Arab Academy for Science, Technology and Maritime Transport

College of Engineering and Technology

Electrical and Control Department

M. Sc. Thesis

Optimal Energy Management System for a Renewable based Micro-Grid

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DECLARATION

I certify that all the material in this thesis that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this thesis reflect my own personal views, and are not necessarily endorsed by the University.

Signed: ______________________________

Date:

We certify that we have read the present work and that in our opinion it is fully adequate in scope and quality as a thesis towards the partial fulfillment of the Master's Degree requirements in

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ABSTRACT

Currently electric distribution networks are aging, and the capital investment cost for substations and networks are increasing severely. For remote areas, supplying electricity is becoming harder as the cost of fuel transportation is increasing which in some cases become unfeasible. On the other hand, non-remote areas are facing other types of problems such as shortage of electricity as the demand on power increases and quality of power and service became poor. The past decades experienced a radical increase in energy production and consumption. Nowadays, the consumption rate increase has lead to supply shortage. Thus, a solution must be reached to solve this shortage as well as greenhouse gas emissions. Renewable energy sources can be considered as an alternative solution to the conventional fossil fuels electricity sources.

Micro-grids have emerged in the electricity sector lately having a promising future accompanied with many benefits. Micro-grids are the small scale version of the main grid, containing a number of loads and distributed generation sources which are most likely renewable based sources. These loads can be supplied locally with electricity and heat efficiently.

This thesis proposes an energy management system for micro-grids. The energy management system aims to optimize the operation of every distributed generation source to ensure minimum possible operational cost and emission levels. The proposed energy management system is implemented using the ant colony technique in a Matlab® environment for developing the optimization algorithm with respect to the combined economic and emission dispatch problem. Also, this research proposes another cost effective solution in micro-grids, where a battery system is installed in the micro-grid as an alternative to load shedding option at the times where the source can’t supply the load demand. The proposed system efficiency is decided upon comparing between the cost of KWh of the battery with the cost of the electricity at the time of cut off.

Two case studies are used to illustrate the benefits of the proposed ant colony energy management system over two optimization techniques; Lagrange technique and the Gradient method. Furthermore, the proposed algorithm evaluates the integration of renewable based sources in the micro-grid which has proven to be cost efficient taking into consideration renewable energy certificates when calculating the capital cost of the renewable sources. Results are obtained and discussed and conclusions are reported.

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LIST OF SYMBOLS

Symbol	Definition of Symbol
a	Cost Coefficient / Relative Importance of the Penalty
b	Cost Coefficient
c	Cost Coefficient
E_T	Total Emission Output
F_c	Total Fuel Cost
F_T	Combined Economic and Emission Dispatch function
Gen_{max}	Maximum Power Output that can be obtained from a given generator
Gen_{min}	Minimum Power Output that can be obtained from a given generator
L_{best}	Shortest Distance obtained
L_k	Tour Distance for ant k
N	Number of Generators
P_{conv}	Total Power obtained from the Conventional Sources
P_d	Total Load Demand
P_{demand}	Total Power demand
P_i	Real output generation of the ith generator
$P_{RE\ sources}$	Total Power obtained from the Renewable Energy Sources
Q	Pheromone Constant
α	Emission Coefficient

β	Emission Coefficient / Relative Visibility
μ	Heuristic Desirability
ρ	Evaporation Rate of Pheromone
τ	Pheromone Amount
Υ	Emission Coefficient

LIST OF ACRONYMS/ABBREVIATIONS

ACRONYM	Definition of Acronym
ACO	Ant Colony optimization
CERTS	Consortium for Electric Reliability Technology Solutions
DER	Distributed Energy Resources
DG	Distributed Generation
DNO	Distribution Network Operator
DS	Distributed Storage
EMS	Energy Management Systems
LC	Local Controller
MCC	Micro-grid Central Controller
MO	Market Operator
NN	Neural Networks
PCC	Point of Common Coupling
PV	Photo Voltaic
RE	Renewable Energy
REC	Renewable Energy Certificates
RES	Renewable Energy Sources
WT	Wind Turbine
Zn	Number of Zones

Chapter One

1 INTRODUCTION

This chapter presents the thesis overview, emphasizing the motivations behind the research and the objectives required to be achieved. It also outlines a brief description of each chapter.

1.1 Thesis Motivations

The past decade witnessed a drastic increase in countries population and industrial technological development. Over the past 10 years, energy production and consumption has increased globally by a 39.8% and 40.8% respectively and this increase can be shown in Figures 1-1 to 1-3. In the meanwhile, the usage of Renewable Energy Sources (RES) has become more desirable due to its long term cost saving compared to its relatively high capital cost while being environmental friendly. Figure 1-4 shows the percentage increase of Renewable Energy (RE) share in energy production around the world from 2002 till 2012 [1].

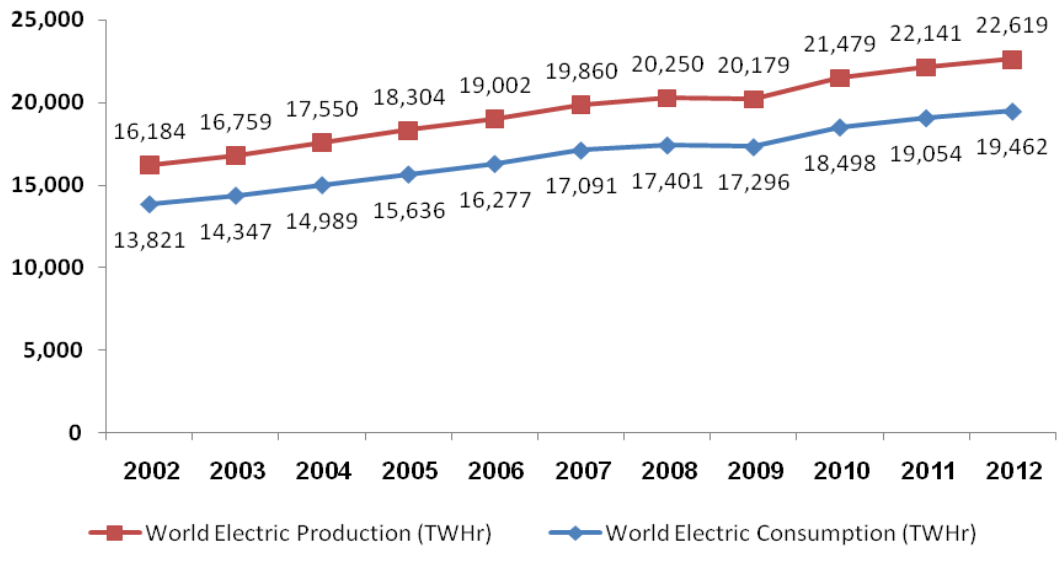

Figure 1-1 World Electric Production and Consumption 2002-2012 [1]

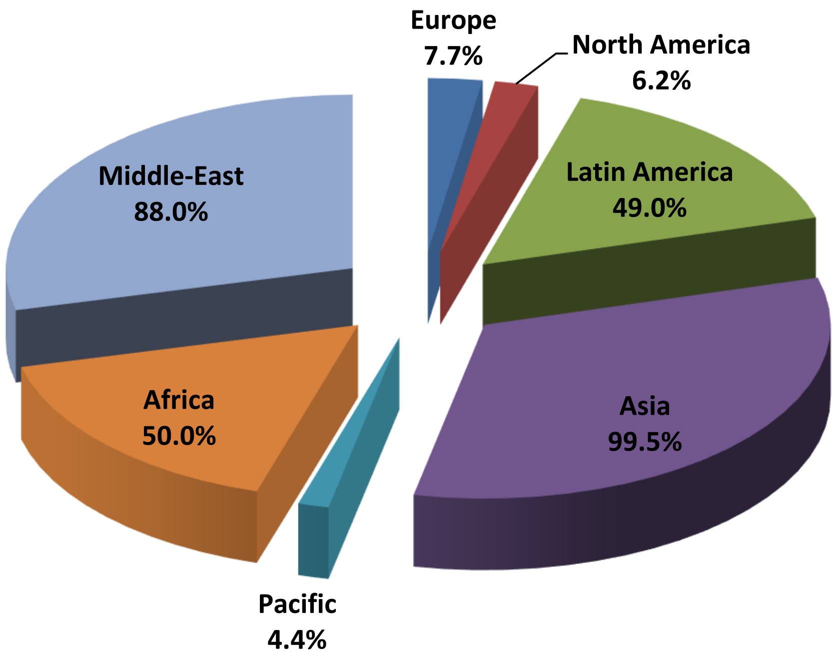

Figure 1-2 Energy Production % Increase 2002-2012 globally [1]

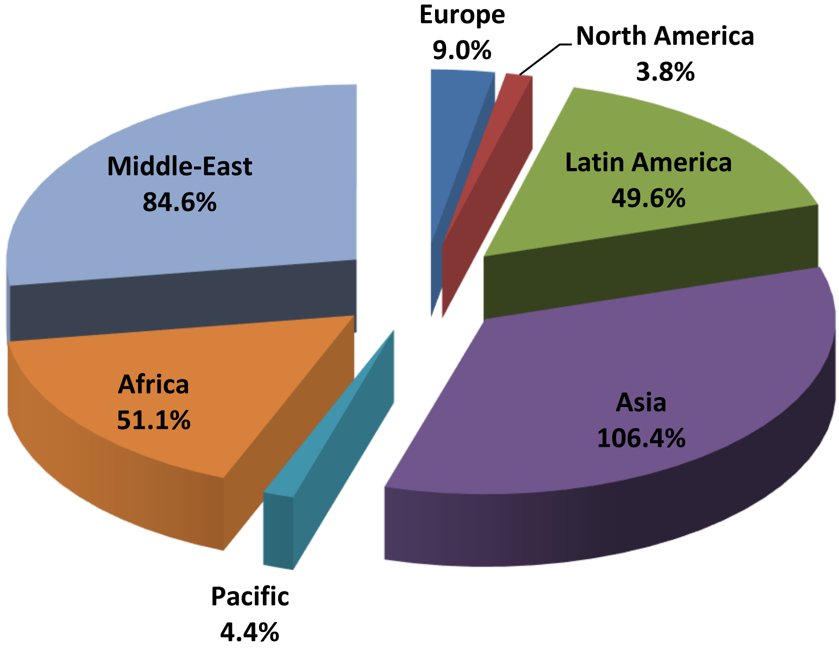

Figure 1-3 Energy Consumption % Increase 2002-2012 globally [1]

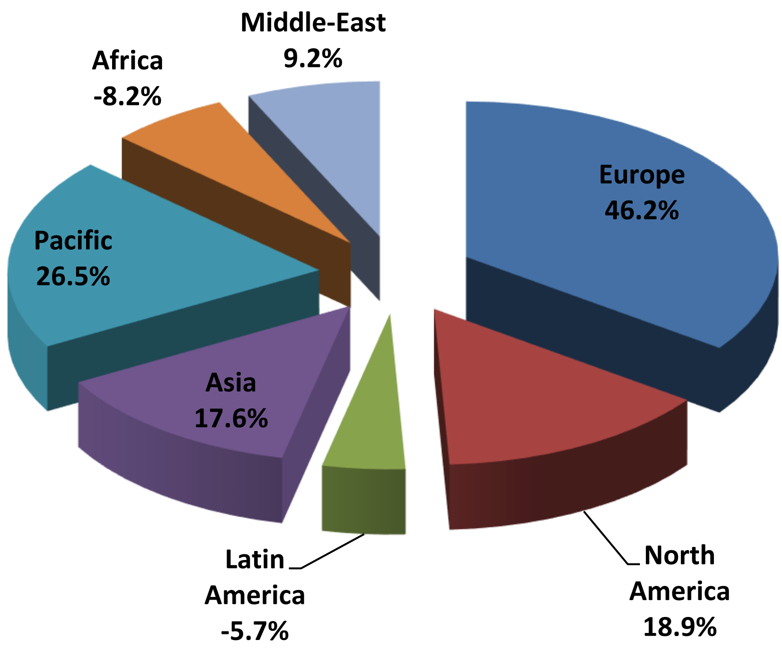

Figure 1-4 Renewable Energy % Share in Electricity Production Increase 2002-2012 globally [1]

Another study was carried out by the International Energy Agency (IEA) which showed the global renewable electricity production in TWhr from 2006 till 2013 and forecasting until 2020. The study showed a very positive increasing trend in the past years and expected further increase in the following years as shown in Figure 1-5

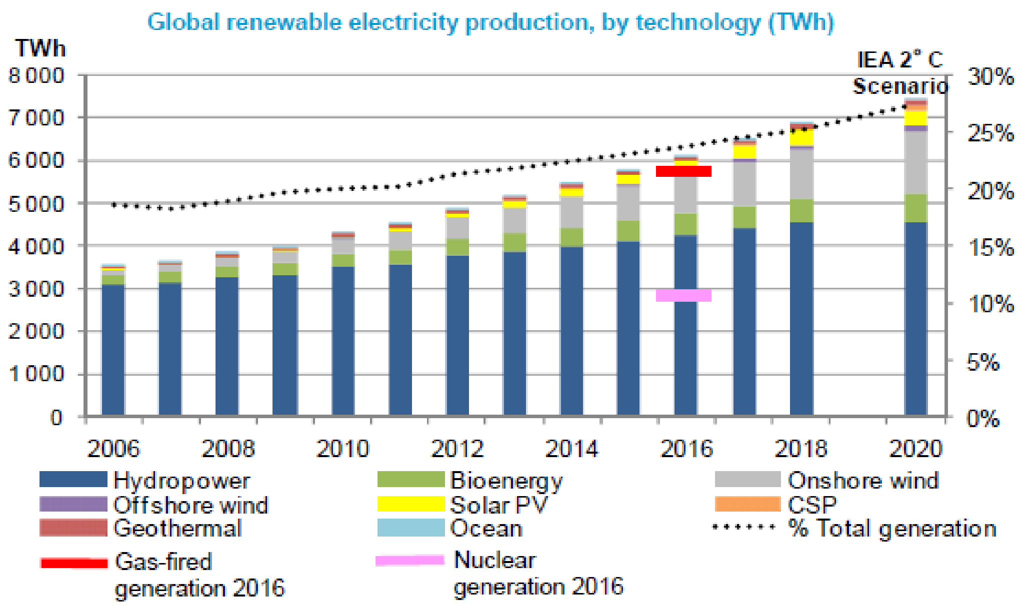

Figure 1-5 Global Renewable electricity production by technology (TWh) [2]

1.2 Thesis Objectives

Micro-grids have emerged as the alternative solution to many disadvantages facing the conventional electrical distribution networks nowadays. Micro-grids offer high levels of security and reliability while facilitating electricity trading with the main grid with the usage of proper management systems. Moreover, they encouraged the integration of RES. Micro-grids are characterized by their dynamic behaviour and multi-constraints environment; thus energy management techniques must be able to accommodate these traits to make micro-grids a more feasible alternative solution to conventional power systems and attract consumers and investors.

This thesis proposes a novel energy management system using the ant colony technique to optimize the operation of hybrid micro-grids consisting of RES and conventional diesel generators. The proposed algorithm was developed in a Matlab® environment. Two case studies have been carried out to illustrate the benefits of the proposed algorithm. These studies are aiming at optimizing the operation of the micro-grid while promoting for the integration of RES (Wind and Solar Energy) in electrical systems. The combined economic and emission dispatch problem is addressed The proposed energy management system assigns the optimal power generated from the Distributed Generating (DG) units to minimize the total operating cost and the emission while attaining continuous supply to the customers. Moreover, Renewable Energy Certificates (REC) have been taken into consideration in the optimization process which decreases the overall investment cost of the renewable sources thus encouraging investors and consumers to seek these RES as their alternate solution.

1.3 Thesis Outline

To achieve the above mentioned objectives, the thesis is organized into multiple chapters. This chapter presents the thesis overview and emphasising on the motivations behind the research and the objectives required to be achieved. A literature survey is presented in Chapter 2 where it introduces previous research work on micro-grids and its various energy management techniques. It discusses also the current state of research and application. Moreover, it focuses on the integration of DG sources with the micro-grids. Finally, it illustrates the Ant Colony Optimization (ACO) techniques focusing on their merits. In Chapter 3, a detailed background on active distribution networks and micro-grids is presented. The micro-grids components alongside with its operation and control schemes while referring to many current micro-grid projects in the world are illustrated. Chapter 4 starts with discussing energy management systems and their benefits, and then it moves on to present the economical dispatch problem. Moreover, the classical ACO technique is explained thoroughly. Finally, the proposed energy management system based on the ant colony technique is illustrated; the optimization problem is formulated as well as the economical dispatch problem. A flowchart of the proposed algorithm is illustrated. Chapter 5 discusses all the case studies used to verify and present the merits of the proposed energy management system. First, verification of the proposed algorithm was carried out through using a micro-grid integrated with conventional fossil fuel based sources. The obtained results have been compared with other techniques to verify the proposed algorithm. The second case study was intended to promote for the integration of renewable based sources in micro-grids. All case studies addresses the combined economic and emission dispatch problem. Finally, results have been discussed and evaluated. Finally, Chapter 6 summarizes and concludes the thesis main points. This chapter outlines the contributions of the presented research and suggests future work.

Chapter Two

2 LITERATURE SURVEY

This chapter presents the literature review that discussed Micro-grids, Distributed generation and Ant Colony Technique. The scope of this chapter is to highlight all aspects concerning Micro-grids and its applications, Distributed generation with its various technologies and applications and Ant Colony studies in the field of micro-grids based on DG.

2.1 Micro Grids

Micro-grids are modern small scale versions of the centralized electricity system. They are designed to supply electricity for small communities such as villages and suburbs, or commercial areas. Micro-grids are active distribution network possessing a bidirectional power flow. They are designed to achieve specific goals such as reliability, carbon emission reduction and cost reduction. Micro-grids operate in coordination with the utility to improve customer service during the utility's disturbances; they isolate themselves with minimum or no load disturbance. Micro-grids have emerged in the electric industry increasingly attracting consumers using a convenient switching functionality during both grid connected or isolated modes [3].

