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# Optimal Planning and Operation Management of a Ship Electrical Power System with Energy Storage System

Amjad Anvari-Moghaddam, Tomislav Dragicevic, Lexuan Meng, Bo Sun, and Josep M. Guerrero
Department of Energy Technology, Aalborg University
Aalborg, Denmark
Email: aam@et.aau.dk

***Abstract*— Next generation power management at all scales is highly relying on the efficient scheduling and operation of different energy sources to maximize efficiency and utility. The ability to schedule and modulate the energy storage options within energy systems can also lead to more efficient use of the generating units. This optimal planning and operation management strategy becomes increasingly important for off-grid systems that operate independently of the main utility, such as microgrids or power systems on marine vessels. This work extends the principles of optimal planning and economic dispatch problems to shipboard systems where some means of generation and storage are also schedulable. First, the question of whether or how much energy storage to include into the system is addressed. Both the storage power rating in MW and the capacity in MWh are optimized. Then, optimal operating strategy for the proposed plan is derived based on the solution from a mixed-integer nonlinear programming (MINLP) problem. Simulation results showed that including well-sized energy storage options together with optimal operation management of generating units can improve the economic operation of the test system while meeting the system's constraints.**

***Keywords*— Shipboard power system, energy management, energy storage, optimization.**

## I. Introduction

The need for more efficient offshore systems together with the motivations for the exploitation of advanced power technologies have been the incentive for turning all energy subsystems aboard into more efficient and greener ones. In this context, optimal power management is becoming of great importance in such systems due to its direct impact on efficiency enhancement of ships. With an optimal power management strategy the best out of each unit can be taken and dispatched in a way to satisfy any technical problems [1]. However, a reliable supply of electrical power is essential in any shipboard system. A drill-ship is not immune to this concern. Because of the dynamically positioned (DP) drill-ship, variable speed drives are employed for the ship's propulsion and drilling systems and a dependable power source is needed for the successful operation of both systems. For these reasons, the use of energy storage system (ESS) is one of the most effective solutions for ensuring the reliability and power quality of a drill-ship power system and favors the increased penetration of other means of distributed generation [2]. Moreover, ESS can highly contribute to load demand management and generally to the global energy management of the ship with possible reduction of prime movers which in turn reduces operation cost [3].

In choosing to install an ESS, two important economic factors should be taken into account: feasibility of installing any ESS and sizing of the system in case of feasibility. Sizing means both the amount of energy that will be able to be stored as well as the limit of power that will be able to be put into or taken out of storage at any given time. Regarding the aforementioned points, a number of studies have investigated optimal power arrangements on ships [4]-[15]. For example a hybrid battery/diesel generation system has been explored for ship crane operations in [6] where an auxiliary power system, including diesel engines, battery energy storage systems based on lithium-ion technology, cranes and ship hotel consumers were also taken into account. ESSs have been utilized in converting the bulk carriers to all-electric ships in [7] for minimizing fuel consumption. In the same work, the engine loading levels and energy demand were calculated, and sizing of suitable propulsion system was proposed based on the potential for fuel savings. Merits of a hybrid energy system with flywheel energy storage have been analyzed in [8] from economic/environmental viewpoints. The analysis were mainly focused on the impact of utilizing flywheel energy storage systems on power generation, energy cost, and net present cost for certain configurations of hybrid system. An optimal power management strategy for a standalone hybrid system under uncertainties has been proposed in [9] to minimize the levelized cost of energy and maximize reliability. A robust method of design for wind-PV-diesel configuration was also developed considering uncertain parameters as well as minimal number of probabilistic analysis. An optimal unit sizing method for a stand-alone system has also been discussed in [10] where a metaheuristic approach was utilized to solve the optimal sizing problem with regard to different objectives such as minimization of pollutant emissions, minimization of degradation cost as well as maximization of green energy source penetration.

