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Energy efficient system design by optimizing hybrid power system for Unmanned Surface Vehicle

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Abstract

An electric Vehicle's success mostly depends on the efficient design of the system to deliver the expected performance. The efficient system design is achieved with suitable engine design, drag minimization and intelligent power module management. This paper focuses on the intelligent power module management to overcome the pressure and viscous drag for an Unmanned Surface Vehicle (USV). The USV design under development by Villanova University and the Naval Surface Warfare Center Carderock Division (NSWCCD) Philadelphia is expected to conduct Intelligence, Surveillance and Reconnaissance (ISR) missions in the sea for about two weeks duration. The paper proposes a hybrid power solution to meet the power demands of an USV during the mission. The hybrid power system is designed by a combination of renewable energy resources, conventional fossil-fueled energy sources and energy storage options. The hybrid power system comprises a solar array, a sea wave power converter, a fuel cell system, a diesel generator and a lithium ion battery pack. The paper describes the required drag for an eleven meter Rigid Hull Inflatable Boat (RHIB) platform, modeling of each power source and optimized power solution for a RHIB. A combination of hierarchical and cost function minimization optimization is applied to the hybrid power module design. The optimization approach gives a high priority to the natural energy sources, i.e. sun and wave and minimizes the energy consumption from the storage energy sources, i.e. battery bank, fuel cell system based on H_2 storage and diesel generator based on gasoline. The optimized result provides the individual contribution of each power source to the load demand of an USV. The solar array and wave energy converter supply the maximum energy on the availability of sun and favorable waves. The rest of the energy sources, i.e. battery bank, fuel cell system and diesel generator contribute proportionally to their energy/cost ratio. Results also suggest the appropriate sizing of each power element to support the USV demand during the extended period of the mission.

Keyword: Hybrid Power system design, power optimization, unmanned surface vehicle

1. Introduction

Automotive engineers and researchers are extending their knowledge and experiences in producing better hybrid electric/ electric system designs for reducing carbon emissions in the vehicle transportation sector of the economy. Electric vehicles first came into existence in the mid-19th century, when electricity was the preferred method for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. However, it is still relevant in this century and will remain so in the future to save the environment from the impact of gasoline/ petroleum-based transportation infrastructure.

Electric vehicles include electric cars, electric trains, electric trucks, electric boats, electric motorcycles, and scooters. Three main types of electric vehicles exist

- directly powered from an external power station,
- powered by stored electricity originally from an external power source,
- powered by an on-board electrical generator, such as an internal combustion engine (a hybrid electric vehicle) or a hydrogen fuel cell

Electric vehicles (EVs) differ from fossil fuel-powered vehicles in the way EVs consume electricity. The electricity EVs consume can be generated from a wide range of sources, including fossil fuels, nuclear power, and renewable sources such as tidal power, solar power and wind power or any combination of those. The electricity may then be stored on board using a battery, flywheel, or supercapacitors.

Our paper describes an optimized hybrid power solution for an USV which is under development by Villanova University and the Naval Surface Warfare Center Carderock Division (NSWCCD) Philadelphia is expected to conduct Intelligence, Surveillance and Reconnaissance (ISR) missions in the sea for about two weeks duration in addition to Mine Countermeasures (MCM) mission that keeps man out of the minefield. USV design is proposed with the following objectives –

"*USVs will augment current and future platforms to deliver enhanced steady-state and surge capability to help deter the enemy at the regional, transnational, and global levels. USVs will be highly automated to reduce communication/data exchange requirements and operator loading. They will deploy and retrieve devices, gather, transmit, or act on all types of information, and engage targets with minimal risk or burden to US and Coalition Forces[1].*

The US Navy has proposed four classes of vehicles according to capabilities, objectives of operation, and mission duration.

- Xclass (small)
- Harbor Class (7 meter)
- Snorkeler Class (7meter)
- Fleet class (11 meter)

We have selected Harbor class and Fleet class as seen in the figure 1 for our study. Both of the vehicles support ISR operation and gun payload for the mission.

Figure 1: Harbor and Fleet Class USV

An USV design methodology is explored for a unique hybrid power system. For the present work, the hybrid power system includes the following power sources:

- solar panels,
- wave energy harvester,
- battery bank,
- fuel cell system, and
- diesel generator

Villanova University's research group has performed the sizing analysis, weight analysis, modeling and characterization of each power source for an USV hybrid power system [2-5]. The present work is an extension of previously studied power sources, in a unique framework given in figure 2 to provide an optimized solution for the design of a hybrid power system for a USV to perform ISR operations.

The framework for optimizing the USV power system in figure 2 shows a hybrid power system arrangement with five power sources and a USV load profile. The solar array and wave harvester directly feed the USV load on the availability of sun and wave. The control variables, constraints and bounds are set to use solar and wave energy to their maximum limit and minimize the use of other more expensive power sources. Solar power (or wave power) charges the battery when the supply is higher than the demand. The other three energy sources, i.e., battery bank, fuel cell system and diesel generator contribute to the load demand if solar energy and wave energy output are not sufficient.

