On energy management optimization for microgrids enriched with renewable energy sources

Muhammad Fahad Zia

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Par
Muhammad Fahad ZIA

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Rapporteurs avant soutenance :

Corinne ALONSO	Professeur, Université de Toulouse
Bruno FRANCOIS	Professeur, École Centrale de Lille

Composition du Jury :

Président :		
	Nouredine HADJSAID	Professeur, Université Grenoble Alpes
Rapporteurs :		
	Corinne ALONSO	Professeur, Université de Toulouse
	Bruno FRANCOIS	Professeur, École Centrale de Lille
Examinateurs :		
	Emmanuel DELALEAU	Professeur, ENI Brest
	Jean Frédéric CHARPENTIER	Maître de Conférences – HDR, Ecole Navale
	Abdelkrim BENCHAIB	Manager R&D – HDR, SuperGrid Institute
Co-encadrant :		
	Elhoussin ELBOUCHIKHI	Enseignant Chercheur – HDR, ISEN Yncréa Ouest, Campus de Brest
Directeur de thèse :		
	Mohamed BENBOUZID	Professeur, Université de Bretagne Occidentale

To my father and six extra-ordinary women in my life,
my mother, three sisters, wife, and daughter

Abstract

The current electric power system is facing the challenges of environmental protection, increasing global electricity demand, high reliability requirement, cleanliness of energy, and planning restrictions. To evolve towards green and smart electric power system, centralized generating facilities are now being transformed into smaller and more distributed generations. As a consequence, the concept of microgrid emerges, where a microgrid can operate as a single controllable system and can be assumed as a cluster of loads and distributed energy resources, which may include many renewable energy sources and energy storage systems. The energy management of large numbers of distributed energy resources is needed for reliable operation of microgrid system. Therefore, energy management is the fundamental part of the microgrid operation for economical and sustainable development. In this regard, this thesis focuses on proposing energy management optimization models for optimal operation of microgrid system that include proposed practical Li-ion battery degradation cost model. These different energy management models include objective functions of operating cost of distributed generators, emission cost of conventional generation source, maximum utilization of renewable energy sources, battery degradation cost, demand response incentives, and load shedding penalization cost, with microgrid component and physical network constraints. A comprehensive conceptual seven layer model is also developed to provide standardized insights in implementing real transactive energy systems.

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List of Publications

1st authored Journal Publications:

- M. F. Zia, E. Elbouchikhi, and M. Benbouzid, "Microgrids energy management systems: A critical review on methods, solutions, and prospects," Applied Energy, vol. 222, pp. 1033–1055, Jul 2018.
- M. F. Zia, E. Elbouchikhi, and M. Benbouzid, "Optimal operational planning of scalable DC microgrid with demand response, islanding, and battery degradation cost considerations," Applied Energy, vol. 237, pp. 695–707, Mar 2019.
- M. F. Zia, E. Elbouchikhi, M. Benbouzid, and J. M. Guerrero, "Energy management system for an islanded microgrid with convex relaxation," IEEE Transactions on Industry Applications, vol. 55, no. 6, pp. 7175–7185, Nov 2019.
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- M. F. Zia, M. Nasir, E. Elbouchikhi, M. Benbouzid, J. C. Vasquez, and J. M. Guerrero, "Energy management system for a hybrid PV-wind-tidal-battery based islanded DC microgrid: modeling and experimental validation," Submitted to IEEE Transactions on Smart Grid, 2020.

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Conference Publications:

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- M. F. Zia, E. Elbouchikhi, M. Benbouzid, and J. M. Guerrero, "Microgrid transactive energy systems: A perspective on design, technologies, and energy markets," in IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society. IEEE, Oct 2019.
- M. F. Zia, M. Nasir, E. Elbouchikhi, M. Benbouzid, J. C. Vasquez, and J. M. Guerrero, "Energy management system for an islanded renewables-based DC microgrid," Accepted in 2nd International Conference on Smart Power & Internet Energy Systems (ICSPIES), IEEE, 2020, pp. 1–6.

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List of Abbreviations

MG	Microgrid
CGS	Conventional Generation Source
RES	Renewable Energy Source
ESS	Energy Storage System
DER	Distributed Energy Resource
DR	Demand Response
SG	Smart Grid
TES	Transactive Energy System
IRENA	International Renewable Energy Agency
ICT	Information and Communication Technology
EV	Electric Vehicle
MPPT	Maximum Power Point Tracking

Chapter I

Context

1 Background

Traditional electric power system can be broadly divided into three main categories: electricity generation, transmission, and distribution systems [9]. The generating stations are connected to the distribution system through transmission lines and the distribution system supplies electricity to all loads in a particular region. For a number of reasons, mainly technical and economical, individual power systems are connected together to form power pools. These regional or area electric grids operate independently, but are also interconnected to form a utility grid.

Rapid increase in global population, digitization, and industrial evolution are the major causes of growing electricity demand. Figure 1 shows the estimated global energy demand in various sectors. It is predicted to go beyond 30 TWh by 2040. Residential and commercial sectors will be largest electricity consumption sectors in 2040. Transportation demand will be more than double by 2040, but it represents only 2% of total energy demand. Such high electricity demand requires more installation of electric power generation sources. However, electricity is mainly generated using centralized conventional generation sources (CGSs), which are located far from load ends. These CGSs are normally diesel, gas, and coal-fired electric power generators, which are the major sources of carbon emissions and global warming. Hence, carbon emissions will increase with more CGSs installation. The world carbon emissions trend is presented in Fig. 2. Global emissions have

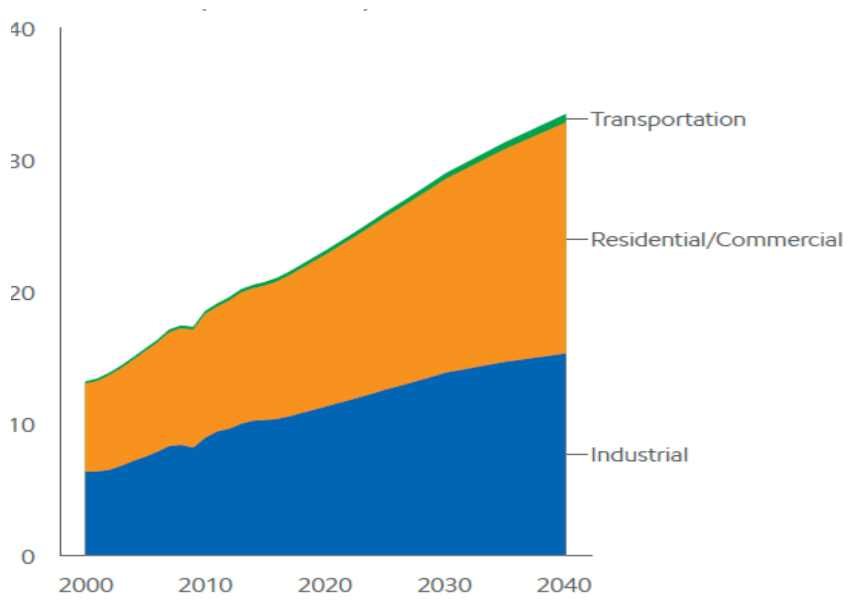


FIGURE 1: Sector-wise global electricity demand [1].

increased by almost 40% from 2000 to 2015. Emissions have started declining in Europe and North America since 2010. The increasing trend in emissions will continue towards its peak from 2015, which shall start declining just before 2040.

In view of the above discussion, the traditional electric power system suffers from the following issues:

- **Environmental challenges:** Traditional power generation systems are responsible for man-created carbon emissions [10, 11]. Hence, alternative solutions are required to overcome this emission problem. Besides, natural catastrophes such as hurricanes, earthquakes, tornado make the electricity grid highly susceptible to failure. Power outages during hurricane Katrina and Sandy have exposed the vulnerability of a traditional electric power system.
- **Infrastructure challenges:** With decreasing investments and aging infrastructure, it has become difficult to make improvements to meet the increasing load demand leading to congestion and unreliable power supply.
- **Integration of innovative technologies:** With the existing infrastructure, it will be difficult to integrate advancements in materials, power electronics and communication technologies.

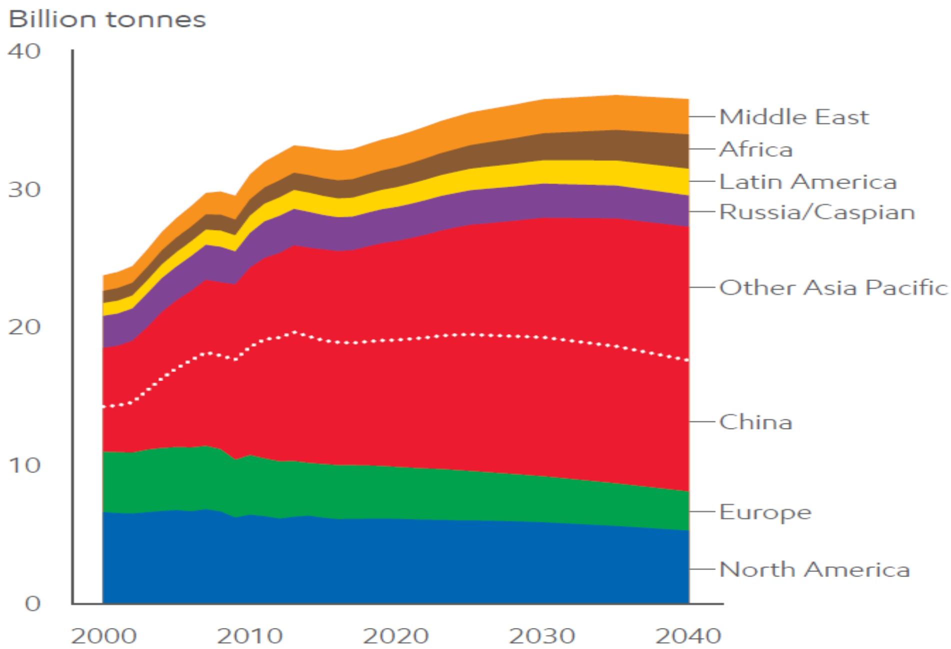


FIGURE 2: Global carbon emissions trend [1].

The world needs an alternative environmental friendly solution to overcome the above-mentioned problems of centralized power system. In this regard, government policies and academic research was focusing on technology maturity and deployment of renewable energy sources (RESs), such as solar energy, wind energy, marine energy, biomass, and so on, for at least two decades. RESs have gained high potential in large scale deployment in the last decade, which aims to achieve objectives of meeting increasing energy demand, achieving sustainability, and reducing carbon emissions [12]. Moreover, they can be installed on distribution side, close to load ends, which reduces transmission line congestion problems. The global installation of RESs was 921 GW in 2016, as shown in Fig. 3. China is leading in RESs installation with 258 GW market, while US has installed power capacity of 145 GW. The RESs market is of 300 GW in EU-28 countries.