In this paper, an effective optimization model is presented for optimal sizing of ESS and economic dispatch of controllable units for a typical drill-ship's power system. The model is formulated as a single-objective constrained mixed-integer nonlinear programming (MINLP) optimization problem. The primary variables include the energy and power capacities ($E_{ESS,max}$, $P_{ESS,max}$) of the ESS (which is a flywheel in this special case) as well as the optimal power outputs of other dispatchable units ($P_{DG,i}$) for a given time period. The objective function is also defined as the minimization of the sum of operating costs and appropriately annualized installation costs.

The rest of the paper is organized as follows: Section II deals with optimal planning and economic dispatch problem of a drill-ship's power system. The case studies and simulation results are provided in Section III, whereas Section IV draws the paper's conclusions.

## II. Problem Formulation

Optimal planning and economic dispatch of a drill-ship's power system for a specific system load is formulated as follows:

### A. Chronological Load Curve

The load curve of a drill-ship power system in a given section (e.g., port, center and starboard) and a mission profile (e.g., dynamic positioning, drilling, survival or failure) defines the power demand over a specific time horizon, T. If the time period T is divided into M intervals, $\Delta T(j)$, with $j$=1, 2,…, $M$, the respective ship's load demand $P_D(j)$ can be considered constant and set to the average demand value of the $j^{th}$ period:

$$\int_{t_{j-1}}^{t_j} p_D(\mathrm{t}).dt = P_D(j).\Delta T(j)\ ;\forall j = 1,2,\ldots,M \tag{1}$$

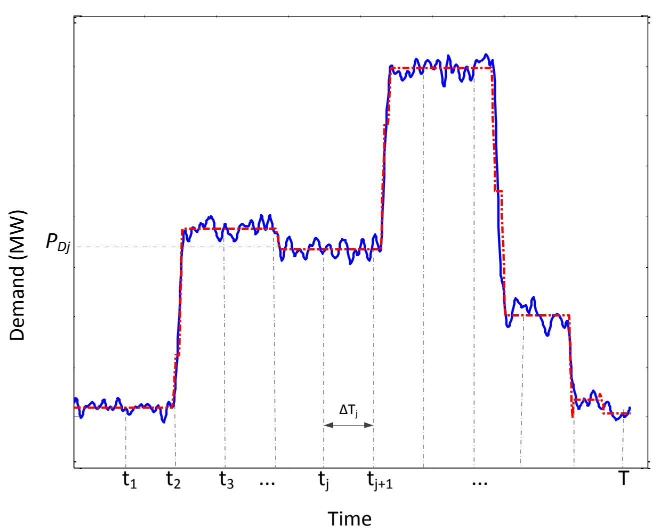



Fig. 1. Chronological load curve and its average form over specific time intervals

As observed in Fig. 1, smaller time interval $\Delta T$, results in more accurate estimation of the real chorological load curve of the system, however for the sake of simplicity as well as practical reasons time interval $\Delta T$ could vary from 5 minutes to 1 hour.

### B. Electric Power Plant

It is assumed that the shipboard electric power plant is divided into $N$ bus sections divided in $N$/2 switchboard rooms. Each bus section is fed from a main diesel generator (DG) and all consumers are supplied from these bas bars. At each time interval, output of a DG unit is technically limited by lower and upper active power bounds as follows:

$$P_{DG,i}^{min} \le P_{DG,i}(t) \le P_{DG,i}^{max}\ ; \quad \forall i \in N \tag{2}$$

For each DG unit, the respective operation cost ($OC_i$) is obtained by the fuel cost function $FC_i$, which is usually a second or third order polynomial of $P_{DG,i}$, and the start-up/shut down cost function $SUSDC_i$ which is defined by an exponential term:

$$\begin{aligned} OC_i(t) = &\underbrace{\alpha_{oi} + \beta_{oi} P_{G,i}(t) + \gamma_{oi} P_{G,i}^2(t)}_{FC_i} + \\ &\underbrace{u_i(t)\left(\alpha_{si} + \beta_{si}\left(1 - e^{-\frac{t_{offi}}{\tau_i}}\right)\right)\left(u_i(t) - u_i(t-1)\right)}_{SUSDC_i} \end{aligned} \tag{3}$$

where, $\alpha_{oi}$, $\beta_{oi}$ and $\gamma_{oi}$ are the coefficients of the convex quadratic $FC_i$ function and $\alpha_{si}$, and $\beta_{si}$ are the coefficients for the $SUSDC_i$ function of corresponding units. $\tau_i$ is the thermal time constant and $u_i$ is the on/off state of the $i^{th}$ unit. $t_{offi}$ also denotes the time the unit was cooled.