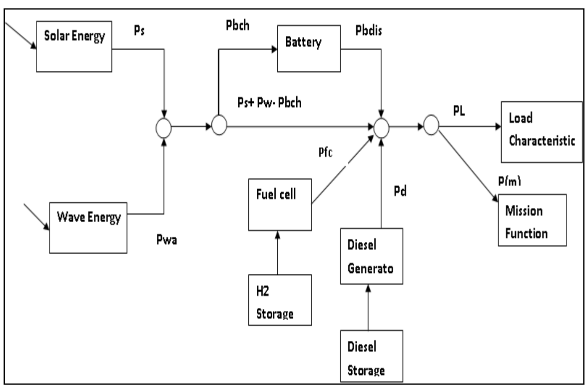

Figure 2: Basic framework for Power Optimization. Solar array power Ps, Wave power Pwa, Fuel cell system output: Pfc, Diesel generator Pd, Battery charging characteristic: Pbch, Battery discharging characteristic

Fellow researchers have worked on hybrid power system controller design and optimization using various methodologies for the hybrid power plants or for electric vehicles (EV). Uzunoglu *et.al.* worked on modeling, controlling and simulating a hybrid system consisting of a photovoltaic(PV), fuel cell(FC) and ultra capacitor (UC) systems for sustained power generation[6]. A three layer intelligent hybrid power management strategy was developed by Haizadeh *et.al*. [7]. Authors described a hierarchical hybrid controller between dual energy sources consisting of a battery bank and a Solid Oxide Fuel Cell (SOFC) system. Jeong *et.al.* [8] also worked on a fuzzy logic-based energy management approach for a hybrid power system. The two other research papers have used the energy hub concept to optimize the hybrid system problem. The energy hub allows the interfacing or coupling between energy demand and energy supply. Fabrizio *et.al*. [9] worked on optimizing multi energy systems in building design. The authors used cost optimization on the energy converters and on the energy storage during the concept state of building design to minimize the initial investment cost. The second paper by Del Real *et. al.*, [10] describes element sizing in a hybrid power system. The objective function minimization is based on the cost efficiency of the system demands. The hybrid system considered in the paper includes wind generation, batteries and fuel cell power sources.

The present paper contributes by developing a unique simplified solution based on modular optimization. The approach uses two modules (1) prioritizing based on availability and (2) cost consumption optimization. The solar array power and wave power sources are prioritized based on their availability during the day and night and the cost optimization is applied to the remaining sources so as to minimize the cost/energy ratio.

2 Mission USV

The USV is expected to conduct an ISR mission relying on power supplied by a unique hybrid system. The hybrid power system employs a diesel generator, lithium-ion battery pack, fuel cell system, wave power and a solar array. Currently, the assumed speed requires the USV to begin by running on diesel power for 3 hours at 45 knots from a mother ship to the area of deployment. It then switches over to the hybrid scheme and runs for 336 hours at 5 knots while performing surveillance in stealth mode. Finally it returns to the mother ship on diesel power running at 45 knots for 3 hours [1]. Every aspect of the hybrid power system for this mission must be closely analyzed and properly sized if the USV is to accommodate the resources for accomplishing a mission of such long duration. The stealth mode for the mission is defined by activities such as strategic and tactical intelligence collection, Chemical, Biological, Nuclear, Radiological, Explosive detection and localization, near-land and harbor monitoring, deployment of leave-behind surveillance sensors, and specialized object mapping, detection, and localization.

2.1. Savitsky model for Drag-Weight Analysis:

Fleet class/Harbor class vehicles support ISR operation and Mine Countermeasures (MCM) of mission. We have taken this vehicle as a reference for our load profile estimation. The MCM USV craft is one of the Navy systems designed to "get the man out of the minefield." The MCM USV craft was designed by the NSWCCD Combatant Craft Division. Design specifications of MCM craft are given in the table 1.

Table1: Fleet Class USV design specification

Length	12.192 meter (40ft)
Beam	3.5 meter (11.5 ft)
Draft	0.671meter (2.2ft)
Displacement	10,252kg (22600lb)
Payload	1814.4kg (4000lb) + fuel
Power	2x540 mHp (783.45 kW)
Tow Force	1134kg (2500lb)@25 kts

Our paper has used a hydrodynamic modeling for prismatic planing surface by D. Savitsky [11] to estimate the power requirements for the fleet class MCM USV. The empirical planing equation given by Savitsky describes the lift drag, wetted area, center of pressure, and proposing stability limits of planing surface as a function of speed, trim angle, dead rise angle and loading. These results are then combined to formulate a simple computational procedure to predict Horse Power requirement of the planing hull. The average dynamic pressure(P_d) of a planing surface is calculated by equation (1), which then provides the mean velocity (V_1) over the bottom of the planing surface as a function of speed of surface (V), dynamic pressure (P_d) and mass density of water (ρ) in equation (2). Equation (3) provides the drag of the planing surface (D) and equation (4) computes the effective HP as a function of drag and speed of the boat.

