DESIGN AND DEVELOPMENT OF HYBRID MICROGRID FOR A SHIP

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY

in

ELECTRICAL ENGINEERING

(With specialization in System and Control)

By

CRISTIN RAJAN

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)

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CANDIDATE'S DECLARATION

I hereby declare that this thesis entitled **DESIGN AND DEVELOPMENT OF HYBRID MICROGRID FOR A SHIP**, submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Electrical Engineering with specialization in System and Control is an authentic record of the work carried out by me during the period June 2018 through May 2019, under the supervision of **Dr. BARJEEV TYAGI, Department of Electrical Engineering, Indian Institute of Technology, Roorkee**. The matter presented in this thesis has not been submitted by me for the award of any other degree of this institute or any other institutes.

Date:

Place: Roorkee **CRISTIN RAJAN**

CERTIFICATE

This is to certify that the above statement made by the candidate is true to the best of my knowledge and belief.

Dr. Barjeev Tyagi
Associate Professor
Department of Electrical Engineering
Indian Institute of Technology Roorkee

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ABSTRACT

In this thesis the technology of hybrid microgrid in which PV solar cells in conjunction with energy storage devices seek to reduce dependence on conventional diesel generators to meet the shipboard electrical load requirements. 230V loads which include general lighting, navigation and communication equipment, public address system which constitute a considerable share of online electrical load in any shipping vessel is the primary focus. DC power from solar cell is converted to AC power using suitable converters or drives for the same. The entire shipboard power system is modelled using Matlab Graphical User Interface Development Environment. A Power Management System to carry out optimal power generation and scheduling is designed which include diesel generator fuel cost optimisation is implemented to control the hybrid microgrid here used.

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ABBREVIATIONS

BESS	Battery Energy Storage Systems
DG	Diesel Generator
GUIDE	Graphical User Interface Development Environment
HVAC	Heat Ventilation and Air Conditioning
P/EMS	Power/Energy Management System
SOC	State of Charge
SPS	Ship Power System
SQP	Sequential Quadratic Programming
ED	Economic Dispatch

CHAPTER 1

A BRIEF OVERVIEW

1.1 Introduction

The shipping industry plays a crucial role in the Indian economy. The industry contributes to 95 percent of the nation's trade by volume, 42 percent of the total Indian tonnage and 8 percent of the entire world trade [1]. There is no doubt that any positive influence in this industry ie. any cost efficiency improvement project would help the economy as a whole. With India's unique geographical location along the major sea routes and its 7500 km long coastline [2], it is certain that the industry would flourish in the coming years and any investment in the same should be safe. With government initiating projects aimed at sustainable growth in this sector viz, Sagarmala, various port modernization projects and revamping inland waterways [3], improving cost efficiency here would be synergistically beneficial.

Currently, electrical load requirement on shipping vessels are mostly met using conventional means of energy ie. diesel generators. On an average, generation cost of diesel generator is Rs 17 per KWh whereas using a photovoltaic cell it can be brought down to Rs 5 per KWh [4], with existing technology, which is a considerable reduction in operational cost. With this level of savings, it can be expected that the project would achieve breakeven in less than 10 years. Besides, photovoltaic energy conversion efficiency which is currently close to 21% can be expected to improve over time [5].

As per the estimates of International Maritime Organisation, CO_2 emission due to shipping industry worldwide is estimated at 3.3% of total emission [6]. According to accepted industrial standards, an efficient diesel generator on an average emits close to 1.22kg CO_2 per KWh [7]. Implementing this proposed model would lead to over 0.7 tonne reduction in CO_2 emissions per vessel in a day, helping us towards achieving 'Post 2020 Climate Action Plan' (35 percent CO_2 reduction by the year 2030).

In this thesis, the technology of hybrid microgrid is used wherein PV solar cells in conjunction with energy storage devices seek to reduce dependence on conventional diesel generators to meet electrical load requirements. 230V loads which include general lighting, navigation and communication equipment are our primary focus. DC power from solar cell is converted to AC power using suitable converters or drives for the same. A Power Management System to carry out optimal power generation and scheduling is designed and implemented to control the shipboard hybrid microgrid.

The major constraints constitute the space and weight of additional components added as part of project implementation, may affect vessel stability and structural integrity. Customised design of solar panels has to be carried out to ensure efficient utilization of areas exposed to sunlight.

This thesis provides an overview of shipboard microgrid and discusses different methods of power and energy management in such systems which are essential for controlling, monitoring and optimizing the overall system performance.

1.2 Literature Review

In paper [8] hybrid shipboard power systems along with the architecture and related system components is presented. It emphasise on power and energy management solutions for ship board microgrid. Paper [9] highlights different stages in evolution of marine vessel's development and discusses new challenges of moving towards a hybrid AC/DC and pure DC power systems, the challenge of electrical stability, harmonic pollution, and power quality in stand-alone microgrids like the marine vessel, the role of battery energy storage systems (BESS), and the move toward emission-free operation among others. Paper [7] is about estimation of carbon footprints from diesel generator emissions. Paper [10] is on Stand-alone micro-grid distributed generator optimization with different battery technologies which aims at a minimum optimization goal of overall costs, including equipment investment costs, replacement costs, operation and maintenance costs, fuel costs and environmental conversion costs, and for the condition in the system power supply constraints. Paper [11] which is on sustainable energy management system for isolated microgrids gives the equivalent CO_2 emissions of diesel generator units. Paper [12], Patch Antenna Design with Improved Sequential Quadratic Programming for Automotive Applications gives an overview of the optimisation algorithm used in this thesis. Paper [13] titled 'A new economic dispatch algorithm considering any higher order generation cost functions' presents the benefits in using higher order functions in fuel cost optimisation of diesel generator units. The advantage of using sequential quadratic programming over conventional methods is discussed in paper [14], 'A Comprehensive Study On Combined Economic and Emission Dispatch Optimization Problem'.

CHAPTER 2

SHIP POWER SYSTEM

The ship board power system is a standalone microgrid. It is important to ensure vigilance while implementing a network on board ships. Primary concern would be the survivability and continuity of power supply. Continuity of supply is ensured by optimally choosing the size and number of generators and switchboards, distribution board positions so as to isolate the faulty networks [9]. Considering the commercial aspects, a vessel should be fuel efficient and in the present days it should be eco-friendly too. International Maritime Organisation (IMO) has formulated stringent control measures so as to reduce the carbon footprint. Conventionally, AC distribution is used on board but in the recent past, advancement has happened with regard to the DC distribution.

2.1 Marine Vessel Power Systems and Microgrids

SPS functions as islanded mode while at sea and is part of terrestrial grid when at shore. Due to the close similarity of SPS with that of normal microgrid, many control strategies that are used in a normal microgrid can also be applied in SPS. To name a few are power sharing methods between generators, voltage and frequency control, power quality improvement and P/EMS (Power/Energy management system). P/EMS plays a major role in SCADA, future operating state prediction, decision-making strategies and optimal set-point calculation [9]. PMS handles the power balance in an efficient manner while EMS looks after the optimal performance of SPS by taking into account fuel-saving and carbon footprint reduction. Power and energy management system also needs to ensure power/energy demand during ship berthing. During berthing, all generator units are shut down and ship loads are met by shore to ship power supply known as cold ironing [10]. If the shore supply fails P/EMS should automatically start the generators on board to ensure uninterrupted power supply to the loads.