Figure 2-1 illustrates a typical micro-grid model, where it's connected to the grid at only one point called Point of common coupling (PCC). Micro-grids facilitate renewable energy sources integration such as photovoltaic, wind and fuel cell generations and increase the penetration of DG providing high quality and reliable energy source [4]

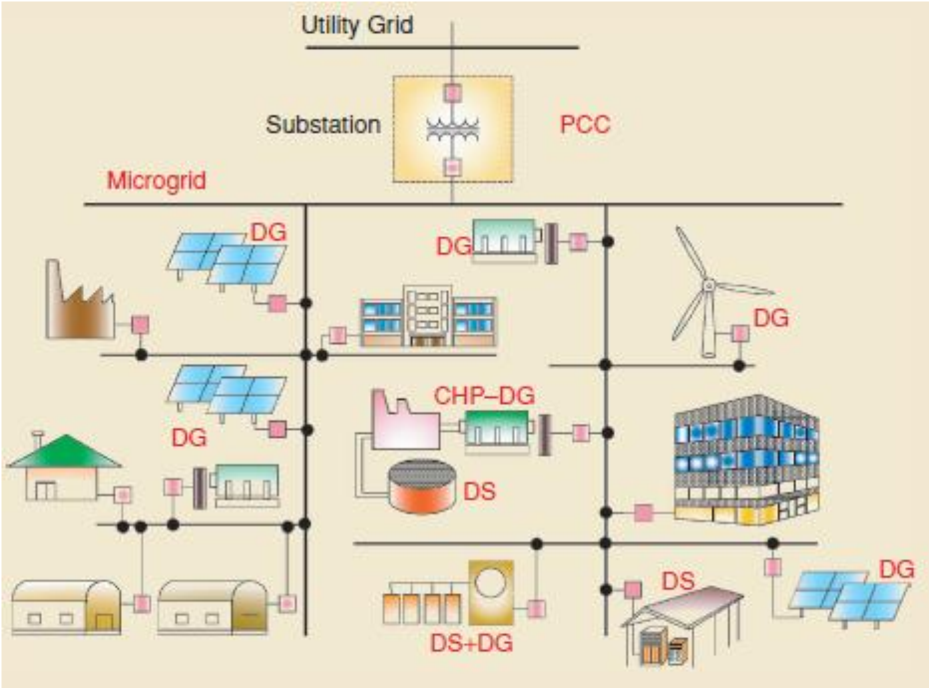

Figure 2-1 Micro-grid example

Several researches are currently in progress aiming at developing and standardizing of islanding and interconnected operating strategies, grounding and protecting schemes for the Micro-grids. The new Energy and Industrial Technology Development Organization and the ministry of economy, Trade and Industry in Japan have carried out field tests in integrating new energy sources into local distribution networks, and were able to develop an optimum operation and control system for a Micro-grid insuring technical feasibility, but economical and environmental benefits were yet to be further studied. In Canada, researches and developments were held in cooperation with the electric utility industry, focusing on development of control and protection strategies for Micro-grid operation and islanding, and studying the impact of high penetration of DG in existing protection strategies [5].

In [6], opportunities and challenges facing the integration of micro-grid with existing utilities were discussed trying to conclude efficient steps and methods to minimize the challenges that might arise to this type of integration with DG systems. These challenges require cutting edge technology strategies in power electronic interfaces, utility communications, and supervisory control systems, as well as non-technical challenges such as unit prices of DG and reserve requirements. In [7], a CERTS (Consortium for Electric Reliability Technology Solutions) micro-grid concept was studied. Two main principles were studied; a system perspective for customers, utilities and society is essential to be able to capture full benefits of integrating DER into a system. Secondly, enhancing the value of micro-grid and lowering the cost would accelerate the adoption of these concepts from a business point of view. The main reason behind the author's work was to accelerate the realization of the benefits offered by the integration of DG such as increasing the power quality of most of the loads in the system.

Focusing on the development of a novel energy management system (EMS) based on the application of Neural Networks (NN), authors in [8] studied the effect of using the energy management system (EMS) to the micro-grid. The energy management system is able to autonomously make decisions and determine accurately the appropriate dispatch of generators in case of DG integration in the network. The purpose of the work was to minimize the total cost of energy, where significant savings in energy cost were achieved. In [9], an enhanced power management system for smart micro-grid was proposed using power inverters at PCC. The proposed strategy utilized the change in local grid frequency to control the active power generation and consumption in the micro-grid, which successfully resulted in enhancing the micro-grid power management system during grid connected operation. On the other hand in [10], active power and frequency response in the micro-grid was investigated with respect to different configurations of a DG based micro-grid and different control modes; unit power control and feeder flow control. A comparison between four different configurations was presented to elaborate the advantages and disadvantages of each configuration. In the field of protection, comprehensive analyses showed the impact of fault currents on network protection while in grid connected mode [11].

2.2 Distributed Generation

Distributed generation (DG) is a term that refers to small scale technologies for energy production that is integrated within the distribution systems close to the end user customers. They are connected to medium or low voltage depending on the application. There are various types of DG technologies, such as micro-turbines, fuel cells, solar and wind power generators, Figure 2-2. DG has a very noticeable potential in improving power quality, increasing reliability of energy supply. RES based DGs have a great environmental benefit in reducing harmful greenhouse gases [12].

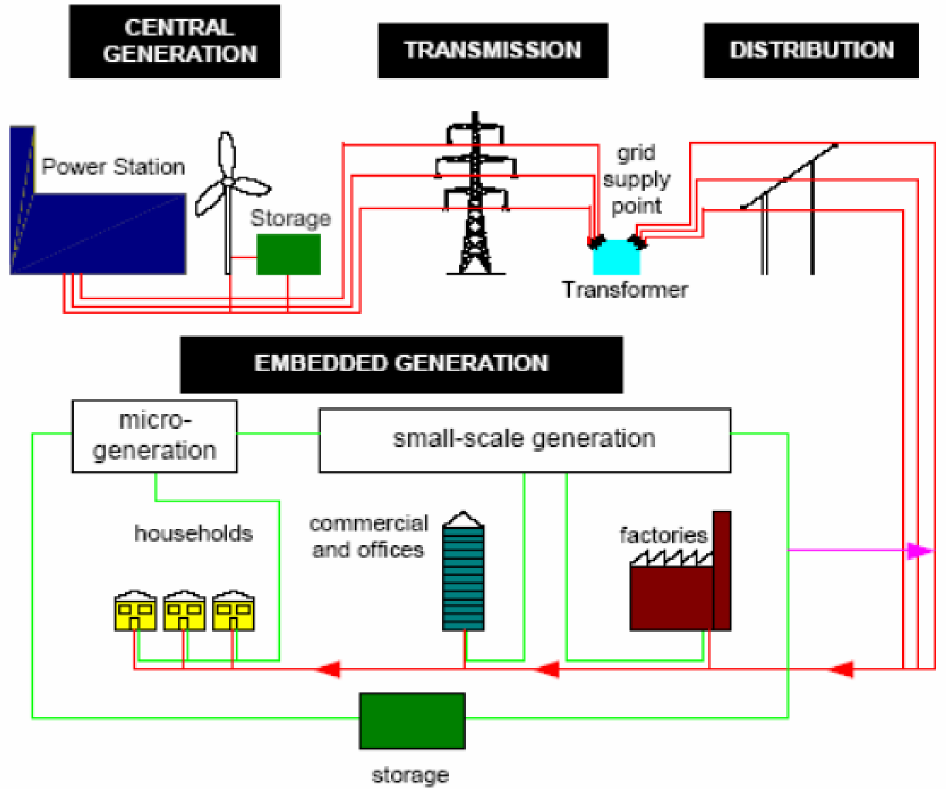

Figure 2-2 Electric Distribution System Diagram [12]

In [13-16], various DG implementation issues were identified such as; the identification of a proper DG location and sizing. In [13], a hybrid technique was proposed including Genetic Algorithm and NN identifying the possible DG locations. This technique was implemented using Matlab and was compared to the conventional Newton-Raphson method. Moreover, in [14], a methodology was proposed by the authors to find the optimal size and location for installing a DG unit. This methodology was tested with 69-node radial system distribution system with single and multiple DG units. In [15], a procedure was proposed based on Genetic Algorithm, capable of allocating the optimal DG location on a MV distribution network. Similar studies were carried out in [16] presenting analytical methods to determine the optimal location to place a DG in a radial system for the purpose of minimizing the power losses.

In [17], real and reactive power management strategies were studied in a multiple DG micro-grid system of electronically interfaced DG units. The author introduced three power management systems for an autonomous micro-grid. A dynamic model for a multiple DG micro-grid system was developed. The results indicated that the adopted power management system and electronically controlling the DG units showed a significant improvement on the micro-grid dynamic behaviour in the case of islanding operating. On the other hand, [18] addressed two main challenges associated with the operation of micro-grid integrated DG; which are control and protection. A control strategy was presented for inverter based DG units to control voltage and frequency during islanded operation. Secondly, a protection scheme was proposed to protect both the lines and DG units during islanded operation. Finally, both the control and protection schemes are coordinated to avoid undesired tripping of DG units while trying as well to avoid tripping of non critical loads to achieve full system supply. This scheme used a digital computer simulation approach in PSCAD/EMTDC.

2.3 Ant Colony Optimization Technique (ACO)

Ant colony optimization (ACO) is a type of swarm intelligence technique that took inspiration from the social behaviour of insects and other animals. In real life, ants are capable of finding the shortest path to a food source from their nest using their pheromones. Pheromones are chemical substances deposited from ant's bodies on the ground leaving a trail to a favourable path to the food source for each ant. These favourable paths are used by other members of the ant colony depending on the intensity of these pheromones in succeeding visits to the food source. ACO technique uses this phenomenon and applies it to solve real life optimization problems [19]. Many techniques were used to solve this specific problem such as linear programming, quadratic programming, non linear programming, genetic algorithms and ant colony techniques. In [20], the economic dispatch problem was studied and a solution using the ACO technique was proposed. The proposed technique was tested on a standard IEEE 26-Bus RTS which showed that the ACO is highly efficient and versatile. [21-22], the economic load dispatch and generation scheduling problem was studied using the ACO approach, both were tested on an IEEE 14-Bus and 30-Bus systems. Optimum results within reasonable times with high flexibility, accuracy and robustness were obtained. In [23-27], the economic dispatch problems was studied and different types of ACO techniques were proposed with different case studies which all resulted in high cost savings with high effectiveness and flexibility. In [28], the combined economic and emission problems was addressed with transmission losses. They compared between three methods, Genetic Algorithm, Ant Colony algorithm and the Lambda techniques and it was found that the Ant Colony algorithm was more efficient than all other methods in minimizing the cost and the thermal emissions. In [29], two computational intelligence methods were compared which are the Ant Colony algorithm and Particle Swarm Optimization and the advantages of both methods were discussed.

This thesis addresses the problem of economic dispatch optimization. Determining the optimal power output for generating units in any given power system while maintaining minimum operating cost possible while satisfying the load demand, is a need in modern power systems and specially in Micro-grids.

Chapter Three

3 MICRO-GRIDS OPERATION AND CONTROL

Micro-grids have emerged in the electricity industry attracting customers and investors. They offer many benefits and on the other hand many challenges. Micro-grids increase overall reliability of electrical systems, emissions reduction, and cost improvement. They have various amount of applications capability.

3.1 Active Distribution Networks and DGs

Current electricity networks are considered as passive distribution networks since it has a unidirectional power flow from the source to the demand load. In the last decade, active distribution networks have been emerging in the market of electricity networks integrating the basic concept of the passive distribution networks with what is known as Distributed energy resources (DERs) [3]. DERs might change the unidirectional energy flow into a bidirectional energy flow. They turn the distribution networks into active networks. Active distribution networks provide more flexibility in addition to increasing reliability to customers and in most cases generating revenue for the DERs owners. DERs are on site local distribution sources integrated within distribution systems connected directly to households, factories and to lower voltage distribution networks intended to supply their loads. DERs consist of DGs and Distributed storage sources DSs [12].

Active distribution networks incorporating DERs interest was triggered by the technological development and innovations in DG technologies. Another reason for the active distribution networks penetration in the electricity market was due to the substantial increase in customer requests of more reliable source of electricity and in addition to the high capital cost of electrical substations with difficulty in transmission lines construction in remote areas. Moreover, the market liberalization offered high flexibility for customers to choose the suitable source of electricity that satisfies their loads with the optimum cost for them. DERs offer a revenue stream to their owners. In the modern electricity market nowadays; selling energy back to the main grid became possible as much as desirable for main grids as the continuous demand on electricity has increased and typical large substations or power plants are not becoming the only solution anymore [30].

3.2 Micro-Grids

Micro-grids have emerged attracting a lot of customers while offering the alternative solution to most of disadvantages and problems facing conventional substations and electrical distribution networks nowadays. Micro-grids can be defined as small scale active distribution networks incorporating distributed energy resources. They are designed to supply electricity and heat for factories, small communities, or remote areas where the normal electric supply of the main grid is difficult to provide. DERs installed within the micro-grids or sometimes called micro-sources are mostly renewable energy based, and they are installed close to the customers to supply electricity and heat efficiently. The connected loads on the micro-grid may be critical or non-critical or in most cases both. Depending on the mode of operation and the priority and importance of the loads; load shedding mode is adjusted to accommodate the needs of the micro-grid operation policies. From the main grid point of view, a micro-grid can be seen as a single aggregated load. A typical micro-grid configuration can be shown in Figure 3-1

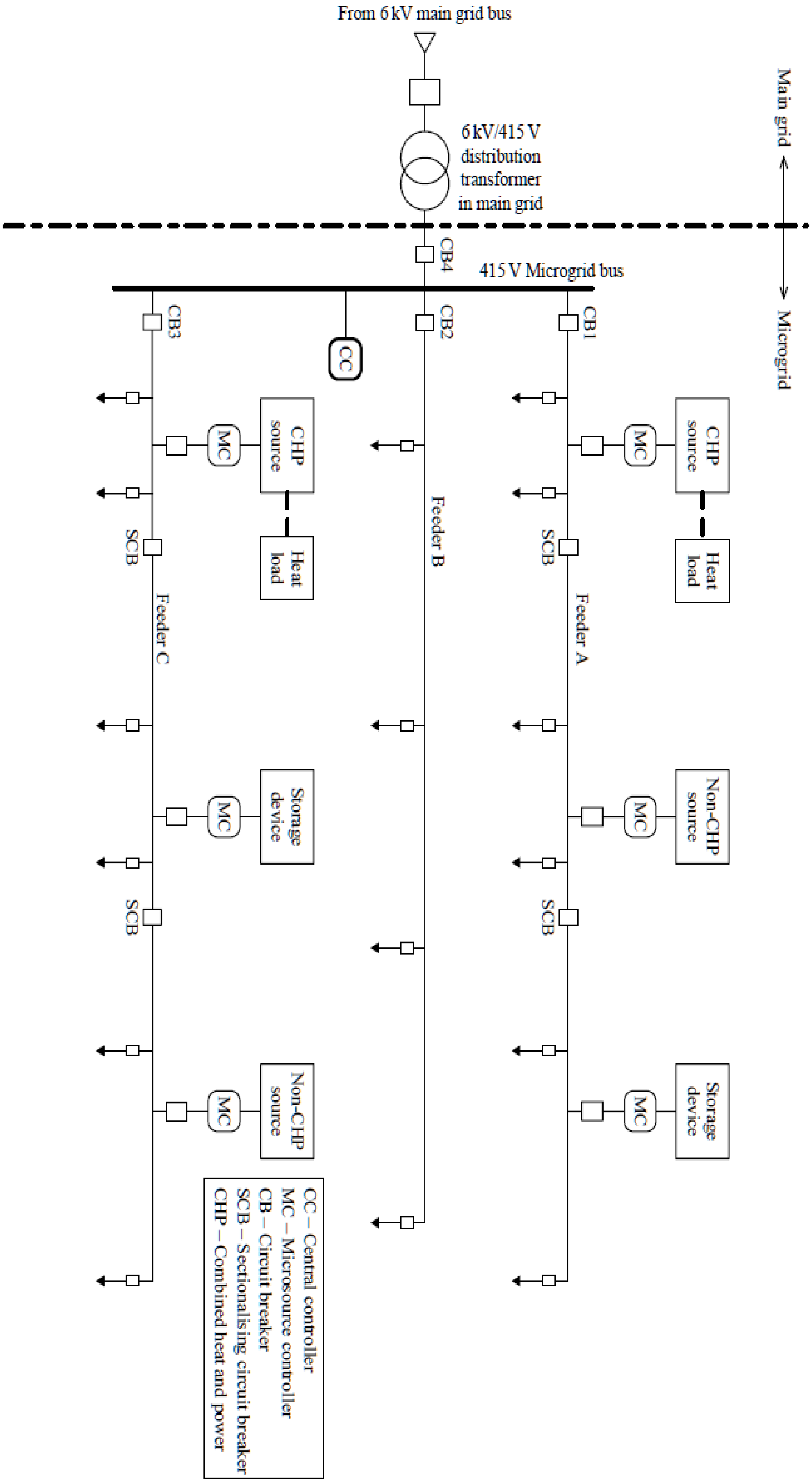

Figure 3-1 A typical Micro-grid structure [3]

The Consortium for Electric Reliability Technology Solutions (CERTS) has carried out many micro-grid test projects and proposed a micro-grid architecture that is shown in also in Figure 3-2

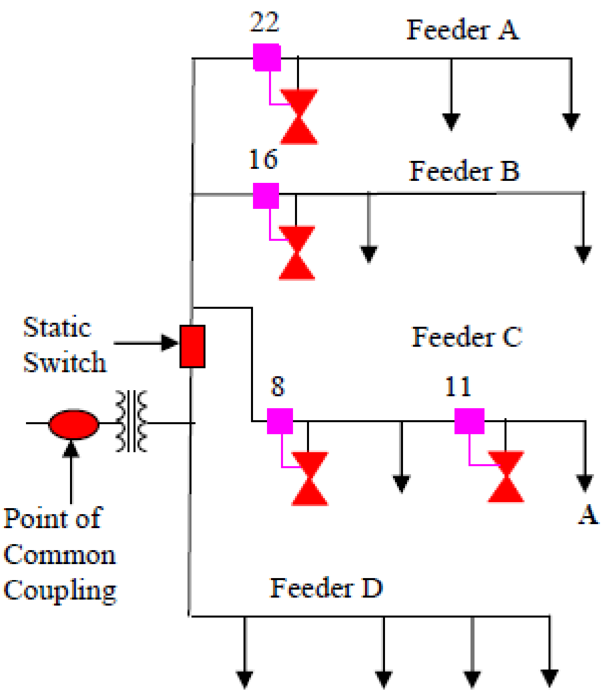

Figure 3-2 CERTS Micro-Grid Structure [31]

At point of common coupling between the micro-grid and the main grid, micro-grids have the ability to autonomously island themselves from the main grid at the times of disturbances and outages. They can supply their loads with minimum or no load disturbance. Feeders A, B, and C are considered as critical load feeders, so micro-sources were installed next to their loads, Feeder D is considered as a non critical load feeder therefore no micro-sources were installed on this feeder. At any undesired or unplanned occurrence such as power outage or low voltage levels, by using the static switch; Feeders A, B and C can be easily islanded from the main grid and depend totally on the micro-sources installed next to their loads. On the other hand, feeder D is cut out during islanding. When the main grid is up for service again, the static switch closes and power flows through all feeders supplying all loads [31].