$$Pd = \frac{\Delta}{\lambda b^2 \cos\tau} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$V_1 = V\left(1 - \frac{2\,P_d}{\rho V^2}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$D = \Delta\, \tan\tau + \frac{\rho {V_1}^2 c_f \lambda b^2}{2\cos\beta\, \cos\tau} \ldots\ldots\ldots\ldots (3)$$

$$EHP = \frac{D\,V}{550}\, hp \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

where the design specifications are close to the MCM USV as below:

λ, mean wetted length bean ration is 2.6 ft
b, beam of planing surface is 10 ft
V, horizontal velocity component of planing is 8-18 fps (5-11kts)
ρ,1.94 is mass density of water
Δ, load on water is 25,286 lb
τ, trim angle of planing area is 3 degree
c_f, friction-drag coefficient is considered 0.00224
β, angle of dead rise of planing surface is 10 degree

Figure 3 shows the drag-velocity relation given by equation (3) for velocity range from 0-70 fps (0-41kts). The figure clearly shows drag force is around 1350 lb for 8 fps (5 kts) as required for the USV ISR mission. Figure 4 is a graphical representation of equation (4) that gives kWatt power requirement of an USV for a range of speeds of the vehicle. The Power requirement for 5 kts speed of a fleet class USV is 20kWatts. In the next section, we discuss the load profile of the USV mission based on the power requirement estimated by Savitsky's model.

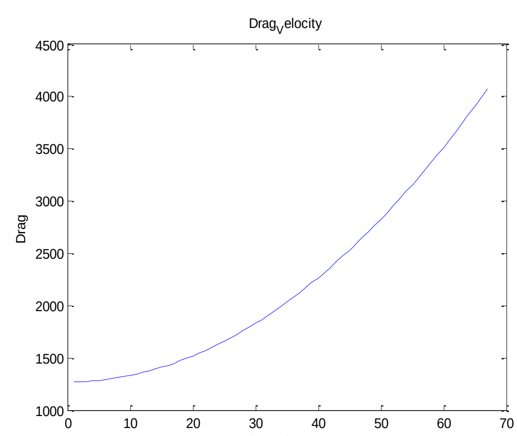

Figure 3: Drag velocity relation for USV

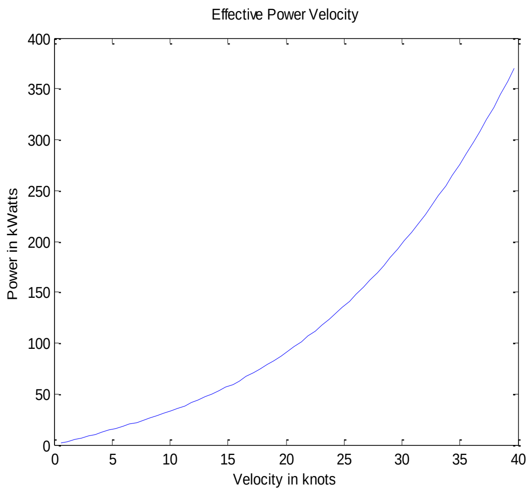

Figure 4: Power requirement for USV for mission speed

2.2. Load profile for USV: The USV load profile for stealth operation consists of a static demand (Pl) as shown in figure 5 and a random demand (Pm) as shown in figure 6. The Pl profile describes an initial high power requirement for propulsion to achieve a constant speed (5kts) of the boat. This peak signal is 75% higher than the 20kW (estimated power for MCM USV craft for 5kts) followed by a constant power demand to power up the payloads to perform ISR operations during the mission and further reduced to a lower value to run just mandatory load for smooth sailing of the USV vehicle. The Pl load profile is modeled as the sum of sinusoidal signals and is given by equation (5) and is shown in Figure 5:

$$Pl = f\{\sum(a\mathrm{Sin}(b*t+c))\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where a, b and c are constants and t is time.

The mission objective also includes some random power (Pm) requirement 10% of Propulsion power (2kW) to accommodate sudden actions needed for security such as generation of acoustic signals, magnetic signals, and pressure signals for an object detection and to operate lethal payload (deck gun). A uniform pseudorandom number generator algorithm in Matlab is used to generate the random number streams shown in figure 6. The streams are independently generated each time the algorithm is executed.

The load profile (Pl) and random power demand (Pm) determine the total power requirement for the USV on the hybrid power system during operation.

