PLANNING AND OPERATION OF HYBRID AC-DC MICROGIRD WITH HIGH PENETRATION OF RENEWABLE ENERGY SOURCES

M.BASEER

PhD

2022

Planning and Operation of Hybrid AC-DC Microgird with High Penetration of Renewable Energy Sources

Muhammad BASEER

Submitted for the Degree of

Doctor of Philosophy

School of Biomedical and Electronics Engineering

Faculty of Engineering and Informatics

University of Bradford

2022

Abstract

Muhammad Baseer

Planning and Operation of Hybrid AC-DC Microgird with High Penetration of Renewable Energy Sources

Keywords

Interlinking converter, hybrid microgrid, distributed generators, energy storage system

A hybrid ac/dc microgrid is a more complex but practical network that combines the advantages of an AC and a DC system. The main advantage of this network is that it connects both alternating current and direct current networks via an interlinking converter (IC) to form a unified distribution grid. The hybrid microgrid (HMG) will enable the direct integration of both alternating current (AC) and direct current (DC) distributed generators (DGs), energy storage systems (ESS), and alternating current and direct current (DC) loads into the grid. The alternating current and direct current sources, loads, and ESS are separated and connected to their respective subgrids primarily to reduce power conversion and thus increase overall system efficiency. As a result, the HMG architecture improves power quality and system reliability. Planning a hybrid microgrid entails estimating the capacities of DGs while taking technical, economic, and environmental factors into account. The hybrid ac-dc microgrid is regarded as the distribution network of the future, as it will benefit from both ac and dc microgrids. This thesis presents a general architecture of a hybrid ac-dc microgrid, which includes both planning and design. The goal of the Hybrid ac-dc microgrid planning problem is to maximise social welfare while minimising total planning costs such as investment, maintenance, and operation costs. This configuration will assist Hybrid microgrid planners in estimating planning costs while allowing them to consider any type of load ac/dc and DER type. Finally, this thesis identifies the research questions and proposes a future research plan.

Authors’ Publication Record

Journal Paper:

- Baseer, M., Mokryani, G., Zubo, R.H. and Cox, S., 2019. Planning of HMG with high penetration of renewable energy sources. *IET Renewable Power Generation*, (Impact Factor:3.605)

Co-Authors’ Publications

- Ullah, Z., Mirjat, N.H. and Baseer, M., 2022. Optimisation and Management of Virtual Power Plants Energy Mix Trading Model. International Journal of Renewable Energy Development, 11(1). (Impact Factor:1.67)

Refereed Conference Papers:

- Al-Jaafreh, M.A.A., Mokrani, Geev., Asharaa, Abdalfettah., Anthony, O.I., Zubo, Rana., Baseer, Muhammad,. (2020). Techno-Economic Viability Test of Renewable Energy Supply Options in Developing Countries: Jorden Case Study. IMDC 2020.

Acknowledgment

First and foremost, I would like to thank ALLAH (God) for giving me the Opportunity to expand my knowledge and horizons. I am also grateful to ALLAH for the successful completion of my PhD thesis.

Special thanks and gratitude to my supervisor Dr. Geev Mokryani for giving me the opportunity to conduct the research work under his supervision. His scientific wisdom and experience have helped me in achieving my research objectives.

Finally, many thanks for my parents without them I wouldn't achieve my studies. Their help was a large part of what kept me going and thanks to my wife and kids for their patience and their presence in my life provided a fundamental sense of balance and happiness.

Dedication

To my Dad Mr. Muhammad Naseer for the efforts he puts into my life.

Table of Contents

Abstract i
Acknowledgment iii
Dedication iv
List of Figures viii
List of Tables x
List of Nomenclature and Abbreviations xi
Chapter 1 Background and Motivation 1
1.1 Patness and Novelty 1
  1.2 Aim 8
  1.3 Objectives 9
  1.4 Organization of the Thesis. 9
Chapter 2 Literature Review 11
  2.1 Microgrid Introduction 11
  2.2 Microgrids Classification 15
  2.2.1 AC Microgrids 15
  2.2.2 DC Microgrids 15
  2.2.3 Hybrid ac/dc microgrids 16
  2.2.4 Hybrid ac/dc microgrid advantages and disadvantages 17
  2.3 Power Topologies 19
  2.4 Hybrid ac/dc microgrids Control Strategies 22
  2.4.1 Modelling 23
  2.4.2 Power Management 24
  2.4.3 Coordinated Control 25
  2.4.4 Stability Studies 26
  2.4.5 Power Quality 27
  2.4.6 Protection Strategies 27
  2.5 Planning of Hybrid ac-dc microgrid 27
  2.5.1 Objectives of Hybrid ac-dc microgrid Planning 28

2.5.2 Constraints of Hybrid ac-dc microgrid Planning 28
2.6 Uncertainty Modelling in Hybrid ac-dc microgrid. 29
2.7 Optimization methods for Hybrid ac-dc microgrid Planning 31
Chapter 3 Planning and Operation of Hybrid ac-dc Microgrid 34
3.1 Introduction 34
3.2 Background, Motivation and Literature Review.......................................36
3.3 Main Contributions of the Current work 39
3.4 Aim and approach..40
3.5 Uncertainty Modelling 40
3.5.1 Wind speed modeling 42
3.5.2 Modelling of Solar irradiance 43
3.5.3 Load demand uncertainty modeling 44
3.6 Modelling approach 45
3.7 Hybrid ac-dc Microgrid Model 48
3.7.1 Planning and Operation of hybrid AC-DC microgrid 49
3.7.2 Constraints:...51
3.7.3 Hybrid microgrid electricity market model 54
3.8 Case study and Simulation Results 55
3.9 Conclusion 67
Chapter4 Planning and opertion of multi-carrier energy systems with distributed injection of renewable energy resources. 69
4.1 Introduction 69
4.2 Background and Related research: 70
4.3 Contribution to present work 73
4.4 Structure of integrated planning: 74
4.5 Planning and operation methodology of multi-carrier energy systems:....75
4.5.1 Hybrid AC-DC microgrid network model 76
4.5.2 CHP model 76
4.5.3 Boiler model..78
4.5.4 Gas network model...79
4.5.5 Heat network model...82

4.6 Case study:...86
4.7 Results and discussions 89
4.8 Conclusion...94
Chapter 5 Conclusions and Recommendations for Further Work.............................96
5.1 Conclusion...96
5.2 Future work recommendations 97
References...98

List of Figures

Figure 2-1 Microgrid scheme..13

Figure 2-2 General Architecture of Hybrid ac-dc microgrid 19

Figure 2-3 Hybrid Multi-microgrid 20

Figure 2-4 Hybrid Multi-microgrid: Multiple dc subgrid 21

Figure 2-5 Hybrid Multi-microgrid: Multiple ac subgrid 21

Figure 2-6 SST based three stages Hybrid microgrid...22

Figure 3-1 WTs Speed power curve….………………………………………………43

Figure 3-2 Load, wind, and irradiation curves ………………………………………47

Figure 3-3 Scenario tree …………..…..…………………………………….……………48

Figure 3-4 Proposed Hybrid Microgrid Electricity Market Structure ………………54

Figure 3-5 Single-line diagram of Hybrid ac-dc microgrid …………………………56

Figure 3-6 Total yearly dispatched Wind active power at bus 2…………….....……63

Figure 3-7 Total yearly dispatched Wind active power at bus 3………….....……64

Figure 3-8 Total yearly dispatched Wind active power at bus 6…………….....……64

Figure 3-9 Total yearly dispatched Wind active power at bus 8………….....……65

Figure 3-10 Total yearly dispatched Wind active power ……….....………….....……65

Figure 3-11 Total yearly dispatched PV active power ……………………...……66

Figure 3-12 Total Net Social Welfare over the planning horizon ……….………....66

Figure 4-1 MCEMGN general structure….…………………………………………...75

Figure 4-2 Hybrid AC-DC microgrid………………………………………………...86

Figure 4-3 Natural Gas network……………………………………………………..86

Figure 4-4 Heat network...87

Figure 4-5 Planning cost 90

Figure 4-6 Total PV output power over the Planning period…………………..…...91

Figure 4-7 Total WT output power over the Planning period 91

Figure 4-8 Total CHP's output power over the Planning period...........................92

Figure 4-8 Total Electrical energy sold over the Planning period…...…………......93

List of Tables

Table 2-1 Hybrid Microgrid Power Topologies……………………………………….22

Table 3-1 AC branch data…………………………………………………………..57

Table 3-2 DC branch data…………………………………………………………..58

Table 3-3 AC bus data………………………………………………………………59

Table 3-4 DC bus data………………………………………………………………60

Table 3-5 Active power bid prices for the WT's …………………………………….61

Table 3-6 Active power bid prices for the PV's……………………………………...62

Table 4-1 Configuration of CHP on the sub-networks ……………………………..88

Table 4-2 Configuration of Boiler on the sub-networks …………………………….88

List of Nomenclature and Abbreviations

a) Index and Sets

y	Index for year
h	Index for feeders
s	Index for scenarios
n,b	number of gas network nodes
g,k	number of heat network nodes
t	Index for time
a	Set of all DGs
i	Set of DC DGs

b) Parameter

C_{AC}	Generation price for AC DGs
C_{DC}	Generation price for DC DGs
CC_a	Annualized investment cost of DGs
CR	Annualized investment cost of ac to dc rectifier
CI	Annualized investment cost of dc to ac inverter
r	Discount rate
CC^{chp}	Annualized investment cost of CHP
$C\mathrm{ap}^{chp}$	Capacity of the CHP
OMC^{chp}	Operation & maintenance cost of CHP
life^{chp}	Lifetime of CHP
CC^{boiler}	Annualized investment cost of Boiler
$C\mathrm{ap}^{boiler}$	Capacity of the Boiler
OMC^{boiler}	Operation & maintenance cost of Boiler
life^{boiler}	Lifetime of Boiler
P^{LIMIT}	Flow limits between utility grid and microgrid
RR	Capital recovery rate
ER	Rectifier efficiency
EI	Inverter efficiency
ρ	Market price
$CC_{gas}^{P.line}$	Annualized investment cost of pipeline for gas network
$CC^{G.station}$	Annualized investment cost of gas station for gas network
$NG^{\lim}$	Flow limit for Natural gas

$CC_{heat}^{P.line}$	Annualized investment cost of pipeline for Heat network
$CC_{heat}^{H.source}$	Annualized investment cost of Boiler for Heat network
T_s	Node start temperature
T_g	Ground temperature
η^{Boiler}	Boiler efficiency
η_{elec}^{CHP}	Electrical efficacy of CHP
η_{Heat}^{CHP}	Heat efficacy of CHP
R_{up}	Ramp-up time for CHP
R_{down}	Ramp-down time for CHP
η^{Boiler}	Efficiency of the boiler

c) Variables

IC	Total Investment cost
OMG	Operation and maintenance cost
P^{MAX}	DGs power capacity
P^{Fexch}	Powe exchange at feeder
P^{Gexch}	Power exchange with grid
W	Binary decision variable for dc bus
f	Binary decision variable for the connection of DG with feeder
d	Binary decision variable for the connection of DG with feeder
P_E^{Grid}	Electrical energy exchange between MCEMGN and grid
P_G^{GN}	Energy exchange between MCEMGN and gas network
P_H^{HN}	Energy exchange between MCEMGN and heat network
x	Binary decision variable for DG
IC^{boiler}	Cost of boiler
IC^{chp}	Cost of CHP
$Fuel^{chp}$	Fuel used by CHP
H^{boiler}	Fuel used by Boiler
$\mathrm{Cos}t^{gas}$	Cost of gas energy generation
$\mathrm{Cos}t^{heat}$	Cost of heat energy generation

Chapter 1 Background and Motivation

1.1 Patness and Novelty

The electricity demand has increased many folds during the last two decades which necessitates more efficient power grid operation and the penetration of more energy units that can be generated from the generating units. The increase in population, good standards of living, decline in production from traditional energy resources (natural gas, coal, petroleum etc.) are the main factors of present energy crisis. There are also many disadvantages of using fossil fuel e.g emission of hazardous gases which caused global warming and pollution. The major disadvantage of centralized generating units is their inefficiency because of line losses and poor waste heat recovery. Distributed renewable energy resources (DERs) like wind, solar, hydro plants, tidal energy and fuel cells are pollution free, environment friendly and are abundantly available in nature, are the suitable resources for electrical power generation. The most important benefit of DER is that it can be integrated at any point of microgrid which reduces transmission losses if the point of connection is near to the load. In case of rural or remote area where power transmission is itself a challenge, the distributed generation is a viable solution.

It is clearly evident that the energy demand is increasing rapidly globally which in return increases a huge dependency on fossil fuel energy resources, which also leads to increase in global warming and pollution [1]. It has been analysed that the global demand for energy in the upcoming 25 years is expected to grow over 50 % given the economic development and population growth. According to the report of International energy agency (IEA), the total energy consumption has increased from 6.106 Mtoe in 1973 to 13.371 Mtoe in 2012, and this increasing tendency is foreseen[2]. The fossil fuels shares 81% of the total energy consumed in 2012. But the reduction in fossil fuel production, emission of CO_2, global warming and pollution have compelled researchers to find new ways of energy generation.

The United Kingdom (UK) has become a world leader to force the climate change act in 2008 and also introducing the reforms for electricity market for participating renewables, particularly solar and wind power [3]. The government of UK has set out priorities to meets the target and have also allocated five-yearly carbon budgets. UK have also restricted the amount of greenhouse gas it can legally emit in a five-year period. The UK is currently in the third carbon budget period (2018 to 2022) [4].

The Paris Agreement builds upon the Convention and for the first time brings all nations into a common cause to undertake ambitious efforts to combat climate change and adapt to its effects, with enhanced support to assist developing countries to do so. As such, it charts a new course in the global climate effort [5]. The United Nations Framework Convention on Climate Change (UNFCCC) has taken concrete steps towards the prevention of climate change and to take control over global warming by ramping up the research and development to increase the penetration of more renewable resources of energy which has the capacity of replacing fossil fuels [6].

Conventionally, the centralized nature of the power supply systems in the world and most of it’s dependency is on fossil fuels. There have been many resources for the production of power in big generation facilities that can provide low cost energy generation in a highly populated area. Due to increasing cost of operation, maintenance, and extension of existing power transmission networks from centralised grids, many decentralised systems have now shifted towards distributed generation for local power supply. Given the high cost of oil, renewable energy resources are also very vital and important alternative for such isolated systems. The cost to expand transmission, and the cost of transportation for fuel, along with the target to reduce carbon emissions, the renewable energy resources are the best alternative and solution of world’s energy crises.

Renewable energy sources (RES) are considered to be most abundantly available energy resources which are eco-friendly. Many national and international organizations have carried out research to investigate the integration of renewable energy resources with power grid in the fallowing decade [7]. However, there are huge challenges needs to be addressed in the near future. In this context it is clear that the renewable energy resources are the best suitable and promising clean energy source.

Although it is evident that the energy cost from conventional resources is lesser than from the renewables, an optimised mix of conventional resources with renewables energy resources are capable of reducing the overall energy cost for isolated systems, which are also referred as microgrids [8]. Distributed generation in microgrid systems normally range from 5kW to 10MW in capacity, near or at the end-user to supply the electric power required [8].

A very clear and precise definition regarding microgrid and it’s functionality is stated in [9]: A microgrid is defined as a cluster or formation of electricity sources and electrical loads in one or many locations that either may be or may not be connected to conventional power system or to the grid. The most important and intriguing feature is that the microgrid has the ability to control over its operation, allowing it to be operated more reliably as an island [10]. The microgrid’s success will heavily depend on the availability of renewable energy resource and the economics related to the distributed energy resources.

The Increasing oil prices and decrease in fossil fuel production, extreme climatic conditions are the main contributors for the motivation to direct mankind to fulfil our energy needs and requirements from renewable energy resources, away from a conventional or centralized energy system to a decentralized and more hybrid power system [11]. The work done so far in microgrid design has used deterministic methods, but the majority of the referred work anticipate or acknowledges the stochastic nature of renewable energy generation and demand. It has been really very challenging to develop or propose joint stochastic models to the design small microgrids with high renewable penetration due to the involvement of multiple disciplines, as well as economic and environmental factors [12]. Developing microgrid models that incorporates planning and operation of microgrids by considering their inability to dispatch power and uncertainties related to renewable energy resources and demands is the prime and important goal. Planning models that incorporates a long time period horizon with large time intervals while microgrid's operation models that incorporates a short time horizon with smaller time intervals and by considering both concurrently is almost impossible in real world systems.

It is evident that the success of these clusters of these mixed technology generation, grouped with possible storage, loads that can controlled and other microgrid components will empower microgrid systems to success [13]. Long term environmental, economic and utility systems benefits are evident, strategies and policies are required to such microgrids to propel to a wider audience. There are some technological, regulatory and economic issues which restrains the spread and deployment and integration of renewable systems in an existing power system [14]. The undispatchability and uncontrollability of the renewable energy systems is the issue of significance importance. Majority of the recent designs assume that renewable resources are dispatchable. It is practically not feasible to consider the renewable energy resources as dispatchable which in most cases regarding the recent microgrid designs.

Electricity is the commodity that is consumed almost instantaneously once it is generated. The electricity demands are fluctuating hence power system planners may perform complex and multistage planning processes that will enable the generators to deliver the required or agreed amount of energy and vary their energy output promptly on a short notice [15]. To deal with this problem of undispatchability and uncontrollability of renewables, it is recommended to use RES in conjunction or combination with generators that are controllable and use energy storage system. The combinations of RES with storage systems and controllable generators ("Hybrid Microgrid", HMG) are considered to be more feasible and attractive alternatives only in areas such as islands, villages and oases, where it is very expensive to expand power transmission lines from the central grid to feed the loads in remote areas [16].

The consideration towards installation of HMG has been popular due to two major reasons:

- Renewable systems and energy storage units are getting more bigger and less expensive.
- Reliance on the central grid is shrinking, which in return enables higher penetration of renewables and distributed energy generation.

The traditional power grid which normally had three layer architecture generation, transmission and distribution is transforming into a modernised decentralized system with many microgrids integrated together with distributed generating units and smart communication to allow high penetration of renewables [17]. In this context, an optimal strategy must be introduced which has a choice of right mix of renewable energy resources which plays an critical role in planning and operation of the HMG. Extensive research is been performed in this area but the uncertainties related to renewable energy resources and highly pricey energy storage solutions is making this process of technology selection very challenging.

In HMG, a local grouping of energy generating sources and loads is formed, which can feed its localised demand and thus improves grid efficiency [18]. The HMG concept reduces the number of reverse connections in an individual AC or DC grid while also allowing renewable AC and/or DC sources and loads to connect to the power system. Although AC power systems have improved significantly over the last few decades, advances in power electronics have completely revolutionised the major domains of power systems and changed the load profile for end users [18]. Modern appliances such as laptops, mobile phones, electric vehicles, televisions, remote controls, and so on run on DC power, which is typically supplied by an AC-DC converter.

Hybrid microgrids has benefits of both ac and dc microgrid types[19]. Furthermore, the number of required power converters would be drastically reduced, improving microgrid efficiency and lowering investment and operation costs. This report introduces hybrid ac/dc microgrid as a viable solution compared to individual ac or dc microgrids and focuses on its planning. The objective of the hybrid microgrid planning is to minimize the microgrid total cost, including investment cost of distributed energy resources (DERs) and converters, operation cost of DERs, the cost of energy exchange with the utility grid, and the cost of unserved energy during the planning horizon[20]. The economic viability of the microgrid planning is investigated in this report and it is shown how the optimal DER generation mix, the type of feeders, as well as the point of connection of DERs to feeders can be determined by updating the traditional ac microgrid planning model.

1.2 Aim

The aim is to investigate and optimize the planning and design of Hybrid AC-DC microgrid with integration of renewable energy resources.

1.3 Objectives

The main objectives of this research are as follows:

1) Model the uncertainties related to load demand, wind and solar power through scenario tree approach.
2) Propose a novel approach for the planning and operation of Hybrid AC-DC microgrid within a electricity market environment by maximising the net social welfare by taking into consideration the impact of solar and wind penetration.
3) Propose a new methodology for planning and operation of multi-carrier energy systems with distributed injection of renewable energy resources.

1.4 Organization of the Thesis.

The thesis is composed of five chapters, the contents of chapters is summarized as follows:

Chapter 2: This chapter gives overview of the microgrids, which includes details of microgrids including the types and technologies, the challenges faced to increase penetration of distributed generation. This chapter also discusses the planning models which includes objectives, related constraints, uncertainties modelling methods, and conclusion.

Chapter 3: This chapter includes the planning and operation of hybrid ac-dc microgrid. This chapter aims to introduce a novel hybrid AC-DC microgrid planning and design model within a microgrid market environment to maximize net social welfare (NSW). Scenario Tree approach is used to model the uncertainties related to load demand, wind speed and solar irradiation. A study on a real 28-bus real hybrid AC-DC microgrid is caried out to check the validity of the proposed model.

Chapter 4: This chapter Includes the optimal energy flow study in proposed MCEMGN operation framework. The prior study on multi energy systems which includes microgrids, natural gas network and heat network is limited and in the best of our knowledge, there is no literature so far regarding the planning and operation modeling that considers the nexus of hybrid microgrid, NG network and heat network while considering WTs, PV and dispatchable load uncertainties. This chapter discusses a very novel approach for MINLP model for planning and operation of multi-carrier energy systems by minimizing cost considering the uncertainties that are associated with dispatchable load demand and DGs subjected to network constraints.

Chapter 5: This chapter summarizes the conclusion and recommends the future work.

Chapter 2 Literature Review

2.1 Microgrid Introduction

In this chapter, a literature review of the research is presented. This review will cover details of Microgrid, it's types and technologies, applications and benefits, the challenges faced when penetration of DGs increases, methods used for uncertainty modelling, different optimization tools to optimize power flow, DGs location and problem size.

The traditional electric grid structure works on the principle of centralized generation mostly from the consumption of fossil fuels. The dependency on fossil fuels, aged power network, increase in energy consumption and poor energy quality, are among many reasons that have led to requirement of modification of this existing system. According to the report of International energy agency (IEA), the total energy consumption has increased from 6.106 Mtoe in 1973 to 13.371 Mtoe in 2012, and this increasing tendency is foreseen[1]. The fossil fuels shares 81% of the total energy consumed in 2012. But the reduction in fossil fuel production, emission of CO_2, global warming and pollution have compelled researchers to find new ways of energy generation. Renewable energy sources (RES) are considered to be most abundantly available energy resources which are eco-friendly. Many national and international organizations have carried out research to investigate the integration of renewable energy resources with power grid in the fallowing decade

[3-7]. However there are huge challenges needs to be addressed in the near future.

There are two main reasons of poor efficiency of utility grids (a) higher consumption levels (b) ageing factor. According to IEA, in 2011 the world wide total power losses in the transmission system were 8% approximately [8].

One of the attractive solutions of these problems is to integrate RES with the existing system of power grid. But to integrate RES with power grid in a distributed, reliable and in an efficient manner is a big challenge. The installed capacity of RES will double in 2023 [8]. Smart grid is another most attractive solution proposed for this problem [9][9-16]. It is expected that electric market will undergo same evolution as internet did in twentieth century and this concept is named as Energy internet [17] or Enernet [18].

A microgrid is a small-scale low voltage power grid on the distribution side is one the best possible solution to improve power flow. It also reduces power losses at transmission level through distributed generation interconnection, loads and energy storage systems (ESS) in the same grid [19-25]. Microgrids can be operated in two modes (1) It can be operated in islanded mode (2) It can be operated in conjunction with the utility grid known as grid connected mode [58]. Fig. 2-1 demonstrates a typical microgrid which involves DERs, distribution network and loads. The point of common coupling (PCC) is a point where microgrid can be connected or disconnected from the utility grid. The evolution of multiple-microgrids is because of limited capacity of microgrids. If several microgrids are interconnected then multiple-microgrids can be formed which can operate in both isolated or grid connected mode.

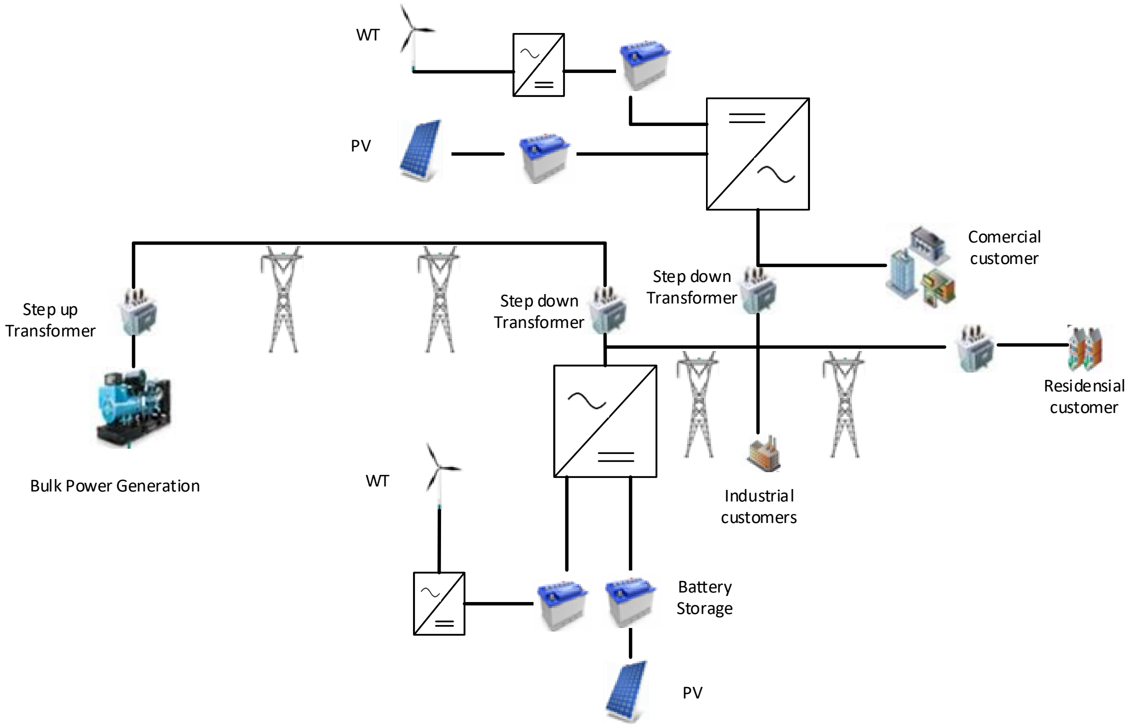


Figure 2-1 Microgrid scheme

Microgrids offers many benefits and advantages including improved power efficiency, reliability, reduction in cost, low transmission losses, less pollution, low carbon emission and eco-friendly. However, there are many issues like control, operation and protection of microgrids. There are many methods proposed in the literature for the successful operation of microgrids. According to IEEE standard 1547, DGs are allowed to integrate with utility grid but in case of fault it has to isolate from the utility grid. This approach is applicable to small scale microgrids which are grid connected. But in case of very high penetration of DGs, it will be very difficult and damaging for the utility grid if all DGs are disconnected instantly. There are several literatures available which have enlightened several aspects of this network: control strategies [21,23,26-33,34-36,37-39], test beds [19,23,25,40] techniques used for optimization and software used [41-46], devices used for protection [32,37,39,47,48], etc.