In order to ensure smooth operation during islanding and non-islanding, micro-grids must have certain features which can be explained as follows:

- The static switch must be installed and be able to autonomously island the micro-grid from any disturbance.

- Micro-sources must be able to supply the loads in the micro-grid or at least part of the load taking into consideration critical and non critical loads while ensuring steady voltage and frequency levels.

- When connection to the main grid is needed after islanding, static switch must ensure that the islanded loads and the main grid are synchronized before closing again to ensure smooth transient operation.

- Plug and play control must be implemented as well; it facilitate the installing of any unit at any point in the electrical system without the need of re-engineering the system controls.

3.2.1 Micro-Grids Operation and Control

Micro-grids have two operation modes which are the grid connected mode and the island mode. In the grid connected mode, micro-grid remains connected to the grid whether it's totally or partially supplying certain loads. In the Island mode, micro-grid islands itself from the main grid supplying its priority loads and in other cases supplying all of its loads. The micro-grid control system must ensure the supply of electrical energy and heat energy as well to the required loads, participation in the energy market. Figure 3-3 shows the control architecture of a micro-grid [32-33].

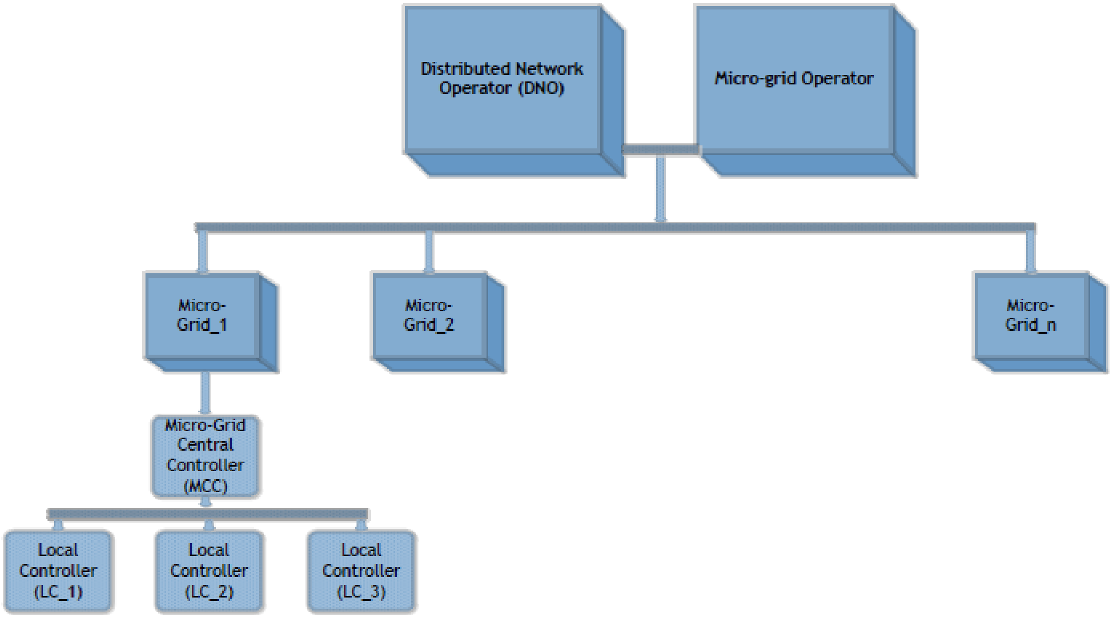

Figure 3-3 Micro-Grid Control Architecture

Control Levels can be explained as follows:

Distribution Network Operator (DNO):

Distribution network operator is responsible for an area where more than one micro-grid exists.

Micro-grid Control central controller (MCC):

It's considered as the main controller for each micro-grid and acts as the interface between the DNO and the micro-grid. Also, it is responsible for maximizing the micro-grid value while optimizing its operation.

Local Controller (LC):

Local control units associated with every distributed generation resource unit and every controllable load.

In order to ensure that the operation and management of the micro-grid is carried out in a smooth and stable manner, control units must be installed at the micro-source level and on a central level. These control level are explained as follows:

Micro-Source Control

The function of the micro-source control is to independently control the power flow and voltage level for the micro-sources. It participates in the process of economic generation scheduling, energy management and demand side management. A micro-source controller does not depend on other micro-sources in taking decisions to enable fast and efficient responses. There are different types of Control configuration for the micro-sources that must be known [30]:

1. Unit Power Control Configurations:

    - Each micro-source regulates the voltage magnitude at its connection point and the power that is being injected to the point from the source.

    - Every micro-source regulate to constant power output meaning that when load increase, extra energy is taken from the main source.

2. Feeder Flow control Configuration:

    - Each micro-source regulates the voltage magnitude at its connection point and the power flowing in the feeder.

    - Micro-grid is seen as a constant load from the main grid side, when load increase micro-sources supply this extra load and main grid maintain constant power supply.

3. Mixed Control Configuration:

    - Some micro-sources use the feeder flow control while others use the unit power control.

    - Micro-sources can have both control configurations and use the optimum configuration depending on its needs [31].

Central Control

Central Controller manages the overall control of the micro-grid operation and protection through the micro-source controllers. It provides the power dispatch and voltage set points for all micro-source controllers. Central Controller has two functional modules that can be explained as follows.

1. Energy Management Module:

    - Provides set points for active and reactive power output, voltage and frequency levels for micro-sources.
    - It must maintain continuous supply of electricity and heat to customers.
    - Ensure operation in optimum modes with minimum cost and minimum emissions.
    - Ensure operation at highest efficiency with minimum losses.

2. Protection Co-ordination Module:

    - Quick response to main grid faults or micro-grid faults.
    - Adapts to micro-grid change from the grid connected mode to the island mode or vice versa and choose the correct operation mode according to the current fault.
    - Helps in synchronizing the micro-grid to the main grid when it is desired to switch from the island mode to the grid connected mode [30].

Micro-grids posses certain characteristics that make its energy management, control and operational strategies significantly different from any other conventional systems. These characteristics can be explained as follows [32]:

1. Micro-grids incorporate distributed energy resources (DERs) which are mostly renewable energy sources with different capacities and characteristics, and depending on the type and level of penetration of these DERs; steady state and dynamics of these DERs change and therefore changing the management and control strategy of the system.

2. The unpredictability of the renewable energy sources such as the wind speed and the solar radiation must be taken into consideration in management strategies.

3. Micro-grids must maintain operation while having the facility of either connecting or disconnecting DERs units and loads.

4. In the autonomous mode, the micro-grid has no dominant source of energy or infinite bus like in conventional distribution systems.

5. In most cases micro-grids supply heat beside energy to all or parts of the loads.

3.2.2 Micro-Grid Control Schemes

There are two control schemes for a micro-grid that have been proposed to date. These can be defined as follows:

<u>Centralized Micro-grid Control</u>

The Centralized control scheme is best suited for micro-grids where owners of micro-sources and loads share the same goals and seek cooperation to meet them [32]. Figure 3-4 shows the flow of information in this scheme [32,34].

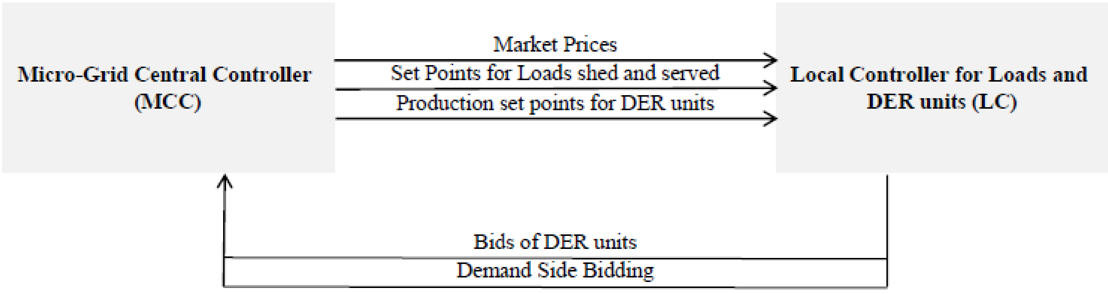

Figure 3-4 Information Flow in the Centralized Control scheme

The following are the characteristics of this scheme:

1. Micro-grid central controller (MCC) is provided with all relevant data regarding each DER unit in the micro-grid like cost functions, technical characteristics and mode of operation. Moreover it's provided with all the outputs of the forecasting systems regarding wind speed, solar radiations and expected load profiles.

2. MCC optimize the micro-grid power operation by issuing control set points for the DER units and set points for controllable loads assigning loads that should be shed and loads that should be served.

3. Based on market prices and the DER unit capacities, local controllers (LC) of the DER units issue bids to MCC regarding their production level and LCs of the controllable loads issue bids for their demands with respect to their priorities.

Decentralized Micro-grid Control

Decentralized control scheme is best suited for micro-grid where micro-sources have different owners where DER units and loads are provided with the maximum autonomy possible [32,34].

The following are the characteristics of this scheme:

1. Autonomy of the local controllers indicates that every LC has certain intelligent skills with the ability to communicate with each other and the choice of taking independent decisions.

2. A market environment is developed using multi-agent systems (MAS), which can be developed using many artificial based methods such as neural networks and fuzzy systems.

3. Multi-agent system is a more developed form of conventional distributed control systems. It facilitates the control of large and complex systems. Each agent is assigned to a different component of the micro-grid system developing local intelligence in determining future actions. Moreover, each agent sends a buying or a selling bid to the micro-grid controller where it performs its process to determine the optimum operation for the micro-grid in each period. A schematic diagram of the decentralized control structure can be shown in Figure 3-5.

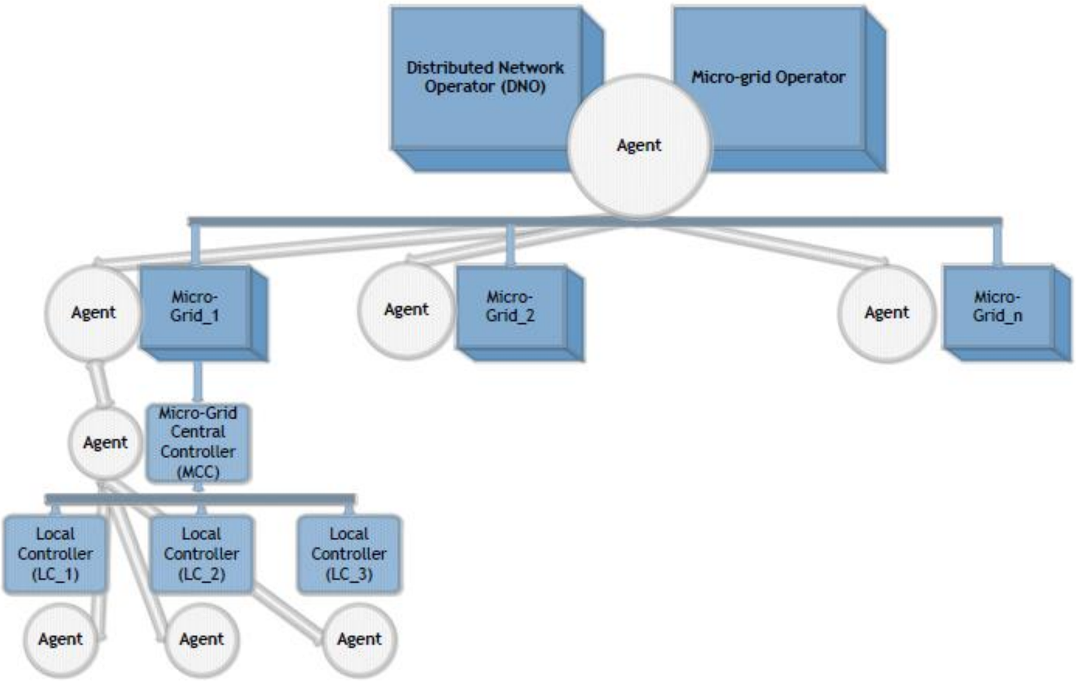

Figure 3-5 Micro-grid decentralized Control structure MAS

3.3 Existing Micro-Grid Projects

3.3.1 National Technical University of Athens (EU) Micro-Grid

The National Technical University of Athens has presented a laboratory scale micro-grid project installed at the university premises. The micro-grid contains two PV generators, wind turbine generator, battery energy storage, controllable loads and a controlled interconnection to the local LV grid; Figure 3-6 [35].

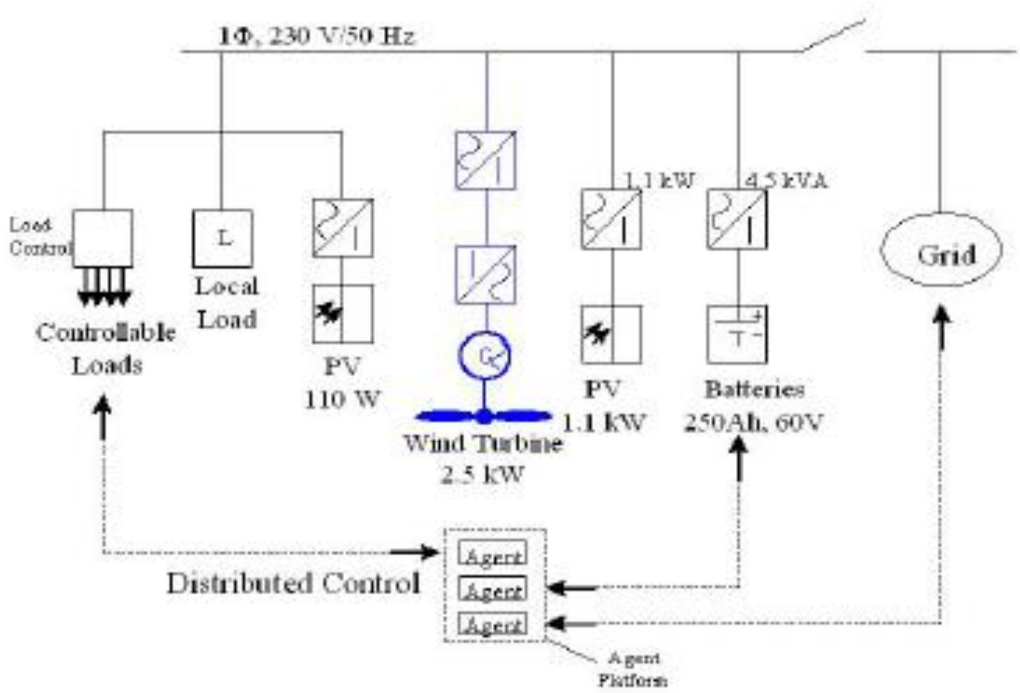

Figure 3-6 National Technical university of Athens Micro-grid [35]

The PV generator, wind generator and battery storage unit are connected to the AC grid via fast-acting DC/AC power converters. The converters facilitate the micro-grid operation in both grid connected mode or island mode. This project was completed successfully achieving standard technical and commercial protocols and hardware to allow easy installations of distributed energy resources with plug and play capabilities.

3.3.2 Micro-Grid at Boston, British Colombia, Canada

In collaboration with the electric utility industry and the Micro-grid R&D activities and other manufactures and stakeholders; Hydro Boston Bar substation was developed. The micro-grid can go into the island mode of operation islanding a 3 MW peak load and 8.6 MVA hydroelectric generation. The micro-grid effectively employs a single large generation station to control the net sub-system behaviour, and it can be shown in Figure 3-7 [36,37]

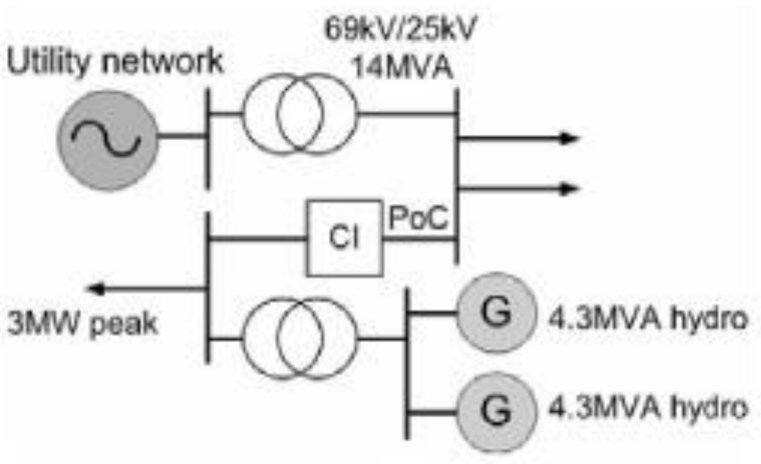

Figure 3-7 Boston-Canada Micro-grid

3.3.3 Hachinohe Micro-Grid Project in Japan

In collaboration between Mitsubishi Research Institute and Mitsubishi Electric with Hachinohe City, a micro-grid based in Hachinohe was developed. It has 130 KW PV, 20 KW WTs, battery storages, and three large gas engines 510 KW fed by sewage and waste gas by product, Figure 3-8 [36,37].