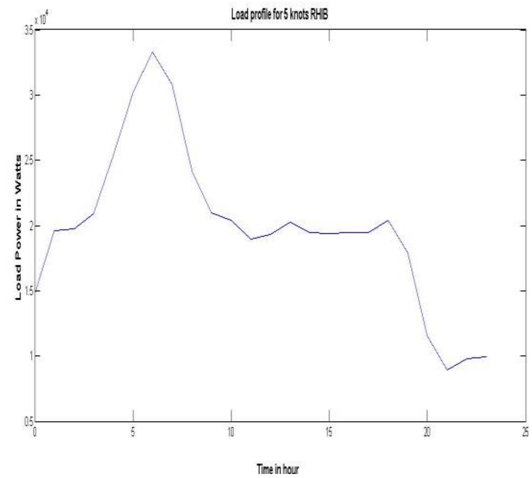

Figure 5: Load profile of USV

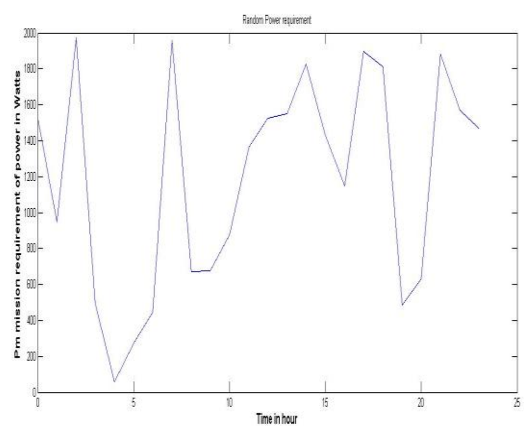

Figure 6: Random power demand Pm for USV operation

3. Power Sources

3.1 Solar Array Power

The USV master plan [1] suggests an eleven meter fleet class for ISR operations. Fifteen nominally 200W solar panels conveniently fit onto the eleven meter vessel. The solar panel output power Ps is modeled using experimental data. Solar power is seen as a function of solar radiation intensity (G) and time (t) [12].

Equation (6) shows a power fit on the experimental data of solar array power and solar intensity range from 700W/m^2 to 1000W/m^2 collected in Philadelphia during the month of April 2009. Solar intensity vs time (0-24 hour) relation has been taken from the National Solar Radiation database [13]. The general model gaussian fit is shown in equation (7).

Ps (G) = a*G ^{b} ………………………(6)

where, a and b are constants.

$G(t) = a1e^{(-((t-b1)/c1)^2)}$……………(7)

where, a1, b1and c1 are constants.

Combining equations (6) and (7) represents solar power for fifteen panels as a function of time shown in figure 7 and given by equation (8).

$Ps = a(a1e^{-((t-b1)/c1)^2})^b$…………(8)

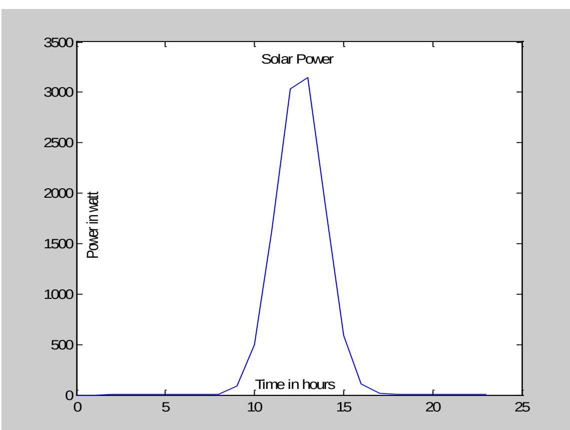

Figure 7: Solar Power (Ps) vs a day time

3.2 Wave Power

The wave power P^t_{wa} at time t is a function of wave oscillation (F_{wa}) and linear generator conversion factor (C_{wa}) given in equation (9):

$0 \leq P_{wa}^t \leq [C_{wa} \, F_{wa}]$…………………………(9)

A numerical model of the Octagonal Linear Generator (OLG) was used for the wave power computation. The model was based on the wave energy conversion (WEC) design of a direct driven permanent magnet buoy [14]. A model of the octagonal permanent magnet linear generator with a translating armature, shown in figure 8, is designed to extract the energy from the relative movement of the structure with respect to the incident wave.

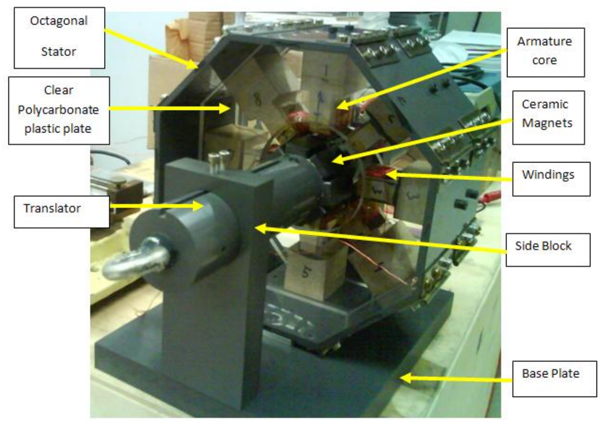

Figure 8: Octagonal Linear Generator as power take-off

The harvester design extracts energy by capturing the oscillating motion of the waves to provide mechanical back and forth input movement to a permanent magnet linear generator shaft. The concepts of the Pelamis wave energy converter and the longitudinal flux linear generator have been adapted to design an octagonal linear generator [15]. The evaluation of the design and performance of the model was done to estimate the capability of the device as an additional power source for a USV.