In this context, the number of RESs-based generation sides are largely increased, which are more affordable every day. In some regions, wind and solar plants are cost-competitive with traditional generation technologies at utility scale [13–15]. Hence, there is a need to increase renewable energy share in total energy consumption with the time. Therefore, a renewable energy roadmap is presented in Fig. 4 to show how to increase 66% utilization of renewable energy in total energy consumption by 2050. With current trend, renewable energy share increases only around 0.25% annually and it

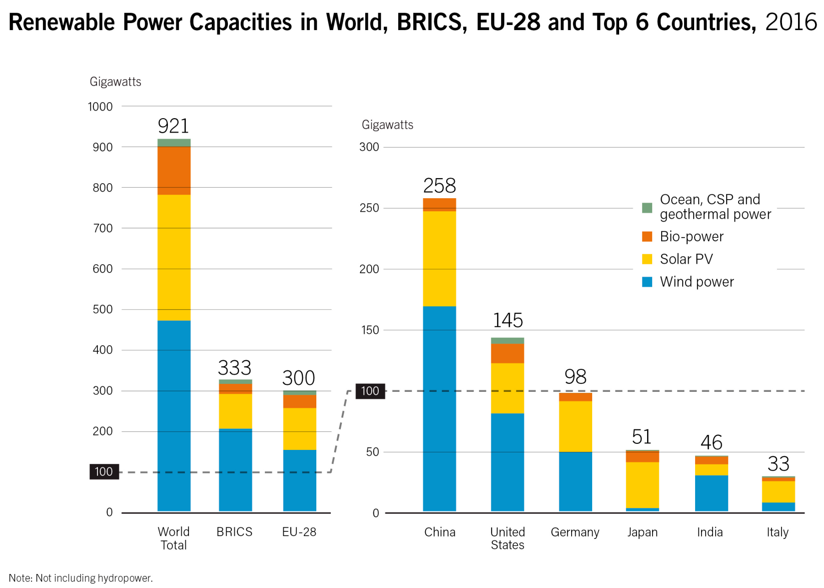


FIGURE 3: RESs global deployment status. [2].

shall be only 25% of total energy consumption by 2050. However, International Renewable Energy Agency (IRENA) presents Vigorous renewable energy road map (REmap) to accelerate renewable energy share by 1.5% each year so that 60% of total energy consumption can be met through renewable enregy by 2050 [3].

Nowadays, electric power systems are evolving to more complex and interacting sets of systems at multiple levels by means of the development of new technologies, along with innovations in business models and policies. In this way, the whole system tends to be a conglomerate of smarter grids that interconnect hardware, software and communication technologies [16–18]. The European Technology Platform Smart Grids defined a smart grid (SG) as "an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies" [19]. In SG, information and communication technology (ICT) enhanced appliances can adjust their electricity demand according to grid conditions and local energy generation. Currently, grid operators can already have agreements with industries on electricity demand for economic use of the electricity grid [20], but ICT technologies can enable a diverse set of household appliances to automatically shift their demand [21]. For example, a smart washing machine can start its cycle when PV solar panels are producing energy, stops operating when production is low because of a passing cloud, and continue its

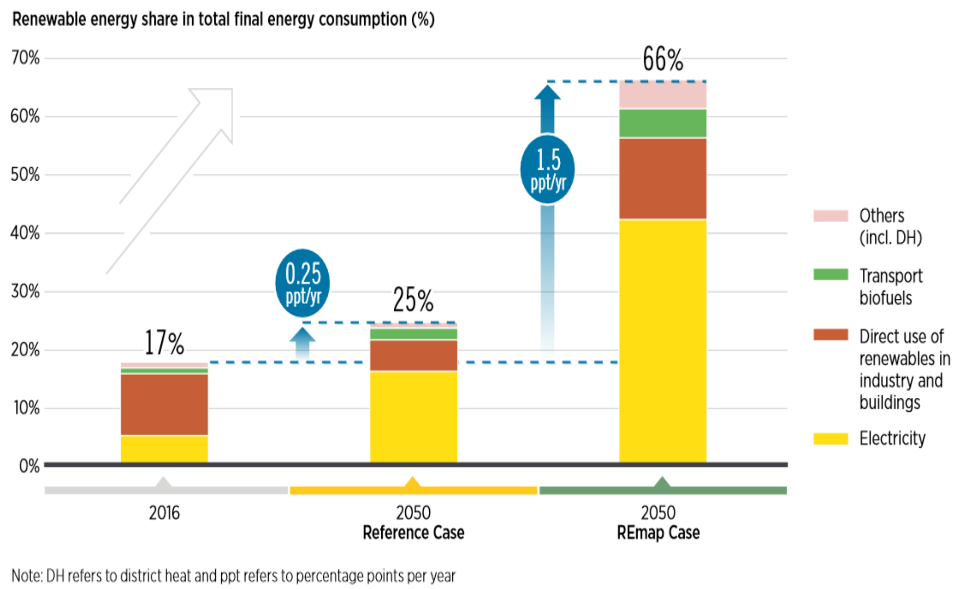


FIGURE 4: Roadmap for renewable energy share enhancement by 2050 [3].

operation again when the sky is clear again [22, 23]. However, all of the electrical appliances are not suitable for shifting their demands subject to grid conditions, for example, the electricity demands of appliances such as lightning and television can largely be considered as non-shiftable demands. Hence, demand response (DR) can also reduce the impact of clean energy technologies on the demand side, by alleviating peaks in electricity demand of technologies such as heat pumps and electric vehicles (EVs).

Accordingly, distributed solutions are becoming an integral part of the modern electric power system, providing improvements in energy efficiency, generation, and demand-side flexibility, as well as integrating diverse distributed energy resources (DERs) such as renewable energy sources (RES), energy storage systems (ESS), electric vehicles, smart devices and appliances, among others [24–26]. In this context, distributed autonomous systems known as microgrids (MGs) have appeared as a natural component of the SG to provide controllability and management to local power areas and enhance the power system with resiliency properties [27].

1.1 Microgrid

Microgrids have been defined in [28] as "low-voltage and/or medium voltage grids equipped with additional installations aggregating and managing largely autonomously their own supply and demand-side resources, optionally also in the case of islanding". Based on the standard IEEE 1547.4, a distributed islanded resources system (considered as MG) fulfills four conditions: (i) integrate DERs and loads, (ii) have the capability of being disconnected (in parallel) from the electric power system, (iii) contain the local electric power system and (iv) be purposely planned [29]. Therefore, an MG can operate in an interconnected mode linked to the main grid at the point of common coupling (PCC) or in islanded (autonomous) mode when it is disconnected from the main grid [30].

An example of an MG system is shown in Fig. 5. It integrates a variety of components including power consumers (loads), power converters (PC), and DERs such as RESs and CGSs and ESSs [31,32]. In grid-connected mode, MG trades surplus energy with the main grid to increase its revenue, but it operates in islanded model in case of disturbances or failure of main grid to ensure system stability and provides supply to critical loads while ensuring system stability. MG ensures continuous supply to critical loads in islanded mode with the effective management of DERs, load shedding, and DR. The central controller and local controllers (LCs) are used for supervisory operation of MG system [33]. Hence, the effective management and coordination of DERs in MG results into improved system performance and sustainable development [34]. Various types of sustainable energy systems used in MG applications are presented in Table I.1. Communication technology should be selected based on MG application to have a cost-effective reliable interaction between MG components. In this regard, Figure 6 presents the selection and comparison of communication technologies based on key factors; coverage area, data rate, and deployment cost.

MGs can be classified on the basis of power type, operation mode, and control, as presented in Figure 7. MGs can be used for a variety of application like: (a) remote, isolated and off-grid areas, namely remote communities, mountains, and military compounds; (b) grid-connected configurations, namely critical infrastructures, university campuses, commercial centers and industries. In general, MGs can be owned by a utility, a customer, or an independent power producer. The main advantage of MG in power and energy field is having an ability to disconnect itself from main grid due to disturbances, blackout, disruption, or economic reasons [61]. Hence, this definition results in dividing MG into two main types in terms of operation mode:

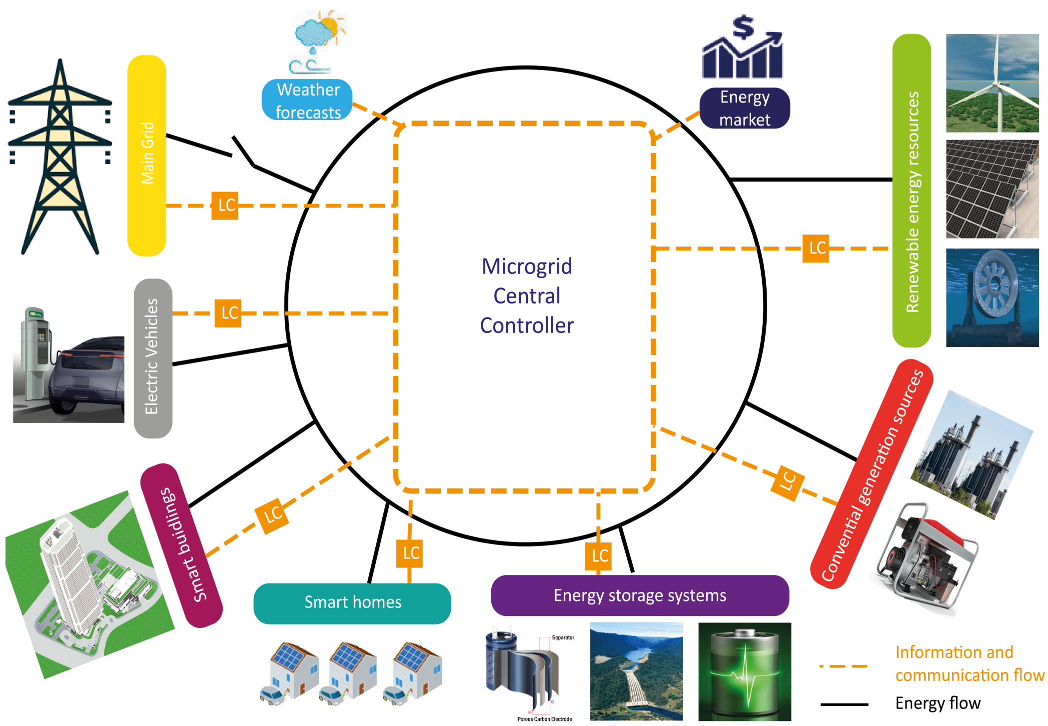


FIGURE 5: MG general scheme. [4].

TABLE I.1: Sustainable energy systems in MG.

References	PV	Wind	Fuel cell	Tidal	Biomass	Hydro	Combined heat and power
[35], [36], [37], [38]	✓	✓					
[39]	✓					✓	
[40]	✓	✓					✓
[41], [42], [43]	✓		✓				
[44]	✓		✓	✓			
[45]		✓	✓				
[46], [47], [48]	✓	✓	✓				
[49]	✓	✓					✓
[50]	✓				✓	✓	
[51]	✓	✓			✓		
[52]	✓	✓	✓				✓
[53], [54], [55], [56]	✓	✓	✓				
[57]	✓	✓					✓
[58]		✓			✓		
[59]	✓	✓				✓	
[60]	✓		✓	✓			

grid-connected MGs and islanded MGs.

1.2 Grid-connected Microgrid

In a grid-connected MG, an MG is connected to a main grid or a network of multi-MGs. In such type, MG trades energy with main grid or other MGs to maximize its energy trading profit [62]. It buys energy when local generation is insufficient to meet load demand and injects excess power to main grid in case of local generation more than load demand and ESSs fully charged. As MG is connected to main grid, frequency at PCC voltage is set by main grid and MG cannot change it [63]. Moreover, it can act as a grid-supporting unit by adapting its power to provide ancillary services to the main grid network, depending on its state, for avoiding unstable.

