

**[Optimal Sizing and Operation Methodologies  
for Renewable Power Integration]**

BY

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A Thesis Presented to the  
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DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the  
Requirements for the Degree of

**MASTER OF SCIENCE**

In

**ELECTRICAL ENGINEERING**

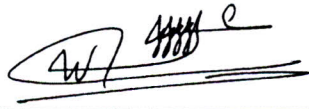
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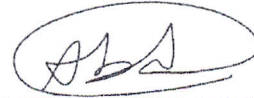
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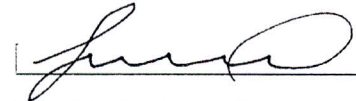
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OPTIMAL SIZING AND OPERATION  
METHODOLOGIES FOR RENEWABLE POWER  
INTEGRATION

BY

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2020

*I dedicate this thesis to my whole family, especially my parents and my wife whose love,affection,guidance, and support have aided and motivated me towards this accomplishment.*

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# LIST OF SYMBOLS AND ABBREVIATIONS

|                        |                                                                    |
|------------------------|--------------------------------------------------------------------|
| $\eta$                 | Unit price of electricity                                          |
| $\eta_{BESS}(t)$       | Efficiency of the BESS                                             |
| $\eta_{BESS}^{cha}(t)$ | Charging efficiency of the BESS                                    |
| $\eta_{BESS}^{dis}(t)$ | Discharging efficiency of the BESS                                 |
| $\Delta t$             | Incremental time for the optimization and has been taken as 1 hour |
| $a_i, b_i, c_i$        | Fuel cost coefficient of generator unit, $i$                       |
| $A_f$                  | Swept area of the wind turbine                                     |
| $C_{d.gen}$            | Total cost of diesel generators                                    |
| $C_{RE*}$              | Related cost of renewable                                          |
| $CMG_{ex}$             | Cost of power exchange between the grid and the microgrid          |
| $CMG_{units}$          | Total cost of microgrid generators                                 |

|                  |                                                  |
|------------------|--------------------------------------------------|
| $CRF$            | Capital recovery factor                          |
| $d_i, e_i, f_i$  | Emission cost coefficient of generator unit, $i$ |
| $DC_{BESS}$      | Daily cost of BESS                               |
| $DGC_{BESS}$     | Daily generator cost of BESS                     |
| $DOD_{BESS}(t)$  | Depth of discharge of the BESS at hour $t$       |
| $E_{BESS}(t)$    | Energy capacity of the BESS at hour $t$          |
| $E_{BESS}^c(t)$  | Battery BESS total capacity in MWh               |
| $E_{BESS}^{max}$ | Rated energy capacity of the BESS                |
| $EC_{BESS}$      | Cost of BESS energy per MWh                      |
| $EM$             | Emission cost of diesel generator                |
| $EM$             | Emission cost                                    |
| $FC$             | Fuel cost of diesel generator                    |
| $fc_i$           | Fixed cost of unit $i$                           |
| $G_i$            | Generator unit $i$                               |
| $I$              | Number of units                                  |
| $i$              | Unit index                                       |
| $IC_{WT}$        | Investment cost on wind turbine                  |

|                  |                                                        |
|------------------|--------------------------------------------------------|
| $J$              | Objective function                                     |
| $K_{max}$        | Power coefficient                                      |
| $l_y$            | life time of project                                   |
| $MC$             | Maintenance cost                                       |
| $n_c^{DOD}$      | Number of cycles of energy storage at a particular DOD |
| $OC$             | Operating cost                                         |
| $P_D(t)$         | Demand at time $t$                                     |
| $P_g$            | Grid power                                             |
| $P_i$            | Generator output power of unit $i$                     |
| $P_{BESS}(t)$    | BESS net power at time $t$                             |
| $P_{BESS}^{max}$ | Rated power capacity of the BESS                       |
| $P_{ch}(t)$      | BESS charging power at time $t$                        |
| $P_{dis}(t)$     | BESS discharging power at time $t$                     |
| $P_{gmax}$       | Maximum grid power                                     |
| $P_{grid}(t)$    | Grid power at time $t$                                 |
| $P_{grid}^{max}$ | Maximum grid power                                     |
| $P_{grid}^{min}$ | Minimum grid power                                     |

|                 |                                                |
|-----------------|------------------------------------------------|
| $P_{i,t}$       | Generator output power of unit $i$ at hour $t$ |
| $P_i^{max}$     | Maximum power output of unit $i$               |
| $P_i^{min}$     | Minimum power output of unit $i$               |
| $P_{wt}(t)$     | Wind power at time $t$                         |
| $P_W^{max}$     | Maximum power from the wind turbine            |
| $PC$            | Paid cash at time $t$                          |
| $PC_{BESS}$     | Cost of BESS power per MW                      |
| $PC_{wt}$       | Daily Cost of wind power                       |
| $PLP$           | Power loss probability                         |
| $RC$            | Received cash at time $t$                      |
| $RC_{RE}$       | Wind related cost of renewable                 |
| $SOC(t)$        | BESS state of charge at time $t$               |
| $SOC_{max}$     | BESS maximum state of charge                   |
| $SOC_{min}$     | BESS minimum state of charge                   |
| $T$             | Number of hours                                |
| $t$             | Time in hour                                   |
| $T_{i,t}^{OFF}$ | OFF time of unit $i$ at hour $t$               |

|                 |                                                                                                          |
|-----------------|----------------------------------------------------------------------------------------------------------|
| $T_{i,t}^{ON}$  | ON time of unit $i$ at hour $t$                                                                          |
| $TCF$           | Total cash flow                                                                                          |
| $u_i, y_i, z_i$ | Binary decision variables for unit $i$ indicate the state of ON/OFF, start up/shut down of the generator |
| $U_{pg}(t)$     | Unit price of grid electricity at time $t$                                                               |
| $U_{pm}(t)$     | Unit price of microgrid electricity at time $t$                                                          |
| $v_{CI}$        | Cut in Wind speed                                                                                        |
| $v_{CO}$        | Cut out Wind speed                                                                                       |
| $v_t$           | Wind speed at time $t$                                                                                   |
| $vc_i$          | Variable cost of unit $i$                                                                                |
| BES             | Battery energy storage                                                                                   |
| BESS            | Battery Energy Storage System                                                                            |
| CRF             | Capital Recovery Factor                                                                                  |
| DOD             | Depth of Discharge                                                                                       |
| DSC             | Daily Schedule cost                                                                                      |
| EMS             | Energy Management Strategy                                                                               |
| ESS             | Energy Storage System                                                                                    |

|      |                                  |
|------|----------------------------------|
| GWO  | Grey Wolf Optimization           |
| IC   | Investment cost                  |
| LP   | Linear Programming               |
| MC   | Maintenance cost                 |
| MDT  | Minimum Down Time                |
| MILP | Mixed-Integer Linear Programming |
| MUT  | Minimum Up Time                  |
| NLP  | Non-Linear Programming           |
| OC   | Operation cost                   |
| PLP  | Power Loss Probability           |
| PSO  | Particle Swarm Optimization      |
| PV   | Photovoltaic                     |
| SOC  | State of Charge                  |
| TOC  | Total cost                       |
| WT   | wind turbine                     |

# THESIS ABSTRACT

**NAME:** Umar Taiwo Salman (g201706090)  
**TITLE OF STUDY:** Optimal Sizing and Operation Methodologies for Renewable Power Integration  
**MAJOR FIELD:** ELECTRICAL ENGINEERING  
**DATE OF DEGREE:** April 2020

*Renewable energy (RE), particularly solar and wind, have attracted a lot of attention due to inherent benefits, and nations have set ambitious goals to enhance the penetration of renewable power into their electricity networks. However, the RE like photovoltaic (PV) and wind are uncertain, intermittent and unpredictable. Therefore, there is a need to optimize their usage when they are available. Moreover, attention is given to the use of the energy storage system (ESS) to store RE when they are available and dispatch them for usage when they are not, through an efficient energy management system (EMS). However, the ESS has to be optimally sized because of its huge cost. The ESS can enhance the reliability of the power system by compensating for the gaps in RE sources and consequently reduces the cost of operation of the microgrid systems. This thesis presents an EMS to size the battery energy stor-*

*age system (BESS) for the operation of microgrids. Sizing of BESS was done for a wind penetrated microgrid for 12 Calendar months under a case study of Eastern Province of Saudi Arabia and different methodologies were adopted. Furthermore, the operation of BESS was done for different microgrid configurations while considering its state of health, degradation, depth of discharge, lifetime and the best methodology was recommended for wind power. Findings from the results showed the effectiveness of the study.*

## ملخص الرسالة

الاسم: عنوان الدراسة:

التخصص: قسم الطلاب

تاريخ الدرجة العلمية:

اجتذبت الطاقة المتجددة (RE) ، وخاصة الطاقة الشمسية وطاقة الرياح ، الكثير من الاهتمام بسبب الفوائد المتأصلة ، وقد وضعت الدول أهدافاً طموحة لتعزيز اختراق الطاقة المتجددة في شبكات الكهرباء الخاصة بها. ومع ذلك ، فإن الطاقة الكهروضوئية مثل الرياح والرياح غير مؤكدة ومتقطعة وغير متوقعة. لذلك ، هناك حاجة لتحسين استخدامها عند توفرها. علاوة على ذلك ، يتم الانتباه إلى استخدام نظام تخزين الطاقة (ESS) لتخزين الطاقة المتجددة عندما تكون متاحة وإرسالها للاستخدام عندما لا تكون متاحة ، من خلال نظام إدارة الطاقة الفعال (EMS) ومع ذلك ، يجب أن يكون ESS بحجم مثالي بسبب تكلفته الضخمة. يمكن لـ ESS تعزيز موثوقية نظام الطاقة عن طريق تعويض الثغرات في مصادر الطاقة المتجددة وبالتالي تقليل تكلفة تشغيل أنظمة الشبكة الصغيرة. تقدم هذه الأطروحة EMS لحجم نظام تخزين طاقة البطارية (BESS) لتشغيل microgrids. تم إجراء تحجيم BESS لميكروجريد اختراق الرياح لمدة 12 شهراً تقويمياً بموجب دراسة حالة للمنطقة الشرقية بالمملكة العربية السعودية وتم اعتماد منهجيات مختلفة. علاوة على ذلك ، تم تشغيل BESS لتكوينات microgrid المختلفة مع مراعاة حالتها الصحية وتدهورها وعمق التفريغ وعمرها وأفضل طريقة لطاقة الرياح. أظهرت النتائج من نتائج الدراسة فاعلية الدراسة.

# CHAPTER 1

## INTRODUCTION

### 1.1 Work Motivation

Renewable energy (RE) is gaining more popularity in recent years and nations are endeavoring to increase its integration into their energy-mix. It was reported in [8] that the renewable power capacity of the world increased by 8% in 2018 alone with more than 90 countries have added up to 1GW of renewable power out of which more than 30 had above 10GW. As an increase in the world population triggers the demand for more energy, there is also the quest for cleaner energy sources because the conventional sources are known to be environmentally unfriendly due to the emission of greenhouse gases. Solar, wind, hydro, geothermal, biomass, etc are common RE sources that are promising alternatives and are fast becoming popular in the world. As part of its vision 2030, Saudi Arabia has joined the race to increase its renewable penetration to 58.7GW by 2032 [2] with solar photovoltaic (PV) and wind accounting for 40MW and 16MW respectively as shown in Figure 1.1.

Meanwhile, the electricity sector seems to be the hottest spot for renewable power



Figure 1.1: The renewable energy target of KSA [2]

like wind power and PV to thrive following the growing installation of wind and PV across the world, moreover, they serve as good contributions to several already installed hydropower generation across the world. However, the integration of RE into the power system requires the energy storage systems (ESS) and is very critical for the smooth operation of the microgrid through which the RE are connected to the main grid [9], [10].

ESS serves as a key component of the microgrid system and provides great support for the microgrid during its operation and performs functions like load leveling, peak shifting to support the peak demand [10]. In this thesis, the methodologies for sizing and operation of the battery energy storage system (BESS) are studied to minimize the operation cost of the microgrid and consequently results to minimum investment cost of the BESS. An efficient strategy for optimal operation of BESS is developed to achieve minimum operation cost and a healthy operation of the BESS.

## 1.2 Problem Definition

when discussing the concept of electrical power in a microgrid, many factors such as power demand, population, level of industrialization, geographical location amongst many others are being analyzed. Other aspects that are even more important when planning the operation of a microgrid are renewable energy sources, energy storage, power demand, seasonal demand variation, interest rate to mention a few. It is noted in [11] that, weather conditions do not only affect electricity production from both solar and wind but also electricity demand. However, the highest demands are observed in the summer months and the lowest-demands occurred in the months of Spring [12]. Incidentally, renewable power generation from wind also varies with season and this can have significant effects on the operation of a wind-penetrated microgrid in different seasons. However, in the months or season of lower wind speed resorting to smaller wind power, the BESS provides the needed support. Figure 1.2 shows the possible wind power generation for the year 2018 and the year 2017 adapted from the wind profile of a station Dhahran city. Higher wind powers are observed between hours of 3600 and 5700 corresponding to around June, July August and September which are essentially the summer months in Saudi Arabia [13], [14].

Sizing of the BESS is greatly affected by the amount of wind power at any point in time. A large amount of wind power leads to over-sizing of the BESS and consequently leads to a high investment cost. Besides, an undersized BESS might not provide the economic and operational benefits for the microgrid [15]. Since the power from the wind is not reliable throughout the hours, the microgrid has to rely on ex-

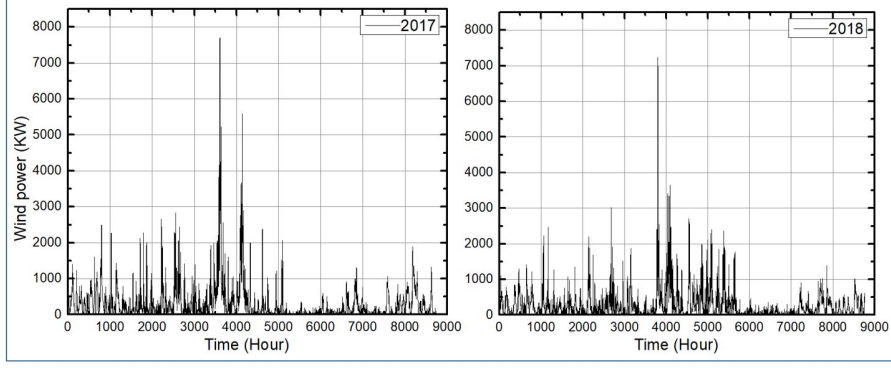


Figure 1.2: Wind power profile for 2018 and 2017 of Dhahran [3]

tensive support from the BESS. Consequently, more stress is imposed on the BESS whenever the demand exceeds the renewable outputs. These stress can affect some of the parameters of the BESS during the operation of the microgrid. Some of these parameters, including state of charge, depth of discharge, lifetime, efficiency, energy capacity, power capacity life cycle, battery aging, etc as noted in [16], [17] may be affected by the operation of the BESS in the microgrid [18]. Thus this study presents a strategy to size and operates the BESS considering the underlying challenges mentioned in this section by following the highlighted objectives in Section 1.3.

## 1.3 Thesis Objectives

The thesis objective are stated as follows:

1. Comprehensive review on capacity optimization approaches for battery energy storage systems (BESSs).
2. Design and development of optimal sizing methodologies for BESS considering four different configurations of a microgrid (MG) as follows: :
  - (i) Solar PV based MG
  - (ii) Wind powered MG
  - (iii) Hybrid PV/wind penetrated MG
  - (iv) MG with conventional and distributed renewable power mix .
3. Propose efficient algorithms for optimal operation of BESS considering cost optimization and battery lifetime.
4. Comparative study of sizing methodologies for BESS and recommend the best for wind power

## 1.4 Thesis Outline

This thesis comprises of six chapters.