Of course there are a few differences in the working of SPS and normal microgrid which is summarised in this section. The rotational inertia is limited since a few number of generators are available. This in turn would affect the frequency of the SPS when some sudden load changes occur. Scheduling of generators is not possible in SPS due to the unpredictable nature of load profile. So instead of using generator scheduling, load sharing is met by droop control. Both active and reactive power change rapidly in SPS because of the unique load profile. Taking into consideration of the survivability factor a SPS should operate even if there is a single line fault. Due to the compact nature it is easier to implement a centralised control in SPS [9]. Finally, SPS should be able to withstand higher amount of shock, vibration, moisture and salinity.

2.2 Drawbacks of conventional SPS

The marine industry has been witnessing a steady growth over the last couple of centuries. But it has led to the over dependency on conventional fuels and emission of green-house gases. The conservative nature of this industry has restricted it from using the advanced technology systems which are more eco-friendly. A study conducted showed that the global fleet emission of various green-house gases was around 4,600,000 tonne [6]. This includes 320,000 tonne in NO_x, 70,000 tonne in SO_x and 4,100,000 tonne in CO_2.

CHAPTER 3

HYBRID SHIPBOARD MICROGRID: SOLAR-ESS-DG

3.1 SPS Architecture

The generic architecture of shipboard power system which is integrated with Solar-DG-ESS is depicted in Fig.1 [10]. Integration of renewables with other sources and storage devices is done in a distributed manner. To reduce transmission losses main prime mover can be operated close to loads which would help in increasing reliability of the network.

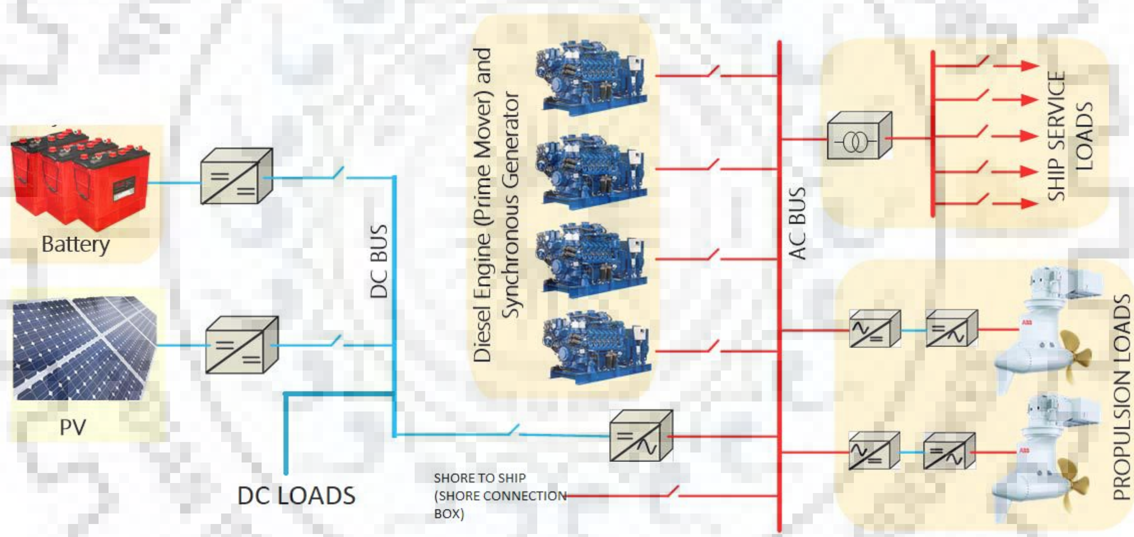

Fig 3.1: Generic architecture of hybrid AC/DC SPS

As shown in Fig.3.1 this architecture consists of AC and DC buses. AC bus is primarily supported by diesel generators and the DC bus by batteries and renewables. Even though the load profile of SPS varies from vessel to vessel it can be observed that on an average 90% of the total electrical load is taken up by the propulsion system [10]. The other major loads would include navigation and communication equipment, manoeuvring system, general lighting loads and electrical pumps. The dynamic nature of this network is challenging and needs to be addressed.

The variation of voltage and frequency that might arise in the system is being taken care of AVR's and governors in the supply side.

As shown in Fig.3.1, DC to AC, DC to DC bidirectional converters are used in hybrid SPS. For ESS, DC to DC converters ensures proper charging and discharging of batteries. Buck converters are used to step down the voltage to required levels both at supply and demand sides. Using power converters in SPS helps in a centralised control via communication link apart from harmonic and reactive power compensation, frequency regulation or current/voltage restoration.

Using ESS can improve engine efficiency significantly. The higher energy density (Wh/kg) and power density (W/kg)which is observed in Li-ion batteries [10] is the most commonly used ESS in SPS.ESS improves power quality and helps in providing uninterrupted power supply to all essential loads [10]. It acts as an energy backup device; i.e when one generator which is online gets disconnected from the network ESS can cater the temporary load requirement till another generator comes online. Oversizing of generators can be avoided if there is sufficient battery backup on-board.

In this paper, the hybrid shipboard micro-grid is composed of diesel generators (DG), photovoltaic array (PV) and energy storage system (ESS).DG acts as the main source of power, the ESS for storing excess energy and improving the reliability of the system.

3.2 PV model

The model of the PV array has been taken from HOMER Pro (Hybrid Optimization of Multiple Electric Renewables) microgrid software [15]. It is a tool designed by HOMER Energy and is a global standard in the optimization of microgrid design. HOMER uses the following equation to obtain the output of PV array neglecting the de-rating factor of PV cell

$$P_{pv}(t) = P_{stc}\frac{G_c(t)}{G_{stc}}\{1 + k[T_c(t) - T_{stc}]\} \tag{3.1}$$

Where

Pstc	=	the rated capacity of PV array, ie the power output at standard test condition
G_{stc}	=	the incident radiation at standard test condition [1kW/m^2]
T_{stc}	=	the PV cell temperature under standard test conditions [25°C]
$T_c(t)$	=	the PV cell temperature in the current time step [°C]
$G_c(t)$	=	the solar radiation incident on the PV array in the current time [kW/m^2]
k	=	the temperature coefficient of power [%/^{0}C]

24 hour solar irradiance data of Mumbai port is obtained for a particular day of year from NREL [16] (National Renewable Energy Laboratory). From the data obtained and using the equation 3.1 the 12 hour solar power output is obtained and is as shown in table 3.1.

Time (hours)	**$G_c(t)$ (kW/m^2)**	**$T_c(t)$ (^0C)**	**$P_{pv}(t)$ (kW)**	**Time (hours)**	**$G_c(t)$ (kW/m^2)**	**$T_c(t)$ (^0C)**	**$P_{pv}(t)$ (kW)**
05:30	0	27	0	12:30	0.965	36	60.1195
06:00	0.004	28	0.266	13:00	0.962	37	59.2592
06:30	0.15	28	9.975	13:30	0.95	38	57.855
07:00	0.293	29	19.2794	14:00	0.925	37	56.98
07:30	0.453	30	29.8074	14:30	0.893	37	55.0088
08:00	0.642	32	41.7942	15:00	0.854	36	53.2042
08:30	0.745	32	48.4995	15:30	0.785	36	48.9055
09:00	0.8	33	51.52	16:00	0.728	35	45.864
09:30	0.856	33	55.1264	16:30	0.625	35	39.375
10:00	0.894	34	56.9478	17:00	0.464	34	29.5568
10:30	0.921	34	58.6677	17:30	0.243	34	15.4791
11:00	0.946	35	59.598	18:00	0.067	33	4.3148
11:30	0.953	35	60.039	18:30	0.021	32	1.3671
12:00	0.968	36	60.3064	19:30	0	31	0