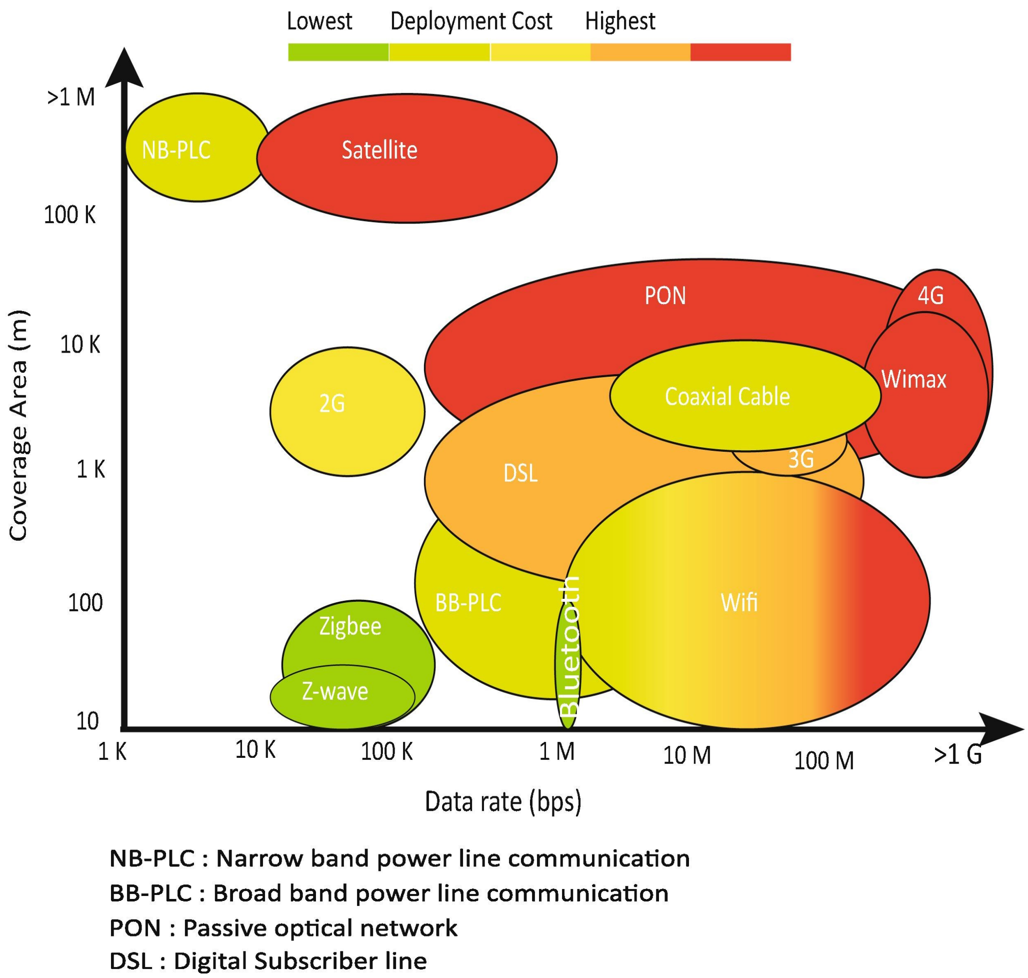


FIGURE 6: Comparison of communication technologies for MG application [4].

1.3 Islanded Microgrid

Islanded MG, as the name indicates, is not connected to a main grid. This mode of operation can be temporary, when the MG is voluntarily disconnected from the main grid, or permanent. In such MGs, DERs ensure system voltage and frequency stability as well as supply demand balance. DERs are divided into categories of grid-following and grid-forming energy sources, where the latter are responsible for system voltage and frequency stability [64,65]. In islanded MG, at least one DER must be grid-forming for system control and stability. Hence, islanded MG must be properly designed and sizing should be done such that loss of load probability or load shedding can be reduced [66].

In remote areas without electricity, islanded MGs are considered as a best option to provide electricity [67–69]. For example, in [69], authors have studied seven cases in different parts of the world with different requirements to

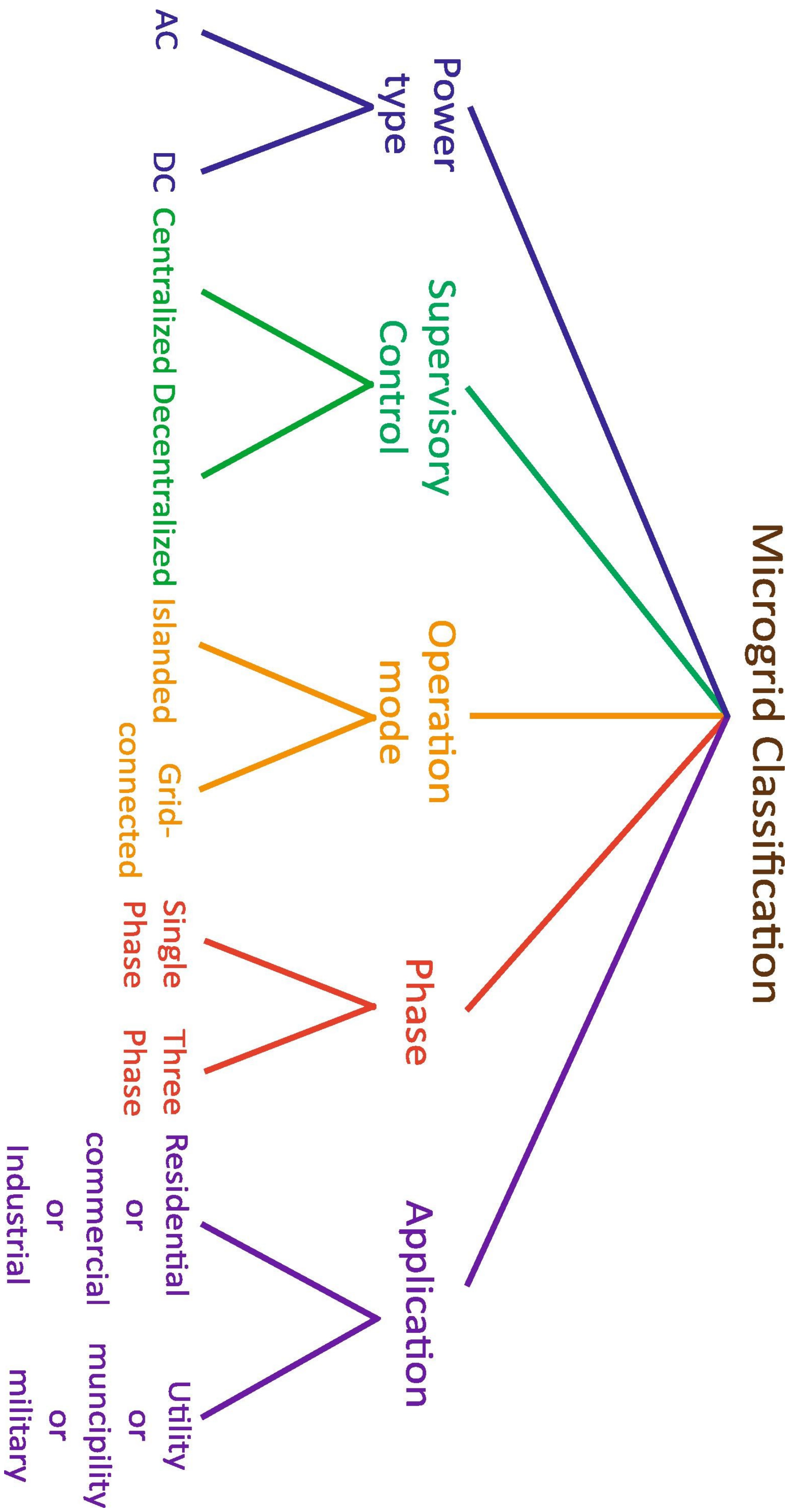


FIGURE 7: MG classification [4].

show that utilizing the islanded MG approach immensely benefits the community. Therefore, MGs are a promising solution for remote areas. Hybrid MGs incorporate RESs and conventional generation units, mostly diesel generators, in islanded communities, but fuel costs for such conventional units are high [69,70].

2 Microgrid Components

An MG contains many components from power, communication, infromation, and security related domains. However, the manuscript only focuses on the components that have been used in this thesis. In this regard, an MG generally consists of DERs, ESSs, power electronic converters, and loads. In DERs, PV, wind turbine, tidal turbine, and diesel generator are considered. The details of these MG components are provided in the following subsections.

2.1 PV System

PV system is a renewable energy system and a non-dispatchable generator due to exogenous input source (solar energy). In a PV system, solar panels convert sunlight intro electrical energy with the help of semiconducting materials that exhibit photovoltaic effects. Figure 8 presents one of the largest Longyangxia Dam Solar Park with 850 MW capacity.

The output power of PV system, P_t^s, is estimated by (I.1) [71], which takes into account factors of solar irradiance, G_t, and ambient temperature, T_t.

$$P_t^s = N^s P_{STC}^s \left[\frac{G_t}{G_{STC}} (1 - \gamma (T_{c,t} - T_{STC})) \right], \; t \in \mathcal{T} \tag{I.1}$$

where P_{STC}^s, G_{STC}, and T_{STC}, are output power of PV array, solar irradiance, and ambient temperature at standard test conditions, respectively. N^s represents total number of PV arrays connected in series and parallel combinations. γ defines the temperature-dependent degradation coefficient of a PV panel. PV cell temperature is denoted by $T_{c,t}$, and it is computed as:

$$T_{c,t} = T_t + \frac{G_t}{G_{NOCT}} (NOCT - 20), \quad t \in \mathcal{T} \tag{I.2}$$

where G_{NOCT} is solar irradiance at nominal operating cell temperature.

FIGURE 8: Longyangxia Dam solar park.

For maximum power extraction from PV panels, maximum power point tracking (MPPT) methods are used [72, 73]. Normally, PV panel voltage and current are increased by connecting solar cells in series and parallel, respectively. Subsequently, PV panels are also connected in series and parallel combinations for having required power production from PV system. However, PV systems are not able to meet load demand at all times due to the intermittent nature of solar energy and non-availability of sunlight at nights. Hence, additional DERs need to be installed with PV systems.

2.2 Wind Turbine

WT converts wind power into mechanical power using aerodynamics, which is fed to generator for conversion into electrical power. The modern WTs are generally composed of rotor, generator, gearbox, power transformer, and power electronic converters. Figure 9 shows the San Gorgonio Pass wind farm of 615 MW capacity and it is located in California in United States. The largest Gansu wind farm in China is expected to reach 20 GW capacity by 2020. WTs are categorized into two main types: horizontal-axis and vertical-axis WTs. However, horizontal axis WTs have been widely manufactured and installed at large scale. The electric power produced by wind turbine is proportional to cubic power of wind speed. MPPT methods are used for extracting maximum electric power from WTs [74]. The WT output power, P_t^w, can be modeled as:

$$P_t^w = \begin{cases} 0, & \mathrm{v}_t < \mathrm{v}_{ci} \\ \frac{1}{2}\rho_{air} C_{pw} A_w \mathrm{v}_t^3, & \mathrm{v}_{ci} \leq \mathrm{v}_t < \mathrm{v}_r \\ \frac{1}{2}\rho_{air} C_{pw} A_w \mathrm{v}_r^3, & \mathrm{v}_r \leq \mathrm{v}_t \leq \mathrm{v}_{co} \\ 0, & \mathrm{v}_t > \mathrm{v}_{co} \end{cases} \quad t \in \mathcal{T} \tag{I.3}$$

where ρ_{air} is air density. A_w and C_{pw} are WT swept area and power coefficient, respectively.

