

Energy Management and Ancillary Services for Shipboard Microgrid

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Submitted by

Atul Kumar Choudhary

Regd. No. : 801742007

Under the Guidance of

Dr. Surya Prakash

Associate Professor, EIED



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Thapar Institute of Engineering & Technology, Patiala

(Declared as Deemed-to-be-University u/s 3 of the UGC Act., 1956)

Post Bag No. 32, Patiala – 147004

Punjab (India)

DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "**Energy Management and Ancillary Services for Shipboard Microgrid**", in partial fulfillment of the requirements for the award of the degree of **Master of Engineering in Power Systems**, submitted to Electrical & Instrumentation Engineering Department of Thapar Institute of Engineering & Technology (Deemed to be University) is an authentic record of my own work carried under the supervision of **Dr. Surya Prakash**. It refers to other researcher's work which is duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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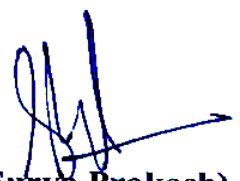
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(Atul Kumar Choudhary)

Roll No.: 801742007

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Date: *14 Aug, 2019*


(Dr. Surya Prakash)

Associate Professor
Electrical & Instrumentation Engineering Department
Thapar Institute of Engineering & Technology, Patiala

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(Atul Kumar Choudhary)
(801742007)

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LIST OF ABBREVIATIONS

LFC	Load-frequency control
EMS	Energy Management System
PV	Photovoltaic
ESS	Energy storage system
DG	Distributed Generation
MG	Microgrid
WT	Wind turbine
MF	Membership function
BESS	Battery energy storage system.
GOA	Grasshopper Optimization Algorithm
LI	Lithium Ion
DPS	Diesel Power System
SCSS	Super Capacitor Storage System
T_{FC}	Time constant of fuel cell
T_{IC}	Time constant of the interconnection device
T_{IN}	Time constant of inverter
K_{FC}	gain constant of fuel cell
Δf	Frequency Change
R	Regulation Parameter
FL	Fuzzy Logic
PVC	Photovoltaic cell
SEMS	Ship Energy Management System
SBM	Shipboard microgrid
FPID	Fuzzy PID
FOPID	Fractional-Order Fuzzy PID
FOFPD+I	Fractional-Order Fuzzy PD+I
PSO	Particle Swarm Optimization
FC	Fuel Cell
PI	Proportional Integral
PID	Proportional Integral Derivative

ABSTRACT

Due to the rapid increase in electrical energy requirements in marine power systems (MPSs), and to reduce the consumptions of fossil fuel, there is an emergent need to utilize renewable energy sources (RESs) in MPS, which has been an attractive field of research. The aim of this research is to present a novel approach of energy management and ancillary services for a shipboard micro-grid (SBM) integrated RE sources. Therefore, a MPS with PV-WT-FC, Hybrid Energy Storage System (ESS) and Diesel generator (DG) has been developed to relate an exact mobile islanded shipboard microgrid. The Energy management system is based on multi agent systems. The system is proposed with three different agents which are generation agent, load agent and battery agent keeping the information about generation, load demand and battery condition of the microgrid system. Dynamic programming is used to design the algorithms of the presented energy management system (EMS). Load Frequency control has been considered to study ancillary services. The shipboard power system is designed using the transfer function models with above said generating and storage system. Grasshopper Optimization (GOA) based PIDF control technique has been proposed to investigate the performance of LFC scheme of proposed novel SBM. GOA and PSO optimized controllers have been designed and performance evaluation carried out with respect to the conventional Fuzzy and ANFIS controller. The system responses have been analyzed in this work which reveals that the controllers designed are much more significant than the conventional ones. The responses obtained from the proposed controller compared with the literature to justify the novelty and superiority of the proposed controller. Also, the results obtained from the EMS shows a significant reduction of fossil fuel consumptions for the designed microgrid.

Keywords — *Marine Power Systems, Shipboard Microgrids, Load Frequency Control (LFC), Optimization, the fuzzy logic controller (FLC), Isolated Microgrid, Energy Management System, Photovoltaic (PV), Diesel Generator, Wind power generation, State of Charge (SoC), Dynamic Programming.*

CHAPTER 1

INTRODUCTION

1.1 Overview

With the increase in environmental issues, mainly because of global warming and destructive properties of CO₂ emissions as well as the scarcity of fossil fuel resources in the past few years, there is a need of new clean and sustainable energy source. The generation of power from the conventional sources has resulted in an increase in air pollution, therefore continuous efforts are been done to develop technologies which can produce clean power. Renewable Energy Sources (RESs) are one of the most possible alternatives to conventional sources. RESs can be used for power generation integrated with conventional resources. Since the increase in the use of diesel in marine has led to increased emissions of air pollutants. Therefore, there is a need for such marine vehicles, which can effectively be integrated with RE sources. These ships which effectively use integrated RE sources can also be named as hybrid power system ships and can use different sources for generation of energy such as solar, wind, fuel cell, etc. The use of such resources will not only help in reducing the cost of the generation but also help in environmental safety and improving the ship's overall efficiency and power system stability [1].

The Energy requirements in the shipboard are increasing day to day because of the increasing demand of the loads. The diesel generators used for supplying the load demand are not much enough to supply that much load. Therefore, there is a need for introducing and integrating RESs in the shipboard microgrid. RESs like PV, WT, Ocean Wave Energy can be integrated with diesel generators to meet the increasing load demands. Now to maintain a proper balance between the load demand and the power generations from different sources an energy management strategy is required. Energy Management will help in making sure that enough energy is available to all the loads and enough energy storage is there to tackle all the changes in load due to increase in peak load demands and other changes in modes of operation of the system. Therefore Power and energy management is considered as an important step for

providing continuous power supply to all the users under all conditions (i.e. normal or faulty) and is nowadays is often used in many areas as it helps in energy saving from RESs.

However, RESs is having the problem of maintenance and security of the power grid. Also besides these problems, the major problem of stability with respect to generation i.e. because of intermittent behavior of the RESs may affect the system voltage and frequency, making the system unstable. This problem can be prevented by using Energy Storage devices. ESSs such as the battery, flywheel or supercapacitor (SC) energy storage devices can be to store the energy from these intermittent sources and used in case of power requirements. These Energy Storage devices with RESs will help in maintaining the power quality and will make the MPS more reliable [2],[3].

With the use of RESs in the microgrid, there comes the issue of system stability. The system stability depends on the electrical load and frequency of the ship. To control the load and frequency of the ship various controllers are used. Conventional control schemes like PI, PD or PID can be used for Load frequency control of the system. Further Fuzzy based controllers like Fuzzy logic control, ANFIS, etc. can also be used for the control of LFC. In present scenario optimization schemes like GA, PSO, TLBO, GOA, etc. are used for optimal tuning of the gain parameters of the controllers to get the best response out of the system.

1.2 Literature Survey

The power system of a marine vehicle with generation sources like PV, WT, FC, and ESS can be associated with a movable isolated micro-grid (IMG)[1][4][5]. A number of researches [6-10] have been carried out with respect to the application of the IMG in the field of a marine vehicle. Several works have been done in using the islanded microgrid in shipboard. An L-Ion battery with a diesel generator for the operation of a ship crane has been proposed in [6]. In [7] the authors discussed the importance of hybrid PV and diesel system with integration of ESS in an environmental and economic point of view. In [8] the authors have analyzed the finest size of a hybrid PV/battery/diesel vessel power system (PS) but not by taking the marine vehicle into consideration. In [9] the fuel cost has been decreased using a PV system. In [10], a hybrid diesel/ PV/ battery PS was used for stability analysis.

A predictive control model is proposed in order to increase the use of power obtained from the renewable energy resources and therefore reducing the use of power from diesel generator (DG) and respectively the emissions of CO₂ [11]. An integrated power system (IPS) with diesel

generators, photovoltaic panels (PV), fuel cell (FC), and battery in which a decentralized model predictive control (MPC) system has been used to improve the overall efficiency of the ship power system [12].

A study has been done in which the ideal size of a PV generation system, an ESS and a diesel generator for a stand-alone ship power system has been determined to reduce the cost and emissions from the ship [13],[14]. Authors in [15] have presented a solution to the problem of fuel and emissions by integrating renewable energy with the Diesel Generators. They have also developed a 3 phase self-excited induction generator (SEIG) based renewable biofuel generator for a shipboard power system. Researchers in [16] analyzed the operation of BESS and PVs on an electric ship's power system to save the cost of the fuel.

Also, the energy storage system (ESS) can be used in ships such as batteries and supercapacitor storage systems. For proper utilization of these energy sources, we need to make an Integrated Power System(IPS) with a proper Energy Management System (EMS) which can ensure the full utilization of RE sources and reduce the use of fossil fuel [16]. The EMS should be capable of improving the ship's power system robustness due to system collapsing by providing continuous power and minimize fuel consumption. The EMS in combination with other control systems helps to prevent the collapse and to minimize the operational cost of the system. It also maximizes the performance of the vessel and increases the robustness of the system.

1.2.1 Energy Management System

To manage the balance between the generations and loads of a power system a Power and energy management strategy is required. This helps in making sure that enough energy is available to all the loads and enough energy storage is there to tackle all the changes in load due to increase in peak load demands, starting of large motors and other changes in modes of operation of the system[17]. Power and energy management is considered as an important step for providing continuous power supply to all the users under all conditions (i.e. normal or faulty) and is now a day often used in many areas as it helps in energy saving.

Researchers now days are continuously working on the implementation of an energy management system to the microgrid. In some systems, an EMS can be implemented for making important decisions regarding how to use the generators in the best way for efficiently producing electrical power. Many factors like the power requirements of the system, the power availability, the price of electricity, fuel cost, and many other considerations can be decided by using a smart EMS[18]. In electric vehicle power systems, many strategies of energy

management have been developed, which will help in reducing the fuel consumption as well as the flue gases emissions in an operating cycle by predicting the upcoming state or from the present scenario of the vehicle[19].

Going through the uses of the energy & power management in several areas it was found that PEMS is of great importance. In all-electric ship using a proper PEMS can help in controlling and managing the power and energy flow between the variable generators and loads in an efficient way to maintain quality of service. So, an Energy Management System (EMS) should have the capabilities of load and generation dispatch, load and generation scheduling and the control capabilities. It's important to have an average balance between the load demand and the power supply. By optimal scheduling of the power generating units according to the demand of power system can help to use the fuel in an economical manner as well as to achieve high efficiency, and this is only possible because of an EMS. EMS designed for the ship in normal conditions will determine the optimum power generation that must be there at a particular time, and will ensure the all the generators are having power-sharing, whereas in other conditions make sure that limited power is delivered to vital loads.[17]

The poor low-load efficiency conditions and the optimal scheduling of the power sources aboard can be improved by dispatching the controllable units in an emission-aware and cost-effective way. This will help in decreasing fuel consumption and improving the operating cost of a shipboard system [20]. The use power converters like devices in next generation of electric ships will not only help to optimize the behavior of the ship's power system in terms of reliability, size, weight but also increase the efficiency and reduce the cost [21]. An optimization model is used in which the scheduling of residential storage units and energy units charge-discharge operation is done, hence resulting in the cost minimization while minimizing the total peak demands [22]. An EMS was designed based on the Diesel Engines (DE) optimal working speed to minimize the fuel consumption and the correspondingly the polluting emissions [23].

To reduce the transients arising from the load changes the possibility of using the energy storage systems (ESS) has been presented. Using the ESS it was found that battery and supercapacitor energy storage devices can help in transient reduction.[24] Renewable Energy Sources (RES) and BESS could help in improving the fuel efficiency of the diesel engines hence modifying the Specific Fuel Consumption curve of the prime mover used in the system.[25]

An integrated power system (IPS) with photovoltaic panels (PV), fuel cell (FC), battery and two diesel generators in which a decentralized model predictive control (MPC) system is used to design a power/energy management strategy has been studied. This helps to improve the overall efficiency of the system.[12] Researchers in [14] analyzed the operation of BESS and PVs on a ship electric power system to save the fuel cost. The potential of Multi-Agent Systems (MAS) is presented in with the application to the power engineering field. The benefits of using the MAS over the other distributed artificial intelligence techniques have been featured. Also, the design, implementation, and the decision-making approach for MAS have been explained in [26]. Some existing works in which Multi-Agent Systems was used to design the Energy Management System are also presented in [27]. But the concept of Load Frequency Control (LFC) was not included in these studies which are important because of RESs in a shipboard microgrid.

1.2.2 Load Frequency control

LFC has always been a major problem in power system operation and control to supply sufficient and reliable high-quality power. Also because of rapid change in designs of power system i.e. structure, size and integrations of RE source which are uncertain the filed of LFC have become more significant. Also because of the rapid development of the Micro Grids and energy storage systems the Load frequency control has become a challenging task.

To deal with the issue of LFC energy storage system (ESS) are used in ships such as batteries and supercapacitor storage systems to deal with this. In independent MGs, the Renewable Energy Sources and ESSs both must be synchronized to control the frequency fluctuations by balancing the difference between the load demands and the generation from RESs. This process is known as Load Frequency Control (LFC). In shipboard MG the function of LFC is not only to control the frequency of the system but also to improve the whole efficiency of the Ship power system. In previous researches, several works have been done in developing the control strategy for solving the problem of LFC. Controllers based on intelligent, adaptive, robust and Predictive Control [1] have been used in the islanded MGs with Distributed Generations (DGs) in order to solve the problem of LFC.

A new intelligent Proportional–Integral (PI) controller is recommended to increase the robustness of the system for the LFC in MGs [28]. Since, there is a wide change in the operating situations of the LFC, the PI controller which is designed with respect to the minimal conditions cannot work properly in the transient conditions. So, Fuzzy Logic (FL) is used to solve the

problem, because in FL the control parameters can be adjusted according to operation condition [4]. But the problem with FL is that the system is having good performance only for particular membership functions. A complicated robust H-infinity control method for LFC of an islanded Micro Grid has been discussed in [29]. Small signal analysis and hierarchical control and are presented in [30] to improve the robustness of isolated MG. An LFC with Fuzzy PI controllers based on self-adaptive teaching–learning-based optimization is proposed in to improve the dynamic behavior of system [31]. In [32] a frequency control based on fuzzy system is proposed for a hybrid system with PV and diesel where the power fluctuations from PV output were also considered. To minimize the transient fluctuations, a self-tuned dynamic exponent and a fuzzy tuned dynamic PI control technique are designed in [33] to control the amount the charge and power in the different energy storage systems i.e. battery, air compressor air, flywheel, and supercapacitor.

In [34] a hybrid system consisting of WTG, DEG, aqua-electrolyzer (AE), FC along with ESS has been considered. Authors in this study have compared the H-infinity controller with the genetic algorithm (GA) based controller to improve the frequency response. A new modified optimization approach with FOFPD+I controller has been presented for Shipboard MGs for the LFC in [1]. In this, a Modified Black Hole Algorithm (MBHA) is used for tuning the parameters of the FOFPD+I controller. PSO optimization scheme is used for tuning the gain values of the PID controller for a single and two area Load Frequency Control [35], [36]. An LFC for a multi-area interconnected microgrid PS has been designed in which the grasshopper optimization algorithm (GOA) was used. GOA here is used to tune the gain values of the controller of a Fuzzy- PID controller in [37]. GOA is also employed to optimize the FOPI-D controller gains in [38].

In addition, Table 1.1 below presents the Literature review summary about the various types of generation systems, controllers, techniques for optimization and Energy Storage systems used for Load Frequency Control of power system in previous studies.

