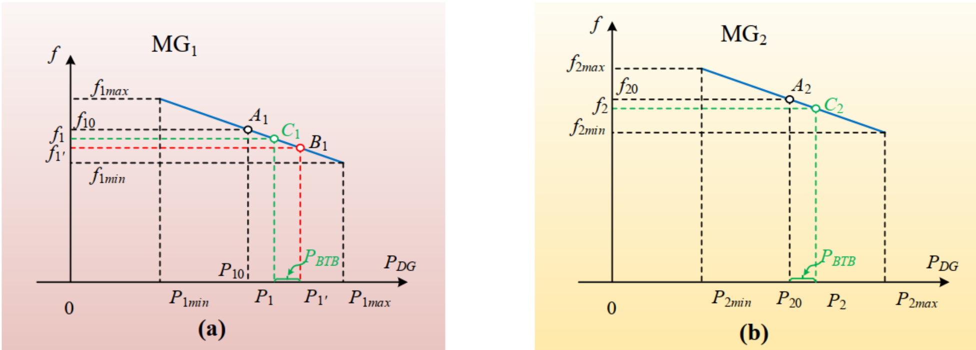


Figure 7.3 – Characteristic of frequency control: (a) droop frequency in MG_1; (b) droop frequency in MG_2 [39].

7.2 Simulation and results

The model presented in Figure 5.1 is also considered in this simulation. Only MG_1 and MG_4 are studied for frequency coordination in this case. MG_1 and MG_4 use grid-forming converters with a conventional frequency droop controller. To show the effectiveness of the multi-frequency control, a comparison study of the multi-frequency control and the single frequency control is presented.

At first, the total load of MG_1 and MG_4 is 3810 W and 500 W, respectively. Due to the higher of load in MG_1, the initial frequency of MG_1 is lower. In t = 2.5*s* and t = 3.5s, 2000 W and 2250 W of load power are added into the MG_1, respectively, which deteriorates the frequency level in MG1.

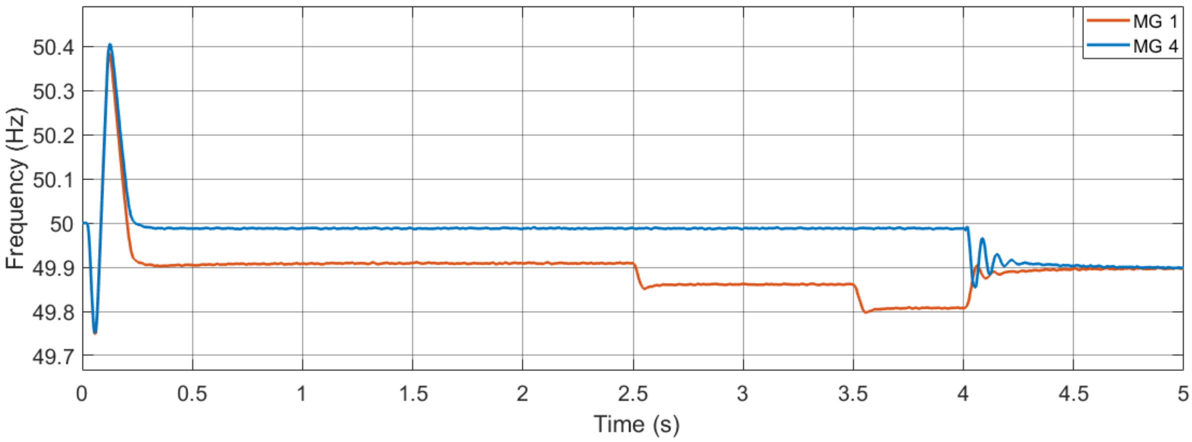


Figure 7.4 - Simulation results for frequency coordination scenario.

Initially, the single frequency controller used in each MG results in different frequencies in steady state. However, by using multi-frequency control, the frequencies are similar in steady state. In fact, the frequency of MG4 with the single frequency control remains constant because there is no disturbance in MG4. But, in the case of the MMG system with the multi-frequency control, the frequencies of both MGs are considered in the BTB converter. The disturbance in MG1 can be recognized by the multi-frequency control. Figure 7.4 shows two frequencies of the MMG system using either single frequency control or the multi-frequency control. In this scenario, it is assumed that the proposed control method is only applied when the MGs reach a critical value (below 48.8 Hz and above 50.2 Hz). Therefore, as shown in Figure 7.4, at time t = 3.5s, when the frequency in MG1 drops by 49.8 Hz, the proposed control is activated. The power reserve in MG4 can then be shared accordingly to recover the MG1 frequency. As a result, the frequency of MG4 drops due to the disturbance in MG1 and the frequency of MG1 has come back to the acceptable value.

8. Load sharing algorithm

Due to the unpredictable nature of energy production from RESs, surplus energy is generated, which could be stored and then used at peak demand times. However, the storage system is considered costly and may also lead to energy losses. Another solution is that the excess energy is sold to other consumers who are in immediate need of it. This is referred to as P2P energy trading, which increases the efficiency of the power system and provides financial incentives to the participants [40]. For this purpose, ERs need to be equipped with suitable energy routing algorithms to effectively deliver energy from the source to the destination in a cost-effective manner.