2.3 Tidal Turbine

TT technology is still in developing phase and mostly applications are currently research-based [75]. TT converts the kinetic energy of tidal currents into mechanical energy through a turbine, which is then fed to generator for producing electrical energy. However, tidal energy has promising potential due to more accurate predictability of tidal currents and high water density. An example of pre-commercial TT is the Sabella project in France [76], as shown in Fig. 10, and the biggest TT is around 2 MW [77]. MPPT methods are also used for TTs to produce maximum power [78]. The TT output power of wind turbine, P_t^m, can be modeled as:

FIGURE 9: San Gorgonio Pass wind farm [5].

$$P_{a,t}^{m} = \begin{cases} 0, & \upsilon_t < \upsilon_{ci} \\ \frac{1}{2}\rho_m C_{pm} A_m \upsilon_t^3, & \upsilon_{ci} \leq \upsilon_t < \upsilon_r \\ \frac{1}{2}\rho_m C_{pm} \wp^m A_m \upsilon_r^3, & \upsilon_r \leq \upsilon_t \leq \upsilon_{co} \\ 0, & \upsilon_t > \upsilon_{co} \end{cases} \quad t \in \mathcal{T} \tag{I.4}$$

where ρ_m is water density. υ_t represents tidal current speed. A_m and C_{pm} are TT swept area and power coefficient, respectively.

FIGURE 10: Sabella tidal turbine [6].

TTs have very high potential in the studied site due to the presence of high tidal currents [79]. However, TT faces many challenges, such as underwater maintenance issue and biofouling [80]. Biofouling may cause disturbances in TT operation and even stop it from working. The cost of TT underwater deployment and maintenance is also very high [81]. In view of high tidal energy potential at Ouessant island in France, TT is considered as a potential RES in this study.

2.4 Energy Storage System

Energy storage is achieved by converting electrical energy into other forms of energy, like potential energy and chemical energy. The electric power produced by RESs, such as tidal, wind, and solar, are intermittent in nature, highly dependent on climate, and are the cause of significant fluctuations in MG system. For reliable and stable operation, ESS can be a viable option for compensating these fluctuations [82]. ESS can store excess energy of DERs for future use when DERs alone are not able to meet load demand. The most common ESSs are briefly explained as below.

Battery: Battery converts electrical energy into chemical energy during charging, which is reversed in case of discharging. The depth of discharge (DOD) defines amount of energy capacity consumed and state of charge (SOC) defines amount of energy capacity left [83]. The battery cycles usage have adverse impacts on battery lifetime. For better battery lifetime, it is preferred to use a more narrow interval of SOC [84]. Batteries are divided into two main types: primary and secondary batteries. Primary batteries are not rechargeable, while secondary batteries can recharge themselves. Batteries are also divided in terms of electrodes and electrolye materials, like Nickel-Cadmium, Lead-Acid, and Li-ion batteries [83].

Flywheel: These are electromechanical storage system that store energy in the form of a kinetic energy using a heavy rotating mass. They are typically used for compensating the fluctuations of combustion engines and residential system [85]. Flywheels are also used as an uninterruptible power supply for critical loads [86,87].

Superconducting Magnetic Energy Storage: This ESS type stores electricity in the magnetic field of the doughnut-shaped coil of a superconducting wire. It offers many benefits such as fast charging (discharging) and high efficiency. However, it is very expensive, and the health risks of a very strong magnetic field are yet to be studied in detail [88].

Compressed Air Energy Storage (CAES): Such ESS compresses the air into an underground reservoir by using the electricity in off-peak times. When needed, air is heated and passed through the turbine to generate electricity. This technology is mostly used for long-range energy storage at the utility level [89].

Pumped Hydro Energy Storage: This system is similar to compressed air energy storage, but instead of compressed air, they pump water from lower ground to a reservoir at higher altitude using the off-peak electricity. During peak times, water is released to spin the hydro generator. However, it is very expensive and limited to potential sites only [90].

ESSs can be classified by considering whether they will be used in short or long term applications. Short-term applications require storage technologies that can supply a large power, but only for a time up to few seconds or minutes. Flywheels and superconducting magnetic energy storage are best options for short-term applications. On the other hand, long-term storage requirements are related to the support of distributed energy generation during several minutes or even hours. These storage technologies are used for uninterruptible power supply or energy management needs, which are associated to high-energy applications. Batteries, pumped hydro and compressed air energy storage are more suited for such applications. However, pumped hydro and compressed air energy storage are very expensive. As batteries are easily transportable and quiet, they are suitable for installation in remote areas and near the load ends [91]. Furthermore, for the MGs energy management, which require high-energy storage technologies for low/medium scale electrical networks, the most used ESSs are based on batteries [26]. Indeed, the most used type of battery for MGs applications is Li-ion battery as it is very mature technology with high efficiency, high energy density, and better cyclelife with competitive cost. Hence, Li-ion battery is used for MG system in this thesis.

2.5 Loads

In an MG, electrical loads are divided into two main categories: critical and non-critical [26, 92, 93]. Critical loads require a high degree of reliability to continuously supply the required energy. While, non-critical loads have the possibility to be shed during emergency mode to balance the system [94, 95]. Additionally, there are some of these non-critical loads that also can be shifted to different time during the day according to the constraints such as power rating and working duration.

In MG energy management problem, the simultaneous generation, storage, and demand management is a challenge that enables more flexibility to the operation and, therefore provides better results [96].

3 Demand Response

Demand Side Management is realized through DR, which is a mechanism for minimizing the load when power supply is limited [97]. The Department of Energy defines DR as [7], "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized".

Figure 11 shows the main concept of DR, which simply means taking proper actions to reduce the electricity consumption during high price hours. In this figure, when the price is high, the demand is reduced from Q to Q_{DR} to reduce the price from P to P_{DR}. In most markets, as a result of the economy of scale, in the long term, when the demand increases the price goes down, but, in the short term, an increase in demand combined with a shortage of supply results in an increase in price. In the electricity market, because of the limitations on the generation side, transmission network and distribution grids, the price usually increases or even spikes the nominal price many times with an increase in demand.

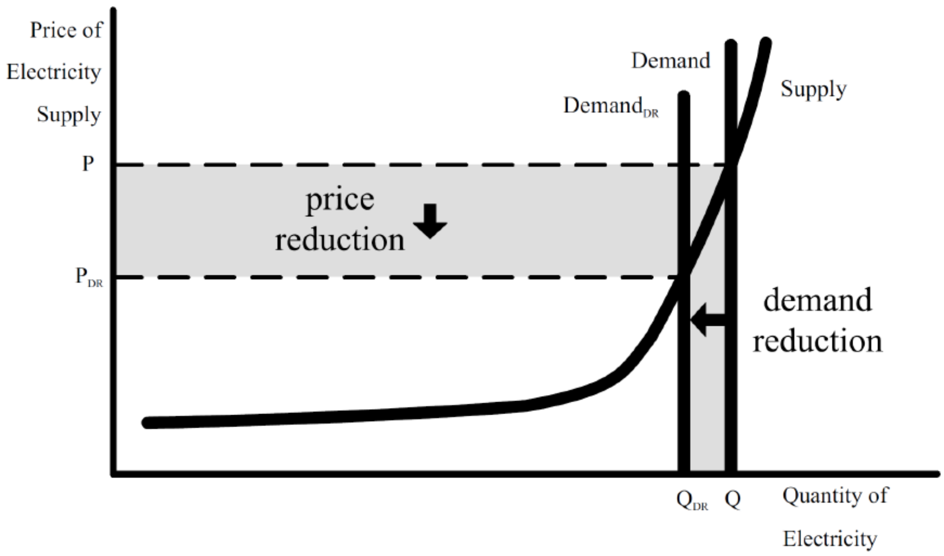


FIGURE 11: DR concept [7].

DR is divided into two main types in terms of motivation: incentive-based and price-based DR.

3.1 Incentive-based DR

In incentive-based DR, consumers are given offers of payment to reduce their consumption when required by MG system. In this type of DR, consumers receive incentives to reduce their demand for ensuring system stability and reliability. Consumers can volunteer or be mandated to participate in such programmes. Once they have committed to the DR programme, they could be subject to penalties if they do not follow their contract [98].

Various approaches have been introduced in this category. In direct load control approach, the utility company or MG operator has remote access to some of the appliances and loads of the consumer to control them when required for system balancing [62, 99]. In another approach called interruptible/curtailable load approach, consumers agree to reduce their load by a certain amount through decreasing or shutting down their interruptible/curtailable loads. Consumer, committed in this approach, receives a discount or bill credit in return [100].

Demand biding, also called buyback, is another approach for incentive-based DR programmes, where large consumers usually participate and bid on their load reduction in the electricity market during peak hours when the price is at its peak [101]. In another approach, called Emergency Demand Reduction, consumers commit to reduce/shift their load in reaction to emergency instances in real-time. Such approach is mostly used to overcome the overloading of transmission and distribution network and can be considered as an ancillary service to the grid [102].

3.2 Price-based DR

Electricity, like many other commodities, has problem of supply demand imbalance. Hence, electricity price may vary, and even rises several times of its average price during peak hours. In this regard, different pricing models have been introduced to induce consumers to shift their consumptions to manage peak load and shape the demand. The most common pricing schemes are discussed as follows:

Flat Rate: Traditionally, electricity was delivered at a flat constant price for all times and for all amounts of energy. In this scheme, the only way to reduce the electricity bill is to reduce the total amount of energy used. This scheme does not truly represent the cost of electricity and does not give any incentive to customers to shift their loads from peak hours. The cost charged to users is the total cost of electricity provision (in long term) divided by the total demand of the grid.

Time of Use: It is a pricing scheme in which the time is divided into periods with different but fixed prices for electricity. Usually, the hours of the days are divided into two or three stages. Three-stage scheme consists of off-peak, mid-peak, and on-peak hours, while the two-stage scheme has on-peak and off-peak times. The stages division is achieved on the basis of the demand profile of the grid. The electricity price increases from off-peak to on-peak hours.

Critical Peak Pricing: Critical Peak Pricing is similar to time of use pricing except that when grid reliability is at critical stage, the price is increased to involve consumers to reduce their demands [103].

Real-time Pricing: Real-Time Pricing, also called dynamic pricing, is when electricity price varies at each time slots based on real price of electricity provisioning [104]. The prices are forwarded to consumers beforehand, for example, a day-ahead or an hour-ahead.

4 Microgrid Energy Management

4.1 Hierarchical Framework for Microgrid Operation

A single control and management system would not be able to make all the necessary decisions to implement a complex electric power system. Therefore, functions required for MG operation have been established under hierarchical dependence [105, 106]. In this way, the decision layers at a higher level of the hierarchy define the tasks and coordinate the lower-level layers.

This architecture also increases the overall system reliability so that it can survive in case of disconnection or damage of one of the control units. It is required to make system, as a whole, less sensitive to disturbance inputs if local units can respond more quickly than a more remote central decision unit [107].

The hierarchical structure for the MG operation and its analogy with classical management concepts can be adapted from [108], as shown in Fig. 12. Longer term planning levels, related to strategic level, have been considered in the power system operation, addressing issues related to maintenance, expansion planning, etc., as reviewed in [109]. These longterm decision making levels are not included in the hierarchy framework considered in this thesis, since they are out of the main scope.