Table 3.1: PV Power output

Available battery capacity $E_{bat}(t)$ depends on battery working point temperature (T_{bat} (t)) which can be taken same as the ambient temperature, E_{stc} is the battery's rated capacity under standard test condition, $T_{bat(stc)}$ (25^0 Celsius) and δ_B is temperature capacitance coefficient (0.01)[11].

$$E_{bat}(t) = E_{stc}[1 + \delta_B(T_{bat}(t) - T_{bat(stc)})] \tag{3.2}$$

CHAPTER 4

MODELLING OF SHIPBOARD MICROGRID

A model for SPS is depicted in figure 4.1. The details of the power sources used in the network is shown below in table 4.1

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No.	Source	Quantity/	Rating
1	Shaft Generator	1	150kVA, 440V,3phase,50Hz
2	Marine Diesel Generator	2	125kW, 440V,3phase,50Hz
3	Maintenance free Battery	10	200Ah, 24V

Table 4.1: Details of Power sources

The photovoltaic panels are designed to give a maximum power output of 60kW. Electrical load is divided into two categories depending on the operating voltage level. Those functioning at 230V are grouped together. It includes general lighting, navigation and communication equipment, public address system, fire detection system and battery charger for general service. Each load can be controlled by the user. Charging of battery is governed by the battery charger for general service. The output of photo voltaic source is connected solely to the 230V bus bar loads. Equipment having higher power rating operates at higher voltage level, ie, 415V. This includes air compressor units, propulsion system, crane, ventilation fans, fuel oil purifier, reverse osmosis plant and other heavy duty pumps. Loads coming under 415V bus bar are met by diesel generators and shaft generator. Loads are then classified as essential loads and non-essential loads. This classification is based on the survivability factor. When any unforeseen situation arises and a blackout occurs then the battery source is taken online just to meet the essential loads. This includes navigation and communication equipment, fire detection system and a few lighting DB. The total network is implemented using MATLAB GUIDE (Graphical User Interface Development Environment) as shown in figure 4.2.Idea behind using GUI is because of its simplicity and is self-explanatory.

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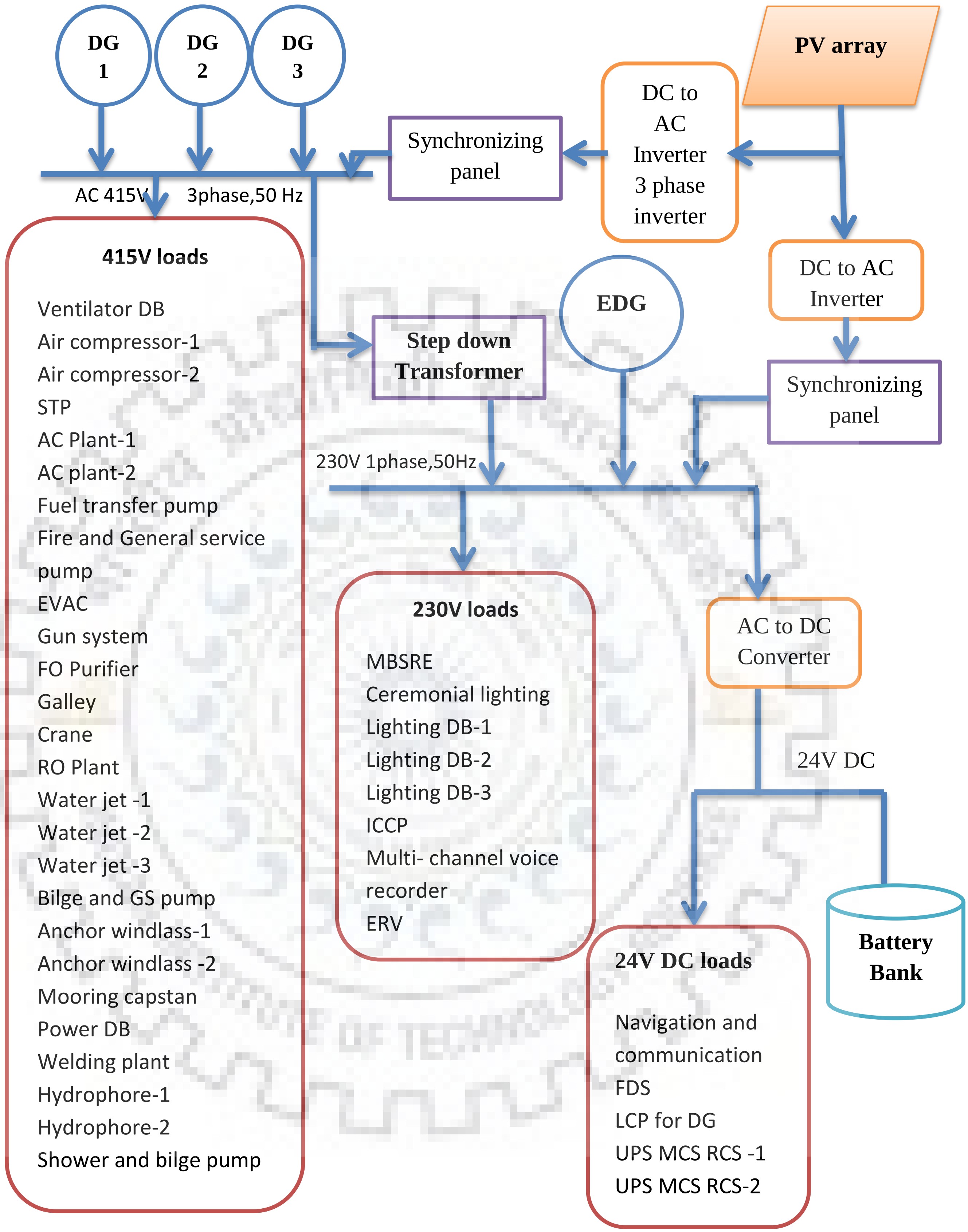