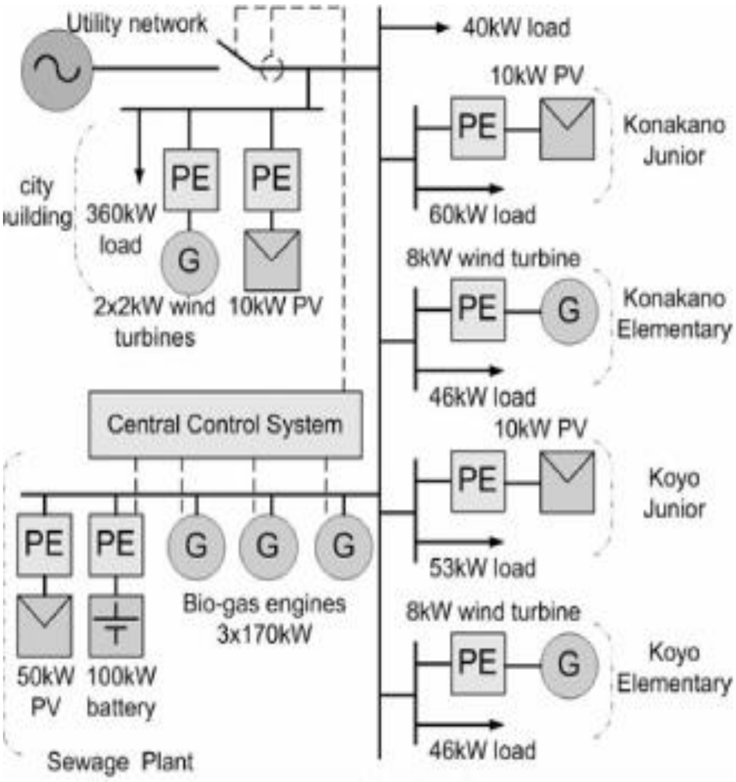

Figure 3-8 Hachinohe-Japan Micro-grid [36,37]

3.4 Micro-Grids Challenges and Benefits

Micro-grids offer valuable benefits on many levels, while still have challenges to encounter and to achieve; they are still a winning candidate over many conventional electrical energy solutions. Before enlisting the many benefits of the Micro-grids, the challenges facing the micro-grid can be explained as follows [3]:

1. Relatively high cost of distributed energy resources specially the renewable bases energy sources.

2. Regulation of micro-grid operation and legislations are yet to be addressed and a suitable market infrastructure should be designed and be legally regulated

3. Technical difficulties are yet to be studied and researched in. Such technical difficulties are ensuring safety operation between islanding mode and grid connected mode, equipment protection, power quality, and energy and demand side management.

On the other hand, micro-grid benefits are:

1. Micro-grids have less environmental impact than conventional stations while reducing emissions.

2. Significant enhancement in voltage and reactive power level due to the reduction in distance between loads and sources.

3. Transmission and distribution congestion decreases.

4. Electricity can reach remote areas where normal power sources could not reach.

5. Micro-grid allows customers to share electricity from the same source in the same area. This increases the awareness towards efficient energy use and reduces the need to import electricity from the grid.

In conclusion, micro-grids represent the best alternative approach to distribution level energy supply. The increase in electricity production and consumption alongside with the many economical and geographical challenges accompanied with the conventional substations and electrical distribution networks. These reasons have given the micro-grids the opportunity to present itself as a future solution to all of those problems. The integration of DERs based on renewable sources was an important benefit that encouraged investors to look no further for an alternative economical and environmental friendly alternative. Micro-grids are the commencement to transforming the current conventional grids into smart grids starting from the point of generation until the customer’s meters.

Chapter Four

4 MICRO-GRIDS ENERGY MANAGEMENT AND ANT COLONY OPTIMIZATION

Micro-grids benefits are accompanied with many challenges that need to be addressed with extensive research. Energy management and economical dispatch are one of those challenges that need to be addressed. Modern techniques were used to address the economical dispatch problem and one of those techniques is the Ant Colony Optimization technique. This chapter discusses the importance of energy management and economical dispatch in electrical distribution networks. Moreover, it explains the classical Ant Colony technique along with the proposed energy management system based on this technique explained comprehensively.

4.1 Energy Management

The increase in energy production and consumption in addition to the increase in renewable share in energy production mentioned earlier in chapter 3 requires robust techniques in energy management. These techniques must aim to reduce the total cost while offering high levels of flexibility in adapting with electrical systems fluctuation.

Many studies have proven that energy management is very cost effective offering 5-15 % savings with minimum and in some cases zero capital expenses. Savings ranging between 30% -70% have been obtained compared to corresponding systems. Smart buildings designed to energy efficient can operate on 20% of the energy saving 80% normally required by same existing buildings. Energy Management has yet proven that its one of the most promising cost reduction and profit improvement systems nowadays [38]. Energy Management can be defined as an effective and efficient system of using or consuming energy while reducing cost to its optimal value and greenhouse gas emissions. Energy Management is responsible for assigning active and reactive power set points to the DER units to optimize their operation [38].

The dynamic nature of micro-grids has been a challenge to energy management systems. In [39], a renewable based micro-grid is modelled using PSCAD software and micro-grid operational management is addressed. On the other hand, novel energy management systems were developed in [40-42] to manage the operations of renewable based micro-grids to obtain minimum operational cost. Multi-agent systems were used as well to develop energy management systems for smart micro-grids in [43,44]. In [8], an intelligent energy management system was developed using NN to minimize overall energy cost.

4.2 Economic Dispatch

The process of best utilizing the available energy resources in any electrical distribution system taking into considerations all constraints in supplying the energy to the load without any interruption at minimum cost and greenhouse emissions is called economical dispatch. This process is the most essential procedure in daily optimization systems. Short term scheduling for generating units with the ability to adapt to any system changes or constraints can eventually save a large amount of cost. In order to make micro-grids a more feasible and viable alternative to conventional power systems, new optimization techniques are required to manage the operations of micro-grids. These techniques must accommodate the dynamic behaviour and the multi-constraints environment of the micro-grids.

Several classical techniques were previously used to address the economic dispatch problem such as homogeneous Linear Programming Algorithm [45]. Nowadays, Modern computational intelligence techniques are emerging to substitute the classical techniques such as Particle-Swarm-Based-Simulated Annealing [46]. In [23-27], the economic dispatch problem was solved using the Ant Colony technique and results showed better cost savings and high effectiveness. In [28], the combined economic and emission dispatch problem was addressed using three methods; Genetic Algorithm, Classical Ant Colony, and Lambda technique. All results were compared and it showed that the Classical Ant Colony algorithm presented the best solution in minimizing the cost and the thermal emissions. In [47], the combined economic and emission dispatch problem was examined using evolutionary computation methods such as the genetic algorithm and evolutionary programming while in [29] the same problem by using

Lagrange technique was addressed. In [48], a power management system for a renewable based micro-grid was developed addressing the economic dispatch problem, two methods were used and their results were compared; Ant Colony and Particle Swarm Optimization. Results were discussed highlighting the merits of the ACO. In [49,50], the combined economic emission dispatch problem was evaluated for a renewable based micro-grid with conventional sources. In [51], the mesh adaptive direct search was used to minimize the total cost of operation of a micro-grid.

4.3 Ant Colony Technique

Ant Colony algorithm is considered as a swarm intelligent system for it’s a self organized decentralized natural system consisting of individuals that coordinate with each other. Swarm intelligent systems have offered new ways of studying and solving computational problems [52].

4.3.1 Ant Colony Basic Principle

In real life, ant colonies are highly structured individuals that are capable of finding the shortest path to a food source from their nest using their pheromones. Pheromones are chemical substances deposited from ants’ bodies on the ground leaving a trail to a favourable path to the food source. These favourable paths are used by other members of the ant colony in succeeding visits. Paths are chosen depending on the intensity of this pheromone. When the intensity of the pheromone increases, this means that this path was considered by the preceding ant as a short or favourable one to the food source. Eventually, one favourable path is selected by all ants which represent the optimal route to reach the food source.

Figure 4-1 shows a typical ant colony travelling from their nest to their food source. In the beginning, ants wonder in the two routes without any constraints and based on the time and distance taken by each ant to reach the food source; it places pheromones onto the ground as a guide for the successive group of ants indicating the level of satisfaction of this route. Until eventually, the shortest path will contain the highest intensity of pheromones indicating that it’s the favourable path for the food source.

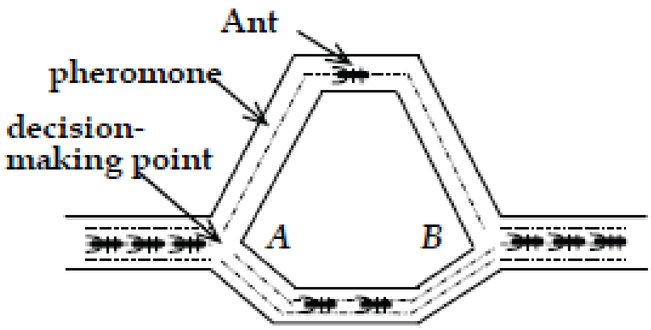

Figure 4-1 Ant Colony Food Search

4.3.2 Classical Ant Colony Optimization Algorithm

ACO is inspired by the ant colony behaviour; it uses this phenomenon and applies it to solve real life optimization problems. For better clarification of the ACO technique, a famous problem called the travelling salesman was used to for the ACO application illustration.

<u>Travelling Salesman problem</u>

The travelling salesman problem is one of the most studied problems in the field of mathematical optimization. It's widely used as a benchmark for many optimization methods. A travelling salesman is located at his hometown; he was asked to take a business trip passing by a number of towns. In this trip, he is only allowed to visit each town only once and he must return to his hometown at the end of this trip. The salesman is faced with a problem of finding the best route for his business trip starting from his hometown passing by all the towns and going back home again. Given that the route he takes must be the shortest one.

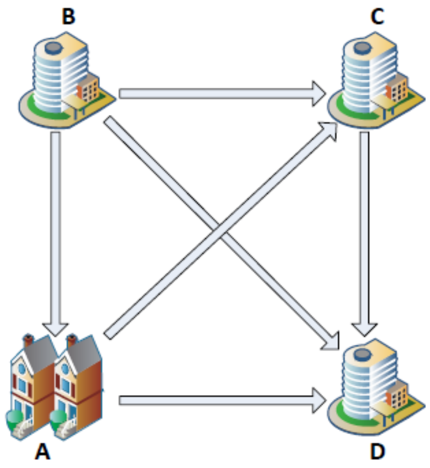

Figure 4-2 Travelling salesman problem representation

Figure 4-2 shows a typical travelling salesman problem construction graph. In order to solve such problem, the basic principle of the ant colony is used here. Where the starting point for the ants would be point A acting as the ant's home. Ants will move around exploring all possibilities in order to obtain the shortest tour to be taken by the salesman. The decision of movement from point A to any other point whether its B, C, or D and the amount of pheromones placed by each ant is based upon a set of rules that can be explained as following [24]:

1. State Transmission Rule

   State transmission rule is used by the ant colony which represents the probability of ant k to go from town i to town j where j belongs to the allowed towns that can be visited.

$$P_{ij}^{k}(t) = \frac{[\tau_{ij}(t)]^{\alpha} \quad [\mu_{ij}(t)]^{\beta}}{\sum_{k \in allowed_k}[\tau_{ik}(t)]^{\alpha} \quad [\mu_{ik}(t)]^{\beta}} \qquad j \in allowed_k \tag{4.1}$$

Where;

τ_{ij} is the pheromone amount between town i and town j

μ_{ij} is the heuristic desirability of going from town i to town j which is inversely proportional to the distance between them

α is the relative influence of the pheromone trail

β is the relative visibility of the allowed towns

2. Pheromone updating Rule

   After completing a visit for one town to another town, ants leave their pheromones on the edge of the arc they have taken, the pheromone updated on every arc is calculated by

$$\tau_{ij}(t+1) = \Delta\tau_{ij} + (1-\rho)\,\tau_{ij}(t) \tag{4.2}$$

$$\Delta\tau_{ij} = [\frac{L_{best}}{L_k}]^a \times Q \tag{4.3}$$

Where;

τ_{ij} is the pheromone amount between town i and town j

ρ is the evaporation rate of pheromone

L_{best} / L_k is considered penalty factor

L_{best} is the shortest distance obtained so far in the iteration

L_k is the tour distance for ant k

Q is a pheromone constant

a is the relative importance of the penalty

3. Stagnation Rule

   There are a number of conditions that can be used to stop the ant's iterations such as assigning a limited number of iteration or CPU time limitations. The most effective method is the stagnation rule, where it stops the search activity once the pheromone levels reach saturation. Once the pheromone in any iteration reaches an unchanged value from the preceding value of the preceding iteration, the iterations stop. Stagnation rule can be illustrated as follows

$$\tau_{ij}(t+1) = \tau_{ij}(t) \tag{4.4}$$

4.4 Proposed Energy Management System

The proposed energy management system was designed using the ant colony optimization technique developed in a Matlab® environment to address the combined economic and emission dispatch problem. Some modifications and enhancements were made to the conventional ant colony optimization algorithm in order to increase its effectiveness, accuracy and robustness while offering high levels of flexibility.

4.4.1 The Optimization Function

The combined economic and emission dispatch problem is addressed as a single optimization problem with respect to fuel cost and emissions function as follows [48]:

$$Min\ (F_t) = \text{Fuel Cost Function} + \text{h} \times \text{Emission Function} \tag{4.5}$$

Fuel Cost Function

The generator fuel cost function is represented as a quadratic equation and can be expressed as follows [48]:

$$F_c = \sum_{i=1}^{N} a_i + b_i P_i + c_i P_i^2 \tag{4.6}$$

Where;

F_c is the total fuel cost,

N is the number of generators,

P_i is the real output generation of the i_{th} generator

a, b and c are the cost coefficients of the i_{th} generator.

Emission Function

The total emission of atmospheric pollutants caused by operation of fossil fuelled generators can be expressed as follows [48]:

$$E_T = \sum_{i=1}^{N} \alpha_i + \beta_i P_i + \gamma_i P_i^2 \tag{4.7}$$

Where;

E_T is the total Emission Output

α, β and γ are the emission coefficients of the i_{th} generator.

Combined Economic and Emission Function

Therefore, the combined economic emission dispatch problem is formulated as a single optimization problem by substituting in equation (4.1) as follows [48]

$$\mathrm{Min}\ (F_t) = \sum_{i=1}^{N} [(a_i + b_i P_i + c_i P_i^2) + h_i\ (\alpha_i + \beta_i P_i + \gamma_i P_i^2)] \tag{4.8}$$

Where; h_i is the price penalty factor which is the ratio between the maximum fuel cost and maximum emission for each generator [48].

$$h_i = \frac{F_c(P_i^{max})}{E_t(P_i^{max})} \tag{4.9}$$

The combined economic emission dispatch problem is constrained by power balance and inequality constraints of a micro-grid.

Power Balance Constraint

Total power generation must satisfy the load demand at any given time. The power balance equation is illustrated as follows

$$P_d = \sum_{i=1}^{N} P_i \tag{4.10}$$

Where;

P_d is the total load demand (Losses were Neglected)

Inequality Constraint

Total power generation for each unit lies between minimum and maximum limits. The inequality constraint can be described as follows:

$$P_i^{min} \leq P_i \leq P_i^{max} \quad (4.11)$$

4.4.2 ACO algorithm for Energy Management System

In order to clearly explain the proposed algorithm, a simple micro-grid is assumed to have 3 conventional diesel generators along side with PV generator and WT generator. The micro-grid has a certain load profile and it's required to optimize the operation of distributed generation units to minimize total cost and total emissions output. The algorithm can be explained as follows:

Parameters Definition

At the beginning, the load demand and the ratings and constants of DG units are defined. Energy produced from RES is favoured to be supplied first to the load before using conventional sources. This means that the optimization process will be carried out to supply the difference between the power demand and the RES output power as shown in the following

$$P_{conv} = P_{demand} - \sum P_{RE\ sources} \quad (4.12)$$

Where;

P_{conv} is the total power obtained from the conventional sources

P_{demand} is the total power demand

$P_{RE\ sources}$ is the total power obtained from the renewable energy sources

<u>Optimization Problem Construction</u>

In order to construct the optimization problem, some important variables must be calculated first. Using the maximum and minimum threshold values of the conventional sources, the available energy that can be obtained from the sources is calculated by subtracting the minimum value from the maximum value of each generator respectively. A matrix called available power is constructed as seen in equation (4.13)

$$\text{Available Power } = \begin{bmatrix} Gen\ 1_{max} - Gen\ 1_{min} \\ Gen\ 2_{max} - Gen\ 2_{min} \\ Gen\ 3_{max} - Gen\ 3_{min} \end{bmatrix} \tag{4.13}$$

Where;

Gen_{max} is the maximum power output that can be obtained from a given generator

Gen_{min} is the minimum power output that can be obtained from a given generator

First feature added to the proposed algorithm is the priority list, where the available energy of the generators is arranged in an ascending manner [24]. The generator with the largest available energy is exempted from the solution search tours done by the ants in order to decrease the search space therefore decreasing the search time. For simplicity, in the case study it's assumed that generator 1 has the largest available energy and generator 3 has the smallest available energy, this means that generator 1 will not be included in the search space. And the allowed generators in the search space to be visited by the ants would be generators 2 and 3.

$$\text{Priority List } = \begin{bmatrix} \text{Gen } 3_{\text{max}}\text{- Gen } 3_{\text{min}} \\ \text{Gen } 2_{\text{max}}\text{- Gen } 2_{\text{min}} \\ \text{Gen } 1_{\text{max}}\text{- Gen } 1_{\text{min}} \end{bmatrix} \tag{4.14}$$

$$\text{Gen Reduced } = [\text{Gen } 1_{\text{max}}\text{- Gen } 1_{\text{min}}] \tag{4.15}$$

In the travelling sales man problem, the salesman was located at his hometown in the beginning of the process, and he has a number of towns to visit. Ants act as the salesman exploring all possible routes that would lead to the shortest path available. In order to apply the same concept of the ants visiting the towns in the proposed energy management algorithm; the available energy for each generator is divided into a number of zones (zn) which is predetermined at the beginning of the process. These zones act like the towns visited by the ants in the travelling salesman problem, but in this case the ants will be visiting the generator zones instead of towns.