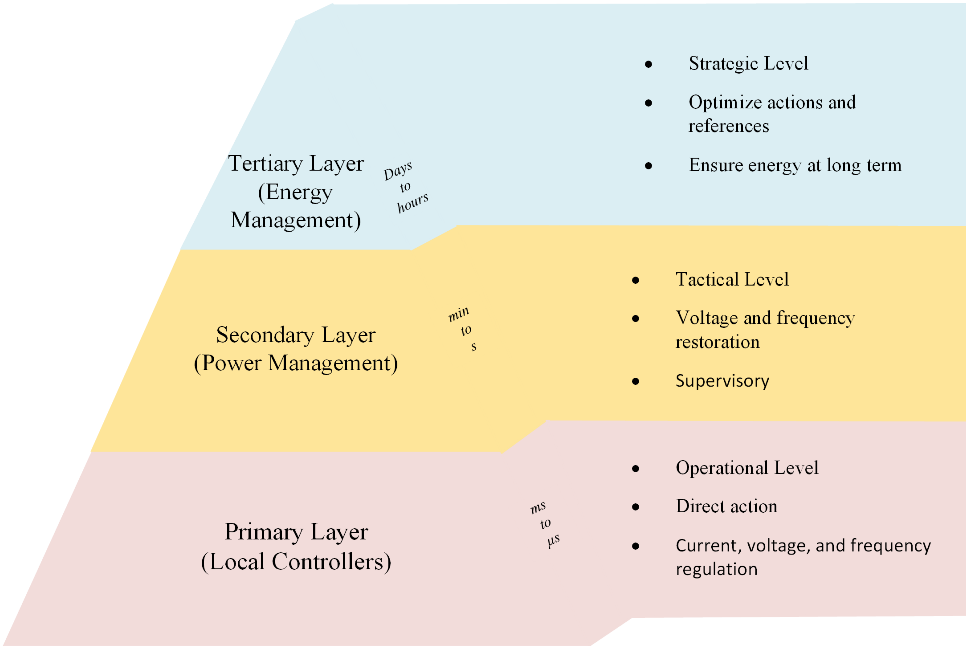


FIGURE 12: MG hierarchical management and control.

It is clear from Fig. 12 that time-scales become shorter moving towards lower layers in the hierarchy, e.g. LCs typically response between micro to milliseconds. The LCs are related to the operational level of management, an execution level, that automatically operates according to the decisions made in upper level. The LCs control loops are responsible for the voltage and current regulation of each unit [65].

Secondary layer is related to power management level that works for horizons between seconds to minutes. This hierarchical layer makes tactical decisions coordinating the operation of the controllers, mainly focuses on the feasibility of the system. It acts on the instantaneous operational conditions toward certain desired parameters such as voltage, current, power, and frequency. The power management strategies include voltage and frequency restoration, and real-time power dispatching among different MG power sources [110].

Tertiary layer refers to strategic energy management level. In this layer, energy management executes decision-making with action times of hours to days. This management layer corresponds to the strategy level which plans the operational scheduling of the microgrid in an optimal way considering the available resources and the operational cost of the units. Energy managements are mainly focused on economics, considering factors like fuel costs, capital costs, maintenance costs, mission profiles, lifetimes, etc [4, 111]. Furthermore, MG-EMS should be able to gather measurement data, as well as historic and forecasting data and thus determine and transfer to the MG optimized references and define control actions to the MG system components.

4.2 Microgrid Energy Management System

The International Electrotechnical Commission in the standard IEC 61970, related to EMS application program interface in power systems management, defines an EMS as "a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities so as to assure adequate security of energy supply at minimum cost" [112].

An MG EMS, also having these same features, usually consists of modules to perform decision making strategies. Modules of DERs/load forecasting, Human Machine Interfaces, and supervisory, control and data acquisition among others ensure the efficient implementation of EMS decision making strategies by sending optimal decisions to each generation, storage, and load units [113]. An MG EMS performs variety of functions as monitoring, analyzing, and forecasting of power generation of RESs, load consumption, energy market prices, ancillary market prices, and meteorological factors as given by Fig. 13. These functions help EMS optimizing MG operation, while satisfying the technical constraints. In this thesis, energy management optimization of MG system is the main focus.

In this way, MG EMS operates and coordinates energy components as DERs, loads, power converters and grid components in order to provide reliable, sustainable, and environmentally friendly energy in an optimal way [114, 115]. It assigns the set points for distributed generation units and commands control for the controllable loads in order to balance the system based on the operating conditions of MG components, some prediction data and status of the system [92]. When the MG is in grid-connected mode, the MG EMS can be oriented to operate bundled in a DR program, promote self-consumption or participate in the electricity market. Meanwhile, in the island mode an MG EMS may be called on to perform unit commitment, economic dispatch, and load control.

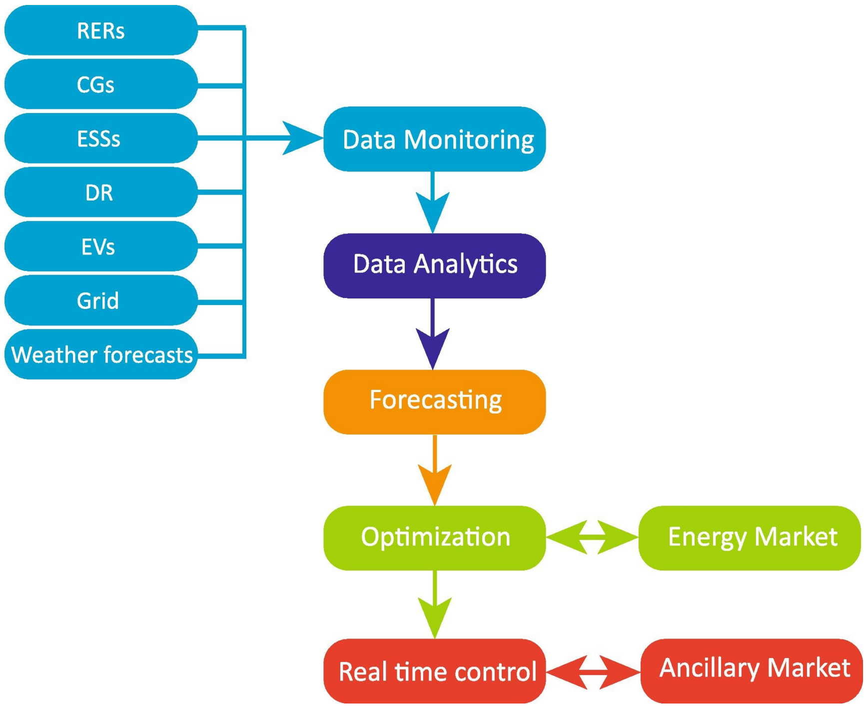


FIGURE 13: MG EMS functions [4].

The supervisory control architecture of MG EMS can be divided into two types, namely, centralized and decentralized EMSs. In centralized control, the EMS collects all information and optimizes decision variables against defined objective. These optimal set points are then sent to DERs LCs for necessary actions. In the decentralized control approach, the local controllers of the DERs interact with each other and with a central controller to operate MG, and this process continues until global and local objectives are achieved. Decentralized approaches are preferred in wide area applications where communication links are not always suitable [116]. For islanded MGs, a high level of coordination is required to balance the demand and supply, which can be better achieved with a centralized approach [96, 117]. This thesis focuses only on centralized MG EMS as it involves applications of neighbourhood area grid-connected MGs and remote islanded MGs.

With the integration of DERs and DR, the MG EMS strategies have been diversified from unit commitment and economic dispatch, as presented in Fig. 14. The other strategies are DERs and controllable loads scheduling, system losses and outages minimization, RESs intermittency management, and sustainable, reliable, and economical operation of MG.

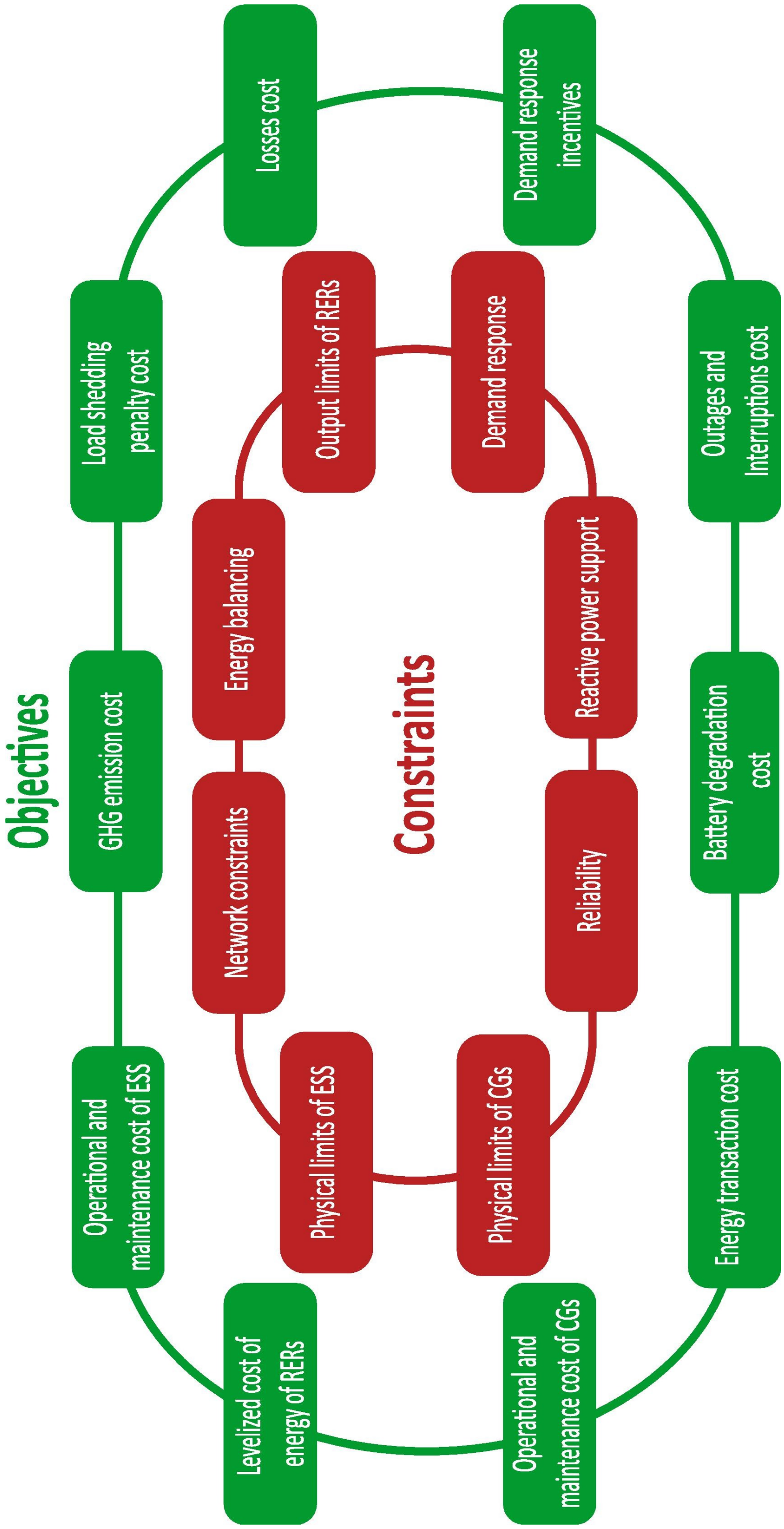


FIGURE 14: MG energy management strategies [4].

5 Optimization Problem

A mathematical optimization problem comprises an objective function to be minimized subject to a set of constraints. The optimization solution determines the values of the variables which minimize the objective function. The constraints ensure that the values of the variables are within the specified limits and satisfy the defined conditions. Depending on the optimization model, an appropriate optimization algorithm is needed [118].

5.1 Linear Programming

A Linear Programming (LP) model consist of the minimization of a linear objective function subjected to a set of linear equality and inequality constraints [118]]. It can be represented in general form as follows:

$$\begin{aligned} \min \quad & C^T z \\ \text{s. t.} \quad & Gz \leq a \\ & Hz = b \\ & z \in \mathcal{Z} \end{aligned} \tag{I.5}$$

where z is an n-dimensional decision vector in feasible region $\mathcal{Z}$, while G and H are $m \times n$ and $p \times n$ parameter matrices, respectively. C is a n-dimensional parameter vector, and a and b are m and p-dimensional parameter vectors, respectively. This model creates a feasible region which comprises the set of all points that satisfy all the constraints. An optimal solution of the LP problem is a point in the feasible region with the smallest value of the objective function.