Fig 4.1: Model of SPS

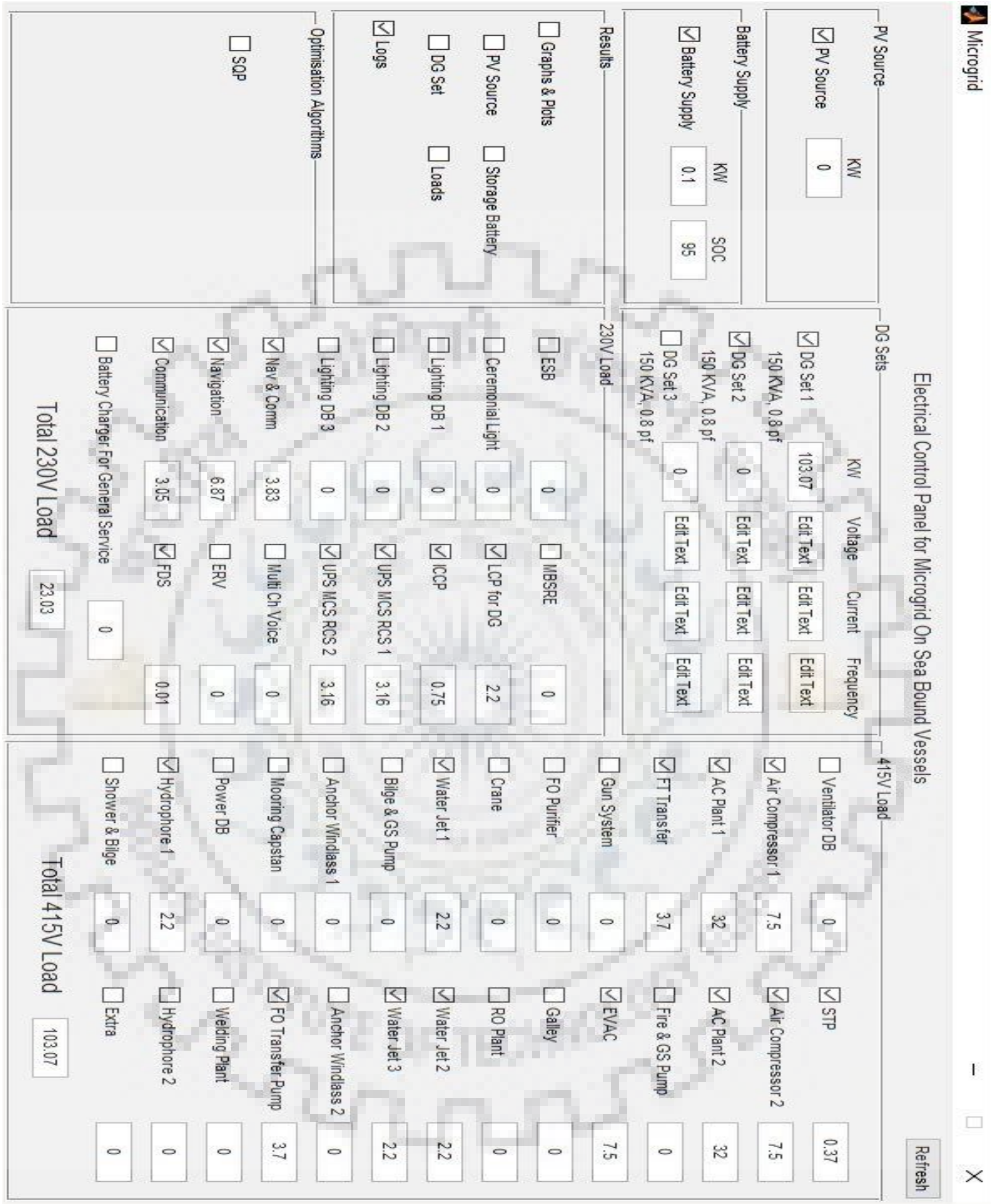

Fig 4.2: MATLAB GUI model of SPS

Different scenarios are considered depending on generator availability, PV availability and battery SOC.

Scenario-1: All diesel generators and PV are available, battery SOC>80%.

In this scenario, if available PV is less than 230V bus bar's total load, the generated P_{pv} will be taken as such to the system. In case if available PV is more than 230V bus bar's total load then the battery charger for general service switches on to 'on' state and the battery starts charging if the SOC of battery is less than SOC_{max}

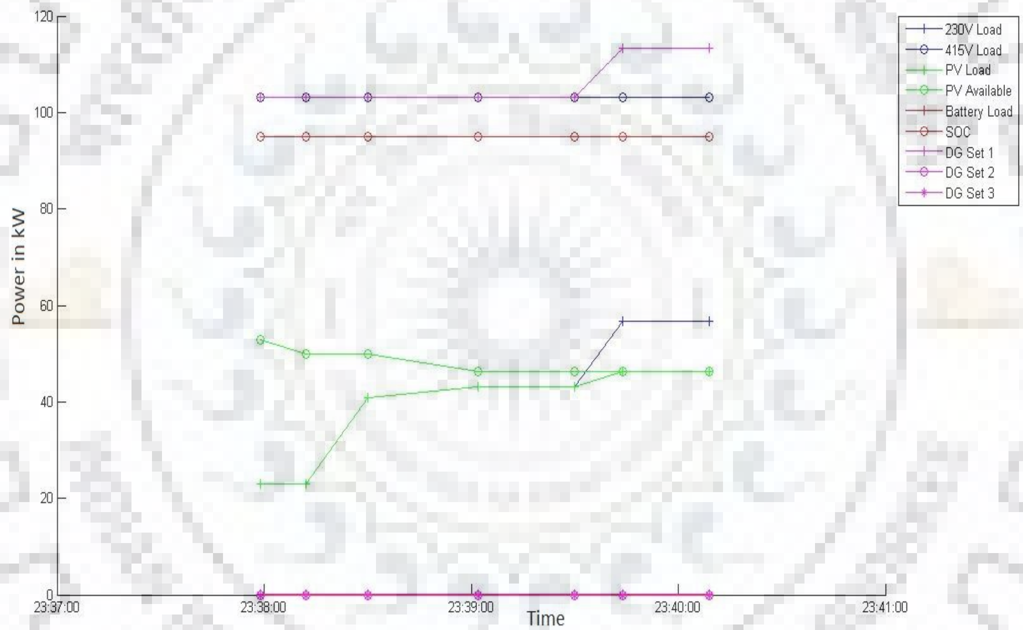

Fig 4.3: Graphical representation of Scenario 1

If the total load demand exceeds available PV, then the diesel generators come online to meet the demand. The order of preference of diesel generators is DG-1 to DG-3.

Scenario-2: All diesel generators and PV are available, battery SOC<80%.

Battery starts discharging only when all the other power sources go offline. Once either PV or diesel generators come online then the battery charger switches on to 'on' state thereby charging battery. General service battery charger moves to 'off' state once the SOC has reached SOC_{max} which is set at 95%.

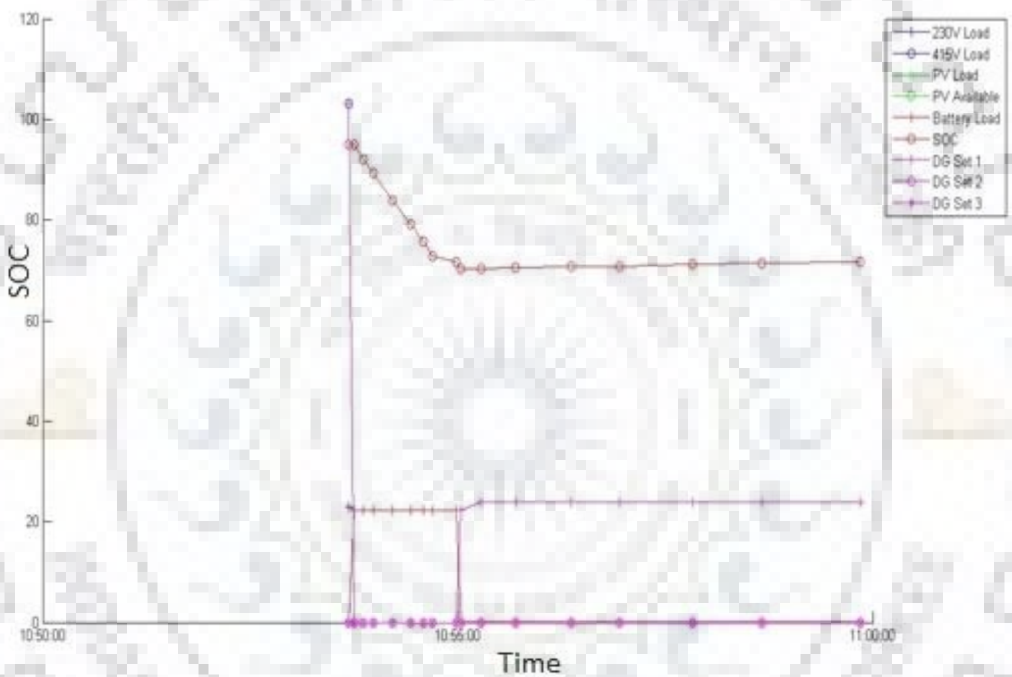

Fig 4.4: Graphical representation of Scenario 2

Scenario-3: All diesel generators are available and PV is not in line.