Chapter 1 presents the motivation for the study, the thesis objectives and a brief description of the thesis document.

Chapter 2 of this study involves two parts: The first part deals with a Comprehensive review on capacity optimization approaches for BESS and the second part discussed the application of BESS in microgrid RE integration.

Chapter three presents the theoretical background of the proposed study. It begins with an overview of the concept of microgrid, battery energy storage systems, types, and characteristics. In the second part, the modeling equation for sizing the BESS is presented along with objectives and associated constraints. The chapter also describes the model of the microgrid components, such as wind turbine, PV, diesel generator, BESS, main grid and case study. All equations for the microgrid operation for the different microgrid configurations and strategies are discussed.

Chapter four discussed the results BESS sizing for the 12 Calendar months. Furthermore, the results of the sizing of BESS in various methodologies are discussed.

Chapter five presents the results of the microgrid operation strategy of BESS for the wind-penetrated microgrid. Besides, the chapter discussed the result of the microgrid strategy of each configuration.

chapter six finally highlights the conclusion and recommendation.

## CHAPTER 2

# LITERATURE REVIEW

The problems associated with uncertainty and fluctuation of the RES have been addressed in many studies. A common solution is the combination of two or more RES to form a hybrid renewable system (HRES) [19], [20], [21], [22]. In this technique, the RES are combined optimally to compensate for each other. For instance, in a hybrid PV/wind combination, while the PV generation is naturally abundant during the day, the wind generation is always available through out the day and night to compensate for a reduced generation of PV in the day and supply fully when the PV is no longer available. Some extensive review of HRES are presented in [23], [24], [25], [26]. Although HRES introduces extra control issues on the power system, however, some of the control problems associated with HRES have been addressed in [27], [28], [29].

As the penetration of RE within the microgrid increases, the BESS continues to offer solutions to the technical challenges associated with power systems [30], [31]. These technical challenges include but not limited to reliability, power quality, frequency control, voltage control, power protection [32], [33]. However, the BESS itself

must be operated optimally and safely to prevent it from being overstretched and to ensure its durability [30]. Besides, it has been demonstrated in [34] that the BESS could be protected by some control schemes. Yet, some parameters or characteristics of BESS such as state of charge (SOC), depth of discharge (DOD), lifetime, efficiency, capacities, life cycle, battery aging, etc may be affected by the operation of the BESS in the microgrid [16], [17]. Moreover, the importance of every parameter of the BES is largely dependent on the application for which the BES will be used [18]. Furthermore, as there are different types of BES technologies with different characteristics such as specific power, Specific energy, cycle life, energy density, power density, efficiency, operating cost, and efficiency [1], [18]. The application for which the BESS will be used will determine which technology to adopt or which parameter is more important [18].

The criteria indicators for sizing the BESS have been classified into financial, technical, and hybrid indicators [35]. The hybrid criterion combines the technical and financial indicators to size the BESS where for example the financial indicator is optimized subject to the technical based constraint. Like in [15], [36], the rated sizes of BESS were determined by minimizing the operation costs under some reliability constraints. There are various techniques used in the sizing of BESS, some of these techniques include the analytical method, probabilistic method and direct searched methods[35]. In the direct searched method, a mathematical optimization model may be developed as linear programming (LP), non-linear programming(NLP), mixed-integer programming (MIP), mixed-integer linear programming (MILP), mixed-integer non-linear programming (MINLP) problems.

Usually in the sizing of BESS, the formulation of the problem is always defined based on the objective function of the proposed problem which may be cost-based or priced based or both [37], in which case, the objective may be the minimization of the cost or maximization of the profit. The objective function is controlled by an iterative process which terminates when the best results are reached. In recent studies, several types of methodologies have been adopted for the sizing of BESS with renewable energy. However, continuous research is needed for the proper integration of renewable energy sources (RES) with BESS in the emerging smart microgrids.

There are three approaches for analyzing the capacity optimization in BESS, these include fluctuation stabilization approaches, energy balance approach, and economic stabilization approach [38]. In any of these approaches, the BESS is modeled around the parameter of interest using any suitable optimization method. Nevertheless, the criteria and approach for obtaining the optimal size of any storage depend largely on the particular applications and the capabilities of the power networks [39]. Figure 2.1 summarizes some parameters that determine the type of approach to use.

Since the installation of BESS required a huge cost, its oversizing will prevent commercial usage of the BESS by the microgrid operators and results in high tariffs. Hence the optimal size of the BESS required for any application must be determined. [40] The LP and the MILP which apply to problems with one or more constraint has the advantage that it adds at least one more integer type constraint and has been used in many papers [30-34]. Shivashankar, et al in [41] present a novel mixed-mode energy management strategy suitable for sizing the operation of PV, fuel cell, and BESS. They used PSO and the LP and MILP optimization approach for operating a

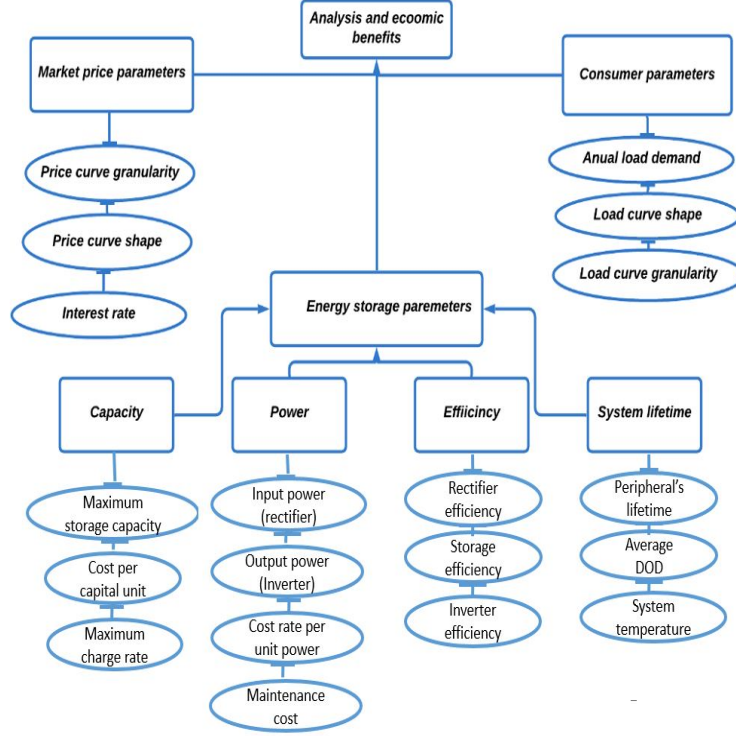


Figure 2.1: Parameters for determining BESS economics

microgrid at minimum operating cost. In [42], a comparison study of optimal operational size and cost between four different types of battery technologies (Lead-acid, lithium-ion, vanadium redox, and Sodium sulfur) in a hybrid PV and wind power plant carried out using the MILP. The MILP approach reveals that lithium-ion outperforms others followed by the lead-acid while the vanadium redox battery showed the least among the four technologies. Reference [43], [44] used MILP to size optimal PV-BESS configuration in a household considering step-wise power tariff. Also, the MILP algorithm was used to investigate the optimal planning and operational cost of BESS in a stand-alone microgrid, [45],[46]. Additionally, [46] used the algorithm to optimize the replacement cost of BESS by adopting the SOC and power demand to reduce its aging to the minimum. The authors conclude that the MILP is a strong

optimization technique for sizing of BESS in the various studies.

Another approach used for sizing BESS is based on forecasting errors in renewable energy sources like PV and wind generations[47]. Due to the stochastic nature of these sources, there is a need for proper compensation of the static error[47]. This is suitably done with the use of BESS. In [48], [49], the sizes of BESS have been optimized with wind power curtailment using the Monte Carlo simulations. Furthermore, in [49], the stochastic data of wind and PV were generated using the Monte Carlo method. The objective function was to minimize the cost. It was found that the minimum cost obtained is better improved in the case where uncertainty is considered as compared to where it is not. The authors in [50] presents a scholastic dynamic programming approach to optimize the operation of the BESS leading to maximal lifetime value. The result showed that it is economical to operate residential batteries when the effect of stochastic generation is considered. In [51], a scheduling algorithm was used to find the profitability condition of batteries for energy arbitrage in real-time markets which can lead to optimal sizing of BESS. Results showed that such a good forecast resorts to high profitability. Morteza et al in their recent study [52], presents a new two-step based method for optimal sizing of BESS in an off-grid microgrid using the convex optimization technique. The study after solving a unit commitment problem then determines the optimal size of BESS using the convex optimization technique. The optimal values for operational cost and total cost obtained in Convex optimization were found to be lower than what was obtained in the heuristic optimization method. In [53], Shiewei Xia et al did a stochastic cost-benefit analysis model and converted it to the deterministic problem making use of point estimation method with parallel

branch-bound algorithm and Cholesky decomposition. The study revealed that at low charging/discharging efficiency and high installation cost of the BESS, it is not profitable to install BESS in such a microgrid network. Similarly in [54], the authors made use of branch and bound technique for an optimal energy management study in an on-grid microgrid made up of Wind-PV-Battery system, the study showed that the optimal value for the state of charge (SOC) in the daily operation system results in minimum cash flow.

In [55], the optimal size of BESS was obtained in a PV penetrated microgrid for a commercial building in Iran through the use of financial evaluation analysis and the optimal size of BESS used in the network were obtained. Recursive techniques based on dynamic programming (DP) for sizing of the BESS are presented in [56], [57], [58], [59], [60]. The sizing of BESS in the operation of solar PV microgrid for electricity and desalinated water production was studied in [56]. Two algorithms; DP and ordinal optimization were used to find the optimal output of the cost function. The optimal scheduling problem of Vanadium redox battery (VRB) was solved in [57] using the DP algorithm. The authors considered the efficiency and operating characteristics of VRB to determine the optimal size of VRB power and energy rating required for both island and grid-connected mode microgrid. Reference [58] used DP for a double layer optimization strategy in an electricity market system of a microgrid to determine the optimal size of BESS and in [59] and in [60] the optimal cost of peak shaving service and power consumption from the main grid for an intensive PV penetration in a PV tied microgrid with BESS was obtained.

Special scenarios of BESS sizing are presented in [61], [62], [63], [64], [44]. In

[63], a life cycle planning methodology of BESS in microgrids was presented and the optimal sizes of BESS were obtained under multi-scaled decision parameters to meet the demand growth. In [64], the optimal values of BESS for an islanded DC microgrid using an incremental cost approach were studied while in [52], the convex optimization technique was used for minimization of a unit commitment problem. Besides, the study in [64] evaluates the feasibility of installing a given battery unit to achieve the minimum running cost.

Heuristic methods have been used to solve optimization problems involving BESS sizing. Although their solutions are not perfect, they give sufficiently practical solutions and are suitable for non-linear problems. Meta-heuristic optimization techniques like particle swarm optimizer (PSO), Genetic algorithm (GA), firefly algorithm (FA), GWO, Harmony search algorithm (HSA), Lightning search algorithm (LSA), Gravitational search algorithm (GSA), etc are commonly being adopted recently for BESS sizing. However, these algorithms are used in non-linear complex optimization problems because of their simplicity, easy implementation and the need not for gradient calculation [65], [66].

Reference [67], [68] used the advanced PSO to optimize the cost of power system including BESS. In [67], [69], [70] the authors optimized the capacity of hybrid energy storage involving BESS-super capacitor in a solar and wind hybrid power system. The optimization objective here was the minimization of full life cycle cost and in [68], the overall cost of designing a hybrid power system including the BESS was optimized. The results, when compared with the conventional iterative method, showed that the PSO gives better performance. In [71], the authors used PSO for optimization of

the capacity of BESS in a stand-alone system of a hybrid PV-wind power system. It further designed a controller to allow a component to supply weather dependent loads. The model was seen to perform well at different weather and temperatures. An improved annealing PSO was proposed in [69] to optimize the one-time investment cost and operation cost of the complete life cycle of a hybrid storage system made up of BESS and supercapacitor in a wind/PV microgrid. Authors in [70] combined both PSO Nelder-Mead Simplex method to minimize the battery power stress and also improves its lifetime. An interesting formulation of stand-alone microgrid was developed in [72], the authors evaluate the optimum size of BESS at a minimal total cost of BESS to prevent the microgrid from loss of stability and system collapse. The nobility of the approach lies in the use of PSO based-frequency control mechanism. The minimization was done to cover for 15 years and the result obtained was compared with what was obtained using the analytical and convectional sizing approach. In [73], a feasibility study to determine the optimal size of BESS with load shedding was conducted. The study used the PSO-based approach with a load shedding scheme and was seen to perform better frequency control as compared to the optimal sizing of BESS-based analytic method with load shedding scheme.

The GA method has been implemented in [74], [75], [76], [77] for BESS capacity optimization with renewable energy were studied. In [74], a smart home management strategy system was studied, the objective was to optimize the size of BESS for a PV penetrated microgrid under different electricity price mechanisms and considering the uncertainty in PV. The study revealed that only the PV system is needed in a household under step-wise power tariff but BESS must be equipped along with the PV

system under the real-time pricing and time-of-use pricing. However, the PV system is installed only when the subsidies reach a certain economic level.

The study in [75] implements a multi-objective GA to size RES-BESS penetration in a small isolated grid and reference [76] utilized an improved genetic algorithm to determine the optimal planning and operation of BESS in smart grids. The model developed was tested on a 22kV grid in Thailand and the results showed that Optimal BESS planning could improve the efficiency of the grid. In [78], the authors developed a non-dominated sorting GA-II to find the optimal size of the BESS and penetration degree of wind energy in the planning of a wind turbine microgrid. The findings showed that the proposed study can reduce annual power loss costs and the cost of energy.

Authors in [79] presented FA to size the BESS. The study took note of the SOC of the BESS during the sizing optimization. Sharmistha Sharma et al in [80] proposed quasi-oppositional swine influenza model-based optimization with quarantine (SIMBO-Q) to size the BESS for an operation cost minimization of the microgrid. In the study, the total operation cost of the microgrid was minimized with consideration for the BESS capacity. It was noted that when a large number of variables are involved, the SIMBO-Q requires a large number of iteration to converge. However, this setback has been addressed by introducing a quasi-opposition based learning concept in the basic SIMBO-Q algorithm to improve its computational efficiency. Moreover, the study in [81] presented an improved bat algorithm for optimal sizing of microgrid operation using a cost-based formulation for the objective function. The simulation was repeated using PSO, GA, BA, and IBA. The results showed that BA and IBA

gave lower average operation cost of the microgrid with IBA having the least value resulting in the better solution quality when compared with others. In [82], the authors consider the efficiency power supply probability and energy cost to size the BESS using the grasshopper optimization algorithm. The study was done under an islanded microgrid penetrated with the wind, solar PV, and diesel generators, and its results were compared with other heuristic techniques.

Authors in [17], [83] considered the lifetime of BESS in a wind-ESS penetrated microgrid. A component sizing of the lithium battery was done by formulating an objective function based on capacity degradation of the BESS and operation cost of the BESS in [83]. Simulations done by the rule-based and genetic algorithm showed that the operation cost was well optimized. Besides, authors in [17] considers the DOD of the BESS when modeling the real-time of battery operation cost. The firefly algorithm used for the simulation shows that the operation cost was well minimized and the lifetime is improved. In [84], the authors optimized the operation of the BESS to maximize its lifetime value. The study in [85] considers the efficiency of the BESS in an EMS considered for a grid-tied microgrid while the authors in [86] used a computational method to improve the efficiency of the BESS in an islanded microgrid.

The optimal scheduling problem of VRB was solved in [57] by considering the efficiency and operating characteristics of VRB, its power, and energy rating required for both islanded and grid-connected microgrid operation mode were determined. Authors in [16] considered battery aging to formulate a day-ahead microgrid operation and its findings indicate an improvement in the battery lifetime.