### C. Energy Storage System

Considering an energy storage unit, the update function for the state of charge ($SOC$) is given by [16]:

$$\begin{aligned} E_{ESS}(t+1) = &E_{ESS}(t) + P_{ESS,ch}(t) \cdot \Delta T \cdot \eta_{ch} \\ &-\left(P_{ESS,dch}(t) / \eta_{dch}\right) \cdot \Delta T \end{aligned} \tag{4}$$

$$\begin{aligned} &0 \le P_{ESS,ch}(t) \le P_{ch,\max} \cdot u_{ESS}(t) \\ &0 \le P_{ESS,dch}(t) \le P_{dch,\max} \cdot \left(1 - u_{ESS}(t)\right) \\ &0 \le E_{ESS}(t) \le E_{ESS,\max} \\ &P_{ch,\max} = P_{dch,\max} = P_{ESS,\max} \end{aligned} \tag{5}$$

where, $E_{ESS}$ is the ESS energy capacity limited by an upper bound named $E_{ESS,max}$, $P_{ch,max}$ and $P_{dch,max}$ are the ESS maximum charging and discharging powers and $\eta_{ch}$ and $\eta_{dch}$ are the ESS charging and discharging efficiencies, respectively. Similarly, $u_{ESS}(t)$ is a binary variable that shows the ESS status at time $t$ ("1"=charging and "0"=discharging).

### D. Objective Function

The objective function to be minimized is the expected cost of operation and amortization over the examined time $T$:

$$Min \left\{ \begin{aligned} &\sum_{t \in T} \sum_{i \in N} OC_i(t) + \\ &\alpha \cdot \left( C_{E_{ESS,\max}} \cdot E_{ESS,\max} + C_{P_{ESS,\max}} \cdot P_{ESS,\max} \right) \end{aligned} \right\} \tag{6}$$

In the mentioned objective function, the first term denotes the total operation cost of shipboard electric power plant while the second term corresponds to the cost components of the ESS which are the storage unit cost $C_{E_{ESS,max}}$ ($/MWh) and the power conversion unit cost $C_{P_{ESS,max}}$ ($/kW). $\alpha$ is a dimensionless scaling parameter used to express the cost of the ESS on a predefined time interval basis.

### *E. Constraints*

The proposed optimization problem should be solved subject to the following equality constraint and those previously mentioned for different components:

$$\sum_{i\in N} P_{DG,i}(t) + P_{ESS,dch}(t) - P_{ESS,ch}(t) = P_D(t) + P_{OL}(t) \quad ; \quad \forall t \in T \tag{7}$$

where $P_{OL}$ is the ohmic losses of the system that can be safely assumed negligible, as the onboard distribution network between generators and loads is not extended but limited in a few meters of three phase cables and electric bus-bars.

## III. Simulation Results

The simulation example considers one of the variations of a case study in [2] where a typical drill-ship should be operated economically in a steady-state environment. The shipboard power plant is equipped with 6 diesel generators of nominal active power of 7.0 MW connected to 11 kV main switchboards (SWBDs). All SWBDs can be interconnected by bus tiebreakers and operated in different configurations (e.g., three-split, two-split, and close-ring) depending on the situation at that time. Supply and demand sides' setting and distribution are illustrated in Fig. 2, and are characterized as follows:

- There are three main 11-kV buses/SWBDs, each with two DGs having circuit breakers that allow them to be connected or disconnected. In this study, DGs are operated in close-ring mode with the fuel cost functions and technical constraints as shown in Table 1.