5.2 Mixed-Integer Linear Programming

In linear programming models, all the decision variables are continuous or, in other words, the values of the variables are real numbers, and, when any of the variables is an integer, it is transformed into as a mixed-integer linear programming problem, which is generally modeled as [119]:

$$\begin{aligned} \min \quad & C^T z \\ \text{s. t.} \quad & Gz \leq a \\ & Hz = 0 \\ & z_i \in \mathcal{Z}, \qquad i = 1, 2, ..., l \\ & z_j \in \{0, 1\}, \quad j = 1, 2, ..., k \end{aligned} \tag{I.6}$$

where z represents n-dimensional decision variables, containing both real, z_i and binary, z_j decision variables such that $n = l + k$. The constraints define the feasible region in which the optimal solution of mix-integer linear programming problem must have to lie.

5.3 Non-Linear Programming

Optimization problems comprising a non-linear objective function and/or constraints are referred to as Non-Linear Programming problems [53], which can be formulated in general form as follows:

$$\begin{aligned} \min \quad & F(z) \\ \text{s. t.} \quad & G(z) \leq 0 \\ & H(z) = 0 \\ & z \in \mathcal{Z} \end{aligned} \tag{I.7}$$

where F, G, and H are linear or non-linear functions, and z represents the decision variables in feasible region $\mathcal{Z}$. Non-linear programming problems are more difficult to solve than linear programming ones.

5.4 Mixed-Integer Non-Linear Programming

Many optimization problems comprise discrete decisions and non-linear constraints. Such models, referred to as mixed-integer non-linear programming problems, include discrete as well as continuous decision variables, and a non-linear objective function and/or non-linear constraints. The mixed-integer non-linear programming can be represented as follows:

$$
\begin{aligned}
\min \quad & \sum_{i=1}^{l}\sum_{j=1}^{k} F(z_i, z_j) \\
\text{s. t.} \quad & G(z_i, z_j) \le 0 \quad \forall\, i, j \\
& z_i \in \mathcal{Z}, \qquad\quad i = 1, 2, ..., l \\
& z_j \in \{0, 1\}, \quad j = 1, 2, ..., k
\end{aligned} \tag{I.8}
$$

where, F and G are linear or non-linear functions. z_i and z_j are continuous and integer decision variables, respectively. $\mathcal{Z}$ is a bounded polyhedral set. Large scale mixed integer non-linear programming problems are typically difficult to solve because of the expansive search tree; in such cases, a good solution may be sufficient, as opposed to finding an optimal solution, given the computation time restrictions [120].

5.5 General Microgrid Energy Management Optimization Problem

In this thesis, the energy management is implemented by scheduling MG components. The schedules are generated to meet an objective. The main objective is to minimize the MG operating costs, although other objectives might be added as well. To achieve the objective, an optimisation problem should be solved. An optimisation problem can be developed based on the model of DERs, battery and DR. The general optimisation problem can be presented as follows:

$$
\begin{aligned}
\min \quad & \sum_{t \in \mathcal{T}} OC(MG)_t \\
\text{s. t.} \quad & \text{DERs } Constraints \\
& \text{ESS } Constraints \\
& \text{DR } Constraints \\
& \text{Balancing } Constraint
\end{aligned} \tag{I.9}
$$

In this optimisation problem, OC(MG) represents overall operating cost of MG systems over scheduling horizon, $\mathcal{T}$. The decision variables can be distributed generators, battery, DR, and load shedding powers.

The following steps have been taken for solving microgrid energy management optimization problem:

- The objectives of MG energy management mechanism are defined.
- The MG components and their characteristics and requirements are identified.
- The characteristics and requirements of MG components are mathematically modeled.
- The models are incorporated into the optimisation problem.
- The developed optimisation problem is solved.

6 Transactive Energy

As the DERs penetration increases in electric power systems, transactive energy is becoming one of the most revolutionary and efficient strategies to the future SG. Transactive energy combines information and energy in order to enable transactions that implement highly coordinated self-optimization. [121]. Transactive energy is defined by the GridWise Architecture Council [122] as "a system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter."

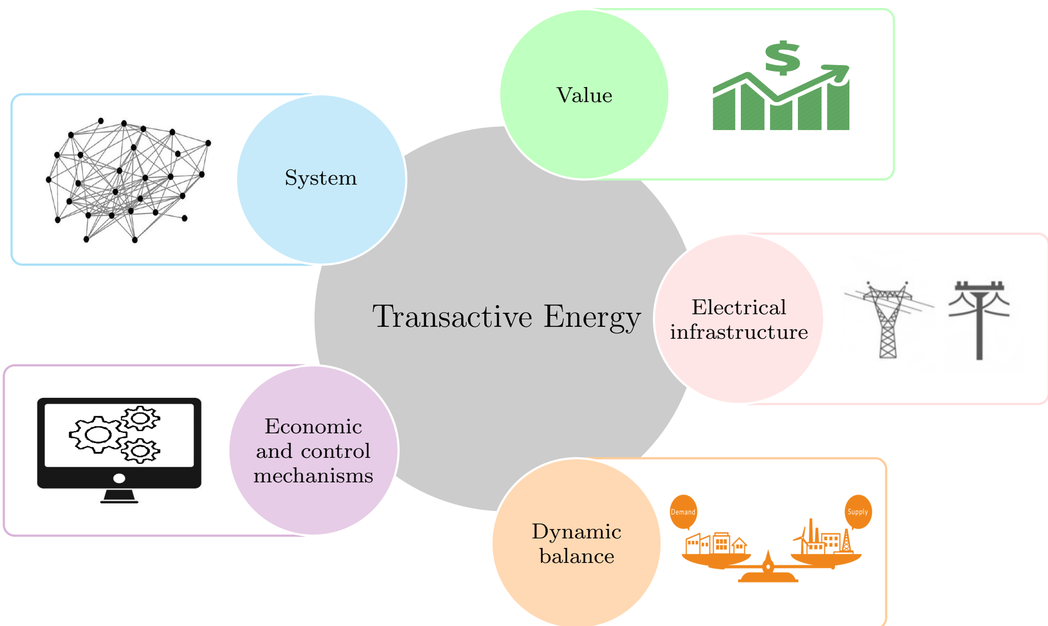


FIGURE 15: Transactive energy concept [8].

Figure 15 presents transactive energy concept, which illustrates that the transactive energy exploits potentials of information, control, automation, and economic tools for bidirectional energy exchange on electricity market price that satisfy system operational constraints. The transactive energy approach offers electric energy producers and consumers a way to match energy supply and energy demand more closely and to balance them. If energy suppliers and users can reach an agreement on the equilibrium value of electricity price, then both producers and users can carry out the transaction at that price.

Decentralized transactive energy system cannot be realized without integration of distributed ledger technology (DLT) like blockchain. DLT introduces distributed ledgers in transactive energy system (TES) that capture data about identities, contracts, pricing, transactions and payments of all TES players. DLT also provides benefits of data immutability and transpacterancy, which enable TES players to trade with each other in local energy markets without necessity of knowing or trusting each others, or the need of a central intermediary. Hence, DLT can realize a decentralized market environment within a TES [123].

There have been a few transactive energy pilot demonstration projects in the research and industry, and hence its definitions are kept broad enough to accommodate diverse smart assets, loads, consumers, prosumers and communication technologies. Advanced Metering Infrastructure (AMI) that facilitates bidirectional communication among transmission and distribution system operators as well as end-users has been an instrumental in the TES pilot demonstrations. Some of these small scale TES projects are Brooklyn MG [124], power matching city [125], and Allgau MG [126]. In the context of transactive energy, the main focus of this thesis is to propose a conceptual transactive energy system framework that can be adapted as a standard for implementing real transactive MG and SG systems.

7 Thesis Contributions

This thesis addresses the modeling, design and implementation of EMS to economically optimize the operation of small scale MGs based on renewable energy sources and battery-based energy storage systems, especially for remote areas. The main motivation is to reduce the gap between optimization theory and MGs energy management under different scenarios. This thesis is mainly focused on achieving and implementing energy management optimization models for MGs with adaptable functional algorithms and structures that take into account the relevant physical and regulatory constraints and can be expanded in the case of having more resources of similar characteristics.

The MG components that have been considered are distributed generators, energy storage systems, loads and the connection to the main grid. Defined optimization models simultaneously optimize the use of all the controllable resources at the operation level. Related to RESs, many previous works have modeled them as non-dispatchable sources. However, recent advances in power electronics enable to perform power curtailment of these resources. In this regards, it is established and modeled that the energy available by the RESs can be curtailed or set to zero.

Besides, Li-ion batteries have been chosen as energy storage systems due to their high energy density, efficiency, and cyclelife. Accordingly, a practical battery degradation cost model has been developed for their proper operation, which includes temperature and depth of discharge dependent mathematical regression models. First regression model accounts the temperature affects on battery capacity and cyclelife performance, and the latter include depth of discharge affects on battery capacity and cyclelife. These regression models and battery investment, operational, and residual cost factors were used for developing a battery degradation cost model that was integrated in energy management optimization model for representing a realistic battery levelized operating cost. Finally, incentive-based DR is considered for encouraging customers to participate in demand-side management that eventually helps in reliable MG operation with minimum operating cost. The DR potential is also extensively analyzed by considering different shiftable durations and power ratings of aggregated controllable loads with respect to total load.

Therefore, this thesis makes original contributions to the knowledge in the fields of MG EMS development, especially for remote areas, by applying optimal decision-making approaches. The most important contributions of this thesis are highlighted below:

- State of the art on MG EMS is performed. The EMS objectives, constraints and communication infrastructure are explored. The solution methods for MG EMS implementation are studied.

- Economic objectives of DC MG are achieved by modeling an optimal EMS for its operational scheduling. In this EMS, a practical battery degradation cost model is developed, which includes the effects of ambient temperature and depth of discharge on battery performance. An incentive-based demand response model is also proposed for effective responsive load shifting and encouraging customers participation.

- An optimal EMS is developed for operation and control of islanded DC MG, which consists of only RESs and ESSs. The developed EMS contains two stages: optimization and implementation. In optimization stage, the objective is to maximize the utilization of RESs while also maintaining battery cyclelife performance. The implementation stage updates decision strategies of optimization stage, which are then sent to LCs only once to utilize low bandwidth and avoid security threats.

- An integer-free relaxed convex EMS model is developed for islanded AC MG. Battery, demand response, and power flow constraints are relaxed into convex constraints. The economic and environmental objectives are achieved, while satisfying technical constraints.The developed EMS model greatly reduces the computational time.

- With the increasing penetration of residential customers in terms of local generation and demand response, which are also called prosumers, the concept of transactive energy is emerging in the electric power system.. Microgrids are currently best solutions for integrating such prosumers in electric power system. However, data integrity and transparency of customers need DLT to be integrated in electric power system. In this regard, TESs need to be studied and analyzed at MG and SG levels. Therefore, state of art on MG TES is performed. The distributed ledger technologies, blockhcain, directed acyclic graph, holochain, hashgraph, and tempo, and local energy markets, peer-to-peer and community' are analyzed and compared. A seven layer conceptual architecture is proposed that defines the standardization and function for implmentation of an MG TES, and its effective is also studied and analyzed with a practical case study of Brooklyn microgrid.