To construct the zones matrix for every generator, first for every generator, a zone step must be calculated and it can be shown as follows

$$\text{Generator Zone Step} = \frac{\text{Gen}_{\text{max}} \text{-} \ \text{Gen}_{\text{min}}}{\text{Number of zones}} \tag{4.16}$$

Where;

Generator zone step is the power difference between every zone in the generator's available energy

As previously assumed, the allowed generators in the optimization process are generators 2 and 3. After calculating the zone step for every generator, the available energy is divided into ranges before being further divided into zones. A matrix called Power matrix is constructed containing the range of the available energy that can be obtained from every generator. These ranges are constrained by the maximum and minimum thresholds of every generator. Power matrix can be calculated as follows

$$\text{Power} = \begin{bmatrix} Gen\ 3_{max} & Gen\ 2_{max} \\ Gen\ 3_{P1} & Gen\ 3_{P1} \\ Gen\ 3_{P2} & Gen\ 3_{P2} \\ \vdots & \vdots \\ Gen\ 3_{P_{zn-1}} & Gen\ 2_{P_{zn-1}} \\ Gen\ 3_{min} & Gen\ 2_{min} \end{bmatrix} \tag{4.17}$$

Where;

$Gen\ 3_{P1} = Gen\ 3_{max} - Gen\ 3_{Zone\ Step}$

$$Gen\ 3_{P2} = Gen\ 3_{max} - 2 \times Gen\ 3_{Zone\ Step}$$

$$Gen\ 3_{P_{zn-1}} = Gen\ 3_{max} - zn \times Gen\ 3_{Zone\ Step}$$

Now, the range of the available energy from the Power matrix is divided into zones using the number of zones (zn). Zones matrix is constructed as follows

$$\text{Zones} = \begin{bmatrix} Gen\ 3_{zone\ 1} & Gen\ 2_{zone\ 1} \\ Gen\ 3_{zone\ 2} & Gen\ 2_{zone\ 2} \\ \vdots & \vdots \\ Gen\ 3_{zn} & Gen\ 2_{zn} \end{bmatrix} \tag{4.18}$$

Where;

$$Gen\ 3_{zone\ 1} = Gen\ 3_{max} - \left(\frac{Gen\ 3_{max} - Gen\ 3_{P1}}{2}\right)$$

$$Gen\ 3_{zone\ 2} = Gen\ 3_{P1} - \left(\frac{Gen\ 3_{P1} - Gen\ 3_{P2}}{2}\right)$$

$$Gen\ 3_{zn} = Gen\ 3_{P_{zn-1}} - \left(\frac{Gen\ 3_{P_{zn-1}} - Gen\ 3_{min}}{2}\right)$$

The proposed algorithm is intended to address the combined economic and emission dispatch problem mentioned in equation (4.8), to optimize the total operational cost and the emissions output. Substituting the zones power values from the Zones matrix in the economic and emission dispatch problem formula will calculate the cost matrix which will represent the cost of operation of every zone that might me selected by the ant in its tour search for the optimum dispatch to satisfy the load.

$$\text{Cost} = \begin{bmatrix} \text{Gen } 3_{\text{cost } 1} & \text{Gen } 2_{\text{cost } 1} \\ \text{Gen } 3_{\text{cost } 2} & \text{Gen } 3_{\text{cost } 2} \\ \vdots & \vdots \\ \text{Gen } 3_{\text{cost zn}} & \text{Gen } 3_{\text{cost zn}} \end{bmatrix} \tag{4.19}$$

Where;

Gen_{cost} is the total operational cost of producing the amount of power in this zone for any given generator

Solution Construction

After the problem has been constructed, the process of optimization and solution exploration starts. According to the number of ants used in the process, the accuracy of the optimum solution is defined. Larger number of ants means that the probability of exploring new solutions increase but it increases the search time as well. Ants start their exploration tours from their hometown which would be the zones of generator 3. Using the state transmission rule in equation (4.1); a matrix called Probability matrix is constructed which represents the probability of every ant visiting the zones of the following generator. Ants are only allowed to visit the generators which were previously determined in the beginning of the process which will be in this case generator 2. In order to ensure that every possible solution in the process has been explored and assessed; the proposed algorithm is designed to make sure that all the ants will visit all zones in every generator by the end of every iteration.

After exploring all the possible results by every ant, the tour record for every ant is saved in a matrix. After then, the remaining energy needed by each tour to meet the P_{conv} is obtained from the generator reduced from the optimization process which was earlier assumed to be generator 1.

$$\text{Ant Tour Record } = \begin{bmatrix} Gen\ 3_{solution\ ant\ 1} & Gen\ 2_{solution\ ant\ 1} \\ Gen\ 3_{solution\ ant\ 2} & Gen\ 2_{solution\ ant\ 2} \\ Gen\ 3_{solution\ ant\ 3} & Gen\ 2_{solution\ ant\ 3} \\ \vdots & \vdots \\ \vdots & \vdots \\ Gen\ 3_{solution\ ant\ n} & Gen\ 2_{solution\ ant\ n} \end{bmatrix} \tag{4.20}$$

$$Gen\ 1_{solution} = \ P_{conv} - \ (Gen\ 3_{solution} + \ Gen\ 2_{solution}) \tag{4.21}$$

Where;

$Gen\ 3_{solution}$ and $Gen\ 2_{solution}$ are the power values that were obtained by any given ant in each tour

Gen $1_{solution}$ is the amount of power needed from generator 1 to satisfy the P_{conv} in every given tour

After calculating the remaining power for every tour for each ant, the cost for every tour is calculated based upon the Cost matrix. The minimum tour cost is selected which would represent the optimum dispatch for the load on demand as follows. Only after then, pheromones related to every generator zone will be updated based on the pheromone updating rule using equation (4.2).

$$Optimum\ Dispatch\ Power = [Gen\ 3_{solution} \quad Gen\ 2_{solution} \quad Gen\ 1_{solution}] \tag{4.22}$$

$$Optimum\ Dispatch\ Cost = [Gen\ 3_{solution\ cost} \quad Gen\ 2_{solution\ cost} \quad Gen\ 1_{solution\ cost}] \tag{4.23}$$

Last feature added to the proposed algorithm is a zooming feature. Followed by the end of every iteration, the algorithm uses the best solution obtained by the ants in the current iteration and creates around it another search space, thus zooming in on the best solution and providing new maximum and minimum power values for each generator for the following iteration [24]. Zooming will result in updating the Power and Zones matrix for the following iteration in search for better and more accurate results. Algorithm will continue on zooming and searching for the best result until the pheromone saturation level is reached; pheromone stagnation occurs when two following iterations have the same pheromone values.

All the above steps are carried out on unit time basis based on the demand load present at that time. After all iterations are completed, proposed algorithm scans all results and select the optimum set-point for the conventional generators to achieve minimum cost and minimum emission per unit time while satisfying the load. A flow chart for the proposed algorithm is illustrated in Figure 4-3.

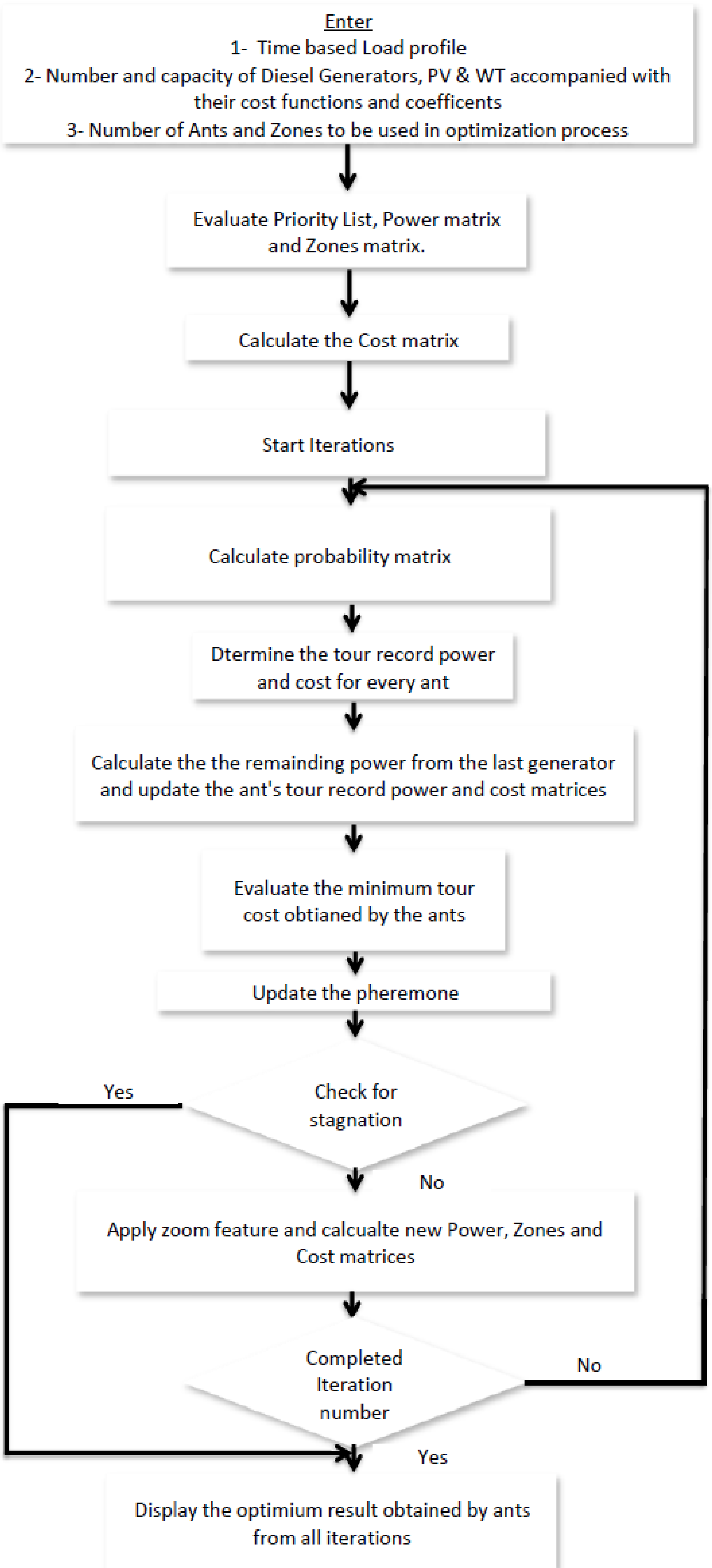

Figure 4-3 Proposed Algorithm Flow Chart

Chapter Five

5 SIMULATIONS & RESULTS

In order to verify the effectiveness of the proposed energy management system based ant colony technique, multiple case studies are carried out and results were presented in this chapter. First case study was carried out on a micro-grid with conventional diesel generators. The second case study was carried out on a hybrid micro-grid containing renewable sources alongside with conventional sources. Various scenarios were studied to promote for the integration of the renewable based sources such as PV and WT in micro-grids. Moreover, renewable energy certificates are taken into consideration which eventually saves a large amount of cost. Finally, a feasibility study is carried out to decide upon the integration of battery system in the micro-grid if it is cost effective or not.

5.1 Renewable Energy Certificates (REC)

Energy produced from sustainable sources is the same as energy produced from fossil fuel sources since it can't be distinguished when being transmitted or distributed. Although energy produced from the renewable based sources are environmental friendly. REC act as a tracking system to sustainable sources owners, as every 1 MWh green energy produced, represents one renewable energy certificate. To the owners, they act like a guarantee that this owner is producing energy using renewable based sources.

RECs can be sold to customers and consumers in an open market as a commodity. Thus, it creates an income stream for the green energy provider to produce more electricity. It allows customers who can't acquire these renewable sources at their homes to enjoy the benefits of having clean energy as their source of electricity.

5.2 Proposed EMS-ACO algorithm Verification

In [48], Lagrange technique was used to address the combined economic dispatch problem in a micro-grid containing five conventional diesel generators. The proposed algorithm was used to study the same micro-grid with the same coefficients. Tables 5-1 and 5-2 show the generation power limits and fuel and emission coefficients.

Table 5-1 Generators Maximum and Minimum Power values

	Max Power (MW)	Min Power (MW)
G 1	75	10
G 2	125	20
G 3	275	30
G 4	250	40
G 5	300	50

Table 5-2 Generators Fuel and Emission Coefficients

	Fuel Cost Coefficients			Emission Coefficients		
	a ($/hr)	**b ($/hr)**	**c ($/hr)**	**α (kg/hr)**	**β (kg/hr)**	**γ (kg/hr)**
G 1	0.008	2	25	0.018	-0.805	80
G 2	0.003	1.8	60	0.015	-0.555	50
G 3	0.0012	2.1	100	0.0105	-1.355	60
G 4	0.001	2	120	0.008	-0.6	45
G 5	0.0015	1.8	40	0.012	-0.555	30

Different scenarios have been carried out in this case study at different demand loads. Table 5-3 shows a comparison between the dispatch output power between Lagrange technique and the proposed algorithm for each generator at each demand load, Figures 5-1 to 5-4.

Table 5-3 Comparison between Generators Dispatched Power Using Proposed ACO Technique and Lagrange's Technique

P_d (MW)		250	300	350	400
G 1	***Lagrange***	49.9	59.9	59.9	79.9
	ACO	74.1	75.0	74.9	74.7
G 2	***Lagrange***	50.1	60.1	70.1	80.1
	ACO	43.3	63.2	78.4	97.2
G 3	***Lagrange***	49.8	59.8	69.8	79.8
	ACO	30.1	33.2	36.4	41.3
G 4	***Lagrange***	49.9	59.9	59.9	79.9
	ACO	44.7	44.7	47.0	54.0
G 5	***Lagrange***	50.1	60.1	70.1	80.1
	ACO	57.8	83.9	113.2	132.9

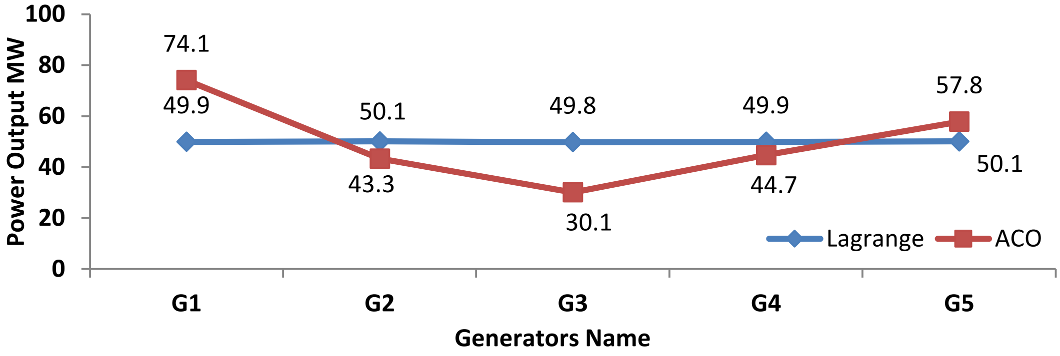

Figure 5-1 Scenario-1 (250 MW Load Demand)

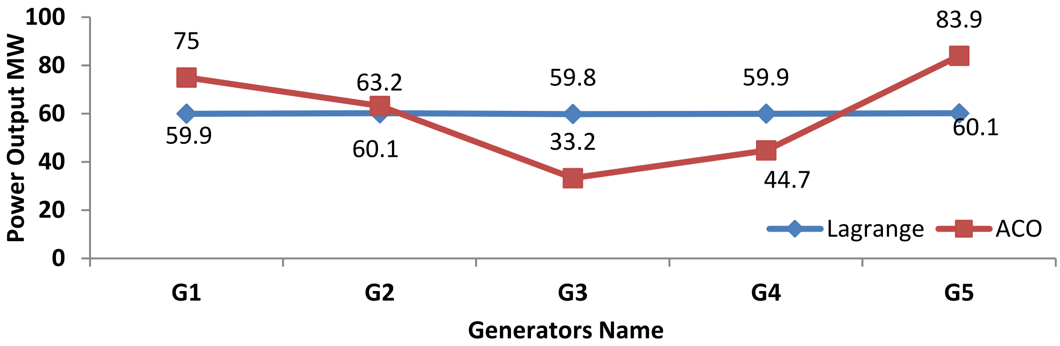

Figure 5-2 Scenario-2 (300 MW Load Demand)

