Journal of Computations & Modelling, vol.3, no.4, 2013, 41-60
ISSN: 1792-7625 (print), 1792-8850 (online)
Scienpress Ltd, 2013

Optimal Operation of War-Ship Electric Power System Equipped with Energy Storage System

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Abstract

The electrification of war-ship power systems has become a very appealing alternative for the development of more efficient and environmentally friendly ships. Energy storage systems (ESS) will have a key role in such systems as they can lead to fuel consumption reduction and increase overall ship efficiency and reliability. In this paper the operation of a war-ship power system equipped with ESS is analysed from the economical point of view. The analytic formulas for the estimation of the system marginal cost of ship electric systems have been developed in [1] leading to a Lagrange no-linear mathematical equation. The method proposed in [1] could be a convenient tool for the technical-economical assessment of such systems. The obtained mathematical equations and the general

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Article Info: *Received* : July 1, 2013. *Revised* : August 30, 2013.
Published online : December 1, 2013.

methodology adopted in [1] have been used for the purposes of this paper and are applied a Hellenic Navy MEKO type frigate. First, the method is briefly described and finally the respective results for the electric power system derived for the Hellenic Navy MEKO type frigate are presented and commented.

Keywords: Economic dispatch, war-ship power system, energy storage system, system marginal cost

1 Introduction

Nowadays, the economic crisis and the environmental issues have been the reasons for turning all energy subsystems aboard (including power generation units) into more efficient ones. This policy involving green power technology in many cases is summarized in "take the best out of each unit but having resolved any technical problems emerged". Ship power plant configurations involve combinations of diesel engines, gas turbines, steam power plants, fuel cells, energy storage systems (ESS) and possibly renewable resources. Especially, in military aspects reliability and viability are also critical parameters. Energy storage systems have limited implementation in ships with the exception of submarines. But during last years different energy appealing storage technologies (high power flywheels, super capacitors, SMES or high energy REDOX, flow batteries) with different operating characteristics are available [2-6]. Mainly, ESS lead to more economic operation of the electric power system, while they can also be used to support voltage and frequency, manage peak loads, improve power quality, defer upgrade investments and provide uninterruptible power for sensitive onboard loads.

In this paper, the operation of a war-ship power system equipped with energy storage system is analysed from the economical point of view based on

Lagrange method. The proposed method is compared with the basic scenario of using only thermal units. The energy and power balances are taken into account for the under study time period of ship power system operation in order to derive the system marginal cost. Finally, it is applied to total load demand of Hellenic Navy MEKO type frigate indicatively and the obtained results are compared and discussed.

2 Basic Theory on Ship Electric Power System Operation with Energy Storage System

The optimum economic operation of electric power systems is known as economic dispatch. The optimum operation of the thermal and hydro-thermal continental power systems (with or without transmission losses) has been already thoroughly analyzed in the literature [7-8]. Here, the optimum operation of ship electric power system supported by energy storage system will be analyzed.

2.1 The Chronological Load Curve

The chronological load curve of the ship power system defines the 15-minutes average power demand over a specific time horizon, T. The under study time period T is divided into M intervals, DT_j, with j=1, 2,…, M. In each time interval DT_j ship load demand P_{Dj} is considered constant and it is calculated by:

$$\int_{t_{j-1}}^{t_j} p_D(t)\cdot dt = P_{Dj}\cdot DT_j \text{ [kWh]} \tag{1}$$

As the time interval DT_j tends to zero, the P_{Dj} will actually tend to the demand load demand $p_D(t)$, as it becomes apparent from Figure 1.

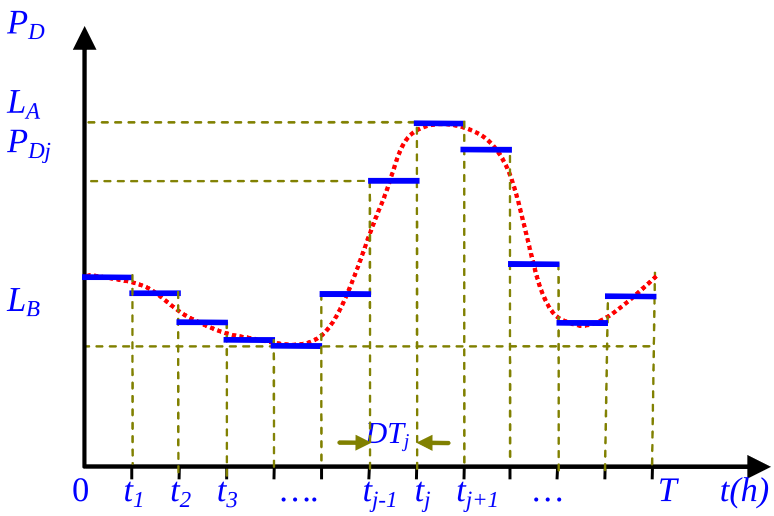

Figure 1: Chronological load demand curve during period T and its transformation in a chronological load curve of constant demand levels

2.2 The Thermal System

It is assumed that the thermal system consists of N thermal generating units connected to the same bus. Let the i^{th} unit produces output active power $P_{THi,j}$ during the j^{th} time interval, bounded by the technically minimum active power, P_{minTHi}, and the technically maximum active power P_{maxTHi} of the unit. The respective constraints are formulated as:

$$P_{\min \mathrm{TH}i} \leq P_{\mathrm{TH}i,j} \leq P_{\max \mathrm{TH}i} \ \text{[kW]} \quad (2)$$

where i=1, 2,…, N and j=1, 2,…, M.