A linear generator wave power model is described by a set of equations. The electromotive force of one coil for a single phase is given by equation (10), current output is given by equation (11) and wave power linear generator output is given by equation (12).

$$e(t) = 2Nv(t)\{l_s B[x(t)] + 2(l_s' - l_s)B'[x(t)]\}$$ ………………...(10)

$$i(t) = \frac{1}{L_m}\int e(t) \quad , \qquad L_m = \frac{\mu_0 \pi D_m N^2 l_s'}{2k_s\delta}$$ ……(11)

where,

- l_s is the length of the magnet
- l'_s is the length of one side of the coil
- v(t) is the velocity of sea wave
- B[x(t)] is the flux density along the permanent magnet
- x(t) is the shift of the linear generator translator with respect to the incident wave.
- B'[x(t)] is the flux density over the (l'_s – l_s) zone
- L_m = Magnetizing inductance
- μ_0= Permeability of free space = $4\pi 10^{-7}$ m kg s^{-2} A^{-2};
- D_m = Mean diameter of the winding ;
- N = number of turns ;
- K_s = saturation factor
- δ = air gap

$$P_{wa} = e(t)i(t)$$ ………………………….(12)

Considering the model specifications as N = 800, ls' = 0.127m ,ls = 0.048m, B[x(t)]= Bmax ∫ v(t)], and Bmax = 0.244 Tesla, the wave power output Pwa is plotted as a function of the frequency shift of the linear generator shaft (translated into the wave frequency) given in figure 9. The expected power generated at low frequency (1m/sec) is approximately 50Watt.

The wave power parameters are not included in the optimization because we would like to use the maximum wave power on its availability and hence, we fixed the wave amplitude and angular velocity at 1m and 0.6 π rad/sec[Vm sin (2πft)] respectively to generate a maximum power of 50watt with the wave generator model for the present study.

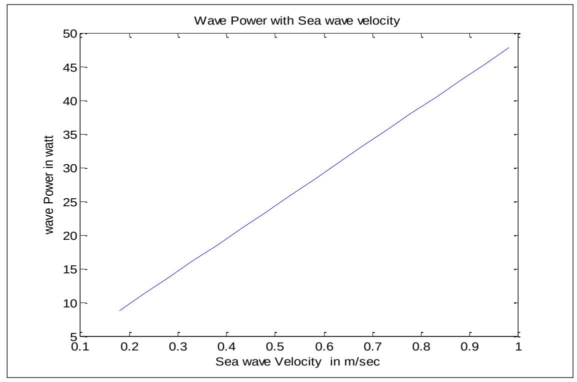

Figure 9: Wave Power output of scaled-up model at fixed wave amplitude

3.3 Diesel Generator

The diesel generator provides the power needed to propel the USV at high speed (45 knots) to and from the mother ship to the deployment area and back to the mother ship. The noisy and costly diesel power is not used during the stealth mode of USV operation. The diesel generator power Pd output given in equation (13) is a function of diesel storage capacity D_s and generator conversion factor C_d.

$$0 \leq P_d \leq [Cd, Ds]$$ ………………(13)

Ds is measured as diesel consumption in gal/hour, here, upper and lower bounds of the consumption are 2≤ Ds≤160. Equation (14) and figure 10 show the Pd based on the statistical data available through Diesel Services and Supply [16].

$$P_d = 25.954\, e^{0.1809\, Ds}$$ ……………….(14)

3.4 Battery bank

$\bar{E}_B^t$ is Energy stored in the battery bank, which should not attain a value more than 93% of its maximum value E_B and should never fall below 20% of the maximum E_B during deep discharge as seen in equation (15).

$$0.2 \max \bar{E}_B \leq E_B^t \leq 0.93 \max \bar{E}_B$$ ……..(15)

The battery gets charged whenever the available solar power or the wave power is higher than the load demand. This charging current collects as battery energy if battery energy is less than 93% of maximum E_B.

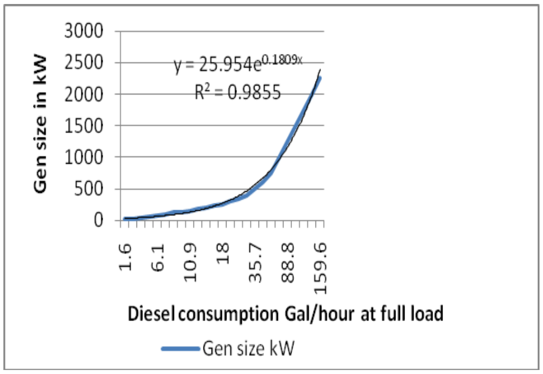

Figure 10: Diesel Power (Pd) vs. Diesel consumption

The collected energy during charging is

$E_{Bchar}= f$ (Ichar, Vb, tchar), where Ichar is charging current, Vb is battery terminal voltage and tchar is charging time.