Energy routing is demand-driven and hence the source and destination for a given power packet is not known ahead. Therefore, the appropriate match between producers and consumers with different demand and supply requirements is determined by using a process known as subscriber matching. Transmission scheduling is essential to avoid congestions and failures at the power system. Finding an efficient transmission path is also critical for energy routing to reduce transmission loss [40]. In this section, several energy routing algorithms are discussed, and simulation results of the proposed algorithm are presented and analyzed.

8.1 Functions

The problem of energy routing algorithms has gained considerable attention from the research community in recent years. Existing literature indicates that energy routing algorithms are supposed to serve three major functions to facilitate P2P energy trading: subscriber matching, finding energy efficient path, and transmission scheduling [40].

- Subscriber matching

Energy routing is demand-driven and energy request messages sent from consumers to the router do not include specific destination address. The consumers agree to join in energy trading with a particular destination address (supplier) after checking which suppliers satisfy their power requirement. ERs have to supply the necessary information and services to help consumers finish the task. Moreover, energy routing algorithms must determine suitable matches between consumers and suppliers based on the requirements of consumers and generation capability of producers. Several factors need to be taken into account, while executing subscriber matching comprising price, distance, customer priority, power type and amount, capacity of supplier, etc. Different from data packet routing, which is mostly one-to-one mode, energy routing could happen in many-to-many mode.

- Energy efficient path

Finding out the energy efficient paths (less energy loss path) for transporting energy is crucial to reduce transmission loss. Transmission loss can be influenced by various factors such as impedance of the power link, distance, congestion, energy conversion loss, etc. Furthermore, one needs to know that even though a given path is detected to be shorter than others, it might not be an exact path if the ERs and links along that path do not support the power rate, type and capacity of the power to be transmitted as it may lead to overheating and failure.

- Transmission scheduling (congestion control)

The integrating of DERs into the existing power system poses several challenges such as bidirectional power flows, voltage fluctuations, uncertainties in renewable power generation and dynamic changes in the demands from customers. This can cause congestion and even failure of the power system if appropriate transmission scheduling is not performed to regulate the power flow within the system. This issue of power flow management is regarded as the optimal power flow (OPF) problem. Therefore, ERs are also required to perform transmission scheduling to prevent the power system from congestion.

8.2 Routing approaches

The existing literature points out that there are three types of strategies employed for developing energy routing algorithms: graph theory based approaches in [31], [41] and [42], game theory based routing method [43], [44] and autonomous systems [45]. In this section, three categories of energy routing algorithms will be discussed.

- Graph theory based routing algorithms

One of the techniques utilized for developing energy routing algorithms are graph based methods. Routing algorithms that fall under this category mainly concentrate on identifying energy efficient paths relied on a weighted energy network graph.

A graph theory based energy routing algorithm that determines the lowest cost path for an e-LAN is introduced in [31]. The authors propose a dynamic routing algorithm based on open shortest path first (OSPF). ERs use a graph traversal algorithm to detect all the possible routing paths. Therefore, searching for an efficient transmission is determined based on the new digraph, which avoids overflow.

The paper in [41] presents a secure energy routing mechanism that efficiently and dynamically routes renewable energy between houses in MGs. The security system is based on public key cryptography and takes into account threats such as spoofed route signaling, denial-of-service attacks and fabricated routing messages. Presuming that energy sharing efficiency information is available initially, the paper proposes an algorithm for requesting energy in the network securely. A router requiring energy sequentially transmits encrypted energy request messages to other routers until it has acquired enough energy. The major objective of the algorithm is to prevent unnecessary and redundant transmissions from malicious routers. Nevertheless, factors such as powers rate, capacity of ERs and power links, dynamic network topology changes were not mentioned by the authors. The authors assume that the efficiency between routers is fixed and calculated initially, when the routers are installed.

To minimize the transmission cost, reference [42] introduces a distributed energy routing protocol, which can calculate an optimal transmission route based on the supply and demand information of all nodes and the capacities of the power links. To determine an optimal route, firstly, all demand nodes must send out their demand information to all other nodes. After that, all supply nodes send back their supplied power and link information such as length, link cost and existing load. Once this information is received by all nodes, one of the demand nodes (the node with the highest demand) acts as a master node and computes the optimal route for all demand supply node pairs. A new master node is nominated for each transmission cycle. The proposed protocol includes two sub-protocols: global optimal energy routing protocol (GOER) and local optimal energy routing protocol (LOER). GOER, which considers the optimal transmission path as a global optimization problem attains the best result. Nonetheless, the computational complexity of GOER increases quickly with the size of the network. Thus, in order to deal with this issue, the authors introduce an LOER protocol that separates the power system into multiple regions. Each smaller region is treated as a sub-problem of a bigger region and optimal routes are resolved bottom-up as in multiple-layer optimization. The optimal transmission path for each individual region is found by the LOER and then the overall optimal energy routes are found based on GOER. The LOER reduces the computational complexity but doesn't provide the optimal result as GOER does. There are two problems related with this protocol: first, the optimal route is decided by one master which greatly influences the performance and security of the protocol. Second, the complexity is very high as it increases with the number of supply/demand requests and energy links.