Fuel cost function $F_{THi}(P_{THij})$ is usually a second or third order polynomial of $P_{THi,j}$. The transmission losses can be safely assumed negligible, as the onboard transmission network between generating units is not extended but limited in a few meters of three-phase cables or electric bus-bars.

2.3 The Energy Storage System

Energy storage system (ESS) can greatly contribute to the optimal operation of the ship electric power system and increase operation safety and reliability. In the following analysis an appropriate ESS, such as a vanadium redox flow battery [5-6], which either can store the energy produced by the thermal system or supply energy to the load. The respective electric power system is shown in Figure 2.

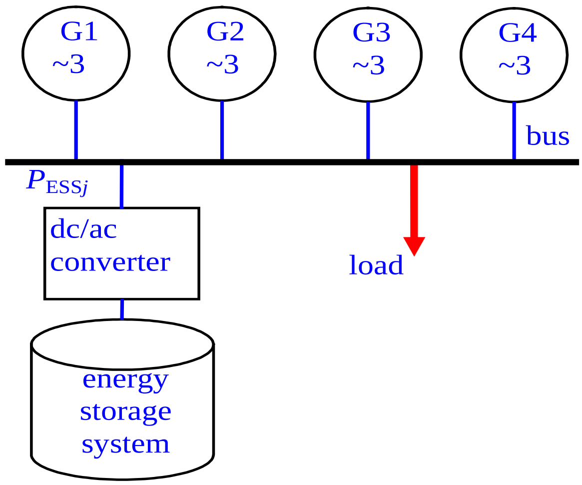

Figure 2: Ship electric power system with 4 generators connected at the same bus and ESS.

The stored energy in ESS is lower limited by the minimum active stored energy E_{minESS} defined by reliability and reserve reasons and upper limited by the maximum active stored energy E_{maxESS} defined by technical ESS specification. In each time interval DT_j the ESS energy level E_j (at the end of time interval) should satisfy the following inequalities.

$$E_{\text{minESS}} \leq E_{\text{ESS}j} \leq E_{\text{maxESS}} \text{ [kWh]} \tag{3}$$

where j=0, 1, 2,…, M.

In each time interval DT_j the ESS can operate with one of the following modes:

i. Storage: ESS stores energy by absorbing power $P_{\mathrm{ESS}\ell}$ from the thermal system. The respective time intervals are represented by DT_ℓ and ESS power is limited by the technically maximum active power, $P_{\text{ESS-storage}}$, of the dc/ac converter:

$$0 \le P_{\mathrm{ESS}\ell} \le P_{\text{ESS-storage}} \ \text{[kW]} \tag{4}$$

During time interval DT_ℓ the ESS energy variation is given by:

$$E_{\mathrm{ESS}\ell} - E_{\mathrm{ESS}(\ell-1)} = \eta_{\text{ESS-storage}} \cdot P_{\mathrm{ESS}\ell} \cdot DT_\ell \ \text{[kWh]} \tag{5}$$

Where, $\eta_{\text{ESS-storage}}$ is the performance coefficient of the ESS and dc/ac converter during storage mode of operation.

ii. Supply: ESS supplies power $P_{\mathrm{ESS}k}$ to ship electric load. The respective time intervals are represented by DT_k and ESS power is limited by the technically maximum active power, $P_{\text{ESS-supply}}$, of the dc/ac converter:

$$0 \le P_{\mathrm{ESS}k} \le P_{\text{ESS-supply}} \ \text{[kW]} \tag{6}$$

During time interval DT_k the ESS energy variation is given by:

$$E_{\mathrm{ESS}(k-1)} - E_{\mathrm{ESS}k} = \frac{P_{\mathrm{ESS}k} \cdot DT_k}{\eta_{\text{ESS-supply}}} \ \text{[kWh]} \tag{7}$$

Where $\eta_{\text{ESS-supply}}$ is the performance coefficient of ESS and dc/ac converter during supply mode of operation.

iii. Out of operation: ESS does not operate. In mathematical point of view it can be considered either as storage mode or as supply mode with zero production/storage power. The energy losses in this mode of operation can be ignored as the air-condition system of a war-ship limits them significantly.