The generic microgrid architecture, energy management optimization models, and laboratory-scale experimental setup demonstrated in this thesis can promote further exploration of smart management of microgrid and its engineering application.

8 Thesis Outline

The contents of this thesis are structured in seven main chapters with brief introduction presented at the end of this chapter. Each chapter deals with different subjects and aspects, as follow:

- Chapter 1 contains manuscript introduction. The need of RESs, ESSs, and DR is explained for realization of a sustainable and reliable power system. MG components, types, and EMS concept are presented and thesis contributions are discussed.

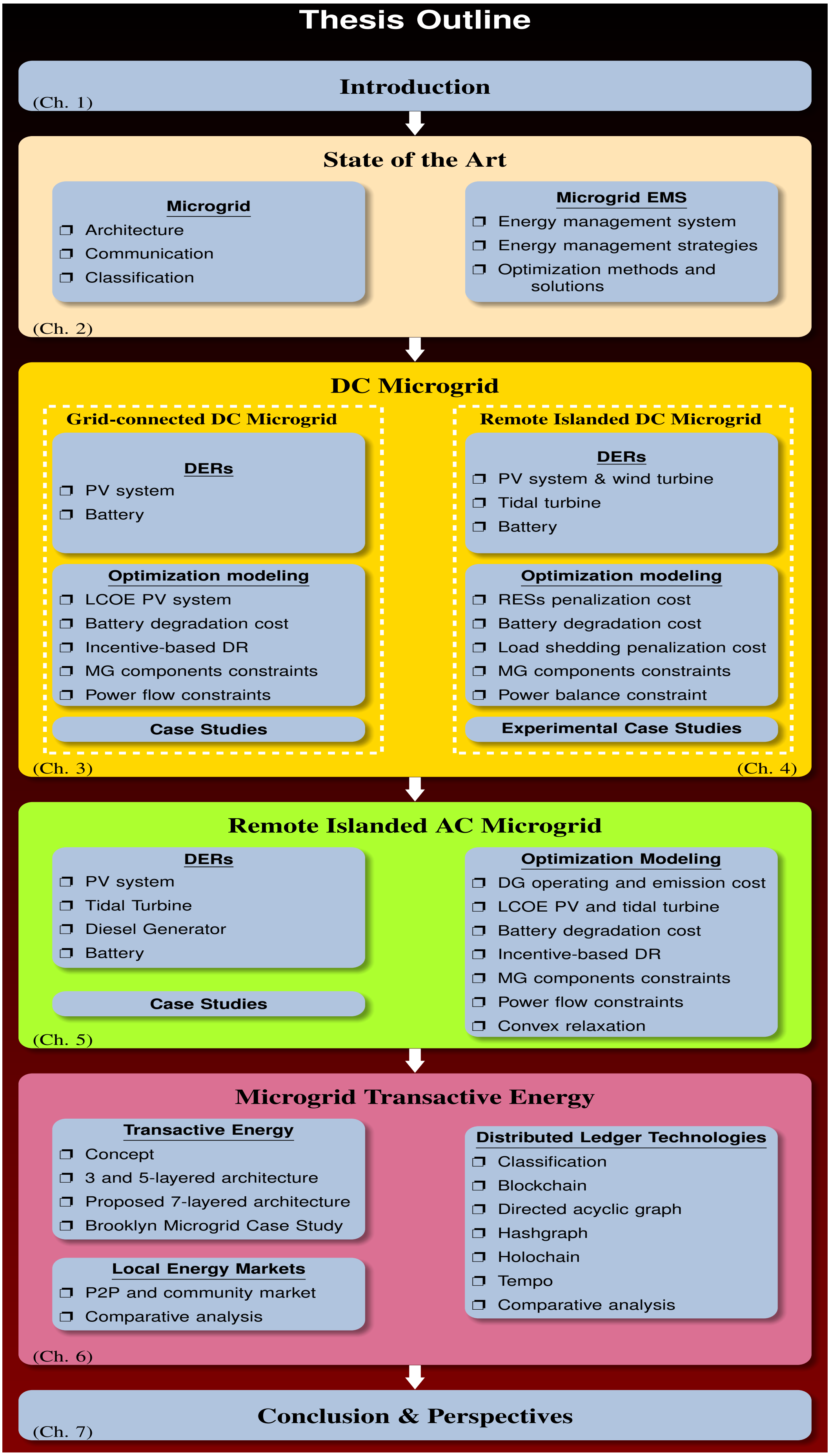
- In chapter 2, MG architecture is presented. State of art on MG-EMS is discussed in detail. A literature review on MG EMS and sustainable energy sources of MG system is also discussed. A comparative analysis of communication technologies for MG operation is also presented. The optimization methods and objectives of MG EMS are presented and critically compared in details. The real-time applications of MG EMSs are also highlighted. Finally, the demerits of MG EMSs are presented.

- In chapter 3, an optimal EMS is developed for a grid-connected DC MG. DC MG consists of a PV system and Li-ion battery. A novel Li-ion battery degradation cost model is developed that considers effects of temperature and depth of discharge and incentive-based demand response models are developed. The levelized cost of energy of PV system is also computed. The developed EMS achieves economic objectives for optimal operation of DC MG.

- In chapter 4, islanded DC MG operation is optimized using a two-stage EMS. The two-stage EMS consists of optimization and implementation stages. The optimization stage is responsible for determining optimal decisions considering objectives of maximizing utilization of RESs and minimizing battery degradation cost and load shedding. These decisions are updated by implementation stage for updating decision strategies according to generation demand comparison, and they are then sent only once to LCs for necessary actions. The developed EMS is also experimentally verified to prove its effectiveness.

- In chapter 5, an integer-free relaxed convex EMS model is developed for islanded AC MG. The developed convex EMS greatly reduces the computational time with very low optimality gap. The EMS model includes economic and environmental objectives and determines optimal decision strategies, while satisfying system constraints.

- In chapter 6, TE concept in MG system is introduced. A detailed seven layer architecture for MG TES realization is proposed and practical Brooklyn MG is taken as a case study for its validity. Various popular DLTs, blockchain, directed acyclic graph, holochain, hashgraph, and tempo, are discussed in detail. These DLTs are also compared in terms of key parameters, in terms of scalability, mining, security, technology maturity, latency, energy consumption, and popularity among others. Moreover, local energy market types and their comparison are also presented in the framework of MG transcative operation. Finally, recommendations are presented by highlighting future research and technological gaps in MG TES practical implementation.
- In chapter 7, a summary of this thesis is provided with future work.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Chapter II

Paper I

Microgrids energy management systems: A critical review on methods, solutions, and prospects

The microgrid concept is introduced to have a self-sustained system consisting of distributed energy resources that can operate in an islanded mode during grid failures. In a microgrid system, the energy management system is essential for optimal use of the distributed renewable energy sources, conventional generation sources, energy storage systems, and demand response in intelligent, secure, reliable, and coordinated ways. Microgrid energy management system is a computer that contains set of application and support services for achieving its efficient operation that ensures reliable power supply to local demands. An energy management system normally contains data processing, data analysis, forecasting, and scheduling modules to achieve systematic operation of microgrid systems. In terms of scheduling techniques and objective used for microgrid energy management systems, numerous objectives and solution methods are discussed. Objectives can vary depending upon the type of distributed energy resources being used and they can be based on levelized cost of renewable energy sources, battery degradation cost, operation and maintenance cost of energy storage systems, operating and emission costs of conventional generation sources, load shedding penalty cost, reactive power support, demand response pricing among others. The solution methods can be rule-based method, classical optimization methods such as linear and non-linear programming methods, metaheuristic methods such as genetic alogrithm, particle swarm optimization, and tabu search, artificial intelligence methods such as neural network and agent-based methods, and hybrid methods. The selection of a solution method depends on various factors such as choice of optimal or non-optimal strategies, convergence criterion, and computational time complexity. Hence a comparative and critical analysis on decision making strategies and their

solution methods for microgrid energy management systems are extensively discussed. A comparative graphical analysis on communication technologies is also discussed for efficient implementation of microgrid energy management systems. Finally, insights into future directions and real world energy management system applications are discussed.

The paper has been published in the Applied Energy, vol. 222, pp. 1033–1055, Jul 2018.

Chapter III

Paper II

Energy management system for an islanded microgrid with convex relaxation

Nowadays, remote rural areas and islands meet their electric power demand using conventional generation sources, mainly diesel generators. However, the diesel generators involve the expensive cost of fuel transport to these remote areas. Moreover, diesel generators are also the main cause of greenhouse gas emissions, thus increasing environmental pollution and global warming. In this regard, integration of renewable energy sources and energy storage systems are needed to overcome adverse climatic effects caused by conventional generation sources and also meet local electric power demand. The advancements in renewable generation sources and battery storage systems pave the way for microgrids. Microgrids are becoming a viable solution for meeting local electric power demand in remote area applications, such as oceanic islands and remote rural areas. In this paper, an islanded microgrid is considered as a case study for Ouessant island in Brittany region in France. The islanded microgrid contains tidal turbine and PV system as renewable energy sources, diesel generator as a conventional generation source, and Li-ion battery as an energy storage system. The economic operation of the microgrid is achieved by including battery degradation cost, levelized costs of energy of PV system and tidal turbine, operating and emission costs of diesel generator, demand response incentive cost, and network constraints. The developed model leads to a non-convex mixed integer nonlinear programming problem, which unfortunately can converge to a local optimum solution. The battery, demand response, and power flow constraints have therefore been relaxed. Hence, the original non-convex energy management model is converted to a convex second–order cone model to achieve an optimal decision strategy for islanded microgrid operation with a global or near-global solution. Numerical simulations are carried out to prove the effectiveness of

the proposed strategy in reducing the operating and emission costs of the islanded microgrid. It is shown that the developed convex EMS formulation has an optimality gap of less than 1% with reduced computational cost.

The paper has been published in the IEEE Transactions on Industry Applications, vol. 55, no. 6, pp. 7175–7185, Nov 2019.

Chapter IV

Paper III

Optimal operational planning of scalable DC microgrid with demand response, islanding, and battery degradation cost considerations

DC microgrids have gained attention of both researchers and industrialists due to the advantages of technology maturity of DC renewable generation resources, increasing integration of DC loads in distribution power system, and advancements in power electronic devices. Moreover, DC microgrids also do not suffer from the problems of reactive power and frequency issues. In this regard, a grid-connected DC microgrid system is considered, which consists of PV system, Li-ion battery, and demand responsive load. The optimal non-linear energy management model is developed for DC microgrid scheduling, whose objective is to minimize the overall operating cost. The objective function includes levelized cost of energy of PV system, battery degradation cost, demand response incentive cost, grid energy trading cost, and load shedding cost. For cost modeling of Li-ion battery, a practical battery degradation cost model is developed considering real data of its characteristics dependence on temperature and depth of discharge. The regression model are developed for modeling temperature and depth of discharge-dependent aging behaviors of Li-ion battery. These regression models are then used for battery degradation cost modeling of Li-ion battery, which also includes its investment cost, operation and maintenance costs, and discount rate for its economic cost modeling. DC microgrids can also use demand response incentive for active consumers' participation. Apart from energy price, scheduled islanding responsive demand response incentive is also introduced to encourage customers to shift load during scheduled grid-tie line maintenance. Levelized cost of energy of PV system is calculated for both hot and cold climate regions. Optimal operation of DC microgrid cannot

be achieved without considering nodal voltages and system losses. Hence, network constraints are also included in the proposed model. Extensive numerical simulations are carried out to prove the effectiveness of the proposed approach. The achieved results would aid in DC microgrids adoption planning that would expectedly replace traditional AC grids in the future.