In this scenario, the load demand is met exclusively by diesel generators. The order of preference is same as above. In this condition, depending on the SOC of battery, the battery gets charged if the SOC drops below SOC_{min}.

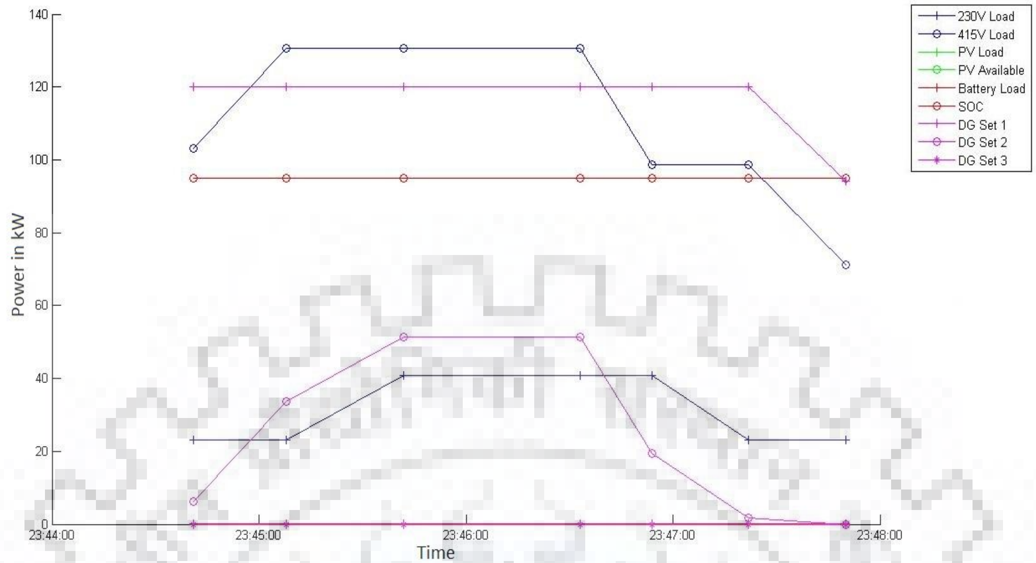

Fig 4.5: Graphical representation of Scenario 3

Scenario-4: Diesel generators are offline while PV source is available.

In this scenario, the moment when diesel generators go offline, the survivability factor is to be considered wherein essential loads are retained in 'on' state. The load demand of essential loads is fulfilled by battery and PV source.

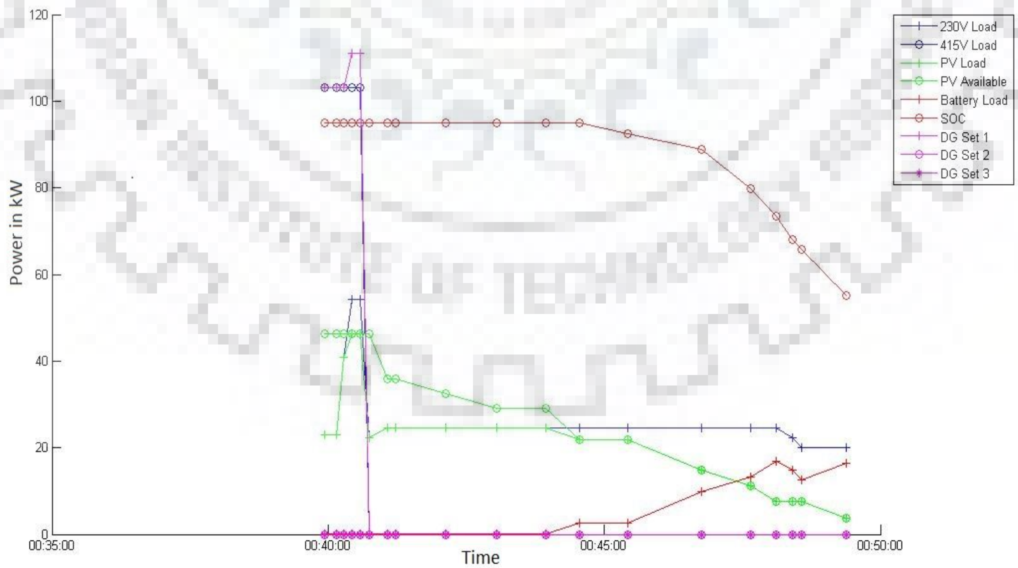

Fig 4.6: Graphical representation of Scenario 4

Power flow optimisation

The general form of the cost function which is denoted as $C(P_i)$ (Rs/hour) is a quadratic convex cost function of the form

$$C(P_i) = aP_i^{\ 2} + bP_i + c \tag{4.1}$$

Where a, b and c are the cost coefficients [18]. Such rough approximation may deviate the economic dispatch (ED) solution [14]. So in order to improve ED solution higher order approximation is to be taken. In this paper we make use of a third order polynomial of the form [14] .

$$C(P_i) = aP_i^{\ 3} + bP_i^2 + cP_i + d \tag{4.2}$$

The optimization problem needs to be solved subject to the equality and inequality constraints which are shown below.

$$\sum_{i=1}^{n} P_i = P_{demand} \tag{4.3}$$

$$0 \leq P_{i,generation} \leq P_{i,max} \tag{4.4}$$

Here in ship board microgrid the optimisation is carried out for two diesel generators having different cost functions. The power to be generated (P_{demand}) by these generators should be total load minus the solar power generated. The maximum power that can be generated by one individual generator is restricted to 120kW.

$$C(P_1) = a_1P_1^3 + b_1P_1^{\ 2} + c_1P_1 + d_1 \tag{4.5}$$

$$C(P_2) = a_2P_2^3 + b_2P_2^{\ 2} + c_2P_2 + d_2 \tag{4.6}$$

$$C_{total} = C(P_1) + \ C(P_2) \tag{4.7}$$

The cost coefficients are as shown in table 4.2. The cost coefficients of the generators used are obtained from diesel fuel consumption chart [17][18].

DG-1		DG-2	
a_1	3.4567*10^{-4}	a_2	-1.5809*10^{-3}
b_1	-0.04666	b_2	0.3594035
c_1	16.9555	c_2	-6.775888
d_1	287	d_2	730.45

Table 4.2: Cost Coefficients

The optimisation of equation (8), subject to constraints equation (4) and equation (5) is carried out using Sequential Quadratic Programming (SQP). SQP follows an iterative approach and optimises constrained non-linear problems [14]. It has higher accuracy than linear programming method. The SQP algorithm followed in this paper is shown in figure 4.7.Different scenarios are considered depending on PV availability and optimisation.