- Game theory based routing algorithms

Energy routing algorithms have also been introduced based on different types of gaming techniques. These algorithms mostly focus on subscriber-matching problems. Reference [43] proposed a game theory based approach for energy routing of a MMG system. The method uses a two-step methodology to implement efficient energy routing; price-based subscriber matching followed by optimal transmission path computation. First, each supply and demand node plays a game to choose the amount of electricity to sell/buy and the desired sale and purchase price. After that, each node submits the amount to buy/sell along with the related purchase/sell price to a central controller. The central controller undertakes a stock exchange pricing scheme to find an optimal transaction price that maximizes the revenue for all involved parties based on the supply and demand information of each node. In the second step, the method uses the Hungarian transportation optimization algorithm to identify the optimal transmission path.

A power dispatching protocol that divides the operation of packetized router into three different functions including subscriber matching, transmission scheduling and power packet transmission is proposed in [44]. The scheme presumes a local area packetized-power network (LAPPN) that contains a central ER connecting several end customers with the main grid. The parties interact with each other using unique IP addresses where producers send a power packet tagged with the address information of the consumers and the routers transmit the power packet to the correct destination address. The subscriber-matching process includes four stages: registration, information sharing, ranking and matching. Matching theory is a branch of game theory to design and establish matching between elements belonging to two different sets. A heuristic transmission scheduling algorithm is recommended to arrange the power transmission channels for each demand-supply pair to acquire fair power line occupation and to decrease load fluctuation in the grid. However, the proposed approach only works for a local energy network. Furthermore, uncertainties in production and demand oscillation are not taken into account.

- Autonomous systems for energy routing

The work in [45] presents a distributed energy routing algorithm for an active network that is based on a multi-agent system (MAS) technology. MAS assumes that each power element in the distributed power system acts as an autonomous agent implementing agent software. The OPF problem is then specified as minimum cost flow problem that considers both the shortest path and the maximum flow capacity and it is solved by cost-scaling push- relabel (CS-PR) method. The suggested system and algorithm allow network elements to operate in an autonomous way based on demand/supply information from their immediate neighbors. With that, energy is dynamically rerouted towards optimal paths depending on the state of the system. Therefore, the algorithm supports self-stabilizing and self-healing functions in feedback to fluctuation in demand/supply, cost or topology.

Finally, a summary of energy routing algorithms is given in Table 4 [40]. The table explains various aspects of the previous research including the problem addressed, the technique used for the algorithm and its weaknesses and strengths.

Table 4: Summary of energy routing algorithms

Ref.	Addressed problem	Method	Strengths	Weaknesses	Remarks
[31]	Efficient energy path for heavy loads	Graph Theory	-Dynamic network -Heavy loads	-Complexity -Distance and congestion not considered	Adopt OSPF based routing approach to support demand driven dynamic energy network topology

[41]	Secure routing	Graph Theory	-Security	-Static network topology -Efficient energy path considers congestion only	Does not provide algorithm for finding the energy efficient path rather suggests a distributed shortest path algorithm
[42]	Find optimal transmission route	Graph Theory	-Dynamic network	-Complexity	Consider both static and dynamic networks
[43]	Price based subscriber and optimal transmission path	Game Theory	---	-Subscriber matching is based on price only and uses central controller	Suggest the utilization of the Hungarian transportation optimization algorithm to find an optimal path
[44]	Subscriber matching and transmission scheduling	Game Theory	-Subscriber matching based on power type of users, generation capacity of producers and transmission loss	-Transmission loss is linear function of distance only -Price not considered for subscriber matching -Complexity	Assumes DC power line that operate in Time Division Multiplexing mode
[45]	Dynamic routing to solve congestion problem	Autonomous Routing	-Local self-stabilizing and self-healing	-Solves only congestion problem	Network elements operate in an autonomous way based on demand/supply information from their immediate neighbors

Even though different algorithms targeting the different problems mentioned earlier have been proposed, none of the existing literature solved all of these problems effectively. Developed algorithms need to support dynamic energy network topology and condition changes. Existing power routing algorithms are not computationally efficient with respect to transmission scheduling indicating that some improvements are needed in this area. Aside from this, it is important to know that there are no existing algorithms that provide a solution for all problems discussed earlier.

8.3 Proposed routing algorithm

Adopting the concept of ERs from section 4 graph theory based energy routers are used in this section to solve the power routing problem. The topology of MMGs in [31] is considered, as shown in Figure 8.1.

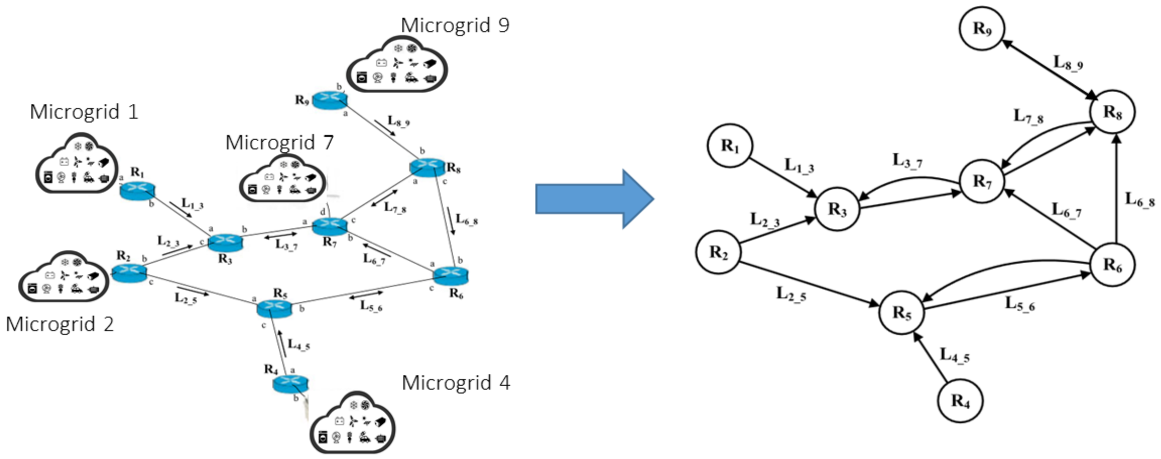


Figure 8.1 – The topology of the MMGs and its equivalent digraph [31].