Table 1. Electric power plant specifications

| | $DG_i$ | $\alpha_{oi}$ (¢) | $\beta_{oi}$ (¢/kW) | $\gamma_{oi}$ (¢/kW$^2$) | $\alpha_{si}$ (¢) | $\beta_{si}$ (¢) | $P_{DG,i}^{min}$ (MW) | $P_{DG,i}^{max}$ (MW) |
|---|---|---|---|---|---|---|---|---|
| Plant #1 | 1 | 450 | 10 | 13.5 | 10 | 20 | 0 | 7 |
| | 2 | 430 | 12 | 13.0 | 12 | 24 | 0 | 7 |
| Plant #2 | 3 | 460 | 12 | 13.5 | 12 | 18 | 0 | 7 |
| | 4 | 390 | 58 | 5.6 | 11 | 19 | 0 | 7 |
| Plant #3 | 5 | 370 | 57 | 5.4 | 11 | 21 | 0 | 7 |
| | 6 | 340 | 52 | 5.2 | 12 | 20 | 0 | 7 |

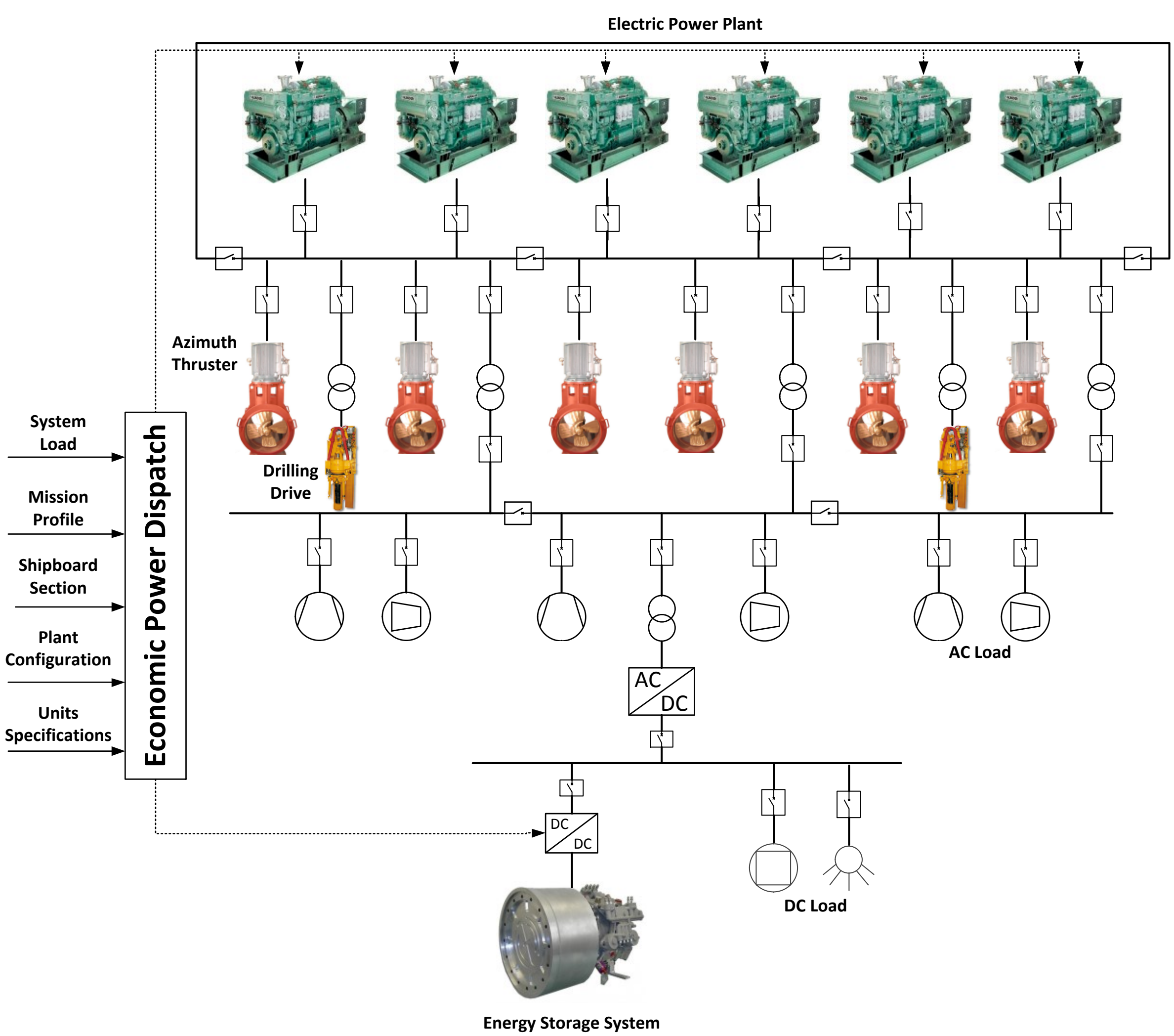



Fig. 2. Configuration of simulated drilling vessel

- There are six azimuth thrusters with nominal power of 5.5 MW arranged in a standard geometric layout (two for each main SWBD),
- There are several feeders extended from the main SWBDs providing needed power to topsides through 11kV/690V or 11kV/440V transformers,
- There is an ESS connected to a DC bus which regulates any excess or deficit produced power and contributes in energy management of the drilling vessel,