3 Ship Electric Power System Optimal Operation

Let define as $F_{tot,j}$ the total hourly fuel cost of the power system for the j^{th} time interval DT_j. It is obtained as the sum of the fuel costs of the units:

$$F_{tot,j} = \sum_{i=1}^{N} F_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,j}\right) \ \text{[€/h]} \tag{8}$$

where j=1, 2,…, M.

The total fuel cost F_{tot} of the power system for the time period T, is calculated by:

$$F_{tot} = \frac{1}{T} \cdot \sum_{j=1}^{M} \sum_{i=1}^{N} F_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,j}\right) \cdot DT_j \ \ [\text{€/h}] \tag{9}$$

In storage mode the active power balance constraint for each time interval DT_ℓ is given by:

$$\sum_{i=1}^{N} P_{\mathrm{TH}i,\ell} = P_{\mathrm{D}\ell} + P_{\mathrm{ESS}\ell} \ \ [\mathrm{kW}] \tag{10}$$

In supply mode the active power balance constraint for each time interval DT_k is given by:

$$\sum_{i=1}^{N} P_{\mathrm{TH}i,k} + P_{\mathrm{ESS}k} = P_{\mathrm{D}k} \ \ [\mathrm{kW}] \tag{11}$$

The target is to determine the generating levels of the units subject to the active power balance constraint such that total fuel cost F_{tot} is minimized during time period, T. In this case, it is not correct to minimize separately the hourly fuel cost $F_{tot,j}$ for the j^{th} time interval DT_j, as it happens in classical economic dispatch of thermal units [7-8]. This is a result of the ESS energy variation during storage or supply mode (eq. (5) and (7)). This problem can be solved with the well-known Lagrange method. Eq. (9) is studied for the storage and supply modes separately. In storage mode the respective part of Lagrange equation for each time interval DT_ℓ is obtained by integrating eq. (10) and (5) into eq. (8) with use of the Lagrange multipliers, i.e. λ_ℓ for eq. (10) and w_ℓ for eq. (5):

$$L_\ell = \begin{cases} \frac{1}{T} \cdot \sum_{i=1}^{N} F_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,\ell}\right) \cdot DT_\ell \\ +\lambda_\ell \cdot \left(P_{\mathrm{ESS}\ell} + P_{\mathrm{D}\ell} - \sum_{i=1}^{N} P_{\mathrm{TH}i,\ell} \right) \cdot \frac{DT_\ell}{T} \quad [\text{€/h}] \\ +w_\ell \cdot \begin{pmatrix} E_{\mathrm{ESS}\ell} - E_{\mathrm{ESS}(\ell-1)} \\ -\eta_{\text{ESS-storage}} \cdot P_{\mathrm{ESS}\ell} \cdot DT_\ell \end{pmatrix} \end{cases} \tag{12}$$

Eq. (10) has been multiplied with the factor DT_ℓ/T, so as the first two terms of eq. (12) be similar to the respective terms of eq. (9). The use of this multiplication factor maintains the constraint of eq. (10) active and the property of Lagrange multiplier λ_ℓ to represent system marginal cost during time interval DT_ℓ [7-8].

In supply mode of operation the respective part of Lagrange equation for each time interval DT_k is obtained by integrating the eq. (11) and eq. (7) into eq. (8) with use of Lagrange multipliers, i.e. λ_k for eq. (11) and w_k for eq. (7):

$$L_k = \begin{cases} \dfrac{1}{T} \cdot \sum_{i=1}^{N} F_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,k}\right) \cdot DT_k \\ +\lambda_k \cdot \left(P_{\mathrm{D}k} - \sum_{i=1}^{N} P_{\mathrm{TH}i,k} - P_{\mathrm{ESS}k}\right) \cdot \dfrac{DT_k}{T} \quad [€/\mathrm{h}] \\ +w_k \cdot \left(E_{\mathrm{ESS}k} - E_{\mathrm{ESS}(k-1)} + \dfrac{P_{\mathrm{ESS}k} \cdot DT_k}{\eta_{\text{ESS-supply}}}\right) \end{cases} \tag{13}$$

Two more conditions should be added: the initial ESS energy should be equal to E_{in} and the final ESS energy should be equal to E_{fin}.

$$E_0 = E_{in} \quad [\mathrm{kWh}] \tag{14}$$

$$E_M = E_{fin} \quad [\mathrm{kWh}] \tag{15}$$

Where, E_0 is the initial stored energy at the beginning of time period T and E_M is the final stored energy at the end of T.

Eq. (14) can easily be taken into consideration, as an initial condition for E_{ESS}, while eq. (15) should be added as an equality constraint to the total Lagrange equation.