In this topology, the ERs constitute the set of nodes R = {R_1, R_2, … R_n} and the power links constitute the set of edges L = {L_{i-j}, …} (L_{i-j} is the power link between two ERs R_i and R_j). The possible route from source A to destination B is expressed as

$$rout(A \longmapsto B) \coloneqq A \equiv R_i, R_j, \dots R_k \equiv B \quad (9)$$

where R_i, R_j, … R_k are the ERs along this path.

The power information for all the sources, loads, links and ERs is presented in Table 5, Table 6 and Table 7. In these tables, P_{total}, $P_{available}$ and *eff* are the total power capacity, available power capacity, and efficiency of the devices, respectively. Also, *r* is the power link impedance and V_{trans} is the transmission voltage in the corresponding power link.

Table 5: Power information of the sources and loads

Micro-grid	P_{total}/kW	$P_{available}$/kW	*eff*
MG_1	6.0	5.5	0.96
MG_2	12.0	9.2	0.95
MG_4	5.0	4.0	---
MG_9	14.0	10.9	0.96
MG_7	22.0	22.0	---

Table 6: Power information of the energy routers

Router	Port	P_{total}/kW	$P_{available}$/kW	*eff*
R_1	R_{1a}	20.0	19.5	1
	R_{1b}	15.0	9.0	0.98
R_2	R_{2a}	15.0	12.2	0.97
	R_{2b}	15.0	14.0	0.98
	R_{2c}	15.0	13.0	0.98
R_3	R_{3a}	18.0	12.0	1
	R_{3b}	15.0	14.0	0.98
	R_{3c}	15.0	15.0	1
R_4	R_{4a}	15.0	9.0	0.98
	R_{4b}	10.0	9.0	1
R_5	R_{5a}	15.0	13.0	1
	R_{5b}	18.0	12.0	0.98
	R_{5c}	15.0	15.0	1
R_6	R_{6a}	20.0	20.0	0.98
	R_{6b}	20.0	20.0	1
	R_{6c}	18.0	18.0	1
R_7	R_{7a}	25.0	25.0	1
	R_{7b}	20.0	20.0	1
	R_{7c}	25.0	23.0	1
	R_{7d}	25.0	25.0	1
R_8	R_{8a}	20.0	18.0	0.98
	R_{8b}	20.0	20.0	1
	R_{8c}	18.0	12.0	0.98
R_9	R_{9a}	20.0	14.0	0.98
	R_{9b}	20.0	16.9	1

Table 7: Power information of power links

Power link	P_{total}/kW	$P_{available}$/kW	r/Ω	V_{trans}/V
$L_{1\text{-}3}$	30	24	0.6	400
$L_{2\text{-}3}$	20	19	0.64	400
$L_{2\text{-}5}$	20	20	0.51	400
$L_{3\text{-}7}$	45	45	0.94	400
$L_{4\text{-}5}$	24	18	0.19	400
$L_{5\text{-}6}$	20	20	0.45	400
$L_{6\text{-}7}$	40	40	0.24	400
$L_{8\text{-}9}$	32	26	0.6	400
$L_{6\text{-}8}$	30	30	0.21	400
$L_{7\text{-}8}$	30	30	0.21	400

This section focuses only on power losses. The power loss depends on the impedance of the power link, the amount of existing power on the link, efficiency of ERs, and rated power of the load.

The energy losses in an ER consist of the power conversion losses and power cable transmission losses inside the ER. The latter term can be ignored since the power cables inside the ERs are very short. The conversion losses of an ER are not a fixed value. For simplicity, the efficiency of a converter is considered as a constant measured under the rated power, and thus, the conversion losses are linearly proportional to the converted power. The total power losses of an energy router are expressed as

$$W_i = ((1 - eff_{ix}) + \left(1 - eff_{iy}\right))\Delta P_i \tag{10}$$

where port *x* is the input port, port *y* is the output port and ΔP_i is the added power value through these ports.

Also, the added power losses in a power link between two ERs R_i and R_j are calculated as

$$W_{i-j} = \frac{r_{i-j}}{v_{i-j}^2}((\Delta P_{i-j} + P_{i-j})^2 - {P_{i-j}}^2) \tag{11}$$

where P_{i-j} is the already existing power in the link, ΔP_{i-j} is the added power through this link, r_{i-j} is the link resistance and V_{i-j} is the link voltage.

The total cost is the sum of all nodes' and edges' power losses along the power transmission path:

$$C = \sum W_i + \sum W_{i-j} \tag{12}$$

A source selection and power allocation algorithm is proposed in this section to minimize the cost function (i.e., the power losses) in Equation (12). First, all sources and one load are considered and all the possible paths from the sources to the load are found. Then, power losses based on load power for all the paths are calculated and source and path with minimum losses are selected. Compliance with all constraints is checked and the final power value for this source and path is specified. At the next step, the procedure will be repeated for the remaining power until the total output power meets the power rate of the load. The routing algorithm flowchart is shown in Figure 8.2.