## CHAPTER 3

# RESEARCH GAP

In addition to the review in the of the previous study as discussed in Chapter 2. Although Atherton et al [87], investigated the relationship between the size of a wind farm, wind farm variability, and ESS. The study found that larger wind farms require smaller proportion of ESS capacity compared to smaller wind farms an that the pay-back period for investment on ESS is longer in small wind farms than in large. The study did not report the impact of operating such a large wind farm on the BESS. Similarly, in [88], the study compared the economic and technical performance of two energy storage in a large wind farm, the study found that the pumped storage has better economic performance than the BESS due to the short discharge time in BESS. The study compared the performances of two ESS but the effect of wind variability due to different sites was not investigated. Ziyu et al in [89] investigated the economic impact of reusing a BESS in wind farms and stated that it is not profitable to invest in a used battery for wind farms given the present prices of the wind energy. However, it may become profitable in the future if the prices of wind energy improve. If they have tested this with different sizes of wind farms, some of the pending ques-

tions would have been answered. Moreover, the study did not explain technical effect the wind farm has on the both the new and the resused BESS.

None of the studies in the past, suggested a 100 penetration of wind power into the existing energy mix portfolio with the BESS requirement to meet the load profile of the Eastern Province of KSA. Therefore, the issues which are addressed in this study are as follows:

1. This study carried out sizing and observation of BESS for 12 calendar months; taking note of the variability that exist within each month in terms of operation cost and BESS investment as presented [90].

2. Investigate the energy management strategy in a grid-tied microgrid as discussed in [90] and compared the optimal operation of BESS in PV system versus wind based [91].

2. Compute the operation cost of the wind farm under each Scenario and Cases.

3. Investigate the economic and technical impact of the wind farm on the optimal operation of the BESS and other distributed generation considering wind power potentialities.

4. To study the operation of BESS considering the parameters of the BESS such as its state of health, efficiency, degradation, lifetime and depth of discharge, and recommend the best for wind power.

5. To study the operation of BESS considering the parameters of the BESS such as its state of health, efficiency, degradation, lifetime and depth of discharge, and recommend the best for wind power.

6. Conduct a performance assessment of the wind farm distributed generation

and verify which configuration is better. Finally, the assumed scenarios in this study differentiate it from many others seen in the literature. The thesis's findings suggest where future improvement could be examined.

## CHAPTER 4

# THEORETICAL BACKGROUND

### 4.1 Introduction

A microgrid can either connects or disconnects from the grid so it can operate in both island and anti-island modes. A typical microgrid consisting of solar PV, wind, BESS, utility grid, backup generator and different load categories. The huge cost and unpredictable nature associated with the intermittent RE resources complicate their planning, integration, and operation in the electric power system [92]. To ensure the smooth operation of the renewable-dependent microgrid, ESS are very important in microgrid system to reduce the effect of variability in the output power as a result of the uncertainty and intermittency of the RES. This is particularly important especially in the case of island operation of the microgrid. The BESS is the most popular in use today, occupying the highest by percentage the total number of installed and projects already in operation [93], [94].

The BESS, made of specially developed batteries is used to store electric charge. The electric energy so stored can be used later. The BESS has attracted researchers'

attention in the recent time leading to commercialization of the BESS technology. The BESS has numerous advantages over other types of ESS and this is the reason why it is the most utilized type of ESS. The BESS occupies less space, has no restriction to any location [1] and a reduction in price by almost 50% in the last three years. Besides, the BESS have higher energy and power densities than many other ESS like compressed air storage (CAES) and pumped hydrogen storage (PHS) as presented in table 4.1. The BESS are based on the following type of battery technologies; lead-acid, lithium ion (Li-ion), vanadium redox (VR), sodium sulphur (NaS), zinc bromide and metal air and flow batteries [95], [96].

It is known that the Li-ion based BESS offers the highest power and energy densities and is consequently the most expensive technology and most widely used. Although the lead-acid based BESS is cheaper and is good for application involving fast charging/discharging and where large storage capacity is need, it is has short life cycle and poor energy and power densities [96], [97]. NaS based BESS also has high power and energy densities after Li-ion but has some hazardous effect due to the explosive reaction of sodium with air [96]. The selection of a particular BESS is largely dependent on the application on which it is intended for and performance requirement. Other factors may include the cost, size and regulatory issues. Table 4.2 summaries some important characteristics of some BESS technologies considered when selecting the type of BESS to be used for an application. Also, 4.1 shows some characteristics of different ESS technologies.

Table 4.1: Energy and power densities of some technologies [1]

| Technology | Power density<br>(W/I) | Energy density<br>(Wh/I) |
|------------|------------------------|--------------------------|
| Nas        | 120 - 160              | 150 - 300                |
| Lead-acid  | 90 -700                | 50 - 80                  |
| Li-ion     | 1300 - 1000            | 200 - 400                |
| CAES       | 0.2 - 0.6              | 2 - 6                    |
| PHS        | 0.1 - 0.2              | 0.2 - 2                  |

Table 4.2: Advanced Battery Technology Characteristics [1]

| Technology | Capacity costs<br>(\$/kWh)                                 | Life Cycle<br>No. charging/Discharging<br>cycles to 80% DOD | %Round Trip<br>Efficiency AC-AC      |
|------------|------------------------------------------------------------|-------------------------------------------------------------|--------------------------------------|
| Li-ion     | Very high (\$600 -<br>\$1200Kwh)                           | Medium (2,000 - 5,000)                                      | Very High (85%<br>to 95%)            |
| VRB        | Medium (\$350 -<br>\$500Kwh)                               | High (up to 10,000)                                         | Medium Very High (70%<br>to 75%)     |
| NaS        | Medium (\$350 -<br>\$500Kwh)                               | Medium (3,000 - 5,000)                                      | High (Very High (85%<br>to 90%))     |
| ZnBr       | Low (\$150 -<br>\$250Kwh)                                  | High (>10,000)                                              | Meidum Very High (70%<br>to 75%)     |
| Comments   | Cost do not include<br>the cost excludes installation cost | For wind or solar storage                                   | Efficiency & frequency are important |

## 4.2 Microgrid Modelling

In this study, a grid-tied microgrid of the type whose block diagram is shown in Figure 4.2 is presented. The block diagram is made of renewable energy sources which are wind and solar PV, diesel generators, BESS and the utility grid. Different combination of microgrids can be assumed depending on the combination of sources and operational mode considered in different case studies.

The PV and the wind generation system can be combined to form a hybrid renewable generation system in which case. The maximum available energy is trapped from both PV and wind generation. The battery energy storage is used as electrical storage while the diesel generators serve as back up power for the microgrid when there is output from the renewables are down. Also, the microgrid is grid-connected, excess power is exported to the grid if the power output from the RES is higher than the demand. However, power is imported from the grid to support the microgrid when the

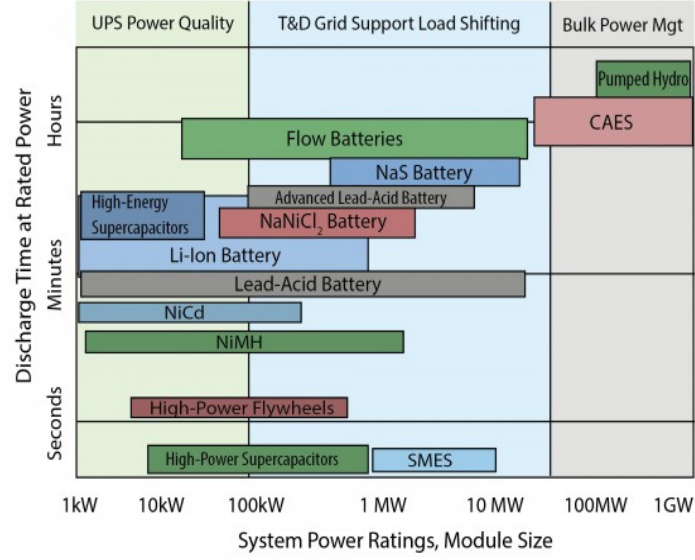


Figure 4.1: Characteristics of different ESS technologies [4]

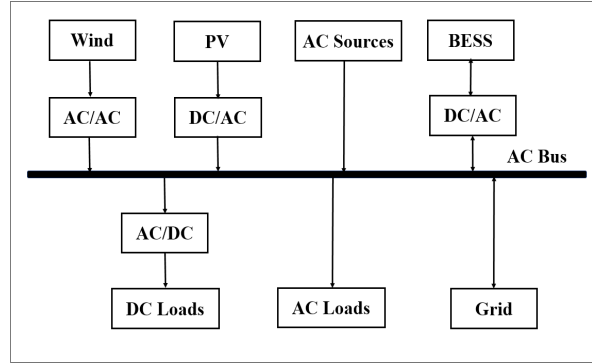


Figure 4.2: Block diagram of a microgrid

demand exceeds the output power from RES. This is necessary to ensure the power balanced to maintain power balance at all times. Furthermore, there exist DC/AC and AC/AC converters serving as a connection interface for both the PV, BESS, and wind. The detailed analysis of the role of these converters is not discussed.

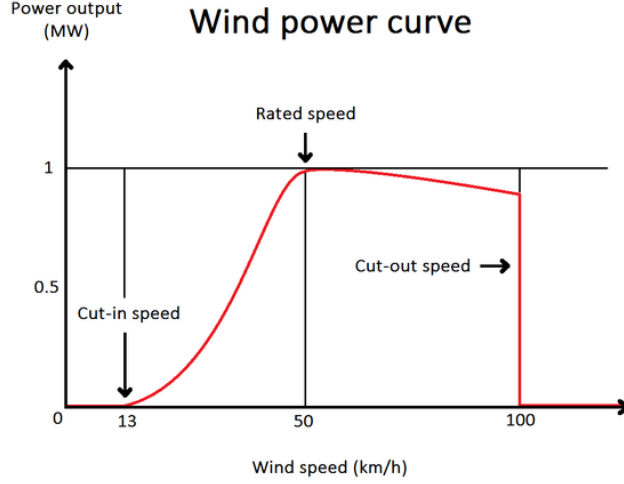


Figure 4.3: Wind power vs Wind speed [5]

#### 4.2.1 The wind turbine subsystem

Wind power,  $P_w$  is largely dependent on wind speed,  $v$  and the relationship between wind power and wind speed is cubical as shown in Figure 4.3. The wind power is usually calculated from the wind speed [36] as presented (4.2).

The wind power, expressed in is given by the (4.1).

$$Pw = \frac{1}{2} \times K_{max} \times \rho \times A_f \times v^3 \quad (4.1)$$

Where,  $A_f$  is the swept area by rotor of the wind turbine,  $\rho$  is the density of air and  $K_{max}$  is the power coefficient.

$$P_{W_t} = \begin{cases} 0 & v_t < v_{CI} \text{ or } v_t \geq v_{CO} \\ P_W^{max} \frac{v_t - v_{CI}}{v_R - v_{CI}} & v_{CI} \leq v_t < v_R \\ P_W^{max} & v_R \leq v_t < v_{CO} \end{cases} \quad (4.2)$$

The daily cost of wind power dissipation,  $C_{wt}$ , presented in [17] is given by the product of the initial cost of wind turbine and the power dispatch as in (4.3)

$$C_{WT} = \sum_{t=1}^T P_w(t) \times IC_{WT} \times CRF. \quad (4.3)$$

CRF is the capital recovery factor which can estimate the present value of the wind turbine with consideration given to lifetime of project and interest rate. This is expressed in (4.4).

$$CRF = \frac{1}{360} \times \frac{i_i(1+i_t)^{l_y}}{(1+i_t) - 1} \quad (4.4)$$

#### 4.2.2 Diesel generator

A diesel generator in a microgrid acts as a backup source like energy storage when the available wind power cannot meet up with the demand. This way, it can improve the system's reliability and help to smooth the output power from the wind. In [17], [37], the operation cost of diesel generators in terms of power dispatch is calculated using the equation formulated in (4.17). This equation includes the fuel cost  $FC$  and emission cost,  $EM$ . The  $FC$  is expressed in (4.5) where  $a_i$ ,  $b_i$  and  $c_i$  are fuel cost coefficients of generator unit  $i$ . Furthermore, the emission cost is included as part of the operation cost of the diesel generator [37]. The  $EM$ , is given by (4.6). So that the total operating cost of the diesel generator units becomes (4.17),  $d_i$ ,  $e_i$  and  $f_i$  are emission cost coefficients of generator unit  $i$ . The parameters of the diesel generators used in this study are given in table 6.2. Note that  $C_{d.gen} = CMG_{ex}$ .

$$FC = \sum_{t=1}^T \sum_{i=1}^I [a_i P^2 i, t + b_i P i, t + c_i] \quad (4.5)$$

$$EM = \sum_{t=1}^T \sum_{i=1}^I [d_i P^2 i, t + e_i P i, t + f_i] \quad (4.6)$$

$$C_{d.gen} = FC + EM \quad (4.7)$$

To linearize the cost function of the diesel generator, equation 4.8 is proposed.

$$CMG_{units} = \sum_{t=1}^T \sum_{i=1}^I [fc_i u_{i,t} + vc_i p_{i,t} + su_i y_{i,t} + sd_i z_{i,t}] \quad (4.8)$$

$$CMG_{units} = \sum_{t=1}^T \sum_{i=1}^I [fc_i u_{i,t} + vc_i p_{i,t}] \quad (4.9)$$

Where  $u$ ,  $y$ , and  $z$  are decision variables and are binary variables. Which can either be 1 or 0. The binary variable indicates the state of ON or OFF of the generators. For example the value of  $u_{i,t} = 1$  means that the generator  $i$  ( $G_i$ ) is ON at hour  $t$ , if it is  $u_{i,t} = 0$ ,  $G_i$  is OFF. Similarly if  $y_{i,t} = 1$ , it means the  $G_i$  will start up at hour  $t$ . Also, if  $z_{i,t} = 1$ ,  $G_i$  is shuts down at that hour. Because the values of  $u_{i,t}$ ,  $y_{i,t}$  and  $z_{i,t}$  are integers as they represent the unit commitment status of the generators, the optimization problem is suitably solved using the MILP method [44]. However, where if The parameter  $fc_i$  and  $vc_i$  are fixed and variable costs of unit  $i$  respectively while  $su_i$  and  $sd_i$  are the start up shut down costs of unit  $i$  respectively. The  $fc_i$  is the

no-load cost of the unit  $i$  and  $vc_i$  depends on the power output  $p_i$  from the unit  $i$  since it is a variable. The MILP allows for more parameters to be accommodated in the model of the optimization problem especially in the generator constraints given room for more controls. [98]. If the binary values  $[u_i y_i z_i]$  are fixed at [100] throughout the optimization time, then, equation 4.8 is reduced to 4.9 and the LP is suitable to solve such problem. where  $i$  is the unit index,  $I$  is the number of units,  $t$  is the hour index,  $T$  is the number of hours respectively. Essentially, the linearized equation leads to easy modeling, simplicity, and faster solution.

### 4.2.3 Grid System

As earlier stated, the utility acts as an alternative source to the microgrid and, it can also feed on the microgrid. When the output from the other DER cannot meet up with the demand, the utility grid will have to supply the remaining power to ensure balance. On the other hand, when the output of the RE generations exceeds the demand, the excess power is sold to the utility grid. The power supplied (imported) or purchased (exported) by the utility grid  $P_{grid}(t)$  is given by:

$$P_{grid}(t) = P_D(t) - \left[ \sum_{i=1}^I P_i(t) + P_{BESS}(t) + P_w(t) \right] \quad \forall t \in T \quad (4.10)$$

Where  $P_D(t)$ ,  $P_{BESS}(t)$ ,  $P_i(t)$ ,  $P_w(t)$  are power demand, battery power, diesel generator power and wind power respectively.