The total Lagrange equation of eq. (9) with use of eq. (12) and (13) and integration of eq. (15) based on the respective Lagrange multiplier e_{fin} is formulated by:

$$L_{tot} = \sum_{\ell} L_\ell + \sum_{k} L_k + e_{fin} \cdot \left(E_M - E_{fin}\right) [€/\mathrm{h}] \tag{16}$$

The optimality conditions are obtained by setting the partial derivatives $\frac{\partial L_{tot}}{\partial P_{\mathrm{TH}i,\ell}}, \frac{\partial L_{tot}}{\partial P_{\mathrm{TH}i,k}}, \frac{\partial L_{tot}}{\partial P_{\mathrm{ESS}\ell}}, \frac{\partial L_{tot}}{\partial P_{\mathrm{ESS}k}}, \frac{\partial L_{tot}}{\partial E_{\mathrm{ESS}\ell}}, \frac{\partial L_{tot}}{\partial E_{\mathrm{ESS}k}}$ equal to 0. More specifically, the optimality conditions are:

$$\frac{\partial L_{tot}}{\partial P_{\mathrm{TH}i,\ell}} = 0 \Rightarrow \frac{dF_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,\ell}\right)}{dP_{\mathrm{TH}i,\ell}} \cdot \frac{DT_\ell}{T} - \lambda_\ell \cdot \frac{DT_\ell}{T} = 0 \Rightarrow \lambda_\ell = \frac{dF_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,\ell}\right)}{dP_{\mathrm{TH}i,\ell}} \text{ [€/kWh]} \quad \text{for each } \ell \tag{17}$$

$$\frac{\partial L_{tot}}{\partial P_{\mathrm{TH}i,k}} = 0 \Rightarrow \frac{dF_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,k}\right)}{dP_{\mathrm{TH}i,k}} \cdot \frac{DT_k}{T} - \lambda_k \cdot \frac{DT_k}{T} = 0 \Rightarrow \lambda_k = \frac{dF_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,k}\right)}{dP_{\mathrm{TH}i,k}} \text{ [€/kWh]} \quad \text{for each } k \tag{18}$$

$$\frac{\partial L_{tot}}{\partial P_{\mathrm{ESS}\ell}} = 0 \Rightarrow \lambda_\ell \cdot \frac{DT_\ell}{T} - w_\ell \cdot \eta_{\text{ESS-storage}} \cdot DT_\ell = 0 \Rightarrow w_\ell = \frac{\lambda_\ell}{\eta_{\text{ESS-storage}} \cdot T} \text{ [€/kWh/h]} \quad \text{for each } \ell \tag{19}$$

$$\frac{\partial L_{tot}}{\partial P_{\mathrm{ESS}k}} = 0 \Rightarrow -\lambda_k \cdot \frac{DT_k}{T} + w_k \cdot \frac{DT_k}{\eta_{\text{ESS-supply}}} = 0 \Rightarrow w_k = \frac{\eta_{\text{ESS-supply}} \cdot \lambda_k}{T} \text{ [€/kWh/h]} \quad \text{for each } k \tag{20}$$

$$\frac{\partial L_{tot}}{\partial E_{\mathrm{ESS}\ell}} = 0 \;\&\; \frac{\partial L_{tot}}{\partial E_{\mathrm{ESS}k}} = 0 \Rightarrow \frac{\partial L_{tot}}{\partial E_{\mathrm{ESS}j}} = 0 \text{ for } j = 1,2,\ldots, M \tag{21}$$

Because in eq. (12) and (13) there is no discrimination for $E_{\mathrm{ESS}\ell}$ and $E_{\mathrm{ESS}k}$, eq. (21) becomes:

$$\frac{\partial L_{tot}}{\partial E_{\mathrm{ESS}j}} = 0 \Rightarrow \frac{\partial}{\partial E_{\mathrm{ESS}j}} \sum_j \left(\ldots + w_j \cdot \left(E_{\mathrm{ESS}j} - E_{\mathrm{ESS}(j-1)} + \ldots \right) \right) = 0 \Rightarrow$$

$$w_j - w_{j+1} = 0 \Rightarrow w_{j+1} = w_j \text{ for } j=1,2,\ldots,(M\text{-}1) \tag{22}$$

$$w_M + e_{fin} = 0 \Rightarrow e_{fin} = -w_M \text{ for } j=1,2,\ldots,(M\text{-}1) \tag{23}$$

From eq. (22) and (23) it stands that:

$$w_1 = w_2 = \ldots = w_{M-1} = w_M = -e_{fin} \triangleq w \tag{24}$$

According to eq. (17) and (18) the load should be dispatched to the units so as the respective incremental costs at each time interval DT_j are equal to λ_j. The Lagrange coefficient λ_j is known as system marginal cost and it varies over the time period T together with ship electric load. From eq. (19), (20) and (24) it stands that:

$$w = \frac{\lambda_\ell}{\eta_{\text{ESS-storage}} \cdot T} = \frac{\eta_{\text{ESS-supply}} \cdot \lambda_k}{T} \quad \text{for each } k,\ \ell$$