There are many issues regarding control and protection of microgrids and their possible solutions which includes:

1) The conventional power grid works on the principle of unidirectional power flow. But with the integration of DGs, the power flow will be bidirectional which means the conventional control and protection schemes will be no longer applicable [59].
2) In the case of fault current, it is limited to 2p.u for GDs with inverter, which is impossible to sense for traditional overcurrent relays [59].
3) Microgrids operates at low voltage as compare to traditional utility grid so it needs small transient stability and signal stability analysis for the smooth operation of microgrids [60].
4) In case of conventional power generation where bulk of the power is generated at the generation side with high inertia and then it is dispatched to different load locations but in case of microgrids energy generation is at different pockets so it will have low inertia. Hence in the case of microgrids, a new special mechanism is required to control power flow [60].
5) A special and efficient form of communication is required between the GDs and storage devices.

2.2 Microgrids Classification

Microgrids can be divided into three groups according to their topologies namely, ac microgrids, dc microgrids and hybrid ac/dc microgrids [23,39,40,49-56].

2.2.1 AC Microgrids

An AC microgrid facilitates the direct integration of DG units with the utility grid with very minimum modifications. The structure of the AC microgrid is suitable to facilitate any modification in voltage levels with the help of transformers operating at low frequency and it has very efficient fault management protocols. But regarding these benefits, there are some issues with AC microgrids out those two are of significant importance. First, any incoming DG unit has to synchronize and secondly the reactive power circulation contributes into the power losses. There are many literatures available that has discussed the integration of AC microgrids [19, 24, 40, 50].

2.2.2 DC Microgrids

The renewable energy resources are found abundant in nature and are eco-friendly, the penetration of dc-based DG units, loads and ESS units, are leading to new era of DC distribution system. There are scores and scores of benefits of DC distribution system, which includes more efficiency, less converters will be used, no synchronization is required for DGs, there will be no reactive current circulation in the network. But to gain benefits of DC distribution system, the existing system has to be modified and the cost for cause will be very huge. There are many literatures available in which the benefits of DC distribution system are discussed over AC distribution system [22,23,39,50,53,54].

2.2.3 Hybrid ac/dc microgrids

A Hybrid ac/dc microgrid is a more complex but practical network which pools up the benefits of AC system and DC system [22,51,52,53,55]. The main advantage of this network is that it combines both ac and dc networks together through an interlinking converter (IC) to form a unified distribution grid. This hybrid microgrid (HMG) will allow the direct integration of both ac-based DGs and dc-based DGs, ESS and ac-based and dc-based loads into the grid. The ac and dc sources, loads and ESS are separate out and connected to its respective subgrid mainly to reduce the power conversion, thus overall efficiency of the system increases. The architecture of HMG thus improves power quality and reliably of the system.

HMG has gained its importance where the reliability, availability and power quality are the highest priorities e.g data centres [63], telecom towers etc. Beside these advantages, the power rid-through ability can be improved through dc subgrid [64] and voltage profile and be improved for ac subgrid [65]. HMG can serve as virtual active power filter to improve power quality [66] or it can be used as reactive power compensator [67]. The dc subgrid can be used a charging station for electric vehicles [68, 69]. The most important fact which differentiate HMG from all other distribution systems that it provides an appreciable amount of reliability to customers’ nodes by appropriate DERs allocation according to the size, sight and type [70].

2.2.4 Hybrid ac/dc microgrid advantages and disadvantages

HMG is a very unique and interesting idea for the implementation of smart grid concept. A typical design of HMG is shown in Fig. 2-1, where both networks ac and dc can easily distinguished.

The advantages of Hybrid ac/dc microgrids are:

1) Integration

   The integration of ac-based for dc-based devices to HMG can be done at any stage with the minimum number of converter stages. On both ac subgrid and dc subgrid, the incoming units can be integrated at any time which makes this system more flexible to load requirement.

2) Synchronization

   The synchronization on ac side will follow the same conventional process to integrate any incoming DG while there is no need for synchronization on the dc side.

3) Voltage transformation

   On the ac side of HMG, the voltage transformation is done through transformers while on the dc side it will be done through dc-dc converters.

4) Economic feasibility

   Although the cost of implementing the HMG concept is high as compare to compare to traditional ac distribution system but the investment will repay back more quickly as the total number of interface stages are reduced.

However, there are some disadvantages of Hybrid ac/dc microgrids which are:

1) Protection

   There is a lot of work has been done on the protection of ac distribution system and this field is already developed but in the case of dc subgrid, there is a lot of work needs to be done like fault detection system, over current protection, voltage surges etc.

2) Uncertainty

   The wind speed and solar irradiation are the two factors which are the main concerns for this system and these factors forced the designer to think about grid connectivity and stand by generating units to compensate any decrease in power generation.

3) Control complexity

   The control strategy for HMG is much more complicated and complex as compare to ac grid and dc grid individually. As it combines the both grids so the a robust mechanism is required to control ac devices and dc devices especially in the presence of interlinking converter which makes this job more difficult.

2.3 Power Topologies

HMG consist of ac subgrid and dc subgrid interconnected by one or more interlinking converters and ac subgrid is also connected with the utility grid at a point known as point of common coupling (PCC). The power topologies can be divided into three main categories (a) Conventional topologies (b) Multi-microgrid topologies and (c) Solid state transformers Topologies. A brief introduction of each category is explained below.

(a) Conventional topologies

In this type of HMG, a single IC with its filters is used to connect three phase ac subgrid and dc subgrid. This type of topology is used for Greenfield installation which is having single owner. The conventional or traditional topology is shown in Fig 2-2, is mainly used in networks of low voltages, has been used in [66,78-113]. The basic difference in these topologies is either the IC used or the location of storage unit e.g storage unit can be used on dc subgrid [80,81] or it can be used on the ac subgrid side [84].

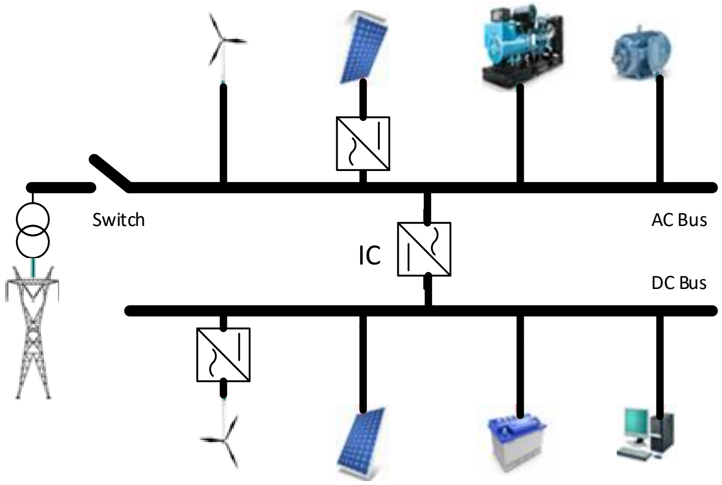


Figure 2-2 General Architecture of Hybrid ac-dc microgrid

(b) Multi-microgrid topologies

In Multi-microgrid topologies, ac subgrids and dc subgrids are owned by different owners. These neighbouring microgrids are independently operated and then integrated together for economic benefits and to synergized technology. In this way the performance, reliability, backup, power quality and economic optimization will further increased. This topology is best described in [114] where a common ac bus is used to integrate different ac and dc microgrids for islanded mode of operation shown in Fig 2-3. Each of these microgrids is also capable to switch to grid connected mode as well.

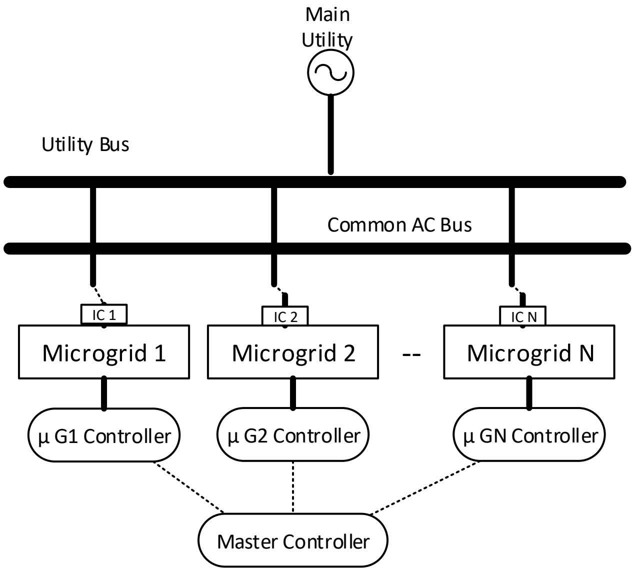


Figure 2-3 Hybrid Multi-microgrid

In [115], authors have used one ac subgrid but multiple dc subgrids, shown in Fig. 2-4 and also one multiple ac subgrids and single dc grid as shown in Fig 2-5 to demonstrate HMG structure.

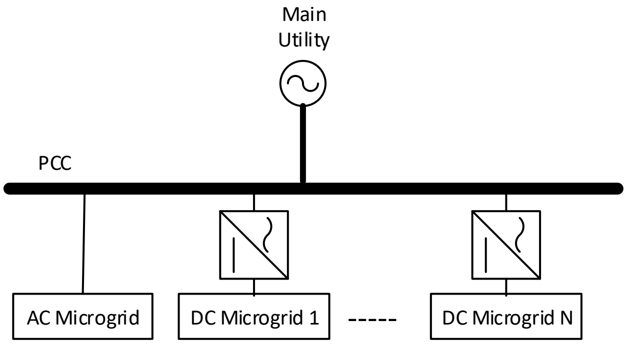


Figure 2-4 Hybrid Multi-microgrid: Multiple dc subgrid

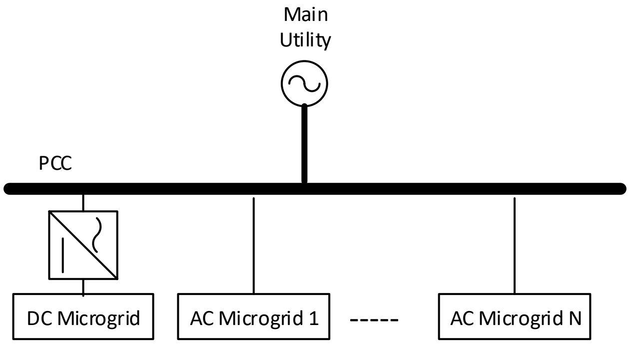


Figure 2-5 Hybrid Multi-microgrid: Multiple ac subgrid

(c) Solid state transformers (SST) topologies

The conventional and multi-microgrid uses single stage IC but separate filters and isolation transformer. The SST acts as an IC that connects ac subgrid, dc subgrid and the main utility grid but the basic difference between this topology and above mentioned topologies is that it uses IC, filters and isolation transform as a one compact device. SST has two tasks to do, first it acts like an energy distributer secondly it has to act like an ordinary transformer. In [60], an SST based HMG is discussed in which three components are shown in FIG 2-6, rectifier, dc-dc converter and an inverter. This SST will coordinate between different neighbouring ac and dc grids [120,121] and also performs ancillary service to the grid [117].

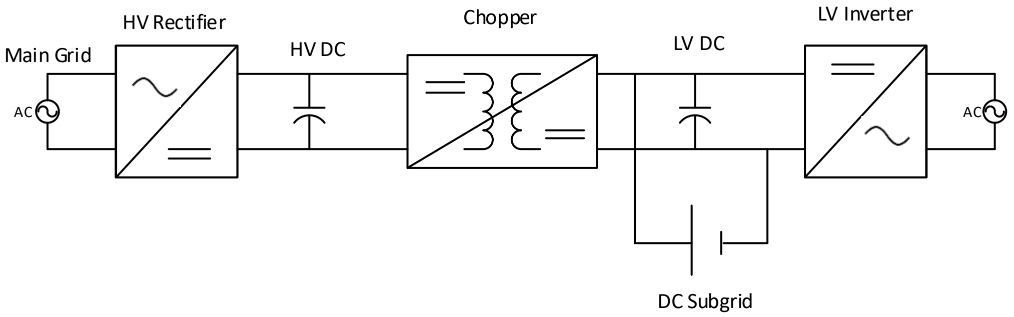


Figure 2-6 SST based three stages Hybrid microgrid

The SST based topology (single phase) is very useful to integrate smart houses [119]. Table 2-1 includes the type of power topology used, voltage level and references it covered.

Table 2-1 Hybrid Microgrid Power Topologies

Power Topologies	**Reported Voltages**	**References**
Conventional topology	ac side-260/380/400/415V dc side-400/600/700/800V	[66],[78 - 113]
AC/DC multi-microgrid	ac side-1.21/4.16kV dc side-0.6kV	[109],[114-116]
SST based topology	ac side-120/380/415V dc side-200/400V	[117 - 122]
Other topologies	ac side-0.2/0.4/0.48/3.5Kv dc side-0.3/0.8/3.5/10kV	[65],[67],[68] [123] - [129]

2.4 Hybrid ac/dc microgrids Control Strategies

The control strategies for ac microgrids and dc microgrids have been thoroughly studied for the last twenty years [73,74]. But the research regarding HMG really picked up its pace from the last six years, for example, power management strategies [77], control related strategies [75,76] and power related topologies [74].

The control section of HMG is of significant importance hence it needs a very comprehensive research effort. There are many sub areas of control which includes modelling for network which includes its components and system, power quality, coordinated control, protection strategies and stability analysis. There are number of objectives associated with the control e.g power control, voltage control, energy storage management, steady state and transient state stability improvement, increase in stability margin, current control, improving power factor and fault management etc.

2.4.1 Modelling

To test a control strategy, an accurate and precise test bed of HMG model is required. The power management topologies have used aggregated model of HMG [94,131]. But to study detailed aspects like power quality, power dispatch, planning for distribution network modelling is required.

A generic algorithm for power flow is discussed in [148] for islanded HMG using Newton trust region method. Most of the components such as DGs, bus bar, loads, IC, distribution cables are being modelled. Admittance based model of HMG is being proposed by the authors in [68]. Y-bus matrix and steady-state equations for converters, inverters and IC are also included in this model. Newton-Raphson method is applied to study the network that consists of ac section and dc section.

2.4.2 Power Management

Power management basically constitute of active and reactive power control, ac bus and dc bus voltage control and storage unit control.

a) Active Power Control

The amount of active power flow among the subgrids and IC has to be decided at each instant. The frequency on the ac subgrid and voltage magnitude on the dc subgrid expresses the loading condition of each subgrid [134].

b) Reactive Power Control

Reactive power flow is not a major concern for IC or dc subgrid as it is only demanded on the ac subgrid side. The IC will only contribute in reactive power when there is a supply of active power from dc side towards ac side [156]. IC can also act as a static compensator when reactive power generation on ac side becomes insufficient [108].

c) Storage Control

DGs like wind and solar are having intermittency in output. There is a need of efficient energy management system (EMS) that will use energy storage units to compensate any shortfall in energy supply [81, 87] to maintain energy balance [93, 103, 107]. For that purpose batteries are the best option can be placed on the dc side. Batteries are generally on the dc side to maintain the dc bus voltage level in islanding mode [81, 87, 93,106]. But due to the existence of multiple-grid forming units the batteries requirement has reduced significantly [160].

d) Voltage Control

Voltage control in HMG can be classified into two categories (a) Islanded mode and (b) Grid connected mode. In islanded mode, the voltage magnitude on the dc side is controlled by storage units and on the ac side the droop based inverters are responsible to maintain voltage level [83, 87]. In grid connected mode, the dc side voltage level is maintained by IC. There are many literatures available for bus control in islanded mode and grid connected mode [69, 92, 93, 128, 130, 135].

e) Parallel IC control

The basic aim for multiple IC is to allow bulk of power being exchange between ac and dc subgrids. On ac side, due to unmatched line impedances, DGs are unable to share their rated reactive power share [71]. Similar problem also occurs on dc side because of unmatched line resistance [72, 73]. In [115], Author suggests that power sharing problem also exist in an approach where multiple parallel ICs are used. This is due to voltage sensing problem as multiple parallel ICs are sensing unequal voltages. ICs are controlled by centrally to overcome these problems [84, 88, 138, 139].

2.4.3 Coordinated Control

The control function can be divided into three stages (1) primary level (2) secondary level and (3) tertiary level [161]. The first level or primary level consists of faster loops and their execution time is much less as compare to secondary or tertiary level control. According to [162], there is another classification which divides control scheme into (1) Decentralized (2) distributed and (3) centralized control.

(1) Decentralized Control

This type of control is preferred to execute primary control tasks such as bus voltage, power sharing and frequency regulation. In this method, the control task will act on the information gathered locally. But the deviation from mean in steady state in terms of frequency and voltage occurs due to decentralized control [94].

(2) Distributed Control

A consensus over global variables is a special characteristic of distribution control [163]. In [80], a real time power management control algorithm was implemented for both islanded mode and grid connected mode of HMG.

(3) Centralized control

In this approach, a centre based controller has bidirectional communication with both sides of the system to collect information from the components and send setpoint information back to the components. This type of topology is applied where accurate power management is required [97, 151] and where optimal energy exchange between the grids is required [84, 94].

2.4.4 Stability Studies

The instability of the HMG can occurs due to any change in system or control parameters or any change in generation or loading. The instability in case of islanded mode can be caused due to change in parameters in load [82] or in line inductance [89] or due to change in droop constant value [155] or hierarchical control levels [88], etc.

2.4.5 Power Quality

The main objective of the HMG is to improve power quality for both subgrids. Most power topologies which are being proposed considered balanced loading condition. But unbalanced loading condition is very common and especially it has adverse effects on dc subgrid in islanded mode. The unbalanced loading condition can inject harmonics of 100HZ on dc subgrid side [92] and it also cause high order current harmonics. In [156], authors have deployed control topology of multiple ICs using unbalanced grid condition.

2.4.6 Protection Strategies

The only literature available so far that discusses the protection scheme for HMG is in reference [132]. The authors have discussed different types of faults that can occur on both subgrids of HMG operation and also have suggested their solutions. On ac side, zero sequence currents are of critical importance and it is used to detect faults. While on dc side, the magnitude of rate of change of capacitor current is used to detect faults.

2.5 Planning of Hybrid ac-dc microgrid

Planning of hybrid microgrid means to estimate the capacities of DGs, taking into account technical, economic and environmental consideration. Hybrid ac-dc microgrid is considered as the future of distribution network which will have benefits of both ac and dc microgrids. Only few studies can be found on planning of hybrid ac-dc microgrid. A comparative analysis of ac and dc microgrids has been performed in [166] and it also reviewed the topologies used for the interaction of ac and dc subgrids and with the utility grid. In the best of our knowledge, there is no literature available in the planning and design of hybrid microgrid in grid connected mode.

2.5.1 Objectives of Hybrid ac-dc microgrid Planning

1) Maximization of renewable DG penetration.

2) Maximization of DG capacity

3) Reduction in system losses

4) Minimization of investment, maintenance and operation cost

5) Maximization of social welfare

2.5.2 Constraints of Hybrid ac-dc microgrid Planning

There are two types of constraint involved in Hybrid ac-dc microgrid planning, equality constraints and inequality constraints

a) Equality Constraints

These constraints are related to active and reactive power balance at each bus of the system.

b) Inequality Constraints

These constraints are related to voltage limits, line thermal limits, active power and reactive power generation limits, phase angle limit, Power factor limit, current limits, total line losses limits, battery charging and discharging limits, Power exchange between ac and dc subgrids limits.

2.6 Uncertainty Modelling in Hybrid ac-dc microgrid.

Uncertainty in HMG cause due to high proportion of intermittent energy sources will cause too much trouble to utility microgrid by affecting its stable operation and safety. There are several approaches to model the uncertainties in distribution system which includes probabilistic method, interval analysis, robust optimization, hybrid probabilistic approach and information gap decision theory (IGDT)[167]. There is no literature so for that has discussed Uncertainty Modelling in Hybrid ac-dc microgrid but I will try to use existing topologies to model uncertainties issue in Hybrid ac-dc microgrid. These topologies are described as follows:

1) Robust optimization

Robust optimization topology was suggested by Soyster in 1973 [168]. In this method, uncertainty related to input parameters is described by uncertainty groups. The main advantage of this topology is that the decision still remains optimal even in a worst-case where a specific parameter is being investigated within a specified group.

2) Interval analysis

This topology was introduced by Moor in 1966 assuming that uncertain parameters are basically obtained values came from a recognized interval. This topology is almost similar to the probabilistic modelling with a uniform probability density function (PDF). This technique finds the bounds of output variables.

3) Probabilistic Approach

This topology was introduced by Dantzing in 1955 [169]. In this topology, it is assumed that the PDF of input parameters variables are known. Probabilistic approach can be subdivided into two categories, numerical and analytical approaches. Monte Carlo Simulation (MCS) is the most common stochastic approach which is basically characterize as numerical approach. MCS is further divided into three types (1) Sequential Monte Carlo Simulation (SMCS) (2) Pseudo-Sequential Monte Carlo Simulation (3) Non-Sequential Monte Carlo Simulation.

4) Analytical Approach

The idea behind the analytic approach is to do arithmetic with PDF of stochastic input variables [170]. This approach is further divided into two groups, based on linearization and based on PDF approximation. Based on linearization, it is further classified into convolution method, cumulants method, Taylor series expansion and first order Second moment method (FOSMM). Similarly based on PDF approximation is further classified into Point estimate method (PEM) and Unscented Transformation (UT).

5) Possibilistic Approach

Zadeh has introduced the idea of fuzzy arithmetic [171] in which membership functions are used to explain input parameters. A fuzzy evaluation tool was suggested for analysis of DGs effect on active power loss and the capability of distribution system to supply its loads even in the presence of uncertainties.

6) Hybrid Possibilistic-probabilistic Approach

This approach is used to present how the random and Possibilistic parameters can handle uncertain parameters [172]. The Fuzzy and Monte Carlo Simulation have used Hybrid Possibilistic-probabilistic approach to analyse the uncertain power production from DGs on active power loss in distribution networks.

7) Information gap decision theory (IGDT)

Yako Ben-Haim proposed IGDT in 1980 [173]. This technique measures the difference between parameters value and their estimated value. In this technique, PDF and membership function are not used for input parameters.

2.7 Optimization methods for Hybrid ac-dc microgrid Planning

The emergence of DGs with their application in distribution system has led to establishment of Microgrids. Planning of hybrid microgrid means to estimate the capacities of DGs, taking into account technical, economic and environmental consideration. Various planning techniques were employed to optimize microgrids characterized as conventional methods, intelligent search-based methods and the prospective methods. Same techniques can also be used to optimize hybrid ac-dc microgrids.

2.7.1 Conventional Methods

These are also called non-heuristic or classical methods. These methods includes linear programming (LP), non-linear programming (NLP),mix integer non-linear programming (MINLP), direct approach (DA), optimal power flow based approach (OPFA), ordinary optimization (OD), analysis approach (AO) and continuous power flow (CPF).

a) linear programming (LP)

Linear programming (LP) is defined as n method to optimize a linear objective function subject to linear constraints [174]. LP technique was employed to optimize a linear system in [175, 176] to gain maximum penetration of DGs. There is no literature available so far that have investigated the linear objective function in case of HMG.

b) Non-linear programming (NLP)

In NLP, a mathematical technique uses derivatives for computation. The first step in this iterative method is to identify the search direction specified by first derivatives of the equation. This is first order method which includes reduced gradient topology [177]. The successive quadratic programming [178] and Newton Raphson method [179] are known as second order methods, involves the second order partial derivatives of power flow equations and constraints.

c) Mix integer non-linear programming (MINLP)

In [180], an optimal planning of HMG is discussed. Numerical and probabilistic techniques are used via software application. Authors in [181] investigated the IEEE 9bus distribution system. An optimized planning via MINLP by using GAMS software, is done by adding the solar unit into the traditional 9bus distribution system. Load demand is fulfilled by solar energy. Beta PDF is used to model uncertainties. This model cannot integrate other energy sources like renewable and fossil fuel sources.

Chapter 3 Planning and Operation of Hybrid ac-dc Microgrid

3.1 Introduction

A hybrid AC-DC microgrid (HMG) integrates both AC and DC distributed generators (DGs), as well as AC and DC loads, into the grid. The AC and DC sources and loads are separated and connected to their respective subgrids primarily to reduce power conversion and thus increase system efficiency. The purpose of this chapter is to introduce a novel hybrid AC-DC microgrid planning and design model within a microgrid market environment in order to maximise net social welfare (NSW). NSW is defined as the present value of total demand payment minus the present value of total planning cost, which includes the cost of distributed energy sources (DERs) and converters, the cost of DER operation, and the cost of energy exchange with the utility grid subject to network constraints. To model the uncertainties associated with load demand, wind speed, and solar irradiation, the Scenario Tree approach is used. The proposed model's effectiveness is validated through simulation studies on a 28-bus real hybrid AC-DC microgrid.

3.2 Hybrid AC-DC Microgrid

Microgrids are thought to be the distribution network of the future. The proximity of DERs to loads and the utilisation of DGs in microgrids distinguish microgrids from the existing conventional power grid. Microgrids also promise to provide good power quality, improved reliability, lower power losses, less network congestion, and an efficient and environmentally friendly energy system.

The current focus of microgrid development is primarily on ac microgrids, which are standard conventional ac power systems. However, with current advancements in dc loads (such as LED lights, data centres, computers, and communication centres) and dc DERs (such as fuel cells, solar panels, and energy storage devices), hybrid ac-dc microgrids are more advantageous. HMG combines the advantages of both alternating current and direct current systems. There are ac and dc bus bars in HMG, and the bus bar selected depends on the type of load and DER connected. AC-based DERs and loads could be connected to alternating current buses, while DC-based DERs and loads could be connected to direct current buses. As a result, the required number of converters and inverters would be reduced, lowering planning costs and improving system efficiency. Integration of DGs would be facilitated by a simplified interface, which is a difficult task in ac microgrids. These benefits of HMG can usher in a revolutionary and highly viable option for future power grid development. A hybrid ac-dc microgrid is proposed to reduce the number of power conversions and to make it easier to integrate DGs of alternating current and direct current to their respective grids. The proposed model has two sides of operation, as shown in the one-line diagram, ac subgrid and dc subgrid. Interlinking converters connect the alternating current and direct current subgrids (IC).

This general architecture has the following advantages.

1) If the hybrid ac-dc microgrid's loads can be supplied from both ac and dc subgrids, the reliability and efficiency can be improved due to the availability of alternative resources. The integration of ac based DGs on ac subgrid and dc based DGs on dc subgrid makes this system more flexible.

2) The integration of ac-based DGs on an ac subgrid and dc-based DGs on a dc subgrid increases the system's flexibility.

3) In general, ac-based resources and loads have a larger share than dc-based resources and loads. As a result, the ac link can be regarded as the system's primary energy carrier.

4) The servicing capacity on the alternating current and direct current sides can be adjusted to meet the system's needs.

3.2 Background, Motivation and Literature Review

Electricity demand is rising, necessitating greater penetration from generating units and more efficient power grid operation [182]. The main contributors to the current critical situation are population growth, improved living standards, pollution, and a decrease in the production of traditional energy resources such as (natural gas, petroleum, coal, and so on). There are numerous drawbacks to using fossil fuels, such as the emission of gases that contribute to global warming and pollution [183]. With the passage of the Climate Change Act in 2008 and the subsequent implementation of electricity market reforms, the United Kingdom (UK) established itself as a global leader in renewables, particularly wind power [184]. To meet these targets, the UK government has established five-year carbon budgets that are currently in effect until 2032. They limit the amount of glasshouse gases that the United Kingdom can legally emit over a five-year period [185].