Table 1.1 below presents the Literature review summary about the various types of generation systems, controllers, techniques for optimization and Energy Storage systems used for Load Frequency Control

Author Name (Year)	Generation System	Energy Storage System	Controller	Technique	References
Amin Safari (2019)	DIESEL + WIND		ANN	PSO	[39]

Hongyue Li (2019)	DE+WT+PV	Battery	Sliding Mode Control	Lyapunov theory	[40]
Anil Annamraju (2018)	DE+WT+FC+PV	Battery	PI,FUZZY	GWO,PSO	[41]
Ameli (2017)	WTG+PV	battery	PI	PSO	[42]
Pablo F. Frack (2015)	DE+WT+FC+PV	SC	PI	Droop control	[43]
Hossam Ali (2019)	Thermal+WT+PV	Battery	(I controller) and coefficient diagram method (CDM)	virtual inertia control	[44]
Mohamed I. Mosaad (2014)	Thermal		PID, ANN, ANFIS	GA	[45]
Salma Elkawafi (2016)	DE+PV		PI	LMI(Time Delay)	[46]
Yanhe Xu (2018)	PV+hydro+thermal		PI	Artificial sheep algorithm (ASA)	[47]
S. Kayalvizhi (2017)	DE+PV+WT+FC	Battery	Fuzzy	Model Predictive Control	[48]
Kezhen Liu(2019)	DE+PV+WT+FC	FESS + Battery	linear active disturbance rejection control (LADRC)		[49]
Poluri Srimannarayana (2018)	Wind+Fuel+Diesel+Electrolyzer system		PID	Mosquito Flying Optimization	[50]
Ahmadreza Abazari(2019)	WTG, FC, DEG,PV	FESS+ BESS	fuzzy droop controller	ABC algorithm	[51]
Han Yunhao(2018)	DE+PV	Battery		coordinated control strategy	[52]
Mazin Mustafa Mahdi (2018)	SG+PV	Battery	Adaptive Proportional-Integral (API) controller	uses a model reference adaptive controller (MRAC)	[53]
Wondworsen Eshetu (2018)	WT+PV+Micro Turbine+Diesel + EV		Fuzzy	ANFIS	[54]
Mohammad Hassan Khooban (2019)	Sea+DE+PV	FESS+ BESS	PI	Black Hole Algorithm (BHA)	[55]
Mohammad-Hassan Khooban (2016)	DE+FC+PV+WT+ EV	FESS+ BESS	PI	Optimal General Type-II FLS	[28]
Mohammad-Hassan Khooban (2018)	DE+PV+WT	FESS+ BESS	SMC controller	optimal model-free nonlinear Technique	[56]
Ahmed Fathy (2019)	PV+thermal+WT		ANFIS+PI	ALO	[57]

Chittaranjan Pradhan (2019)	Thermal+Hydro +WT		Fuzzy logic	Modified Jaya Algorithm	[58]
Prakash Chandra Sahu (2018)	WT+PV+ Microturbine+ DE+FC	FESS+ BESS	Fuzzy Controller	Improved-salp swarm optimized type-II	[59]
Sandeep D. Hanwate (2018)	Thermal		PID	Quadratic Regulator Approach with Compensating Pole (QRAWCP)	[60]
A. Madureir (2017)	Microturbine +PV+FC+WT	FESS		Centralized Secondary Control	[61]
Jonglak Pahas (2015)	WT+Thermal	PHEV		Multiple Model Predictive Control (MMPC)	[62]
Hassan Bevrhan (2016)	DE+MT+FC +PV+WT	FESS+ BESS		H_{∞} and μ -synthesis robust control techniques	[63]
Chengshan Wan (2018)	PV+DE+WT	Battery	Double Sliding Mode Controllers	Disturbance Observer	[64]
Attia A. El-Fergan (2016)	PV+DE+WT	SMES+ BESS	PID	social-spider optimizer(SSO)	[65]
Alireza Ghafour (2018)	Windfarms+ Microgrids		Fuzzy-Adaptive Control	modified hierarchical coordinated or droop control	[66]
Hamid Reza Baghaee (2018)	WT+PV+FC	Battery	Sliding Mode Control	Lyapunov function theory and Fractional Order	[67]
Mohammad Reza Khalghani (2017)	Distributed Generator (DG), a load, a wind turbine and two EVs		PID controller	Hebb Learning Mohammad	[68]
Xin Wang(2018)	WT+EV+MT		Robust Controller	MPC	[69]
Manoj Kumar Debnath (2017)	Thermal+Hydro + Gas		Cascaded PD-Fuzzy-PID controller	Hybrid GWO-TLBO technique	[70]
M. Rezasudin Basir Khan(2018)	Mini-hydro		Self-tuning PD	Fuzzy	[71]
Meysam Gheisarnejad (2019)	Ocean+DE+PV	FESS+ BESS	Fractional Order Fuzzy PD/fuzzy PI	enhanced JAYA (EJAYA) algorithm	[72]
Mohammad-Hassan Khooban (2018)	Sea Wave+ DE+PV+WT	FESS+ BESS	Fractional Order Fuzzy PD+I	Modified Black Hole Optimization	[1]

				Algorithm (MBHA)	
Navid Vafamand (2019)	Sea Wave+ DE+PV+FC	FESS+ BESS	Robust Stabilizing Controller	LMI technique and the Lyapunov stability	[73]
Moataz Elbaz(2012)	DE+PV	Battery			[74]
A. Hasib Chowdhury (2015)	SG+W+PV	Battery			[75]

1.3 Research Motivation

The dependency on electricity of all marine and other vehicles is increasing day by day. On the other hand, the electricity generated from the diesel generator is costly and not much enough to meet the demands, which results in a gap between demand and supply. This gap in the energy leads to the problem of energy scarcity and hence to frequency fluctuations in the power system and can only be filled by using some distribution generators. Integration of renewable sources is one of the best solutions, as they not only reduce the dependency on fossil fuels but also the cost. However, the integration of such sources poses a different kind of problems due to their uncertain availability. Therefore, a shipboard microgrid is studied with distributed generation and renewable integration under a deregulated environment becomes of great interest. Now the main problems which rise in the proposed microgrid are

1. Ensuring the proper availability and balance of Energy.
2. Maintaining the load and frequency.

To solve these problems some control schemes must be introduced. The problem of Energy imbalance and scarcity can be handled by designing an Energy Management System which will maintain the balance between load and generations. EMS will also help to reduce the overall fuel consumption in ships. According to some works by using a proper EMS they saved up to 18% [23], 13.5% [76] and 2.86% [77] of the fuel without using RE sources. Further using RE sources in the shipboard can help in more reduction of fuel consumption. To maximize the use of energy produced by the renewable resources an idea of integration of RE sources to the ship-board microgrid has been presented. An instantaneous energy management scheme for the hybrid ships power system has also been presented which ensures the energy sustainability for the ship. In addition, load frequency control (LFC) has been a great field of research in the past few years there are lots of work which has been done in the Frequency control of a

Microgrid. But the literature [1-5], [33] shows that there are only a few works related to the Load Frequency control in the Shipboard microgrid (SMG).

Therefore, this work focuses on Energy management and frequency control of a shipboard microgrid power system with distributed generation and Wind-Solar-Ocean integration under a deregulated environment with the help of both conventional, Intelligent and optimized controllers.

Load Frequency Control(LFC) has two main tasks:

- Maintaining frequency and generated power output (megawatt) in the interconnected power system.
- Controlling the change in tie line power between different areas.

1.4 Objective of the Work

The review of the current technical literature reveals the need to introduce an improved Energy Management System and load frequency control techniques for the shipboard microgrid. With respect to this background, the main objectives and contributions of this thesis are as follows:

1. To develop a shipboard microgrid system consisting of diverse sources like PV cell, wind turbine generator, Ocean wave generator, Fuel Cell, Supercapacitors, battery system, diesel generator.
2. To develop an Energy Management System for the designed system for cost reduction using dynamic programming.
3. To develop a transfer function model of isolated Shipboard Microgrid.
4. To design a controller and simulate the developed model for performance evaluation.
5. To conduct the sensitivity analysis for the designed system.

1.5 Organization of the Dissertation

The work carried out in this project has been coordinated in chapters. The organization of these chapters is as follows:

Chapter 1 deals with Introduction and Literature Review. The past works on the microgrids and the shipboard power system, Energy management and problem of Load Frequency Control (LFC) are briefly reviewed.

Chapter 2 deals with the details of the system under study. The chapter presents the modeling of the shipboard microgrid. Model for WT, PV, Sea wave Generator, Diesel Generator, Energy Storage systems, etc. are discussed here.

Chapter 3 deals with the different control techniques proposed in the research. The procedure for designing different Controllers such as conventional controller, Artificial intelligent controllers, Optimized Controllers for LFC are discussed.

Chapter 4 deals with simulation results and discussion. The reliability, robustness, and effectiveness of the proposed controller techniques are presented and simulated results are discussed.

Chapter 5 deals with the conclusion and future scope of the work and Reference.

CHAPTER 2

SHIPBOARD MICROGRID

2.1. Microgrid

Microgrids can be defined as the energy networks that consists of the integration of the various energy sources with suitable energy storage systems. Microgrids can work in two modes i.e. grid-connected and islanded modes and are capable of transferring power between both these modes of operation. Some microgrids may have no connection available to the main grid, such as those made for remote communities or industrial spots; these microgrids always work in islanded mode and are referred to as isolated microgrids. Since Microgrids are having the capability to be controlled locally, therefore they do not get affected during the blackouts or when there is a fault at the grid. In islanded mode, they are capable of supplying continuous supply to their local loads. Since these microgrids are also having renewable energy sources and energy storage systems like batteries.

The overall system efficiency of the system can be increased using DC microgrids [78]. According to various publications, to solve the operational issues of the shipboard grid DC microgrids can play an important role. For meeting the heavy non-linear Loads demands DC microgrid with Solar PV generation and hybrid energy storage (supercapacitors and Li-ion batteries) can be used. A DC is having the capability of injecting reactive power as an ancillary service which will help in voltage support in a microgrid [79].

2.1.1 Isolated shipboard microgrid Modeling

The design of the ship's power system is some but similar to an isolated/ stand-alone microgrid system. The ship service loads and the propulsion loads are connected to the same electrical network. An Isolated SMG represented in Fig. 2.1 employs distributed generations such as WTs, FCs, PVs, and ESS units like Battery Energy Storage (BES) System and Super Capacitor Storage (SCS) System to encounter the load demands [14]. The operations between the power generated on the ship and the microgrid are organized by the Ship Energy management system

(SEMS) using the bidirectional communication links which share the information among all the components of the system. The design of the ship's power system is some but similar to a stand-alone/isolated microgrid system. A common electrical network is used to connect the load's ship service and propulsion. Generally, the power systems of the ship consist of an electrical system for services like communication, weapons, hotel load, navigation and all other auxiliary loads and a mechanical system for propulsion. All these equipment requires power to operate and this power is supplied by the distributed generators (DGs) used in the ship power system.



Fig 2.1 Shipboard Micro Grid

2.1.2 Diesel Power System Model

Since the diesel power system (DPS) is having many benefits such as high efficiency, low maintenance, less starting time, etc. these are the proper backup units in the islanded shipboard MGs. These controllable DPS can also help in tracking the load demand and always give a fast and reliable response [80]. The voltage or power fluctuations from the uncontrollable DGs like WT, PV and changing load demands can be successfully balanced by the DPS. The DPS used in this work is designed using the transfer function model of 1st order for both the governor and as well as the generator followed by a saturation function [5] as shown in Fig 2.2.

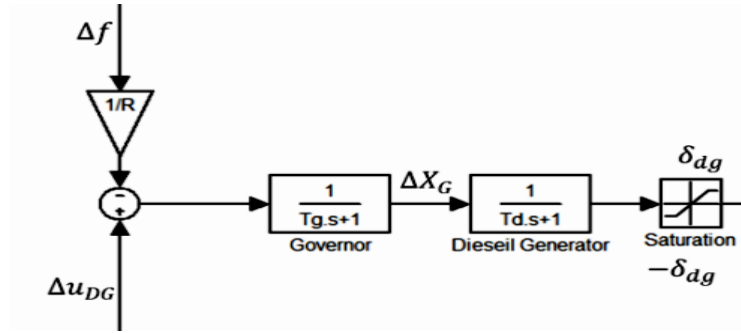


Fig 2.2 First order model for a Diesel Generator

The Diesel Power system(DPS) is used as a backup in the shipboard power system i.e. output power from the DPS is only provided during higher power requirements or when the voltage and frequency are unbalanced.

2.1.3 Photovoltaic Model

Photovoltaic cells (PVC), are prepared from semiconductor materials to generate electrical energy from the light energy (photons). The equivalent circuit diagram of PVC is placed in Fig.2.3 and represented by a series resistor (R_s), light current (I_L), which causes power loss due to boundary and external contacts. A parallel resistance (R_{sh}) is also used which produces a small leakage current. The power obtained from the PVC is irregular because it depends on the irradiance of the sun and temperature; therefore, the model of the PVC is represented by a random power source [1], [4], [5]. Here the Photovoltaic model is given as a disturbance for the LFC to the microgrid of the ship.

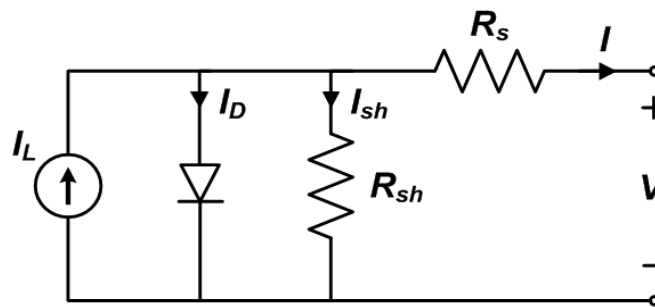


Fig 2.3 Electrical Equivalent Circuit for a PV Cell

The instantaneous current and diode current of PVC is represented by the following equations:

$$i_{pv}(t) = I_L - I_D \quad (2.1)$$

$$I_D = I_{rs} (e^{\gamma(v_{pv}(t)+i_{pv}(t)R_S)} - 1) \quad (2.2)$$

$$\therefore i_{pv}(t) = I_L - I_{rs} (e^{\gamma(v_{pv}(t)+i_{pv}(t)R_S)} - 1) \quad (2.3)$$

Where v_{pv} and i_{pv} denotes the voltage and current through the PVC array.

2.1.4 Ocean Wave Energy Generator Model

From the recent improvements in ocean wave energy generators, it is possible to generate electricity from the Sea Waves. Since the energy generated from the ocean waves falls under the categories of RESs, there is still some work to be done to exploit this source of energy to its full. The ocean wave energy is converted into electricity using a device known as ocean wave energy converter (OWEC). This OWEC is considered a renewable source of energy here in this proposed system of LFC and is represented by a simple linear first-order transfer function ignoring all the nonlinearities of the OWEC [1].

2.1.5 Wind Turbine Generator Model

The power generated from WTG is directly proportional to the wind velocity (V_w). Therefore, the equation below presents the power (P_w) produced by the wind turbine:

$$P_w = \frac{1}{2} \rho A_r C_p (\gamma, \beta) V_w^3 \quad (2.4)$$

where ρ is the density of air in $[\text{kg}/\text{m}^3]$, A_r denotes the area of the blades of the turbine in $[\text{m}^2]$, C_p denoted the power coefficient, and V_w denotes the speed of wind in (m/s). The above equation(Eq.4) is used to model the performance of the wind turbine as a function of blade pitch and tip speed ratio angle. The tip speed ratio of the WT is the ratio of the speed at the tip of the blade to the wind velocity [81]. The value of A_r for a vertical axis turbine is given as:

$$A_r = 2hr \quad (2.5)$$

Here, h denotes the turbine rotor height. Therefore, the torque (T_T) produced by the Wind Turbine is given as:

$$T_T = \frac{P_w}{\omega} = \frac{\rho A_r C_p V_w^3}{2\omega} \quad (2.6)$$

The wind turbine (WT) model considered here for the study is the same as a wind turbine in [81][82], and is modeled using MATLAB/Simulink.

2.1.6 Fuel Cell Model

The Fuel Cells (FCs) can be defined as static electrochemical devices, which transforms the chemical energy into electrical energy. In this work, the Proton Exchange Membrane Fuel Cell (PEMFC) were used because of their ability to operate at lower temperatures i.e. (80–100°C) and also because of their quicker ignition time. These abilities make PEMFC as a potential choice to be used in commercial as well as residential areas [83]. Because of their simple assembly and high power density, PEMFC is perfect to be used in the shipboard power system. Moreover, the dynamic model of the PEMFC is discussed in [84]. The output voltage (V_{cell}) of PEMFC is given as:

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \quad (2.7)$$

$$\eta_{act} = -B \ln(CI_{FC}) \quad (2.8)$$

$$\eta_{ohmic} = -R^{int} I_{FC} \quad (2.9)$$

C denote the empirical large constant.

$$E = N_o [E_o + \frac{RT}{2F} \log[\frac{p_{H_2} \sqrt{p_{O_2}}}{p_{H_2O}}]] \quad (2.10)$$

The dynamic model of PEMFC is developed, and simulated with help of above equations (Eq.2.7-2.10) where E_o denotes the voltage across each cell when open circuited, p_{H_2O} denotes the water's partial pressure, and p_{O_2} denotes the partial pressure of oxygen.

2.1.7 Energy Storage System

The ESS should supply quick energy to the shipboard power system. It will also help to reduce the oscillations in the power system. The ESS considered here are the batteries and SCSS because of their good performance. Batteries are robust and are less costly which makes them perfect and very practical to be used in a shipboard MGs. The BES model consists of a voltage controlled source, E and an internal resistor [84][85]. The battery voltage and state of charge (SOC) are expressed by the following equations:

$$E = E_o - \frac{KQ}{Q - \int idt} + A \exp(-B \int idt) \quad (2.11)$$

$$SOC = 100 \left(1 - \frac{1}{Q} \int idt \right) \quad (2.12)$$

The parameters A , B , E_o , K , Q are mentioned in table 1.

2.1.8 Ultra/Super Capacitors (SCs) Model

The Ultra/Super Capacitors (SCs) consists of two metal electrodes with a dielectric material in between. The SC bank is represented by a group of equivalent capacitors and a group of equivalent resistances. Fig 2.4. demonstrates the equivalent circuit of the SC bank unit which comprises a series resistance (R_s) having a charging and discharging resistance, a capacitor (C_{sc}) for self-discharging losses and parallel resistance (R_p). The SC bank is described through its voltage produced $V_{sc}(t)$ and energy quantity (E_{sc}). The amount of energy needed determines the size of the SC bank [83].

The SC bank is made by a combining number of SCs in series and parallel. SCSS is having more capability of exchanging power and a high density of energy storage capacity. Also, the high efficiency of these devices is one of its greatest advantages. One more advantage of SCSS is its faster response and longer life. SCSS can provide essential energy during the time of instabilities in the system because of different renewable energy sources, hence removes the fluctuations.