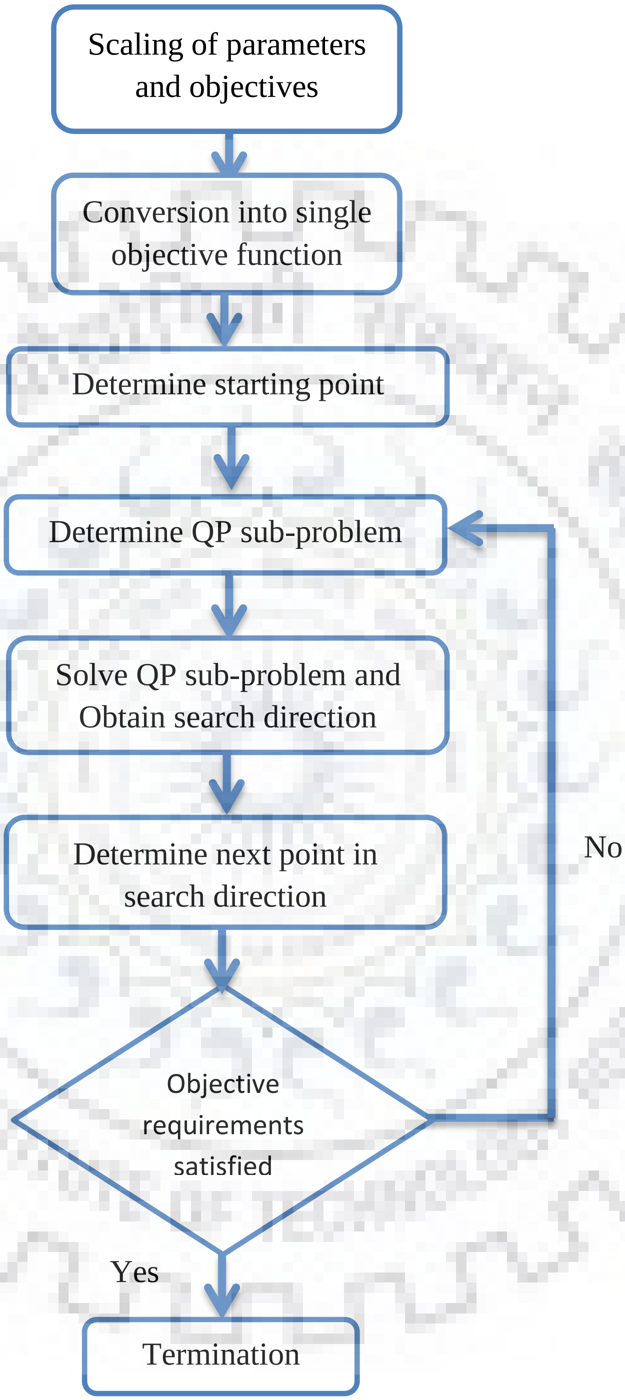

Fig 4.7: Illustration of the SQP optimization flow

Scenario 1

12 hour load-generation profile while PV is offline, without optimisation

The total load demand is met by the diesel generators. Since fuel cost optimisation is not carried out, DG-1 gets loaded to the maximum generation capacity followed by DG-2. This is shown in the figure given below.

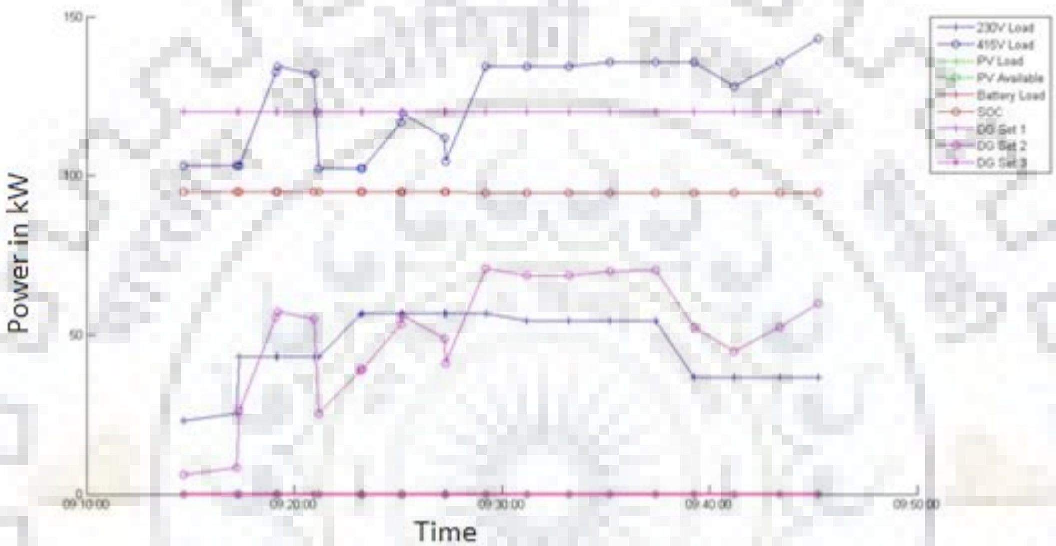

Fig 4.8: 12 hour load-generation profile without optimisation, PV offline

Scenario-2

12 hour load-generation profile while PV is online, without optimisation

In this case the diesel generators are operated to handle total load minus the solar power output. See figure 4.9

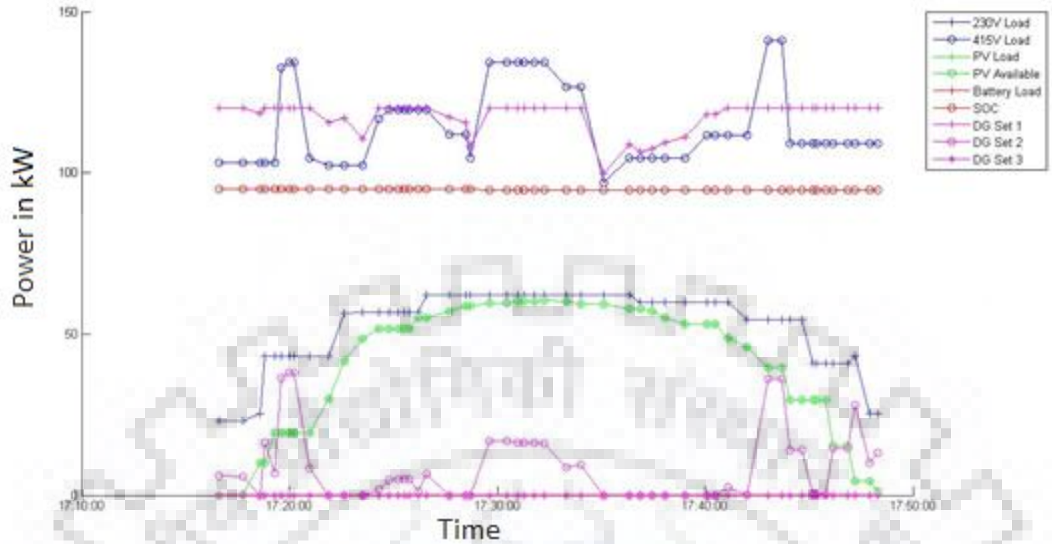

Fig 4.9: 12 hour load-generation profile with PV, without optimisation

Scenario-3

12 hour load-generation profile while PV is offline, with optimisation

In this case as shown in figure 4.10 when a load is coming online, at that instant the optimisation algorithm is initiated so that the diesel generators are generating the required power in a cost effective manner.