Microgrids are viewed as the distribution system of the future [186]. Microgrids form a local grouping of energy generating sources and loads that can feed its localised demand, improving grid efficiency. The microgrid concept reduces the number of reverse connections in an individual AC or DC grid while also allowing renewable AC-DC sources and loads to connect to the power system [187]. Although AC power systems have improved significantly over the last few decades, advances in power electronics have completely revolutionised the major domains of power systems and changed the load profile for end users. Modern appliances such as laptops, mobile phones, electric vehicles, televisions, remote controls, and so on run on DC power, which is typically supplied by an AC-DC converter [188]. The integration of DC technology into the existing system must be seamless. Hybrid AC-DC microgrids, in particular, can make DC power integration into existing AC systems easier [189].

Both AC and DC microgrids can benefit from hybrid microgrids. Furthermore, the number of required power converters would be drastically reduced, improving microgrid efficiency and lowering investment and operation costs [190]. So far, prior research on hybrid AC-DC microgrid planning has been limited, with only a few literatures available on modelling of individual DC or AC microgrid planning. [191] discussed various aspects of ac and dc microgrids. A planning model was created that determines the optimal DG generation mix as well as the type of microgrid, i.e., ac or dc. Ref. [192] provides a comprehensive review of technologies used in AC and DC microgrids, as well as different parameters, topographies, benefits, and drawbacks of each technology. It is stated that DC microgrid has more advantages than AC microgrid, particularly over longer distances. DC lines, for example, have lower line losses and more transmittable power. In contrast, DC protection systems are more expensive than AC protection systems. More research is needed into the standardisation and islanding control techniques used in DC systems. Finally, it is suggested that hybrid microgrids may be a more viable solution than DC microgrids. Without taking uncertainties into account, Ref. [193] proposes a decentralised multiagent-based real-time control model of a hybrid microgrid. The uncertainties in microgrid are investigated in Ref. [194]. Ref. [195] investigates dynamic assessment for hybrid microgrids. Different sources of uncertainty are investigated in Ref. [196]. The microgrid planning solution is divided into two subproblems: investment and operation. A coordinated real time control algorithm for hybrid AC-DC microgrid sources is presented in Ref. [197], and simulation results are validated with experimental results. The authors of Ref. [198] proposed energy management and operational modelling of hybrid microgrids. They investigated the time dependence impacts on the network over a 24-hour period to determine the optimal operation of a hybrid microgrid. According to Ref. [199], a hybrid microgrid can provide reliability to customer nodes by allocating appropriate DGs based on their size, location, and type. In Ref. [200], the goal of microgrid planning is to determine the optimal size and type of DG to be installed with a combination of heat and power systems. The authors of Ref. [201] present a hybrid microgrid that can integrate various small-size DGs into an existing power system. A hybrid microgrid decoupled control model is developed and its performance is evaluated. The incorporation of DGs in a hybrid microgrids model is proposed in Ref. [202]. At the DGs' connection point, an additional dc line is assumed. Ref. [203] discusses hybrid AC-DC planning. A comprehensive review of control strategies is provided in Ref. [204], with a focus on modelling, power management and control, stability, protection strategies, and power quality. Finally, research gaps are identified, and potential solutions are proposed.

3.3 Main Contributions of the Current work

The existing studies lack planning of hybrid AC-DC microgrid under uncertainties as most of the research is mainly focused on operation of HMG. Authors in [192-195] and [197-202] has discussed operation of microgrid while authors in [196] discussed planning of AC microgrid. Authors in [194,196] discussed uncertainty modeling in AC microgrids.   Comparison of the existing studies and the proposed model is shown in Table 1. To the best of Authors knowledge, there is no literature available that considers the planning of HMG within the electricity market. This chapter proposes a novel approach for planning of hybrid AC-DC microgrid within a novel microgrid market environment by maximizing net social welfare (NSW) considering uncertainties associated with DERs and dispatchable load demand.

3.4 Aim and approach

It is evident that the prior work on microgrid planning is very limited and to the best of authors’ knowledge there is no literature available regarding the planning and design of hybrid AC-DC microgrid within a market environment considering uncertainties and power flow of interlinking converters. This chapter proposes a novel approach for planning of hybrid AC-DC microgrid within a novel microgrid market environment by maximizing NSW considering uncertainties associated with DGs and dispatchable load demand subject to network constraints and power flow of interlinking converters. Scenario Tree approach is used to model the uncertainties related to load demand, wind speed and solar irradiation. The method evaluates the optimal amount of active power generated by WT and PV over the planning horizon.

3.5 Uncertainty Modelling

The increased penetration of renewable resources in electrical networks necessitates a novel approach to uncertainty modelling. The load levels approximate the demand cure in long and medium term power system models. In the case of high penetration of renewable resources, however, the accuracy of the traditional method cannot be guaranteed, resulting in applicable distortions in modelling results. Furthermore, the price-dependent resource penetration necessitates a new methodology, i.e. an increase in the number of load blocks.

To accommodate the increase in renewable generation, a new approach to modelling load levels with high PV and wind penetration has been considered, dividing the traditional load duration into manageable blocks. The following criteria were considered when splitting the load, solar irradiation, and wind curves: quarter, working or non-working day, and day or night. The criteria for quarters and working or non-working days are fixed. The day or night criteria best fits the uncertainty modelling for solar irradiation and has been considered as a suitable option in this model.

The load, wind, and solar irradiation curves are used to model uncertainty in a distribution system for each individual load block. Daily historical demand data is arranged from higher to lower values while maintaining the correlation between wind and PV production data from different days. Demand blocks are used to approximate the load duration curve. The length of the demand blocks varies along the load duration curve in order to accurately include peak demand in the model. Wind and PV productions are arranged from higher to lower values for each demand block in order to be represented alongside demand. All combinations of demand, wind power factor, and PV power factor levels are considered for each demand block. Within the demand block, each combination is assigned a probability equal to the probability of the demand factor level multiplied by the probability of the wind power factor and PV power factor levels. For the current scenario, 48 demand blocks, three demand factor levels, three wind power factor levels, and three PV power levels have been considered.

The problem is formulated as a stochastic-programming-based model with the goal of maximising nett social benefit. The associated scenario-based deterministic equivalent is written as a mixed-integer non-linear programme with guaranteed finite convergence to optimality and efficient off-the-shelf software. The stochastic programming model, as described below, can be mathematically formulated as a scenario-based deterministic equivalent based on [205]. The probability tree depicts the dynamics of the random parameters as well as the non-predictive nature of the decisions.

3.5.1 Wind speed modeling

Weibull PDF is used to model wind speed variation [206-209]. The PDF function that describes the relationship between wind speed and WT output power is given in [210].

$$PDF(v) = (\frac{k}{c})(\frac{v}{c})^{k-1} \exp\left[-(\frac{v}{c})^{k} \right] \tag{3.1}$$

where *v* represents speed of wind*, c* is the Weibull PDF scale index and *k* represents the shape index. The WT's generated power can be evaluated by using its power curve as follows [211, 212]:

$$P_w(v) = \begin{cases} 0, & 0 \le v \le v_{ci} \\ P_{rated} \times \dfrac{v - v_{ci}}{v_r - v_{ci}}, & v_{ci} \le v \le v_r \\ P_{rated}, & v_r \le v \le v_{co} \\ 0, & v_{co} \le v \end{cases} \tag{3.2}$$

where P_w is WTs generated power, P_{rated} represents the rated power, v_{ci} represents the cut-in speed, rated speed of WTs is represented by v_r and v_{co} is cut-off speed. The WTs Speed power curve is shown in Fig 1.

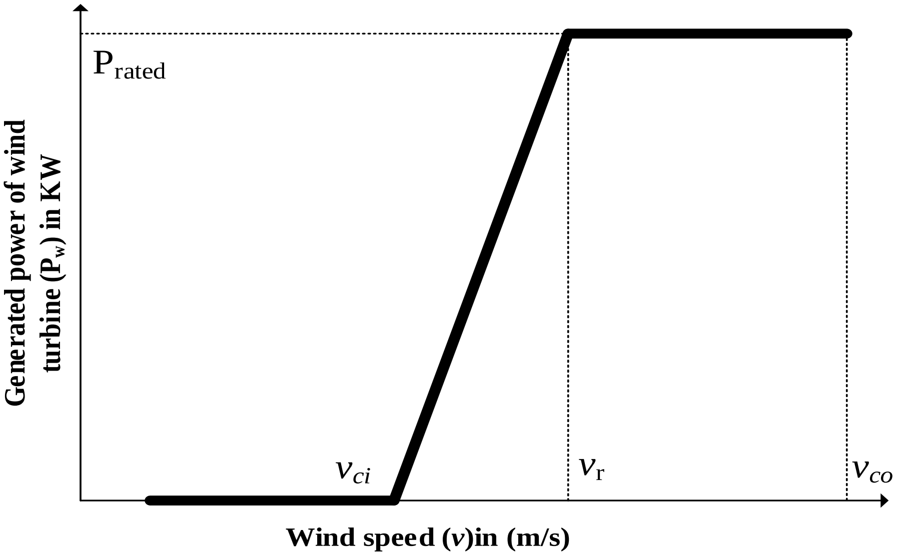


Fig.3-1. WTs Speed power curve

At the bus *i* and for scenario *s,* the active wind power is calculated as follows:

$$0 \le P_{i,s}^{w} \le \gamma_{i,s}^{w} \times P_{i,rated}^{w} \tag{3.3}$$

where $\gamma_{i,s}^{w}$ represents the percentage of the WT's generated active power

3.5.2 Modelling of Solar irradiance

The solar irradiance modelling is done by using Beta PDF which is described as follows:

$$PDF(s)=\begin{Bmatrix} \dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)+\Gamma(\beta)} \times s^{\alpha-1} \times (1-s)^{\beta-1}, & 0 \le s \le 1, 0 \le \alpha, \beta \\ 0 & else \end{Bmatrix} \tag{3.4}$$

where *s* is the solar irradiance (kW/m^2). α and β are the parameters of Beta PDF which are derived as follows:

$$\beta = (1-\mu)\times\left(\frac{\mu\times(1-\mu)}{\sigma^2}-1\right) \quad (3.5)$$

$$\alpha = \frac{\mu\times\beta}{1-\mu} \quad (3.6)$$

where μ is the mean and σ is the standard deviation of the random variable. The output power of PV is calculated with the help of Eqs. 7 and 8 respectively, the solar irradiance and the cell temperature as follow [213, 214]:

$$P_{pv} = P_{STC}\times\frac{G}{1000}\left[1+\delta\left(T_{cell}-25\right)\right] \quad (3.7)$$

$$T_{cell} = T_{amb}+\left(\frac{NOCT-20}{800}\right)G \quad (3.8)$$

where P_{pv} represents the PV output power in MW, P_{STC} represents the power under standard test condition in MW, δ represents the power-temperature coefficient in (%/°C), T_{cell} represents the cell temperature in °C, T_{amb} represents the ambient temperature in °C, $NOCT$ are the national operating cell temperature conditions in *°C*, *G* is the solar irradiance in (W/m^2).

3.5.3 Load demand uncertainty modeling

To model load demands at each bus, Normal PDF is used. The normal distribution PDF for uncertain load l is [215-216]:

$$PDF(l) = \frac{1}{\sigma_l\sqrt{2\pi}}\times\exp\left(-\frac{\left(l-\mu_l\right)^2}{2\sigma_l{}^2}\right) \quad (3.9)$$

The genetic algorithm (GA) and support vector machine (SVM)-based load forecasting use point forecasts, which do not estimate the full distribution of possible future values, whereas probabilistic forecasts provide the full distribution of possible future values and quantify the uncertainties in the forecasts. The two existing techniques for DG system reliability assessment are Monte Carlo simulation and analytical state enumeration. According to previous research, all uncertainties associated with DGs can be expressed by random variables X, which are described in terms of probability density functions (PDF), f(x) [205].

3.6 Modelling approach

To model the uncertainties associated with wind speed, solar irradiance, and load demand, hourly data consisting of load demand, wind speed, solar irradiance, and price must be available for one year (8760 h). The steps that follow describe the methodology for modelling uncertainty.

Step-1: The data is divided into four seasons: summer (June-August), spring (September-November), winter (December-February), and autumn (March-May), with each season lasting 2190 hours. Data is factorised by dividing it into peak load demand, wind speed, and solar irradiation.

Step 2: To construct the demand curve, arrange daily historical demand data for 8760 hours in descending order while maintaining the hourly correlation between demand, wind, and PV production. The ordered demand curve depicts zones where high values have a significant impact on NSW and, as a result, network investment.

Step 3: The wind speed and solar irradiation curves are also constructed by arranging data in each zone block from higher to lower values. For each time zone, a cumulative distribution function is calculated, which is then divided into three levels or segments: high, medium, and low. The level formulation is similar for load demand, wind speed, and solar irradiation.

Step 4: For each demand block, all demand, wind power factor, and PV power factor combinations are considered. Within the demand block, each combination is assigned a probability equal to the probability of the demand factor level multiplied by the probability of the wind power factor and the PV power factor levels.

Step 5: Scenarios are developed for time blocks by combining different levels of data. Each load level ll is made up of a scenario s that includes the average demand factor _(ll,s)d, the maximum wind power level _(ll,s)wind, and the PV power level _(ll,s)pv. For the current case study, 108 scenarios were generated by multiplying four demand blocks, three demand factor levels, three wind power factor levels, and three solar power factor levels and 3 levels for PV power.

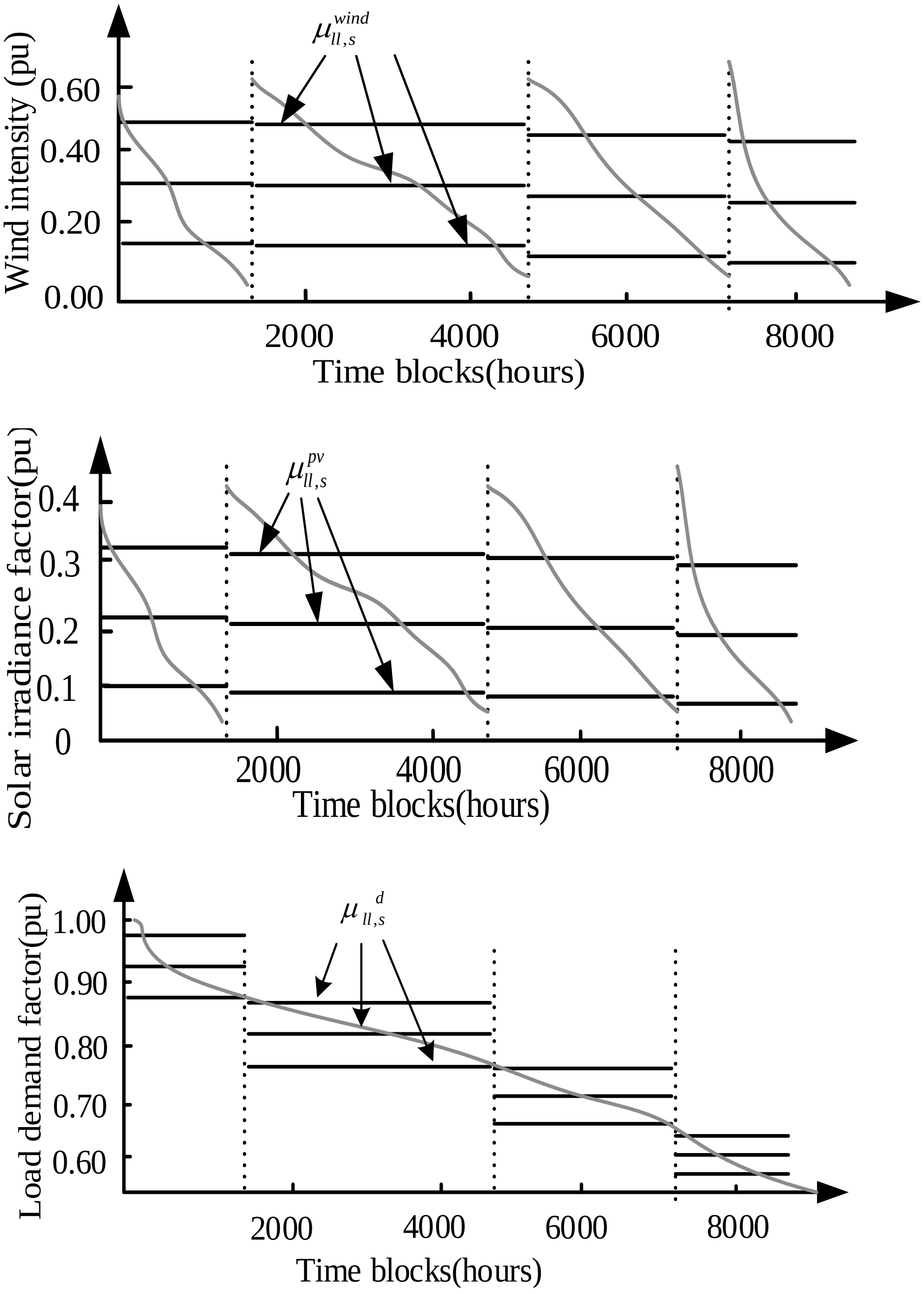


Fig. 3-2. Load, wind & irradiation curves

Fig.3-3 shows scenario-tree associated to each single considered variable (demand, wind and PV irradiation). The scenario tree depicts the dynamics of the random parameters as well as the unpredictable nature of the decisions. In this modelling, it is assumed that there are n possible future scenarios, with each scenario representing a different source of uncertainty.

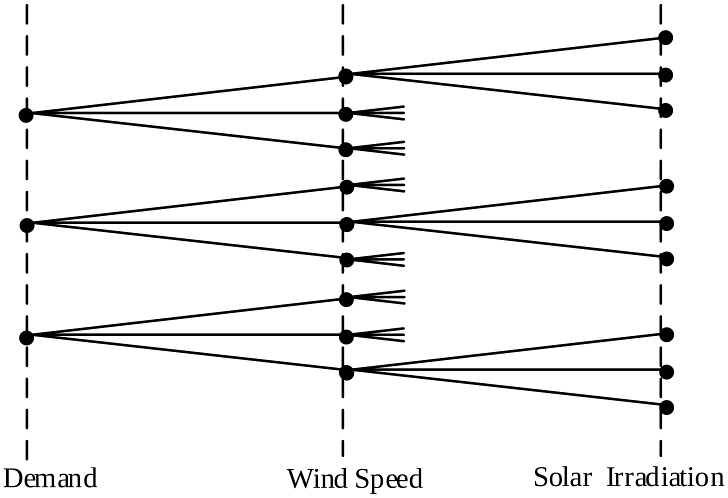


Fig. 3-3 Scenario tree

3.7 Hybrid ac-dc Microgrid Model

In this chapter, a general architecture of HMG (as shown in Fig 3.1) is proposed to reduce number of power conversions as in a traditional ac or dc grids and to facilitate the integration of ac-based or dc-based sources and loads. Hybrid ac-dc microgrids can also me termed as multiple-energy career system. The energy management and control of HMG is more complex and complicated than traditional ac or dc grids.

In ac/dc microgrids, only ac/dc buses are available, whereas in HMG, both ac bus and dc bus exists. A point with a transformer where ac grid and dc grid is required to connect with the utility grid is known as point of common coupling (PCC).The connection of ac bus with PCC is straight forward but a converter is required before connecting dc bus with utility grid. The selection of DERs will depend on capacity, location, cost and nature of operation required. Proper converters are required to connect each DRE with its associated feeder. If dc based DER is required to connect with ac feeder then dc-to-ac inverter will be used and if ac based DER is required to with dc feeder then ac-to-dc converter is required. This is also true in case of loads in which a proper converter is required to connect it with its opposite feeder.

3.7.1 Planning and Operation of hybrid AC-DC microgrid

In this proposed hybrid AC-DC microgrid model, renewable-based distributed generators (DGs), controllable DGs, DC and AC loads are connected through separate DC and AC links. An operation model of hybrid microgrid is proposed in which mixed integer nonlinear model is suggested to balance the generation and load taking into account the interconnection of DC and AC subgrids for maximizing the social welfare. The efficiency of the proposed model is established through the simulation studies on a test hybrid AC-DC microgrid.

The objective of HMG planning problem is to maximize the net social welfare (NSW) (10). It jointly maximises the consumers' benefits and minimises the total planning cost (13). The total planning cost consists of investment cost (IC) of all DGs and converters, operation and maintenance cost (OMC) of all DGs as well as the power exchange with utility grid. The cost for one planning year is the sum of IC and OMC.

$$
\begin{aligned}
\text{Maximise SW} = {} & \Big(\sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} c_{h,s,y}^{LAC} P_{h,s,y}^{LAC} + \sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} c_{h,s,y}^{LDC} P_{h,s,y}^{LDC}\Big) - \Big(\sum_{s=1}^{NS}\sum_{y=1}^{NY} c_{slk,s,y} P_{slk,s,y} \\
& + \sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} c_{h,s,y}^{WIND} P_{h,s,y}^{WIND} + \sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} c_{h,s,y}^{PV} P_{h,s,y}^{PV} + \sum_{s=1}^{NS}\sum_{y=1}^{NY} \mathrm{C}_{s,y}^{PG}\Big)
\end{aligned}
\tag{3.10}
$$

where C^{PG}= RR(IC + OMC) (3.11)

Note that capital recovery rate RR is present in cost function, calculated as

$$
\mathrm{RR} = \frac{1}{(1+r)^{t+1}} \tag{3.12}
$$

where *t* is the planning horizon and *r* is the discount rate and the planning horizon is considered to be for ten years period.

$$
\begin{aligned}
\mathrm{IC} = {} & \sum_{a=1}^{NG}\sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} CC_a P_{h,s,y}^{MAX} f_{ha} + CR\sum_{a=1}^{NG}\sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} P_{h,s,y}^{WIND} f_{ha} d_h + \\
& CI\sum_{a=1}^{NG}\sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} P_{h,s,y}^{PV} f_{ha}(1-d_h) + \sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY}\{CIP_{h,s,y}^{LAC} d_h + \\
& CRP_{h,s,y}^{LDC}(1-d_h)\} + CIP^{LIMIT} W
\end{aligned}
\tag{3.13}
$$

$$
\begin{aligned}
\mathrm{OMC} = {} & \sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} CostAC_{h,s,y} + \sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} CostDC_{h,s,y} + \\
& \sum_{h=1}^{NB}\sum_{s=1}^{NS}\sum_{y=1}^{NY} \rho_{h,s,y} P_{h,s,y}^{Fexch}
\end{aligned}
\tag{3.14}
$$

Where

$$
CostAC = C_{AC} \times P^{Gwind} \;\; and \;\; CostDC = C_{DC} \times P^{Gpv} \tag{3.15}
$$

3.7.2 Constraints:

The objective function is subjected to fallowing investment and operation constraints. Constraints are of two types (a) Equality constraints and (b) Inequality constraints.

1) *DER Connectivity:* Each DER is connected to only one feeder.

$$\sum_{a=1}^{NG} f_{ha} \leq 1 \tag{3.16}$$

2) *Installed capacity:* Installed capacity is greater than peak load demand is shown in Eq. (3.17).

$$\sum_{a=1}^{NG} P_{h,s,y}^{LAC} + \sum_{a=1}^{NG} P_{h,s,y}^{LDC} \leq \sum_{h=1}^{NB} \sum_{a=1}^{NG} \{P_{h,s,y}^{WIND} + P_{h,s,y}^{PV}\} f_{ha} \tag{3.17}$$

3) *Power balance:* Equation (3.18) represents the power balance equation which has to be satisfied at each bus.

$$\begin{aligned} &\sum_{a=1}^{NG} P_{h,s,y}^{LAC} \times ((d_h / EI) + (1-d_h)) + \sum_{a=1}^{NG} P_{h,s,y}^{LDC} (d_h + (1-d_h)/ER) \\ &= \sum_{a=1}^{NG} P_{h,s,y}^{WIND} \times (ER \times d_h + (1-d_h)) + \sum_{a=1}^{NG} P_{h,s,y}^{PV} (d_h + \\ &EI(1-d_h)) + P_{h,s,y}^{Fexch} (ER \times d_h + (1-d_h)) \end{aligned} \tag{3.18}$$

AC Power generation limit: Power generated by AC based DGs is limited by their installed capacity is shown in Eq. (3.19).

$$0 \leq P_{h,s,y}^{WIND} \leq P_{h,s,y}^{MAX} \tag{3.19}$$

4) *DC Power generation limit:* Power generated by DC based DGs is limited by their installed capacity.

$$0 \leq P_{h,s,y}^{PV} \leq P_{h,s,y}^{MAX} \tag{3.20}$$

5) *Maximum Power:* Total installed capacity of all DGs is equal to sum of total generated power.

$$P_{h,s,y}^{MAX} = \sum_{a=1}^{NG} P_{h,s,y}^{WIND} + P_{h,s,y}^{PV} \tag{3.21}$$

6) *Voltage limits:* Voltage at each bus is limited by the boundary values.

$$V_h^{\min} \leq V_h \leq V_h^{\max} \tag{3.22}$$

where *h* is the number of AC and DC buses, *a* is set of generators buses. It is assumed that WTs are installed at buses 2, 3, 6 and 8 while PVs are installed at buses 16, 17, 20 and 22. It should be noted that buses 1 to 14 belong to ac subgrid and buses 15 to 28 to dc subgrid. . $c_{h,s,y}^{LAC}$ and $c_{h,s,y}^{LDC}$ are the bid prices for AC and DC load demands, respectively at bus *h*, scenario *s* and year *y*. $P_{h,s,y}^{LAC}$ and $P_{h,s,y}^{LDC}$ are the active power for ac and dc load demand respectively at bus *h*, scenario *s* and year *y*. The investment cost (3.13) comprises of DG investment cost (first term) and the cost of converters (rest of the terms). The investment cost of DG is calculated as installed power capacity $P_{h,s,y}^{MAX}$ times the capital cost CC_a of distributed energy resources (DER). The $P_{h,s,y}^{MAX}$ will be determined at the time of planning. A binary decision variable f_{ha} is also introduced in the investment cost of DG. The f_{ha} has two functionalities, first it gives information that DG is installed and secondly it also gives information about the bus to which DG is connected. If f_{ha} is 1 in planning, this means DG *a* will be installed and will be connected to bus h. The next four terms in the investment cost are modelled using binary decision variable d_h that determine the type of bus, i.e. AC or DC. If d_h is 1 in planning it means it is dc feeder and for ac feeder d_h is set to zero. If d_h is zero it means feeder is ac and an additional cost of inverter (CI) will be added if dc-based DG is to be used in planning to connect with ac grid. Similarly if d_h is set to 1 in the planning problem then feeder is said to be dc and an additional cost of rectifier (CR) will be added if AC DG is to be used to connect with dc feeder. The second and third terms in (3.13) represents the cost of converter and inverter on the generation side, respectively. While fourth and fifth terms in (13) represent the cost of converter and inverter on the load side. The last term in (3.13) represents the cost of inverter required to connect dc feeder with utility grid. A binary decision variable *W* is also introduced in last term. If *W* is set to zero it means there is no dc feeder but if *W* is set to 1 it means at least one feeder is dc. P^{Limit} is the flow limit between the microgrid and the utility grid.