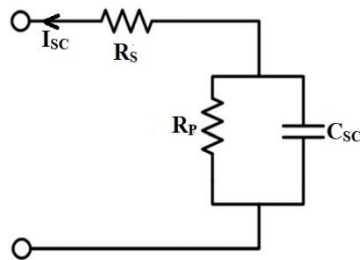


Fig 2.4 Equivalent circuit of Supercapacitor

The Voltage generated by the SC is given as:

$$V_{SC}(t) = V_i e^{-\frac{t}{R_s \cdot C_{sc}}} \quad (2.13)$$

Whereas, E_{sc} denotes the total energy drawn from the supercapacitor.

$$E_{sc} = \frac{1}{2} C (V_i^2 - V_f^2) \quad (2.14)$$

2.2. General scheme of the MG for Energy Management

The block diagram of the system is presented in Fig. 2.5 The figure of the system shown is essentially a power system of a ship which consists of different power generating units as well as the propulsion system and the service loads, the power system considered generates its power from the solar PV panels, fuel cell, wind power generator, and diesel generators. The instantaneous power which is generated from these renewable sources i.e. solar and wind are measured using M1 and M2 meters, respectively whereas the DM measures the power generation from the Diesel Generator [86].

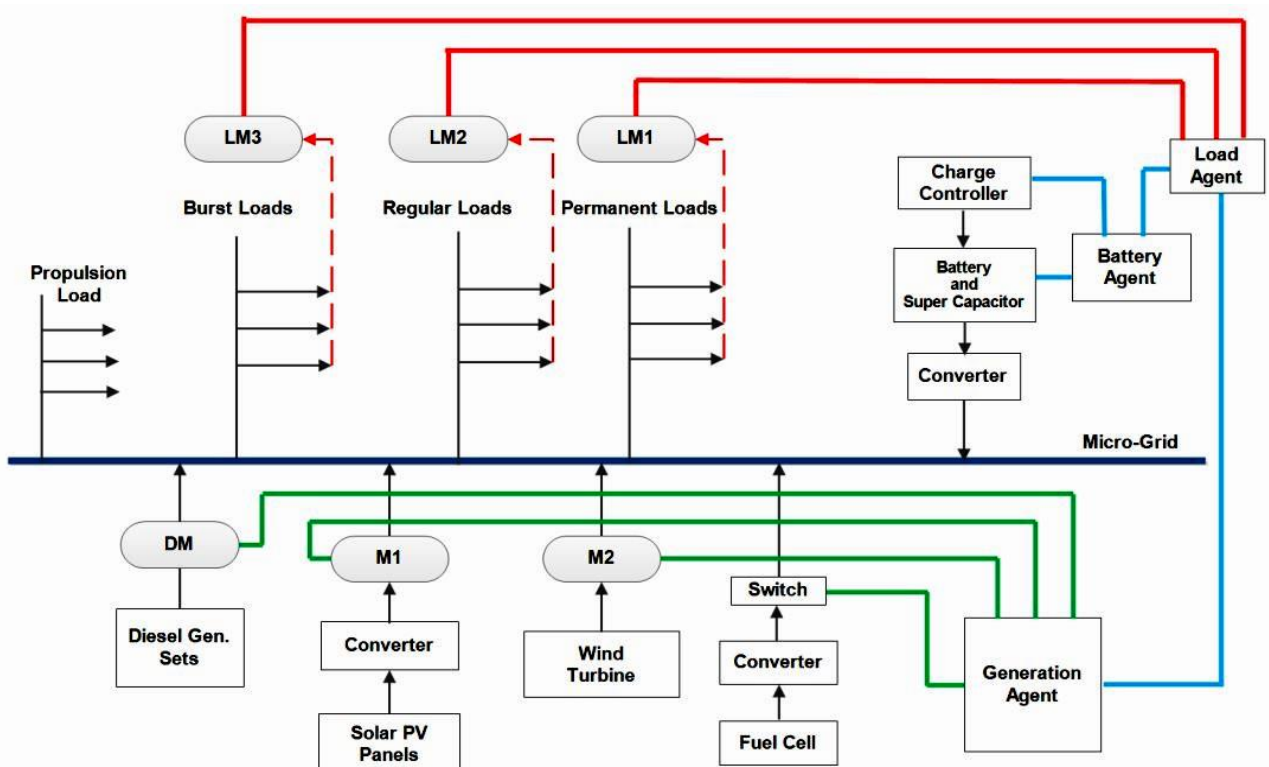


Fig 2.5 Block Diagram of the Proposed EMS

The power converting devices such as inverters are used to convert the DC power generated from solar PV and fuel cell into AC power. A switch is used as a controller to switch on or off the FC as shown in figure 2. A common bus is there which collects all the power from the different sources and is connected to the shipboard. The system also has a suitable BESS and SCESS, which is a hybrid storage system to overcome the issue of the fluctuating nature of Renewable Energy sources. The Loads connected in the service load of the ship micro-grid are classified into permanent, regular and burst loads, shown in figure 2. The load demands from

these different loads can be measured through 3 Load Meters (LM), which are labeled as LM1, LM2, and LM3 for different loads, respectively as used in [86].

For controlling and managing the different power system components an EMS is required. So, according to the need of the system a MAS-based EMS is proposed which can ensure a balance system operation between the generated and the required powers as in [87]. In this work, for designing the EMS three agents were identified and developed which are the generation, load and battery agents. The agents developed are the controllers based on software which work in synchronization with each other. The function of each agent is to obtain information individually from their related field which may be the amount of power generated, the condition of the battery, the load demands and the information about the other agents in its closeness. Suitable decisions are made regarding the power flow and the load scheduling based upon this information. Fig. 2.6, 2.7 and 2.8 show Generation, Load and Battery Agents respectively.

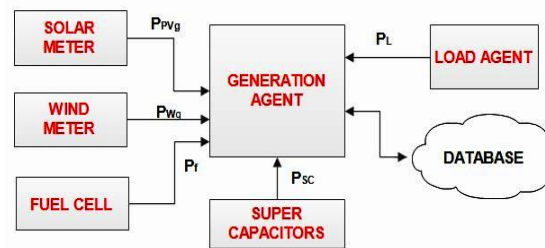


Fig 2.6 Schematic of Generation Agent

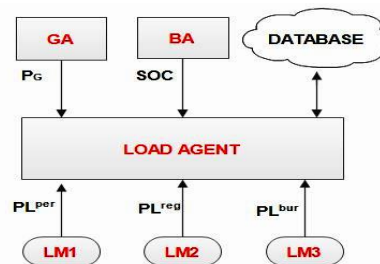


Fig 2.7 Schematic of Load Agent

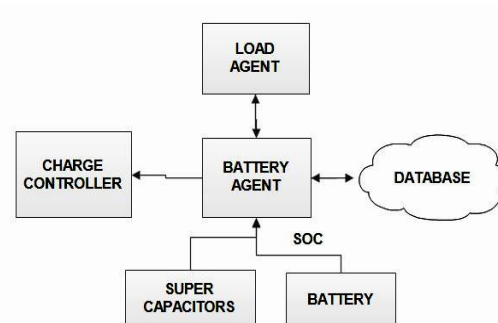


Fig 2.8 Schematic of Battery Agent

2.2.1 Formulation of the problem

The total power which the ship can generate is given as

$$P_G(t) = \sum_{i=1}^n P_{g_i}(t) \quad (2.15)$$

Where, i is the total number of generating units, the In

$$P_G(t) = P_{dg}(t) + P_{pv_g}(t) + P_f(t) + P_{wg}(t) + P_b(t) + P_{sc}(t) \quad (2.16)$$

The system which we have designed is based on the battery's real-time state of charge $SOC(t)$. $SOC_{\min} \leq SOC \leq SOC_{\max}$, are the constraints of $SOC(t)$, where SOC_{\min} and SOC_{\max} shows the min and max limits of $SOC(t)$.

Mode 1:

In this mode, if $SOC < SOC_{\min}$ or $P_{pv_g}(t)$ and $P_{wg}(t)$ are not available then,

$$P_G(t) = P_{dg}(t) \quad (2.17)$$

Now if, $P_{dg}(t) > P_L(t)$

$$\text{Then, } P_{plus}(t) = P_G(t) - P_L(t) \quad (2.18)$$

If this $P_{plus}(t) > 0$, then the extra power generated is feed to the battery storage system.

Mode 2:

If $SOC_{\min} \leq SOC \leq SOC_{\max}$ and $P_{pv_g}(t)$ $P_{wg}(t)$ are available, then

$$P_G(t) = P_{pv_g}(t) + P_{wg}(t) + P_{fg}(t) + P_{sc}(t) + P_b(t) \quad (2.19)$$

Here, the different generating units are used as per the load requirements.

Now if, $P_G(t) > P_L(t)$

$$\text{Then, } P_{plus}(t) = P_G(t) - P_L(t) \quad (2.20)$$

If this $P_{plus}(t) > 0$, then the extra power generated is feed to the battery storage system.

Now here if there further increase in load demand then the generation is shifted to the Diesel generator for excess load demand.

$$\text{i.e. } P_G(t) = P_{dg}(t) + P_{PVg}(t) + P_{wg}(t) \quad (2.21)$$

and the load demands are met accordingly.

Mode 3:

If $SOC > SOC_{\max}$ and, $P_{PVg}(t)$ or $P_{wg}(t)$ are available

$$P_G(t) = P_{pv}(t) + P_{wg}(t) + P_{fg}(t) + F_{SC}(t) + P_b(t) \quad (2.22)$$

Here, the different generating units are used as per the load requirements.

Since, SOC_{\min} and SOC_{\max} are the limits of $SOC(t)$. Similarly, let E_b^{\min} and E_b^{\max} are indications of Energy stored in the battery. Now if, $P_D(t) > P_G(t)$ then, $P_{plus}(t) = P_G(t) - P_L(t)$. If this $P_{plus}(t) > 0$, then the extra power generated is feed to the battery storage system. P_{plus} Is the surplus power and is used to charge the BESS.

Now, the battery charging and discharging equations are given as

$$P_{BC}(t) = [P_G(t) - P_L(t)]\eta c \quad (2.23)$$

$$P_{BD}(t) = [P_L(t) - P_G(t)]\eta d \quad (2.24)$$

respectively where ηc and ηd are the charging and discharging efficiency of the battery system. Also, the battery will charge and discharge according to the following equations

$$E_b(t + \Delta t) = E_b(t) + (P_{BC}(t) \times \Delta t)\eta c \quad (2.25)$$

$$E_b(t + \Delta t) = E_b(t) - (P_{BD}(t) \times \Delta t)\eta d \quad (2.26)$$

respectively where $E_b(t+\Delta t)$ can be denoted as the energy stored in BESS at the end of the time interval Δt . Also, the Energy in output and Consumption of fuel according to [88] are calculated as:

$$E = P * hr * d \quad (\text{kWh}) \quad (2.27)$$

$$C = E * Ckwh \quad (\text{Liters}) \quad (2.28)$$

respectively.

Where, E & P = active electric energy & electric power in the output of the diesel engine in kWh & kW.

hr = number of hours the generator set runs in a day.

d = number of days the power generator runs.

Ckwh = Fuel Consumption per kWh.

C = Consumption of fuel in litres.

2.3. General scheme of the MG with Load Frequency Control

The general scheme of shipboard MG with secondary ALFC controller is given in Fig. 2.9.

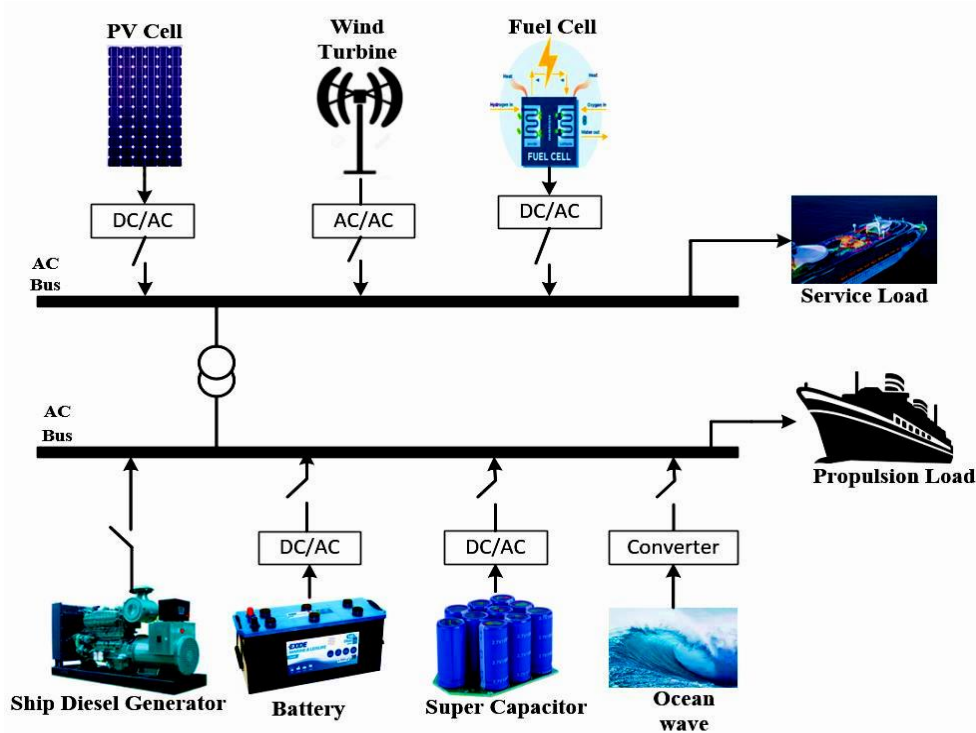


Fig 2.9 System investigated for LFC in a shipboard MG

The schematic of the proposed secondary LFC scheme for a ship consisting of PVC-Sea-WT-Fuel Cell-Diesel Generator-Energy storage system (batteries & supercapacitors) and power disturbance ΔP_D loads is represented in Fig.2.1. The nonlinear dynamics of DGs and storage systems are linearized to give a simple dynamic model of the power system. Dc/ac inverters and dc/dc converters are employed to connect the dc source to ac MG as represented in Fig. 2.9 [1],[88]. Additionally, PEMFC and diesel ship power are used for secondary LFC of the isolated shipboard MG. The Frequency deviations (Δf) obtained from the shipboard microgrid shown in Fig 2.10 is given as:

$$\Delta f = (\Delta P_D + \Delta P_{PV} + \Delta P_{FC} + \Delta P_{sea} + \Delta P_{WT} + \Delta P_B + \Delta P_{SC} - \Delta P_L - D\Delta f) / 2H \quad (2.29)$$

CHAPTER 3

CONTROL METHODOLOGY

3.1 Dynamic programming for Energy Management System

Dynamic Programming is a technique for resolving a complex problem by converting it into a group of simpler small problems. These sub-problems are solved one by one, once at a time, and their solutions are stored in the form of memory-based data structure i.e. array, map, etc.

The EMS designed here is done on the basis of the dynamic programming algorithm. Dynamic programming algorithm remembers the results from the past and uses those results to find the new results. For optimization of the problems where there are multiple solutions, but we need to find only the best one, dynamic programming method is generally used.[89] The algorithms used in the proposed system are described below with the help of the Flowchart representations. Fig 3.1 represents the flowchart for the Mode 1 of the Energy Management System which is when the value of the SoC of the battery lies between the range of maximum and minimum values i.e. ($SOC_{min} \leq SOC \leq SOC_{max}$). In this case/Mode the system will work according to the designed EMS system.

Fig 3.2 represents the flowchart for the Mode 2 of the Energy Management System which is when the value of the SoC of the battery is either greater than the maximum value or less than the minimum value i.e., when ($SOC < SOC_{min}$) and ($SOC > SOC_{max}$). In this case/Mode the system will work according to the designed EMS system.