$\Rightarrow$ For storage mode: $\lambda_{\ell 1} = \lambda_{\ell 2} = ... \triangleq \lambda_{\text{storage}}$ (25)

$\Rightarrow$ For supply mode: $\lambda_{k1} = \lambda_{k2} = ... \triangleq \lambda_{\text{supply}}$ (26)

$$\Rightarrow \quad w = \frac{\lambda_{\text{storage}}}{\eta_{\text{ESS-storage}} \cdot T} = \frac{\eta_{\text{ESS-supply}} \cdot \lambda_{\text{supply}}}{T} \tag{27}$$

$$\Rightarrow \quad \lambda_{\text{storage}} = \eta_{\text{ESS-storage}} \cdot \eta_{\text{ESS-supply}} \cdot \lambda_{\text{supply}} \tag{28}$$

According to eq. (25) and (26) system marginal cost λ_j should be equal to λ_{storage} during the storage mode and λ_{supply} during supply mode in order to minimize F_{tot}. Theoretically, each generating unit should operate at the same generating level during each ESS mode of operation while load variations should be covered by the ESS.

The Lagrange coefficient w, as obtained in eq. (27), is the equivalent marginal cost of the stored energy per hour, which should be also constant for all time intervals. If the no-operation mode is approached by the equivalent term of the storage mode, the coefficient $\eta_{\text{ESS-storage}}$ should be equal to 1.0, as the ESS does not operate, and the respective marginal cost is equal to $\lambda_{\text{no-operation}}$. Similarly, if the no-operation mode is approached by the equivalent term of the supply mode, the coefficient $\eta_{\text{ESS-supply}}$ should be equal to 1.0 and the respective marginal cost is equal to $\lambda_{\text{no-operation}}$. So eq. (27) is modified as:

$$w = \frac{\lambda_{\text{no-operation}}}{T} = \frac{\lambda_{\text{storage}}}{\eta_{\text{ESS-storage}} \cdot T} = \frac{\eta_{\text{ESS-supply}} \cdot \lambda_{\text{supply}}}{T} \tag{29}$$

This means that the equivalent marginal cost of the stored energy per hour w is equal to:

(1) system marginal cost, $\lambda_{\text{no-operation}}$, during the out of operation mode of ESS divided by the time period T,

(2) system marginal cost, λ_{storage}, during ESS storage mode of operation divided by the time period T and the respective performance coefficient $\eta_{\text{ESS-storage}}$,

(3) system marginal cost, λ_{supply}, during ESS supply mode of operation multiplied by the respective performance coefficient $\eta_{\text{ESS-supply}}$ and divided by the time period T.

If the variable system marginal cost $\lambda_{\text{TH-}j}$ of the power system based on the thermal units only [7-8] in each time period DT_j is known then ESS mode of operation is determined as:

(1) *Storage* if $\lambda_{\text{TH-}j} \leq \lambda_{\text{storage}}$,

(2) *Out of operation* if $\lambda_{\text{storage}} \leq \lambda_{\text{TH-}j} \leq \lambda_{\text{supply}}$,

(3) *Supply* if $\lambda_{\text{supply}} \leq \lambda_{\text{TH-}j}$.

After the determination of λ_j, the generating levels of the units $P_{\text{TH}i,j}$ ($M \cdot N$ unknown variables) and the power levels of the energy storage system $P_{\text{ESS}j}$ (M unknown variables) are calculated by eq. (17)-(18) and eq. (10)-(11) respectively. Afterwards, the $M \cdot N$ inequalities from the units technical constraints and M inequalities related to the ESS technical constraints should be checked over the time period T. If violation of one inequality exists, i.e. $P_{\text{TH}2,j} < P_{\text{minTH}2}$, then the output active power should be set to equal to the violated limit, i.e. $P_{\text{TH}2,j} = P_{\text{minTH}2}$. Next, the load demand $P_{\text{D}j}$ should be reset to $P'_{\text{D}j} = P_{\text{D}j} - P_{\text{TH}2,j}$ and the optimization process is repeated for the rest of the units, i.e. without considering unit 2.

4 Computational Algorithms for System Marginal Cost

4.1 General

Next, it is assumed that the fuel cost of the i^{th} generating unit, $F_{THi}(P_{THij})$, is a polynomial of third order of P_{THj}.

$$F_{\mathrm{TH}i}\left(P_{\mathrm{TH}i,j}\right)=a_i+b_i\cdot P_{\mathrm{TH}i,j}+c_i\cdot P_{\mathrm{TH}i,j}^2+d_i\cdot P_{\mathrm{TH}i,j}^3 \tag{30}$$

Where a_i, b_i, c_i, d_i are the proper economic coefficients and next they are considered known.