The operation and maintenance cost (3.14) includes three parts, the first and second terms represents the generation cost of DGs while third term represents the cost of energy purchased from the grid. The generation cost of DGs is the sum of amount of energy produced by each DG (CostAC/CostDC) times the price of its generation $C_{h,s,y}$. The third term in (3.14) represents the total energy exchange with the grid times the market price at the time of exchange of power. The total energy exchange with the grid (P_M) is equal to the sum of energy exchange at each feeder ($P_{h,s,y}^{Fexch}$).

3.7.3 Hybrid microgrid electricity market model

A hybrid AC-DC microgrid electricity market model is proposed in this section. The hybrid microgrid market operator (HMMO) is a platform that enables market activities for end user customers, controls the operational facilities and it buys active power from bilateral contracts or through the pool. Dispatchable loads (DLs), WTs and PVs sends offers and bids prices of active power in form of blocks to the hybrid microgrid market (HMM) every hour. To maximize the NSW, the HMMO combines offers and bids prices. Fig 3-4 shows the proposed hybrid AC-DC microgrid electricity market model.

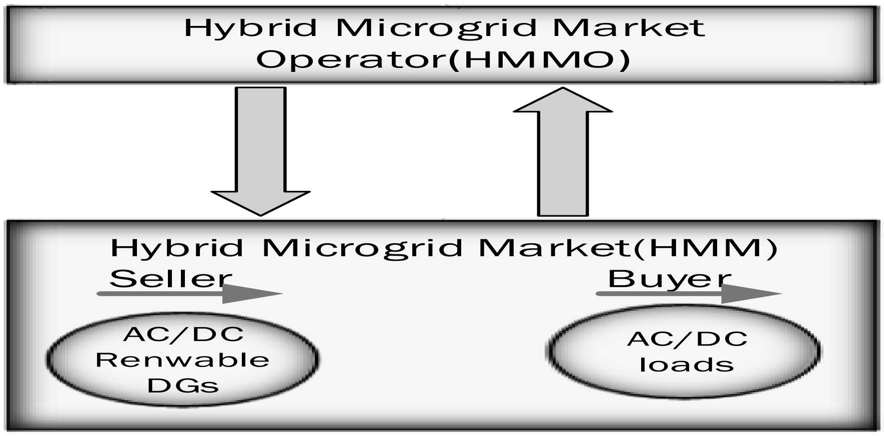


Fig. 3-4 Proposed Hybrid Microgrid Electricity Market Structure

Two major responsibilities of the HMMO within this structure are:

1) To receive demand bids from HMM and offer an aggregated bid to the wholesale energy market.
2) From the wholesale energy market, it will receive schedule of WTs, PVs and DLs according to the market prices one day ahead. WTs, PVs and DLs will provide

offer and bid prices and active power quantity information for every 24-hour trading period one day ahead.

HMM would submit their bids to the HMMO and later be notified by HMMO on the amount of awarded power. The amount of power exchange with distribution network is assigned by HMMO, hence it is known to the HMMO in advance which minimizes uncertainties caused by the HMM. Once the power exchange with the utility grid and HMM is known in advance for the 24 hours of the next day, the HMM would solve a market-based scheduling problem to optimize the scheduling of its DGs and loads.

3.8 Case study and Simulation Results

The effectiveness of the proposed method is verified through the simulation studies on a 28-bus real hybrid AC-DC microgrid based [217]. The single-line diagram of a 28-bus real hybrid AC-DC microgrid is shown in Fig. 3-5.

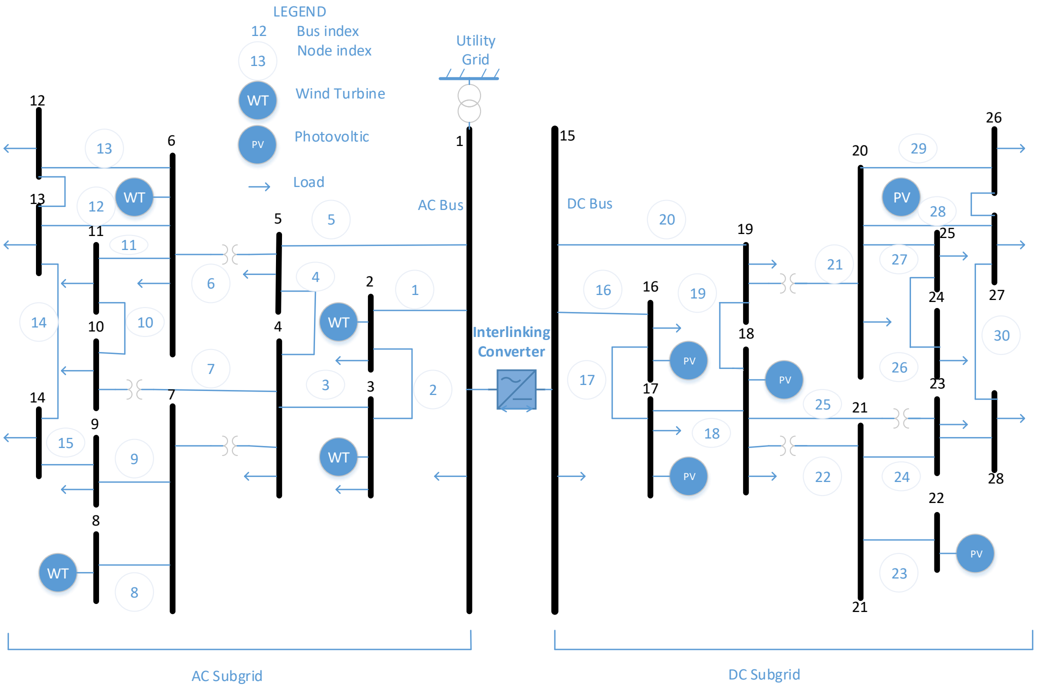


Figure 3-5 Single-line diagram of Hybrid ac-dc microgrid

It constitutes of an AC subgrid with conventional DG sources, DC subgrid with DC sources and an interlinking converter (IC) which links the two subgrids together. Each of the subgrids includes their individual loads. The hybrid AC-DC microgrid is connected to the utility grid during normal grid operation. The proposed hybrid AC-DC microgrid reduces multiple power conversion processes in an individual AC or DC grid.

The branch data for ac and dc branches is represented in tables 3-1 and 3-2 respectively.

Table 3-1 AC branch data

Branches	R(p.u)	X(p.u)
1-2	0.01938	0.05917
1-5	0.05403	0.22304
2-3	0.04699	0.19797
2-4	0.05811	0.17632
2-5	0.05695	0.17388
3-4	0.06701	0.17103
4-5	0.01335	0.04211
4-7	0	0.20912
4-9	0	0.55618
5-6	0	0.25202
6-11	0.09498	0.1989
6-12	0.12291	0.25581
6-13	0.06615	0.13027
7-8	0	0.17615
7-9	0	0.11001
9-10	0.03181	0.0845
9-14	0.12711	0.27038
10-11	0.08205	0.19207
12-13	0.22092	0.19988
13-14	0.17093	0.34802

Table 3-2 DC branch data

Branches	R(p.u)	X(p.u)
15-16	0.028101	0
15-19	0.0783435	0
16-17	0.0681355	0
16-18	0.0842595	0
16-19	0.0825775	0
17-18	0.0971645	0
18-19	0.0193575	0
18-21	0	0
18-23	0	0
19-20	0	0
20-25	0.137721	0
20-26	0.1782195	0
20-27	0.0959175	0
21-22	0	0
21-23	0	0
23-24	0.0461245	0
23-28	0.1843095	0
24-25	0.1189725	0
26-27	0.320334	0
27-28	0.2478485	0

Active and reactive load values including $V_{\min}$ and $V_{\max}$ are shown Table 3-3 for ac buses while in Table3-4 active load value, $V_{\min}$ and $V_{\max}$ are represented for dc buses. The voltage limits are assumed to be between $V_{\min}$ =0.94p.u and $V_{\max}$ =1.06 p.u for ac side and $V_{\min}$ =0.99p.u and $V_{\max}$ =1.16 p.u for dc side

Table 3-3 AC bus data

Bus No.	P_{load} (p.u)	Q_{load} (p.u)	$V_{\max}$ (p.u)	$V_{\min}$ (p.u)
1	0.0	0.0	1.06	0.94
2	0.017	0.027	1.06	0.94
3	0.055	0.895	1.06	0.94
4	0.012	0.039	1.06	0.94
5	0.076	0.016	1.06	0.94
6	0.022	0.075	1.06	0.94
7	0.0	0.015	1.06	0.94
8	0.0	0.08	1.06	0.94
9	0.055	0.166	1.06	0.94
10	0.068	0.058	1.06	0.94
11	0.015	0.018	1.06	0.94
12	0.011	0.016	1.06	0.94
13	0.028	0.058	1.06	0.94
14	0.019	0.05	1.06	0.94

Table 3-4 DC bus data

Bus No.	P_{load} (p.u)	V_{max} (p.u)	V_{min} (p.u)
15	0.0	1.16	0.99
16	0.0057	1.16	0.99
17	0.0042	1.16	0.99
18	0.0080	1.16	0.99
19	0.0276	1.16	0.99
20	0.0012	1.16	0.99
21	0.0	1.16	0.99
22	0.0	1.16	0.99
23	0.0195	1.16	0.99
24	0.009	1.16	0.99
25	0.035	1.16	0.99
26	0.061	1.16	0.99
27	0.038	1.16	0.99
28	0.0049	1.16	0.99

The market-based optimal power flow is used to maximize the NSW in order to find the optimal capacity of WTs and PVs. The load increment is assumed to be 3% yearly over the planning horizon. In this chapter, it is assumed that buses 2, 3, 6 and 8 are four possible locations for WTs to be installed at AC subgrid and 8, 15, 16, 17, 20 and 22 are five possible locations for PVs to be installed at DC subgrid, respectively. It is notable that the selection of possible locations of WTs and PVs relies on non-technical factors such as legal requirements, space/land availability and other amenities. It is assumed that four 660kW WTs at buses 2, 3, 6 and 8 while five 440kW PVs at buses 15, 16, 17 18 and 20 are installed. WTs and PVs can be allocated at AC and DC buses, respectively. For each scenario, this is represented by three blocks in the WT's and PV's offer with the following price presented in Tables2and3respectively.

Table 3-5 Active power bid prices for the WT's

Bus No.	Active power bid price list for WT's Blocks (MW@£/MWh)		
	b_1	b_2	b3
2	2.51@280	1.90@270	1.46@250
3	1.10@270	0.70@260	0.15@250
4	0.02@260	0.03@250	0.01@240
5	1.18@250	1.12@240	1.15@230
6	01.9@240	0.61@240	0.32@230
7	0.91@250	0.59@230	0.49@230
9	0.21@240	0.52@220	0.29@220
10	1.41@240	0.89@210	0.42@220
11	1.50@230	0.90@210	0.49@210
12	0.45@220	0.21@200	0.34@190
13	0.69@220	0.21@190	0.22@180
14	0.35@190	0.15@180	0.17@170

Table 3-6 Active power bid prices for the PV's

Bus No.	Active power bid price list for PV's Blocks (MW@£/MWh)		
	b1	b2	b3
15	0.81@240	1.60@230	1.16@220
16	1.13@240	0.70@230	0.15@210
17	0.92@230	0.03@220	0.01@210
18	0.78@220	6.12@220	3.15@200
19	1.90@220	0.61@220	0.26@200
20	0.91@210	0.59@220	0.51@190
21	0.21@200	0.20@210	0.19@190
22	1.41@200	0.89@210	0.52@180
23	1.50@190	0.90@200	0.49@180
24	0.45@190	0.21@200	0.14@170
25	0.69@190	0.21@190	0.31@170
26	0.35@190	0.15@180	0.09@160
27	0.35@180	0.35@170	0.39@160
28	0.35@180	0.35@170	0.35@160

Assuming a load growth of 3% for each year of the planning horizon, the dispatched wind active power increases proportionally to the load demand growth. This is mainly due to the proportional relation between wind generation and the size of the blocks in the WT's offer and to the assumption of a proportional load increase at all buses that alleviates voltage and thermal constraints as shown in Fig. 6, 7, 8 and 9 respectively. The total yearly active power dispatched by WTs at all candidate buses is shown in Fig. 10. The dispatched PV active power at each candidate bus also increases proportionally to the load demand growth as the 3% load growth for each year is also assumed for each year of the planning horizon as shown in Fig. 11. As expected, due to the WTs and PVs installations, the NSW also increases proportionally to load demand wind and solar generation during each year of the planning horizon, as shown in Fig. 12. In Fig.13, the comparison of the social welfare for first twenty scenarios for year 1 and year 10 is shown. It can be seen in that social welfare increases in each scenario in the last year compared to one in the first year.

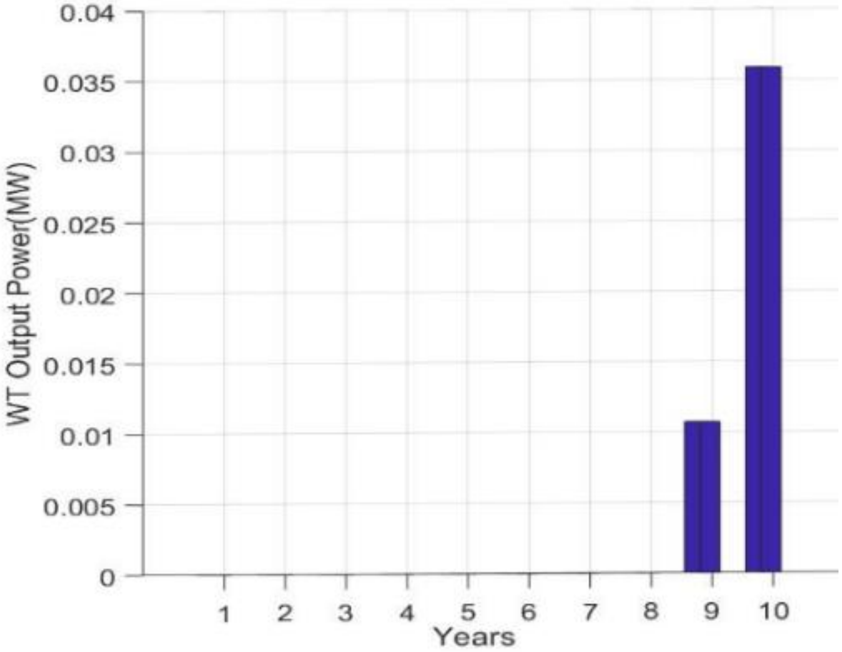


Fig. 3-6. Total yearly dispatched Wind active power at bus 2

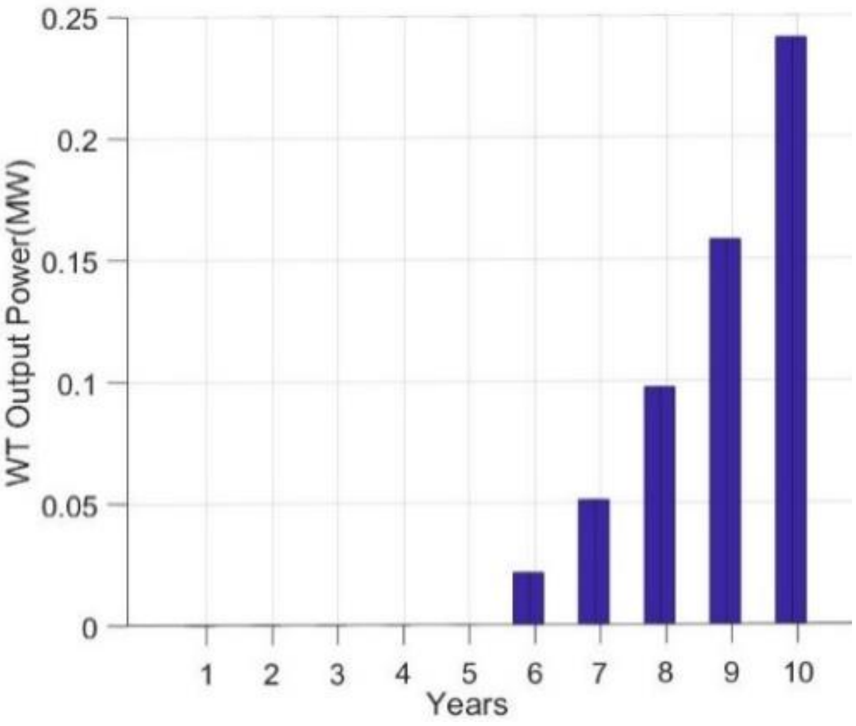


Fig. 3-7. Total yearly dispatched Wind active power at bus 3

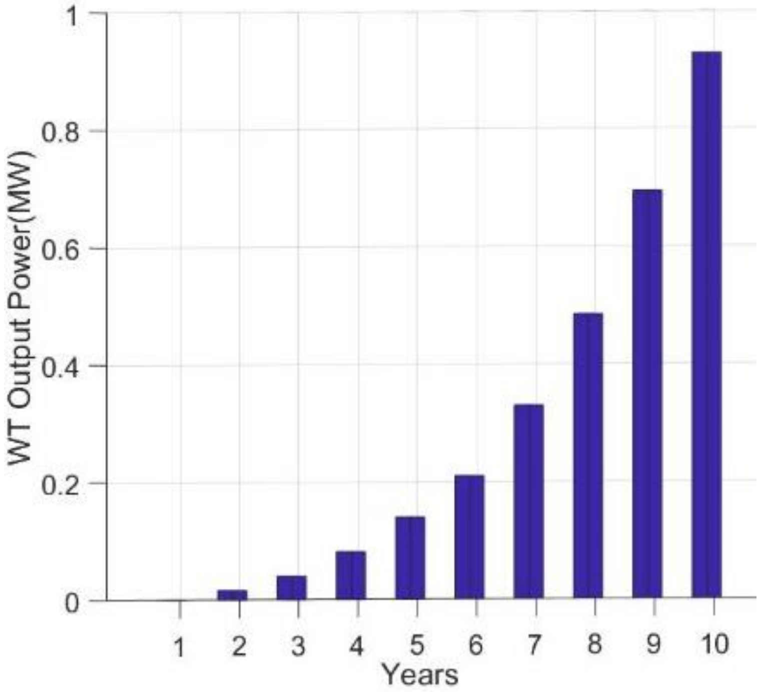


Fig. 3-8. Total yearly dispatched Wind active power at bus 6

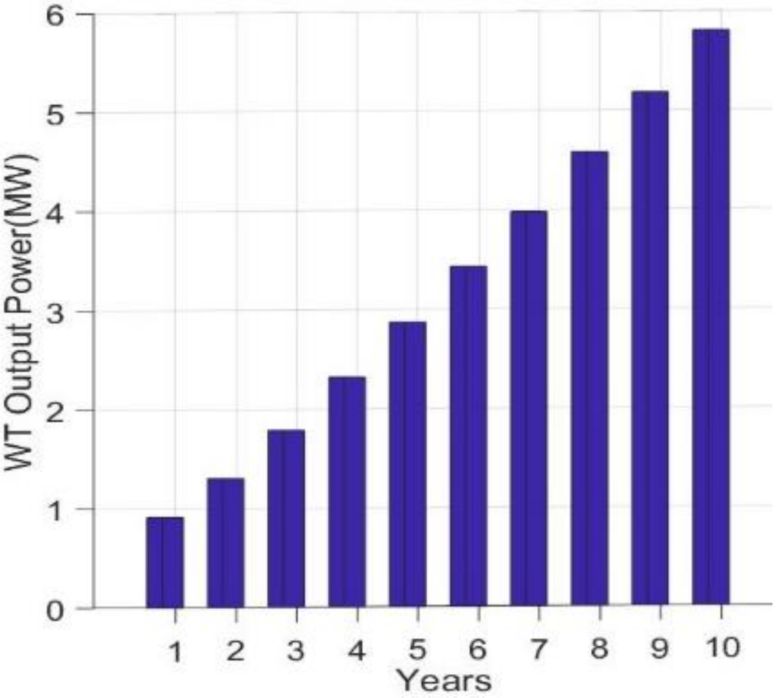


Fig. 3-9. Total yearly dispatched Wind active power at bus 8

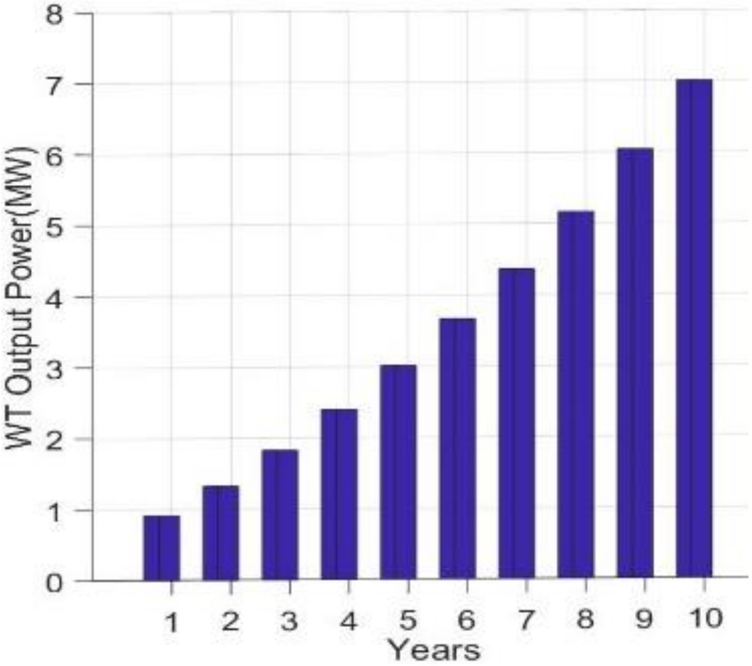


Fig. 3-10. Total yearly dispatched Wind active power

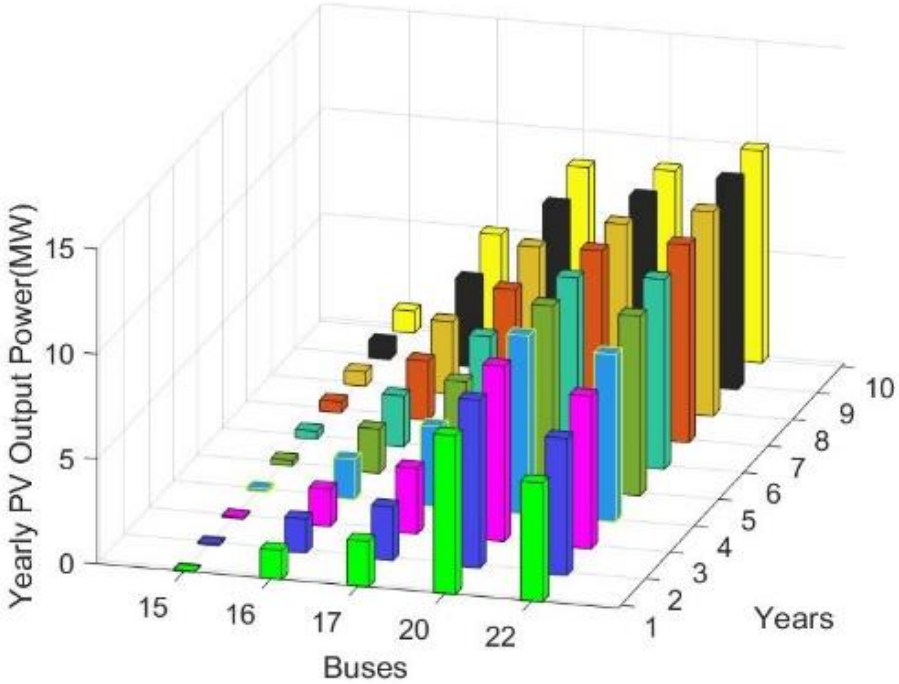


Fig.3-11. Total yearly dispatched PV active power

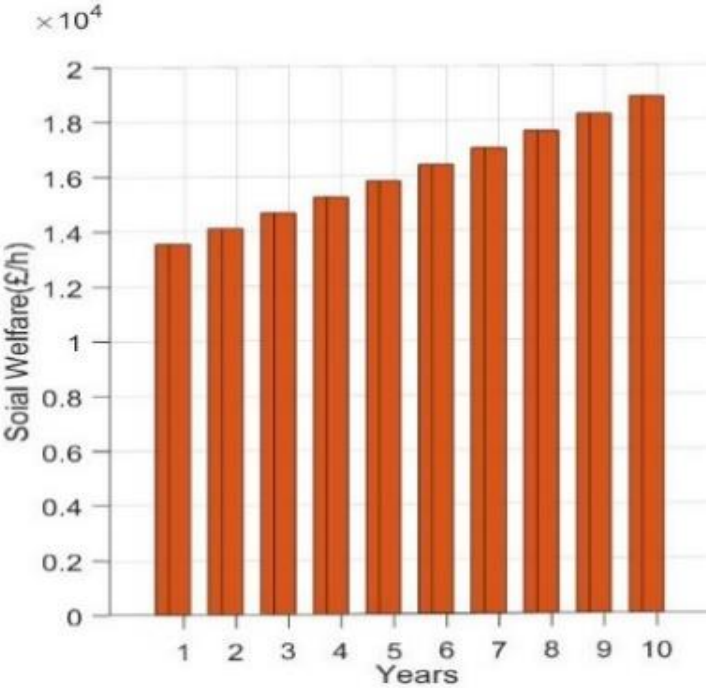


Fig. 3-12. Total Net Social Welfare over the planning horizon

The proposed method has been implemented in GAMS environment and the non-linear program solver MINLP is used on a PC with Core i7 CPU and 16 GB of RAM. Market based active optimal power flow is used to maximize the social welfare subject to network constraints.

3.9 Conclusion

In this chapter, a novel stochastic approach for planning and design of hybrid microgrids within a market environment was proposed. The method evaluates the amount of active power generated by WT and PV that can deliver to the load and the amount of active power injected or absorbed from the grid. Scenario based approach is used to model the uncertainty related to the wind speed, solar irradiation and load demand.

The proposed model numerical simulation proves the viability of hybrid AC-DC microgrid in supplying loads. The objective of hybrid AC-DC microgrid planning problem is to maximize NSW to simultaneously maximise consumers' payments and reduce total planning cost.

The proposed configuration will help hybrid AC-DC microgrid planners to estimate planning cost with flexibility to consider any type of load ac/dc and the type of DERs. Different components of hybrid AC-DC microgrid were explained, followed by developing the hybrid AC-DC microgrid planning model with the objective of determining the optimal DERs generation mix and reduced planning cost.

In this chapter, for the sake of simplicity, AC based conventional DG sources are placed on AC subgrid and DC sources are placed on DC subgrid. However, we aim to develop the proposed formulation to be able to accommodate AC based conventional DG sources and DC sources on both AC and DC subgrids and in optimal locations. Authors are also working on active network management (ANM) schemes that includes coordinated voltage control (CVC) of on-load tap changers (OLTCs) and adaptive power factor control (PFC) which will offer a feasible solution for HMMO for optimal active management and optimal planning and operation of the HMG.

Chapter 4 Planning and operation of multi-carrier energy systems with distributed injection of renewable energy resources.