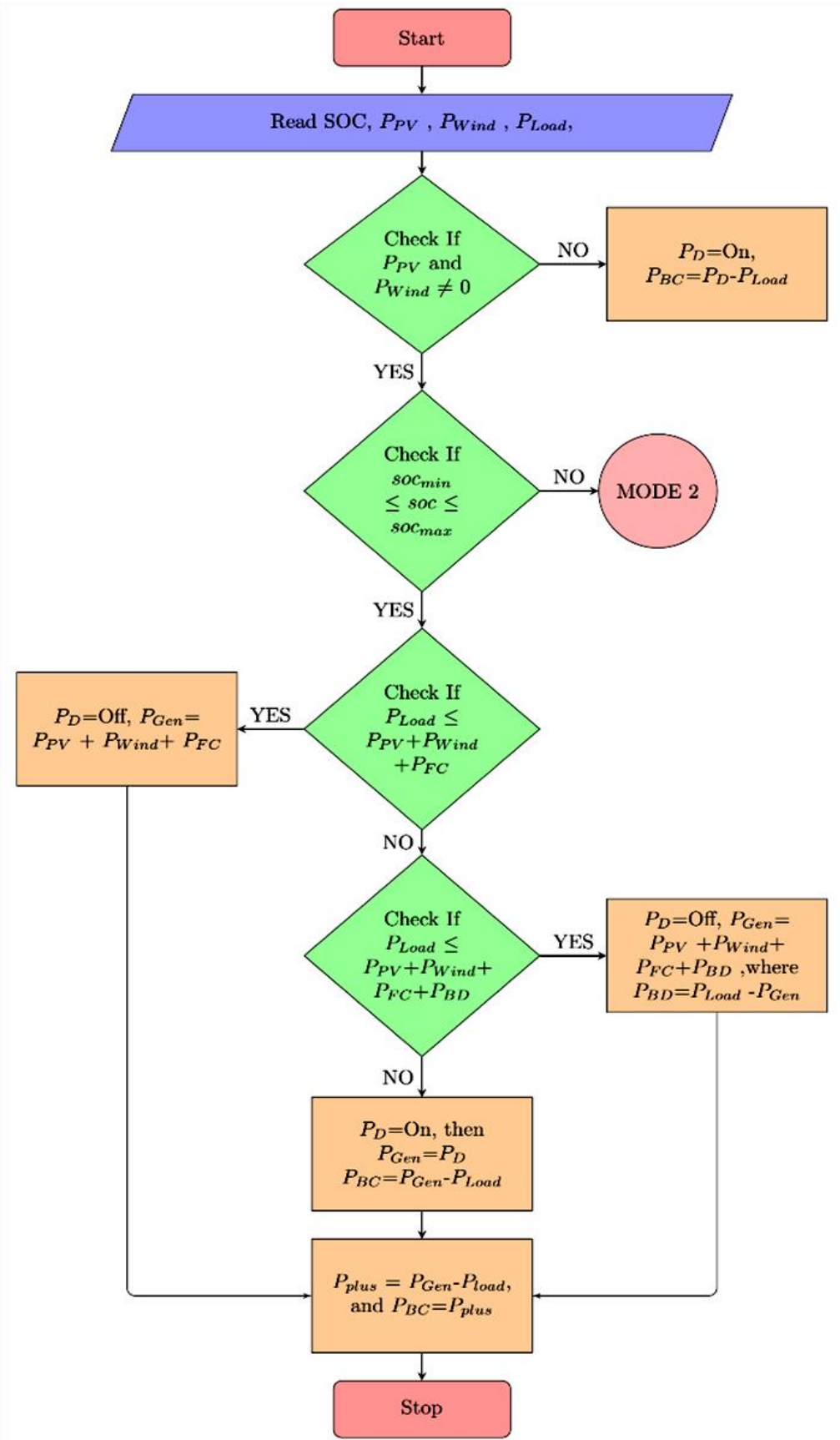


Fig 3.1. MODE 1: Power Management Algorithm, when $SOC_{min} \leq SOC \leq SOC_{max}$

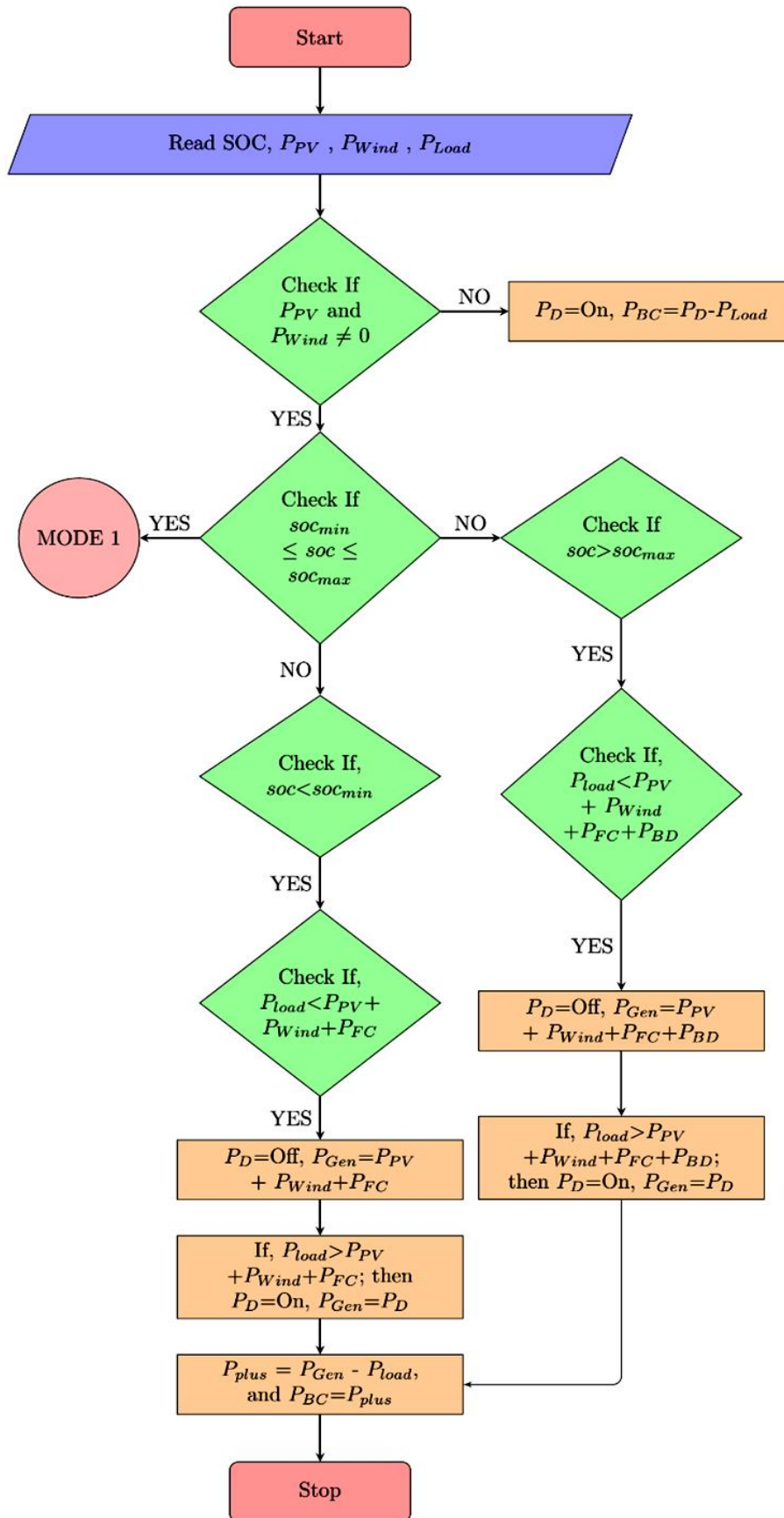


Fig 3.2. MODE 2: Power Management Algorithm, when $SOC < SOC_{min}$ and $SOC > SOC_{max}$

3.2 Control Techniques for Load Frequency Control

3.2.1 PI Controller

A PI-Controller is a combination of Proportional and Integral Controllers as shown in Fig. 3.3. The equation of the PI controller is shown in Eq. (3.1)

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt \quad (3.1)$$

Where $e(t)$ is the error signal, k_p is the proportional gain, k_i is the integral gain and $u(t)$ is the output of the controller. In LFC the error signal $e(t)$ is ACE and controller output $u(t)$ is the input to the governor.

By varying the value of gains K_p & k_i the controller is tuned to give the desired output. The proportional controller gives a proportional output signal according to the input error signal and the integral controller makes the system more robust.

For tuning the controller, first proportional gain k_p is adjusted to a value such that the system error becomes minimum. If the output of the system is not equal to the desired value or if there is need of any fine adjustment then the integral gain is adjusted such that the error becomes acceptable with keeping proportional gain constant. By repeating the above process, the gains of the controller are adjusted such that the error becomes the minimum and the output of the system becomes similar to the desired output. But this method is time-consuming and isn't that much effective. Another way is to optimize the value of k_p and k_i with the help of optimization algorithms like a genetic algorithm or particle swarm optimization.

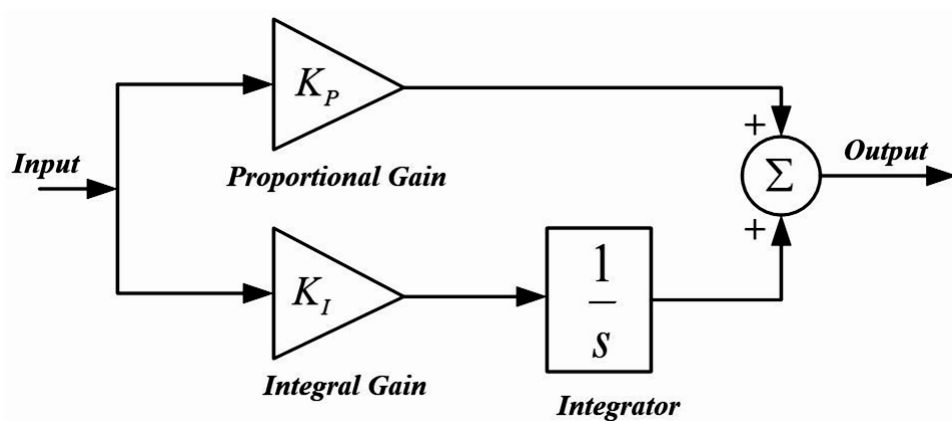


Fig 3.3 Block Diagram of the PI controller

3.2.2 PID Controller

Proportional Integral Derivative Controller also a conventional controller just like the PI controller. PID controller has three components Proportional, Integral and Derivative controller gains as shown in Fig.3.4. By adjusting the value of these three gain parameter the controller could be tuned to operate in numerous operations. In it the P is proportional to the error $e(t)$ such that if the error is large and negative the control output will be large and negative taking into account the gain factor k_p . Term Integral part takes the past value and integrates them over time to give output. In the event that proportional part is can't wipe out the error completely, at that point integral term endeavors to take out the rest of the mistake by adding a controlled impact because of the memorable estimation of the error. Once the error is diminished, the integral term will cease to grow. The Derivative part gives the best estimation of the future trend of the error, based on the current rate of change of error. The faster the change the more noteworthy the controlling or damping impact.[90]

For tuning the controller, first, adjust the proportional gain to such a value that the system error becomes minimum. If the output of the system is not equal to or near the desired output then the integral gain is adjusted such that the error becomes negligible with keeping proportional gain constant. By repeating the above process, the gains of the controller are adjusted such that the error becomes the minimum and the output of the system becomes similar to the desired output. But this method is time-consuming and isn't that much effective. The output of the controller is given by Eq. (3.2).

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{d}{dt} e(t) \quad (3.2)$$

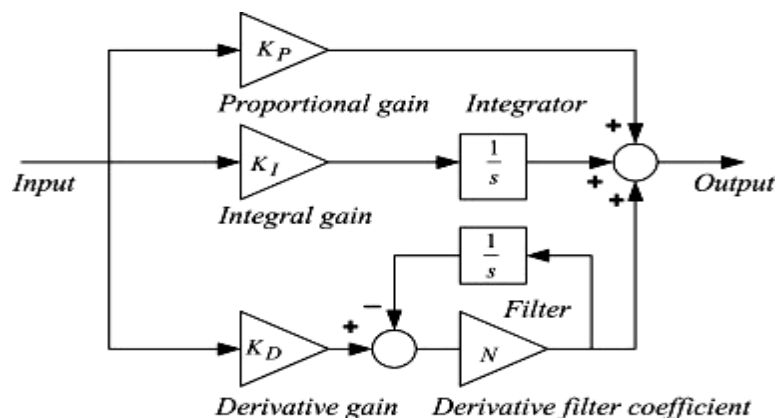


Fig. 3.4 Block Diagram of PID controller with Filter

3.2.3 Fuzzy Logic based Controller

Fuzzy Logic Based Controller has been used in load frequency control for quite a long time and has proven its robustness in comparison to conventional controllers. Block diagram of the Fuzzy Logic Controller is shown in Fig. 3.5, which has two inputs namely error and change in the error of the system and one error correcting signal output. In LFC the error and change in error are the ACE and d/dt of ACE. The inputs crisp signals are first fuzzified into fuzzy values with the help of fuzzifier. The resulting fuzzy values are then fed to the inference system which acts as a kernel of the controller and simulates the human decision-making crosschecking the values with the provided rule base. Fuzzy rule base holds the knowledge about the operation of the process of the domain which inference engine utilizes to determine the output of the controllers with respect to the inputs. The fuzzy output from the inference system is then passed onto defuzzifier, which converts the fuzzy values to crisp and hence the desired output is obtained [91].

For designing a Fuzzy Logic Controller, first, the input and output of the plant must be recognized. The input signals are then expressed in some linguistic label using fuzzy subsets such as Large Positive(LP), Medium Positive(MP), Small Positive(SP), Very Small(VS), Small Negative(SN), Medium Negative(MN), and Large Negative(LN). Formulate the membership function for each fuzzy subset that was obtained in the previous process. Construct the rule base according to the input-output relation. Table 3.1 below shows the rule base for the designed fuzzy based controller.

Table 3.1 Rule Base for Fuzzy controller

$e/\Delta e$	LP	MP	SP	Z	SN	MN	LN
LP	LP	LP	LP	MP	MP	SP	Z
MP	LP	MP	MP	MP	SP	Z	SN
SP	LP	MP	SP	SP	Z	SN	MN
Z	MP	MP	SP	Z	SN	MN	MN
SN	MP	SP	Z	SN	SN	MN	LN
MN	SP	Z	SN	MN	MN	MN	LN
LN	Z	SN	MN	MN	LN	LN	LN

All the data obtained is then fed into the Fuzzy Editor in MATLAB and a FIS file is generated. In this study, Mamdani membership functions have been used.

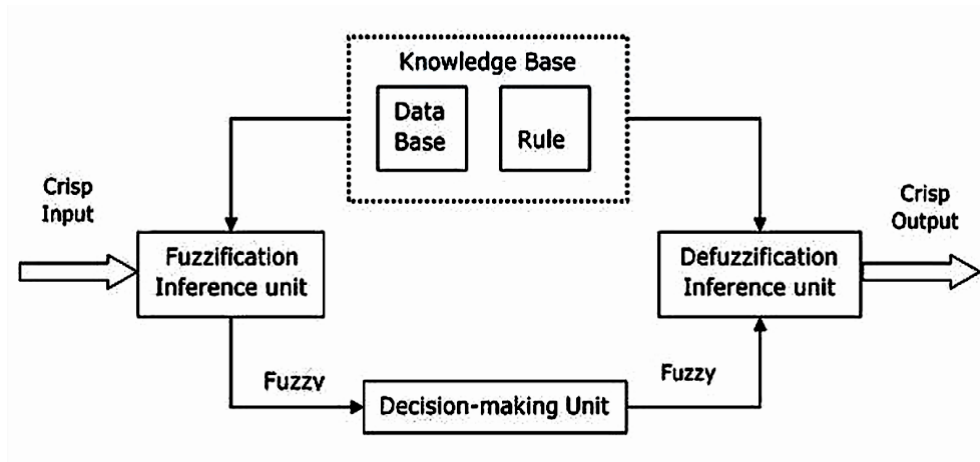


Fig 3.5 Block Diagram of Fuzzy controller

3.2.4 ANFIS based Controller

ANFIS is a method of combining both Adaptive neural network (ANN) and FLC. It is having advantages of both fuzzy and ANN *which helps in* designing a model that uses the learning ability of a neural network and the knowledge of fuzzy theory in an interpretable manner and to optimize its parameters. Fig 3.6 represents the block diagram for Neuro-Fuzzy controller system. The fuzzy based membership functions having certain rules figures out the input to the ANFIS. A set of output characteristics defines these rules and then an output having a single value is attained from the Membership Functions (MFs) at the output. The presented controller employs the fuzzy logic system with an architecture of ANNs having five layers in order to have the advantage of both the methods [92].

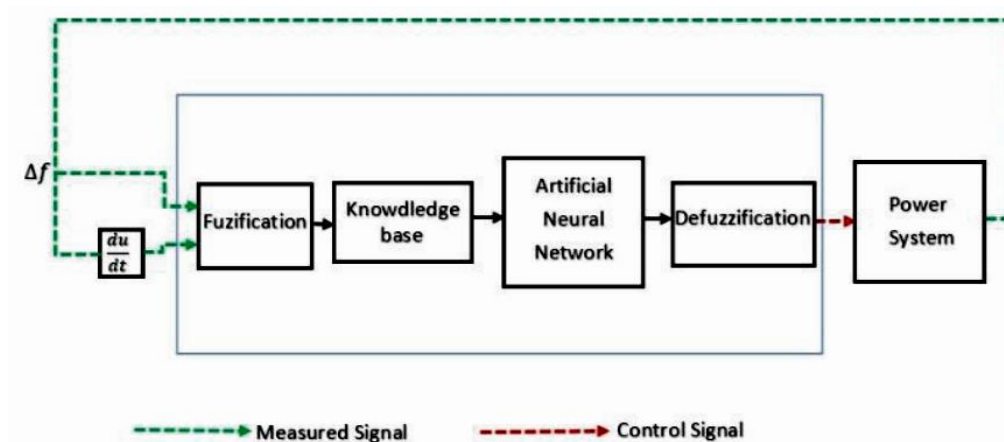


Fig 3.6 Block Diagram of the Neuro Fuzzy Controller

The MFs of fuzzy are chosen randomly in a fixed number. The MFs parameters are estimated as a combined computation of LS (least squares) and backpropagation in case of ANFIS. Fig 3.7 shows the basic structure for the presented ANFIS system.