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Chapter V

Paper IV

Energy management system for a hybrid PV-wind-tidal-battery based islanded DC microgrid: Modeling and experimental validation

DC microgrids are becoming integral part of a modern power system due to the growing penetration of DC distributed energy resources and loads, with added advantage of no harmonics and synchronization issues. They can be used for providing electricity to off-grid remote communities, like remote villages, mountains, and islands. In this regard, an islanded DC microgrid is used as a case study for poviding electricity to local load demand at islands. For exploiting tidal energy source, island with tidal energy potential is studied in this chapter. An islanded DC microgrid consists of only renewable energy sources and batteries for achieving environmental sustainability and reducing global warming. Hence, it consists of tidal turbine, PV system, wind turbine, and Li-ion battery. For economic operation of islanded microgrid, a two-stage energy management model is proposed. First stage involves optimal decision making for scheduling the energy sources with the objectives of supply demand balance and maximum RESs utilization. The objective function includes battery degradation cost, energy wastage penalty cost on renewable energy sources, and load shedding cost. While the second stage, referred as adjustment stage, updates scheduled references of first stage on the basis of aggregated day-ahead generation and load profiles in order to avoid massive communication expenditures in real-time. The decision of second stage are forwarded to local controllers, where renewable energy sources local controllers follow the power references and battery local controller is responsible for real-time power balancing and voltage regulation of DC bus of microgrid system. The proposed energy management model has been experimentally validated using four Danfoss converters and dSpace

1006 module. One of the converter is used as a constant power load device to generator real-time load demand profile. The experimental results of high and low renewable generation cases prove the effectiveness of proposed energy management model in achieving optimized operation for islanded DC microgrid.

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Chapter VI

Paper V

Microgrid transactive energy: Architectures, distributed ledger technologies, and market analysis

Distributed generation and prosumers are changing the way the revenue owes in the energy value chain and changing the value chain itself. The increasing integration of prosumers naturally implies the requirement of establishing an electricity trading mechanism for prosumers to trade electricity with each other. In this regard, transactive energy (TE) concept has been proposed in the literature both in microgrid and smart grid perspectives. Prosumer concept and digitilization offer the exciting potential of microgrid transactive energy systems at distribution level for reducing transmission losses, decreasing electric infrastructure expenditure, improving reliability, enhancing local energy use, and minimizing customers' electricity bills. Distributed energy resources, demand response, distributed ledger technologies, and local energy markets are integral parts of transaction energy system for emergence of decentralized smart grid system. Distributed ledger technology solves the problem of third party need or central data-center. It is also more secure as information is shared in a distributed manner. Therefore, this chapter discusses transactive energy concept and proposes seven functional layers architecture for designing transactive energy system. These functional layers are user, network, system operator, market, distributed ledger, communication, and regulation layers. The proposed architecture is compared with practical case study of Brooklyn microgrid for proving its effectiveness in implementation of real transactive enregy systems. Moreover, this chapter explains the widely known distributed ledger technologies (blockchain, directed acyclic graph, hashgraph, holochain, and tempo) alongwith their advantages and challenges. The local energy market concept is presented and critically analyzed for energy trade within a transactive energy system. This paper also reviews the potential and challenges of peer-to-peer and

community-based energy markets. Proposed architecture and analytical perspective of distributed ledger technologies and local energy markets pave the way for advanced research and industrialization of transactive energy systems.

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Chapter VII

Conclusion and Perspectives

1 Conclusions

This thesis proposes energy management systems for the operation of microgrids equipped with battery units and renewable energy sources, applied in different scenarios. Energy storage systems integration provides the microgrid with some flexibility for its management since they allow energy reallocation during a scheduled time horizon according to predefined objectives. In microgrids, battery-based storage systems are the most suitable storage technology to perform this task since they have sufficient energy capacity. Furthermore, the microgrids under study also include renewable energy sources, whose power can be curtailed, which provide another degree of freedom to the microgrid energy management. Finally, demand response is a very important aspect for demand side management, and it can become effective player in achieving efficient energy management and operation of microgrid.

The proposed energy management optimization algorithms are focused on economic objectives and are modeled in a generic way, in order to enable the expandable functionality by including more devices of similar characteristics. Simultaneous generation and demand scheduling are performed, providing commands or curtailment references to the distributed energy resources, while shedding or shifting the controllable loads. The optimization problems are formulated as deterministic models that can be solved by open-source/commercial tools. In this way, current development of solvers is exploited and the proposal can therefore be reproduced in real applications.

In order to deal with battery wearing, a practical Li-ion battery degradation cost model is developed that includes the effects of temperature and depth of discharge on battery capacity and cycle life. The Li-ion battery degradation cost model also includes the investment and operation and maintenance costs of Li-ion battery along with discount rate factor to determine its wearing cost. Moreover, for demand response, models of aggregated controllable loads with their shifting duration and shiftable power rating are developed and integrated in the energy management optimization algorithm. The demand responsive model also considers forward and backward shifting instants in day-ahead scheduling for achieving its efficient operation in microgrid system. Load shedding is also included for ensuring reliable and stable management of microgrid system.

The energy management model for remote islanded AC microgrid was originally non-convex mixed-integer non-linear programming problem, which usually consumes a lot of computations before reaching a feasible solution (normally local optimum). Therefore, this optimization model was relaxed into a convex non-linear programming formulation for an islanded microgrid that optimizes its operating and emission costs. DG operating and emission costs are modeled. Levelized cost of energy models were developed for tidal turbine and PV system. Battery degradation cost was also formulated, which includes temperature and depth of discharge-dependent aging effects. An incentive– based demand response and microgrid network model were also incorporated in the energy management system to facilitate active participation of consumers and satisfy system constraints. The developed second-order cone programming model has achieved the global optimal solution with a lesser optimality gap and reduced computational cost.

An optimization model was developed to minimize the operating cost of a grid-connected DC microgrid. The objective of developed model includes Li-ion battery degradation cost model, scheduled islanding-dependent demand response incentive, and levelized cost model of PV system. System losses and nodal voltages were also studied, as they are imperative in achieving realistic and efficient operation of a DC microgrid. The operating cost of DC microgrid can be minimized through introducing islanding responsive demand response incentive and increasing the value of the shifted load demand and the demand response shift duration. For remote DC microgrid case, a two-stage energy management model is developed that ensure optimal decision strategies against defined economic objectives for remote islanded DC microgrid with minimum use of communication bandwidth. The proposed energy management model is also experimentally validated for proving its effectiveness in real applications.

For effective integration of transactive energy concept into electric power system, a comprehensive conceptual seven layer architecture was developed that gives an insight about physical, technical, communication, and information functions of transactive energy system. Popular distributed ledger technlogies, blockchain, holochain, directed acyclic graph, hashgraph, and tempo, are also extensively discussed with their comparative performance analysis. Finally, local energy market concept and its types, community-based and peer-to-peer energy markets, are also discussed with their advantages and potential challenges. The developed seven layer transactive energy system model can be an effective framework for implementing a real transactive microgrid and smart grid systems.

2 Future Work

The thesis contributions show the following promising aspects that can be investigated in the future:

- Implementation of management strategies at planning level and their integration in operation level with proper constraints to consider important factors, like maintenance and replacement of some microgrid components.
- Analyzing the effects of the proposed microgrid energy management startegies on performance of distribution system operator.
- Considering other renewable energy sources with good local energy generation potential, like biomass and wave power generators, for a multi-carrier energy microgrid.
- Adaptation and study of renewable uncertainties on remote islanded microgrid operation using artificial intelligence.
- Consideration of multi-microgrid systems by combining local and centralized energy management systems. Implementation of the whole system with smart Internet-of-things devices, and analysis of their integration and limitations in respect of their functions and system hierarchies.
- Integrating transactive energy for ensuring the privacy of the local users and their economic benefits using distributed ledger technologies.

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DOCTORAT BRETAGNE LOIRE SCIENCES POUR L'INGENIEUR

Université de Bretagne Occidentale

Titre : Contribution à l'optimisation de la gestion d'énergie dans les micro-réseaux à base de ressources renouvelables

Mots clés : Micro-réseau, gestion de l'énergie, ressources renouvelables, stockage d'énergie, réponse à la demande, optimisation sous contraintes.

Résumé : Le réseau électrique actuel est confronté à plusieurs défis liés aux exigences environnementales, à l'augmentation de la demande mondiale d'électricité, aux contraintes de fiabilité élevées, à la nécessité d'une énergie décarbonisée et aux restrictions de planification. Afin d'évoluer vers un système d'énergie électrique respectueux de l'environnement et intelligent, les installations de production centralisées sont de nos jours transformées en de plus petites centrales de génération distribuées. Le concept de micro-réseau émerge ainsi. Le micro-réseau peut être considéré comme un système de distribution basse tension avec un ensemble de charges contrôlables et de ressources énergétiques distribuées, qui peuvent inclure de nombreuses sources d'énergie renouvelables et des systèmes de stockage d'énergie. La gestion d'énergie d'un grand nombre de ressources énergétiques distribuées est nécessaire au bon fonctionnement d'un micro-réseau afin d'en assurer la stabilité, la fiabilité et la disponibilité. Par conséquent, un système de gestion d'énergie est au cœur de l'exploitation des micro-réseaux afin d'en assurer un développement économique et durable. À cet égard, cette thèse se focalise sur la proposition de modèles d'optimisation de système de gestion de l'énergie pour une exploitation optimale des micro-réseaux. Une gestion d'énergie optimale requière la prise en compte de plusieurs contraintes techniques, économiques et environnementales. De plus, ces travaux de recherche prennent en considération un modèle pratique du coût de dégradation des batteries Li-ion. Le problème de gestion d'énergie optimale se traduit ainsi par un problème d'optimisation sous contraintes. La fonction objective regroupe le coût d'exploitation des générateurs distribués, le coût des émissions de gaz à effet de serre des sources de production conventionnelles, l'obligation d'une utilisation maximale des sources d'énergie renouvelables, le coût de dégradation des batteries, les différentes incitations afin de modifier le profil de la demande et des pénalités en cas de délestage. Les contraintes quant à elles sont liées aux contraintes techniques des différents sous-systèmes du micro-réseau. Par ailleurs, un modèle conceptuel complet à sept couches est également développé afin de fournir des informations normalisées sur la mise en œuvre d'une nouvelle économie de l'énergie.

Title : On energy management optimization for microgrids enriched with renewable energy sources

Keywords : Microgrid, energy management, renewable energy sources, energy storage system, demand response, optimization

Abstract : The current electric power system is facing the challenges of environmental protection, increasing global electricity demand, high reliability requirement, cleanliness of energy, and planning restrictions. To evolve towards green and smart electric power system, centralized generating facilities are now being transformed into smaller and more distributed generations. As a consequence, the concept of microgrid emerges, where a microgrid can operate as a single controllable system and can be assumed as a cluster of loads and distributed energy resources, which may include many renewable energy sources and energy storage systems. The energy management of large numbers of distributed energy resources is needed for reliable operation of microgrid system. Therefore, energy management is the fundamental part of the microgrid operation for economical and sustainable development. In this regard, this thesis focuses on proposing energy management optimization models for optimal operation of microgrid system that include proposed practical Li-ion battery degradation cost model. These different energy management models include objective functions of operating cost of distributed generators, emission cost of conventional generation source, maximum utilization of renewable energy sources, battery degradation cost, demand response incentives, and load shedding penalization cost, with microgrid component and physical network constraints. A comprehensive conceptual seven layer model is also developed to provide standardized insights in implementing real transactive energy systems.