The derivative of $F_{THi}(P_{THij})$ with respect to $P_{\mathrm{TH}i,j}$ is calculated as:

$$\lambda_j=b_i+2\cdot c_i\cdot P_{\mathrm{TH}i,j}+3\cdot d_i\cdot P_{THi,j}^2 \text{ for } i=1,\ldots,N \tag{31}$$

From eq. (31) the generating level of the i^{th} unit can be calculated as a function of the respective system marginal cost λ_j:

$$P_{\mathrm{TH}i,j}=\begin{cases}\dfrac{-c_i+\sqrt{c_i^2+3\cdot d_i\cdot\left(\lambda_j-b_i\right)}}{3\cdot d_i}, & d_i\neq 0\\[2ex] \dfrac{\lambda_j-b_i}{2\cdot c_i}, & d_i=0\end{cases} \tag{32}$$

4.2 Classical Economic Dispatch of Thermal Power System

Using Gauss-Seidel classic technique the determination of $\lambda_{\mathrm{TH},j}$ is achieved as following:

1) For j^{th} time period $\lambda_{\mathrm{TH},j}^{(0)}$ and $\lambda_{\mathrm{TH},j}^{(1)}$ are initialized. The number of the operating generators for each time interval is chosen as to satisfy spinning reserve requirement.
2) Determination of the generating levels of the units $P_{\mathrm{TH}i,j}$ based on eq. (32).
3) Calculation of the active power imbalance $\varepsilon^{(k)}$:

$$\varepsilon^{(k)}=\sum_{j=1}^{N}P_{\mathrm{TH}i,j}{}^{(k)}-P_{D,j} \tag{33}$$

4) Step to next iteration:

$$k = k + 1 \tag{34}$$

5) If k=1, step 2 is executed else continue with step 6.
6) Convergence check: if $|\varepsilon^{(k)}| \leq$ convergence limit then step 8 is executed else we continue with step 7.
7) Determination of $\lambda_{\mathrm{TH},j}^{(k)}$: Based on Newton-Raphson method the $\lambda_{\mathrm{TH},j}^{(k)}$ is determined as:

$$\lambda_{\mathrm{TH},j}^{(k)} = \lambda_{\mathrm{TH},j}^{(k-1)} - \frac{\lambda_{\mathrm{TH},j}^{(k-1)} - \lambda_{\mathrm{TH},j}^{(k-2)}}{\varepsilon^{(k-1)} - \varepsilon^{(k-2)}} \cdot \varepsilon^{(k-1)} \tag{35}$$

   Afterwards, step 2 is executed.
8) After the determination of $\lambda_{\mathrm{TH},j}$ and the generating levels of the units, $P_{\mathrm{TH}i,j}$, the N inequalities from the technical constraints should be checked.

4.3 Economic Dispatch of Thermal Power System with ESS

The determination w and λ_j is obtained in a similar in a way similar to that of paragraph 4.2 with some necessary modifications due to ESS presence.

In this case initial w is obtained as weighted mean value $\lambda_{\mathrm{TH},j}$ the system marginal costs $\lambda_{\mathrm{storage}}$ and $\lambda_{\mathrm{supply}}$ during the storage mode and the supply ESS mode of operation should be estimated in order to determine ESS mode during each interval. Stop criterion used is in this case study is system energy imbalance over the time period T. Finally the violation of technical constraints as in step 8 of paragraph 4.2 is checked.

5 Case Study

5.1 Thermal Power System

The developed methodology is applied to the total load demand of the Hellenic Navy MEKO type frigate, which is equipped with 4 generators of nominal active power of 750 kW with 0.8 inductive power factor. The total active energy produced by the ship electric generators was registered by the control and monitoring system “NAUTOS” every 15 minutes for a period of 20 days (8-31 January 1998) with the ship at berth. In this case there is no electric power provided by the shore, consequently the total electric power produced by the ship’s generators equals to the total load demand. The maximum load demand in anchor for the period under study was approximately 1200 kW and the average load demand 500 kW, approximately. During the 8.2% of the examined period the load demand has been larger than the nominal active power of one generator (750 kW). The equivalent load curve is given in Figure 3.

A simple thermal electric power system without transmission losses is assumed, consisting of four thermal units with the following fuel cost functions and technical constraints:

$$F_{\mathrm{TH},1}\left(P_{\mathrm{TH},1}\right)=18{,}1+0{,}058\cdot P_{\mathrm{TH},1}+4\cdot 10^{-5}\cdot P_{\mathrm{TH},1}^{2}$$

$$F_{\mathrm{TH},2}\left(P_{\mathrm{TH},2}\right)=18{,}0+0{,}0585\cdot P_{\mathrm{TH},2}+4\cdot 10^{-5}\cdot P_{\mathrm{TH},2}^{2}$$

$$F_{\mathrm{TH},3}\left(P_{\mathrm{TH},3}\right)=17{,}9+0{,}059\cdot P_{\mathrm{TH},3}+4\cdot 10^{-5}\cdot P_{\mathrm{TH},3}^{2}$$

$$F_{\mathrm{TH},4}\left(P_{\mathrm{TH},1}\right)=18{,}1+0{,}058\cdot P_{\mathrm{TH},4}+4\cdot 10^{-5}\cdot P_{\mathrm{TH},4}^{2}$$

$$75\leq P_{\mathrm{TH},1},\ldots,P_{\mathrm{TH},4}\leq 750\ \left[\mathrm{kW}\right]$$

Where, the measurement unit of the fuel cost functions is the monetary unit (m.u.) per hour, while $P_{\mathrm{TH}i}$ is measured in kW.