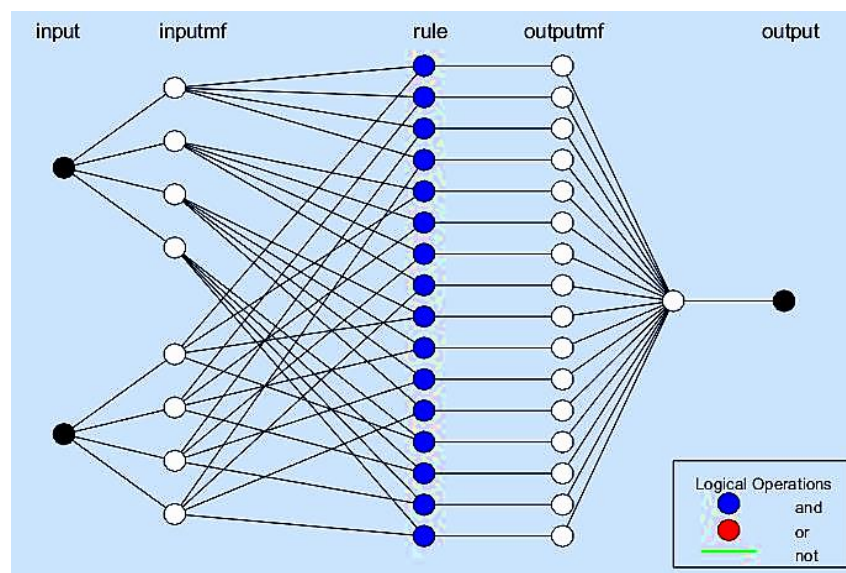


Fig 3.7 Structure for ANFIS

The model used is a Sugeno model of first-order having two inputs and the fuzzy rules used are of Sugeno's type IF-THEN rules. The first layer consists of all the Membership functions. The values of the second layer are obtained from the first layer. The nodes present in the first layer are adaptive in nature. The function of the Second layer is to check the weight of each Membership Function. Nodes of this layer are of non-adaptive nature. The products are given out by the second layer by multiplying the incoming signals. The strength of firing rules is represented by the nodes. The third layer also known as the rule layer consists of neurons which are used for matching the fuzzy rules. The total number of layers decides the number of fuzzy rules. The weights are calculated and normalized for each node. The node in this layer is also non-adaptive [93]. The nodes in the fourth layer are adaptive. Therefore, the inference rules are used to provide the output in this layer. The inputs of the fourth layer are summed together and then the crisp sets are obtained as the output of the fuzzy sets. The fifth layer is a single layer and the node in this layer is non-adaptive, but this node is used to compute all the incoming signals to obtain the output [94].

Following steps are followed for designing the ANFIS controller [93]:

- (i) A fuzzy logic system (FLS) with a particular set of rules is simulated and the data

generated is used as *the* Training and Testing data.

- (ii) Three outputs i.e, Area Control Error (ACE), d(ACE)/dt and the output signal are used to represent the training data inputs.
- (iii) To create ANFIS.fis file **anfisedit** command is used.
- (iv) The collected data is used for training and generating the FIS and using gbell MF up to desired no. of epochs.
- (v) The resulted FIS file is saved to workspace or file.

3.2.5 Particle swarm optimization (PSO)

In 1995, James Kennedy and Russell Eberhart developed a robust stochastic optimization algorithm technique i.e. PSO, which uses the intelligence and the positions of the swarms to find the best possible solution.[94,96]. The advantage of using PSO is that it can give high-quality solutions in a small period of time and is having a stable convergence characteristic with respect to the genetic algorithm. According to [36] these advantages of the PSO makes it useful to be used for many power system applications such as AVR systems, Voltage/VAR control systems, and power factor correction systems.

PSO uses the particles which fly in the search space at a certain velocity using their swarm behavior to achieve the best possible way to resolve the problem. The velocity of all particles is adjusted according to the particle's flying experience as well as the flying experience of other particles.

The velocity and the position of all particles are updated at every step until a termination criterion is achieved. The searching procedure automatically comes to end when the iteration reaches the max number or the predetermined output is achieved. The velocity (v_i) and the position (x_i) of the i^{th} particle of the swarm at $(t+1)^{\text{th}}$ iteration are determined by the following two equations:

$$v_{iD}^{t+1} = K(v_{iD}^t + c_1 r_1 (p_{iD}^t - x_{iD}^t) + c_2 r_2 (g_{iD}^t - x_{iD}^t)) \quad (3.3)$$

$$x_{iD}^{t+1} = x_{iD}^t + v_{iD}^{t+1} \quad (3.4)$$

where $i = 1$ to n and n defines the swarm size,

D defines the dimension of the problem space,

c_1 and c_2 are defined as the positive constants,

r_1 and r_2 are defined as the random numbers uniformly distributed in $[0,1]$,

t represents the number of iterations,

p_i and g represent the best earlier position of the i^{th} particle and present position of the best particle among all the particles in the swarm, respectively.

The flowchart for a basic PSO algorithm is shown in Fig.3.8.

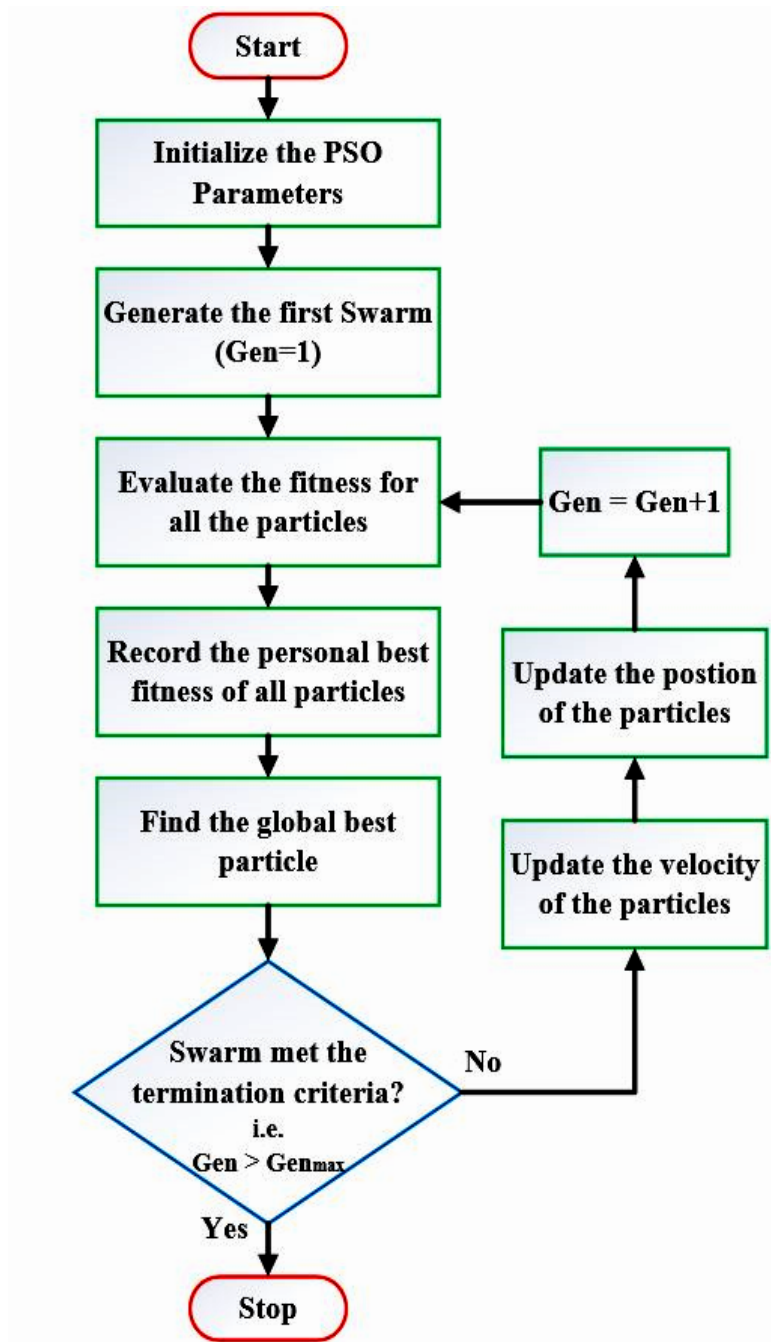


Fig 3.8 Flowchart for basic PSO algorithm

Objective function used for optimization is based on Integral Time Absolute Error (ITAE),

$$\text{Min. } J_{ITAE} = \int_0^{t_{sim}} \left[\sum_{i=1}^6 |ACE_i| \right] * t_{sim} * dt,$$

given as:

3.2.6 Grasshopper optimization algorithm (GOA)

GOA, which was first introduced by Saremi et al. is a stochastic population-based optimization technique [97]. This technique uses the swarming behavior of grasshoppers in nature to identify the best possible way of solving the problems. The mathematical equations and formulas used for simulating the swarming behavior of the Grasshopper are given below. The movement of grasshoppers is mainly affected by three parameters which are: social interaction, gravity force and wind advection [98].

The position of the i^{th} grasshopper is denoted as X_i and is characterized by the equation:

$$X_i = S_i + G_i + A_i \quad (3.6)$$

where S_i denotes the social interaction, G_i denotes the gravity force, and A_i shows the wind advection on an i^{th} grasshopper.

Social Interaction is one of the most important parameters is calculated by the following equation:

$$S_i = \sum_{\substack{j=1 \\ j \neq i}}^N s(d_{ij}) \hat{d}_{ij} \quad (3.7)$$

Where d_{ij} is the distance between i^{th} and j^{th} grasshopper. \hat{d}_{ij} is the unit vector between the i^{th} and j^{th} grasshopper.

s denotes the strength of the social forces adjusted by parameters f (attraction strength) and l (attractive length scale), and is calculated using the following equation,

$$s(r) = fe^{\frac{-r}{l} - r} - e^{-r} \quad (3.8)$$

The G component, which is the gravity force is given as follows:

$$G_i = -g \hat{e}_g \quad (3.9)$$

Where g denotes the gravitational constant and \hat{e}_g is the unit vector towards the center of the earth.

The A component, which is the wind advection of grasshopper, is calculated as follows:

$$A_i = u\hat{e}_w \quad (3.10)$$

u is denoted as a drift constant and \hat{e}_w is a unit vector of wind direction. Putting the value of S , G , and A , the equation is expanded as:

$$X_i = \sum_{\substack{j=1 \\ j \neq i}}^N s(|x_j - x_i|) \frac{x_j - x_i}{d_{ij}} - g\hat{e}_g + u\hat{e}_w \quad (3.11)$$

Further, the equation (3.11) is improved and is given as:

$$X_i^d = c \left(\sum_{\substack{j=1 \\ j \neq i}}^N c \frac{ub_d - lb_d}{2} s(|x_j^d - x_i^d|) \frac{x_j - x_i}{d_{ij}} \right) + \hat{T}_d \quad (3.12)$$

ub_d and lb_d in the above equation denote the upper and lower bound in D^{th} dimension. \hat{T}_d is the value of the D^{th} dimension in the objective which is the best solution up to that time. The parameter c is then updated with the following equation:

$$c = c_{\max} - l \frac{c_{\max} - c_{\min}}{L} \quad (3.12)$$

c_{\max} and c_{\min} here are the max and min value, l is the current iteration and L is a maximum number of iterations. The pseudo code for the Grasshopper optimization is shown in Fig.3.9

```

Initialize the swarm  $X_i$  ( $i=1, 2, \dots, n$ )
Initialize  $c_{\max}$ ,  $c_{\min}$ , and maximum number of iterations
Calculate the fitness of each search agent
 $T =$  the best search agent
while ( $l <$  Max number of iterations)
    Update  $c$  using Eq.(3.12)
    for each search agent
        Normalize the distances between grasshoppers in  $[1, 4]$ 
        Update the position of the current search agent at the equation (3.11)
        Bring the current search agent back if it goes outside the boundaries
    end for
    Update  $T$  if there is a better solution
     $l = l + 1$ 
end while
Return  $T$ 

```

Fig 3.9 Pseudo code for GOA algorithm

Also the flowchart for GOA algorithm is shown below in Fig. 3.10

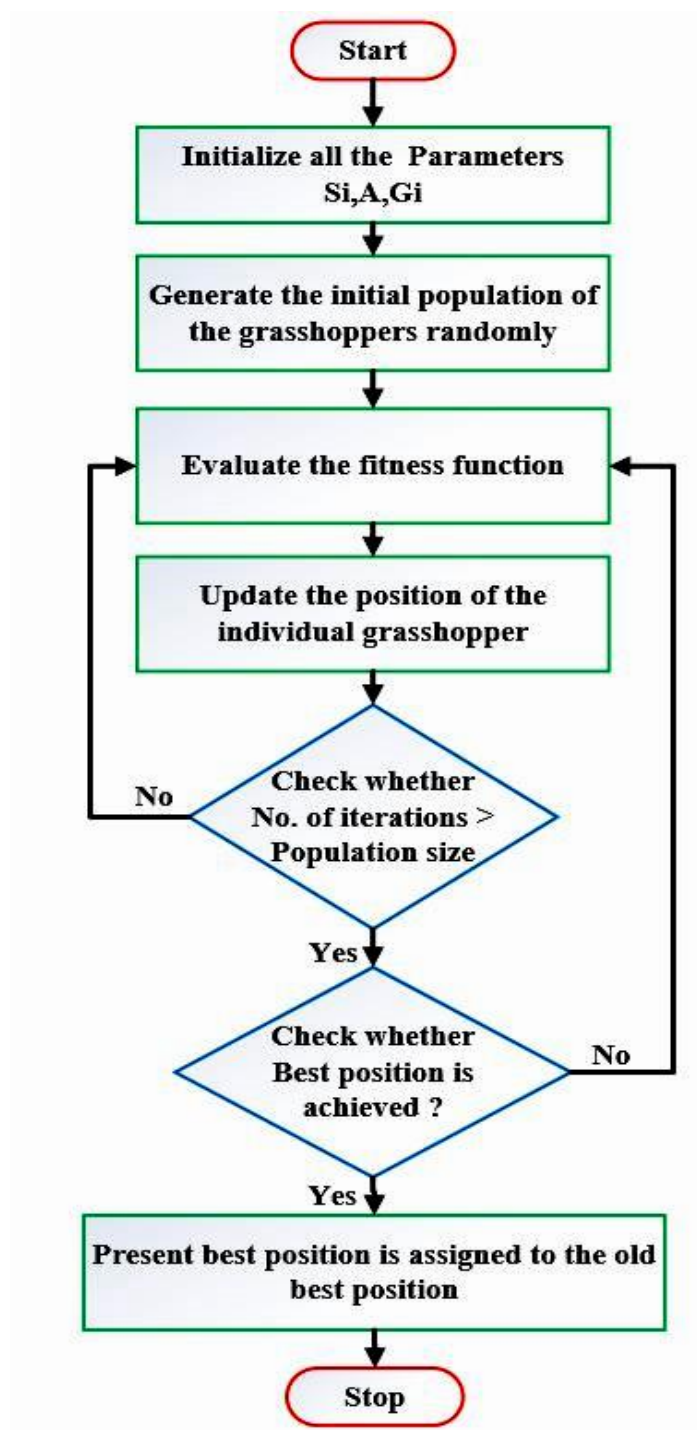


Fig 3.10 Flowchart for GOA algorithm

- **Advantages of GOA**

1. Rather than using the local optimal conditions, Grasshopper optimization technique uses global optimal conditions to find the solutions for a given space.
2. GOA maintains a balance between exploiting and exploring the global optimum

solution of the optimization problem.

3. It is easy to find the most promising region from the given search space by using the Grasshoppers.
4. Most accurate solutions are obtained using GOA for unconstrained optimization problems. The optimum point obtained from GOA is accurate and promising.
5. Most promising and correct results for constrained optimization problem are obtained using GOA as compared to other techniques.

CHAPTER 4

RESULTS AND DISCUSSIONS

A ship microgrid has been considered here for the purpose of simulation work. PV panels, wind generator, Sea Wave generator, fuel cell, and diesel generators are used as the generation system in the microgrid considered. Table 4.1 below shows the details assumed for the power generation system. A hybrid energy storage system consisting of the Battery energy storage system (BESS) and the supercapacitor storage system is also used in the proposed shipboard microgrid.

Table 4.1 Specification of Ship Generation System

S.No.	Source	Rating
1	Diesel Generator	750 kW
2	Solar PV	200 kW
3	Wind	150 kW
4	Fuel Cell	100 kW
5	Super Capacitors	100 kW
6	BESS	200 kWh

4.1 Energy Management System

The Energy Management system designed here is based on the state of charge (*SoC*) of the battery. BESS is used for storing excess energy in the proposed system. 95% and 15% are the estimated max and min limits of the *SoC* of the BESS respectively. There is no change in generated power and load demands for a period of 60 minutes. The classification of loads have been done as permanent, regular, and burst loads and are categorized in Table 4.2

Table 4.2 Ship Service Load Categorization

Critical Loads	Baseline Loads	Regular Loads
Control Panels	Electric Ovens	Washing Machines
Communication Systems	Fans	Microwave
Computer	Water Heaters	Water Pumps
Lighting	Refrigerator	Television
	Air Conditioners	Air Cooler

The following section explains the results obtained from the simulations done on the system proposed. The proposed system considered here consists of the service load on a ship including a power generation system. Solar PV panels, a wind turbine, diesel generators, and a fuel cell system are included in the power generation system. The simulations have been done by taking the solar and wind power generations for a random day.

The power required by the ship's devices changes throughout the day. This power required can be denoted as $P_L(t)$ and is conveyed by Load Agent to Generation Agent. Similarly, due to the unpredictable nature of renewable energy sources the power generated in the ship changes with time which are calculated by Generation Agent as $P_{PVg}(t)$ and $P_{wg}(t)$.

This work is done to completely handle the power requirements in a ship by reducing the difference between power generation and load demand. There must enough SoC available to discharge the battery and use the fuel cells according to the rule base of the agents, otherwise, the power required is provided by the diesel generators.