4.1 Introduction

The advancements in economical energy systems and the interdependency of different energy infrastructures have compelled many countries to modify their energy polices. The interaction between Natural Gas Network (NGN), electricity system and heat distribution network is increasing day by day due to the use of natural gas-based generators which uses natural gas (NG) to produce electricity and heat. The integration of different energy systems has increased the energy systems flexibility and reliability. In this chapter, a novel Mixed-Integer Non-Linear Programming (MINLP) model is proposed for the planning and operation of Multi-carrier energy microgrid network (MCEMGN) which integrates Electricity-NG-heat system which includes NGN, Hybrid AC-DC microgrid and heat distribution network. The proposed framework optimized the planning and operational cost of the MCEMGN system by considering the nodal and the energy flow constraints of all networks. The proposed Hybrid AC-DC microgrid (HMG) allows integration of both AC and DC distributed generators (DGs), AC and DC loads into the grid directly. The proposed MCEMGN includes various energy independent gears e.g combine heat and power (CHP) units, Boiler and DG’s. Uncertainties related of Wind, Solar power generation and load demand have been considered in this model as these factors affect the operation of the integrated Gas-Heat-Electricity system. The effectiveness of the proposed model is validated through the simulation studies on a 28-bus real hybrid AC-DC microgrid, 15-node gas network and 14-node heat distribution network.

4.2 Background and Related research:

The rising fuel prices and energy crisis have compelled many counties to look for more flexible and reliable energy production and consumption sources. In response to improve the energy production and consumption, multi-carrier energy system is the most attractive and economical option. The reduction in fossil fuel production, the dependency of humans on different forms of energy resources and efforts by the different countries to reduce the greenhouse gas emission has elevated the importance of natural gas (NG) as a fuel for the production of electricity [218]. The usage of NG for the production of electricity has increased the interdependency of the NG and electricity network [219]. The good living standard, high fuel prices, central generation capital cost, pollution increase, decrease in energy production form traditional energy resources are the main causes of current critical situation [220]. The use of NG for electricity production the efficient DG's has changed the energy sector dramatically as well as the electricity network enforcement planning [221]. The integrated energy systems are more economical and advantageous then independent energy systems [222]. By adding gas-fired generators into the electrical system, the capacity of the system also increases and system becomes more eco-efficient as the gas-fired units have less capital investment cost, offers more operational flexibility and low carbon emission then other thermal generators [223].

By considering the benefits of the integrated system mentioned above, many research works have gained attention on coordination between electricity network and NG network. In [224], an hourly demand response model of electrical power network and NG transmission constraints are studied. In [225], planning in NG network and electric system is studied by considering the uncertainties and has maximized social welfare. In [226], a short-term optimal operation of both NG network and electricity network is studied by considering the constraints regarding pipelines, extraction and storage. In [227], the steady-state model of NG network and electricity system is analyzed by taking into consideration the effect of heat on the flow of NG. In [228], the operation cost minimization of considered by evaluating the short-term unit commitment with NG system. In [229], the effect of penetration of wind turbines on multi energy system is studied and the ramp-up time of gas generators, storage and compression facilities of gas are also studied. In [230], the incorporation of hydro and NG systems under the penetration of WT's is studied. In [231], the optimal size, location and output power of DGs is located in a muti-carrier energy system. In [232], the problems cased in electrical system economic operation due to gas flow, security, supply and storage are discussed. In [233], the gas-fired generating units are considered as the power injectors into the electricity network. The factors such as pressure fluctuation, storage and security are not considered in the planning which might affect the economical operation of the electricity network. In [234], the planning and operation model of hybrid ac-dc microgrid is proposed considering the uncertainties related to wind and PV. In [235], a non-convex programming problem have developed for hybrid electricity system. In [236], Newton's method is applied to analyze the integration of electrical system with NG network by considering some constraints such as temperature and gas supply fluctuation. In [237], a study based on nexus of British gas network and electricity system is carried out considering the uncertainties related to wind. In [238], an optimization topology is proposed for the nexus of gas and electricity network by taking into the consideration the uncertainties related to wind and demand response. In [239], a steady-state formulation is studied for the nexus of NG and electricity network by taking into the consideration the electricity market price. In [240], a MINLP model for multi-carrier energy systems proposed by using linearization method to obtain the global optimal solution. Different Energy carriers can be integrated to the systems such as CHP, boiler, power to gas (P2G) units, gas compressors and heat pumps etc [241-242]. The advancement of MCE systems has been studied in several recent publications. An optimization model has been studied for multi generation microgrid which considers renewable energy resources, thermal energy and electrical energy storage [243]. A real time energy optimization for muti generation that includes internal combustion engines, cooling units, chillers and boilers was studied [244].

In order to achieve efficient and reliable MCE system, smart grids is an ideal area to employ the MCE system concept. Hybrid microgrid offers more benefits than AC or DC microgrid types. There will be a reduction in power converters required for power conversion which will increase the microgrid's efficiency and will lower investment cost and operational costs [245]. The studies so far on the planning of hybrid AC-DC microgrid is very limited and only few literatures discuss the modeling of hybrid microgrid planning.

To the best of our knowledge, this study is considered the first study to focus on multi-carrier energy systems, which involves planning and operation of hybrid AC-DC microgrid with NG network and heat network, by considering the uncertainties related to solar, wind and NG supply. This chapter proposes a novel MINLP multi-carrier energy systems model which involves hybrid AC-DC microgrid and NG network and heat network by minimizing the planning and operational cost by considering the uncertainties that are associated with WTs, PV, gas-fired generating units and dispatchable load demand.

4.3 Contribution to present work

The prior study on multi energy systems which includes microgrids, NG network and heat network is limited and in the best of our knowledge, there is no literature so far regarding the planning and operation modeling that considers the nexus of hybrid microgrid, NG network and heat network while considering WTs, PV and dispatchable load uncertainties. This chapter discusses a very novel approach for MINLP model for planning and operation of multi-carrier energy systems by minimizing cost considering the uncertainties that are associated with dispatchable load demand and DGs subjected to network constraints. In this work, the optimal energy flow is studied in proposed MCEMGN operation framework.

4.4 Structure of integrated planning:

Historically, the energy demands for the end-users are met through different energy vectors e.g the electricity demand is met with the grid supply and a different system will be used to fulfil the heating and gas demand. For sustainability and affordability point of view, the cost price for gas, heat and electricity is of vital importance. The end-user can save a lot of capital by investing into more reliable and efficient devices [246]. The power systems flexibility in traditional decoupled energy system can be added by integrating these systems together in the form of multi energy system (MES) [247].

The proposed MCEMGN systems schematic diagram is shown in Fig. 4-1. The MCEMGN consists of electricity network, gas network and heat network, and different types of energy consumers, and energy equipment which are interdependent. The HMG is connected to gas network through CHP. The CHP is the coupling equipment between gas, electricity and heat networks. The boiler unit interlinks gas and heat networks. The traditional MG only supplies to the electrical loads, in the case of MCEMGN the heat, gas and electrical loads can be supplied. The MCEMGN can provide heat, gas and electricity energies to it’s customers in a secure and economical way. The MCEMGN can operate in grid connected manner or in islanded manner.

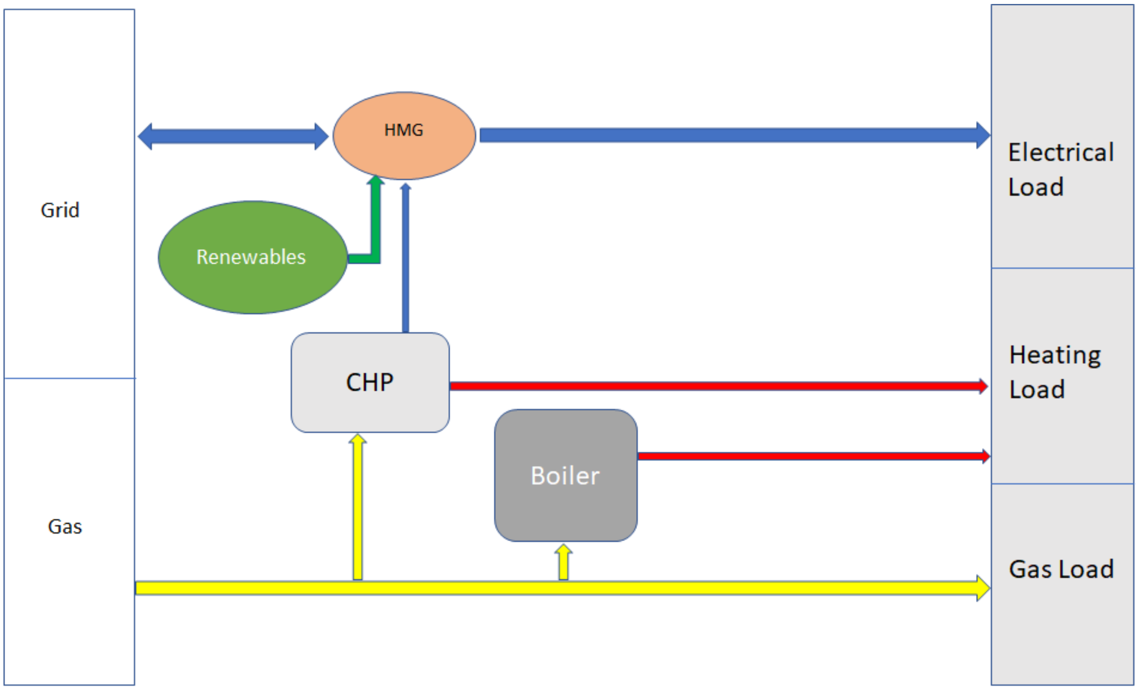


Figure 4-1 MCEMGN general structure

4.5 Planning and operation methodology of multi-carrier energy systems:

The objective of this planning and operation problem is to jointly minimize the total planning cost in the Multi-carrier energy microgrid network (MCEMGN). The net Investment cost comprises of different costs such as electrical energy cost exchange between MCEMGN and upstream Electrical distribution network, gas energy cost exchange between MCEMGN and upstream gas distribution network and heat energy cost exchange between MCEMGN and upstream heat distribution network.

$$\min \ \text{Cost}=\sum(\phi_E^{Grid}.P_E^{Grid}+\phi_G^{GN}.P_G^{GN}+\phi_H^{HN}.P_H^{HN}) \tag{4.1}$$

The minimization must satisfy the energy flow of each network. Hence the equality an in-equality constraints about each network must be satisfied. The following section will discuss the energy flow analysis in integrated electricity-gas-heat system.

4.5.1 Hybrid AC-DC microgrid network model

The hybrid AC-DC microgrid network of MCEMGN includes DG's, converters, inverters, DER's and electrical loads. The electrical network must satisfy the power balance in each node. The modeling of hybrid AC-DC microgrid network is discussed in detail in the chapter No. 3. The planning cost $\mathrm{Cos}t^{E}$ is the sum of OMC^{E} and CC^{E} times capital recovery rate (CRR).

$$\mathrm{Cos}t^{E} = CRR(CC^{E} + OMC^{E})$$
(4.2)

where CRR is determined as

$$\mathrm{CRR}=1/(1+d)^{y+1} \tag{4.3}$$

where *y* is planning period and *d* is the discount rate.

4.5.2 CHP model

The combine heat and power units (CHP) are used to generate heat and power simultaneously to reduce the curtailment of PV and wind power. The CHP units also has environmental and economic benefits for microgrid. The CHP can provide heat and power continuously for longer period hence provides more stability to the multi-energy system. The CHP unit cost comprises of annualized investment cost (CC^{chp}), fuel cost ($Fuel^{chp}$) and Operation and maintenance cost (OMC^{chp}) [248].

$$IC^{chp} = \sum [CC^{chp} + OMC^{chp} + Fuel^{chp}] \tag{4.4}$$

where

$$CC^{chp} = (\mathrm{Cap}^{chp}) \times \left[\frac{\sum Cap.\mathrm{Pr}\,ice^{chp}}{\mathrm{life}^{chp}} \right]$$

(4.5)

where Cap^{chp} is the capacity of the CHP and $Cap.\mathrm{Pr}\,ice^{chp}$ is the price of the CHP capacity in (£/kw) and life^{chp} is the life of the CHP in years.

The CHP model is subjected to following investment and operation constraints

a) Hourly energy delivered:

The hourly power (Electricity + thermal) delivered to the load must be less than the installed capacity of the CHP (Cap^{chp}).

$$Power^{chp} + Heat^{chp} \leq \sum \mathrm{Cap}^{chp} \tag{4.6}$$

b) Fuel Constraint:

The amount of fuel (gas) which CHP uses depends upon the natural gas price ($\mathrm{Pr}\,ice^{NG}$), amount of heat and electricity produced and its efficiency.

$$Fuel^{chp} = \sum \Pr ice^{NG} \times [(\eta_{elec}^{CHP} \times Power) + (\eta_{Heat}^{CHP} \times Heat)] \tag{4.7}$$

c) Ramp-up and Ramp-down time:

The following equations shows the ramp-up and ramp-down constraints

$$\begin{aligned} Power_n - Power_{n-1} &\leq R_{up} \\ Power_{n-1} - Power_n &\leq R_{down} \end{aligned} \tag{4.8}$$

4.5.3 Boiler model

The boiler uses natural gas as a fuel to produce heat. The boiler with the CHP must attend the heat load requirement of the MCEMGN. The boiler cost comprises of annualized investment cost (CC^{boiler}), fuel cost ($Fuel^{boiler}$) and Operation and maintenance cost (OMC^{boiler}) [248].

$$IC^{boiler} = \sum [CC^{boiler} + OMC^{boiler} + Fuel^{boiler}] \tag{4.9}$$

Where

$$CC^{boiler} = (C\mathrm{ap}^{boiler}) \times \left[\frac{\sum Cap.\Pr ice^{boiler}}{\mathrm{life}^{boiler}} \right] \tag{4.10}$$

where $C\mathrm{ap}^{boiler}$ is the capacity of the boiler and $Cap.\Pr ice^{boiler}$ is the price of the boiler’s capacity in (£/kw) and life^{boiler} is the life of the boiler in years.

The total hourly heat produced by the boiler is shown by the following equation

$$\mathrm{H}^{boiler} = \sum (NG \times \eta^{Boiler}) \tag{4.11}$$

The boiler model is subjected to following investment and operation constraints

a) Hourly Heat delivered:

The heat $Heat^{boiler}$ delivered to the load must be less than the installed capacity of the boiler Cap^{boiler}.

$$Heat^{boiler} \leq \sum Cap^{boiler} \tag{4.12}$$

b) Fuel Constraint:

The amount of fuel (gas) which boiler uses depends upon the natural gas price ($\mathrm{Pr}\,ice^{NG}$), amount of heat produced and its efficiency.

$$Fuel^{boiler} = \sum \mathrm{Pr}\,ice^{NG} \times [(\eta_{Heat}^{boiler} \times Heat)] \tag{4.13}$$

c) Ramp-up and Ramp-down time:

The following equations shows the ramp-up and ramp-down constraints

$$\begin{aligned} Heat_k - Heat_{k-1} &\leq \kappa_{up} \\ Heat_{k-1} - Heat_k &\leq \kappa_{down} \end{aligned} \tag{4.14}$$

4.5.4 Gas network model

The gas network includes gas station, pipelines, boilers, CHP and gas loads. The Gas network cost comprises of annualized investment cost for pipeline $CC_{gas}^{P.line}$,cost for gas station $CC^{G.Station}$ and operation and maintenance for gas network $\mathrm{Cos}\,t^{OMC}$ [247].

$$\mathrm{Cos}\,t^{gas} = CC_{gas}^{P.line} + CC^{G.station} + \mathrm{Cos}\,t^{OMC} \tag{4.15}$$

The Gas network model is subjected to following investment and operation constraints

a) Nodal gas flow:

The nodal gas flow equation has to be satisfied at each node.

$$\sum NG^{Flow} = \sum NG^{Load} + \sum NG^{CHP} + \sum NG^{Boiler} + \sum NG_{nb}^{pipeline} \tag{4.16}$$

where flow through each pipeline is calculated as

$$NG_{nb}^{pipeline} = Sign(NG_{nb}^{pipeline}) \times \left| \pi_n^2 - \pi_b^2 - H_P^{gk} \right|^{0.5} \tag{4.17}$$

$$H_P^{nb} = \frac{0.0375(H_n - H_b) \times (P_a^{gk})^{0.5}}{Z_a T_a^{gk}} \tag{4.18}$$

$$\pi_a^{nb} = \frac{2}{3}\left[(\pi_n - \pi_b) - \left(\frac{\pi_n - \pi_b}{\pi_n \pi_b} \right) \right] \tag{4.19}$$

$$\psi_{nb} = \frac{1.14\times 10^{-3}\times T_o (D_{nb}^{GL})^{0.5}\times E_p}{(L^{gk}\partial_n Z T_a \sigma_{nb})^{0.5}}$$

(4.20)

$$\frac{1}{\sigma_{nb}^{GL}} = -2\log\left(\frac{\xi_G}{3.71 D_{nb}^{GL}} + \frac{2.15}{R_{nb}^{GL}}\frac{1}{(\sigma_{nb}^{GL})^{0.5}}\right) \quad (4.21)$$

b) Nodal gas pressure:

The pressure at each gas node must satisfy the following equation

$$\pi_j^{\min} \le \pi_j \le \pi_j^{\max} \quad (4.22)$$

c) Boiler gas consumption:

The amount of gas consumed by the boiler is given by the following equation. This constraint also models the interaction between gas and heat network in terms of operation for planning model.

$$NG_t^{Boiler} = \frac{3.412}{GHV}\left[\frac{\theta_1^{boiler} + a^{boiler}\theta_H^{boiler.\max}}{b^{Boiler}}\right] \quad (4.23)$$

d) CHP gas consumption:

The amount of gas consumed by the CHP is given by the following equation

$$NG_t^{CHP} = \frac{3.412}{GHV}\left[\frac{P_E^{CHP} + \theta_t^{CHP.\max}}{\eta_t^{CHP}}\right] \quad (4.24)$$

where

$$P_E^{CHP} = \eta_t^{CHP} \times \theta_t^{CHP} \tag{4.25}$$

e) Gas flow limits:

The gas flow limits of each pipeline has to be satisfied through following equation

$$\left|NG^{\lim}\right| = \left|NG^{\lim.\max}\right| \tag{4.26}$$

f) Gas-electricity linkage:

The following constraint will explain the linkage between gas network and electricity network.

$$NG_{DG} = \sum (\omega_1 \times S_{DG}) + (\omega_1 \times S_{DG}^2) \times x_{DG} \tag{4.27}$$

4.5.5 Heat network model

The heat network includes pipelines, heat sources and thermal loads. The electric pumps circulate the heated water in the MCEMGN. The Heat network cost comprises of annualized investment cost for heat sources $CC_{heat}^{H.source}$, cost for pipelines $CC_{heat}^{P.line}$ and operation and maintenance for gas network $\mathrm{Cos}\,t^{OMC}$ [247].

$$\mathrm{Cos}\,t^{heat} = CC_{heat}^{P.line} + CC_{heat}^{H.source} + \mathrm{Cos}\,t_{heat}^{OMC} \tag{4.28}$$

The Heat network model is subjected to following investment and operation constraints

a) Nodal Heat flow:

Heat network must satisfy the following nodal heat flow equation

$$H_{hb} = m_{hb} \times c_p \times (T_{start,h} - T_{end,h})$$

(4.29)

where

$$T_{end} = (T_{start} - T_g)\exp\left(-\frac{l \times \tau}{m_{hb} \times c_p}\right) + T_g \tag{4.30}$$

b) Pressure loss equation:

The pressure loss (PL) in the pipeline due to the friction is expressed through Darcy-weishach equation

$$(PL)_{gk}^{H,L} = K_{gk}^{H,L}[sign_m(m_{gk}) - sign_m(-m_{gk})] \times (-m_{gk})^2 \tag{4.31}$$

where

$$K_{hb}^{H,L} = \frac{8L_{hb}^{H,L} \times \sigma_{hb}^{H,L}}{\rho_w^2 \pi^2 g (D_{hb}^{H,L})^5} \tag{4.32}$$

$$\frac{1}{(\sigma_{gk}^{G,K})^{0.5}} = -2\log\left(\frac{\xi_H}{3.71 D_{gk}^{G,K}} + \frac{2.51}{R_{gk}^{G,K}} + \frac{1}{(\sigma_{gk}^{G,K})^{0.5}}\right) \tag{4.33}$$

And Reynolds Number is given as

$$R_{gk}^{h,l} = \frac{\upsilon_{gk} \times D_{gk}^{G,K}}{\mu_w} \tag{4.34}$$

$$\upsilon_{gk} = \frac{4m_{gk}}{\rho_w \pi (D_{gk}^{G,K})^2} \tag{4.35}$$

c) Thermal energy balance equation:

The thermal energy balance equation but be satisfied at all nodes in the MCEMGN

$$H_{g,load} + H_{g,load}^{TSS} = \sum_{g=1}^{Ng} c_p (m_{gk} + m_H^{CHP} + m_H^{Boiler}) \times (T_{start} - T_{end,load}) \tag{4.36}$$

d) Supply temperature balance equation:

The supply temperature balance equation must be satisfied at all nodes in the MCEMGN

$$\begin{aligned}
&m_H^{CHP}(T_{Start,CHP} - T_g) + m_H^{Boiler}(T_{Start,Boiler} - T_g) + m_H^{TSS}(T_{Start,TSS} - T_g) + \\
&\sum_{g=1}^{Ng} Sign_m(m_{gk}) \times \left[m_{gk}(T_{Start} - T_g)\exp[\frac{l \times u}{m_{gk} \times c_p}] \right] = \\
&(T_{Start} - T_g)\left[m_H^{CHP} + m_H^{Boiler} + m_H^{TSS} + \sum_{g=1}^{Ng} Sign_m(m_{gk}) \times m_{gk} \right]
\end{aligned} \tag{4.37}$$

e) Return temperature balance equation:

The return temperature balance equation must be satisfied at all nodes in the MCEMGN

$$\begin{aligned}
&m_H^{Load}(T_{end,load} - T_g) + \sum_{g=1}^{Ng} Sign_m(m_{gk}) \left[m_{gk}(T_{end} - T_g)\exp[\frac{l \times u}{m_{gk} \times c_p}] \right] = \\
&(T_{end} - T_g)\left[m_H^{load} + \sum_{g=1}^{Ng} Sign_m(m_{gk}) \times m_{gk} \right]
\end{aligned} \tag{4.38}$$

f) Start and end nodal temperature:

Start and end temperature at each node must be between min and max allowable temperature

$$T_s^{\min} \le T_s \le T_s^{\max}$$
$$T_r^{\min} \le T_r \le T_r^{\max} \qquad (4.39)$$

g) Heat generation limits:

Heat generation limits of Boiler & CHP are express as follows

$$H^{CHP,\min} \le H^{CHP} \le H^{CHP,\max}$$
$$H^{Boiler,\min} \le H^{Boiler} \le H^{Boiler,\max} \qquad (4.40)$$

h) Start temperature:

Start temperature of Boiler & CHP are express as follows

$$T^{CHP,\min} \le T^{CHP} \le T^{CHP,\max}$$
$$T^{Boiler,\min} \le T^{Boiler} \le T^{Boiler,\max} \qquad (4.41)$$

i) Transmission heat limits:

Transmission heat limits of each heat pipeline are express as follows

$$\left|H_H^{line}\right| = H_H^{line,\max} \qquad (4.42)$$

4.6 Case study:

The proposed MCEMGN model is studies on an integrated 28 bus real hybrid AC-DC microgrid, 15 node gas network and 14 node heat network as shown in Fig. 4-2,4-3 & 4-4 respectively. This 28 bus real hybrid AC-DC microgrid involves different types of customers each having different gas, heat and electricity patterns.

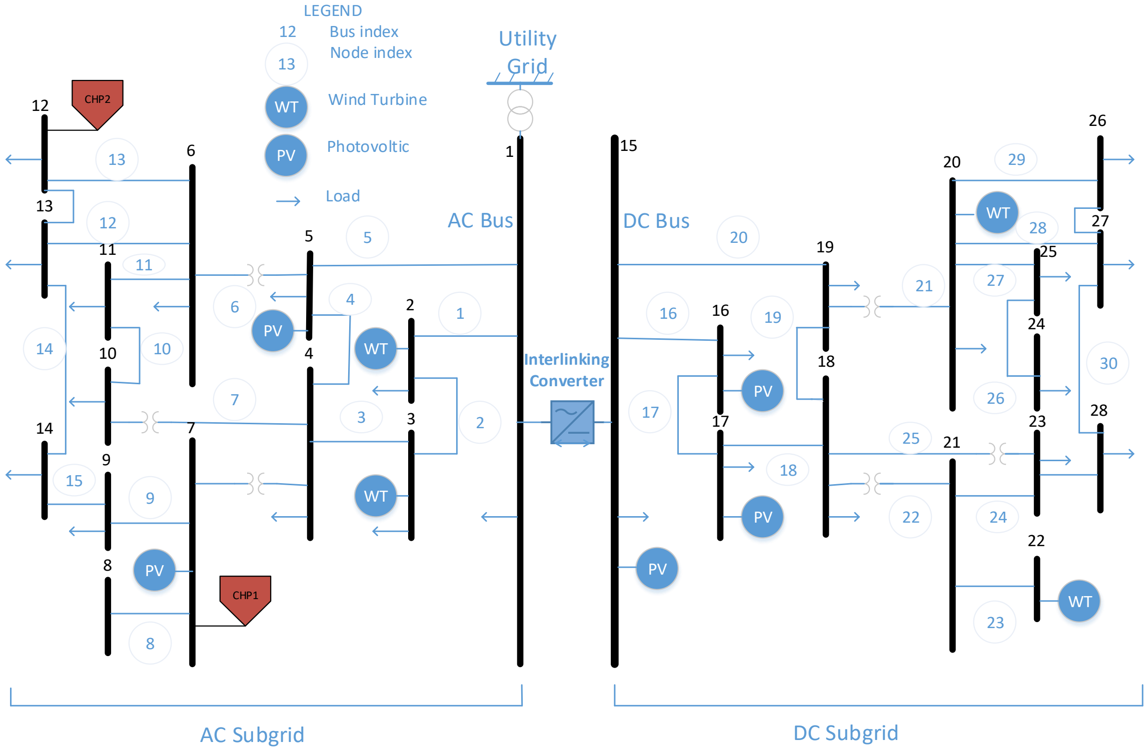


Fig 4-2. Hybrid AC-DC microgrid

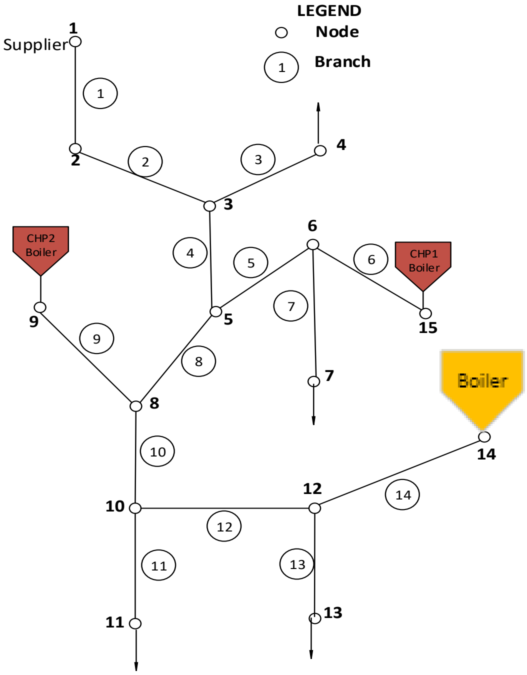


Fig 4-3. Natural Gas network

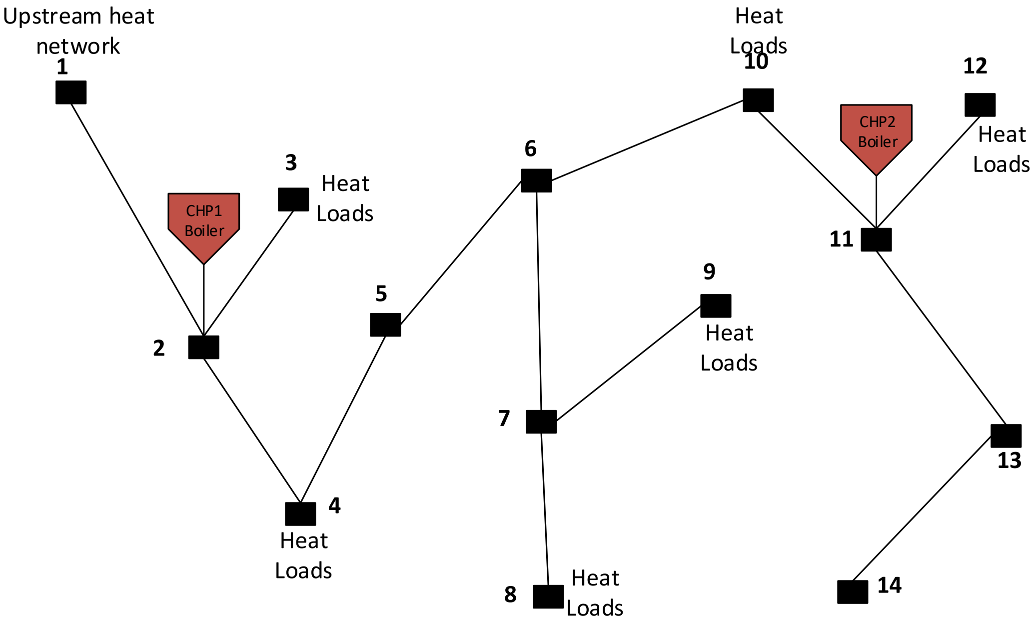


Fig 4-4. Heat network

The proposed MCEMGN systems consists of electricity network, gas network and heat network, and different types of energy consumers, and energy equipment which are interdependent. The hybrid AC-DC midrogrid is connected to gas network through CHP. The CHP is the coupling equipment between gas, electricity and heat networks. There are two CHP units and their configuration in the proposed MCEMGN systems is given in Table 4.1. The boiler unit interlinks gas and heat networks. There is only one Boiler unit for the sake of simplicity and it's configuration in the proposed MCEMGN systems is given in Table 4.2. The configuration of CHP units in MCEMGN systems is given in Table 4.1. There is only one Boiler unit for the sake of simplicity and it's configuration in the proposed MCEMGN systems is given in Table 4.2.