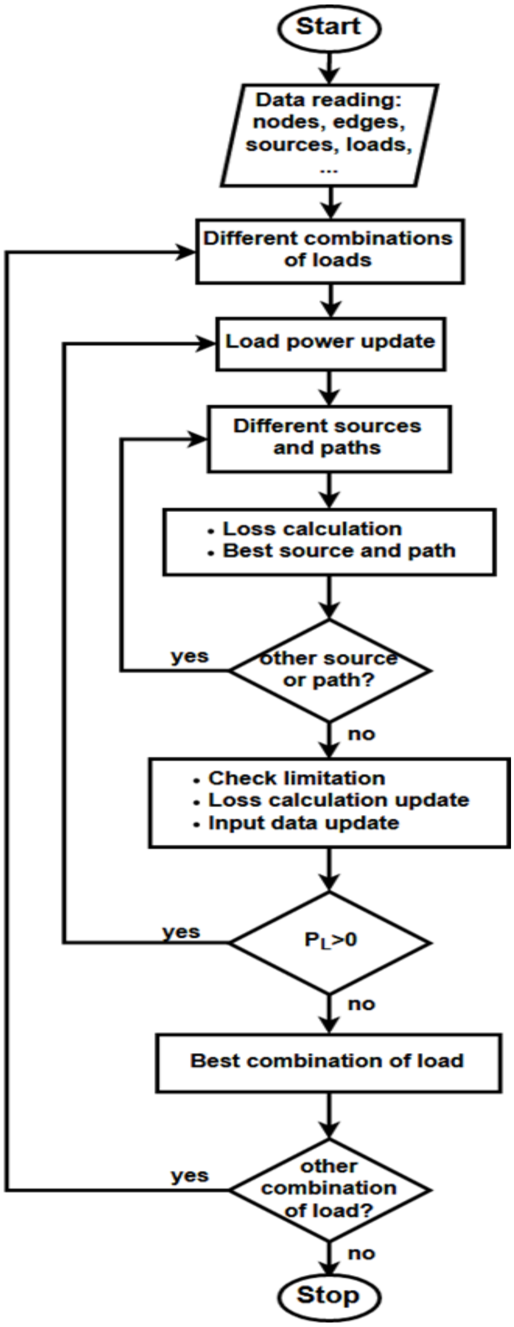


Figure 8.2 – The proposed routing algorithm flowchart

A case analysis is carried out in the next section to verify the proposed routing algorithm. In addition, a comparison is made between the proposed algorithm and an energy routing algorithm found in literature.

8.4 Simulation results

8.4.1 Scenario 1

It is assumed that there are four MGs with surplus energy in Figure 8.3: MG_1, MG_2, MG_4 and MG_9. MG_7 requests 22 kW from other MGs via energy router - R_7. In this simulation, a MG with surplus energy can be considered as a "source" and a MG with deficit energy can be considered as a "load". The other MGs, which are not shown in Figure 8.3, are considered to be working in virtual islanded mode.

$$D_i = [+5500, +9200, 0, +4000, 0, 0, -22000, 0, +10900]\ W$$

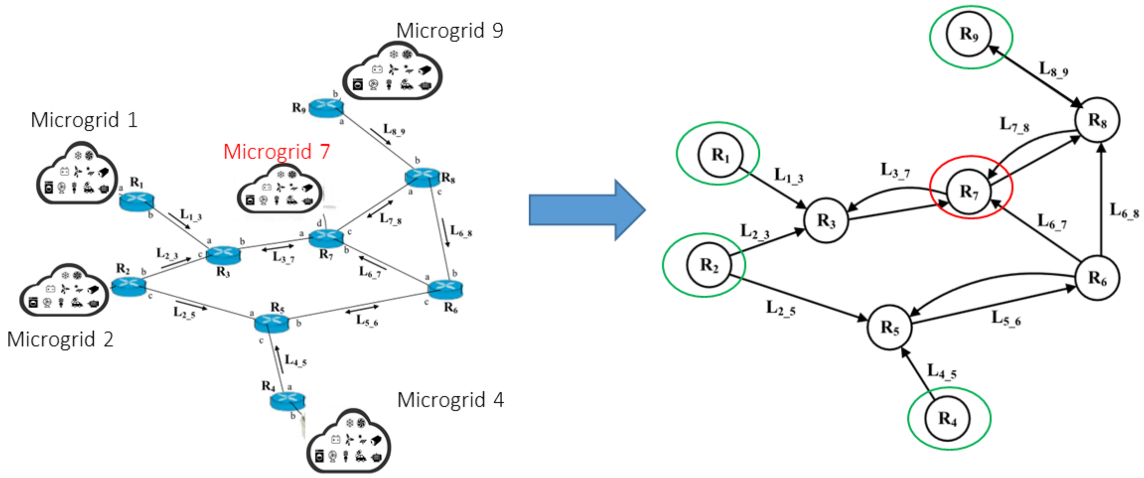
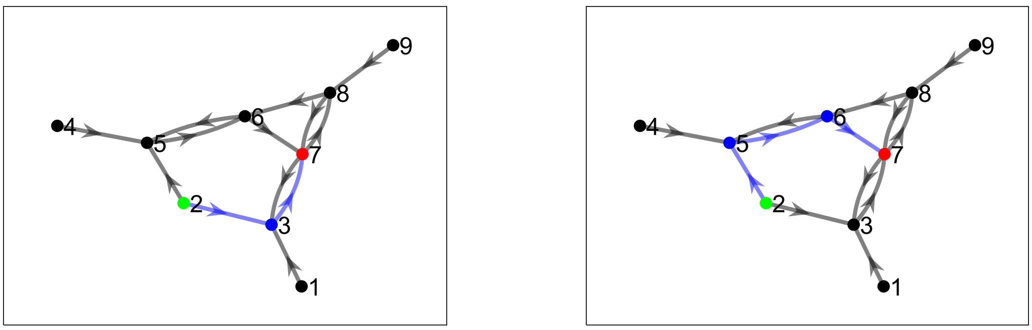