Discharging of the battery is initiated with the optimization module when the solar or the wave power is not sufficient to drive the payload and the battery has more than 20% of its maximum E_B energy. The battery bank supplies the discharge current to meet the remaining power requirement specified by the cost optimization between fuel cell, diesel and battery stored energy. The energy that the battery loses during discharge is given by $E_{Bdis=}$ f(Idischar, Vb, tdischar), where Idischar is discharging current. To define the battery discharging, an experiment was carried out on a battery string (a series connection of 4 cells each of 3.7 volt) to generate the discharge curve. The discharge was conducted for 10 minutes followed by a rest period of one minute. The discharge curve shows the small voltage recovery peaks during the rest period. The linear fit on the battery terminal voltage as a function of discharge time is expressed as equation (16).

$$Vb = -0.0349tdischar + 12.399 \ldots (16)$$

Power output of the battery, as a function of discharge current and discharge time, is shown in equation (17) and plotted in figure 11. The maximum discharge current allowed is 10A and the maximum discharge duration is 3 hours.

$$Pb = Idischar(-0.0349tdischar + 12.399). \ldots (17)$$

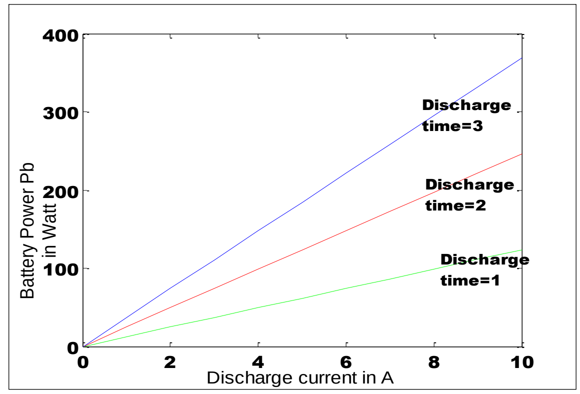

Figure 11: Battery discharge power as a function of discharge current and discharge time

3.5 Fuel cell

A Proton Exchange Membrane Fuel Cell (PEMFC) model described in [6] is used in this study. This model is built on the relationship between the output voltage and partial pressure of hydrogen, oxygen and water.

The FC system parameters used in this model are as follows:

N_0 number of series fuel cells in the stack

N_S number of stacks used in the FC power plant

Ph_2 hydrogen partial pressure [atm]

Ph_2O water partial pressure [atm]

PO_2 oxygen partial pressure [atm]

qh_2 input molar flow of hydrogen [kmol/s]

R universal (Rydberg) gas constant [J/(kmol)]

T absolute temperature [K]

U utilization rate

F Faraday's constant

Ifc FC system current [A]

The cell voltage for the PEMFC is obtained from the sum of the Nernst voltage, the activation over-voltage, and the ohmic over-voltage. The activation over voltage and ohmic voltage are ignored for this study. Assuming constant temperature and oxygen concentration, the FC output voltage may be expressed as in equation (18) [17,18].

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \ldots\ldots\ldots\ldots(18)$$

The Nernst instantaneous voltage may be expressed by equation (19)[17]

$$E = No\left(Eo + \left(\frac{RT}{2F}\right)\left(log\left(\frac{10\,Ph_2\left(Po_2^{0.5}\right)}{Ph2o}\right)\right)\right);..(19)$$

The FC system consumes hydrogen according to the power demand. The hydrogen is obtained from the on-board high pressure hydrogen tanks. Depending on the FC system configuration, and the flow of hydrogen and oxygen, the FC system produces the dc output voltage.

According to the basic electrochemical relationship between the hydrogen flow and the FC system current, the fuel cell current is given by equation (20) [17,19].

$$Ifc = \frac{2FU(10^{-2})qh_2}{NoNs};\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(20)$$

Thus, combining equations (19) and (20), the total power output of the fuel cell is given by equation (21). The fuel cell model generates 5kWatt power at maximum boundary condition (83 psig H_2 pressure and 7.3 lit/min or 0.0073 cubic meter/min, H_2 flow rate), which matches with the given design specification of fuel cell currently used at test-bed of the USV [2].

$$Pfc = E * Ifc;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(21)$$

4. Power module optimization

The optimization approach that we have used divides the problem into discrete time domains and prioritizes the natural energy sources over storage energy sources. Solar power remains active during the sun hours of the day normally 8.00 am to 6.00 pm. The wave power generator is used as an alternate to solar power in the night hours and in addition to solar power in day hours whenever wave conditions are favorable.

Both the natural energy sources (solar power and wave power) help to charge the battery bank if supply is more than the demands of the load. If both the power sources are insufficient to meet the demands then the cost optimization module (battery bank, fuel cell system and diesel generator) serves to meet the static and the random power requirement of the load. This optimization module minimizes an error between the demand and supply energy subjected to the priorities of power sources and under the feasible bounds and constraints. The priority definition is based on the consumption cost and on the availability of each source. The diesel generator which is most costly and noisy has lowest priority. The battery bank has higher priority over the fuel cell system since the stored hydrogen fuel is more expensive than the energy stored in the battery. Also, batteries can be recharged with extra sun or wave power unlike the fuel cell which depends on one-time H_2 storage tank capacity. Solar power and wave power are defined as the highest priority sources when they are available.

