An Energy Management System for Hybrid Energy Sources-based Stand-alone Marine Microgrid

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Abstract. Microgrids are becoming a viable solution for satisfying energy demand of rural and remote areas. Indeed, energy demand of islands can be met by renewable energy sources, energy storage systems, and micro-conventional generation sources-based microgrid systems. The optimal scheduling of these energy sources requires an energy management system for microgrids. Bretagne region in France has huge potential in marine renewable energy sources. Therefore, islands in this region can use tidal turbines with other energy sources to meet their local energy consumption. A case study of stand-alone marine microgrid system for Ouessant island is proposed in this paper. The considered microgrid includes PV system, tidal turbine, diesel generator, and Li-ion battery. The architecture and optimal scheduling of the developed microgrid system is presented to reduce operating and maintenance costs. The developed energy management architecture can help microgrid systems planning for islands in the near future.

1. Introduction
Advancements in renewable energy sources (RESs) technology pave the way for providing energy supply in rural and remote areas. Nowadays, diesel generators (DGs) partially meet the energy demand of these remote areas. However, these conventional electricity production systems suffer from nonavailability of continuous supply of diesel fuel and environmental issues. These issues can be resolved by installing RESs together with battery storage systems. A low voltage system incorporating all these distributed energy resources is termed a microgrid (MG) [1]. MG optimizes scheduling of these energy sources using energy management system. It collects data from energy sources and loads through local controllers (LCs). Then, it performs optimization to determine decision strategies that ensure supply demand balance, while satisfying system constraints [2].

Bretagne region in France has huge potential in marine energy sources. World’s first commercial tidal marine power station of 240 MW is also installed in Bretagne. Tidal marine turbines convert kinetic energy of tidal currents into electrical energy. Researchers and engineers in industry are working on improving its technology readiness level, which has currently reached a mark of 7 [3]. Bretagne region in France has several islands, which are mainly supplied using DGs. Consequently, tidal marine turbines seem to be a viable solution along with other renewable energy sources to meet load demand of these islands. In this context, a hybrid energy sources-based MG system is therefore proposed and studied for Ouessant, one of Bretagne islands.

In stand-alone marine applications, researchers have proposed hybrid energy sources based power generation systems to meet energy demand of islands. Sizing of hybrid renewable energy system for Ouessant island is proposed in [4], which performs sensitivity analysis to study the impact of offshore
wind turbines and tidal turbines on system cost. Optimal energy scheduling model of tidal farm and pumped hydro storage system-based MG is performed in [5] to minimize its operating cost using particle swarm optimization algorithm. In [6], authors proposed a grid-connected MG system, which consists of tidal turbine, PV system, fuel cell, microturbine, and battery. Multi-objective energy scheduling is conducted that aims to minimize operating cost and environmental pollutants. The sizing and energy management of stand-alone hybrid energy system is achieved by optimizing its net present cost using a genetic algorithm [7]. In [8], authors have compared various optimization algorithms performance in achieving multi-objective energy scheduling of hybrid power generation system. A rule-based algorithm is proposed in [9] for a stand-alone hybrid power generation system sizing. However, they have not included degradation effects in computing cost of energy generation sources. Degradation cost of battery storage system is ignored too. Moreover, network constraints are also not taken into account.

In this paper, the proposed hybrid energy sources-based stand-alone marine MG operation will be based on an energy management model that considers DGs operating cost, PV system and tidal turbine levelized costs of energy (LCOE), Li-ion battery degradation cost, and network constraints. Section 2 illustrates the architecture of stand-alone marine MG and includes the mathematical models for power generation output of tidal turbine and PV system. Section 3 explains the detailed energy management system modeling of the developed stand-alone marine MG. Section 4 presents the results of the proposed energy management model for marine MG at Ouessant island. Finally, conclusion is given in section 5.

2. Stand-alone marine microgrid architecture

The hybrid energy sources-based stand-alone marine MG system is presented in figure 1. It consists of tidal turbine, PV system, diesel generator, and Li-ion battery. As the power network of island is small, the supervisory architecture of MG energy management is centralized. All these energy systems send information to MG central controller (MGCC) through local controllers (LCs). MGCC also collects load demand data and determines optimal decision strategies for each system. It sends back these decision strategies to LCs to achieve optimal operation of MG system.