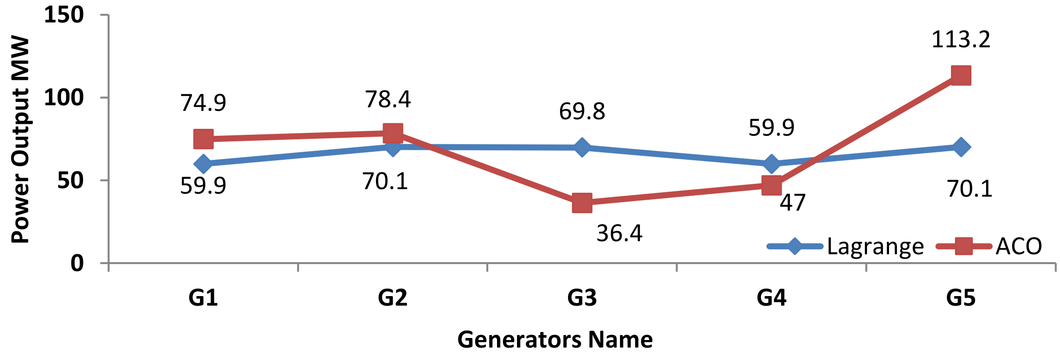

Figure 5-3 Scenario-3 (350 MW Load Demand)

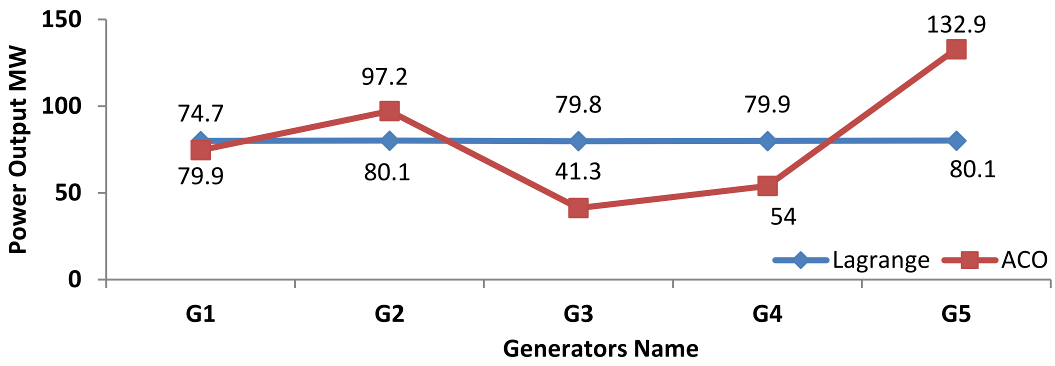

Figure 5-4 Scenario-4 (400 MW Load Demand)

Cost for the dispatched power was calculated for each scenario referring to equation (4.5). Results showed that the proposed algorithm was able to save average 16% overall with savings reaching 18.45% at 300 MW load. Figure 5-5 shows a comparison between the total cost of the Lagrange technique and the proposed algorithm.

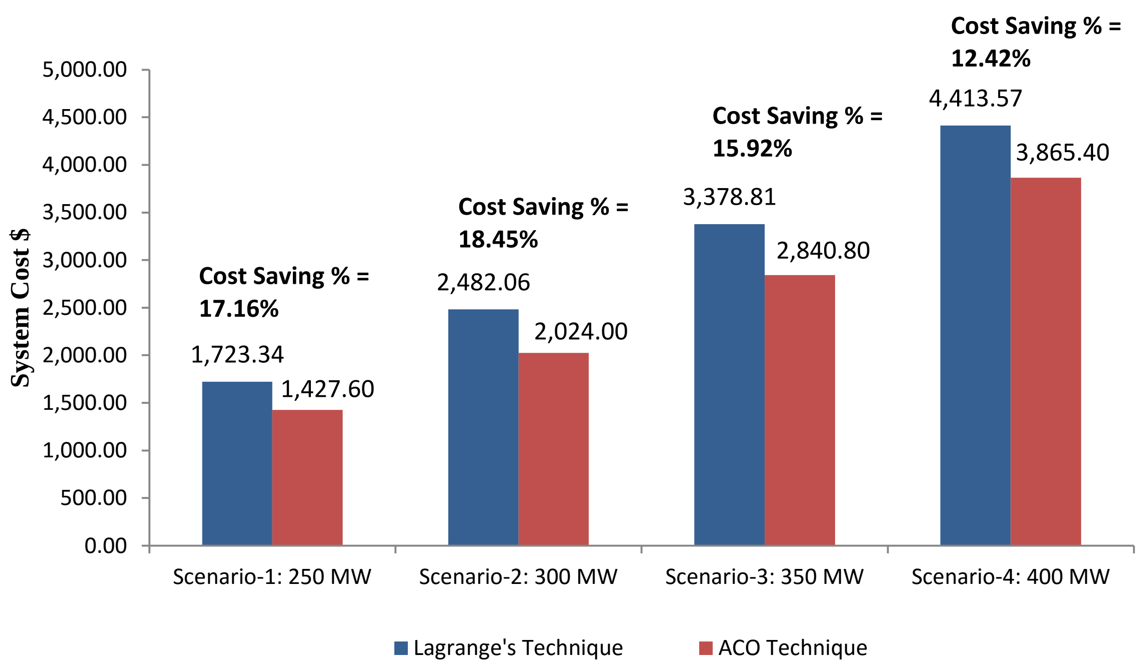

Figure 5-5 Comparison between Total Cost of Operation between Proposed ACO Technique and Lagrange's Technique

5.3 Proposed EMS-ACO algorithm to promote renewable energy sources integration

According to the world wide practice of renewable energy production, transmission and distribution, energy produced from renewable based sources has the first priority always in transmission and distribution over energy produced from conventional sources. Therefore, in any electrical system; generated power from WT and PV is supplied first to the load demand and the remaining demand power is supplied by means of conventional generators.

The proposed EMS is intended to optimize the total generation cost of the system while taking into consideration the capital investment cost as well as the operation and maintenance cost of the WT and PV. The cost function can be described as follows [49]:

$$F(P_w) = a\ I_E P_w + G_E P_w \tag{5.24}$$

$$a = \frac{r}{1-(1+r)^{-N}} \tag{5.25}$$

Where; P_w is the WT and PV generation, a is the net present value coefficient, r is the interest rate assumed to be 9%, N is the investment lifetime assumed to be 20 years, I_P is the investment cost per installed power ($/KW), G_E is the operation and maintenance cost per unit generated ($/KW).

Results obtained by the Gradient method using the daily load demand reported in [2] were compared with the proposed EMS using the same load profile. It has been taken in consideration that the results obtained by the Gradient method in [2] addressed the economic dispatch problem without considering the emission impact in the optimization process. The emission cost function, equation (4.7), was calculated separately and then added to the economic dispatch problem results of the Gradient technique. Emission coefficients values were obtained from [48]. However, the proposed EMS used equation (4.6) when addressing the economic dispatch problem and equation (4.8) when addressing the combined economic emission dispatch problem.

The proposed EMS addressed the same case study mentioned in [49] under the same system environment and constraints. It provided an hourly optimum dispatched power configuration and total operational cost while minimizing the total emission output. The results were compared to those of the Gradient technique results mentioned in [49]. The comparison was carried out using the same fuel coefficients and power constraints. An hourly load profile was proposed in the case study that can be shown in Figure 5-6. The hybrid micro-grid is assumed to have three conventional generators in addition to non-dispatchable WT and PV. The conventional generators maximum and minimum power limits are described in Table 5-4 and the fuel cost coefficients are described in Table 5-5. The daily PV and WT power generation output based on the given solar radiation and wind speed are shown in Figure 5-7 and 5-8 respectively [49].

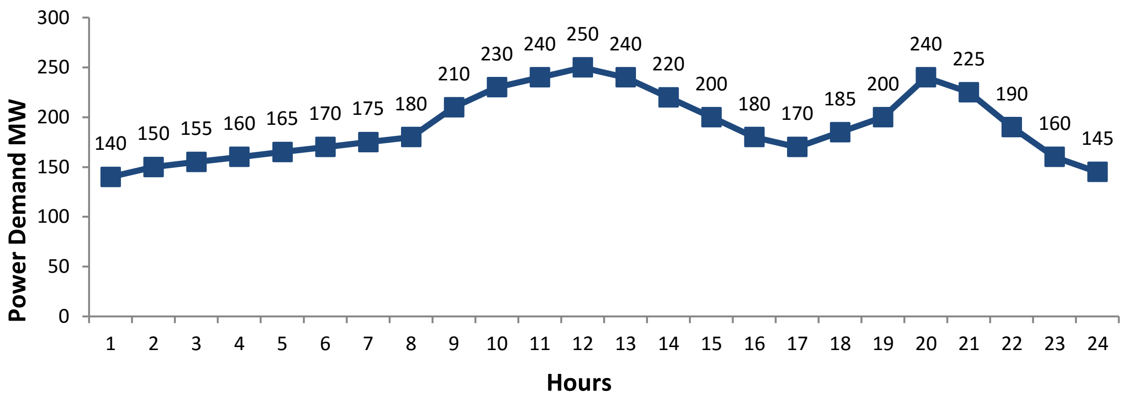

Figure 5-6 Hourly Load Profile

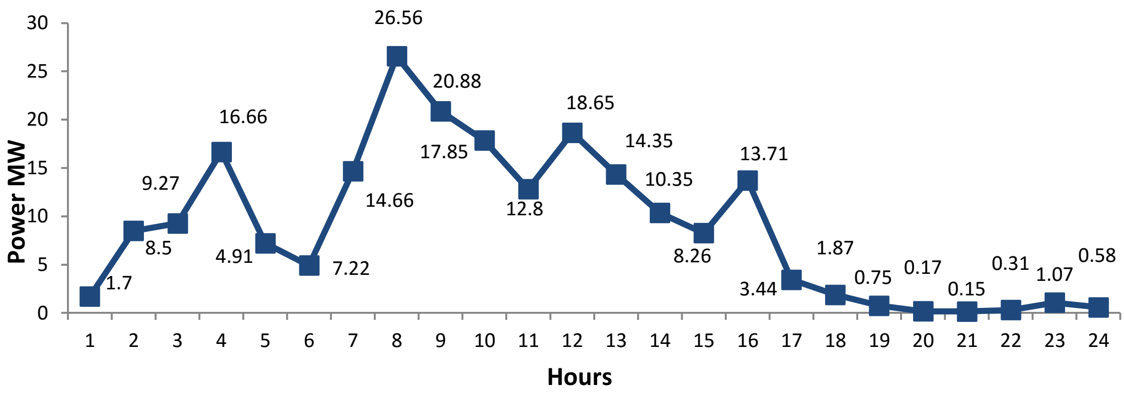

Figure 5-7 Hourly WT output power

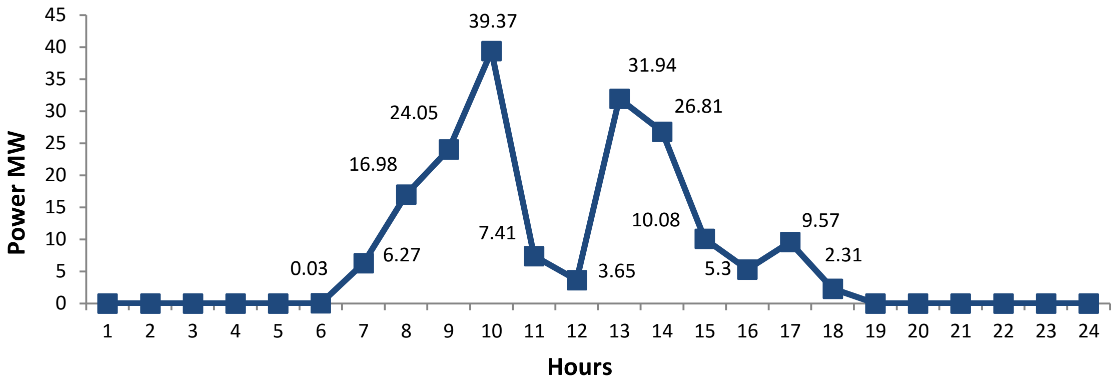

Figure 5-8 Hourly PV output power

Table 5-4 Generators Maximum and Minimum Power limits

	Max Power (MW)	Min Power (MW)
G 1	150	37
G 2	160	40
G 3	190	50

Table 5-5 Generators Fuel Coefficients

	a ($/hr)	b ($/hr)	c ($/hr)
G 1	1530	21	0.024
G 2	992	20.16	0.029
G 3	600	20.4	0.021

Two case studies were considered; both addressed the combined economic emission dispatch problem and the economic dispatch problem with no emission impact. The total operational cost of both case studies was calculated using equation (4.5) when addressing the combined economic emission dispatch problem and equation (4.6) when addressing the economic dispatch problem only. First case study studied the micro-grid proposed in [49] with and without adding WT to the system thus showing the effect of adding renewable sources in the micro-gird on the total cost. The second case study deals with the integration of the WT and PV in the micro-grid with the consideration of renewable energy certificates for the PV.

5.3.1 First Case study

For the first case study, two scenarios were carried out. In the first scenario, three conventional sources in the micro-grid are implemented without taking into consideration the WT. On the other hand, the second scenario integrated the WT in the micro-grid alongside with the three conventional diesel generators. The total operational cost for the 24 hour period for the two scenarios are illustrated in Figure 5-9 and 5-10 respectively and the optimum dispatched power and cost per hour for both scenarios are shown in Tables 5-6 and 5-7 respectively.

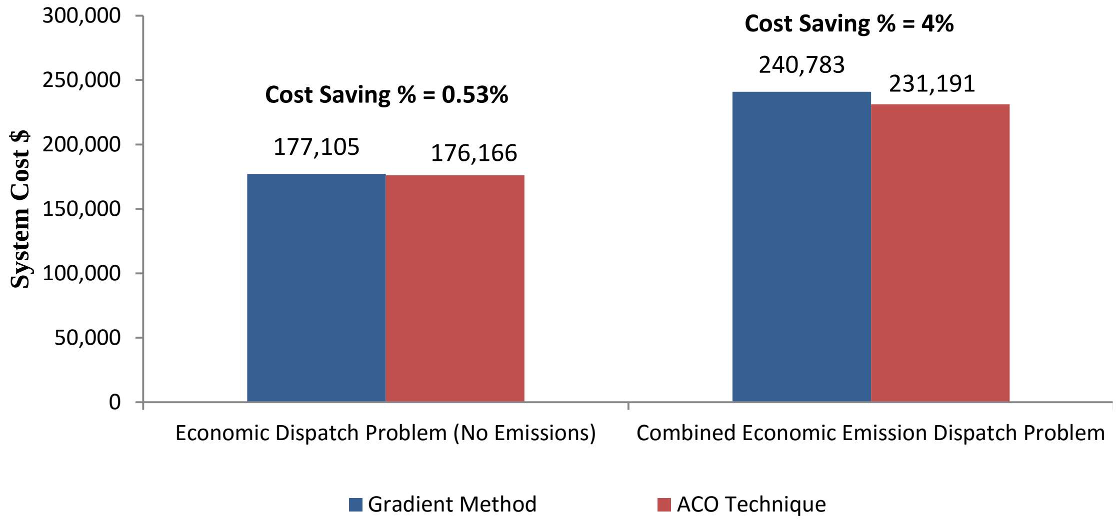

Figure 5-9 Scenario-1: Total Generation Cost Using Gradient Technique and Proposed ACO Technique (without WT)

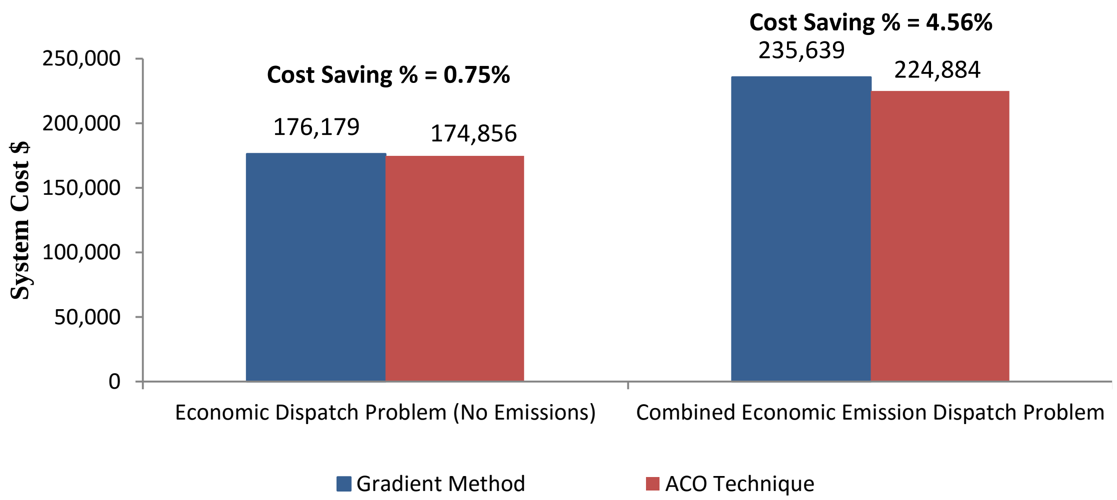

Figure 5-10 Scenario-2: Total Generation Cost Using Gradient Technique and Proposed ACO Technique (with WT)

5.3.2 Second Case study

Same case was addressed taking into consideration the implementation of renewable energy certificate (REC) for the PV. Investment cost per installed power ($/KW) for the solar power can be decrease using REC. Accordingly, two scenarios were carried out to apply the proposed EMS-ACO. The two scenarios introduced the renewable based micro-grid with conventional sources with and without taking into consideration the solar REC. The results for the two scenarios are illustrated in Figure 5-11 and 5-12 respectively and the optimum dispatched power and cost per hour for both scenarios are shown in Tables 5-8 and 5-9 respectively considering the combined economic emission dispatch problem and the economic dispatch problem.