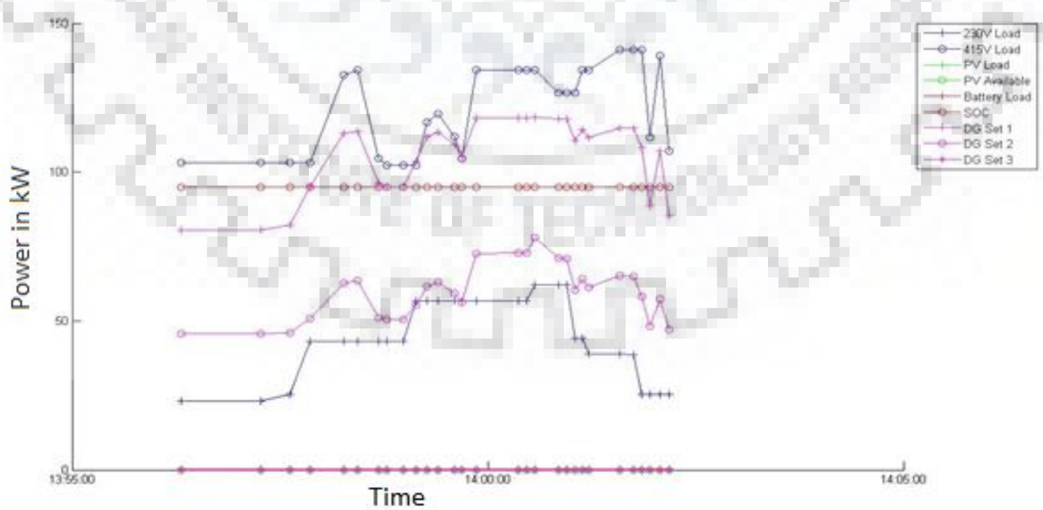

Fig 4.10: 12 hour load-generation profile with optimisation, PV offline

Scenario-4

12 hour load-generation profile while PV is online, with optimisation

As shown in below figure available PV is taken as such into the microgrid and the remaining load is catered by DG-1 and DG-2, whose power generation is governed by SQP algorithm.

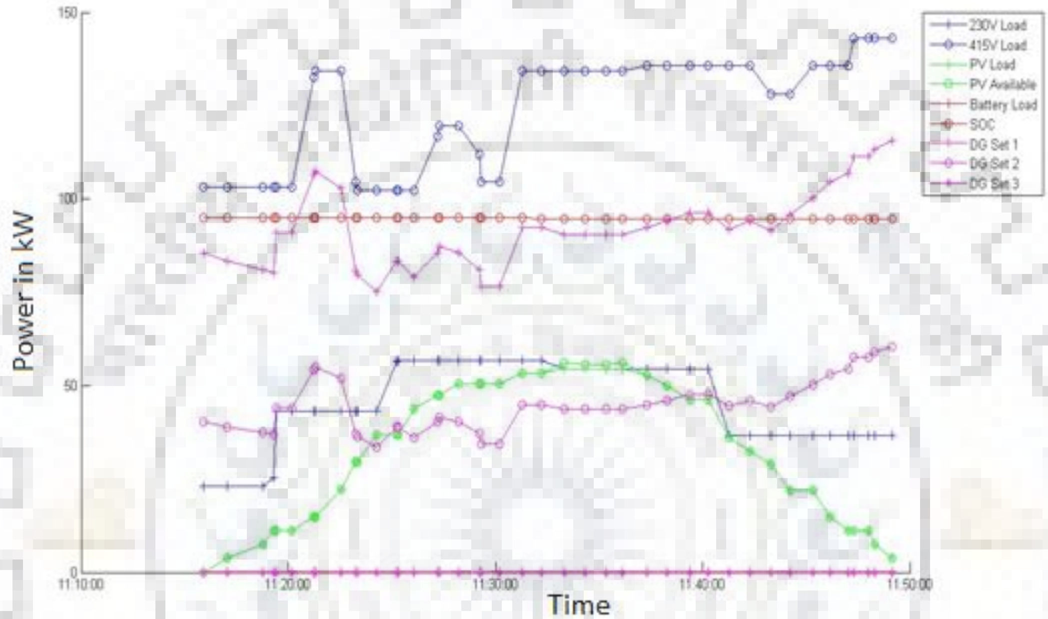

Fig 4.11: 12 hour load-generation profile with optimisation, PV online

Economic feasibility of the proposed model has been carried and the results are as shown in table 4.3, 4.4, 4.5 and 4.6. It is clear that the fuel optimisation with PV is economically feasible and on an average the fuel savings per day comes around 20.5% when compared to one without PV and optimisation. Mere cost optimisation guarantees fuel savings around 2.3%.

Time (hours)	Total load (kW)	PV (kW)	DG 1 (kW)	DG 2 (kW)	Total cost (Rs)
05:30-06:00	126.1	0	120	6.1	2949.21
06:00-06:30	146.11	0.266	120	26.11	3017.48
06:30-07:00	175.71	9.975	120	55.71	3442.15
07:00-07:30	177.21	19.2794	120	57.21	3470.18
07:30-08:00	177.21	29.8074	120	57.21	3470.18
08:00-08:30	147.61	41.7942	120	27.61	3031.15
08:30-09:00	145.41	43.04	120	25.41	3011.47
09:00-09:30	158.91	48.4995	120	38.91	3164.88
09:30-10:00	159.06	51.52	120	39.06	3166.98
10:00-10:30	173.31	55.1264	120	53.31	3398.2
10:30-11:00	181.74	56.9478	120	61.74	3557.11
11:00-11:30	181.74	59.598	120	61.74	3557.11
11:30-12:00	166.74	60.039	120	46.74	3284.56
12:00-12:30	196.34	60.3064	120	76.34	3851.45
12:30-13:00	197.84	60.1195	120	77.84	3882.13
13:00-13:30	190.34	59.2592	120	70.34	3728.95
13:30-14:00	190.24	57.855	120	70.24	3726.91
14:00-14:30	188.03	56.98	120	68.03	3682.17
14:30-15:00	188.03	55.0088	120	68.03	3682.17
15:00-15:30	195.53	53.2042	120	75.53	3834.88
15:30-16:00	190.15	48.9055	120	70.15	3725.09
16:00-16:30	197.15	45.864	120	77.15	3868.02
16:30-17:00	197	39.375	120	77	3864.95
17:00-17:30	183.5	29.5568	120	63.5	3591.67
17:30-18:00	153.9	15.4791	120	33.9	3099.26
18:00-18:30	181.46	4.3148	120	61.46	3551.65
18:30-19:00	149.46	1.3671	120	29.46	3049.41
19:00-19:30	149.46	0	120	29.46	3049.41

Table 4.3: Load-generation data without PV and without optimization

Load (kW)	DG-1 (kW)	DG-2 (kW)	Cost (Rs)	DG-1 (kW)	DG-2 (kW)	Cost (Rs)	Savings (Rs)
126.1	80.43365	45.66635	2548.763	120	6.1	2949.205	400.442
128.31	82.17968	46.13032	2584.618	120	8.31	2945.128	360.5098
146.11	95.36377	50.74623	2884.914	120	26.11	3017.481	132.5665
175.71	112.988	62.72197	3434.957	120	55.71	3442.132	7.175412
177.21	113.6757	63.53429	3464.505	120	57.21	3470.164	5.658452
147.61	96.39925	51.21075	2911.227	120	27.61	3031.144	119.9171
145.41	94.87631	50.53369	2872.691	120	25.41	3011.466	138.7745
159.06	103.8631	55.19692	3117.568	120	39.06	3166.978	49.40988
173.31	111.8329	61.47712	3387.989	120	53.31	3398.185	10.19661
176.25	113.2388	63.01122	3445.577	120	56.25	3452.176	6.598507
168.75	109.4729	59.27709	3299.847	120	48.75	3318.177	18.32993
161.25	105.1936	56.05641	3158.153	120	41.25	3198.598	40.44476
190.85	118.1934	72.65662	3738.981	120	70.85	3739.289	0.307413
196.34	118.3435	77.99648	3851.228	120	76.34	3851.417	0.188597
188.84	117.7965	71.04353	3698.01	120	68.84	3698.506	0.496172
170.94	110.6317	60.3083	3341.995	120	50.94	3355.992	13.99691
178.44	114.2183	64.22173	3488.843	120	58.44	3493.447	4.604091
173.06	111.7089	61.35107	3383.119	120	53.06	3393.676	10.55719
180.06	114.9013	65.15874	3521.04	120	60.06	3524.49	3.449255
179.91	114.8396	65.07041	3518.052	120	59.91	3521.598	3.545796
166.41	108.187	58.22299	3255.194	120	46.41	3279.132	23.93884
136.81	88.67505	48.13495	2725.356	120	16.81	2957.67	232.3137
164.37	107.0284	57.34158	3216.593	120	44.37	3246.334	29.74162
132.37	85.3262	47.0438	2651.264	120	12.37	2945.708	294.4445