The energy demands (load profile) vary according to the mission operation and the class of operations within the given type of fleet. In this work, the energy demand is considered for a MCM craft of USV mission. The objective function to be minimized here is an error between the sum of nonlinear function models of each power source and mission objective. The discrete time optimization is obtained for each single hour separately and in a total period of 24 hours. This can be extended later to 336 hours needed for the ISR mission.

This system design is categorized as a discrete time nonlinear optimization problem with nonlinear constraints. The objective function used is given by equation (22)

Objective Function:

$$f = (PL + Pm) - (Ps + Pwa + \alpha 3 * Pfc + \alpha 1 * Pb + \alpha 2 * Pd); \quad \ldots\ldots\ldots\ldots(22)$$

f, is an error to be minimized
$(PL + Pm)$, is load profile
$(Ps + Pwa + \alpha 3 * Pfc + \alpha 1 * Pb + \alpha 2 * Pd)$; is power sources contribution

PL= Load Profile, Pm = Random demand of Power by USV, Ps= Solar Power, Pwa= Wave Power, Pb= Battery Power, Pfc= Fuel Cell Power, Pd= Diesel Generator Power, α1, α2, α3= Fractional contribution of battery power, diesel generator output and fuel cell power respectively.

4.1. Optimization Algorithm

Figure 12 shows a flowchart of the optimization algorithm which is executed in the Matlab environment. The required power (PL) and power generated by natural energy sources (Ps+Pwa) are compared.

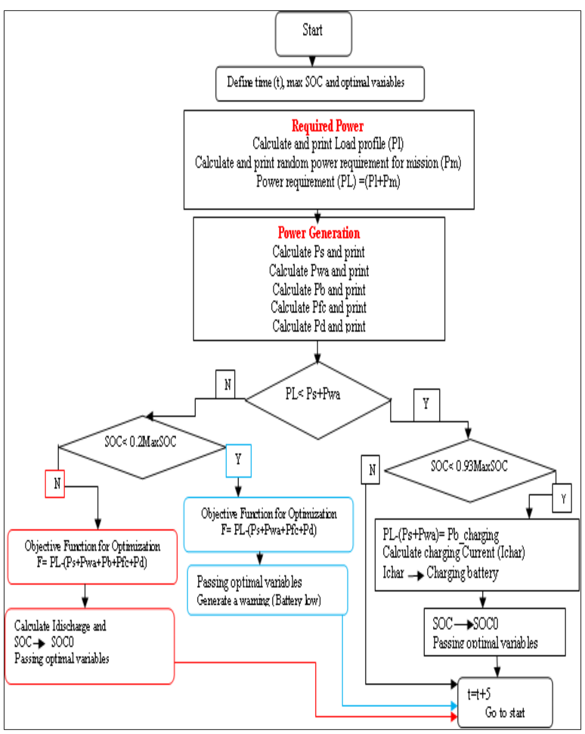

Figure 12: Flow chart of algorithm

If both the natural energy sources generate more than the required power then PL-(Ps+Pwa) charges the battery. Charging current improves the state of charge (SOC) of the battery and proceeds to the next iteration of the algorithm. In this particular case, the path through the flowchart does not invoke the optimization module. Therefore, the optimal variables remain unaltered. The time variable changes by 5 units and the next iteration starts with an interval of 5 minutes. If the required power is higher than the natural resources power then the optimization module takes two paths depending on the battery SOC. If the battery is sufficiently charged, the cost optimization is applied to the battery, fuel cell and diesel generator. However, if the battery SOC is below 20% of its maximum SOC then cost optimization is applied to the fuel cell and diesel generator and the algorithm generates a warning signal for low battery. Whenever the optimization module is executed it passes new optimal variables to the next iteration.

4.2. Results

The discrete time optimization for each hour is achieved using the constraints nonlinear minimization (Fmincon) solver with interior point algorithm in the Optimization toolbox in Matlab [20]. The interior-point approach is a method to solve a sequence of approximate minimization problems using the Quasi-Newton line-search method. Nine control variables are used in the problem to achieve the optimized results. A local minimum that satisfies the constraints is found in every discrete hour separately. Optimization is completed because the objective function is a non-decreasing in feasible directions, and constraints were satisfied to within the default value of the constraint tolerance. Solar power and wave power models are not included in the optimization since both sources should be used at their maximum capacity on their availability. Therefore, both the source models do not have any variables to be optimized except the number of solar panels in use. This would leave the excess energy from the extra solar panels to charge the battery bank.

A scaled down optimized hybrid power system response is shown in figure 13 which exactly follows the load profile (mission objectives) at each hour during operation. Figure 13 also shows the final value of objective function *f =0* which is an error between the load profile and hybrid power system response. The MCM craft USV power requirement is 25 time higher than the load profile shown in figure 13. However, the shape of the profile remains the same for scaled up studies. The results can be seen by scaling up the performance parameters by a factor of 25 for a MCM USV.