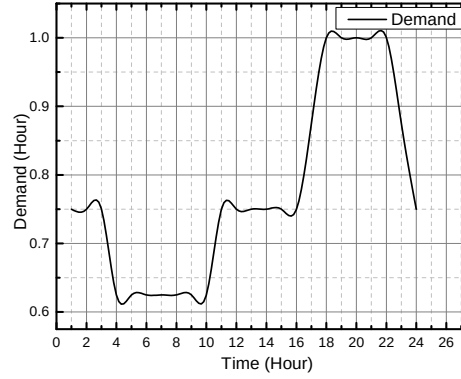


Figure 4.4: Load demand a [6]

#### 4.2.4 System Demand

The load includes the residential, hospitals, offices, and government institutions connected to the distribution networks and has been obtained from the Al-Dhahran city of the Eastern Province of Saudi Arabia [6]. The normalized value of this profile is shown in Figure 4.4 and will be used to test the proposed study. Starting from hour 1 (7 pm), the demand least between hours 4 and 10m and it experienced the highest peak from hours 16 to 22. Notice that the load profile experienced pick values in the afternoon because it contains government institutions and offices.

### 4.3 Optimal Sizing and operation of the ESS

#### 4.4 objectives

Usually in sizing of ESS, the formulation of the problem is always defined based on the objective function of the proposed problem. In [37], optimal operation of ESS

could be defined as cost based or priced based in which case, the objective will be minimization of the cost or maximization of the profit. The optimal algorithm for optimal sizing of BESS, objective function and all associated constraints are discussed in this section. Also the methodology adopted for some of the previous studies and assumptions are presented.

There are many methods of sizing energy storage. This section is focused on discussing the technique or method used in this thesis. Because different microgrids have different energy sources, components and capacities, it is necessary to consider the particular application case for optimal sizing of the ESS as discussed in Chapter 2. In this regard, energy rating and power rating are considered important decision parameters.

#### 4.4.1 Objective Function

Generally in grid-connected microgrid, the objective function may be the minimization of the of the cost function. In [99], the objective function is expressed as:

$$Min(OC + MC + IC) \quad (4.11)$$

where,  $MC$  = cost of maintaining the ESS

$OC$  = cost of operating the microgrid

$IC$  = ESS investment cost

And this is subject to the associated constraints which are discussed later in this section.

In the formulation of the problems solved in this thesis, the following equations were proposed.

#### 4.4.2 Problem formulation for sizing of BESS

In the formulation of the proposed strategy, a wind power microgrid system of the types shown in Figure 4.5 is presented. The optimal operation cost of the microgrid is computed, leading to optimal sizes of energy capacity,  $E_{BESS}^{max}$  and power capacity,  $P_{BESS}^{max}$  of the BESS. In Scenario 1, the microgrid is grid-connected and the other sources of power apart from the windfarm are the grid and the BESS. The optimal sizes of BESS required to operate the microgrid optimally for 24 hours are computed. The microgrid is operated such that maximum power is consumed from the wind power  $P_w$ , and also to ensure that grid power,  $P_{grid}$  imported is minimized as much as possible. In Scenario 2, the microgrid is off-grid but three diesel generators are used as backups for the system. It is desired that the generators operate for minimum times so that power  $P_i$ , is only consumed from a unit  $i$ , this ensures that wind power is efficiently utilized. The BESS is connected to the microgrid at the point of common coupling. Charging and discharging of the BESS takes place through the power converters which allow for proper control during smooth operation, however, the converter topologies and their control are not discussed in this study. In both Scenarios, the BESS is discharged during hours of high demand  $P_D$  and or lower  $P_w$ , and it is charged during the hours of low demand and or higher wind output. However, the BESS power,  $P_{BESS}$  and energy,  $E_{BESS}$  at any time during its operation are maintained between  $P_{BESS}^{max}$  and  $E_{BESS}^{max}$ .

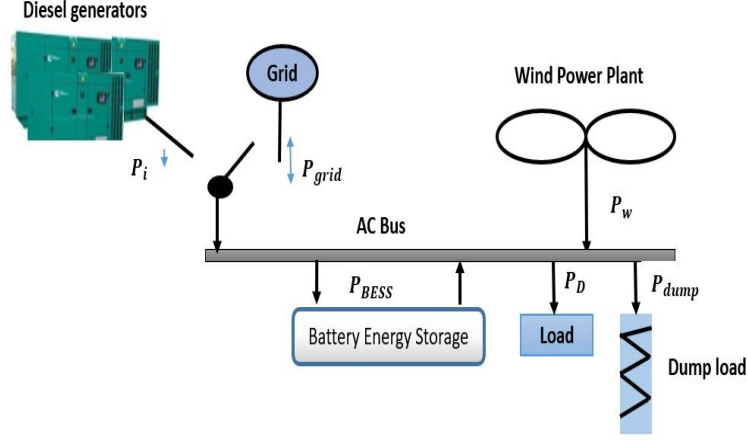


Figure 4.5: The proposed microgrid architecture

In order to prevent over-charging and consequently over-sizing of the BESS during the hours of high generation from the windfarm, the excess power is allowed to dispatch through the dump load,  $P_{dump}$  attached to the microgrid in Figure 4.5. These strategies adopted ensured efficient power management optimal sizing of the BESS within the microgrid. The adopted strategies in this paper summarized into Scenarios 1 and 2 are as follows:

### Scenario 1

It is assumed that the windfarm can supply substantial power to meet the demand at any point in time, the microgrid is grid-connected and the excess power can be sold to the grid. However, if the wind source is not enough to meet the demand, power can be bought from the grid to meet the supply or to charge the BESS.

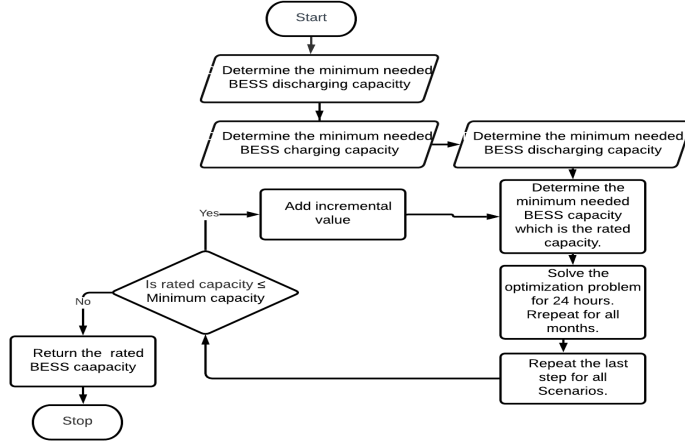


Figure 4.6: Flowchart of the optimization algorithm

## Scenario 2

There is enough power from the windfarm to meet the load, the BESS is fully charged but the grid is not ready to buy power from the microgrid. So the excess power is dispatch through the dump load to prevent overcharging and oversizing of the BESS.

## Scenario 3

The microgrid is off-grid, three diesel generators are connected to support the windfarm and the BESS. The generators start to operate only when the output from the windfarm is low and where the SOC of the BESS is low.

The cost function is the objective of the optimization problem. This total cost which is to be minimized includes ESS' investment cost, operation cost and cost of

power exchanged. As presented in [100], the objective function for the optimal sizing problem is presented in the following equations as follows.

$$TOC = \min.(CMG_{units} + CMG_{ex} + C_{RE*} + IC_{ESS}) \quad (4.12)$$

where  $CMG_{units}$  is the costs of operating the microgrid's diesel generators,  $RC_{wind}$  is wind-related cost,  $CMG_{ex}$  is the cost of power exchange between the microgrid and the utility, and  $IC_{ESS}$  is the investment cost of the ESS. These quantities have been defined in the following subsections.

### **Problem formulation for operation of BESS**

In this case, the formulated problem is also based on the overall cost of operation  $J$ , of the microgrid which is the objective function which is to be minimized. The objective function is then expressed in (4.13). The optimization problem is solved using NLP optimization in GAMS software.

$$J = DSC + DC_{BESS} \quad (4.13)$$

The daily schedule cost of the microgrid is to be minimized and is expressed as in (4.14). The optimal battery size will minimize the operation cost of the microgrid.

$$DSC = \min.DGC + C_{BESS} \quad (4.14)$$

Where  $DGC$  is the cost of distributed generation expressed in (4.15).

$$DGC = CMG_{ex} + C_{c.gen} + C_{WT} \quad (4.15)$$

While the daily cost of the battery,  $DC_{BESS}$ , is expressed as in (4.16).

$$DC_{BESS} = E_{BESS}^c \times \left( \frac{MC}{365} + CRF \times IC_{BESS} \right) \quad (4.16)$$

Where  $MC$  is the yearly maintenance cost on the BESS in  $\$/MWh$  covering the lifetime of the BESS and  $CRF$  is the capital recovery factor of the BESS.

#### 4.4.3 Battery energy storage model

The BESS utilized in this study is the lithium-ion based. The lithium-ion battery technology has a good power density, high energy density, high efficiency, and longer life cycle when compared with other technologies [101], [102]. Figure 4.1 shows the characteristics of some battery energy storage technologies. Principally the function of the BESS in a microgrid is to prevent power mismatch.

In the sizing of BESS, the equations (4.17) formulates the investment cost of the BESS. The optimal sizes of the BESS are the rated energy and rated power ( $E_{BESS}^{max}$  &  $P_{BESS}^{max}$ ) of the BESS and are the decision variables in that equation while the cost of 1 MWh (or KWh) of BESS and the cost of 1MW (or KW) are  $EC_{BESS}$  and  $PC_{BESS}$  respectively are parameters of BESS.

$$IC_{BESS} = PC_{BESS} P_{BESS}^{max} + EC_{BESS} E_{BESS}^{max} \quad (4.17)$$

It is known that the cost of ESS increases with an increase in depth of discharge (DOD) since the ESS discharge more powers. However, a decrease in BESS discharge power leads to a decrease in the capacity of the ESS and consequently make the DOD be high. The formulation of the cost function of BESS power charge/discharge at any time  $t$  as a function DOD and battery power is presented in [17], [103]. The cost function of BESS in terms of DOD during charging and discharging operation is expressed as in (4.18). Where  $n_c^{DOD}$  is the number of cycles of energy storage at a particular DOD. The relationship between DOD and the number of cycles of different battery energy storage technologies is shown in Figure 4.7. This relationship is defined in (4.21). Also the relationship between the  $DOD$  and  $SOC$  is defined in (4.19) [17].

$$C_{BESS} = \frac{IC_{BESS} \times P_b(t) \times \Delta t}{E_{BESS}^c \times n_c^{DOD}(t) \times \eta_{BESS}^2} \quad (4.18)$$

$$DOD_{BESS} = 1 - SOC_{BESS}(t) \quad (4.19)$$

The study in [103] showed that the achievable cycle count (number of cycles) at a specific DOD for a lithium-ion battery with characteristics of the type shown in Figure 4.7 assumes the equation of the form in (4.20).

$$n_c^{DOD} = \frac{a}{(D_{BESS}(t))^b} \quad (4.20)$$

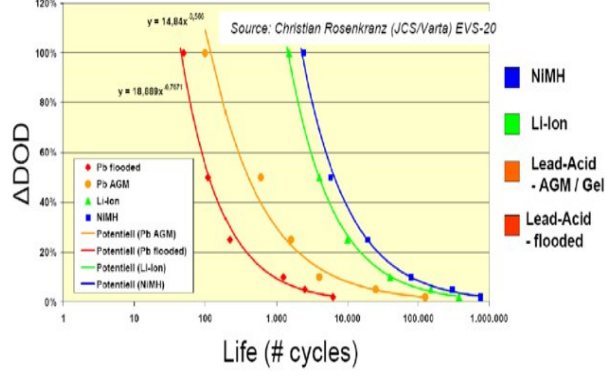


Figure 4.7: Depth of discharge versus number of cycles of battery energy storage [7]

Where  $a$  and  $b$  are some battery parameters which can be obtained experimentally. However, an approximated best-fitted curve for lithium-ion battery in Figure 4.7 produces the values of  $a = 694$  and  $b = 0.795$  [103]. Therefore, equation (4.21) is proposed and has been included in the simulation of the study.

$$n_c^{DOD} = \frac{694}{(DOD_{BESS}(t))^{0.795}} \quad (4.21)$$

The state of charge of the BESS represented by SOC is given by (4.22). Where  $\eta_{BESS}^{cha}$  and  $\eta_{BESS}^{disch}$  represent the charging and discharging efficiencies of the BESS.  $E_{BESS}^c$  is the battery BESS total capacity in  $MWh$ ,  $IC_{BESS}$  is the investment cost of the ESS and  $\Delta t$  is the incremental time for the optimization and has been taken as 1 hour in this study.

$$SOC_{BESS}(t+1) = \frac{P_{BESS}^{cha} \times \Delta t \times \eta_{BESS}^{cha}}{E_{BESS}^c} - \frac{P_{BESS}^{disch} \times \Delta t}{E_{BESS}^c \times \eta_{BESS}^{disch}} \quad (4.22)$$

#### 4.4.4 Main grid model

The main grid, interchangeably used as the grid or utility in this study acts as alternative source of power to the microgrid apart from the wind farm, BESS and diesel generator. Power is either bought (imported) from or sold (exported) to the grid as stated earlier. To compute the cost of power exchanged with the main grid, (4.23) is proposed. We assume a positive convention for power imported from the grid and a negative sign for the power exported from the main grid. The cost of exchanged power,  $\eta$  with the utility is assumed to be \$20 per MW in this study. It is noted that the value of the objective function is more when power is imported and less when power is exported.

$$CMG_{ex} = \sum_{t=1}^T \eta P_{grid}(t) \quad (4.23)$$

The  $P_{grid}(t)$  assumes a positive sign when power flows from the main grid to the microgrid and a negative when the power flows to the main grid from the microgrid.

### 4.5 Methodology

#### 4.5.1 Sizing

The methodologies adopted for sizing in this study are LP, NLP, MILP, MINLP which are used to solve the optimization problems (Chapter 5) in each study according to the optimization objectives and associated constraints. Where the problem assumes a quadratic function, the NLP is used to calculate the objective function of the optimiza-

tion problem because of the non-linearity of equations (4.5), (4.6) and (4.17) which essentially define the real phenomenon. In another formulation, where the problem is formulated with binary constraint, the MINLP is used to solve the optimization. However, where the optimization equations are linearized, the LP and MILP are used to solve the optimization problem [44]. The  $C_{d.gen}$  is then formulated as (4.8). The formulation of the binary constraints leading to MINLP and MILP are explained in the constraints sections.

### 4.5.2 Operation

The LP, NLP and MINLP have been used to solve the formulated problems in the operation studies. The equations and constraints are closely related to the equations used in the sizing problem. Furthermore, the last operation problem was solved using the GWO and PSO as presented in Chapter 6.

### 4.5.3 System Constraints

#### Balance constraint

The balance constraint is formulated as in (4.24):

$$\sum_{i=1}^I [P_i(t)] + P_{BESS}(t) + P_w(t) + P_{grid}(t) = P_D(t) \quad \forall t \in T \quad (4.24)$$

### Grid constraint

The exchanged power between the main grid and microgrid is limited because of the limit of the transmission line connecting the two systems. A constraint is needed to limit this power and it is dependent on the capacity of the transmission line.

$$-P_{grid}^{max} \leq P_{grid}(t) \leq P_{grid}^{max} \quad \forall t \in T \quad (4.25)$$

where  $P_M^{max}$  is the maximum capacity of the transmission line connecting between the microgrid and main grid.

### Diesel generator constraints

The diesel generator output power are limited to the maximum and minimum output power of each of the generator. The constraint is expressed as:

$$P_i^{min} \leq P_i(t) \leq P_i^{max} \quad \forall i \in I, \forall t \in T \quad (4.26)$$

where  $P_i^{min}$  is the minimum power that can be produced by a unit DG  $i$ ,  $P_i^{max}$  is the maximum power that can be produced by unit DG  $i$  and  $I$  is the set of units.