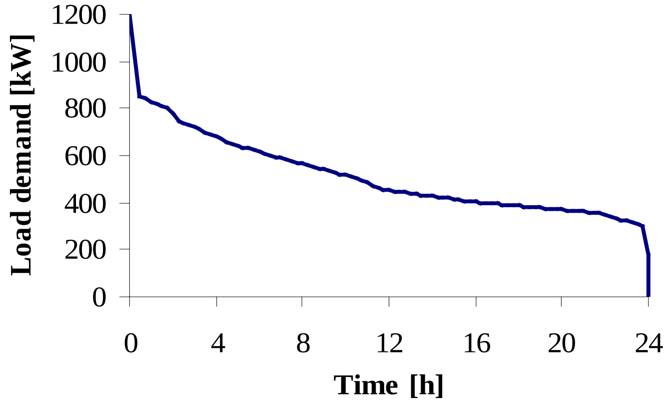

Figure 3: Total load demand duration curve for a period of 20 days (8-31 January 1998) with the ship at "shore" condition.

As the load demand is between 750 and 1500 kW, three generators should operate (1st, 2nd, 3rd). If the load demand is smaller than 750kW, two generators should operate (1st, 2nd), so as always one generator is used for spinning reserve reasons.

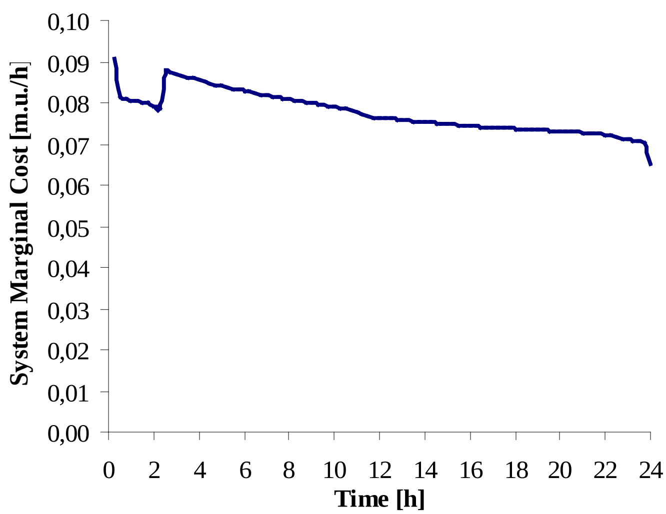

Figure 4: System marginal cost based on thermal power system of the warship

The execution of the classical economic dispatch algorithm (section 4.1) converged after 3 iterations. The results for system marginal cost and thermal units power dispatch are presented in Figures 4 and 5. The total operation cost is 1741.2 m.u. per day, while the total electric energy consumption is 12214 kWh.

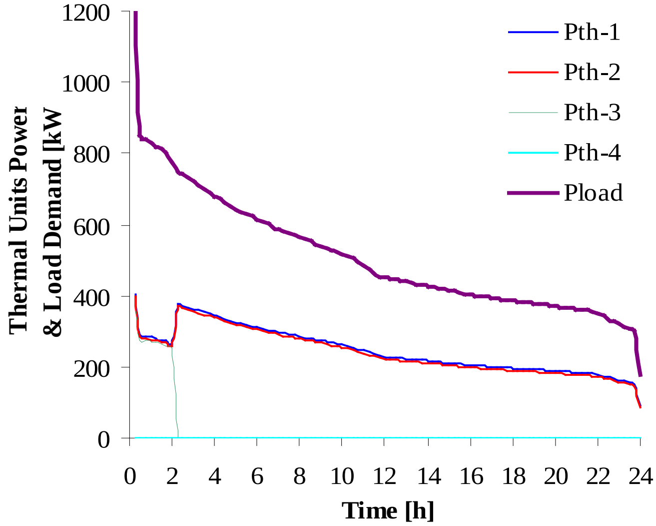

Figure 5: Thermal units power production and load demand based on thermal power system of the warship

5.2 Thermal Power System with ESS

Next, it is assumed that the power system of a typical Hellenic Navy MEKO type frigate comprises 2 ESSs with nominal characteristics 600 kW ± 600 kvar/ 1200kWh. The size of ESSs has been determined so as only one generator operates while the rest three others are out of operation.