Table 4-1 Configuration of CHP on the sub-networks

Unit	Electrical bus	Gas Node	Heat node
CHP 1	8	15	2
CHP 2	12	9	11

Table 4-2 Configuration of Boiler on the sub-networks

Unit	Gas Node	Heat node
Boiler	14	1

The objective is to minimise the planning, operational and maintenance cost and to find the optimal capacity of PVs, WTs ,CHP units and boiler. The increment of 3%

in load for gas, heat and electricity networks is considered yearly over the planning period. The assumed best possible location selection of WTs, PVs, CHP units and boiler depends on the non-technical factors such as space/land availability, legal requirements and other amenities. PVs and WTs can also be allocated at both subgrids AC and DC.

Assuming load growth of 3% for both gas and electricity systems each year of the planning horizon, the active power dispatched is increasing proportionally with the increase in load demand. The entire year is divided into four seasons summer, spring, winter and autumn. Each season is being represented by one single day.

4.7 Results and discussions

In this work, the optimal energy flow is studied in proposed MCEMGN operation framework. The planning horizon is 10 years. The present study aims to present an efficient solution in integrated systems and their effect on each other. The planning problem of the microgrid has been divided into two operation modes.

1) Independent mode:

In this mode all the networks (gas, heat and electricity networks) are studied independently under their respective network constraints presented in section 4.5.

2) Integrated mode:

In this mode the proposed MCEMGN operation framework is tested to validate the effectiveness of the proposed MCEMGN operation framework. The proposed MCEMGN operation framework has been implemented in GAMS environment and the non-linear program solver MINLP is used on a PC with Core i7 CPU and 16 GB of RAM.

The test MCEMGN system contains three energy carriers, containing 28 bus real hybrid AC-DC microgrid, 15 node gas network and 14 node heat networks. The real hybrid AC-DC microgrid in MCEMGN system consist of 30 branches, 15 node gas network contains 14 gas pipelines and heat network contains 13 pipelines. The schematics of MCEMGN systems is shown in Fig 2-4. It is clear from the figures that MCEMGN system consists of various energy sources such as renewables, CHP's and gas-fired boiler. For the sake of simplicity, thermal storage and battery storage is not considered in this study.

The results of the two modes are compared with respect to total planning cost which comprises of investment, operation and maintenance costs. In the mode 1, the planning cost of individual networks were calculated separately without interlinking them together which includes the planning cost for Hybrid AC-DC microgrid, gas network and heating network. In the mode 2, the total planning cost for the MCEMGN systems was calculated. As it is expected, the integrated planning has less total planning cost as compared to the interdependent planning cost as shown the Fig. 4-5.

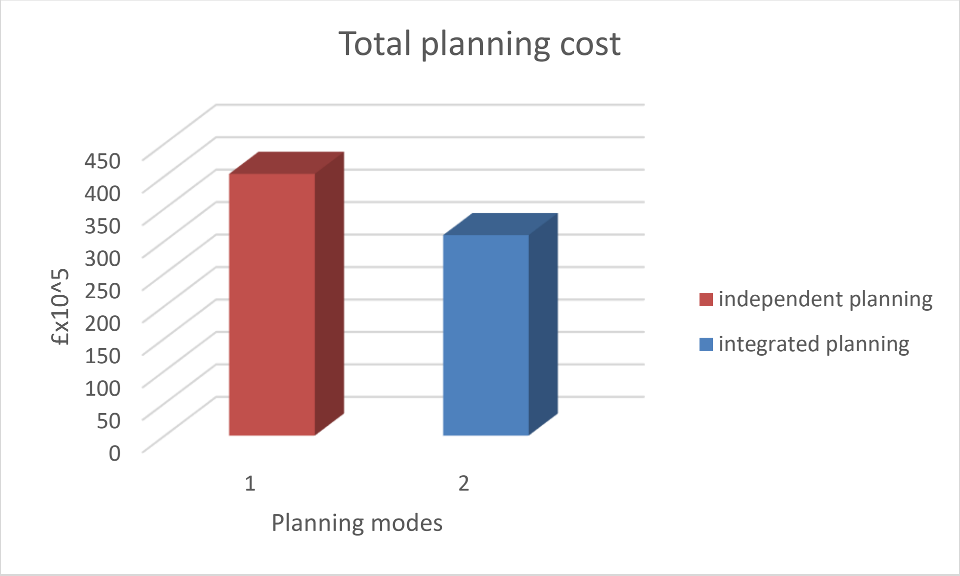


Fig 4-5. Planning cost

The mode 2 illustrates the MCEMGN systems in which the total dispatched power by WT’s and PV’s have been increased as compare to the mode1 as shown in the Fig. 4-6 & 4-7.

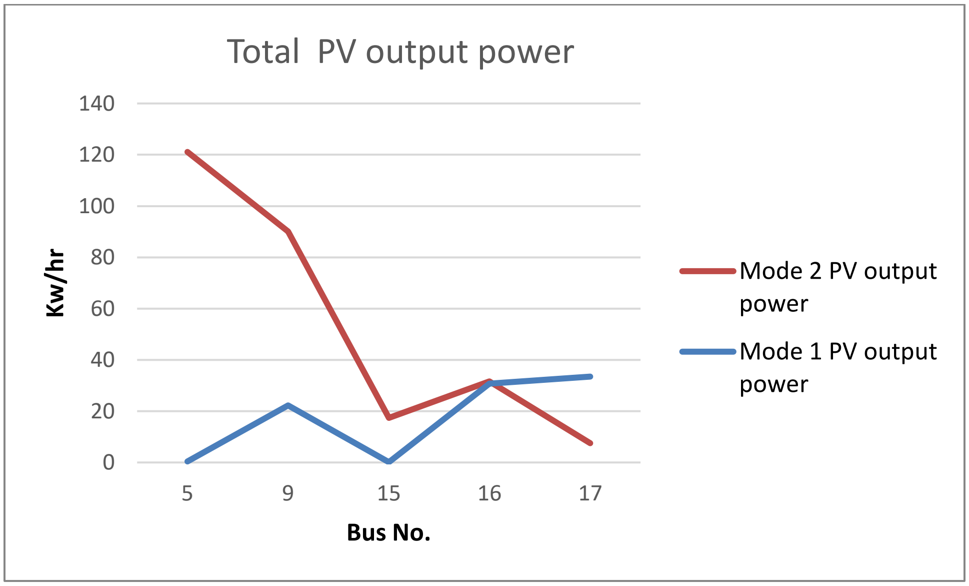


Fig 4-6. Total PV output power over the Planning period

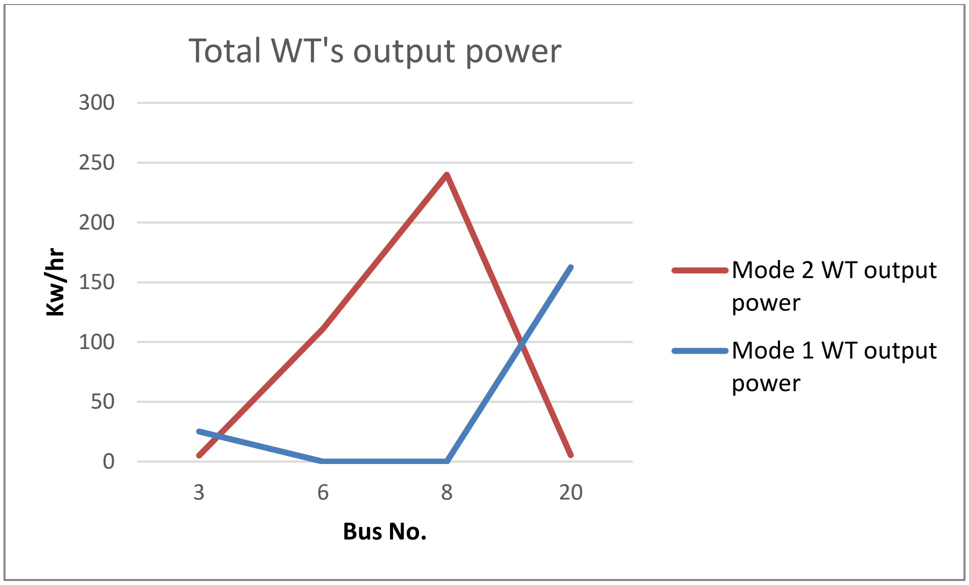


Fig 4-7. Total WT output power over the Planning period

Th Fig 4-6- & 4-7 clearly indicateds that output power dispatched by the PV's and WT's have increased in MCEMGN systems as compared to the mode 1 which shows more renewable penetration.

The Fig. 4-8 shows that as the load increases yearly, the dispatched electrical power output of the CHP units also increase. The dispatched power increment is in line with the 3% yearly load increment. For the sake of simplicity, the thermal energy storage and battery storage is not considered in this study. Although the presence of the thermal energy storage and battery storage will immensely contribute in to the flexibility and reliability of the MCEMGN systems.

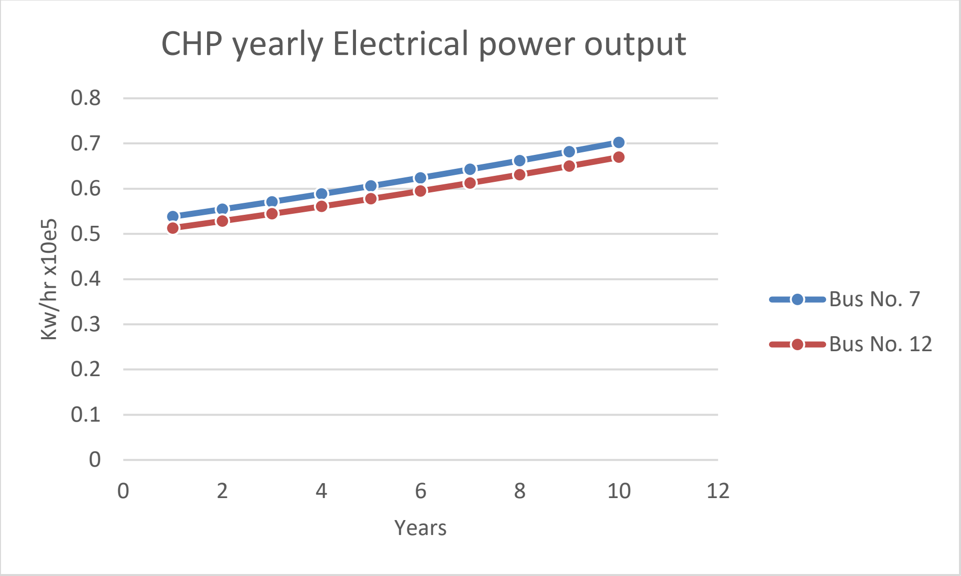


Fig 4-8. Total CHP's output power over the Planning period

Another very interesting result is shown in Fig. 4-9. The total Electrical energy sold to the grid in mode 2 is higher than in mode 1. This shows that the proposed MCEMGN systems is more economical than independent planning.

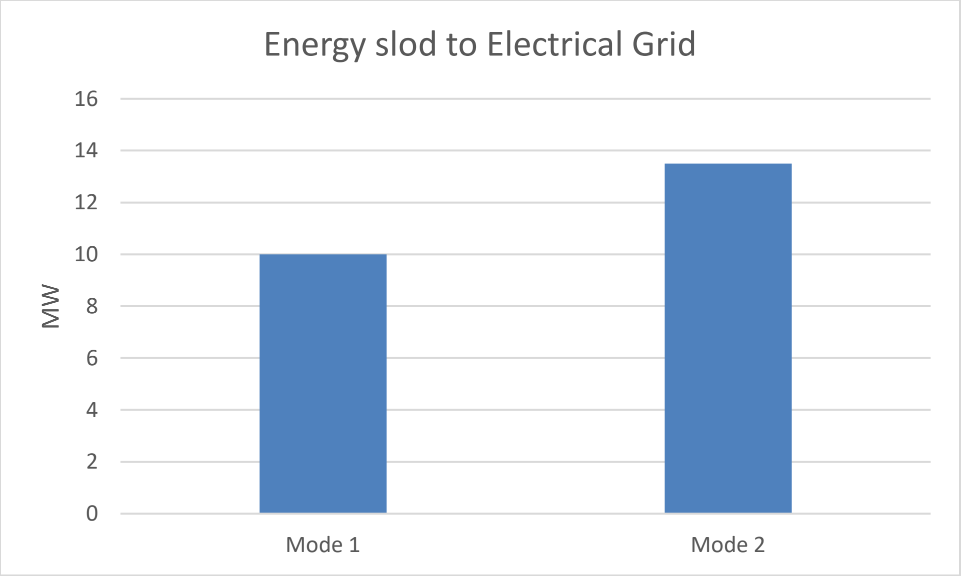


Fig 4-8. Total Electrical energy sold over the Planning period

4.8 Conclusion

This study demonstrates the optimal planning and operation of MCEMGN systems. In this study, different energy systems were integrated to propose a MCEMGN systems. The proposed MCEMGN systems constitutes of electricity network, gas network and heat network. The planning and operation of MCEMGN is carried out by considering the constraints of each energy system. The objective function of MCEMGN system is to minimize the planning and operation costs of the proposed MCEMGN systems. The novelty of this work is the consideration of MCEMGN systems energy flow networks which is very critical for the efficient and economical operation of MCEMGN systems. The proposed MCEMGN systems has hybrid AC-DC microgrid and this study is done on distribution level which is not been done before in regard to MCEMGN systems.

The numerical tests were performed on unique MCEMGN systems. The key and important findings are: (1) the integration of various energy systems makes the MCEMGN systems more reliable and flexible for customers. (2) It is very important to simultaneously consider all the constraints of the all energy system to get an optimal solution without violating any system constraint. (3) The cost effectiveness is demonstrated when network reinforcement is done though MCEMGN systems. The integrated mode network reinforcement costs far lesser than independent mode network reinforcement. (4) The penetration of renewable energy resources is studied in this research work. (5) The uncertainties related to renewable energy resources is also studied in this research work.

In future study, an electricity market will be investigated for the proposed MCEMGN systems. Further the linearization techniques will be applied on the MCEMGN systems model to make the solution as global optimum solution.

Chapter 5 Conclusions and Recommendations for Further Work

5.1 Conclusion

The thesis starts with the literature review and it covers the planning of AC grids and planning of DC grids and the penetration of DG's to minimize the cost. The literature review in chapter 2 shows that most of the research focuses on increasing the penetration of DGs to minimize the cost, improve voltage profile, minimize the losses, etc. The prior research on hybrid microgrid planning is limited and only few studies can be found on modelling or roadmap on individual ac or dc microgrid planning. None of them considers the Hybrid ac-dc microgrid planning. In addition, there is no method to access the uncertainties related to wind speed and solar irradiation in case of Hybrid ac-dc microgrid. There is no literature regarding the power market for Hybrid ac-dc microgrid.

The proposed novel stochastic approach for planning and design of hybrid microgrids within a market environment was proposed. The method evaluates the amount of active power generated by WT and PV that can deliver to the load and the amount of active power injected or absorbed from the grid. Scenario based approach is used to model the uncertainty related to the wind speed, solar irradiation and load demand.

In the next phase of the research, the optimal planning and operation of MCEMGN systems was studied. In this study, different energy systems were integrated to propose a MCEMGN systems. The proposed MCEMGN systems constitutes of electricity network, gas network and heat network. The planning and operation of MCEMGN is carried out by considering the constraints of each energy system. The objective function of MCEMGN system is to minimize the planning and operation costs of the proposed MCEMGN systems. The novelty of this work is the consideration of MCEMGN systems energy flow networks which is very critical for the efficient and economical operation of MCEMGN systems. The proposed MCEMGN systems has hybrid AC-DC microgrid and this study is done on distribution level which is not been done before in regard to MCEMGN systems.

The outcomes of this thesis can be used as tool for distribution network operators to plan an operate a MCEMGN systems that has hybrid AC-DC microgrid and the impact of wind and solar power generation penetration in MCEMGN systems.

5.2 Future work recommendations

The proposed model could be easily considered and extended for further work to include new research areas, such as:

- Linearization techniques will be used to linearize the nonlinear objective function and constraints to find the global optimal solution.
- Network reinforcement roadmap will be discussed to modify any existing system in MCEMGN systems with Hybrid ac-dc microgrid.
- In future study, an electricity market will be investigated for the proposed MCEMGN systems.

References

[1] I. IEA, "International Energy Agency. Key World Energy Statistics," 2017.

[2] R. Gillard and K. Lock, "Blowing policy bubbles: Rethinking emissions targets and low-carbon energy policies in the UK," *Journal of Environmental Policy & Planning*, vol. 19, no. 6, pp. 638-653, 2017.

[3] Act, L., 2013. Local government.[Online] Available at: http://www. legislation. gov. uk/ukpga/2011/20/contents/enacted.

[4] Rogelj, J., Den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K. and Meinshausen, M., 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 C. Nature, 534(7609), p.631.

[5] D. Acke, "Zeroing In: Lessons from the European Climate Foundation's Roadmap 2050 Project," *IEEE Power and Energy Magazine*, vol. 12, no. 5, pp. 42-49, 2014.

[6] UNFCCC, C., 1992. United Nations framework convention on climate change.

[7] Arnold GW. Challenges and opportunities in smart grid: a position article. Proc. IEEE 2011;99(6):922–7.

[8] Brown, T., The futility of carbon reduction.

[9] Marnay, C., Venkataramanan, G., Stadler, M., Siddiqui, A.S., Firestone, R. and Chandran, B., 2008. Optimal technology selection and operation of commercial-building microgrids. IEEE Transactions on Power Systems, 23(3), pp.975-982.

[10] Lasseter, R., Akhil, A., Marnay, C., Stephens, J., Dagle, J., Guttromson, R., Meliopoulous, A.S., Yinger, R. and Eto, J., 2002. Integration of distributed energy resources. The CERTS Microgrid Concept.

[11] Jespersen, P.H., 2016. Introduction to Section 2: Climate Change and Clean Technology. In Rethinking Climate Change Research (pp. 35-146). Routledge.

[12] Birge, J.R. and Louveaux, F., 2011. Introduction to stochastic programming. Springer Science & Business Media.

[13] Battaglini A, Lilliestam J, Haas A, Patt A. Development of supersmart grids for a more efficient utilisation of electricity from renewable sources, J Clean Prod2009;17(10):911–8.

[14] Boroyevich D, Cvetkovic I, Burgos R. Intergrid: a future electronic energynetwork? IEEE J Emerg Sel Top Power Electron 2013;1(3):127–38.

[15] Fadaeenejad M, Saberian AM, Fadaee M, Radzi MAM, Hizam H, AbKadir MZA.The present and future of smart power grid in developing countries, RenewSustain Energy Rev 2014;29:828–34.

[16] Farhangi H. The path of the smart grid, IEEE Power Energy Mag 2010;8(1):18–28.

[17] Gharavi H, Ghafurian R. Smart grid: the electric energy system of the future. Proc. IEEE 2011;99(6):917–21.

[18] Hatziargyriou N, Asano H, Iravani R, Marnay C. Microgrids: an overview of ongoing research, development, and demonstration projects, IEEE Power Energy Mag. 2007.

[19] Liserre M, Sauter T, Hung J. Future energy systems: integrating renewable energy sources into the smart power grid through industrial electronics. IEEE Ind Electron Mag 2010;4(1):18–37.

[20] Huang AQ, Crow ML, Heydt GT, Zheng JP, Dale SJ. The future renewable electric energy delivery and management (FREEDM) system: the energy internet. Proc. IEEE 2011;99(1):133–48.

[21] Patterson BT. DC, come home: DC microgrids and the birth of the Enernet.IEEE Power Energy Mag 2012;10(6):60–9.

[22] Lidula NWA, Rajapakse AD. Microgrids research: a review of experimental microgrids and test systems. Renew Sustain Energy Rev 2011;15(1):186–202.

[23] Nordman B, Christensen K, Meier A. Think globally, distribute power locally: the promise of nanogrids. Computer (Long. Beach. Calif) 2012;45(9):89–91.

[24] Palizban O, Kauhaniemi K, Guerrero JM. Microgrids in active network management - Part I: hierarchical control, energy storage, virtual power plants, and market participation. Renew Sustain Energy Rev 2014;36:428–39.

[25] Planas E, Andreu J, Gárate JI, de Alegría IMartínez, Ibarra E. AC and DC technology in microgrids: a review. Renew Sustain Energy Rev 2015;43:726–49.

[26] Planas E, Gil-De-Muro A, Andreu J, Kortabarria I, De Alegría I Martínez. General aspects, hierarchical controls and droop methods in microgrids: a review. Renew Sustain Energy Rev 2013;17:147–59.

[27] Soshinskaya M, Graus WHJ, Guerrero JM, Vasquez JC. Microgrids: experiences, barriers and success factors, Renew Sustain Energy Rev 2014;40:659–72.

[28] Ustun TS, Ozansoy C, Zayegh A. Recent developments in microgrids and example cases around the world, a review, Renew Sustain Energy Rev 2011;15(8):4030–41.

[29] Palizban O, Kauhaniemi K. Hierarchical control structure in microgrids with distributed generation : Island and grid-connected mode. Renew Sustain Energy Rev. 2015;44:797–813.

[30] Bouzid AM, Guerrero JM, Cheriti A, Bouhamida M, Sicard P, Benghanem M. A survey on control of electric power distributed generation systems for microgrid applications, Renew Sustain Energy Rev 2015;44:751–66.

[31] Arul PG, Ramachandaramurthy VK, Rajkumar RK. Control strategies for a hybrid renewable energy system: a review, Renew Sustain Energy Rev. 2015;42:597–608.

[32] Prasad RD, Bansal RC, Raturi A. Multi-faceted energy planning: A review, Renew Sustain Energy Rev. 2014;38:686–99.

[33] Paliwal P, Patidar NP, Nema RK. Planning of grid integrated distributed generators: a review of technology, objectives and techniques, Renew Sustain Energy Rev 2014;40:557–70 Dec.

[34] Li C, Cao C, Cao Y, Kuang Y, Zeng L, Fang B. A review of islanding detection methods for microgrid, Renew Sustain Energy Rev 2014;35:211–20.

[35] Gopalan SA, Sreeram V, Iu HHC. A review of coordination strategies and protection schemes for microgrids. Renew Sustain Energy Rev.

[36] Siano P. Demand response and smart grids—A survey. Renew Sustain Energy Rev 2014;30:461–78.

[37] Vandoorn TL, De Kooning JDM, Meersman B, Vandevelde L. Review of primary control strategies for islanded microgrids with power-electronic interfaces, Renew Sustain Energy Rev 2013;19:613–28.

[38] Ku Ahmad KNE, Selvaraj J, Rahim NA. A review of the islanding detection methods in grid-connected PV inverters, Renew Sustain Energy Rev 2013;21:756–66.

[39] Khamis A, Shareef H, Bizkevelci E, Khatib T. A review of islanding detection techniques for renewable distributed generation systems. Renew Sustain Energy Rev, 28; 2013. p. 483–93.

[40] Basak P, Chowdhury SP, Halder nee Dey S. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renew Sustain Energy Rev. 2012;16(8):5545–56.

[41] Khadem SK, Basu M, Conlon MF. Parallel operation of inverters and active power filters in distributed generation system—a review, Renew Sustain. Energy Rev 2011;15(9):5155–68.

[42] Justo JJ, Mwasilu F, Lee J, Jung JW. AC-microgrids versus DC-microgrids with distributed energy resources: a review. Renew Sustain Energy Rev 2013;24:387–405.

[43] Hossain E, Kabalci E, Bayindir R, Perez R. Microgrid testbeds around the world: state of art. Energy Convers. Manag. 2014;86:132–53.

[44] Sinha S, Chandel SS. Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems. Renew Sustain Energy Rev 2015;50:755–69.

[45] Fathima AH, Palanisamy K. Optimization in microgrids with hybrid energy systems – a review, Renew Sustain.Energy Rev 2015;45:431–46.

[46] Gamarra C, Guerrero JM. Computational optimization techniques applied to microgrids planning: a review, Renew Sustain.Energy Rev 2015;48:413–24.

[47] Iqbal M, Azam M, Naeem M, Khwaja AS, Anpalagan A. Optimization classification, algorithms and tools for renewable energy: a review, Renew Sustain Energy Rev 2014;39:640–54.

[48] Zhou K, Yang S, Chen Z, Ding S. Optimal load distribution model of microgrid in the smart grid environment, Renew Sustain.Energy Rev 2014;35:304–10.

[49] Viral R, Khatod DK. Optimal planning of distributed generation systems in distribution system: a review, Renew Sustain.Energy Rev 2012;16 (7):5146–65.

[50] Mirsaeidi S, Mat Said D, Wazir Mustafa M, Hafiz Habibuddin M, Ghaffari K. Progress and problems in micro-grid protection schemes, Renew Sustain Energy Rev 2014;37:834–9.