Also, in the unit commitment problem, each generator should not supply infinite power for whole periods because there are limits. The minimum and maximum limits are multiplied by  $u_{i,t}$ , the commitment state of a generator  $i$  at hour  $t$ . It is desired that if  $G_i$  is OFF, then  $P_i = 0$ . If the limits are not multiplied by the commitment state,  $P_{i,t} \neq 0$  and  $P_{i,t}$  should lie between the  $P_{min}$  and  $P_{max}$ . The constraint equation (4.26) is then reformulated as in (4.27).

$$P_i^{min} u_{i,t} \leq P_{i,t} \leq P_i^{max} u_{i,t} \quad \forall i \in I, \forall t \in T \quad (4.27)$$

where  $P_i^{min}$  is the minimum power that can be produced by unit  $i$ ,  $P_i^{max}$  is the maximum power that can be produced by unit  $i$  and  $I$  is the set of units.

The generators are allowed rate of increase/decrease limits referred to as ramp up/ramp down limits for the output power of a generator. Ensuring that  $P_{i,t}$  of a certain generator cannot change freely. The constraint which represents these two limits. This constraint is presented as follows.

$$P_{i,t} - P_{i,t-1} \leq ru_i \quad \forall i \in I, \forall t \in T \quad (4.28)$$

where  $ru_i$  is the ramp-up rate of unit  $i$ .

$$P_{i,t-1} - P_{i,t} \leq rd_i \quad \forall i \in I, \forall t \in T \quad (4.29)$$

where  $rd_i$  is the ramp down rate of unit  $i$ .

When  $G_i$  starts up, it has to be ON for some time, called the minimum up time (MUT) before it shuts down. Similarly, when  $G_i$  shuts down, it remains OFF for some time before it starts up and this is known as the minimum downtime (MDT). These two constraints are formulated below.

$$T_{i,t}^{ON} \geq MUT_i [u_{i,t} - u_{i,t-1}] \quad \forall i \in I, \forall t \in T \quad (4.30)$$

where  $T_{i,t}^{ON}$  is the ON time of unit  $i$  at hour  $t$  and  $MUT_i$  is the minimum up time

of unit  $i$ .

$$T_{i,t}^{OFF} \geq MDT_i[u_{i,t-1} - u_{i,t}] \quad \forall i \in I, \forall t \in T \quad (4.31)$$

where  $T_{i,t}^{OFF}$  is the OFF time of unit  $i$  at hour  $t$  and  $MDT_i$  is the minimum down time of unit  $i$ . Logically, it is expected that  $G_i$  cannot start up and shut down at the same time. This constraint is modelled as in (4.32)

$$y_{i,t} - z_{i,t} = u_{i,t} - u_{i,t-1} \quad \forall i \in I, \forall t \in T \quad (4.32)$$

### Energy Storage System Constraints

The BESS charging and discharging power is limited to its maximum power, which is its optimal size. The BESS acts as a load when it charges and acts as a generator when it discharges. Besides, it is assumed that when the BESS is in the charging mode, its power is negative and positive in the discharging mode. This constraint is formulated as:

$$P_{BESS}^{min} \leq P_{BESS}(t) \leq P_{BESS}^{max} \quad \forall t \in T \quad (4.33)$$

The stored energy in the BESS is limited by its rated energy. Of course, the stored energy is always positive. This constraint is formulated as:

$$E_{BESS}^{min} \leq E_{BESS}(t) \leq E_{BESS}^{max} \quad \forall t \in T \quad (4.34)$$

where  $E_{BESS}(t)$  is the energy stored in the BESS at hour  $t$ .

The equation to calculate the state of charge which essentially is the stored energy at a specific hour is formulated in (4.35).

$$E_{BESS}(t) = E_{BESS}(t-1) - P_{BESS}(t) \quad \forall t \in T \quad (4.35)$$

## 4.6 Performance Analysis

The performance analysis of the microgrid could be modeled based on the reliability analysis and cost of electricity per MWh [17], [104].

### 4.6.1 Reliability Analysis

The microgrid reliability analysis may be measured statistically based on power loss probability (PLP). The PLP of the microgrid measures the chances of time horizon within which the microgrid total distributed generation will not be able to meet the demand. The PLP is calculated in [17] using the (4.36) and (4.37) for the Scenario 1 and Scenario 2 studies respectively.

$$PLP = \frac{\sum_{i=1}^T (P_D(t) - P_{grid}(t) - P_{BESS}(t))}{\sum_{i=1}^T P_D(t)} \quad (4.36)$$

$$PLP = \frac{\sum_{i=1}^T (P_D(t) - P_i(t) - P_{BESS}(t))}{\sum_{i=1}^T P_D(t)} \quad (4.37)$$

### 4.6.2 Cost of electricity

This parameter is measured between all power generation sources and the demand within 24 hours. It is calculated using the (4.38) and (4.39) for Scenario 1 and Scenario 2 respectively.

$$Cost_{elect.} = \frac{C_{WT} + CMG_{ex} + \sum_{i=1}^T C_{BESS}(t)}{\sum_{i=1}^T P_D(t)} \quad (4.38)$$

$$Cost_{elect.} = \frac{C_{WT} + C_{d.gen} + \sum_{i=1}^T C_{BESS}(t)}{\sum_{i=1}^T P_D(t)} \quad (4.39)$$

### 4.6.3 Data and Parameter

In all of the cases considered in this thesis, the microgrid is either operated in the grid-connected mode or off-grid mode. For the grid-connected mode, grid power is bought or sold at \$20 per MW.

Table A.1 and Table A.2 show the parameters of the generators, while Table A.8 and Table A.4 show the BESS and wind parameters used for parts of the studies in Chapter 4 and Chapter 5.

#### Generator parameter

Parameters such as the limits of grid power, generator powers, generator constants, maximum and minimum SOC, maximum battery discharging power, etc are assumed according to the problem of studies. Also, parameters of the BESS and the grid for

studies in Section 5.1 and Section 6.1 respectively are shown in Table A.5. While the parameters of the generators for these Sections are shown in Tables (A.6 and A.7). The proposed strategy is limited to tertiary control of the microgrid. Furthermore, there are no special assumptions for the frequency and voltage magnitude of the microgrid as this is controlled by the utility grid [105].

## CHAPTER 5

# OPTIMAL SIZING OF BESS

In this chapter, the results of sizing of BESS for a wind penetrated microgrid are presented. In Section 5.1, the sizing of BESS was done under the load profile shown in Figure 5.1 while Section 5.2 presents the results of BESS sizing for 12 Calendar months under the load profile shown in Figure 5.2. The distribution generation in both cases include wind, grid and diesel generators.

### 5.1 Optimal Energy Management Strategy Based on Dynamic Energy Dispatch in wind-based microgrid

The optimal operation cost obtained from the simulation is \$51,368.152. This is the minimum cost required to operate the microgrid or to supply all loads within 24 hours. The rated power of the BESS required is 70.622MW while the rated energy of the BESS is 165.450MWh. This puts the investment cost on the BESS as \$14,850.58

The power output from the DGs is reported in Figure 5.5. The generators supply below their maximum capacities between 4 and 12, However, the generators 1, 3 and 4 stepped up their supplies from the 14th hour to react to the high load demands. Generator 3 is bounded to remain at its minimum capacity of 20MW for optimal contribution from the grid and or the BESS. The result shows that the power DGs supply more power during the hours of high demand and high prices, especially in the afternoon. Furthermore, the ESS dispatch and power supplied from the grid are reported together in Figure 5.6.

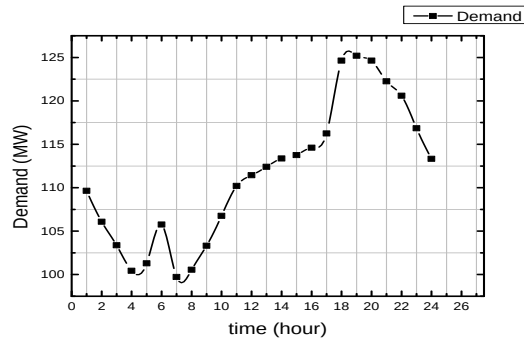


Figure 5.1: Demand profile

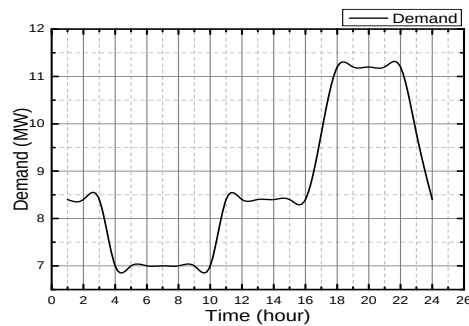


Figure 5.2: Demand profile

It is seen that between the hours 13 and 18, more power is but from the utility, this is because the output from the wind generation is not enough to cater for the high

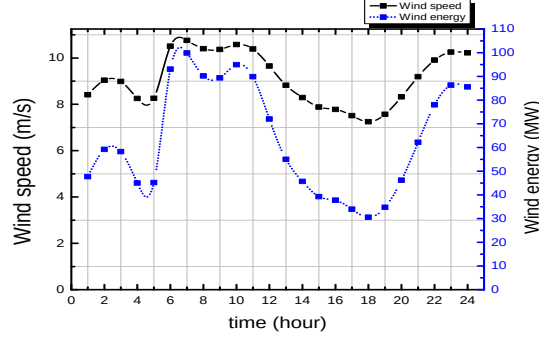


Figure 5.3: Wind speed and wind power

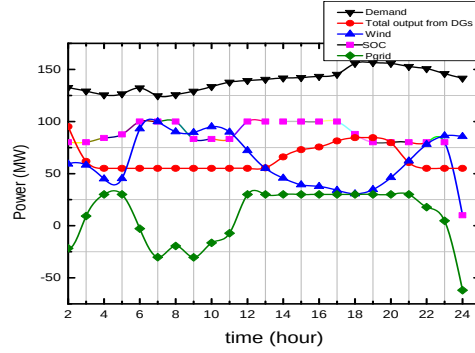


Figure 5.4: Power distribution in the microgrid

demand (Figure 5.1) during these hours, besides the price of electricity during these times is considerably high because these are summer days. The discharge between 18 and 24 is noticed due to the high price of the utility. In Figure 5.4, the power contribution by each of the sources is given with the demand and the state of charge of the BESS. It is seen that SOC is maintained at high values between the hours 12 and 17 but slightly reduced to just above 50% during the rest of the hours. It can be suggested that during the season in this city, it may be more economical to consider adding DGs to a renewable microgrid of this type. Despite allowing the BESS to supply at its maximum capacity, the operational constraints of the microgrid ensure that the dispatch of the BESS dispatch to record minimum cost.

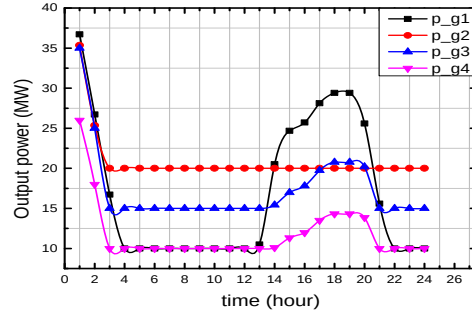


Figure 5.5: Output power from the DGs

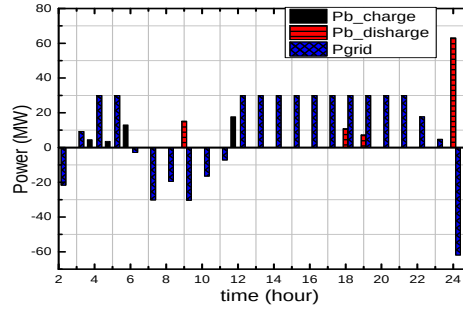


Figure 5.6: Energy Storage power dispatch

## 5.2 Optimal Sizing of Battery Energy Storage for Grid-Connected and Isolated Wind-Penetrated Microgrid

The total operation costs for the three Scenarios together the with respective sizes of BESS are presented in Tables 5.1, 5.2 and 5.3. In Table 5.1, it is seen that operation cost is reduced with the availability of more wind power. The highest operation cost is observed in the month of January when the wind speed is low compared to the rest of the months. In the June and July, there are enough wind powers to meet the maximum demand at all hours and the excess powers are sold to the grid so the lowest

| Table 5.1: Results from Scenario 1 |                    |                           |                          |
|------------------------------------|--------------------|---------------------------|--------------------------|
| Months                             | Total cost<br>(\$) | $E_{BESS}^{max}$<br>(MWh) | $P_{BESS}^{max}$<br>(MW) |
| Jan                                | 6703.813           | 6.592                     | 1.092                    |
| Feb                                | 3711.401           | 2.775                     | 0.94                     |
| Mar                                | 2091.65            | 0.647                     | 0.517                    |
| Apr                                | 4386.114           | 3.039                     | 0.764                    |
| May                                | 6364.4             | 5.83                      | 1.129                    |
| Jun                                | -2971.03           | 2.25                      | 1.53                     |
| Jul                                | -528.635           | 0.622                     | 0.427                    |
| Aug                                | 3041.742           | 2.635                     | 0.695                    |
| Sep                                | 1689.314           | 0.862                     | 0.648                    |
| Oct                                | 7474.306           | 7.644                     | 1.512                    |
| Nov                                | 4725.832           | 4.778                     | 1.019                    |
| Dec                                | 4973.564           | 2.892                     | 0.789                    |
| Total                              | 41662.47           | 18.263                    | 11.085                   |

operation costs are negative in these two months resulting to profits of \$2971.03 and \$528.635 for June and July respectively as seen in Table 5.5. Besides the months of June and July requires lower BESS sizes when compared to other months since excess power has been sold to the grid, consequently, the abundant available wind power has little effects on the energy rating and the power ratings in these months. Moreover, it can be observed that the investment cost on BESS in June is least amongst all other months. The investment on BESS in the month of June appears to be larger than expected but this is due to the larger wind power availability that contributes to the sizes of the BESS rating since there is no dump load. It can also be observed that the month of January recorded the highest BESS investment cost.

The total operation cost in all Scenarios are presented in Figure 5.10 while the

Table 5.2: Results from Scenario 2

| Month | Total cost<br>(\$) | $E_{BESS}^{max}$<br>(MWh) | $P_{BESS}^{max}$<br>(MW) |
|-------|--------------------|---------------------------|--------------------------|
| Jan   | 6703.813           | 6.592                     | 1.092                    |
| Feb   | 6984.991           | 4.721                     | 3.196                    |
| Mar   | 8051.513           | 14.761                    | 2.52                     |
| Apr   | 4489.187           | 3.039                     | 0.764                    |
| May   | 6003.322           | 4.638                     | 1.079                    |
| Jun   | 15074.03           | 24.15                     | 7.531                    |
| Jul   | 13699.77           | 34.51                     | 4.227                    |
| Aug   | 2414.011           | 0.673                     | 0.539                    |
| Sep   | 4796.294           | 6.437                     | 2.066                    |
| Oct   | 4610.209           | 1.041                     | 0.512                    |
| Nov   | 4725.832           | 4.778                     | 1.019                    |
| Dec   | 4875.887           | 2.892                     | 0.789                    |
| Total | 82428.859          | 108.232                   | 25.334                   |

magnitude of exchanged power with grid for Scenarios 1 and 2 together with the power dispatched by the DGs in Scenario 1 are shown in Figure 5.11. Figure 5.11 shows that powers are sold to the grid in Scenario 1 in the month of June and July only. Moreover lower operation costs are recorded in March and September due to lower exchanged power in the two months.