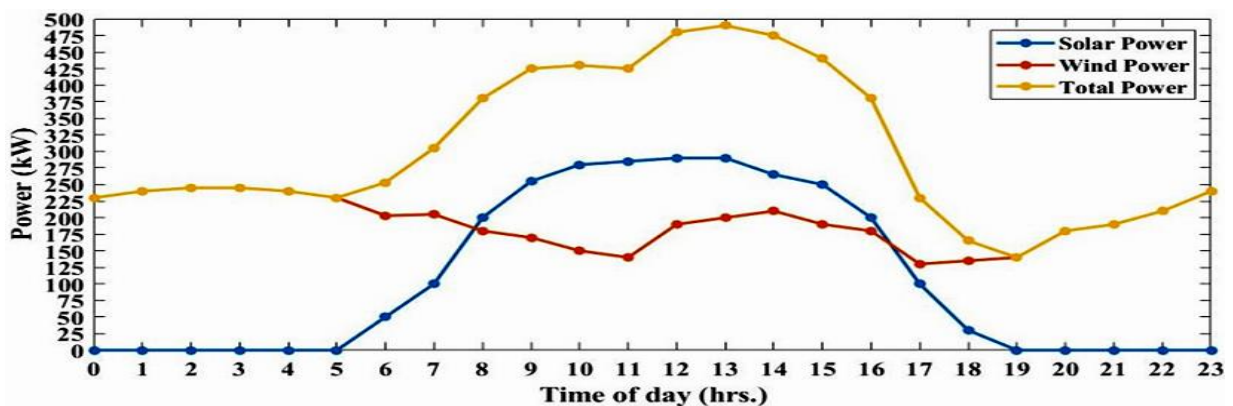
**Fig 4.1.** Power available from PV and wind sources

Fig 4.1 shows the total amount of power that is available from solar PV and wind on the shipboard on a particular day. This power available from RES can be used to drive loads of the shipboard.

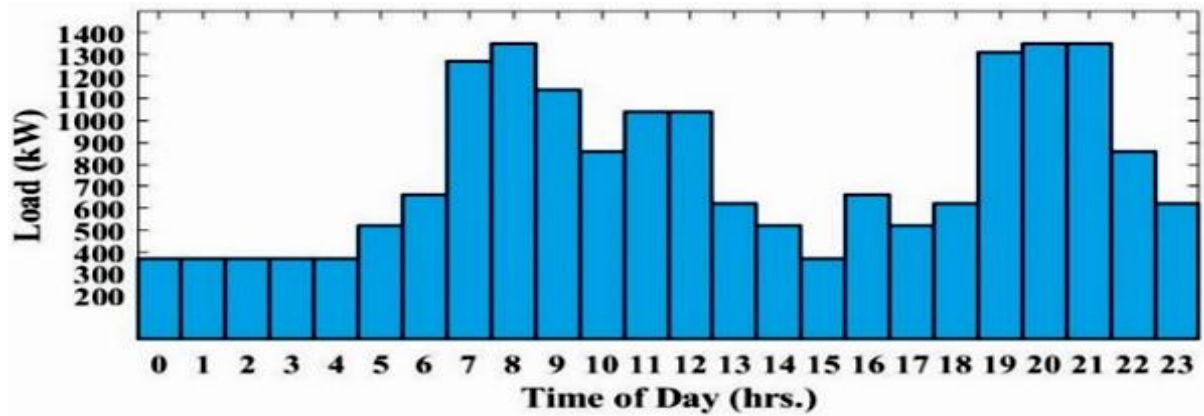


Fig 4.2 Hourly Load Variations

Fig 4.2 shows the total power demanded by the shipboard power system throughout the day for a particular day. The load variation is taken hourly.

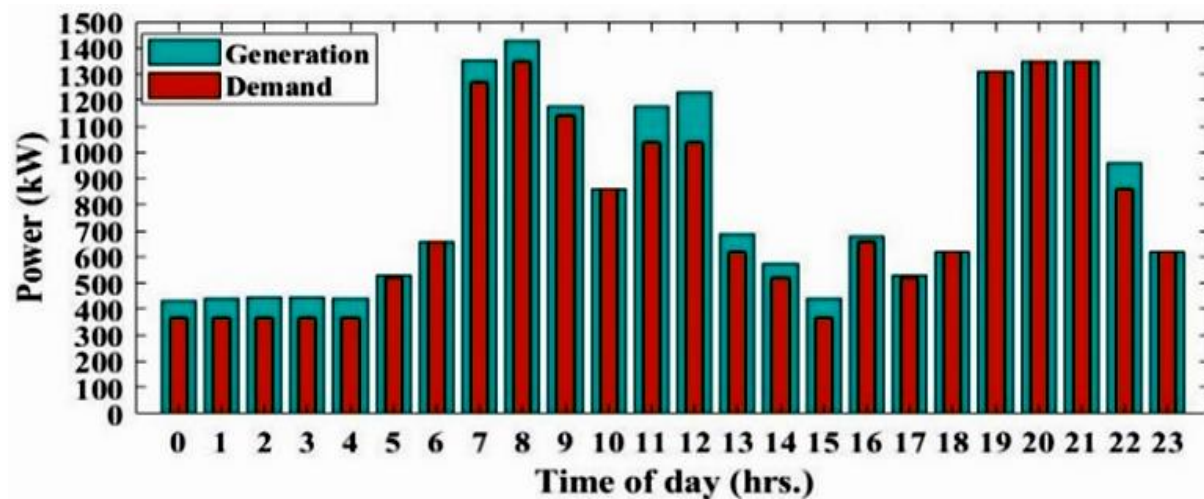


Fig 4.3 Optimum generation with respect to the Hourly load demand with EMS

Fig 4.3 shows the optimal generation from the Integrated power system with respect to the load demand of the system using the proposed Energy Management System. The results obtained show that the more Generation is done through available RE sources, rather than the Diesel Generator, also the difference between the load demand and the generation is less, which means the quantity of excess power generated is less. The excess power generated is fed to the BESS.

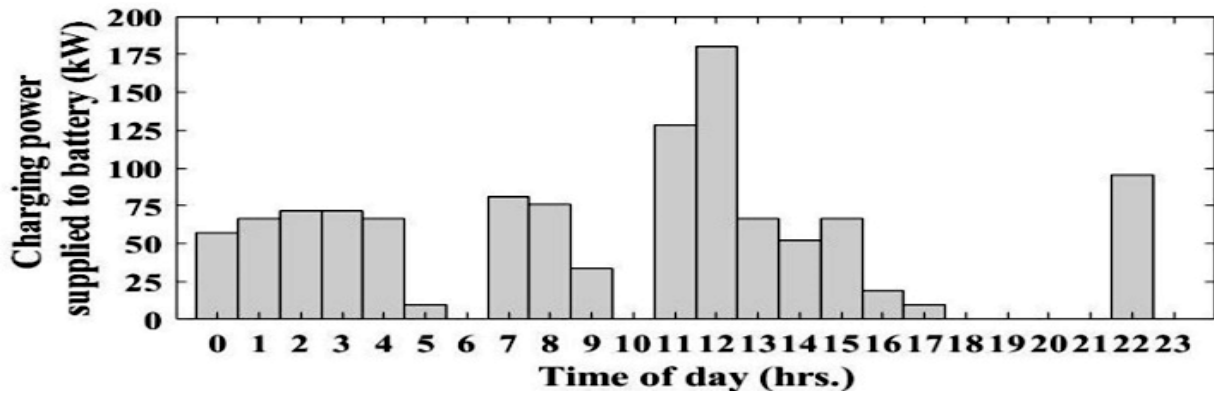


Fig 4.4 Power supplied to the battery for Charging

Fig 4.4 shows the excess amount of power generated from the generating sources which are supplied to the charge the battery and supercapacitors according to the rule base of the EMS. This extra amount of power which is fed to charge the BESS and SCSS is used in the future during the increase in energy requirement.

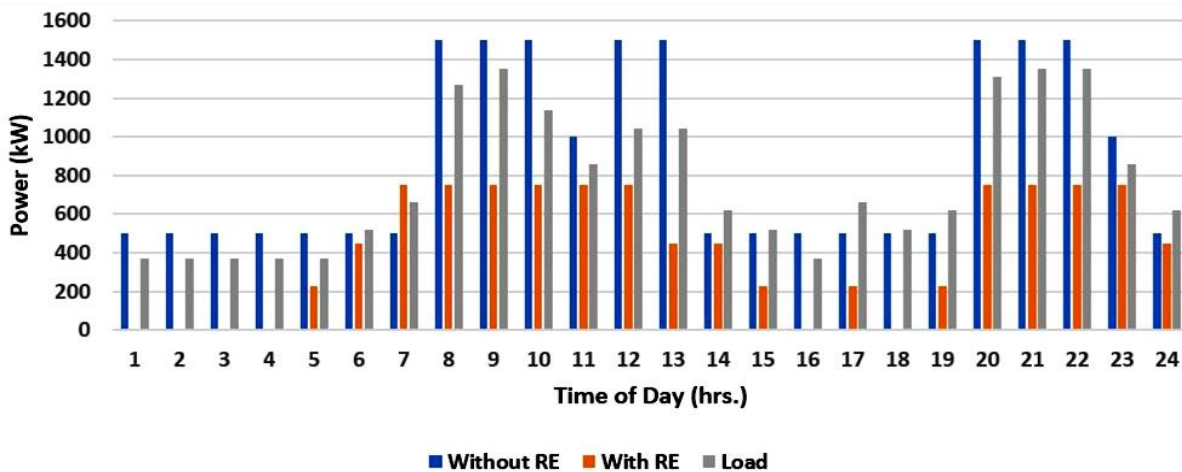


Fig 4.5 Power Generated from the Diesel Generators

Fig 4.5 shows the power generated from the diesel generators during two cases i.e.

1. When the power from the RE sources is absent on the shipboard.
2. When the power from RE sources is available in the shipboard microgrid.

In this work, an Energy Management system is proposed to minimize the diesel generator dependency by using RE based generation system, making the isolated micro-grid self-sustainable. Further, a management system has been designed to achieve the goal of fossil fuel cost reduction. The Energy Management Algorithm designed here satisfactorily shifts the generation in case of a change in demand. Thus, reduces the burden on DG sets. Fig. 4.5 clearly reveals that the integration of RE sources in the shipboard microgrid will help in the reduction of fossil fuel consumption as well as the generation cost. As compared to the previous literature,

only 18% reduction in the fuel consumption was there, but by integrating RE sources to the shipboard microgrid the results obtained shows that there can be up to 50% reduction in fuel consumption which can be obtained using a properly designed EMS. Thus, the results obtained from the simulation shows that the system is an energy efficient and effective solution for power management.

4.2 Load Frequency Control

To show the performance of the proposed Load Frequency Controller based on GOA optimization technique several simulations were done and are presented here. These simulations are performed on the shipboard microgrid model as described in the previous chapter. The complete transfer function model of a shipboard microgrid is represented in Fig. 4.6. In this figure, $2H$ symbolizes the equivalent inertia constant of all directly connected generators and motor loads. The parameters of the shipboard microgrid are given in the Appendix.

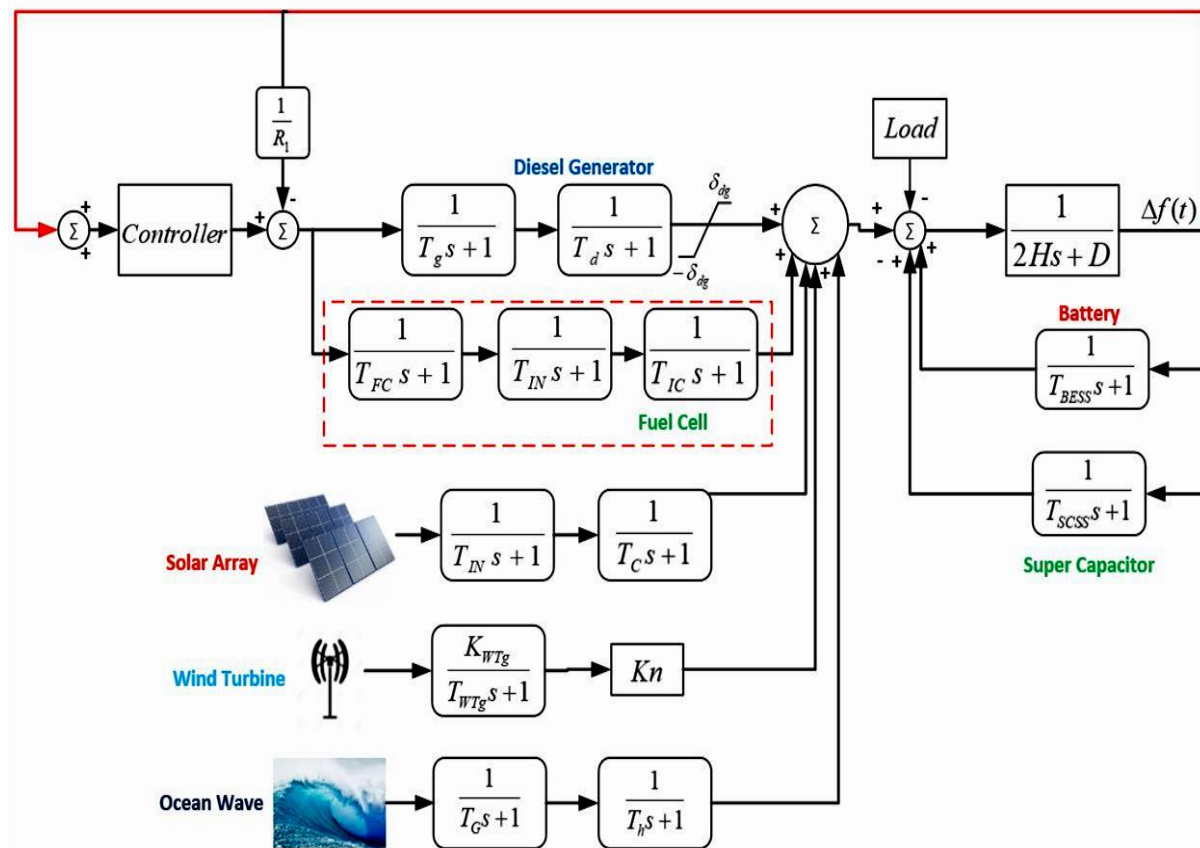


Fig 4.6 The overall shipboard micro grid scheme for LFC

Fig 4.7 below shows the model of the proposed shipboard microgrid which is used for simulation using MATLAB.

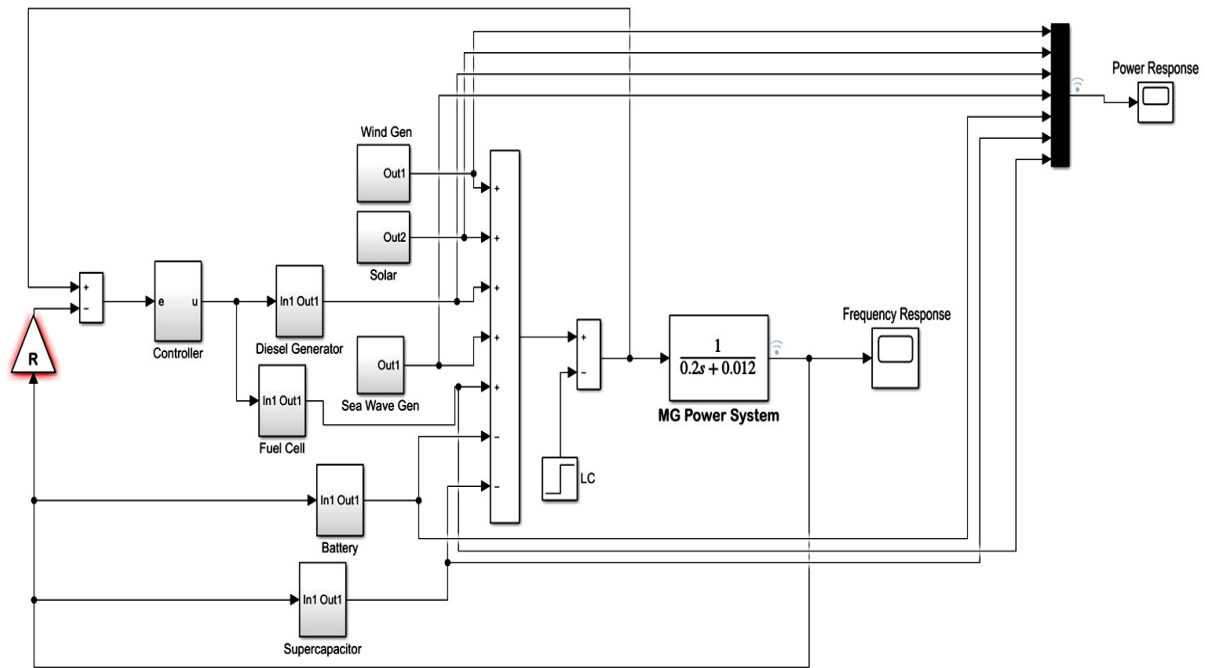
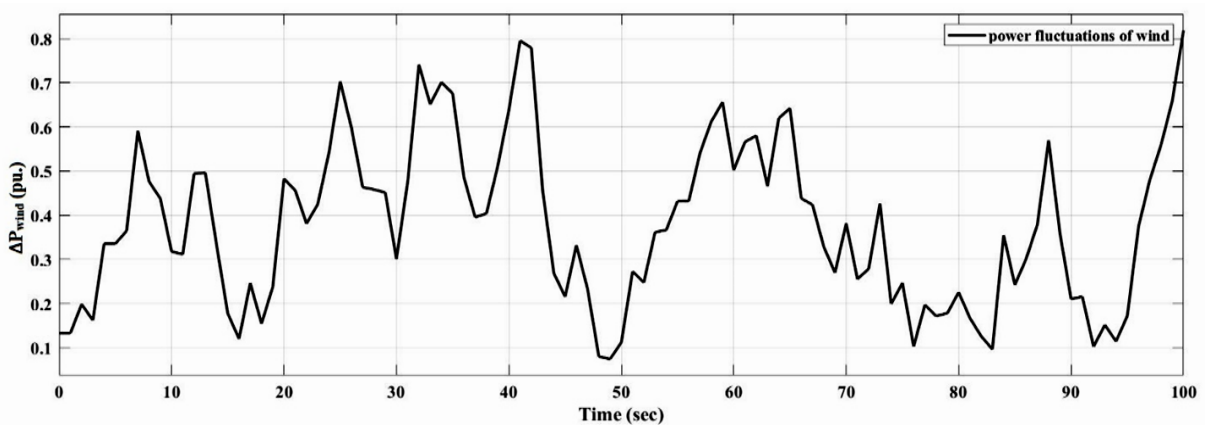