- The consumers are mainly include drilling drives, active heave draw-works drives, cement pumps, firewater pumps, mud pumps and top drives which form the typical load demand of the drill-ship presented by Fig. 3.

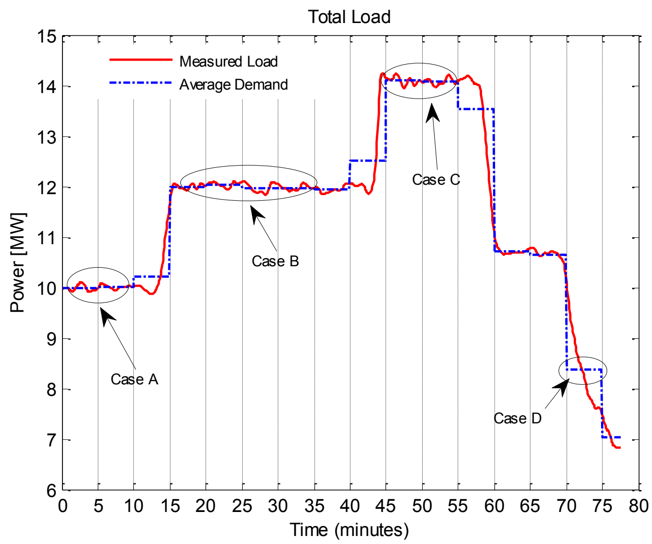
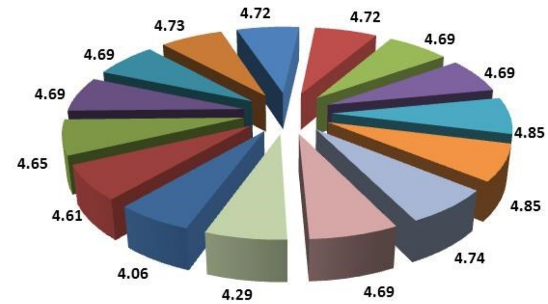


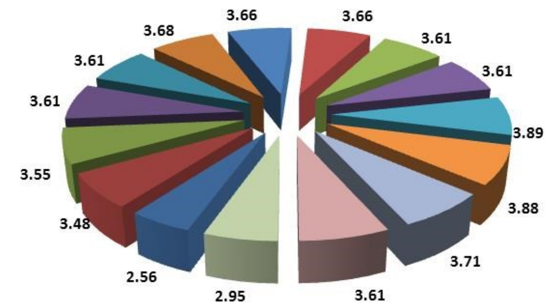

Fig. 3. Electrical load demand of the drill-ship for several mission profiles (Case A- normal DP & normal drilling; Case B- heavy DP & normal drilling, Case C- heavy DP & heavy drilling; and Case D- survival)

It should be mentioned that all of the algorithms and simulations were executed on a PC with an Intel i5-2430M chip running Windows 7(64 bit) with GAMS and Cplex/Dicopt solvers. Since GAMS is a high-level modeling system designed for solving linear, non-linear, and mixed-integer optimization problems, it was selected as the main optimization engine. Also, Cplex/Dicopt solvers are utilized to allow users to combine the high level modeling capabilities of GAMS with the power of such optimizers [17].