In Scenario 2, the microgrid does not sell power to the microgrid but could buy power from the grid. The optimal operation costs, sizes of BESS, investment cost and power imported from the grid are as shown in Table 5.2 and Table 5.5 respectively. Since the power is not exported to the grid, the available wind power is used to supply the load and a part of this load is dispatched through the dump load. However, the operation costs and BESS sizes during the months of June and July are the

Table 5.3: Results from Scenario 3

| Month | Total cost<br>(\$) | $E_{BESS}^{max}$<br>(MWh) | $P_{BESS}^{max}$<br>(MW) |
|-------|--------------------|---------------------------|--------------------------|
| Jan   | 3217.053           | 6.592                     | 1.092                    |
| Feb   | 10638.28           | 12.221                    | 6.196                    |
| Mar   | 10981.98           | 16.83                     | 5.52                     |
| Apr   | 756.857            | 0.616                     | 0.342                    |
| May   | 4136.601           | 8.048                     | 1.579                    |
| Jun   | 9671.815           | 11.432                    | 5.615                    |
| Jul   | 4926.882           | 8.245                     | 2.327                    |
| Aug   | 995.642            | 0.873                     | 0.539                    |
| Sep   | 4181.254           | 6.437                     | 2.066                    |
| Oct   | 3652.037           | 7.006                     | 1.387                    |
| Nov   | 1266.664           | 1.932                     | 0.519                    |
| Dec   | 1882.441           | 2.892                     | 0.789                    |
| Total | 56307.503          | 83.124                    | 27.971                   |

highest in this case due to the large available wind power that requires large-rated energies and rated powers as seen in Figures 5.8 and 5.9. Table 5.2 shows that the total operation cost and the total BESS sizes recorded for all months in Scenario 2 are higher than those of Scenario 1 and Scenario 3. The months of June and July contribute significantly to this cost as a result of the higher availability of wind power that surpasses the demand. Furthermore, Table 5.4 shows the huge amount recorded in Scenario 2 before the introduction of the dump load. When compared, the values from Table 5.4 and Table 5.5 showed that up to 59% and 35% savings on investment cost of the BESS are achievable for the months of June and July respectively.

Also in Table 5.5, it is seen that powers are not imported from the grid during the hours of these months. After June and July, higher operation cost is observed in

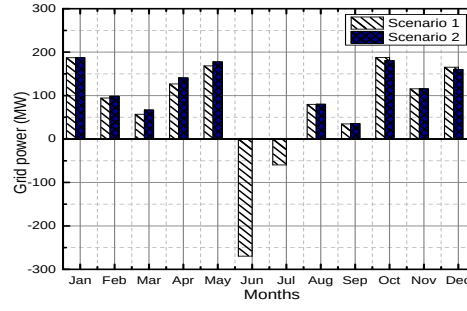


Figure 5.7: Total grid power exchanged in each month of Scenarios 1 and 2

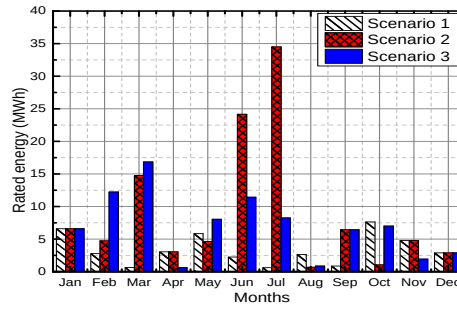


Figure 5.8: BESS rated energy recorded in each month

March and February. However, BESS sizes in March and January higher the other months. Figure 5.7 compared the exchanged powers with the grid in Scenarios 1 and 2. The figure shows negative plots in June and July which indicates exported power in Scenario1.

Table 5.4: Values recorded before the introduction of dump load

| Parameters                | June       | July       |
|---------------------------|------------|------------|
| BESS Investment cost (\$) | 36,700.518 | 21,099.766 |
| $E_{BESS}^{max}$          | 24.150     | 54.510     |
| $P_{BESS}^{max}$          | 25.553     | 6.227      |

It can be observed in Figures 5.8 and 5.9 that the rated energies and rated powers are equal in January and December for all Scenarios. Besides, rated energies, as well

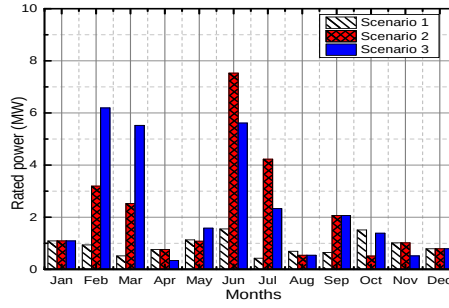


Figure 5.9: BESS rated power recorded in each month

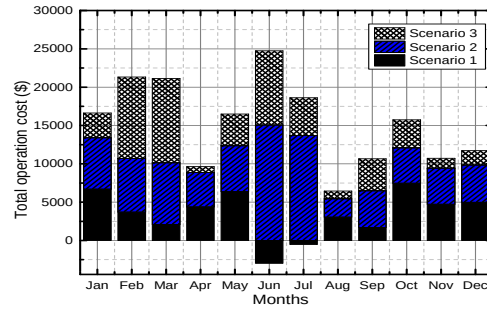


Figure 5.10: Total operation cost of all Scenarios

as rated powers in April and November, are approximately equal for Scenarios 1 and 2. However, it is observed that rated energies and rated powers of BESS are mostly higher in Scenario 2 than other Scenarios. Table 5.5 shows the cost of power exchanged with grid and investment cost on the BESS. The table shows that the total investment cost for BESS in Scenario 2 exceeds that of Scenario 1. Also, the total cost of the exchanged power for Scenario 2 is higher than in Scenario 1. This result shows that Scenario 1 is more economical than Scenario 2.

In Scenario 3, the operation costs and the BESS sizes (Table 5.3), and the cost of operating the diesel generators, (Table 5.6) are graphed in Figures 5.10 and 5.11 respectively. Generally, Scenario 2 is more expensive than Scenarios (1 and 3) with

Table 5.5: Cost of power exchanged and cost of BESS investment for Scenarios 1 and 2

| Months | Scenario 1         |              | Scenario 2         |              |
|--------|--------------------|--------------|--------------------|--------------|
|        | $CMG_{ex}$<br>(\$) | $IC$<br>(\$) | $CMG_{ex}$<br>(\$) | $IC$<br>(\$) |
| Jan    | 3745.545           | 2958.267     | 3745.545           | 2958.267     |
| Feb    | 1889.512           | 1821.889     | 1968.944           | 5016.048     |
| Mar    | 1309.313           | 782.337      | 1337.542           | 6713.971     |
| Apr    | 2709.598           | 1676.516     | 2812.67            | 1676.516     |
| May    | 3551.464           | 2812.936     | 3549.079           | 2454.243     |
| Jun    | -5396.77           | 2425.737     | -                  | 15074.03     |
| Jul    | -1196.37           | 667.734      | -                  | 13699.77     |
| Aug    | 1592.39            | 1449.352     | 1599.24            | 814.772      |
| Sep    | 696.187            | 993.128      | 707.337            | 4088.958     |
| Oct    | 3749.421           | 3724.885     | 3736.214           | 873.995      |
| Nov    | 2308.94            | 2416.892     | 2308.94            | 2416.892     |
| Dec    | 3303.822           | 1669.742     | 3206.145           | 1669.742     |
| Total  | 18263.057          | 23399.415    | 24971.656          | 57457.204    |

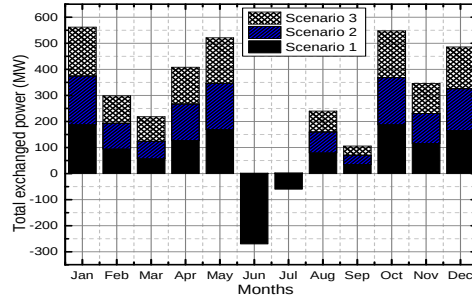


Figure 5.11: Total power exchanged for all Scenarios

June and July having the highest. The huge cost in these months results from the high wind power availability of these two months since dump loads are not installed in this Scenario, the lowest fuel and emission costs are recorded in these two months. Although there are sufficient powers in these two months to cater for the loads without supply from the DGs, the microgrid allows the DGs to run for some time to allow the generators to warm up. Table 5.6 shows the average amount spent as fuel and emission costs. It is observed that a higher amount is spent on fuel in January, October, May, and December, when compared to other months resorting to higher emission costs but not more than about 8% of the total cost of operation is recorded in each month. However, lower costs of fuel are recorded in June and July as may be expected. The total amount spent on DGs in Scenario 3 is about \$1960. This amount is less than 4% of the total amount spent on operation in costs in Scenario 3. The amount shows how less dependent is the microgrid on the DGs, and by extension signifies how friendly the microgrid in Scenario 3 is to the environment. The total amount spent in 24 hour through all months in all Scenarios as observed in Tables 5.1, 5.2, and 5.3 are \$41,662.471 , \$82,428.859 and \$56,307.503 respectively.

Table 5.6: Operation cost of DGs in Scenario 3

| <b>Month</b> | <b>Total cost<br/>from DGs (\$)</b> | <b>Fuel<br/>cost (\$)</b> | <b>Emission<br/>cost (\$)</b> |
|--------------|-------------------------------------|---------------------------|-------------------------------|
| Jan          | 258.785                             | 182.111                   | 76.674                        |
| Feb          | 147.231                             | 110.663                   | 36.568                        |
| Mar          | 150.668                             | 101.522                   | 49.146                        |
| Apr          | 192.563                             | 141.264                   | 51.299                        |
| May          | 229.807                             | 170.713                   | 59.094                        |
| Jun          | 77.744                              | 29.724                    | 48.02                         |
| Jul          | 73.738                              | 26.351                    | 47.387                        |
| Aug          | 130.865                             | 90.318                    | 40.547                        |
| Sep          | 92.296                              | 52.869                    | 39.427                        |
| Oct          | 236.274                             | 175.074                   | 61.2                          |
| Nov          | 161.46                              | 119.791                   | 41.669                        |
| Dec          | 212.698                             | 157.37                    | 55.328                        |
| Total        | 1961.855                            | 1357.77                   | 606.359                       |

This study revealed that Scenario 1 is the cheapest in terms of operation cost and investment cost of the BESS. Moreover, the study found that we can potentially save a significant amount in terms of BESS investment cost and the cost of emission of greenhouse gas. Finally, it can be concluded that the microgrid operation of the type proposed in Scenario 1 is very economical and worth to be considered for efficient dispatch of wind power.

### 5.3 Compare of sizing methodologies

In this section, the results of sizing methodologies are presented. The methodologies include linear programming, non-linear programming (NLP), mixed integer linear pro-

gramming (MILP) and mixed integer non-linear programming (MINLP). These results are presented in Table 5.7. The table shows four different sizing and methodologies which are LP, NLP, MILP and MINLP. The table shows that the value obtained in the NLP is the highest and LP is the lowest. Furthermore, both the MINLP is higher than that of MILP. The optimal solution lies between values recorded in MILP and MINLP since the recorded values in LP are likely to be approximate values. Therefore, the optimal rated energy lies between 152.63 MW to 63.27 MW and rated power lies between 164.45 MW to 165.45 MW in NLP and MINLP respectively.

Table 5.7: Compare of sizing and operation methodologies

| Methodologies | Operation cost<br>(\$) | $E_{BESS}^{rated}$<br>(MWh) | $P_{BESS}^{rated}$<br>(MW) | $IC_{BESS}$<br>\$ |
|---------------|------------------------|-----------------------------|----------------------------|-------------------|
| LP            | 39,385.60              | 148.76                      | 60.66                      | 12,955.2          |
| MILP          | 41,065.52              | 152.63                      | 63.27                      | 13,436.7          |
| NLP           | 42,247.08              | 165.45                      | 70.62                      | 14,850.3          |
| MINLP         | 42,100.52              | 164.35                      | 71.36                      | 14,920.9          |

In Table 5.8, the operation cost are expressed in \$/MW on base of the total loads being supplied in 24 hours in which case it is 3345.5MW, while the rated energy and rated powers are also expressed on a base of 100MW.

Table 5.8: Compare of sizing and operation methodologies

| Methodologies | Operation cost<br>(\$/MW) | $E_{BESS}^{rated}$ | $P_{BESS}^{rated}$ | $IC_{BESS}$<br>\$/MW |
|---------------|---------------------------|--------------------|--------------------|----------------------|
| LP            | 11.77271                  | 1.4876             | 0.6066             | 3.872426             |
| MILP          | 12.27485                  | 1.5263             | 0.6327             | 4.01635              |
| NLP           | 12.62803                  | 1.6545             | 0.7062             | 4.438888             |
| MINLP         | 12.58422                  | 1.6435             | 0.7136             | 4.459991             |

The optimal cost in \$ per MW recorded in MILP and MINLP are 12.27 and 12.58,

while the investment cost of BESS are 4.016 and 4.560 for MILP and MINLP respectively. The table indicates that the MILP gives the minimum value compare to MINLP. This result agrees with report from [106]. The fact the formulating an optimization problem in MILP allows us to accommodate more parameters in the modelling in the form binary is the reason for its improved accuracy. The cost difference when MILP and LP are used to size BESS in [44] results to 12.3% where as in the study, the difference is about 10.1%, however the study in [44] is applied to the islanded microgrid. In [106], the MINLP was an improved NLP obtained by adding mixed integer programming and it has been used to improve the sizing of BESS in [107], [108].

## CHAPTER 6

# OPERATION OF BESS

### 6.1 Energy Management Strategy for Grid-Tied Microgrid

The optimal distribution to supply the microgrid load has been found. The simulation has been run for 48 hours to test and evaluate the model. The minimum cost has been calculated to be about \$1142. Figure 6.1 shows how the load gets its power at every hour. The largest portion comes from the main grid but at the possible minimum cost. The BESS is considered as a load in the charging case. So, the PV and grid powers are divided between the load and BESS. As shown in Figure 6.1, the BESS supplies when the price of grid power is high. Also, the BESS charges when the prices are low. This is how the BESS helps in minimizing the costs. Figure 6.2 shows the stored energy, state of charge, at every hour.

A Special scenario is investigated in Figure 6.3 where the number of solar PV array units is increased. Simulation results show that the total operating cost decreases

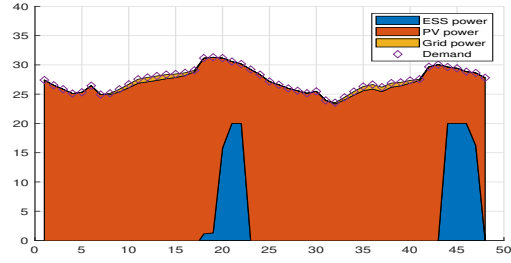


Figure 6.1: Distribution of powers supplying the load

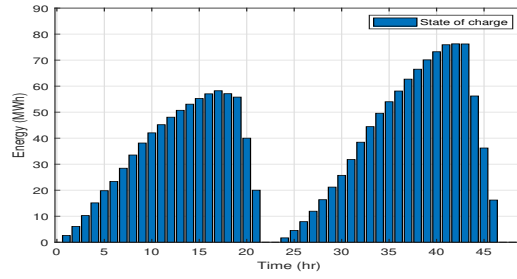


Figure 6.2: State of charge

linearly as the number of PV arrays increases. However, the cost per unit PV array decreases but initially linearly and later became constant. This is evidenced as all optimizing equations are linear. This shows that the system's operating cost becomes more profitable as the network is expanded. Beyond 20 PV array units, the cost per unit PV array unit tends to a constant and extra benefit of expanding the network is less in terms of operating cost.

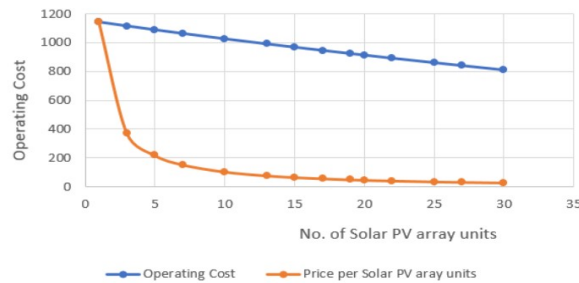


Figure 6.3: Variation Operating Cost with No. of Solar PV array units

## 6.2 Optimal Cost of Operation of Wind-based Microgrid Versus PV-based Microgrid

The optimal cost of operating the microgrid load has been found in the three cases and the results are presented in 6.1. The simulation was done for 24 hours to test and evaluate the models. The minimum cost recorded in all cases correspond to the cost of operating the size of the microgrid for 24 hours. The PV has the highest cost of \$150.05 (\$6.25 per hour), the wind-based recorded \$79.15 (\$3.29 per hour) while hybrid PV/Wind model recorded the least cost of \$53.53 (\$2.23 per hour).