Fig 4.7 Simulink Model of the proposed LFC system

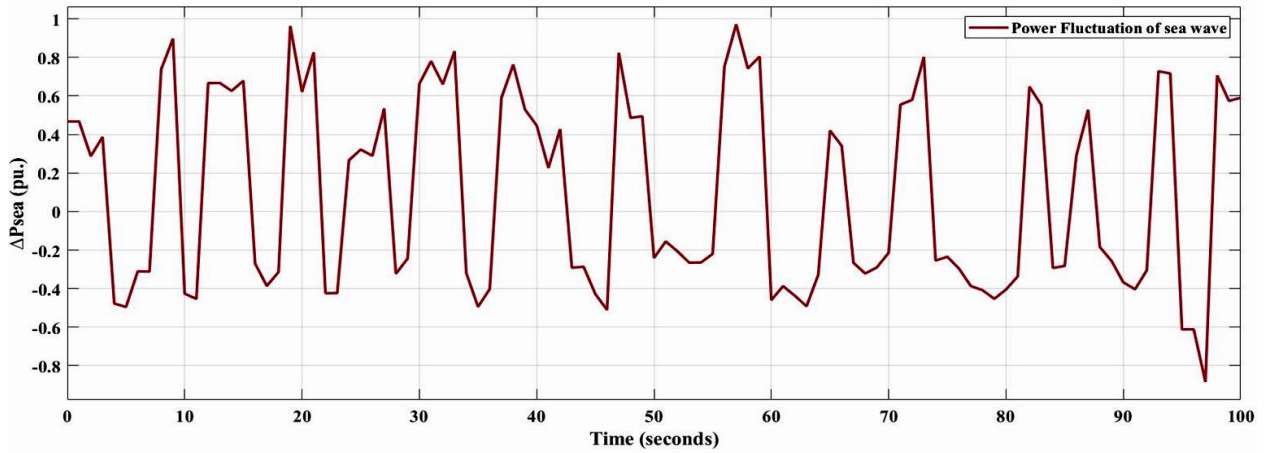
Four different cases are considered here for finding out the robustness and flexibility of different controllers for the proposed shipboard microgrid and to find out which controller is best under different environment and conditions.

4.2.1 Case 1: Variations in Input

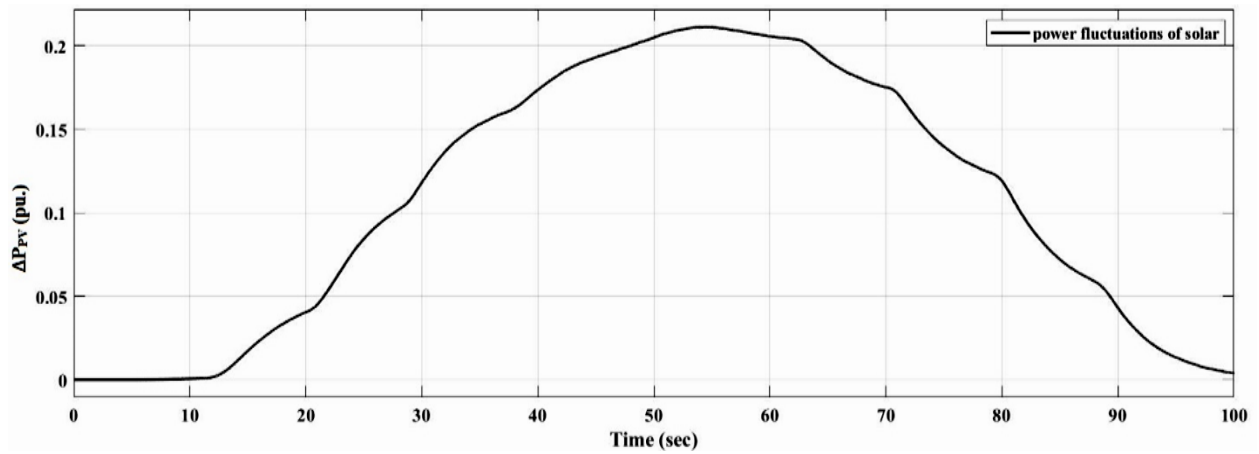
In the first case, the load demand is supposed to be constant in the isolated shipboard MG i.e., $\Delta PL = 0$. Therefore, only the power fluctuations from the generation sources like Wind Turbine (WT) (ΔP_w), and Photovoltaics (PV) (ΔP_{pv}) and sea wave generator (ΔP_{sea}) are considered here for the simulation of LFC system (Fig 4.8). Fig. 4.9 presents the frequency response of the simulated shipboard MG system for the given case.



(a)



(b)



(c)

Fig 4.8 Fluctuations in Power: (a) wind, (b) Sea, (c) Solar

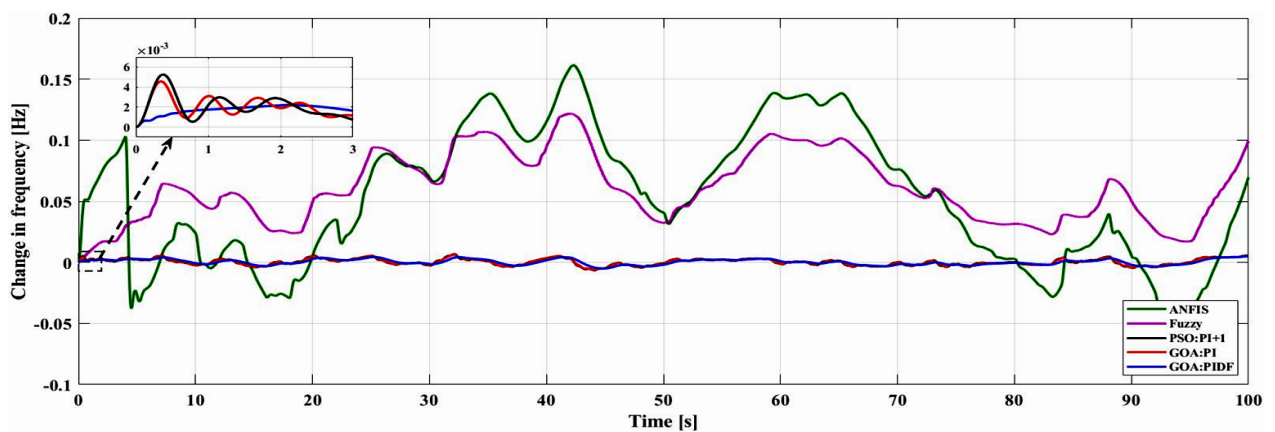


Fig 4.9 Frequency response with respect to the power fluctuation of WPG, PV, and Sea

From Fig 4.9. it is seen that the output obtained for the proposed system is a stable frequency response of the MicroGrid. Also, the response obtained for the proposed system is attained

quicker and with fewer fluctuation as using as compared to other controllers. The table shows that the overshoot obtained from the different controllers.

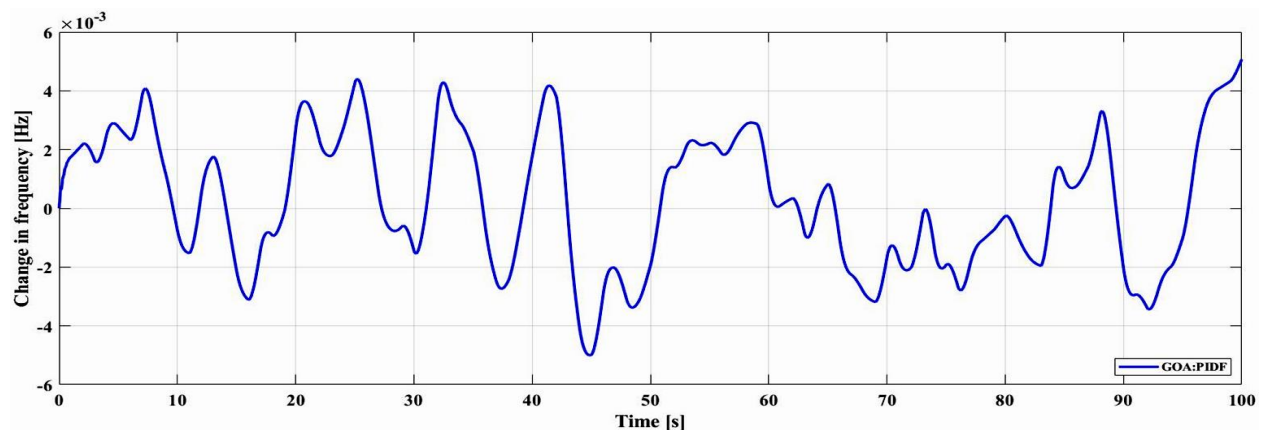


Fig 4.10 Frequency response of Proposed Controller with respect to the power fluctuation of WPG, PV and Sea

It is seen from Fig 4.10 that the PID-F controller tuned using GOA is having a very small overshoot of 0.0041 as compared to others which are 0.00501 for GOA-PI, 0.0052 for PSO-PI+1, 0.121 for Fuzzy and 0.161 for ANFIS.

Table 4.3 Comparison of overshoot during the variation in the input

Controller	Overshoot (Δf Hz)
Fuzzy	0.121
ANFIS	0.161
PSO-PI+1	0.0052
GOA-PI	0.00501
GOA-PIDF(Proposed)	0.0041

4.2.2 Case 2: 20% Step Load change

In this case, a 20% static step load variation is supplied as a disturbance to the LFC along with the power fluctuations of the WT (ΔP_w), PV (ΔP_{pv}), and (ΔP_{sea}). The frequency deviation response of the PSO and GOA based PI and PID-F, ANFIS and Fuzzy controls are shown in Fig 4.11.

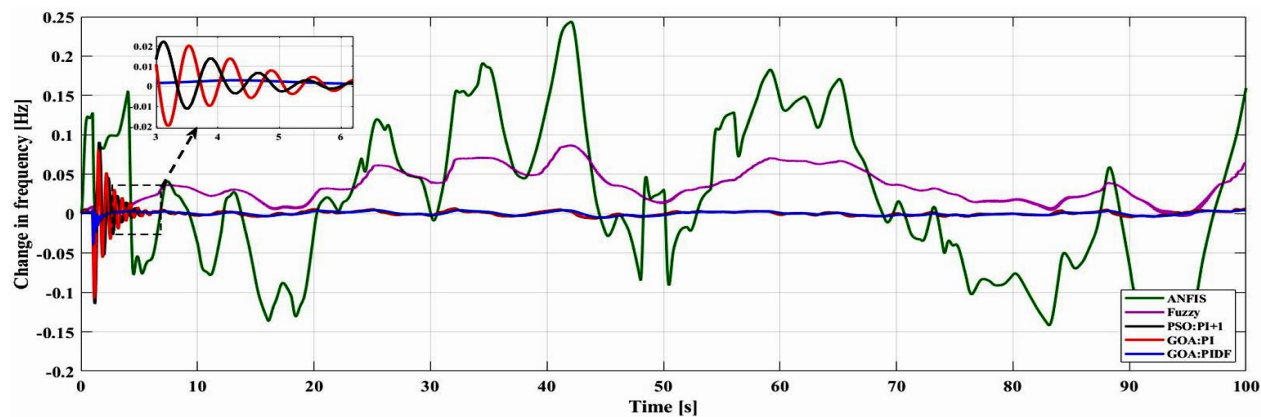


Fig 4.11 Frequency response with respect to the power fluctuation of WT, PV, Sea and 20% step load change.

Fig 4.11 shows that the value of frequency deviations are less for the proposed GOA based PIDF controller, also the frequency deviation is damped faster using the proposed controller in comparison to the ANFIS, Fuzzy and PSO based PI+1 controller. As a result, the system gets more stable output frequency with less fluctuation using the proposed controller as seen in Fig. 4.12.

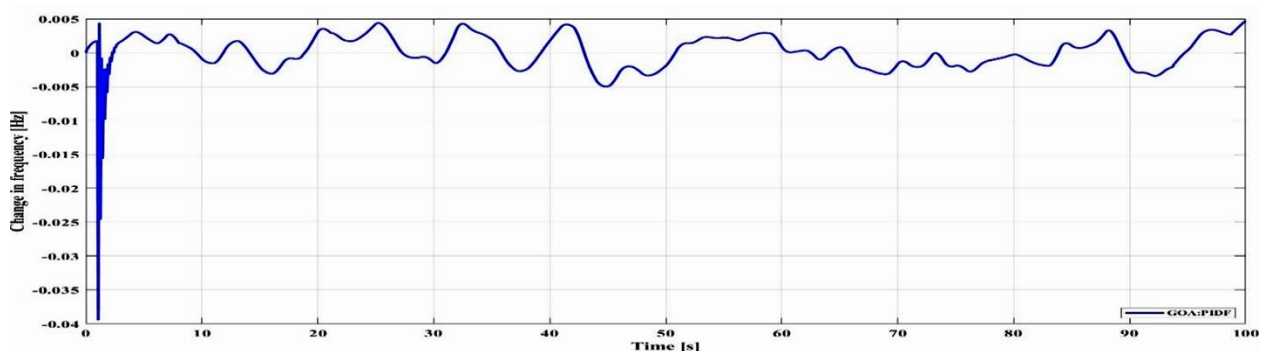


Fig 4.12 Frequency response of Proposed Controller with respect to the power fluctuation of WT, PV, Sea and 20% step load change.

Table 4.4 reveals the overshoot and settling time obtained from different controllers. It is seen that the proposed GOA based PIDF controller is having a very less settling time of 2 sec. and overshoot of -0.0395 Hz as compared to others which are 0.082 Hz for GOA based PI, 0.0905 Hz for PSO based PI+1, 0.0865 Hz for Fuzzy and 0.245 Hz for ANFIS.

Table 4.4 Comparison of overshoot

Controller	Overshoot (Δf Hz)
Fuzzy	0.0865

ANFIS	0.245
PSO-PI+1	0.0905
GOA-PI	0.082
GOA-PIDF(Proposed)	-0.0395

Fig 4.13 below shows the power responses of the generating sources for the proposed system under the condition of 20% step change in the load of the system.

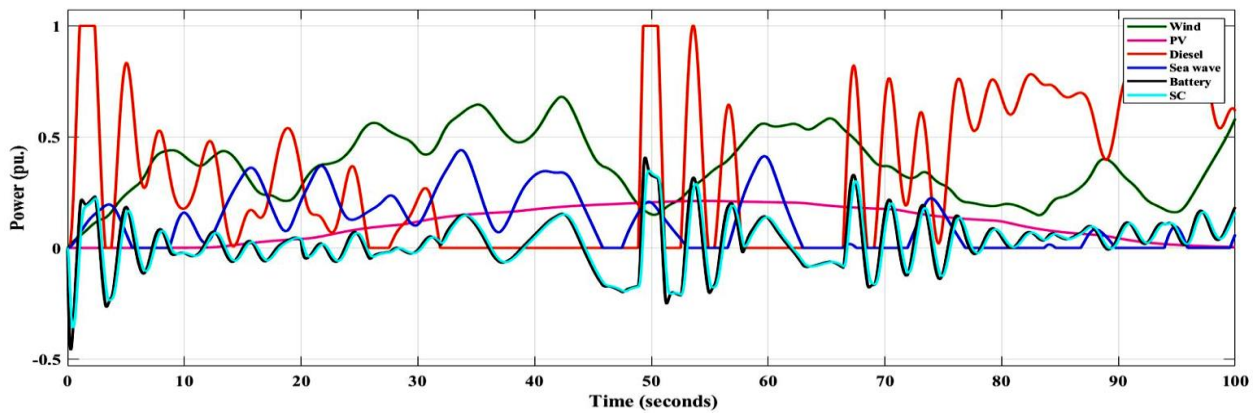


Fig 4.13 Power Response of generating sources for 20% load change.

4.2.3. Case 3: Variable Load

In this case, a multi-step load variation is applied as a disturbance to the system. The step load variations applied to the proposed system are shown in Fig. 4.14. The load varies from the range of 0.01 pu. To 0.05 pu. For a time span of 100 seconds. The Fig 4.15 shows the frequency response of the GOA-PIDF, GOA-PI, PSO-PI+1, ANFIS and Fuzzy controls for these variations in loads.