[51] Palizban O, Kauhaniemi K, Guerrero JM. Microgrids in active network management–Part II: system operation, power quality and protection. Renew Sustain.Energy Rev 2014;36:440–51.

[52] Eghtedarpour N, Farjah E. Power control and management in a hybrid AC/DC microgrid. IEEE Trans Smart Grid 2014;5(3):1494–505.

[53] Hammerstrom DJ. AC versus DC distribution systems did we get it right? In: Proceedings of the IEEE power engineering society general meeting; 2007.p. 1–5.

[54] Jiang Z and Yu X. Hybrid DC- and ac-linked microgrids: towards integration of distributed energy resources. In: Proceedings of the IEEE energy 2030 conference; 2008. p. 1–8.

[55] Kaushik RA and Pindoriya NM. A hybrid AC–DC microgrid: opportunities & key issues in implementation. In: Proceedings of the international conference on green computing communication and electrical engineering (ICGCCEE), 2014. p. 1–6.

[56] Patrao I, Figueres E, Garcerá G, González-Medina R. Microgrid architectures, for low voltage distributed generation. Renew Sustain.Energy Rev 2015;43:415–24.

[57] Starke M, Tolbert LM, Ozpineci B. AC vs. DC distribution: a loss comparison In: Proceedings of the IEEE/PES transmission and distribution conference and exposition,2008. p. 1–7.

[58] Wang P, Goel L, Liu X, Choo FH. Harmonizing AC and DC: a hybrid AC/DC future grid solution, IEEE Power Energy Mag. 2013;11(3):76–83.

[59] Zhu X, Han X, Qin W, Wang P. Past, today and future development of microgrids in China, Renew Sustain Energy Rev 2015;42:1453–63.

[60] Marnay C, Robio FJ, Siddiqui AS. Shape of the microgrid. 2001 IEEE Power Eng. Soc. Winter Meet. Conf. Proc. (Cat. No.01CH37194),vol. 1, IEEE; 2001, p.150–3. doi:10.1109/PESW.2001.917022.

[61] Lopes JAP, Moreira CL, Madureira AG. Defining Control Strategies for MicroGrids Islanded Operation. IEEE Trans Power Syst 2006;21:916–24. doi:10.1109/TPWRS.2006.873018.

[62] Zeineldin HH, Mohamed YARI, Khadkikar V, Pandi VR. A Protection Coordination Index for Evaluating Distributed Generation Impacts on Protection for Meshed Distribution Systems. Smart Grid, IEEE Trans 2013;4:1523–32. doi:10.1109/TSG.2013.2263745.

[63] Li Y, Gao W, Jiang J. Stability analysis of microgrids with multiple DER units and variable loads based on MPT. 2014 IEEE PES Gen. Meet. | Conf. Expo., IEEE; 2014, p. 1–5. doi:10.1109/PESGM.2014.6939345.

[64] Cagnano, A., De Tuglie, E. and Mancarella, P., 2020. Microgrids: Overview and guidelines for practical implementations and operation. Applied Energy, 258, p.114039.

[65] Eriksson, E.L.V. and Gray, E.M., 2017. Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems–A critical review. Applied energy, 202, pp.348-364.

[66] Nasirian, V., Moayedi, S., Davoudi, A. and Lewis, F.L., 2014. Distributed cooperative control of DC microgrids. IEEE Transactions on Power Electronics, 30(4), pp.2288-2303..

[67] Rabeh, R., Ferfra, M. and Ezbakhe, A., 2019. Secondary control of islanded microgrids using PI-evolutionary algorithms under uncertainties. International Journal of Renewable Energy Research (IJRER), 9(4), pp.1827-1837.

[68] Zhang, L., Liang, J., Tang, W., Li, G., Cai, Y. and Sheng, W., 2018. Converting AC distribution lines to DC to increase transfer capacities and DG penetration. IEEE Transactions on Smart Grid, 10(2), pp.1477-1487.

[69] Najafzadeh, M., Ahmadiahangar, R., Husev, O., Roasto, I., Jalakas, T. and Blinov, A., 2021. Recent contributions, future prospects and limitations of interlinking converter control in hybrid AC/DC microgrids. IEEE Access, 9, pp.7960-7984.

[70] Pau, M., Sadu, A., Pillai, S., Ponci, F. and Monti, A., 2016, October. A state estimation algorithm for hybrid AC/DC networks with multi-terminal DC grid. In 2016 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe) (pp. 1-6). IEEE.

[71] P. J. Hart, T. M. Jahns, and R. H. Lasseter, “Performance characteristics of a hybrid CERTS microgrid electric vehicle charging station,” in Proc. IEEE Energy Convers. Congr. Expo. (ECCE), Pittsburgh, PA, USA, Sep. 2014, pp. 3309–3316.

[72] M. S. Rahman, M. J. Hossain, and J. Lu, “Coordinated control of threephase AC and DC type EV–ESSS for efficient hybrid microgrid operations,” Energy Convers. Manag., vol. 122, pp. 488–503, Aug. 2016.

[73] Ceseña, E.A.M., Good, N., Syrri, A.L. and Mancarella, P., 2018. Techno-economic and business case assessment of multi-energy microgrids with co-optimization of energy, reserve and reliability services. Applied energy, 210, pp.896-913..

[74] H. Han et al., “Review of power sharing control strategies for islanding operation of AC microgrids,” IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 200–215, Jan. 2016.

[75] T. Dragiceviˇ c, X. Lu, J. C. Vasquez, and J. M. Guerrero, “Dcˇ microgrids—Part I: A review of control strategies and stabilization techniques,” IEEE Trans. Power Electron., vol. 31, no. 7, pp. 4876–4891, Jul. 2016.

[76] Nascimento, K.R.D.S. and Alencar, M.H., 2016. Management of risks in natural disasters: A systematic review of the literature on NATECH events. Journal of Loss Prevention in the Process Industries, 44, pp.347-359..

[77] E. Unamuno and J. A. Barrena, “Hybrid AC/DC microgrids—Part I: Review and classification of topologies,” Renew. Sustain. Energy Rev., vol. 52, pp. 1251–1259, Dec. 2015.

[78] Sedaghati, R. and Shakarami, M.R., 2019. A novel control strategy and power management of hybrid PV/FC/SC/battery renewable power system-based grid-connected microgrid. Sustainable Cities and Society, 44, pp.830-843.

[79] E. Unamuno and J. A. Barrena, “Hybrid AC/DC microgrids—Part II: Review and classification of control strategies,” Renew. Sustain. Energy Rev., vol. 52, pp. 1123–1134, Dec. 2015.

[80] Nejabatkhah, F., Li, Y.W. and Tian, H., 2019. Power quality control of smart hybrid AC/DC microgrids: An overview. Ieee access, 7, pp.52295-52318.

[81] R. P. S. Chandrasena, F. Shahnia, S. Rajakaruna, and A. Ghosh, “Dynamic operation and control of a hybrid nanogrid system for future community houses,” IET Gener. Transm. Distrib., vol. 9, no. 11, pp. 1168–1178, Aug. 2015.

[82] C. Jin, P. C. Loh, P. Wang, Y. Mi, and F. Blaabjerg, “Autonomous operation of hybrid AC–DC microgrids,” in Proc. IEEE Int. Conf. Sustain. Energy Technol. (ICSET), Kandy, Sri Lanka, Dec. 2010, pp. 1–7.

[83] Schoonenberg, W.C. and Farid, A.M., 2017. A dynamic model for the energy management of microgrid-enabled production systems. Journal of cleaner production, 164, pp.816-830.

[84] X. Liu, P. Wang, and P. C. Loh, “A hybrid AC/DC microgrid and its coordination control,” IEEE Trans. Smart Grid, vol. 2, no. 2, pp. 278–286, Jun. 2011.

[85] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Hybrid AC–DC microgrids with energy storages and progressive energy flow tuning,” IEEE Trans. Power Electron., vol. 28, no. 4, pp. 1533–1543, Apr. 2013.

[86] Hu, J., Shan, Y., Xu, Y. and Guerrero, J.M., 2019. A coordinated control of hybrid ac/dc microgrids with PV-wind-battery under variable generation and load conditions. International Journal of Electrical Power & Energy Systems, 104, pp.583-592.

[87] M. N. Ambia, A. Al-Durra, and S. M. Muyeen, “Centralized power control strategy for AC–DC hybrid micro-grid system using multi-converter scheme,” in Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc. (IECON), Melbourne, VIC, Australia, Nov. 2011, pp. 843–848.

[88] Aljafari, B., Vasantharaj, S., Indragandhi, V. and Vaibhav, R., 2022. Optimization of DC, AC, and Hybrid AC/DC Microgrid-Based IoT Systems: A Review. Energies, 15(18), p.6813.M. Akbari, M. A. Golkar, and S. M. Tafreshi, “Firefly algorithmbased voltage and frequency control of a hybrid AC–DC microgrid,” in Proc. 17th Conf. Elect. Power Distrib. Netw. (EPDC), Tehran, Iran, May 2012, pp. 1–7.

[89] Y. Zhang, H. J. Jia, and L. Guo, “Energy management strategy of islanded microgrid based on power flow control,” in Proc. IEEE PES Innov. Smart Grid Technol. (ISGT), Washington, DC, USA, Jan. 2012, pp. 1–8.

[90] X. Lu et al., “Hierarchical control of parallel AC–DC converter interfaces for hybrid microgrids,” IEEE Trans. Smart Grid, vol. 5, no. 2, pp. 683–692, Mar. 2014.

[91] M. Baharizadeh, H. R. Karshenas, and J. M. Guerrero, “Control strategy of interlinking converters as the key segment of hybridAC–DC microgrids,” IET Gener. Transm. Distrib., vol. 10, no. 7, pp. 1671–1681, May 2016.

[92] Jadav, K.A., Karkar, H.M. and Trivedi, I.N., 2017. A Review of microgrid architectures and control strategy. Journal of The Institution of Engineers (India): Series B, 98, pp.591-598..

[93] Y. Wang, D. Yang, H. Bai, and R. Xia, “Hierarchical management strategy of hybrid microgrid,” in Proc. IEEE PES Asia–Pac. Power Energy Eng. Conf. (APPEEC), Hong Kong, Dec. 2014, pp. 1–4.

[94] J. Khajesalehi, K. Sheshyekani, M. Hamzeh, and E. Afjei, “Maximum constant boost approach for controlling quasi-Z-sourcebased interlinking converters in hybrid AC–DC microgrids,” IET Gener. Transm. Distrib., vol. 10, no. 4, pp. 938–948, Mar. 2016.

[95] P. T. Baboli, M. Shahparasti, M. P. Moghaddam, M. R. Haghifam, and M. Mohamadian, “Energy management and operation modelling of hybrid AC–DC microgrid,” IET Gener. Transm. Distrib., vol. 8, no. 10, pp. 1700–1711, Oct. 2014.

[96] Ahmethodzic, L. and Music, M., 2021. Comprehensive review of trends in microgrid control. Renewable Energy Focus, 38, pp.84-96.

[97] C. Li, S. K. Chaudhary, J. C. Vasquez, and J. M. Guerrero, “Power flow analysis for droop controlled LV hybrid AC–DC microgrids with virtual impedance,” in Proc. IEEE PES Gener. Meeting Conf. Expo., National Harbor, MD, USA, Jul. 2014, pp. 1–4.

[98] R. A. Kaushik and N. M. Pindoriya, “Power flow control of hybrid AC–DC microgrid using master–slave technique,” in Proc. IEEE Conf. Energy Convers. (CENCON), Johor Bahru, Malaysia, Oct. 2014, pp. 389–394.

[99] N. Qachchachi, H. Mahmoudi, and A. E. Hasnaoui, “Optimal power flow for a hybrid AC/DC microgrid,” in Proc. Int. Renew. Sustain. Energy Conf. (IRSEC), Ouarzazate, Morocco, Oct. 2014, pp. 559–564.

[100] Liu, J., Rahman, M.S., Lu, J. and Hossain, M.J., 2016, September. Performance investigation of hybrid AC/DC microgrids during mode transitions. In 2016 Australasian Universities Power Engineering Conference (AUPEC) (pp. 1-6). IEEE.

[101] W. Hu, H. Chen, X. Yang, K. Xu, and P. Hu, “Control strategy of the bi-directional converter for hybrid AC/DC microgrid,” in Proc. IEEE PES Asia–Pac. Power Energy Eng. Conf. (APPEEC), Brisbane, QLD, Australia, Nov. 2015, pp. 1–5.

[102] V. Maryama, V. Zeni, C. Q. Pica, M. S. Ortmann, and M. L. Heldwein, “Unified hybrid (AC/DC) active distribution networks droop-based load-sharing strategy,” in Proc. IEEE PES Innov. Smart Grid Technol. Europe, Istanbul,Turkey, Oct. 2014, pp. 1–6.

[103] A. Bracale, P. Caramia, and F. Mottola, “A cost minimization strategy for the control of hybrid AC–DC microgrids in industrial systems,” in Proc. Int. Conf. Clean Elect. Power (ICCEP), Taormina, Italy, Jun. 2015, pp. 40–47.

[104] P. T. Baboli, S. Bahramara, M. P. Moghaddam, and M. R. Haghifam, “A mixed-integer linear model for optimal operation of hybrid AC–DC microgrid considering renewable energy resources and PHEVs,” in Proc. IEEE Eindhoven PowerTech, Eindhoven, The Netherlands, Jun. 2015, pp. 1–5.

[105] Morais, A.S. and Lopes, L.A., 2016, June. Interlink Converters in DC nanogrids and its effect in power sharing using distributed control. In 2016 IEEE 7th international symposium on Power Electronics for Distributed Generation Systems (PEDG) (pp. 1-7). IEEE.

[106] V. Toro and E. Mojica-Nava, “Microgrids coordination based on heterogeneous multi-agent systems,” in Proc. IEEE 2nd Colombian Conf. Autom. Control (CCAC), Manizales, Colombia, Oct. 2015, pp. 1–5.

[107] T. Ma, M. H. Cintuglu, and O. A. Mohammed, “Control of a hybrid AC/DC microgrid involving energy storage and pulsed loads,” IEEE Trans. Ind. Appl., vol. 53, no. 1, pp. 567–575, Jan./Feb. 2017.

[108] Qiu, H., Zhao, B., Gu, W. and Bo, R., 2018. Bi-level two-stage robust optimal scheduling for AC/DC hybrid multi-microgrids. IEEE Transactions on Smart Grid, 9(5), pp.5455-5466.

[109] M. Hosseinzadeh and F. R. Salmasi, “Power management of an isolated hybrid AC/DC micro-grid with fuzzy control of battery banks,” IET Renew. Power Gener., vol. 9, no. 5, pp. 484–493, Jun. 2015.

[110] Y. Liu, X. Hou, X. Wang, C. Lin, and J. M. Guerrero, “A coordinated control for photovoltaic generators and energy storages in low-voltage AC/DC hybrid microgrids under islanded mode,” Energies, vol. 9, no. 8, p. 651, 2016.

[111] Jiang, T., Deng, H., Bai, L., Zhang, R., Li, X. and Chen, H., 2018. Optimal energy flow and nodal energy pricing in carbon emission-embedded integrated energy systems. CSEE Journal of Power and energy Systems, 4(2), pp.179-187.

[112] P. J. Hart, R. H. Lasseter, and T. M. Jahns, “Symmetric droop control for improved hybrid AC/DC microgrid transient performance,” in Proc. IEEE Energy Convers. Congr. Expo. (ECCE), Milwaukee, WI, USA, Sep. 2016, pp. 1–8.

[113] A. A. Eajal, E. F. El-Saadany, and K. Ponnambalam, “Inexact power sharing in AC/DC hybrid microgrids,” in Proc. IEEE Can. Conf. Elect. Comput. Eng. (CCECE), Vancouver, BC, Canada, May 2016, pp. 1–5.

[114] A. A. Eajal, E. F. E. Saadany, and K. Ponnambalam, “Equal power sharing in islanded AC/DC hybrid microgrids,” in Proc. IEEE Elect. Power Energy Conf. (EPEC), Ottawa, ON,Canada, Oct. 2016, pp. 1–6.

[115] Li, X., Guo, L., Li, Y., Guo, Z., Hong, C., Zhang, Y. and Wang, C., 2017. A unified control for the DC–AC interlinking converters in hybrid AC/DC microgrids. IEEE Transactions on Smart Grid, 9(6), pp.6540-6553.

[116] L. Che, M. Shahidehpour, A. Alabdulwahab, and Y. Al-Turki, “Hierarchical coordination of a community microgrid with AC and DC microgrids,” IEEE Trans. Smart Grid, vol. 6, no. 6, pp. 3042–3051, Nov. 2015.

[117] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of hybrid microgrid with AC and DC subgrids,” IEEE Trans. Power Electron., vol. 28, no.5, pp. 2214–2223, May 2013.

[118] S. Bahrami, V. W. S. Wong, and J. Jatskevich, “Optimal power flow for AC–DC networks,” in Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm), Venice, Italy, Nov. 2014, pp. 49–54.

[119] Mishra, D.K., Ghadi, M.J., Li, L., Hossain, M.J., Zhang, J., Ray, P.K. and Mohanty, A., 2021. A review on solid-state transformer: A breakthrough technology for future smart distribution grids. International Journal of Electrical Power & Energy Systems, 133, p.107255.

[120] S. Falcones, X. Mao, and R. Ayyanar, “Topology comparison for solid state transformer implementation,” in Proc. IEEE PES Gener. Meeting, Minneapolis, MN, USA, Jul. 2010, pp. 1–8.

[121] J. Yan, X. Zhu, and N. Lu, “Smart hybrid house test systems in a solidstate transformer supplied microgrid,” in Proc. IEEE Power Energy Soc. Gener. Meeting, Denver, CO, USA, Jul. 2015, pp. 1–5.

[122] X. She, A. Q. Huang, S. Lukic, and M. E. Baran, “On integration of solid-state transformer with zonal DC microgrid,” IEEE Trans. Smart Grid, vol. 3, no. 2, pp. 975–985, Jun. 2012.

[123] X. Yu, X. She, X. Zhou, and A. Q. Huang, “Power management for DC microgrid enabled by solid-state transformer,” IEEE Trans. Smart Grid, vol. 5, no. 2, pp. 954–965, Mar. 2014.

[124] Y. Liu et al., “Modular multilevel converter with high-frequency transformers for interfacing hybrid DC and AC microgrid systems,” in Proc. IEEE 5th Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG), Galway, Ireland, Jun. 2014, pp. 1–6.

[125] Martin-Martínez, F., Sánchez-Miralles, A. and Rivier, M., 2016. A literature review of Microgrids: A functional layer based classification. Renewable and sustainable energy reviews, 62, pp.1133-1153.

[126] Z. Jiang and X. Yu, “Power electronics interfaces for hybrid DC and AC-linked microgrids,” in Proc. IEEE 6th Int. Power Electron. Motion Control Conf., Wuhan, China, May 2009, pp. 730–736.

[127] A. A. Abdelsalam, H. A. Gabbar, and A. M. Sharaf, “Performance enhancement of hybrid AC/DC microgrid based D-FACTS,” Int. J. Elect. Power Energy Syst., vol.63, pp. 382–393, Dec. 2014.

[128] A. A. A. Radwan and Y. A.-R. I. Mohamed, “Assessment and mitigation of interaction dynamics in hybrid AC/DC distribution generation systems,” IEEE Trans. Smart Grid, vol. 3, no. 3, pp. 1382–1393, Sep. 2012.

[129] M. Davari and Y. A.-R. I. Mohamed, “Robust multi-objective control of VSC-based DC-voltage power port in hybrid AC/DC multi-terminal micro-grids,” IEEE Trans. Smart Grid, vol. 4, no. 3, pp. 1597–1612, Sep. 2013.

[130] R. Majumder, “A hybrid microgrid with DC connection at back to back converters,” IEEE Trans. Smart Grid, vol. 5, no. 1, pp. 251–259, Jan. 2014.

[131] N. Kinhekar, N. P. Padhy, F. Li, and H. O. Gupta, “Utility oriented demand side management using smart ac and micro DC grid cooperative,” IEEE Trans. Power Syst., vol. 31, no. 2, pp. 1151–1160, Mar. 2016.

[132] C. Wang, X. Li, L. Guo, and Y. W. Li, “A nonlinear-disturbanceobserver-based DC-bus voltage control for a hybrid AC/DC microgrid,” IEEE Trans. Power Electron., vol. 29, no. 11, pp. 6162–6177, Nov. 2014.

[133] N. Eghtedarpour and E. Farjah, “Power control and management in a hybrid AC/DC microgrid,” IEEE Trans. Smart Grid, vol. 5, no. 3, pp. 1494–1505, May 2014.

[134] Su, J., Lie, T.T. and Zamora, R., 2020. Integration of electric vehicles in distribution network considering dynamic power imbalance issue. IEEE Transactions on Industry Applications, 56(5), pp.5913-5923.

[135] H. Han, L. Shen, J. Yang, and M. Su, “The coordinated control strategy of hybrid microgrid based on the maximum utilization of PV generation,” in Proc. Chin. Autom. Congr. (CAC), Wuhan, China, Nov. 2015, pp. 1416–1421.

[136] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of AC–DC microgrids with minimised interlinking energy flow,” IET Power Electron., vol. 6, no. 8, pp. 1650–1657, Sep. 2013.

[137] P. Wang, X. Liu, C. Jin, P. Loh, and F. Choo, “A hybrid AC/DC micro-grid architecture, operation and control,” in Proc. IEEE Power Energy Soc. Gener. Meeting, San Diego, CA, USA, Jul. 2011, pp. 1–8.

[138] H. Zhang, J. Zhou, Q. Sun, J. M. Guerrero, and D. Ma, “Data-driven control for interlinked AC/DC microgrids via model-free adaptive control and dual-droop control,” IEEE Trans. Smart Grid, vol. 8, no. 2, pp. 557–571, Mar. 2017.

[139] T.-P. Chen, “Zero-sequence circulating current reduction method for parallel HEPWM inverters between AC bus and DC bus,” IEEE Trans. Ind. Electron., vol. 59, no. 1, pp. 290–300, Jan. 2012.

[140] H. Xiao, A. Luo, Z. Shuai, G. Jin, and Y. Huang, “An improved control method for multiple bidirectional power converters in hybrid AC/DC microgrid,” IEEE Trans. Smart Grid, vol. 7, no. 1, pp. 340–347, Jan. 2016.

[141] Kazerani, M. and Tehrani, K., 2020, June. Grid of Hybrid AC/DC Microgrids: A New Paradigm for Smart City of Tomorrow. In 2020 IEEE 15th International Conference of System of Systems Engineering (SoSE) (pp. 175-180). IEEE.

[142] L. Zhang, F. Gao, N. Li, Q. Zhang, and C. Wang, “Interlinking modular multilevel converter of hybrid AC–DC distribution system with integrated battery energy storage,” in Proc. IEEE Energy Convers. Congr. Expo. (ECCE), Montreal, QC, Canada, Sep. 2015, pp. 70–77.

[143] M. Sahoo and K. S. Kumar, “Bidirectional switched boost converter for AC–DC hybrid microgrid,” in Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC), Fort Worth, TX, USA, Mar. 2014, pp. 2231–2236.

[144] P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous control of interlinking converter with energy storage in hybrid AC–DC microgrid,” IEEE Trans. Ind. Appl., vol. 49, no. 3, pp. 1374–1382, May/Jun. 2013.

[145] C.-C. Hou and Y.-F. Huang, “Diode rectifier with auxiliary converter for hybrid AC/DC microgrids,” IEEE J. Emerg. Sel. Topics Power Electron., vol. 2, no. 4, pp. 1059–1069, Dec. 2014.

[146] A. Karabiber, C. Keles, A. Kaygusuz, and B. B. Alagoz, “An approach for the integration of renewable distributed generation in hybrid DC/AC microgrids,” Renew. Energy, vol.52, pp. 251–259, Apr. 2013.

[147] Sheng, W., Hong, Y., Wu, M. and Ji, Y., 2020. A cooperative control scheme for AC/DC hybrid autonomous microgrids. Processes, 8(3), p.311.

[148] K. Sun et al., “Parallel operation of bidirectional interfacing converters in a hybrid AC/DC microgrid under unbalanced grid voltage conditions,” IEEE Trans. Power Electron., vol. 32, no. 3, pp. 1872–1884, Mar. 2017.

[149] N. R. Tummuru, M. K. Mishra, and S. Srinivas, “Multifunctional VSC controlled microgrid using instantaneous symmetrical components theory,” IEEE Trans. Sustain. Energy, vol. 5, no. 1, pp. 313–322, Jan. 2014.

[150] A. A. Eajal, M. A. Abdelwahed, E. F. El-Saadany, and K. Ponnambalam, “A unified approach to the power flow analysis of AC/DC hybrid microgrids,” IEEE Trans. Sustain. Energy, vol. 7, no. 3, pp. 1145–1158, Jul. 2016.

[151] X. Wang, Y. W. Li, F. Blaabjerg, and P. C. Loh, “Virtualimpedance-based control for voltage-source and current-source converters,” IEEE Trans. Power Electron., vol. 30, no. 12, pp. 7019–7037,Dec. 2015.

[152] C. Opathella and B. Venkatesh, “Three-phase unbalanced power flow using a π-model of controllable AC–DC converters,” IEEE Trans. Power Syst., vol. 31, no. 6, pp. 4286–4296, Nov. 2016.

[153] C. Jin, J. Wang, K. L. Hai, C. F. Hoong, and P. Wang, “Coordination secondary control for autonomous hybrid AC/DC microgrids with global power sharing operation,” in Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc. (IECON), Florence, Italy, Oct. 2016, pp. 4066–4071.

[154] Baharizadeh, M., Karshenas, H.R. and Guerrero, J.M., 2018. An improved power control strategy for hybrid AC-DC microgrids. International Journal of Electrical Power & Energy Systems, 95, pp.364-373.

[155] Q.-C. Zhong and G. Weiss, “Synchronverters: Inverters that mimic synchronous generators,” IEEE Trans. Ind. Electron., vol. 58, no. 4, pp. 1259–1267, Apr. 2011.

[156] Y. Zhu, F. Zhuo, and L. Xiong, “Communication platform for energy management system in a master–slave control structure microgrid,” in Proc. 7th Int. Power

Electron. Motion Control Conf. (IPEMC), vol. 1. Harbin, China, Jun. 2012, pp. 141–145.

[157] D. K. Dheer, S. Doolla, and A. K. Rathore, “Small signal modelling and stability analysis of a droop based hybrid AC/DC microgrid,” in Proc. 42nd Annu. Conf. IEEE Ind. Electron. Soc. (IECON), Florence, Italy, Oct. 2016, pp. 3775–3780.

[158] W. Guo, X. Han, C. Ren, and P. Wang, “The control method of bidirectional AC/DC converter with unbalanced voltage in hybrid micro-grid,” in Proc. IEEE 10th Conf. Ind. Electron. Appl. (ICIEA), Auckland, New Zealand, Jun. 2015, pp. 381–386.

[159] F. Shahnia, R. Majumder, A. Ghosh, G. Ledwich, and F. Zare, “Operation and control of a hybrid microgrid containing unbalanced and nonlinear loads,” Elect. Power Syst. Res., vol. 80, no. 8, pp. 954–965, 2010.

[160] Tian, H., Wen, X. and Li, Y.W., 2018. A harmonic compensation approach for interlinking voltage source converters in hybrid AC-DC microgrids with low switching frequency. CSEE Journal of Power and Energy Systems, 4(1), pp.39-48.