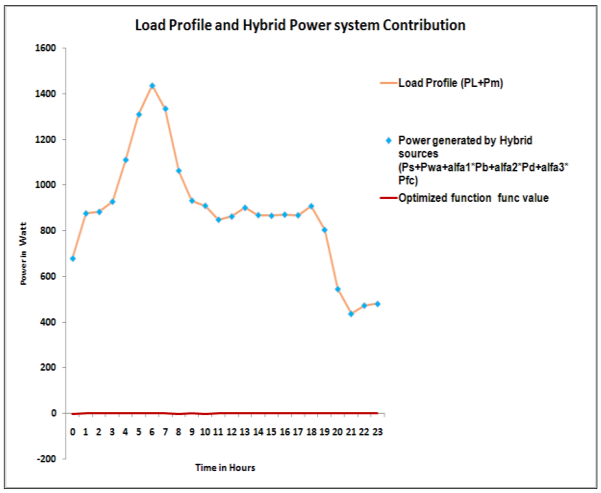

Figure 13: Load profile and Optimized Hybrid Power system response

Figure 14 clearly shows the individual contribution of each source in a scaled down system optimization to meet the load profile where the diesel generator contribution is almost zero. Wave power linear generator contribution is close to 48W constant power for constant wave frequency at 1 Hz and amplitude of 1m. Solar power contributes most during the day hours and forces the battery bank and the fuel cell contributions to their lowest. In the remaining hours of operation, the battery bank (considering 5 parallel strings of 4 series batteries each of 3.7V for this study with maximum discharge current of 10 Amp and maximum voltage is approximately 12 volt. Thus the total maximum power available to the system is 5*10*12 = 600 watt and contributes more than the fuel cell except in the 6^{th}&7^{th} hours where the fuel cell contributes on average 11% more than the battery bank to the load.

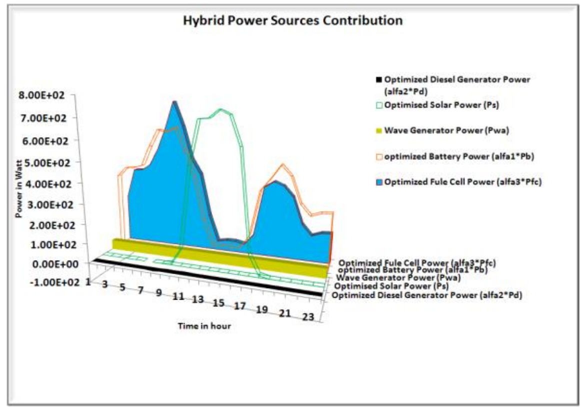

Figure 14: Hybrid power sources contribution to meet Load profile

Moreover, to meet the scaled up load requirement, the solar array's contribution is maximized at the time of availability. The battery and the fuel cell performance should be increased by 25 times. Figure 15 shows the perfomance missmatch in the scaling up of the existing scaled down oplimization model. The function's value is not close to zero in most of the cases. However it is unexpectedly high during the ten to seventeen hours where the battery and the fuel cell outputs are relatively low and the output from the solar panels is not sufficient. Currently, we are working on the scaled up dynamic model and will fix the mismatching by appropriately resizing the sources

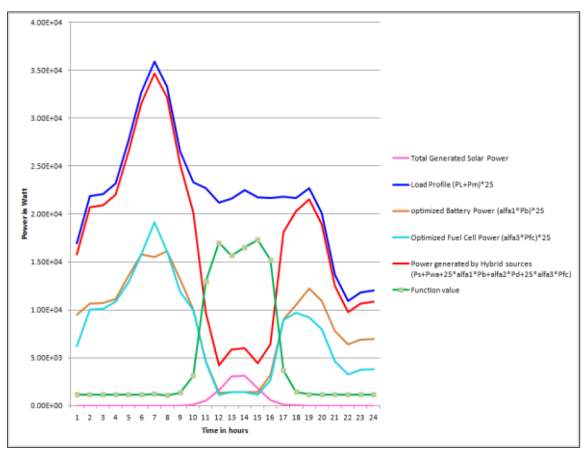

Figure 15: Scaled up optimization model for MCM Craft USV

Conclusion

This paper presents an optimized hybrid power solution f**or** a USV using a combination of hierarchical and cost function optimization for 24 hours. The paper contributes by developing a unique simplified solution based on modular optimization. It describes hydrodynamic modeling for USV drag-Effective Horse Power requirement, individual power sources modeling and load profile of a MCM USV. The optimized results show the mix of hybrid power can support the dynamic and unpredictable demands of the USV. The natural energy sources (solar array and wave energy converter) are used up to their maximum limits and are also used to charge the battery bank to facilitate long duration ISR operation of the USV. The system control variables such as charging/discharging battery currents, number of solar panels, flow rate of hydrogen, hydrogen pressure and fuel storage capacity are selected as the optimizing variables for the optimization algorithm. Feasible constraints and upper/lower bounds on system control variables are defined to ensure the smooth running of the optimization algorithm. These constraints and bounds help to provide better control over variables of each power source during real time operation. Additionally, optimized system control variables make the system remain stable in any discrete hour. The scaled-up model results in a mismatch between the power demand and the power generated. In order to resolve this issue, a complete re-optimization of the power system must be performed.

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