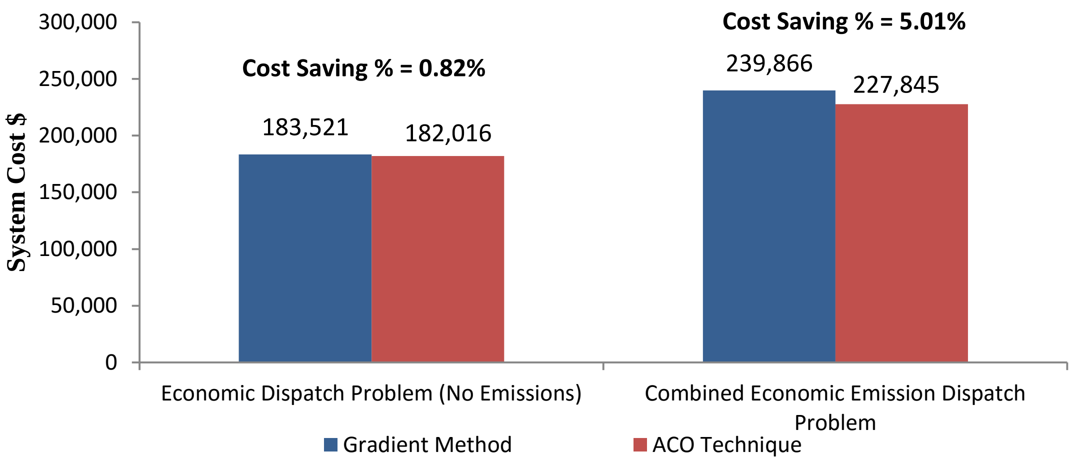

Figure 5-11 Scenario-1: Total Generation Cost Using Gradient Technique and Proposed ACO Technique (without Solar REC)

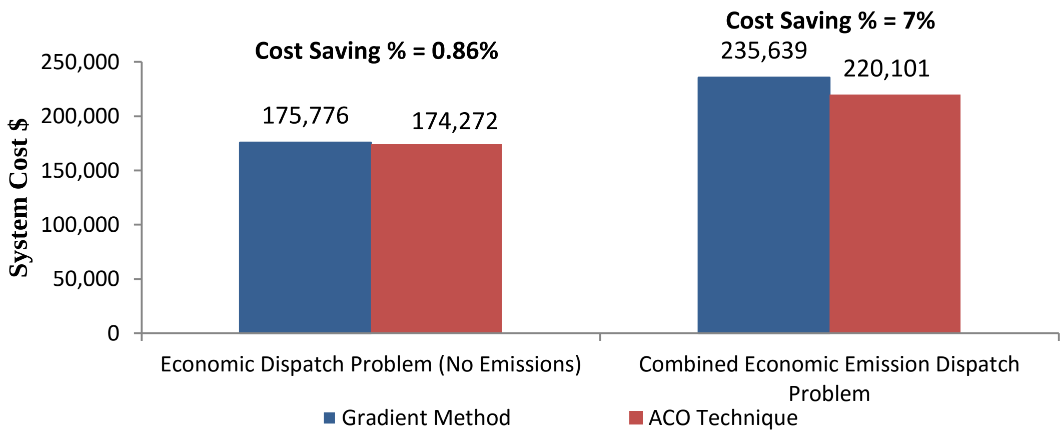

Figure 5-12 Scenario-2: Total Generation Cost Using Gradient Technique and Proposed ACO Technique (with Solar REC)

5.4 Observations

In the EMS-ACO verification case study, the obtained results based were compared to those of the Lagrange technique and it showed that the EMS-ACO saved total average cost 16% as shown in Table 5-6.

Table 5-6 Comparison between Lagrange Technique and proposed EMS-ACO

P_d (MW)	System Cost $		Cost Saving %
	Lagrange's Technique	ACO Technique	
Scenario-1: 250 MW	1,723.34	1,427.60	17.16%
Scenario-2: 300 MW	2,482.06	2,024.00	18.45%
Scenario-3: 350 MW	3,378.81	2,840.80	15.92%
Scenario-4: 400 MW	4,413.57	3,865.40	12.42%

As for promoting for the integration of WT in micro-grids; the amount of cost savings for the first case study can be shown in Tables 5-7 and 5-8 respectively.

Table 5-7 Comparison between Gradient method and proposed ACO in conventional based micro-grid (Without WT)

	Total Generation Cost ($/hr)		Cost Savings %
	Gradient Method	ACO Technique	
Economic Dispatch Problem (No Emissions)	177,105	176,166	0.53%
Combined Economic Emission Dispatch Problem	240,783	231,191	4%

Table 5-8 Comparison between Gradient method and proposed ACO in conventional based micro-grid (with WT)

	Total Generation Cost ($/hr)		Cost Savings %
	Gradient Method	ACO Technique	
Economic Dispatch Problem (No Emissions)	176,179	174,856	0.75%
Combined Economic Emission Dispatch Problem	235,639	224,884	4.56%

It has been noticed that despite the high capital cost of WT, the proposed EMS-ACO was able to save cost in both dispatch problems. These savings can be shown in Figure 5-13.

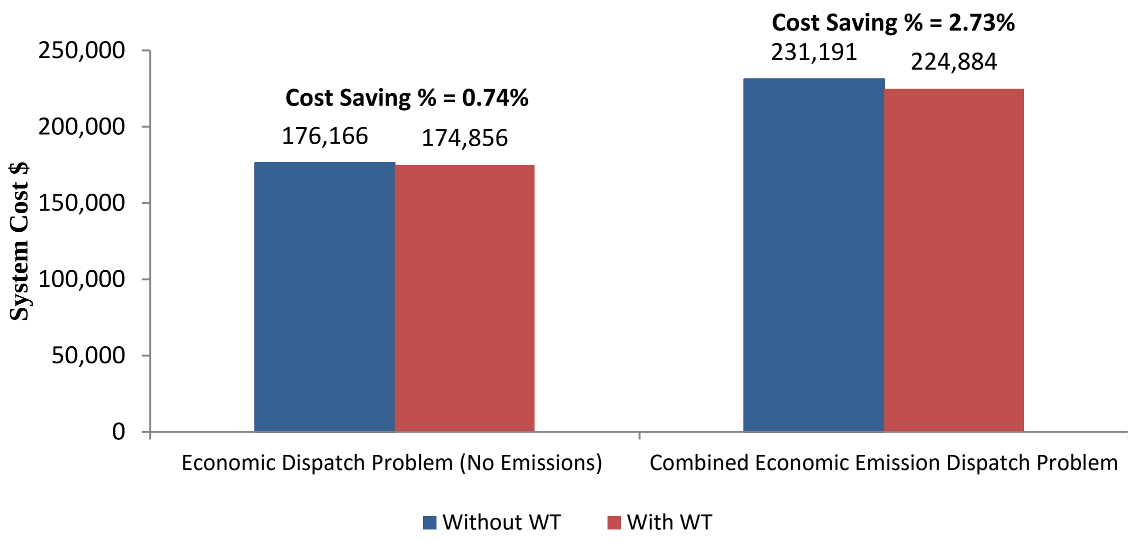

Figure 5-13 Cost saving when integrating WT using the proposed ACO Technique

As for the second case study, amount of cost savings could be illustrated in Tables 5-9 and 5-10 respectively.

Table 5-9 Comparison between Gradient method and proposed ACO in hybrid micro-grid (Without RECs)

	Total Generation Cost ($/hr)		Cost Savings %
	Gradient Method	ACO Technique	
Economic Dispatch Problem (No Emissions)	183,521	182,016	0.82%
Combined Economic Emission Dispatch Problem	239,866	227,845	5.01%

Table 5-10 Comparison between Gradient method and proposed ACO in hybrid micro-grid (With RECs)

	Total Generation Cost ($/hr)		Cost Savings %
	Gradient Method	ACO Technique	
Economic Dispatch Problem (No Emissions)	175,776	174,272	0.86%
Combined Economic Emission Dispatch Problem	235,639	220,101	7%

Moreover, when considering the renewable energy certificate impact on the PV capital cost, the proposed EMS-ACO was able to save a significant amount of cost as shown in Figure 5-14.

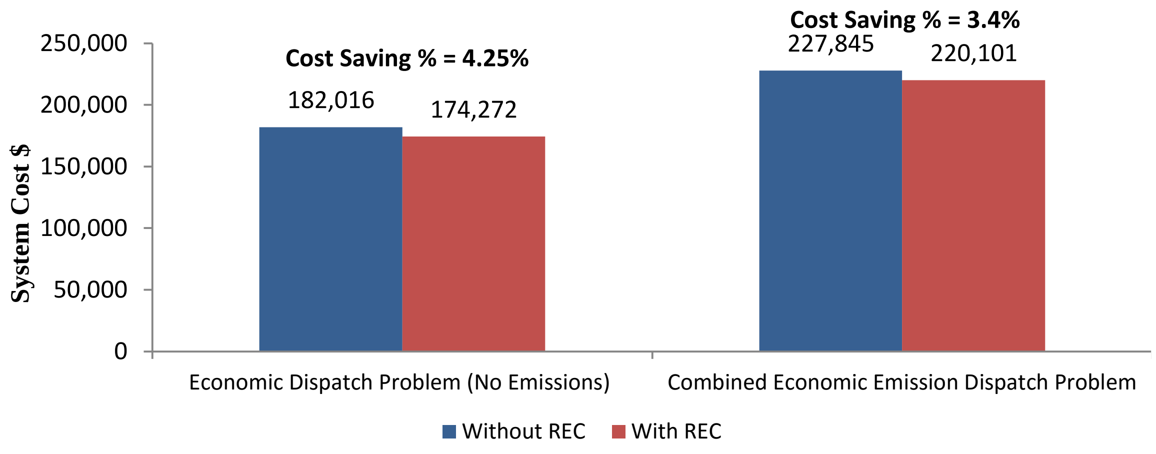

Figure 5-14 Cost saving when considering REC using the proposed ACO Technique

5.5 Battery Storage

In order to increase the reliability of supply to the load and provide cost effective solutions; battery storage systems may just be another promising cost effective solution to be integrated with micro-grid systems. Energy storage technologies have been widely increasing and developed to offer more reliability and diversity to address all types of electrical systems while optimizing the cost as possible.

Energy stored in storage systems could take many forms such as chemical energy in batteries, potential energy in pumped hydro or compressed air, electrical energy in capacitors and mechanical energy in flywheels. Commercial available technologies for storage systems could be summarized in Figure 5-15 [53].

	Lead-acid batteries	Li-ion batteries	NaS batteries	Flow batteries	Fly-wheels	Pumped hydro	Large-scale CAES
Applicable grid system size [kW/MW]	≤10 MW	≤10 MW	≥100 MW	25 kW–10 MW	100 kW–200 MW	Mostly ≥200 MW	≥500 MW
Lifetime [years]	3–10	10–15	15	Cell stack: 5–15; Electro-lyte: 20+	20	25+	20+
Lifetime [cycles]	500–800	2,000–3,000	4,000–40,000	Cell stack: 1,500–15,000	>100,000	>50,000	>10,000
Roundtrip efficiency [%]	70%–90%	85%–95%	80%–90%	70%–85%	85%–95%	75%–85%	45%–60%
Capital cost per discharge power [$/kW]	$300–$800	$400–$1,000	$1,000–$2,000	$1,200–$2,000	$2,000–$4,000	$1,000–$4,000	$800–$1,000
Capital cost per capacity [$/kWh_cap]	$150–$500	$500–$1,500	$125–$250	$350–$800	$1,500–$3,000	$100–$250	$50–$150
Levelised cost of storage [$/kWh_life]	$0.25–$0.35	$0.30–$0.45	$0.05–$0.15	$0.15–$0.25	N/A	$0.05–$0.15	$0.10–$0.20
Annual operating costs [$/kW-yr]	$30	$25	$15	$30	$15	$5	$5

Figure 5-15 Different Energy Storage Technologies

Selection criteria of storage systems are based on a number of metrics which are variable from every electrical system. Depending on the initial cost, batteries capacity, charge and discharge rates, batteries lifetime and the efficiency; the optimum battery storage system is selected. Figure 5-16 shows the comparison between the storage systems based on their discharge rate on different scale of applications [53].

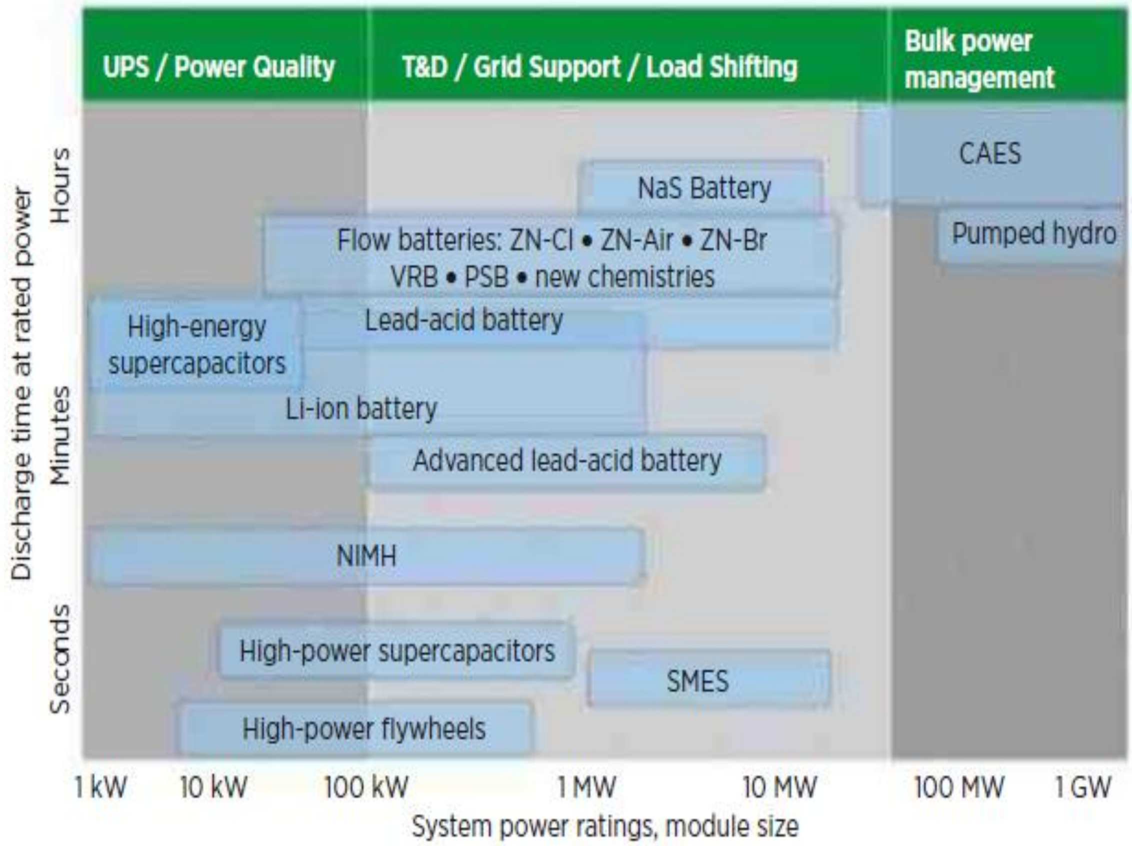

Figure 5-16 Comparison between storage technologies based on discharge rate at different applications

A study is carried out to determine the feasibility of installing a battery storage system in a micro-grid system over defraying the cost of energy cut off. An hourly load profile for a micro-grid is assumed as shown in Figure 5-17 [49]. Moreover, it is assumed that the electricity source can only deliver maximum power 23 MW. Therefore, this will lead to energy cut off at any hour the load exceeds the maximum power.

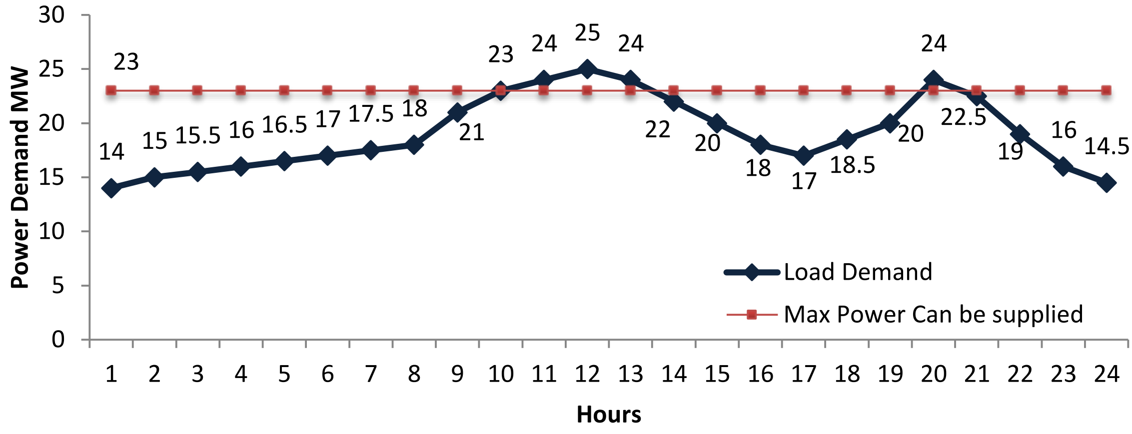

Figure 5-17 Hourly Load Profile with a maximum power delivery of 23 MW

From Figure 5-17, it is clearly observed that there are four hours during the day, the source will not be able to cover the demand. These hours are illustrated in Table 5-11.

Table 5-11 Hours During the day that will not be covered by the source

Hr	Load Demand (MW)	Max Power Can be supplied (MW)	Power Needed (MW)
11	24	23	1
12	25	23	2
13	24	23	1
20	24	23	1

From the above table, we can notice that the energy not supplied during the day is 5 MWh; therefore the battery system that will be installed must be able to satisfy the load at these times. The battery system chosen is lithium-ion batteries due to its high efficiency and relatively better cost than other systems. Lithium-ion batteries storage properties and specifications could be illustrated in Figure 5-18 [53].