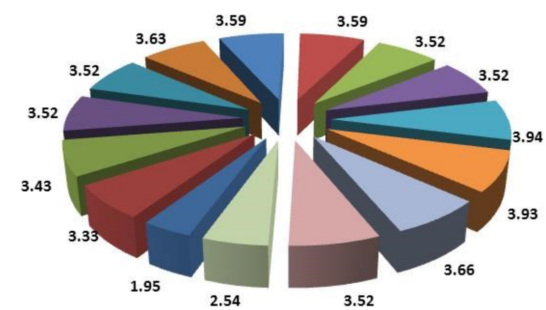
The primary solution results obtained from the solution of the sizing optimization problem are the values for the energy and power capacities of the ESS. To this end, approximate costs for installing ESS based on flywheel technology are considered to be 1600$/kWh and 600$/kW, respectively. By solving the proposed optimization problem, the optimal value for $P_{ESS,max}$ was found to be 1.407 MW and the optimal value for $E_{ESS,max}$ was found to be 2.579 MWh. Simulation results for optimal dispatch of generation units in different power plants are shown in Fig. 4 considering the given load profile. Optimal dispatch of designed ESS under the defined mission profile is also shown in Fig. 5.




(a) Plant #1- DG 1&2




(b) Plant #2- DG 3&4




(C) Plant #3- DG 5&6

T1 T2 T3 T4 T5 T6 T7 T8 T9 T10 T11 T12 T13 T14 T15

Fig. 4. Economic dispatch of DGs (in MW) during 5-minute intervals ($T_i$) for the given load profile

As can be observed from the computer simulations, the proposed optimization model not only shares the load among the generation units in a way to meet the system's constraints, but also dispatches units in an economic way to meet the system's objective. Total operating cost of the electric power plant for the examined period is calculated as 454.65$ which is 13.5% lower than the cost of operation for a plan of action where equal load sharing is the point of interest. Moreover, it can be understood from the operation of the storage unit that during off-peak times (e.g., 0-15 min. in normal DP and drilling mode), the storage unit mainly operates in charging mode to increase the back-up power for critical periods. As the net load rises through the heavy DP or drilling times, the ESS is switched into discharge mode and shaves the peaks off of the load giving the DGs smoother operation and better performance.

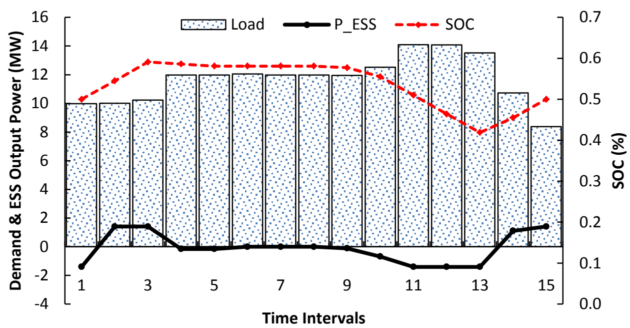



Fig. 5. Optimal operation of ESS

## IV. Conclusion

In this paper, optimal energy storage system sizing together with economic dispatch of a drillship power system was analyzed. A power management optimization model was proposed so that ship operation cost was minimized while system's technical and operational constraints were not violated. Compared to the conventional approaches, the proposed method not only addressed the question of how much energy storage to install, but also provided insight into the scheduling of different electric power plants in a drilling vessel thorough various loading levels and mission profiles.

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