![Figure 1. Stand-alone marine microgrid architecture.](image)

2.1. Tidal turbine

Various marine RESs exist in sea such as tidal current energy, thermal energy, ocean osmosis energy, and wave energy sources. However, tidal current energy has more potential due to high water density, more accurate tidal currents prediction, and relatively mature turbine technologies, which convert kinetic energy of tidal currents into electricity. The tidal energy potential is estimated at 75 GW worldwide, in which Europe has 11 GW potential. In Europe, UK has highest tidal energy potential of 6 GW followed by France with 3.4 GW potential [10]. An example of precommercial tidal turbine farm is the Sabella project in France [11], whose biggest turbine is around 2 MW [12]. A comparative
Performance analysis of tidal turbine drivetrain options is extensively explained in [13], which helps in tidal turbine selection for marine MGs.

External factors, such as tidal current speed and geographical location, affect the power generation output of a tidal marine system. In this paper, the estimated output power of tidal marine turbine system at time $t$ is calculated as:

$$
P_{tm}^m = \frac{1}{2} \rho C_p^m R^2 v_{m,t}^3
$$

(1)

$$
v_{m,t} = v_{nm,t} + \frac{C-a_0}{b_0-a_0}(v_{sm,t}-v_{nm,t})
$$

(2)

Where $v_{m,t}$ is the tidal current speed at time $t$, $\rho$ is the water density, $C_p^m$ is the turbine power coefficient, $R$ is the turbine blade radius, $v_{nm,t}$ and $v_{sm,t}$ are the neap and spring tide current speeds at time $t$, respectively, $C$ is the tidal coefficient for a given tidal semi-diurnal cycle, $a_0$ and $b_0$ are the tidal coefficients for neap and spring water, respectively.

2.2. PV System

The power generation output of a PV system varies with change in irradiance and temperature. Therefore, these factors are included in (3) to compute the PV output power [14].

$$
P_{t}^{pv} = N^{pv} P_{stc}^{pv} \left[ \frac{G_t}{G_{stc}} \left( 1 - \kappa \left( T_t + \frac{G_t}{G_{NOCT}} (NOCT - 20) - T_{stc} \right) \right) \right]
$$

(3)

Where $N^{pv}$ is the number of PV arrays, $P_{stc}^{pv}$, $G_{stc}$, and $T_{stc}$ are the PV array power, temperature, and irradiance at standard test conditions, respectively. $G_t$ is the irradiance at time $t$. NOCT is the nominal operating cell temperature of PV array. $G_{NOCT}$ and $\kappa$ are the irradiance at nominal operating cell temperature and the temperature dependent degradation coefficient, respectively.

3. Problem formulation

A centralized optimal operation of stand-alone MG is achieved by collecting all the necessary information at MGCC and optimizing the day-ahead energy management operation over a 24h time horizon $\Gamma := \{ t_s, t_s + \Delta t, t_s + 2\Delta t, \ldots, t_f \}$. The detail of the proposed model is described in the following.

3.1. Objective function

The objective of the stand-alone MG operator is to ensure the optimal operation of the MG system by minimizing its operating and maintenance cost. The objective function includes operating cost of DG, LCOEs of PV and tidal marine turbine systems, battery degradation cost, and load shedding cost. Equation (4) presents the operating cost function of MG system.

$$
\text{Min} \sum_{t \in \Gamma} \left[ a + b P_{t}^{pg} + c \left( \frac{P_{t}^{pg}}{P_{t}^{pg}} \right)^2 + C_{tm}^m P_{tm}^m + C_{pv}^{pv} P_{t}^{pv} + C_{t}^b \left( \eta_{t}^{ch} \frac{P_{t}^{ch}}{\eta_{t}^{ch}} + \eta_{t}^{dch} \frac{P_{t}^{dch}}{\eta_{t}^{dch}} \right) + C_{loss} P_{t}^{loss} \right] \times \Delta t
$$

(4)

Where $P_{t}^{pg}$ is the DG power output. $a, b, c, \eta_{t}^{ch}$, and $\eta_{t}^{dch}$ are cost coefficients of the DG. $P_{t}^{ch}$ and $P_{t}^{dch}$ are the charging and discharging power of the Li-ion battery, and the curtailed load, respectively. $\eta_{t}^{ch}$ and $\eta_{t}^{dch}$ are the charging and discharging efficiency of the Li-ion battery, respectively. $C_{loss}$ is the lost load value. The LCOE of RESs, tidal turbine and PV system, is:
\[
C_{\text{res}}^{\text{res}} = \frac{C_{\text{in}}^{\text{res}} + \sum_{i=1}^{n} C_{\text{om}}^{\text{res}} (1 + \text{dr})^{-i}}{\sum_{i=1}^{n} E_{\text{an}}^{\text{res}} (1 - \sigma_{\text{res}}^{-1})^{-i} (1 + \text{dr})^{-i}}
\]  