Applicability		10 MW and smaller systems
Useful storage capacity		0.5-10 kWh per battery
Charge rate		0.2-2 kW per battery
Discharge rate		0.5-10 kW per battery
Lifetime	**Time**	10-15 years
	Cycles	2,000-3,000 cycles
	Energy	1,000-30,000 kWh
Roundtrip efficiency		85%-95%
Initial capital cost	**Cost/discharge power**	\$400-\$1,000/kW
	Cost/capacity	\$500-\$1,500/kWh_{cap}
	Levelised cost of storage	\$0.30-\$0.45/kWh_{life}
Operating costs		\$25/kW·yr

Figure 5-18 Lithium ion Battery properties

In order to properly assess the proposed battery system and test its cost effeciciny, the cost of KWh of the battery must be compared with the cost of the electricity of supply. If the cost of KWh of the battery is found to be smaller than that of supply, then the battery system would be cost effective. To calculate the cost of battery and the cost KWh; the following equations are used:

$$\text{Cost of battery } \left({}^{\$}/_{\text{kwh capacity}}\right) = 500\$ \qquad (5.26)$$

$$\text{Energy not supplied } \left({}^{\text{kwh}}/_{\text{day}}\right) = 5000 \text{ kwh} \qquad (5.27)$$

Therefore,

$$\text{Total Battery Cost (\$)} = \text{Cost of battery } \left({}^{\$}/_{\text{kwh capacity}}\right) \times \text{Energy not supplied } \left({}^{\text{kwh}}/_{\text{day}}\right) = 2{,}500{,}000\ \$ \qquad (5.28)$$

The average lifetime of the battery is 10 years; therefore the energy not supplied over the 10 years is calculated as follows

$$\text{Energy not supplied} \left({}^{\text{kwh}}/_{\text{lifetime}}\right)$$
$$= \text{Energy not supplied } \left({}^{\text{kwh}}/_{\text{day}}\right) \times \text{Number of years } \times \text{Number of} \left({}^{\text{day}}/_{\text{Year}}\right)$$
$$= 5000 \times 10 \times 365 = 18{,}250{,}000 \text{ kwh} \qquad (5.29)$$

Now we can easily calculate the cost of KWh of the battery

$$\text{Cost of kwh (\$)} = \text{Total Battery Cost (\$)/Energy not supplied} \left({}^{\text{kwh}}/_{\text{lifetime}}\right)$$
$$= 0.136 \ ({}^{\$}/_{\text{kwh}}) \qquad (5.30)$$

The comparison of the cost of battery installation and the amount of unserved energy during the lifetime of the battery storage system shows that the battery system will cost 0.136 $/ KWH. According to the utility energy tariff at these hours, the battery storage system can represent an economical solution for this supposed grid rather than the load shedding option.

Table 5-12 First Case Study- Scenario-1: Comparison between Total Generation Cost Using Gradient Technique and Proposed ACO Technique (No WT)

P_d (MW)	Economic Dispatch Problem (No emissions)								Combined Dispatch Problem (Emissions)							
	Gradient Method				ACO Technique				Gradient Method				ACO Technique			
	Generation (MW) [49]			Total Gen. cost ($/hr) [49]	Generation (MW)			Total Gen. cost ($/hr)	Generation (MW) [49]			Total Gen. cost ($/hr)	Generation (MW)			Total Gen. cost ($/hr)
	G1	G2	G3		G1	G2	G3		G1	G2	G3		G1	G2	G3	
140	7	11	122	6298	37	45	57	6152	7	11	122	8498	37	44	59	7349
150	15	19	115	6483	41	48	61	6380	15	19	115	8541	40	47	63	7755
155	19	24	112	6579	42	50	63	6495	19	24	112	8593	41	49	65	7963
160	24	28	109	6677	44	51	65	6611	24	28	109	8667	42	51	67	8175
165	28	32	105	6778	46	52	67	6727	28	32	105	8761	44	52	69	8390
170	32	36	102	6881	48	54	69	6843	32	36	102	8875	45	54	71	8608
175	36	40	98	6986	49	55	71	6959	36	40	98	9011	46	55	73	8830
180	40	45	95	7094	51	57	72	7076	40	45	95	9167	47	58	75	9056
210	53	57	100	7795	61	65	84	7787	53	57	100	10525	56	67	88	10482
230	82	87	61	8300	68	71	92	8269	82	87	61	11868	61	72	96	11502
240	91	95	54	8569	71	73	96	8512	91	95	54	12657	64	75	101	12033
250	99	103	47	8848	74	76	99	8757	99	103	47	13529	66	80	104	12578
240	91	95	54	8569	71	73	96	8512	91	95	54	12657	64	75	101	12033
220	74	78	68	8040	64	68	88	8027	74	78	68	11162	59	69	92	10985
200	59	64	77	7548	58	62	80	7549	59	64	77	10008	53	63	84	9993
180	40	45	95	7094	51	57	72	7076	40	45	95	9167	47	58	75	9056
170	32	36	102	6881	48	54	69	6843	32	36	102	8875	45	54	71	8608
185	45	49	92	7024	53	58	74	7194	45	49	92	9344	49	58	78	9285
200	59	64	77	7548	58	62	80	7549	59	64	77	10008	53	63	84	9993
240	91	95	54	8569	71	73	96	8512	91	95	54	12657	64	75	101	12033
225	78	82	64	8168	66	69	90	8148	78	82	64	11505	60	71	94	11242
190	49	53	88	7316	54	59	76	7312	49	53	88	9541	50	60	80	9517
160	24	28	109	6677	44	51	65	6611	24	28	109	8661	42	51	67	8175
145	11	15	119	6387	39	47	59	6266	11	15	119	8509	38	46	61	7550
	Total Generation Cost ($/day)			177,105	**Total Generation Cost ($/day)**			176,166	**Total Generation Cost ($/day)**			240,783	**Total Generation Cost ($/day)**			231,191

Table 5-13 First Case Study- Scenario-2: Comparison between Total Generation Cost Using Gradient Technique and Proposed ACO Technique (With WT)

P_d (MW)	Economic Dispatch Problem (No emissions)								Combined Dispatch Problem (Emissions)							
	Gradient Method				ACO Technique				Gradient Method				ACO Technique			
	Generation (MW) [49]			Total Gen. cost ($/hr) [49]	Generation (MW)			Total Gen. cost ($/hr)	Generation (MW) [49]			Total Gen. cost ($/hr)	Generation (MW)			Total Gen. cost ($/hr)
	G1	G2	G3		G1	G2	G3		G1	G2	G3		G1	G2	G3	
140	5	10	123	6297	37	45	56	6143	5	10	123	8499	37	44	58	7311
150	8	12	121	6474	38	46	58	6335	8	12	121	8499	37	45	59	7558
155	12	16	118	6565	39	47	59	6445	12	16	118	8513	38	46	61	7742
160	10	14	120	6650	39	46	58	6520	10	14	120	8504	38	45	60	7775
165	22	26	110	6759	43	50	64	6686	22	26	110	8631	42	50	66	8207
170	28	32	105	6865	46	52	67	6815	28	32	105	8763	44	52	69	8480
175	24	28	108	6940	44	51	65	6875	24	28	108	8673	42	51	67	8446
180	18	22	113	7013	42	49	62	6925	18	22	113	8575	41	49	64	8363
210	48	52	89	7662	54	59	76	7657	48	52	89	9505	50	60	79	9842
230	52	55	105	8164	62	66	85	8151	52	55	105	10663	56	67	89	10901
240	80	84	62	8450	67	70	91	8425	80	84	62	11643	61	71	95	11580
250	84	88	60	8662	68	71	92	8628	84	88	60	11970	62	73	97	11899
240	79	83	64	8437	66	69	90	8415	79	83	64	11551	60	71	95	11527
220	54	57	99	7967	61	65	84	7960	54	57	99	10504	56	67	87	10646
200	63	70	59	7509	55	60	77	7497	63	70	59	9732	51	60	80	9744
180	29	33	104	7044	46	53	67	6997	29	33	104	8788	44	52	70	8686
170	29	33	104	6870	46	53	67	6823	29	33	104	8794	44	53	70	8518
185	43	47	93	7195	52	57	74	7183	43	47	93	9275	49	58	77	9232
200	59	64	76	7544	57	62	80	7544	59	64	76	9977	53	63	83	9970
240	91	95	54	8567	71	73	95	8511	91	95	54	12643	64	75	100	12027
225	78	82	65	8167	66	69	90	8147	78	82	65	11493	60	71	94	11237
190	49	53	88	7314	54	59	76	7310	49	53	88	9528	50	60	80	9508
160	23	27	109	6674	44	51	64	6605	23	27	109	8649	42	50	67	8148
145	11	15	119	6389	39	47	59	6263	11	15	119	8506	38	46	61	7537
	Total Generation Cost ($/day)			176,179	**Total Generation Cost ($/day)**			174,856	**Total Generation Cost ($/day)**			235,639	**Total Generation Cost ($/day)**			224,884

Table 5-14 Second Case Study- Scenario-1: Comparison between Total Generation Cost Using Gradient Technique and Proposed ACO Technique (Without Solar REC)

P_d (MW)	Economic Dispatch Problem (No Emissions)								Combined Economic Emission Dispatch Problem							
	Gradient Method				ACO Technique				Gradient Method				ACO Technique			
	Generation (MW) [49]			Total Gen. cost ($/hr) [49]	Generation (MW)			Total Gen. cost ($/hr)	Generation (MW) [49]			Total Gen. cost ($/hr)	Generation (MW)			Total Gen. cost ($/hr)
	G1	G2	G3		G1	G2	G3		G1	G2	G3		G1	G2	G3	
140	5	10	123	6297	39	43	56	6143	5	10	123	8498	39	42	57	7313
150	8	12	121	6474	41	43	57	6335	8	12	121	8541	37	45	60	7558
155	12	16	118	6565	42	44	61	6445	12	16	118	8593	39	46	61	7742
160	10	14	120	6650	41	43	59	6520	10	14	120	8667	38	45	61	7775
165	22	26	110	6759	48	44	66	6686	22	26	110	8761	43	50	65	8207
170	28	32	105	6867	52	44	70	6816	28	32	105	8875	43	54	68	8481
175	19	23	113	7209	46	44	65	7123	19	23	113	9011	39	50	65	8574
180	4	8	125	7762	39	42	55	7598	4	8	125	9167	37	41	58	8738
210	28	32	105	8649	52	44	70	8598	28	32	105	10525	43	54	68	10263
230	34	39	100	9713	55	44	74	9682	34	39	100	11868	46	54	72	11506
240	74	78	68	8722	79	44	97	8710	74	78	68	12657	59	69	92	11662
250	80	85	63	8794	83	44	101	8768	80	85	63	13529	61	70	96	11937
240	62	68	63	9654	66	44	84	9648	62	68	63	12657	50	62	82	11941
220	43	47	93	9013	60	44	79	9001	43	47	93	11162	50	58	75	11045
200	42	46	94	7905	60	44	78	7890	42	46	94	10008	46	58	77	9908
180	24	29	108	7268	49	44	68	7205	24	29	108	9167	43	50	68	8789
170	21	25	111	7276	47	44	66	7200	21	25	111	8875	43	50	64	8706
185	41	45	94	7288	59	44	78	7273	41	45	94	9344	46	58	76	9271
200	59	64	76	7544	68	44	87	7544	59	64	76	10008	53	63	84	9970
240	91	95	54	8567	89	44	107	8511	91	95	54	12657	64	75	100	12027
225	78	82	65	8167	82	44	99	8147	78	82	65	11505	60	71	94	11237
190	49	53	88	7314	64	44	82	7310	49	53	88	9541	50	58	82	9510
160	23	27	109	6674	49	43	67	6605	23	27	109	8661	43	50	66	8148
145	11	15	119	6389	41	43	60	6263	11	15	119	8509	39	46	60	7537
	Total Generation Cost ($/day)			183,521	**Total Generation Cost ($/day)**			182,016	**Total Generation Cost ($/day)**			239,866	**Total Generation Cost ($/day)**			227,845

Table 5-15 Second Case Study- Scenario-2: Comparison between Total Generation Cost Using Gradient Technique and Proposed ACO Technique (With Solar REC)

P_d (MW)	Economic Dispatch Problem (No Emissions)								Combined Economic Emission Dispatch Problem							
	Gradient Method				ACO Technique				Gradient Method				ACO Technique			
	Generation (MW) [49]			Total Gen. cost ($/hr) [49]	Generation (MW)			Total Gen. cost ($/hr)	Generation (MW) [49]			Total Gen. cost ($/hr)	Generation (MW)			Total Gen. cost ($/hr)
	G1	G2	G3		G1	G2	G3		G1	G2	G3		G1	G2	G3	
140	5	10	123	6297	37	45	56	6143	5	10	123	8529	38	40	60	7313
150	8	12	121	6474	38	46	58	6335	8	12	121	8648	38	44	59	7558
155	12	16	118	6565	39	47	59	6445	12	16	118	8675	40	44	62	7742
160	10	14	120	6650	39	46	58	6520	10	14	120	8795	39	44	61	7775
165	22	26	110	6759	43	50	64	6686	22	26	110	8758	44	45	69	8207
170	28	32	105	6865	46	52	67	6815	28	32	105	8848	46	49	71	8480
175	19	23	113	6945	42	49	62	6859	19	23	113	8964	44	46	64	8310
180	4	8	125	7046	37	44	55	6882	4	8	125	9308	38	40	58	8022
210	28	32	105	7635	46	52	67	7584	28	32	105	9609	46	49	71	9250
230	34	39	100	8054	48	55	70	8023	34	39	100	10049	51	51	70	9847
240	74	78	68	8409	64	68	88	8397	74	78	68	11520	59	69	92	11349
250	80	85	63	8640	67	70	91	8614	80	85	63	12098	66	68	93	11784
240	62	68	63	8308	56	60	78	8302	62	68	63	10676	55	59	80	10595
220	43	47	93	7884	52	57	74	7871	43	47	93	9982	51	52	80	9915
200	42	46	94	7480	51	57	73	7466	42	46	94	9569	51	55	75	9483
180	24	29	108	7045	45	51	65	6982	24	29	108	9030	48	48	65	8565
170	21	25	111	6873	43	50	64	6797	21	25	111	8872	44	45	68	8303
185	41	45	94	7191	51	57	73	7176	41	45	94	9273	51	55	75	9174
200	59	64	76	7544	57	62	80	7544	59	64	76	9990	53	62	83	9970
240	91	95	54	8567	71	73	95	8511	91	95	54	12646	64	75	100	12027
225	78	82	65	8167	66	69	90	8147	78	82	65	11496	60	70	94	11237
190	49	53	88	7314	54	59	76	7310	49	53	88	9534	55	57	78	9510
160	23	27	109	6674	44	51	64	6605	23	27	109	8667	45	45	69	8148
145	11	15	119	6389	39	47	59	6263	11	15	119	8517	39	44	61	7537
	Total Generation Cost ($/day)			175,776	**Total Generation Cost ($/day)**			174,272	**Total Generation Cost ($/day)**			235,639	**Total Generation Cost ($/day)**			220,101

Chapter Six

6 CONCLUSIONS

6.1 Conclusions

This thesis introduces a novel energy management system to solve the combined economic and emission dispatch problem for micro-grids. The proposed EMS uses the Ant Colony optimization technique to solve the optimization function. The optimization problem is formulated and the proposed technique is explained. Verification of the energy management system based on ant colony optimization was carried out by modelling a micro-grid with five conventional diesel generators. The combined economic and emission dispatch problem is addressed to various demand load scenarios. Their results were compared to the Lagrange technique showing that the EMS-ACO saved total average cost of 16%.

To promote for the integration of renewable energy sources in micro-grid and to prove their cost efficiency, a hybrid micro-grid is modelled having renewable based sources alongside with conventional diesel generators. The combined economic and emission dispatch problem and the economic dispatch problem with no emission impact have been addressed separately in different scenarios. Firstly, the energy management system was applied to a modelled micro-grid. Its results were compared with those of the Gradient method with and without adding WT to show the effectiveness of installing WT in the system. Results showed high cost savings.

Then, the energy management system addressed the hybrid micro-grid when installing WT and PV in its system alongside the conventional diesel generators. Moreover, renewable energy certificates were taken in consideration in one of the scenarios to encourage the investment in renewable based sources. Another cost effective solution was proposed in this thesis, where a feasibility study was carried out to decide upon the cost effectiveness of integrating a battery system within the micro-grid. The price of every kilo watt hour should decide whether integrating a battery system within the micro-grid should effective or not.

The proposed energy management system offered high cost savings while maintaining high levels of flexibility and robustness. This was achieved by promoting for the high feasibility of using renewable based sources as alternative sources of power than conventional fossil fuel sources. Moreover, it encouraged the investing in renewable based sources using the renewable energy certificates. In addition to that, it allows more effective and efficient energy management of the micro-grid. It was clearly observed as well that despite the high capital cost of WT and PV; a substantial amount of money could be saved while reducing the carbon emissions in the environment and increasing the reliability to the customers. This could be easily achieved by the introduction of renewable energy certificates in the electricity market combined with the appropriate legislations and incentives.

6.2 Future Work

Work presented in this thesis could be further explored and more studies could be carried out. Some of these studies could be investigating the optimization of micro-grid systems when it's in the grid connected mode, where the time of use cost could be taken into consideration from the grid side. Another point of research could be exploring the penetration level of renewable energy sources in the micro-grids and finding out the optimum level of contribution of these sources to attain minimum operational cost at all times. The energy management system could be tested on much larger scale micro-grid systems with more complicated load constraints. Also, the energy management system could be further developed and tested on smart grid systems.

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