[161] P. Caramia, G. Carpinelli, F. Mottola, and G. Russo, “An optimal control of distributed energy resources to improve the power quality and to reduce energy costs of a hybrid AC–DC microgrid,” in Proc. IEEE 16th Int. Conf. Environ. Elect. Eng. (EEEIC), Florence, Italy, Jun. 2016, pp. 1–7.

[162] E. Unamuno and J. A. Barrena, “Primary control operation modes in islanded hybrid AC/DC microgrids,” in Proc. IEEE EUROCON Int. Conf. Comput. Tool (EUROCON), Salamanca, Spain, Sep. 2015, pp. 1–6

[163] G. Joos, J. Reilly, W. Bower, and R. Neal, “The need for standardization: The benefits to the core functions of the microgrid control system,” IEEE Power Energy Mag., vol. 15, no. 4, pp. 32–40, Jul./Aug. 2017.

[164] Farrokhabadi, M., Canizares, C.A., Simpson-Porco, J.W., Nasr, E., Fan, L., Mendoza-Araya, P.A., Tonkoski, R., Tamrakar, U., Hatziargyriou, N., Lagos, D. and Wies, R.W., 2019. Microgrid stability definitions, analysis, and examples. IEEE Transactions on Power Systems, 35(1), pp.13-29..

[165] M. Yazdanian and A. Mehrizi-Sani, “Distributed control techniques in microgrids,” IEEE Trans. Smart Grid, vol. 5, no. 6, pp. 2901–2909, Nov. 2014.

[166] A. Bani-Ahmed, L. Weber, A. Nasiri, and H. Hosseini, “Microgrid communications: State of the art and future trends,” in Proc. Int. Conf. Renew. Energy Res. Appl. (ICRERA), Milwaukee, WI, USA, Oct. 2014, pp. 780–785.

[167] Z. Liang, Z. Yuanbo, J. Chi, and K. L. Hai, “Implementing a 3-layer communication architecture for AC–DC hybrid smart microgrid,” in Proc. Asian Conf. Energy Power Transp. Elect. (ACEPT), Singapore, Oct. 2016, pp. 1–4.

[168] Unamuno, E. and Barrena, J.A., 2015. Hybrid ac/dc microgrids—Part I: Review and classification of topologies. Renewable and Sustainable Energy Reviews, 52, pp.1251-1259.

[169] Cetinkaya, U. and Bayindir, R., 2019, December. On&Off-Grid Hybrid Microgrid Design and Dynamic Analysis. In 2019 7th International Conference on Smart Grid (icSmartGrid) (pp. 132-136). IEEE.

[170] Soyster, A.L., 1973. Convex programming with set-inclusive constraints and applications to inexact linear programming. Operations research, 21(5), pp.1154-1157.

[171] Dantzig, G.B.,2010.Linear programming under uncertainty .In Stochastic programming (pp. 1-11). Springer, New York, NY.

[172] Goguen, J.A., 1973. Zadeh LA. Fuzzy sets. Information and control, vol. 8, pp. 338–353. Zadeh LA. Similarity relations and fuzzy orderings. Information sciences, vol. 3, pp. 177–200.

[173] Aien, M., Rashidinejad, M. and Fotuhi-Firuzabad, M., 2014. On possibilistic and probabilistic uncertainty assessment of power flow problem: A review and a new approach. Renewable and Sustainable Energy Reviews, 37, pp.883-895.

[174] Soroudi, A. and Ehsan, M., 2011. A possibilistic–probabilistic tool for evaluating the impact of stochastic renewable and controllable power generation on energy losses in distribution networks—a case study. Renewable and Sustainable Energy Reviews, 15(1), pp.794-800.

[175] Ben-Haim, Y., 2006. Info-gap decision theory: decisions under severe uncertainty. Elsevier.

[176] Stott, B. and Hobson, E., 1978. Power system security control calculations using linear programming, Part I. IEEE Transactions on Power Apparatus and Systems, (5), pp.1713-1720.

[177] Keane, A. and O'Malley, M., 2005. Optimal allocation of embedded generation on distribution networks. IEEE Transactions on Power Systems, 20(3), pp.1640-1646.

[178] Keane, A. and O'Malley, M., 2007. Optimal utilization of distribution networks for energy harvesting. IEEE Transactions on Power Systems, 22(1), pp.467-475.

[179] Wu, F.F., Gross, G., Luini, J.F. and Look, P.M., 1979, May. A two-stage approach to solving large-scale optimal power flows. In Power Industry Computer Applications Conference, 1979. PICA-79. IEEE Conference Proceedings (pp. 126-136). IEEE.

[180] Kermanshahi, B., Takahashi, K. and Zhou, Y., 1998, August. Optimal operation and allocation of reactive power resource considering static voltage stability. In Power System Technology, 1998. Proceedings. POWERCON'98. 1998 International Conference On (Vol. 2, pp. 1473-1477). IEEE.

[181] Albadi, M.H. and El-Saadany, E.F., 2008. A summary of demand response in electricity markets. Electric power systems research, 78(11), pp.1989-1996.

[182] Omer, A.M., 2008. Energy, environment and sustainable development. Renewable and sustainable energy reviews, 12(9), pp.2265-2300.

[183] Act, C.C., 2008. Climate Change Act 2008. See http://www. legislation. gov. uk/ukpga/2008/27/contents (accessed 13/11/2013).

[184] Fais, B., Sabio, N. and Strachan, N., 2016. The critical role of the industrial sector in reaching long-term emission reduction, energy efficiency and renewable targets. Applied Energy, 162, pp.699-712.

[185] Hatziargyriou, N., Asano, H., Iravani, R. and Marnay, C., 2007. Microgrids. IEEE power and energy magazine, 5(4), pp.78-94.

[186] Piagi, P. and Lasseter, R.H., 2006, June. Autonomous control of microgrids. In Power Engineering Society General Meeting, 2006. IEEE (pp. 8-pp). IEEE.

[187] Fang, X., Misra, S., Xue, G. and Yang, D., 2012. Smart grid—The new and improved power grid: A survey. IEEE communications surveys & tutorials, 14(4), pp.944-980.

[188] Justo, J.J., Mwasilu, F., Lee, J. and Jung, J.W., 2013. AC-microgrids versus DC-microgrids with distributed energy resources: A review. Renewable and Sustainable Energy Reviews, 24, pp.387-405.

[189] Lotfi, H. and Khodaei, A., 2017. AC versus DC microgrid planning. IEEE Transactions on Smart Grid, 8(1), pp.296-304.

[190] Basak, P., Chowdhury, S., nee Dey, S.H. and Chowdhury, S.P., 2012. A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid. Renewable and Sustainable Energy Reviews, 16(8), pp.5545-5556.

[191] Planas, E., Andreu, J., Gárate, J.I., de Alegría, I.M. and Ibarra, E., 2015. AC and DC technology in microgrids: A review. Renewable and Sustainable Energy Reviews, 43, pp.726-749.

[192] Yazdanian, M. and Mehrizi-Sani, A., 2014. Distributed control techniques in microgrids. IEEE Transactions on Smart Grid, 5(6), pp.2901-2909.

[193] Prodan, I., Zio, E. and Stoican, F., 2015. Fault tolerant predictive control design for reliable microgrid energy management under uncertainties. Energy, 91, pp.20-34.

[194] Radwan, A.A.A. and Mohamed, Y.A.R.I., 2012. Assessment and mitigation of interaction dynamics in hybrid AC/DC distribution generation systems. IEEE Transactions on Smart Grid, 3(3), pp.1382-1393.

[195] Khodaei, A., Bahramirad, S. and Shahidehpour, M., 2015. Microgrid planning under uncertainty. IEEE Trans. Power Syst, 30(5), pp.2417-2425.

[196] Liu, X., Wang, P. and Loh, P.C., 2011. A Hybrid AC/DC Microgrid and Its Coordination Control. IEEE Trans. Smart Grid, 2(2), pp.278-286.

[197] Hatziargyriou, N., Asano, H., Iravani, R. and Marnay, C., 2007. Microgrids. IEEE power and energy magazine, 5(4), pp.78-94.

[198] Rahman, M.S., Hossain, M.J. and Lu, J., 2016. Coordinated control of three-phase AC and DC type EV–ESSs for efficient hybrid microgrid operations. Energy conversion and management, 122, pp.488-503.

[199] Gu, W., Wu, Z., Bo, R., Liu, W., Zhou, G., Chen, W. and Wu, Z., 2014. Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: A review. International Journal of Electrical Power & Energy Systems, 54, pp.26-37.

[200] Tan, X., Li, Q. and Wang, H., 2013. Advances and trends of energy storage technology in Microgrid. International Journal of Electrical Power & Energy Systems, 44(1), pp.179-191.

[201] Eghtedarpour, N. and Farjah, E., 2014. Power control and management in a hybrid AC/DC microgrid. IEEE transactions on smart grid, 5(3), pp.1494-1505.

[202] Lotfi, H. and Khodaei, A., 2017. Hybrid AC/DC microgrid planning. Energy, 118, pp.37-46.

[203] Mahmud, N. and Zahedi, A., 2016. Review of control strategies for voltage regulation of the smart distribution network with high penetration of renewable distributed generation. Renewable and Sustainable Energy Reviews, 64, pp.582-595.

[204] Zubo, R.H., Mokryani, G. and Abd-Alhameed, R., 2018. Optimal operation of distribution networks with high penetration of wind and solar power within a joint active and reactive distribution market environment. Applied Energy, 220, pp.713-722.

[205] A. N. Celik, "A statistical analysis of wind power density based on the Weibull and Rayleigh models at the southern region of Turkey," *Renewable energy,* vol. 29, pp. 593-604, 2004.

[206] S. S. Reddy, A. Abhyankar, and P. Bijwe, "Market clearing for a wind-thermal power system incorporating wind generation and load forecast uncertainties," in *Power and Energy Society General Meeting, 2012 IEEE*, 2012, pp. 1-8.

[207] G. Mokryani, "Active distribution networks operation within a distribution market environment," in *Sustainable Development in Energy Systems*, ed: Springer, 2017, pp. 107-118.

[208] S. S. Reddy, B. Panigrahi, R. Kundu, R. Mukherjee, and S. Debchoudhury, "Energy and spinning reserve scheduling for a wind-thermal power system using CMA-ES with mean learning technique," *International Journal of Electrical Power & Energy Systems,* vol. 53, pp. 113-122, 2013.

[209] S. S. Reddy and J. A. Momoh, "Realistic and transparent optimum scheduling strategy for hybrid power system," *IEEE Transactions on Smart Grid,* vol. 6, pp. 3114-3125, 2015.

[210] G. Mokryani, A. Majumdar, and B. C. Pal, "Probabilistic method for the operation of three-phase unbalanced active distribution networks," *IET Renewable Power Generation,* vol. 10, pp. 944-954, 2016.

[211] S. Montoya-Bueno, J. Muñoz-Hernández, and J. Contreras, "Uncertainty management of renewable distributed generation," *Journal of Cleaner Production,* vol. 138, pp. 103-118, 2016.

[212] J. Widén, "Correlations between large-scale solar and wind power in a future scenario for Sweden," *IEEE transactions on sustainable energy,* vol. 2, pp. 177-184, 2011.

[213] S. S. Reddy, P. Bijwe, and A. R. Abhyankar, "Joint energy and spinning reserve market clearing incorporating wind power and load forecast uncertainties," IEEE Systems Journal, vol. 9, pp. 152-164, 2015.

[214] S. S. Reddy, P. Bijwe, and A. R. Abhyankar, "Optimal posturing in day-ahead market clearing for uncertainties considering anticipated real-time adjustment costs," IEEE Systems Journal, vol. 9, pp. 177-190, 2015.

[215] Li, Y. and Zio, E., 2012. Uncertainty analysis of the adequacy assessment model of a distributed generation system. Renewable Energy, 41, pp.235-244.

[216] Department of Electrical Engineering 2018, Department of Electrical Engineering website, Comsats University, accessed 20 February 2018, <http://old.cuiatd.edu.pk/secure/researchgroups/ >

[217] Movahednasab, A., Rashidinejad, M. and Abdollahi, A., 2017. Dynamic analysis of natural gas role on capacity expansion in power market. International Journal of Power and Energy Systems, 37(1).

[218] He, C., Liu, T., Wu, L. and Shahidehpour, M., 2017. Robust coordination of interdependent electricity and natural gas systems in day-ahead scheduling for facilitating volatile renewable generations via power-to-gas technology. Journal of Modern Power Systems and Clean Energy, 5(3), pp.375-388.

[219] Owusu, P.A. and Asumadu-Sarkodie, S., 2016. A review of renewable energy sources, sustainability issues and climate change mitigation. Cogent Engineering, 3(1), p.1167990.

[220] Niknam, T. and Kavousifard, A., 2012. Impact of thermal recovery and hydrogen production of fuel cell power plants on distribution feeder reconfiguration. IET generation, transmission & distribution, 6(9), pp.831-843.

[221] Quelhas, A., Gil, E., McCalley, J.D. and Ryan, S.M., 2007. A multiperiod generalized network flow model of the US integrated energy system: Part I—Model description. IEEE Transactions on Power Systems, 22(2), pp.829-836.

[222] Pantoš, M., 2011. Market-based congestion management in electric power systems with increased share of natural gas dependent power plants. Energy, 36(7), pp.4244-4255.

[223] Zhang, X., Shahidehpour, M., Alabdulwahab, A. and Abusorrah, A., 2015. Hourly electricity demand response in the stochastic day-ahead scheduling of coordinated electricity and natural gas networks. IEEE Transactions on Power Systems, 31(1), pp.592-601.

[224] Qiu, J., Dong, Z.Y., Zhao, J.H., Xu, Y., Zheng, Y., Li, C. and Wong, K.P., 2014. Multi-stage flexible expansion co-planning under uncertainties in a combined electricity and gas market. IEEE Transactions on Power Systems, 30(4), pp.2119-2129.

[225] Unsihuay, C., Marangon-Lima, J.W. and De Souza, A.Z., 2007, July. Short-term operation planning of integrated hydrothermal and natural gas systems. In 2007 IEEE Lausanne Power Tech (pp. 1410-1416). IEEE.

[226] Liu, C., Shahidehpour, M., Fu, Y. and Li, Z., 2009. Security-constrained unit commitment with natural gas transmission constraints. IEEE Transactions on Power Systems, 24(3), pp.1523-1536.

[227] Qadrdan, M., Chaudry, M., Wu, J., Jenkins, N. and Ekanayake, J., 2010. Impact of a large penetration of wind generation on the GB gas network. Energy Policy, 38(10), pp.5684-5695.

[228] Kamalinia, S., Wu, L. and Shahidehpour, M., 2014. Stochastic midterm coordination of hydro and natural gas flexibilities for wind energy integration. IEEE Transactions on Sustainable Energy, 5(4), pp.1070-1079.

[229] Sheikhi, A., Rayati, M. and Ranjbar, A.M., 2015, February. Energy Hub optimal sizing in the smart grid; machine learning approach. In 2015 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT) (pp. 1-5). IEEE.

[230] Shahidehpour, M.O.H.A.M.M.A.D., Fu, Y. and Wiedman, T., 2005. Impact of natural gas infrastructure on electric power systems. Proceedings of the IEEE, 93(5), pp.1042-1056.

[231] Manshadi, S.D. and Khodayar, M.E., 2018. A tight convex relaxation for the natural gas operation problem. IEEE Transactions on Smart Grid, 9(5), pp.5467-5469.

[232] Baseer, M., Mokryani, G., Zubo, R.H. and Cox, S., 2019. Planning of HMG with high penetration of renewable energy sources. IET Renewable Power Generation, 13(10), pp.1724-1730.

[233] Frank, S.M. and Rebennack, S., 2015. Optimal design of mixed AC–DC distribution systems for commercial buildings: A Nonconvex Generalized Benders Decomposition approach. European Journal of Operational Research, 242(3), pp.710-729.

[234] Martinez-Mares, A. and Fuerte-Esquivel, C.R., 2012. A unified gas and power flow analysis in natural gas and electricity coupled networks. IEEE Transactions on Power Systems, 27(4), pp.2156-2166.

[235] Kamalinia, S., Wu, L. and Shahidehpour, M., 2014. Stochastic midterm coordination of hydro and natural gas flexibilities for wind energy integration. IEEE Transactions on Sustainable Energy, 5(4), pp.1070-1079

[236] Bai, L., Li, F., Cui, H., Jiang, T., Sun, H. and Zhu, J., 2016. Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty. Applied energy, 167, pp.270-279.

[237] Sohrabi, F., Jabari, F., Mohammadi-Ivatloo, B. and Soroudi, A., 2019. Coordination of interdependent natural gas and electricity systems based on information gap decision theory. IET Generation, Transmission & Distribution, 13(15), pp.3362-3369.

[238] Ghasemi, H., Aghaei, J., Gharehpetian, G.B. and Safdarian, A., 2018. MILP model for integrated expansion planning of multi-carrier active energy systems. IET Generation, Transmission & Distribution, 13(7), pp.1177-1189.

[239] Lotfi, H. and Khodaei, A., 2015. AC versus DC microgrid planning. IEEE Transactions on Smart Grid, 8(1), pp.296-304.

[240] Anand, H., Narang, N., Dhillon, J. S.: 'Multi-objective combined heat and power unit commitment using particle swarm optimization', Energy, 2019, 172, pp. 794–807.

[241] Chen, S., Wei, Z., Sun, G., et al.: 'Multi-linear probabilistic energy flow analysis of integrated electrical and natural-gas systems', IEEE Trans. Power Syst., 2017, 32, pp. 1970–1979

[242] Bracco, S., Brignone, M., Delfino, F., et al.: 'An optimization model for polygeneration microgrids with renewables, electrical and thermal storage: application to the savona campus'. Proc. 2018 IEEE Int. Conf. on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, Italy 2018, pp. 12–15. https://doi.org/10.1109/EEEIC.2018.8493965

[243] Urbanucci, L., Testi, D., Bruno, J. C.: 'An operational optimization method for a complex polygeneration plant based on real-time measurements', Energy Convers. Manage., 2018, 170, pp. 50–61. https://doi.org/10.1016/j.enconman.2018.05.076

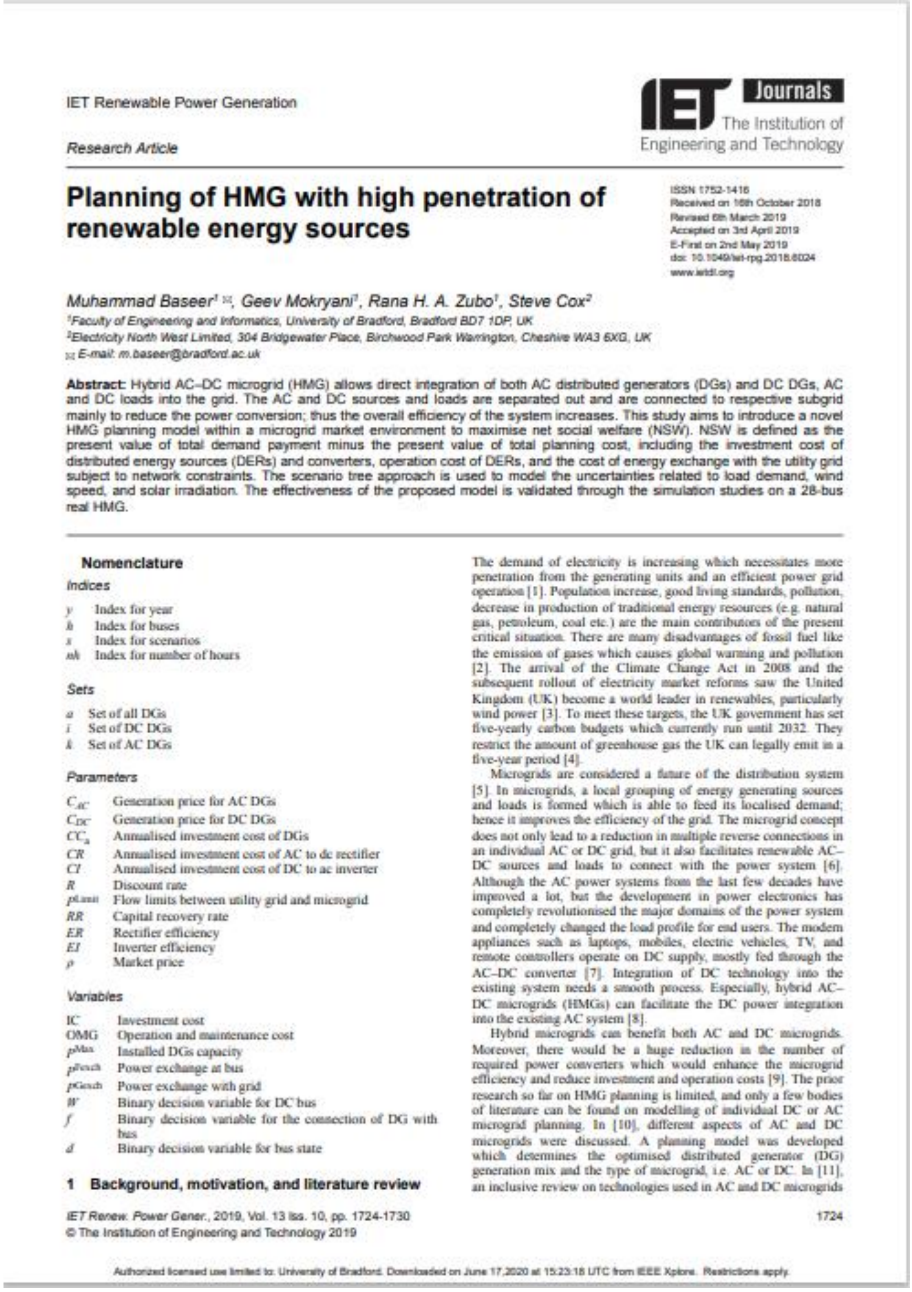
[244] E. A. M. Ceseña, N. Good, and P. Mancarella, "Energy efficiency at the building and district levels in a multi-energy context," in Proc. IEEE Int. Energy Conf. (ENERGYCON), Apr. 2016, pp. 1–6.

[245] P. Mancarella and G. Chicco, "Real-time demand response from energy shifting in distributed multi-generation," IEEE Trans. Smart Grid, vol. 4, no. 4, pp. 1928–1938, Dec. 2013.

[246] Massrur, H.R., Niknam, T. and Fotuhi-Firuzabad, M., 2019. Day-ahead energy management framework for a networked gas–heat–electricity microgrid. IET Generation, Transmission & Distribution, 13(20), pp.4617-4629.

[247] Angarita, J.L., Jafari, H., Mohseni, M., Al-Sumaiti, A.S., Heydarian-Forushani, E. and Kumar, R., 2021. Optimal investment and operation of a microgrid to provide electricity and heat. IET Renewable Power Generation.

SELECTED AUTHOR’S PUBLICATIONS



IET Renewable Power Generation

Research Article

Planning of HMG with high penetration of renewable energy sources

ISSN 1752-1416
Received on 16th October 2018
Revised 6th March 2019
Accepted on 3rd April 2019
E-First on 2nd May 2019
doi: 10.1049/iet-rpg.2018.6024
www.ietdl.org

Muhammad Baseer[1] ✉, *Geev Mokryani*[1], *Rana H. A. Zubo*[1], *Steve Cox*[2]
[1]*Faculty of Engineering and Informatics, University of Bradford, Bradford BD7 1DP, UK*
[2]*Electricity North West Limited, 304 Bridgewater Place, Birchwood Park Warrington, Cheshire WA3 6XG, UK*
✉ *E-mail: m.baseer@bradford.ac.uk*

Abstract: Hybrid AC–DC microgrid (HMG) allows direct integration of both AC distributed generators (DGs) and DC DGs, AC and DC loads into the grid. The AC and DC sources and loads are separated out and are connected to respective subgrid mainly to reduce the power conversion; thus the overall efficiency of the system increases. This study aims to introduce a novel HMG planning model within a microgrid market environment to maximise net social welfare (NSW). NSW is defined as the present value of total demand payment minus the present value of total planning cost, including the investment cost of distributed energy sources (DERs) and converters, operation cost of DERs, and the cost of energy exchange with the utility grid subject to network constraints. The scenario tree approach is used to model the uncertainties related to load demand, wind speed, and solar irradiation. The effectiveness of the proposed model is validated through the simulation studies on a 28-bus real HMG.

Nomenclature

Indices

y	Index for year
h	Index for buses
s	Index for scenarios
nh	Index for number of hours

Sets

a	Set of all DGs
i	Set of DC DGs
k	Set of AC DGs

Parameters

C_{AC}	Generation price for AC DGs
C_{DC}	Generation price for DC DGs
CC_a	Annualised investment cost of DGs
CR	Annualised investment cost of AC to dc rectifier
CI	Annualised investment cost of DC to ac inverter
R	Discount rate
P^{Limit}	Flow limits between utility grid and microgrid
RR	Capital recovery rate
ER	Rectifier efficiency
EI	Inverter efficiency
ρ	Market price

Variables

IC	Investment cost
OMG	Operation and maintenance cost
P^{Max}	Installed DGs capacity
P^{Exch}	Power exchange at bus
P^{Gexch}	Power exchange with grid
W	Binary decision variable for DC bus
f	Binary decision variable for the connection of DG with bus
d	Binary decision variable for bus state

1 Background, motivation, and literature review

The demand of electricity is increasing which necessitates more penetration from the generating units and an efficient power grid operation [1]. Population increase, good living standards, pollution, decrease in production of traditional energy resources (e.g. natural gas, petroleum, coal etc.) are the main contributors of the present critical situation. There are many disadvantages of fossil fuel like the emission of gases which causes global warming and pollution [2]. The arrival of the Climate Change Act in 2008 and the subsequent rollout of electricity market reforms saw the United Kingdom (UK) become a world leader in renewables, particularly wind power [3]. To meet these targets, the UK government has set five-yearly carbon budgets which currently run until 2032. They restrict the amount of greenhouse gas the UK can legally emit in a five-year period [4].

Microgrids are considered a future of the distribution system [5]. In microgrids, a local grouping of energy generating sources and loads is formed which is able to feed its localised demand; hence it improves the efficiency of the grid. The microgrid concept does not only lead to a reduction in multiple reverse connections in an individual AC or DC grid, but it also facilitates renewable AC–DC sources and loads to connect with the power system [6]. Although the AC power systems from the last few decades have improved a lot, but the development in power electronics has completely revolutionised the major domains of the power system and completely changed the load profile for end users. The modern appliances such as laptops, mobiles, electric vehicles, TV, and remote controllers operate on DC supply, mostly fed through the AC–DC converter [7]. Integration of DC technology into the existing system needs a smooth process. Especially, hybrid AC–DC microgrids (HMGs) can facilitate the DC power integration into the existing AC system [8].

Hybrid microgrids can benefit both AC and DC microgrids. Moreover, there would be a huge reduction in the number of required power converters which would enhance the microgrid efficiency and reduce investment and operation costs [9]. The prior research so far on HMG planning is limited, and only a few bodies of literature can be found on modelling of individual DC or AC microgrid planning. In [10], different aspects of AC and DC microgrids were discussed. A planning model was developed which determines the optimised distributed generator (DG) generation mix and the type of microgrid, i.e. AC or DC. In [11], an inclusive review on technologies used in AC and DC microgrids

IET Renew. Power Gener., 2019, Vol. 13 Iss. 10, pp. 1724-1730