Figure 8.3 – The MMG system in scenario 1

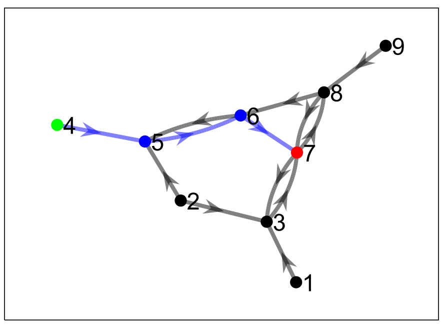
Different optional paths from other MGs to the MG_7 are found out after graph traversal as shown in Figure 8.4:



(a) Energy paths from source 2

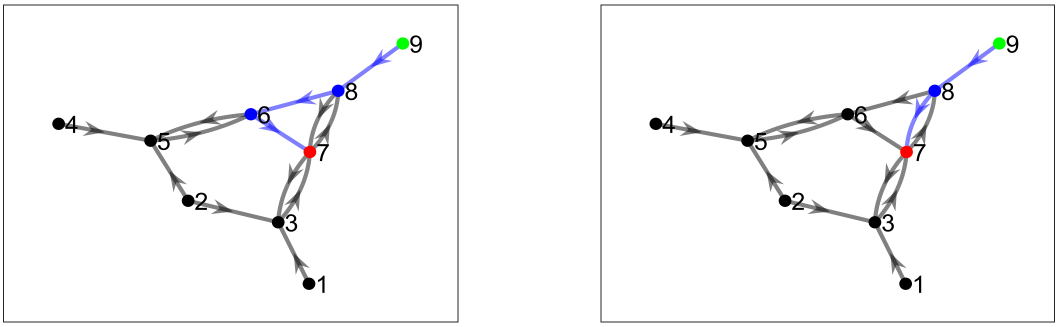
$$path1(MG_2 \longmapsto MG_7) \coloneqq MG_2 \equiv R_2, R_3, R_7 \equiv MG_7$$

$$path2(MG_2 \longmapsto MG_7) \coloneqq MG_2 \equiv R_2, R_5, R_6, R_7 \equiv MG_7$$



(c) Energy path from source 4

$$path1(MG_4 \longmapsto MG_7) \coloneqq MG_4 \equiv R_4, R_5, R_6, R_7 \equiv MG_7$$



(d) Energy paths from source 9

$$path1(MG_9 \longmapsto MG_7) \coloneqq MG_9 \equiv R_9, R_8, R_6, R_7 \equiv MG_7$$

$$path2(MG_9 \longmapsto MG_7) \coloneqq MG_9 \equiv R_9, R_8, R_7 \equiv MG_7$$

Figure 8.4 – Different paths from surplus energy MGs to deficit energy MG7.

The simulation results are shown in Table 8. From the table it can be seen that for the 22kW load, path1 from MG_9 has lower cost and after that, path2 from MG_4 is the second best choice. Finally, MG_7 receives 7100W from MG_2. As a result, the total cost is **2964.6** W.

Table 8: Simulation results of the proposed routing algorithm for scenario 1.

Priority	Source	Path (num.)	Power (W)	Node loss (W)	Edge loss (W)	Total loss (W)
1	MG_4	4, 5, 6, 7 (1)	4000	240	145	385
2	MG_9	9, 8, 7 (2)	10900	436	1092	1528
3	MG_2	2, 3, 7 (1)	7100	497	554.6	1051.6
total			22000	1173	1791.6	2964.6

When applying the energy routing algorithm in [31] to the same scenario the power losses are about **3452 W**, which is higher than the total losses with the proposed method. Therefore, the proposed energy routing algorithm shows advantages compared to the algorithm studied in [31].

8.4.2 Scenario 2

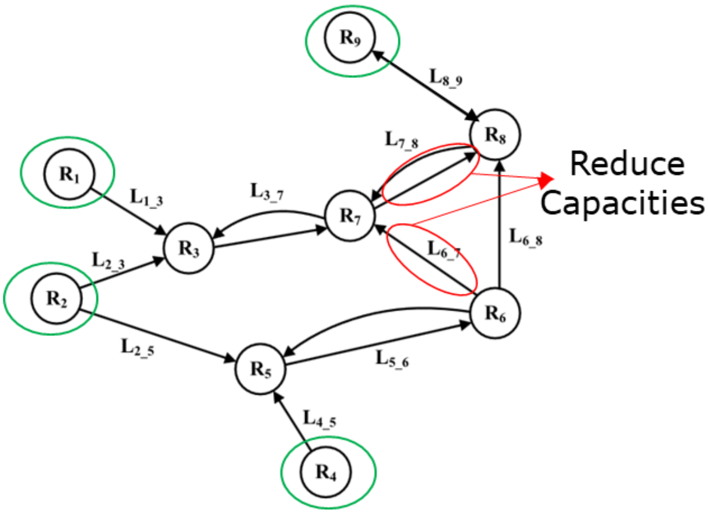


Figure 8.5 – The MMG system in scenario 2.