Figure 6.6 shows the hourly distribution of demand, PV, grid, and battery power. Also shown in the same graph is the SOC of the battery during the operation of the microgrid. The result shows that larger portion comes from the main grid but at the possible minimum cost; the BESS is considered as a load in the charging case at this time. During the afternoon between hours 8 and 17, the SOC of the BESS is seen to rise steadily as the PV and grid powers are divided between the load and BESS. Also, the BESS charges during the late hours (20th to 24th) to enjoy the benefit of low tariffs from the grid and the BESS supplies the microgrid when the price of grid power is high.

Table 6.1: Optimal operation cost of PV/Wind microgrid configuration

| Microgrid configuration | Operation cost (\$) | Operation cost (\$/hour) |
|-------------------------|---------------------|--------------------------|
| PV-based                | 150.05              | 6.25                     |
| Wind-based              | 79.15               | 3.29                     |
| Hybrid PV/Wind-based    | 53.53               | 2.23                     |

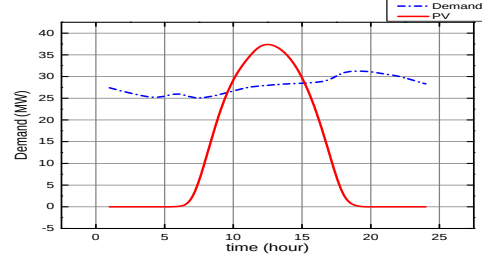


Figure 6.4: PV Generation for Dhahran city [6]

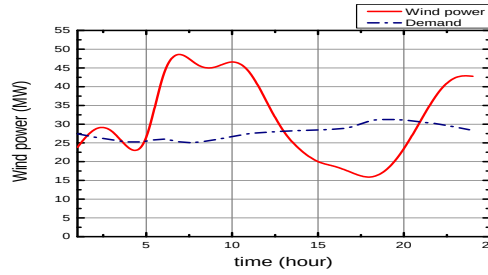


Figure 6.5: Wind Generation for Dhaharan city [6]

The power-sharing distribution of the second case is shown in Figure 6.7. Typically, the SOC of the BESS rises most of the time because the microgrid enjoys the availability of power from the wind energy system. The grid power is supplied for the least of time because the BESS is always charged and readily available to support the microgrid during the early hours (1st-8th) when there seems to be a drop in the wind energy supply.

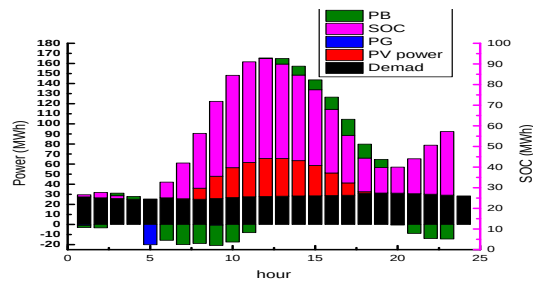


Figure 6.6: Optimal Operation of PV based microgrid

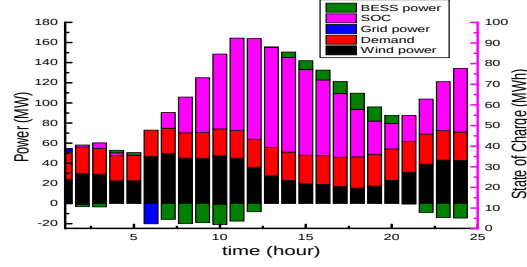


Figure 6.7: Optimal Operation of Wind based microgrid

## 6.3 Operation of BESS for wind-penetrated micro-grid

### Scenario 1

The microgrid is grid-connected and power sharing occurs between wind, BESS, grid to supply the demand.

### Scenario 2

The microgrid is off-grid, three diesel generators are connected in addition to the BESS to support the microgrid. The generators start to operate only when the output from the windfarm is low or where the SOC of the BESS is low to prevent high DOD. In all scenarios, the operation of the microgrid is ensure to prevent the battery from deep discharge to prevent short life cycle of the battery.

#### 6.3.1 Case study

In this study, a microgrid of the different configuration is considered. Operation study is done for the two scenarios. The wind data used are for March and September. These

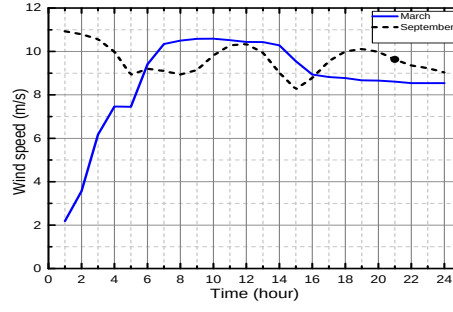


Figure 6.8: Wind profile for Case A

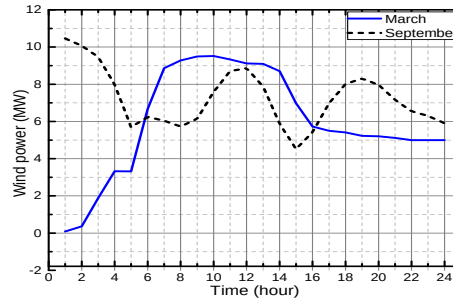


Figure 6.9: Wind profile for Case B

data are carefully chosen to represent fair scenarios for two extreme profiles. The wind speed and power are shown in Figure 6.8 and Figure 6.9 respectively.

Table 6.2: Diesel generator parameters

| Parameters/<br>Diesel gen. | $a$<br>(\$/ $MW^2$ ) | $b$<br>(\$/ $MW$ ) | $c$<br>(\$) | $d$<br>( $kg/MW^2$ ) | $e$<br>( $kg/MW$ ) | $f$<br>(\$) | $P_{min}$<br>$MW$ | $P_{max}$<br>$MW$ |
|----------------------------|----------------------|--------------------|-------------|----------------------|--------------------|-------------|-------------------|-------------------|
| g1                         | 0.012                | 0.8                | 0.3         | 0.12                 | -0.25              | 0.7         | 0                 | 2.5               |
| g2                         | 0.0017               | 0.75               | 0.5         | 0.15                 | -0.35              | 0.7         | 0                 | 3                 |
| g3                         | 0.015                | 0.85               | 0.2         | 0.1                  | -0.15              | 0.6         | 0                 | 2.5               |

### 6.3.2 Scenario 1

In Case A, the daily schedule cost of the microgrid is \$976.719 while the daily cost of BESS is \$139.366 resulting to electricity cost of \$5.31 per MWh for the load profile.

The daily power dispatch of the microgrid from all sources is shown in Figure 6.10 and the DOD in Figure 6.11. In Case B of Scenario 1, the daily schedule cost of microgrid \$694.92 with a BESS daily schedule cost of \$ 67.91047 and the daily electricity cost of \$3.32 per MWh for the load profile. As seen from these results, it is cheaper to operate the microgrid in Case B than that of Case A. The justification for this comes from the excess wind power by which Case B surpasses Case A. The resulting effect translates to a drop in price electricity by 37%. Thus, with the wind power and BESS, we are able optimized the cost of electricity per MWh to \$5.31 and \$3.32 respectively for Cases A and B respectively.

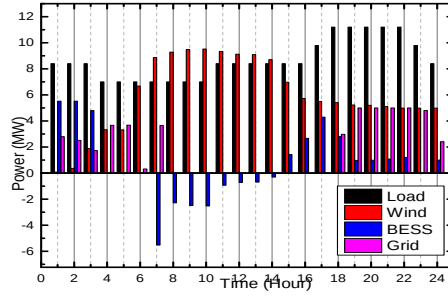


Figure 6.10: Microgrid power dispatch in Scenario 1 case A

In Figure 6.10, it is seen that BESS dispatch its power when the wind output is low as expected, however the level of power dispatch could be seen in the DOD. Figure 6.11 shows that the DOD of the BESS reached up to 0.9 at hours 4 to 7. The DOD is significantly high for about 7 hours in 24 hours where it exceeds 0.8. The BESS operate in a safe condition for more than 70% of the operating hours.

An improved DOD is observed in case B of Scenario 1 as seen in Figure 6.13. The highest DOD is below 0.85. A constant DOD of nearly 0.8 is observed from the 17th

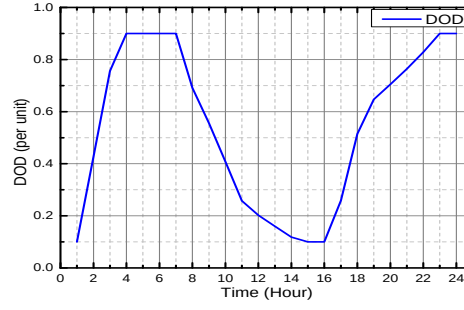


Figure 6.11: DOD of BESS case A, Scenario1

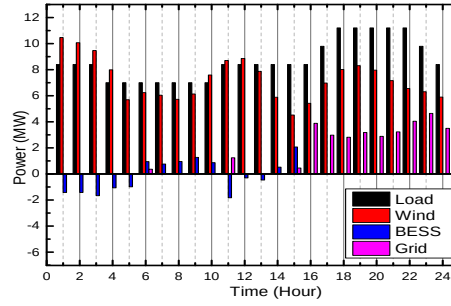


Figure 6.12: Microgrid power dispatch in Scenario 1 case B

hour up to hour 24 because of the steady supply from the grid as observed in Figure 6.12. It is cheaper to consume from the grid at these hours thus limiting the dispatch from the BESS to a healthy operating condition.

### 6.3.3 Scenario 2

In scenario 2, the off-grid microgrid is supported with diesel generators. In case A, the daily schedule cost is calculated to be \$642.542 while the daily cost of BESS is \$235.98 and the price of electricity per MWh is \$3.74. In Case B of Scenario 2, the schedule cost for a day is \$519.52, the Schedule cost for BESS is \$43.02 and the cost of electricity is \$3.28 per MWh. It is observed that the price of daily electricity for

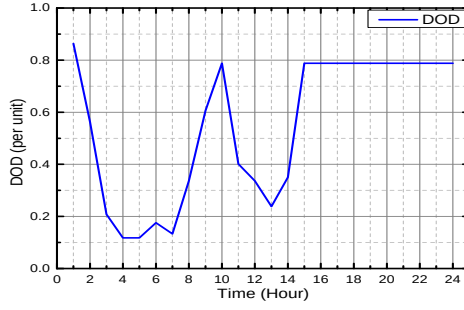


Figure 6.13: DOD of BESS case B, Scenario1

Table 6.3: Schedule cost for all scenerios

| Quantity                | Scen.1 (A) | Scen. 1(B) | Scen.2 (A) | Scen.2 (B) |
|-------------------------|------------|------------|------------|------------|
| DSC (\$)                | 976.7192   | 692.9265   | 642.7332   | 519.5166   |
| $DC_{BESS}$ (\$)        | 139.366    | 34.97615   | 235.9843   | 43.01909   |
| Cost of elect. (\$/MWh) | 5.31064    | 3.321795   | 3.735231   | 3.284667   |
| PLP                     | 0.0564     | 0.0402     | 0.0329     | 0.0306     |

the load profile dropped in Case B by about 12%. However, the price per MWh of electricity is less than what was recorded in both cases of Scenario 1. Figure 6.14 and Figure 6.15 show the profile of the power dispatch by BESS, generators and wind turbine to serve the load in Case A and Case B respectively.

In Figure 6.14, it is observed that the BESS discharged optimally from hour 1 to 3 and and hour 17 to 24, dispatching more of its powers during the hours of lower wind power. The BESS is discharged up to it maximum allowed level and the generators also supplied where the demand is higher. When there is abundant power form the wind, the BESS is charged as seen from hours 6 to 14. The dispatch by the BESS ensures that the DOD of the BESS is maintained below the 0.9 for most of the hour as shown in Figure 6.16. In Figure 6.15, the dispatch of the power for the Case B,

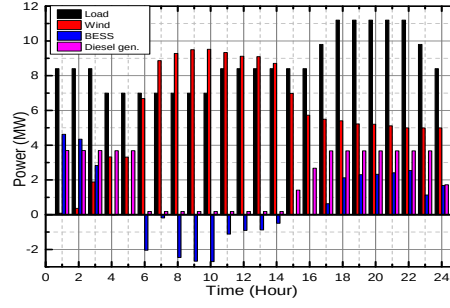


Figure 6.14: Microgrid power dispatch in Scenario 2 case A

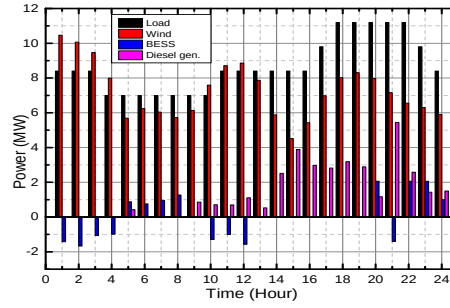


Figure 6.15: Microgrid power dispatch in Scenario 2 case B

Scenario 2 is shown. It is seen that the BESS discharges during hours of high wind powers as noted at hours 1,2, 4, 10, 11, 12 and 21. The BESS discharges only during hours high demand and when the output of the wind turbine is low as observed from hours 4 to 8 and hours 20 to 24. The DOD of the Case B, Scenario 1 is shown in Figure 6.16 with values less than 0.8 most of the hours. This shows that the BESS is not over drained during its operation.

Table 6.3 shows the summary of all cost obtained in all scenarios. It is noted that the daily schedule cost for the microgrid are cheaper for Scenario 2 than in Scenario 1 and Case B is the cheapest. Also, the daily schedule costs for BESS are higher in Scenario 2 than in Scenario 1 in both cases. However, the high values of  $DC_{BESS}$  in

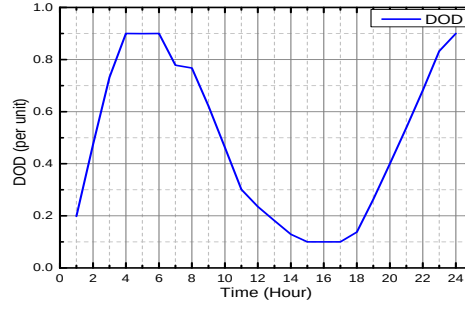


Figure 6.16: DOD of BESS in Scenario2, case A

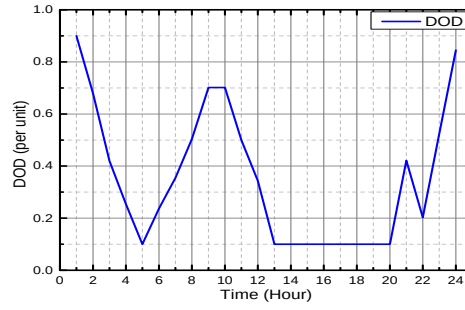


Figure 6.17: DOD of BESS in Scenario2, case B

Scenario 2 resort to cheaper cost of electricity and Scenario 2(B) and Scenario 1(B) are the cheapest as reported in Table 6.3.

The table also shows the power loss probability for all the cases in the two scenarios. The table shows that Scenario 2(B) has the lowest PLP of 0.0306 followed by Scenario 2(A) with PLP of 0.0329, followed by Scenario 1(B) with PLP of 0.042 and Scenario 1(A) has the highest PLP. The implication of this is that Scenario 2 is more reliable in terms of power generation failure than Scenario 1. Also, the fact that the PLP obtained in Case B is less than that of A indicates that the abundance of power in Case B than Case A has boosted the reliability of the microgrid.