The execution of the proposed algorithm (section 4.2) converges after four iterations. The results for system marginal cost with and without ESS, thermal unit no.1 active power and ESS power supply/ storage, are presented in Figures 6 and 7.

From Figure 6 it is obvious that the respective system marginal cost with ESS is smoother than the respective one without ESS. The values of SMC are bigger in Fig. 6 than the respective ones in Fig. 4, which means that the increase of load demand by one kWh is more expensive in the second case.

In Figure 7 the thermal power unit no.1 operates between 420 and 688 kW, which corresponds to the load demand covered by thermal power system. The "new" load demand is significant smoother than the "initial" load demand. ESS supplies power system with active power until 512 kW during peak load periods, while ESS absorbs active power until 245 kW during base load period.

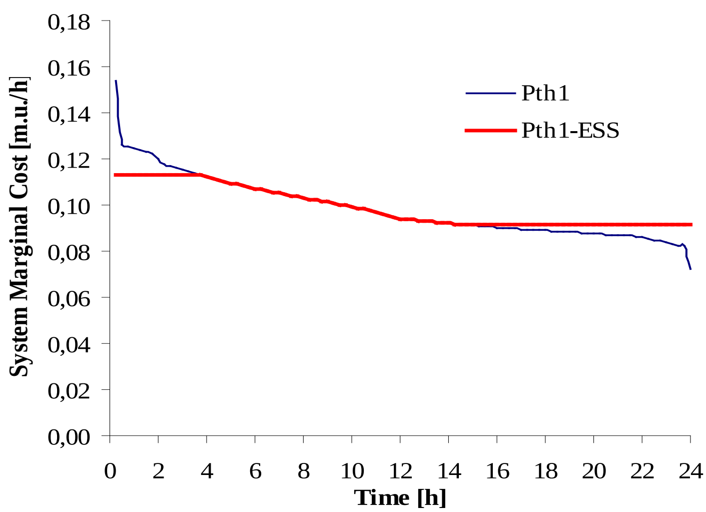

Figure 6: System marginal cost based on thermal power system with ESS of the warship

The total operation cost will be 1411.7 m.u. per day, while the total electric energy consumption is 12310 kWh. The additional energy cost is 96 kWh, but the fuel consumption is reduced and the total cost operation reduction runs into 329.5 m.u. per day, which is a result of better efficiency factor of diesel thermal power unit for loading near to the nominal ones.

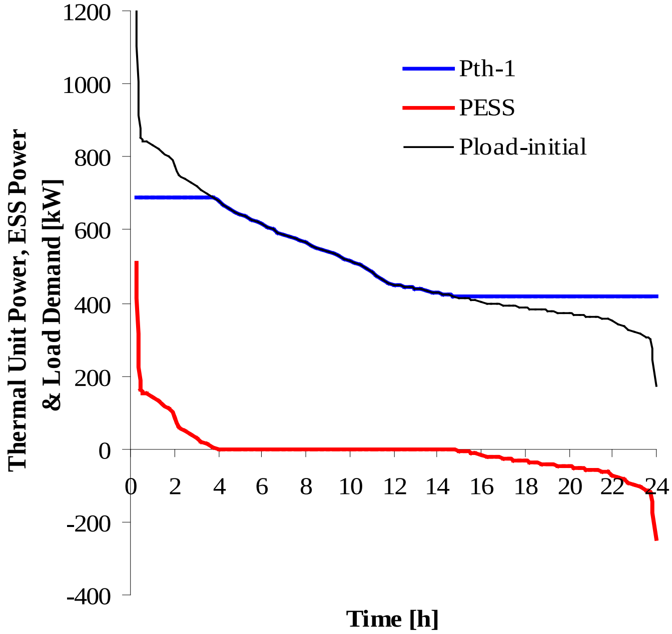

Figure 7: Thermal unit power production, ESS power supply (“-”: storage) and load demand based on thermal power system with ESS of the warship

6 Conclusions

In this paper the operation of a ship electric power system equipped with ESS is analysed from the economical point of view. Energy and power balances are taken into account for a certain time period of ship electric power system operation.

The proposed method is based on the Lagrange non-linear mathematical technique and it is exploited for two case studies:

a) Ship electric power system without ESS.

b) Ship electric power system with ESS.

For method demonstration purposes total load demand of Hellenic Navy MEKO type frigate is used. It is concluded from the comparison of the obtained results that in case of ESS installed onboard total operational power system cost decreases by 19%, approximately. This means that this kind of solution should be investigated more thoroughly taking into consideration other parameters, such as load demand for different ship operation modes, ESS installation cost, ESS annuity depreciation, power system reliability aspects, effects on ship electric system stability, etc.

Acknowledgments. The authors would like to express their appreciation to Dr. I.K. Hatzilau, Emeritus Professor at Hellenic Naval Academy, for his overall contribution on the development of the Electric Circuits Laboratory of Hellenic Naval Academy.

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