In high-power conditions, overflow may occur in some critical power lines. Therefore, in scenario 2, it is assumed that the capacities of edges $L_{7\text{-}8}$ and $L_{6\text{-}7}$ are limited to 5 kW and 7.5 kW, respectively (Figure 8.5).

Table 9: Simulation results of the proposed routing algorithm for scenario 2.

Priority	Source	Path (num.)	Power (W)	Node loss (W)	Edge loss (W)	Total losses (W)
1	MG_4	4, 5, 6, 7 (1)	4000	240	145	385
2	MG_9	9, 8, 7 (2)	5000	200	351.6	551.6
3	MG_2	2, 3, 7 (1)	9200	644	909.4	1553.4
4	MG_9	9, 8, 6, 7 (1)	3500	410	762.7	1172.7
5	MG_1	1, 3, 7 (1)	300	12	46.8	58.8
total			22000	1506	2215.5	3721.5

Table 9 shows the simulation results for this scenario. It can be seen that the total loss of the system is increased. In fact, compared with the previous case, it can be found that although the load power does not change, the power lines $L_{7\text{-}8}$ and $L_{6\text{-}7}$ reach their maximum power capacity limits. Therefore, other paths with more losses replace them, and as a result, the total cost of the system has increased. However, to avoid this problem in [31], a screening process is required to first find out all the power links and ERs ports that meet the rate of the power demand. Others are deleted from the digraph and graph traversal is applied based on the new digraph. Again, the method in [31] results in more losses and calculations.

8.4.3 Scenario 3

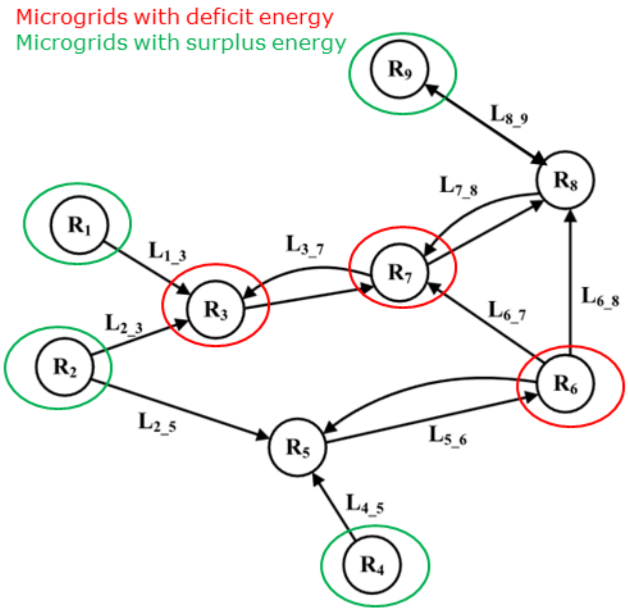


Figure 8.6 – The MMG system in scenario 3.

The proposed algorithm is modified, when there is more than one "load". In this case, the priority of "loads" is important for power losses calculation and selection of the best paths. For this purpose, all the "sources" combination sets are considered and the set with minimum loss is selected. The number of source combination is calculated as:

$$Q_n = N! \tag{13}$$

Where N is the number of sources. For this study, beside node R_7, it is considered that nodes R_3 and R_6 are also acting as loads.

$$D_i = [+5500, +9200, -2000, +4000, 0, -5000, -8000, 0, +10900]\ W$$

Therefore, there are 6 different combinations of load priority, which can be seen in Table 10 along with the simulation results.

Table 10: Comparison of load combination sets.

Set number	Combination	Total losses (W)
1	7-6-3	1550.5
2	7-3-6	1550.5
3	6-7-3	1567.1
4	6-3-7	1567.1
5	3-7-6	1550.5
6	3-6-7	1567.1

As can be seen, three sets have similar power losses. For example, the paths for combination set number 1 (7-6-3) is presented in Table 11. The algorithm determines the lowest cost route (in terms of power losses) according to the features of power transmission and the power sources selected.

Table 11: Results of the proposed routing algorithm for combination set (7-6-3).

Priority	Loads	Power demand (W)	Sources	Power supply (W)	Best Rout
1	MG_7	8000	MG_4 MG_9	4000 4000	4-5-6-7 9-8-7
2	MG_6	5000	MG_2	5000	2-5-6
3	MG_3	2000	MG_2	2000	2-3

8.4.4 Scenario 4

In order to test the autonomy of the ERs-based MMG system, in scenario 4, it is assumed that the connection between ER 7 and ER 8 is lost as shown in Figure 8.7.