Table 4.4: Load-generation data without PV and with optimization

Time (hours)	Total load (kW)	PV (kW)	DG 1 (kW)	DG 2 (kW)	Total cost (Rs)	Savings (Rs)
05:30-06:00	126.1	0	120	6.1	2949.205	0
06:00-06:30	146.11	0.266	120	25.844	3015.169	2.3133763
06:30-07:00	175.71	9.975	120	45.735	3268.155	173.99023
07:00-07:30	177.21	19.2794	120	37.9306	3151.323	318.85516
07:30-08:00	177.21	29.8074	120	27.4026	3029.194	440.98416
08:00-08:30	147.61	41.7942	105.816	0	2698.715	332.43046
08:30-09:00	145.41	43.04	102.37	0	2635.04	376.4271
09:00-09:30	158.91	48.4995	110.411	0	2785.964	378.91322
09:30-10:00	159.06	51.52	107.54	0	2731.133	435.85002
10:00-10:30	173.31	55.1264	118.184	0	2940.197	457.99982
10:30-11:00	181.74	56.9478	120	4.7922	2953.132	603.98057
11:00-11:30	181.74	59.598	120	2.142	2964.643	592.46957
11:30-12:00	166.74	60.039	106.701	0	2715.31	569.24704
12:00-12:30	196.34	60.3064	120	16.0336	2954.76	896.69042
12:30-13:00	197.84	60.1195	120	17.7205	2961.513	920.61366
13:00-13:30	190.34	59.2592	120	11.0808	2944.42	784.52619
13:30-14:00	190.24	57.855	120	12.385	2945.729	781.1855
14:00-14:30	188.03	56.98	120	11.05	2944.401	737.76437
14:30-15:00	188.03	55.0088	120	13.0212	2946.741	735.42437
15:00-15:30	195.53	53.2042	120	22.3258	2987.796	847.08225
15:30-16:00	190.15	48.9055	120	21.2445	2980.625	744.46143
16:00-16:30	197.15	45.864	120	31.286	3068.911	799.10811
16:30-17:00	197	39.375	120	37.625	3147.163	717.78833
17:00-17:30	183.5	29.5568	120	33.9432	3099.787	491.88706
17:30-18:00	153.9	15.4791	120	18.4209	2964.78	134.48248
18:00-18:30	181.46	4.3148	120	57.1452	3468.959	82.691849
18:30-19:00	149.46	1.3671	120	28.0929	3035.764	13.645026
19:00-19:30	149.46	0	120	29.46	3049.409	0

Table 4.5: Load-generation data with PV and without optimization

Time (hours)	Total load (kW)	PV (kW)	DG 1 (kW)	DG 2 (kW)	Total cost (Rs)	Savings (Rs)
05:30-06:00	126.1	0	69.3882	56.7118	2568.09	381.11752
06:00-06:30	146.11	0.266	80.1578	65.6862	2912.37	105.10996
06:30-07:00	175.71	9.975	91.0076	74.7274	3275.56	166.58454
07:00-07:30	177.21	19.2794	86.7506	71.18	3131.38	338.79522
07:30-08:00	177.21	29.8074	81.008	66.3946	2940.29	529.88336
08:00-08:30	147.61	41.7942	58.324	47.4918	2235.71	795.43958
08:30-09:00	145.41	43.04	56.4445	45.9255	2181.72	829.7493
09:00-09:30	158.91	48.4995	60.8302	49.5803	2308.87	856.01047
09:30-10:00	159.06	51.52	59.2645	48.2755	2263.01	903.97757
10:00-10:30	173.31	55.1264	65.0702	53.1134	2435.55	962.65038
10:30-11:00	181.74	56.9478	68.6749	56.1173	2545.96	1011.1546
11:00-11:30	181.74	59.598	67.2293	54.9127	2501.39	1055.7199
11:30-12:00	166.74	60.039	58.8069	47.8941	2249.7	1034.8591
12:00-12:30	196.34	60.3064	74.8066	61.227	2739.02	1112.4333
12:30-13:00	197.84	60.1195	75.7268	61.9937	2768.52	1113.608
13:00-13:30	190.34	59.2592	72.1051	58.9757	2653.18	1075.7654
13:30-14:00	190.24	57.855	72.8165	59.5685	2675.67	1051.2462
14:00-14:30	188.03	56.98	72.0883	58.9617	2652.65	1029.5147
14:30-15:00	188.03	55.0088	73.1635	59.8577	2686.67	995.49717
15:00-15:30	195.53	53.2042	78.2388	64.087	2849.72	985.16075
15:30-16:00	190.15	48.9055	77.649	63.5955	2830.57	894.51871
16:00-16:30	197.15	45.864	83.1262	68.1598	3010.29	857.72847
16:30-17:00	197	39.375	86.5839	71.0411	3125.78	739.17261
17:00-17:30	183.5	29.5568	84.5756	69.3676	3058.52	533.15282
17:30-18:00	153.9	15.4791	76.1088	62.3121	2780.81	318.45615
18:00-18:30	181.46	4.3148	97.2314	79.9138	3489.62	62.033453
18:30-19:00	149.46	1.3671	81.3845	66.7084	2952.69	96.715824
19:00-19:30	149.46	0	82.1302	67.3298	2977.3	72.105059

Table 4.6: Load-generation data with PV and with optimization

From the load generation profile data given in tables,4.3,4.4,4.5 and 4.6, the average fuel consumption comes around 1381.543 litres of diesel fuel per day (assuming 14 hours of vessel operation). The fuel saving with the proposed model is around 20%. The emission factor from diesel generators is roughly around 2.4 to 3.5 kg CO_2/litre of diesel fuel consumption []. By taking 2.6kg of CO_2 per litre, 276.3 litres of diesel fuel would account about 0.718 tonne of CO_2. Thus the proposed model having DG-Solar PV as sources would help in reducing the carbon footprint by 0.7 tonnes of CO_2 per day (considering 10-12 hours of solar radiation available). Thus the proposed model is both economically viable and helps in reducing the carbon footprint.

CHAPTER 5

CONCLUSION

To adhere with the IMO regulations hybrid microgrid is promising for the future ships. In the proposed network the solar photovoltaic cells along with battery take a significant share of the load when available there by reducing the dependency on conventional diesel generators. Apart from reducing the carbon footprint the proposed model is more fuel efficient and can help in space weight saving. In the model proposed in this thesis, power drawn from the PV source is restricted to flow only within the 230V single phase network. With the expected advances in PV technology this can be further extended to the 415V three phase network also. Apart from SQP, different other optimisation algorithms such as Particle Swam Optimisation and Dynamic Programming can be carried out in this network which can help in setting optimal points. Thus P/EMS can bring down the fuel consumption and maintenance cost of ships.

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