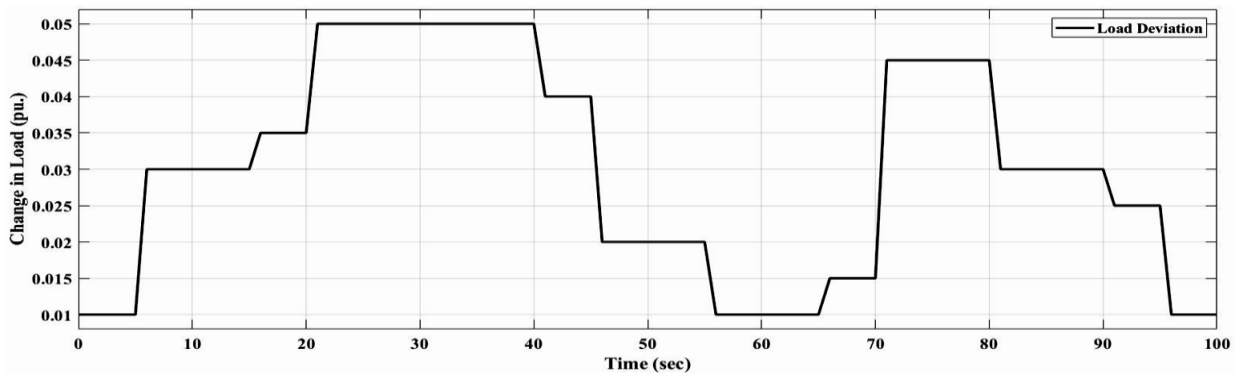


Fig 4.14. Variation in load due to step changes

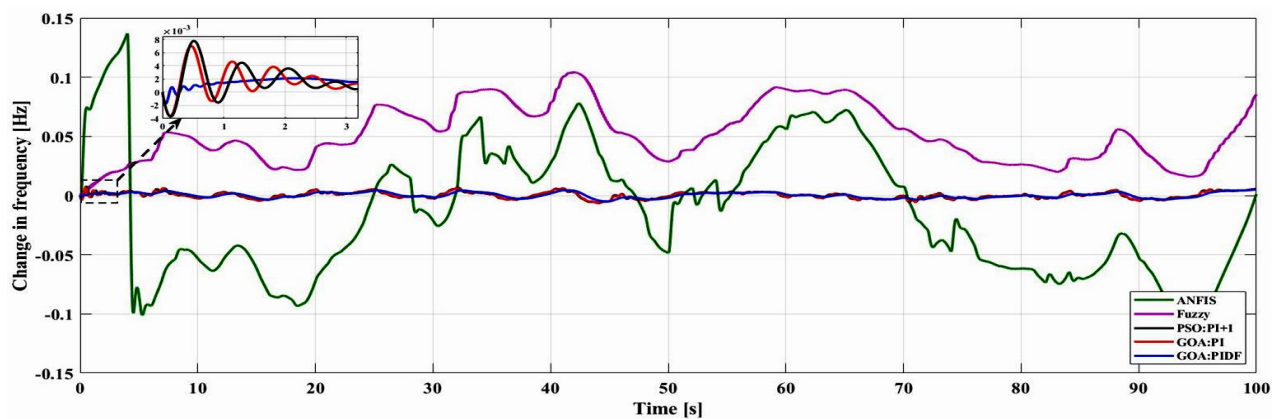


Fig 4.15 Frequency response w.r.t the variable load disturbances and power fluctuation from WT, PV, and Sea.

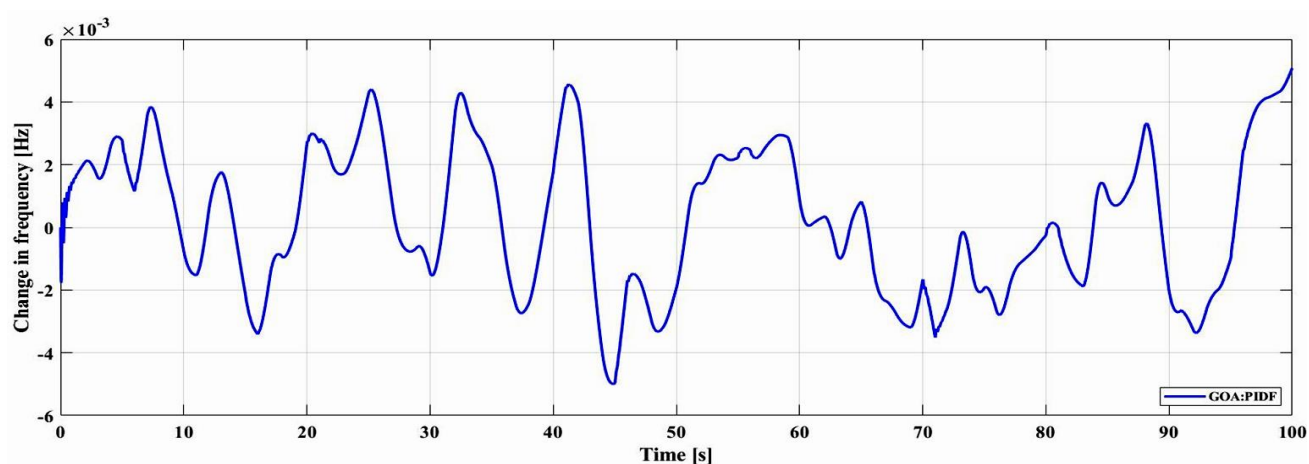


Fig 4.16 Frequency response of Proposed Controller with respect to the variable load disturbances and power fluctuation from WT, PV, and Sea.

From Fig. 4.15 it is seen that the overshoot due to frequent load changes is more successfully managed by using the GOA-PIDF method than other controllers. Fig. 4.16 represents the response using the proposed system.

Table 4.5 Comparison of overshoot during variable load

Controller	Overshoot (Δf Hz)
Fuzzy	0.104
ANFIS	0.13685
PSO-PI+1	0.008
GOA-PI	0.007
GOA-PIDF(Proposed)	-0.00175

Table 4.5 shows that the overshoot obtained from the different controllers. It is seen that the proposed GOA-PIDF is having a very small overshoot of -0.00175 as compared to others which are 0.007 for GOA-PI, 0.008 for PSO-PI+1, 0.104 for Fuzzy and 0.13685 for ANFIS.

According to Fig 4.15 by using the proposed scheme the performance of the LFC in order to reduce the effect of load changes can be enhanced, which will also help in reducing the settling time of the frequency response significantly.

4.2.4. Case 4: Robustness Analysis (Parameter Variations)

For analyzing the robustness of the proposed controller, its evaluation is done by changing some parameters of the SMG. Table 4.6 shows the changes in the parameters which are done in this case study.

Table 4.6 Uncertain parameters of the SMG system

Parameters	Variation Range
R	+25%
D	-15%
H	+45%
T_g	+15%
T_{BESS}	-15%
T_{SCSS}	+25%

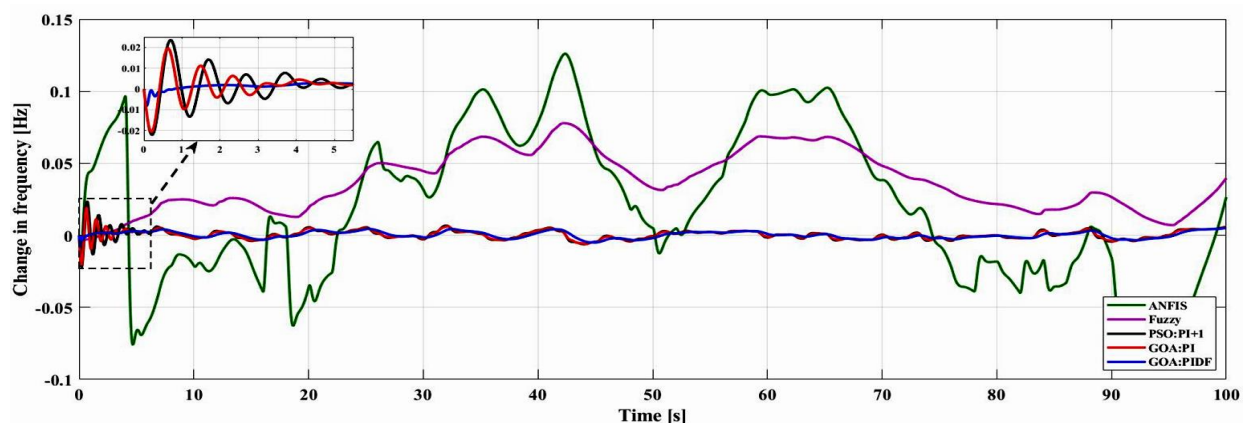


Fig 4.17 Frequency response of the SMG w.r.t. parameter variations.

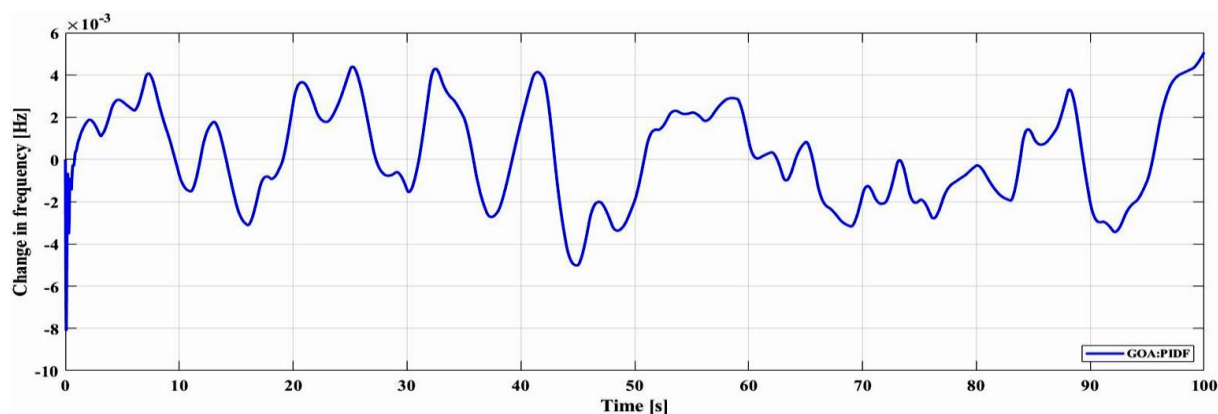


Fig 4.18 Frequency response of Proposed Controller w.r.t. parameter variations.

Fig. 4.17 represents all the response obtained for the LFC in this case of parameter variation. After the parameter variation from -15% to + 45 % as placed in table 4.6, the responses of ALFC reveals that the frequency deviation is within the specified limit which shows the sensitivity and robustness of the proposed control scheme. Fig. 4.18 represents the response obtained for the LFC in this case of parameter variation by using the proposed controller.

Table 4.7 Performance of the proposed system for parameter variations

Controller	Overshoot (Δf Hz)
Fuzzy	0.07785
ANFIS	0.126
PSO-PI+1	0.0235
GOA-PI	0.0197
GOA-PIDF(Proposed)	-0.0081

Table 4.7 reveals the overshoot and settling time obtained using the different controllers. It is seen that the proposed GOA-PIDF is having a very less settling time of nearly 1.42 sec. and an overshoot of -0.0081 Hz as compared to others which are 0.0197 Hz for GOA-PI, 0.0235 Hz for PSO-PI+1, 0.07785 Hz for Fuzzy and 0.126 Hz for ANFIS. These results show that results obtained are much better than the results published by the researchers in [1] by applying MOPI and MOFPI technique for the similar microgrid and their results are placed in table 4.8.

Table 4.8 Performance of existing LFC system (already published)

Controller	Overshoot (Δf Hz)
MOPI [1]	0.062
MOFPI [1]	0.043

As seen from table 4.5 the proposed intelligent controller (GOA-PIDF) improves the performance of the LFC as compared to conventional Controllers, especially the overshoot. Out of all the intelligent controllers proposed GOA-PIDF is more sensitive and robust than others (GOA-PI, PSO-PI+1, fuzzy & ANFIS) in terms of settling time and overshoot in all four cases which reveals the advantage and novelty of the developed control scheme for frequency control of the isolated shipboard microgrid.

4.3 Discussions

The Energy Management Algorithm designed using dynamic programming satisfactorily shifts the generation in case of a change in demand hence reducing the burden on DG sets. Fig. 4.5, clearly reveals that the integration of RE sources in the shipboard microgrid will help in the reduction of fossil fuel consumption as well as the generation cost. As compared to the previous literature only 18% reduction in the fuel consumption was there, but by integrating RE sources to the shipboard microgrid the results obtained shows that up to 50% reduction in fuel consumption can be obtained with a proper EMS. Thus, the results obtained from the simulation shows that the designed system is an energy efficient and effective solution for power management. Also to discuss the problem of ancillary services, an isolated shipboard power system based on renewable penetration was developed and Grasshopper optimization based PIDF controller was designed to investigate the LFC of the SBM and compared to other controllers GOA-PI, PSO-PI+1 and intelligent controllers (fuzzy & ANFIS). The intelligent control technique of GOA-PIDF has been proposed in this work under different conditions with inconsistent renewable energy generation and load disturbances. A GOA based PI and PSO based PI+1 controller was too employed to improve the optimal outputs of the system. Firstly, the frequency deviation is governed using the Fuzzy, ANFIS, PSO-PI+1 and GOA based PI schemes. Afterward, the GOA based PIDF controller is finely tuned and the equivalent error functions are minimized. The proposed method is implemented in the MatLab/Simulink platform. All these processes were done for controlling the load frequency of the Ship Board

microgrid power systems, i.e. diesel, WT, PV, Sea, and FC. The proposed technique is implemented and compared with the existing. Fuzzy, ANFIS and PSO algorithm based controllers. Finally, the dynamic behavior of the shipboard power system and frequency deviation was evaluated. The performance evaluation for robustness analysis reveals that the proposed control technique performs much better than the existing technique (Table 4.7 and 4.8) for the similar shipboard microgrid. This proposed control technique stabilizes the system in terms of settling time and reduces the frequency deviation in terms of peak overshoot, which proves the novelty and superiority of the proposed technique.

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

5.1 Summary of contributions and conclusion

In this entire dissertation presents the problem of energy management and ancillary services for the shipboard microgrid. A multi-agent based EMS is designed to solve the problem of energy availability and reduce the operational cost of the system. In addition, the problem of LFC of the shipboard power system is also been considered as a part of ancillary services and a model with distributed generation under deregulated environment has been developed and simulated in MatLab/Simulink. To solve the problem of Energy Management the Multi-Agents system was employed which keeps the record of power generation, load, and SoC of the battery. The Algorithm for Energy Management is designed using dynamic programming that is capable of satisfactorily shifting the generation in case of a change in demand. Thus, reducing the burden on DG sets.

Also because of constant growth in the use of RE sources and continuous change in load disturbances in a power system, particularly in an isolated MG, it is difficult to sustain and stabilize the frequency within adequate limits hence leading to system instability and collapse. To avoid this issue in shipboard microgrid this work reveals a secondary load frequency control of an isolated shipboard microgrid using intelligent control technique. An SBM was developed consisting of some RE sources and Grasshopper optimization based PIDF controller was designed to investigate the LFC of that SBM. The results obtained using the proposed controllers were finally compared to other controllers like GOA-PI, PSO-PI+1 and intelligent controllers (fuzzy & ANFIS).

So finally, it is concluded that the Energy Management system proposed here to minimize the diesel generator dependency of the ship power system by using RE based generation system is successfully fulfilled. Also, the results obtained for LFC as an ancillary service demonstrates the uniqueness and reliability of the proposed control technique for the shipboard microgrid.

5.2 Future Scopes

The following investigations are recommended for future research based on the results presented in this thesis work:

- In this work, only active power controls of shipboard power system for LFC has been presented and proposed. But in the real-time whenever the power is interrupted then there is fluctuation occur in both the frequency as well as the voltage, so in future, the reactive power can be used to stabilize the system voltage using intelligent control techniques.
- In this thesis, the many renewable energy sources like the sea, PV, wind, FC, etc. are used to design the shipboard microgrid. But these sources have not been used to their best. So in future more convenient solution must be interrogated in order to use the power from all these RE sources to their best.
- Because of the delay caused by communication, there may be some effect on the performance of the controller as the optimal results depend upon the real-time information. So, in the future, as a GSM-based communication link can be established to feed the feedback to the controller.
- Furthermore, more optimization techniques can be used for the tuning of the control parameters of controllers and a two area model can be developed for LFC of the ship microgrid..

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APPENDIX

Parameter	Values	Parameter	Values
Ship Diesel Generator		Battery System	
T_g	2 s	Rated voltage	240 V
T_d	1 s	Rated capacity	390.625 A
R	3 pu MW/sec	Internal resistance	0.0154 Ω
δd_g	0.01 pu MW/sec	Filter Capacity	8 mF
D	0.012 pu/Hz	Filter inductance	2.5 μH
2H	0.2 (pu s)	A	28.8 V
T_{SCSS}	0.2 s	K	3.7501 V
T_{BESS}	0.1 s	E_o	256.95 V
T_C	0.5 s	B	0.0384(Ah) ⁻¹
T_{In}	4 s	Q	410.16 Ah
C_p	0.195	Fuel Cell system	
H	2 m	B_o	0.04777 A ⁻¹
R	0.5 m	C	0.0136
K_{FC}	1/50	CV	2
T_{FC}	4 s	F	96484600 C/kmol
PVC system		N_s	1
A_{pv}	1.5 m ²	N_o	88
N_p	411	K_{H_2O}	7.716×10 ⁻⁶ kmol/atm
N_s	153	E_o	0.8 V
c_{pv}	5×10 ⁴ J/C/m ²	T	343
R_s	1.324 Ω	U	0.8
$T_{c,ref}$	25 °C	R	8314.47 J/kmol/K
Q	1.602 ×10 ⁻¹⁹ C		
e_{gap}	1.17 Ev		
$I_{L,ref}$	2.664 A		

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