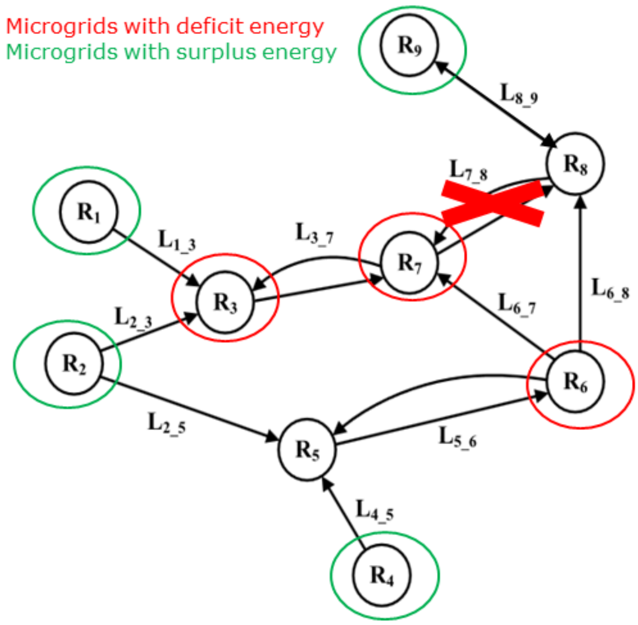


Figure 8.7 – The MMG system in scenario 4

In this scenario, the simulation results of all combinations are shown in Table 12. As can be seen, only the set number 1 and number 2 have the same loss in this case.

Table 12: Comparison of sources combination sets

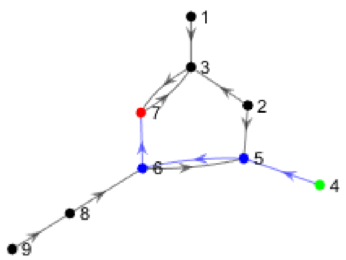
Set number	Combination	Total losses (W)
1	7-6-3	1551.6
2	7-3-6	1551.6
3	6-7-3	1772.1

4	6-3-7	1589.8
5	3-7-6	1562.6
6	3-6-7	1589.8

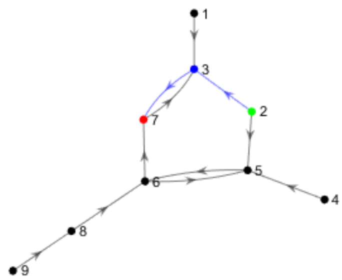
The paths in scenario 4 for the combination set number 1 (7-6-3) are presented in Table 13.

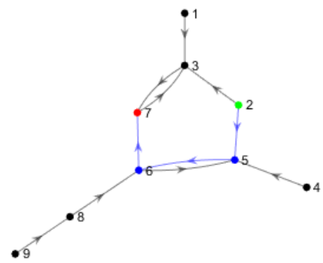
Table 13: Simulation results of the proposed routing algorithm for combination set (7-6-3).

Priority	Loads	Power demand (W)	Sources	Power supply (W)	Best Rout
1	MG_7	8000	MG_4 MG_2	4000 4000	4-5-6-7 2-3-7
2	MG_6	5000	MG_9	5000	9-8-6
3	MG_3	2000	MG_1	2000	1-3



(a) Path from MG_4





(b) Paths from MG_2, the path via 2-3-7 is selected

Figure 8.8 – Different paths to supply MG_7.

The new equivalent graph of the system is presented in Figure 8.8, which describes the possible paths from MG_4 and MG_2 to share the load in MG_7. It can be seen that, in case of failure, the proposed technique can automatically update network status and find the new route to the task.

9. Summary

In this report, in accordance with Task 4.2 of the m2M-Grid project, the interface between physical MGs is developed. Firstly, the MG control approaches that enable cooperation between physical MGs as well as the interconnections between them are presented. For this purpose, the P2P control strategy for interaction in MMG system is selected.

Next, the report introduces the concept of ER as an interface among MGs, with its characteristics, functionalities and topologies for implementation. A DC bus-based ER is developed, which has higher degree of reuse and integration compared to other topologies. The control of ERs relies on the VSCs. The VSCs of the ERs are working in the master/slave mode. The outer-loop controller of the master VSC operates as a DC voltage controller and its objective is to keep a steady and constant DC-link voltage. The rest of the VSCs are the slave converters.

To verify the ER application, a stand-alone MMG system with ER interface is simulated in MATLAB/SIMULINK software. In the case of transient events such as load increase or disconnection/reconnection to the main grid, the ER is able to keep the DC-link voltage stable. In addition, MGs are allowed to exchange the energy directly among them via the ER interface. The energy constraints of the MGs such as the SOC limits are also investigated. In the case study, when the SOC of the BESS system reaches its limit, the role of VSC in ER changes from master to slave.

A methodology for frequency coordination through ERs is introduced in this report. This strategy is applied when MGs are not able to maintain their standard frequency. With that, MGs can be supported by other MGs, which not only improves the reliability of MGs, but also reduces the cost of ancillary services.

Finally, a literature review for routing algorithms is presented, with the advantages and disadvantages of each approach. Then, a graph theory based routing algorithm is proposed for sharing the load among MGs. The objective of the proposed method is to minimize the transmission loss among MGs. Constraints of the transmission lines and power sources are taken into account. In the simulation results, the proposed routing strategy has shown a superior performance in minimization of power loss compared to the existing approaches found in literature. The problem of load sharing between multi-sources and multi-loads is also addressed in the method.

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