In Table 6.4, the results of all scenarios and cases are presented. It can be observed

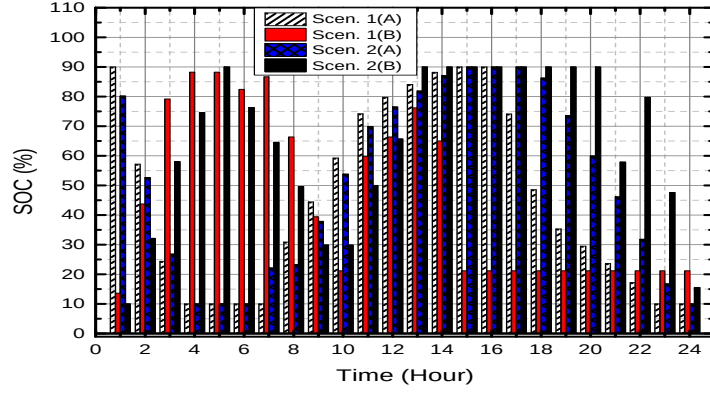


Figure 6.18: SOC of BESS in all Scenarios

that the  $n_c$  which is the number of cycle of energy storage at a particular DOD decreases with increased wind power and demand variations. This is because the BESS charges when the wind power is greater than the demand. This trend is observable in from hours 9 to 19 in column 1 (A) and 1(B) for Scenario 1 Case A and Case B respectively. A similar observation is seen in Scenario 2 from hour 11 to 22 for Cases A and B respectively notably when the diesel generators begin to supply more powers. Other scheduling components shown in Table 6.4 are powers, grid powers, wind power and demand for 24 hours.

In Figure 6.18, the SOC of all cases of Scenario 1 and Scenario 2 are shown. It can be observed that the SOC of the BESS are high at the early hours of Case B of Scenarios 1 and 2 between hours 2 and 8 than Case A of the two scenarios. On the other hand, the SOC of BESS in Case A of the two Scenarios are high from around 11th hour to the 20th hour than those of Case B of the scenarios. These variations reflect the operation of the BESS during the changes in the wind power between the cases. Besides the SOC changes with the demand. In Scenario 1, the SOC decreases

(for both Cases A & B) as the demand increases between hour 17 and 24, this is because microgrid in Scenario 1 is grid-connected and since the imported power into the microgrid is restricted to 5MW, the BESS has to supply the remaining power to satisfy the power balance condition. However, the SOC of BESS in Scenario 2 (A & B) are fairly higher than 60% during these (hour 17 to 22) because the microgrid in Scenario 2 has three backup generator to serve the load and this can serve as good relief for the BESS.

Table 6.4: Scheduling results for cases and scenarios

| Time (hr)<br>Scn. (Case) | Wind (MW)<br>Case A | Wind (MW)<br>Case B | Load | $n_c$<br>1 (A) | $n_c$<br>1 (B) | $P_{grid}$<br>1 (A) | $P_{grid}$<br>1 (B) | $P_{BESS}$<br>1 (A) | $P_{BESS}$<br>1 (B) | $n_c$<br>2 (A) | $n_c$<br>2 (B) | $P_{BESS}$<br>2 (A) | $P_{BESS}$<br>2 (B) | Diesel<br>2 (A) | Diesel<br>2 (B) |
|--------------------------|---------------------|---------------------|------|----------------|----------------|---------------------|---------------------|---------------------|---------------------|----------------|----------------|---------------------|---------------------|-----------------|-----------------|
| 1                        | 0.083               | 10.466              | 8.4  | 4329           | 780            | 2.797               | 0                   | 5.52                | -1.423              | 2513           | 755            | 4.63                | -1.423              | 3.687           | 0               |
| 2                        | 0.365               | 10.069              | 8.4  | 1363           | 1097           | 2.515               | 0                   | 5.52                | -1.669              | 1258           | 945            | 4.349               | -1.669              | 3.687           | 0               |
| 3                        | 1.883               | 9.466               | 8.4  | 867            | 2416           | 1.727               | 0                   | 4.79                | -1.066              | 890            | 1385           | 2.831               | -1.066              | 3.687           | 0               |
| 4                        | 3.328               | 7.992               | 7    | 755            | 3806           | 3.672               | 0                   | 0                   | -0.992              | 755            | 2064           | -0.007              | -0.992              | 3.679           | 0               |
| 5                        | 3.314               | 5.689               | 7    | 755            | 3806           | 3.686               | 0.368               | 0                   | 0.943               | 755            | 4328           | 0.007               | 0.881               | 3.679           | 0.43            |
| 6                        | 6.679               | 6.242               | 7    | 755            | 2764           | 0.321               | 0                   | 0                   | 0.758               | 755            | 2181           | -2.045              | 0.758               | 0.184           | 0               |
| 7                        | 8.861               | 6.04                | 7    | 755            | 3454           | 3.659               | 0                   | -5.52               | 0.96                | 847            | 1583           | -0.184              | 0.96                | 0.184           | 0               |
| 8                        | 9.279               | 5.727               | 7    | 931            | 1651           | 0                   | 0                   | -2.279              | 1.273               | 857            | 1197           | -2.463              | 1.273               | 0.184           | 0               |
| 9                        | 9.493               | 6.14                | 7    | 1108           | 1034           | 0                   | 0                   | -2.493              | 0.86                | 1014           | 921            | -2.677              | 0                   | 0.184           | 0.86            |
| 10                       | 9.52                | 7.591               | 7    | 1417           | 839            | 0                   | 1.234               | -2.52               | -1.824              | 1282           | 921            | -2.704              | -1.298              | 0.184           | 0.707           |
| 11                       | 9.332               | 8.708               | 8.4  | 2039           | 1434           | 0                   | 0                   | -0.932              | -0.308              | 1801           | 1205           | -1.116              | -1.007              | 0.184           | 0.699           |
| 12                       | 9.121               | 8.861               | 8.4  | 2471           | 1651           | 0                   | 0                   | -0.721              | -0.461              | 2194           | 1624           | -0.905              | -1.567              | 0.184           | 1.105           |
| 13                       | 9.095               | 7.872               | 8.4  | 2986           | 2170           | 0                   | 0                   | -0.695              | 0.528               | 2696           | 4328           | -0.879              | -2.22E-16           | 0.184           | 0.528           |
| 14                       | 8.708               | 5.882               | 8.4  | 3788           | 1598           | 0                   | 0.452               | -0.308              | 2.066               | 3531           | 4328           | -0.492              | 0                   | 0.184           | 2.518           |
| 15                       | 6.981               | 4.517               | 8.4  | 4329           | 839            | 0                   | 3.883               | 1.419               | 0                   | 4329           | 4328           | 0                   | 0                   | 1.418           | 3.883           |
| 16                       | 5.727               | 5.425               | 8.4  | 4329           | 839            | 0                   | 2.975               | 2.673               | 0                   | 4329           | 4328           | 0                   | 0                   | 2.673           | 2.975           |
| 17                       | 5.5                 | 6.981               | 9.8  | 2033           | 839            | 0                   | 2.819               | 4.3                 | 0                   | 4329           | 4328           | 0.629               | -8.59E-17           | 3.671           | 2.819           |
| 18                       | 5.407               | 8.016               | 11.2 | 1178           | 839            | 2.979               | 3.184               | 2.814               | 0                   | 3363           | 4328           | 2.122               | 0                   | 3.671           | 3.184           |
| 19                       | 5.224               | 8.308               | 11.2 | 982            | 839            | 5                   | 2.892               | 0.976               | 0                   | 2004           | 4328           | 2.305               | 0                   | 3.671           | 2.892           |
| 20                       | 5.206               | 7.968               | 11.2 | 917            | 839            | 5                   | 3.232               | 0.994               | 0                   | 1437           | 4328           | 2.323               | 2.066               | 3.671           | 1.167           |
| 21                       | 5.116               | 7.158               | 11.2 | 860            | 839            | 5                   | 4.042               | 1.084               | 0                   | 1136           | 1381           | 2.413               | -1.405              | 3.671           | 5.446           |
| 22                       | 4.992               | 6.552               | 11.2 | 807            | 839            | 5                   | 4.648               | 1.208               | 0                   | 942            | 2469           | 2.536               | 2.066               | 3.671           | 2.582           |
| 23                       | 4.992               | 6.303               | 9.8  | 755            | 839            | 4.808               | 3.497               | 0                   | 0                   | 803            | 1161           | 1.136               | 2.066               | 3.671           | 1.431           |
| 24                       | 4.992               | 5.902               | 8.4  | 755            | 839            | 2.408               | 1.498               | 1                   | 1                   | 755            | 794            | 1.683               | 1                   | 1.725           | 1.498           |

## CHAPTER 7

# CONCLUSION AND RECOMMENDATION

### 7.1 Conclusion

In this thesis, a comprehensive review of sizing and operation methodologies for BESS has been studied. We have presented the optimal sizing of BESS in a wind penetrated microgrid for the operation of a grid-tied microgrid and a stand-alone microgrid. We found that the grid-connected microgrid of the type proposed in Scenario 1 is potentially cheaper and requires lesser BESS investment. In particular, we computed the monthly BESS requirements and the amount saved from the emission of greenhouse gases. Furthermore, the results of sizing methodologies of BESS were reported for LP, NLP, MILP, and MINLP and it is found that the MILP gives the least optimal values for the operation cost and rated sizes of the BESS. However, the optimal values recorded in MINLP are lesser than that of MINLP.

Moreover, the operation of BESS was done for four configurations of microgrids

including PV, wind, hybrid PV/wind, and diesel generators. The study found out that the hybrid PV/wind-based microgrid is the cheapest to operate than the wind-based or PV-based and wind-based is cheaper than the PV-based. A strategy was proposed for the operation of the BESS in a wind penetrated microgrid by considering lifetime, DOD and life number of the BESS. We reported the daily scheduled cost of BESS, the daily cost of electricity and reliability analysis of the proposed strategy. Furthermore, the parameters of the BESS such as DOD, number of cycles and power dispatch reported showed that the BESS operated more safely under the stand-alone system. Moreover, the stand alone system has better performance than the grid-connected system and the microgrid operator has more control over the distributed generation in the stand alone system than in the later. Also, the study showed that the loss of power probability of less than 10% is achievable. The loss of power probability is largely dependent on the wind power availability and it is much lower in stand-alone microgrid configuration.

## 7.2 Recommendation

The development of topics of sizing the battery energy storage is still opened for the development of several topics in the future.

While the sizing of BESS in this study focused more on wind penetrated microgrid, a researcher may consider a cost minimization hybrid a wind/PV with the inclusion of several objectives.

Future work should consider the effect of uncertainty in wind power in the formulation

of the optimization problem.

Finally, since the results of the case study considered in this work suggests that a wind-based microgrid is cheaper to operate during summer months. It may be beneficial to investigate the visibility and planning of wind-based microgrid in this region.

## APPENDIX A

# PROOFS

Table A.1: Diesel generator parameters

| Parameters/<br>Diesel gen. | $a$<br>(\$/MW <sup>2</sup> ) | $b$<br>(\$/MW) | $c$<br>(\$) | $d$<br>(kg/MW <sup>2</sup> ) | $e$<br>(kg/MW) | $f$<br>(\$) | $P_{min}$<br>MW | $P_{max}$<br>MW |
|----------------------------|------------------------------|----------------|-------------|------------------------------|----------------|-------------|-----------------|-----------------|
| g1                         | 0.012                        | 0.8            | 0.3         | 0.12                         | -0.25          | 0.7         | 0               | 2.5             |
| g2                         | 0.0017                       | 0.75           | 0.5         | 0.15                         | -0.35          | 0.7         | 0               | 3               |
| g3                         | 0.015                        | 0.85           | 0.2         | 0.1                          | -0.15          | 0.6         | 0               | 2.5             |

Table A.2: Generator parameters for unit commitment study used in LP and MILP

| Gen.unit | $p_{max}$ | $p_{min}$ | ru  | rd  | f   | v   | su | sd |
|----------|-----------|-----------|-----|-----|-----|-----|----|----|
| p1       | 2.5       | 0.1       | 0.2 | 0.2 | 2.5 | 7.5 | 4  | 4  |
| p2       | 3         | 0.2       | 0.3 | 0.3 | 3.5 | 11  | 5  | 5  |
| p3       | 3         | 0.2       | 0.3 | 0.3 | 3.5 | 11  | 5  | 5  |
| p4       | 2.5       | 0.1       | 0.2 | 0.2 | 2.5 | 7.5 | 4  | 4  |

## BESS Parameters

| Table A.3: BESS Parameters          |                |
|-------------------------------------|----------------|
| parameter                           | Value          |
| toprule $SOC_{BESS}^{max}$ (%)      | 90             |
| $SOC_{BESS}^{min}$ (%)              | 10             |
| Initial Capital cost (\$)           | 9000           |
| Round-trip Efficiency (%)           | 90             |
| BESS lifetime (years)               | 3              |
| $P_{BESS}^{max}$<br>Case A (Case B) | 2.52 (2.296)   |
| $E_{BESS}^{max}$<br>Case A (Case B) | 14.761 (7.152) |
| Interest rate (%)                   | 6.5            |

## Wind turbine parameters

| Table A.4: Wind turbine parameters |         |
|------------------------------------|---------|
| parameter                          | Value   |
| Power coefficient                  | 0.45    |
| Blade area $m^2$                   | 3019.07 |
| Air density $kg/m^{-3}$            | 9000    |
| Initial capital cost (\$/MW)       | 2500    |
| Maximum wind power (MW)            | 10      |
| Lifetime (years)                   | 10      |
| Interest rate (%)                  | 6.5     |

Table A.5: Limitations for chosen values

| Parameter   | Value   |
|-------------|---------|
| $P_g^{max}$ | 30 MW   |
| $P_b^{max}$ | 20 MW   |
| $SOC^{min}$ | 10 MWh  |
| $SOC^{max}$ | 100 MWh |

Table A.6: Generator parameters

| Parameter\Units | $a_g$<br>(\$/MW <sup>2</sup> ) | $b_g$<br>(\$/MW) | $c_g$<br>(\$) |
|-----------------|--------------------------------|------------------|---------------|
| g1              | 0.12                           | 8.5              | 69            |
| g2              | 0.17                           | 11.75            | 75            |
| g3              | 0.15                           | 9.33             | 95            |
| g4              | 0.19                           | 10.12            | 65            |

Table A.7: Generator parameters

| Parameter\Units | $P_{min}$<br>(MW) | $P_{max}$<br>(MW) | $RU_0$<br>(MW) | $RD_0$<br>(MW) |
|-----------------|-------------------|-------------------|----------------|----------------|
| g1              | 10                | 50                | 10             | 10             |
| g2              | 20                | 60                | 15             | 10             |
| g3              | 15                | 50                | 10             | 10             |
| g4              | 10                | 40                | 8              | 8              |

Table A.8: Energy storage parameters

| Parameter   | Value |
|-------------|-------|
| $P_{gmax}$  | 40MW  |
| $P_{bmax}$  | 50MW  |
| $SOC_{min}$ | 10MW  |
| $SOC_{max}$ | 100MW |
| $PC_{ESS}$  | \$140 |
| $EC_{ESS}$  | \$30  |

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- Energy Management Strategy Considering Battery Efficiency for Grid-Tied Microgrids During Summer in the Kingdom of Saudi Arabia.  
8th International Conference on Renewable Energy Research and Applications, Published to pages, IEEE (ICRERA 2019) 422–427.  
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- April 2020 Optimal Operation of Battery Energy Storage in a Wind Penetrated Microgrid Considering Depth of Discharge  
Submitted to Elsevier Renewable Energy
- December 2019 Optimal Energy Management Strategy Based on Dynamic Energy Dispatch for a Wind-Penetrated Microgrid  
Accepted at IEEE ICREPQ2020, Granda, Spain; Awaiting presentation
- Dec 2019 Optimal Cost of Operation of Wind Energy-based Microgrid Versus PV-based Microgrid  
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- Intelligent Flexible Priority List for Reconfiguration of Microgrid Demands Using Deep Neural Network  
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