(5)

Where, \(\text{res} = \{m, pv\}\). \(C_{\text{in}}^{\text{res}}\) and \(C_{\text{om}}^{\text{res}}\) are the capital, and operation and maintenance (O&M) costs of a RES, respectively. \(E_{\text{an}}^{\text{res}}\) and \(\sigma_{\text{res}}^{-1}\) are the annual output energy and energy degradation coefficient of a RES, respectively. Similarly, \(\text{dr}\) and \(n\) are the discount rate and system lifetime, respectively.

The degradation cost model of Li-ion battery is taken from [15], which considers power fading and capacity fading effects in modeling. The cost model is given in (6). The regression models of temperature-dependent power and capacity fadings, \(\chi_{t}^\gamma\) and \(\chi_{t}^\gamma\), and depth of discharge-dependent capacity fading, \(\chi_{d}^\gamma\), of Li-ion battery are discussed extensively in [15].

\[
C_{t}^{\text{b}} = \left[ \frac{C_{\text{in}}^{b} + \sum_{i=1}^{n} C_{\text{om}}^{b} (1 + \text{dr})^{-i}}{(1 + \text{dr})^{\gamma_{\text{ref}}}} \right] (1 + \text{dr})^{\gamma_{\text{ref}}} - \text{RV}
\]

(6)

Where \(C_{\text{in}}^{b}\) and \(C_{\text{om}}^{b}\) are the capital and O&M costs of a RES, respectively. \(\text{RV}\) is the value of Li-ion battery at the end of its usable life. \(\gamma_{\text{ref}}\) and \(\Xi_{\text{ref}}\) are the rated cycle life and energy capacity of Li-ion battery, respectively.

### 3.2. Diesel generator constraints

The minimum and maximum active and reactive power output limits of diesel generator are provided in (7) and (8), respectively.

\[
P_{\text{min}}^{\text{g}} \leq P_{t}^{\text{g}} \leq P_{\text{max}}^{\text{g}}
\]

(7)

\[
Q_{\text{min}}^{\text{g}} \leq Q_{t}^{\text{g}} \leq Q_{\text{max}}^{\text{g}}
\]

(8)

### 3.3. Li-ion battery constraints

The minimum and maximum values of charging and discharging powers of Li-ion battery is given in (9). Equation (10) ensures that battery should either charge or discharge. The inter-temporal nature of energy state of Li-ion battery is presented in (11). The battery initial and final energy states should remain the same, i.e. \(\Xi_{t_0} = \Xi_{t_\text{f}}\). The minimum and maximum limit of energy state of Li-ion battery is provided in (12).

\[
0 \leq P_{t}^{\text{dch}}, P_{t}^{\text{dch}} \leq P_{\text{max}}^{\text{dch}}
\]

(9)

\[
P_{t}^{\text{dch}} = P_{t}^{\text{dch}}
\]

(10)

\[
\Xi_{t} = \Xi_{t-1} + \left[ \eta_{\text{ch}} P_{t}^{\text{ch}} - \frac{P_{t}^{\text{dch}}}{\eta_{\text{dch}}} \right] \times \Delta t
\]

(11)

\[
\Xi_{\text{min}} \leq \Xi_{t} \leq \Xi_{\text{max}}
\]

(12)
3.4. Network constraints
In a stand-alone MG system, power flow constraints are necessary for analysis of bus voltages and system losses. Equations (13) and (14) provide the active and reactive power injection equations for bus $i$, respectively. Bus voltages and phase angle difference of buses are constrained by lower and upper bound, as presented in (15) and (16), respectively. $\angle V_{i,t}$ is voltage angle of bus $i$ at time $t$.

\begin{align*}
P_{i,t} &= \sum_{j=1 \atop j \neq i}^{n} \Re \left\{ \frac{\left| V_{i,t}^* \left( V_{j,t}^* - V_{j,t}^* \right) V_{j,t}^* \right|}{V_{j,t}} \right\} \\
Q_{i,t} &= \sum_{j=1 \atop j \neq i}^{n} \Im \left\{ \frac{\left| V_{i,t}^* \left( V_{j,t}^* - V_{j,t}^* \right) V_{j,t}^* \right|}{V_{j,t}} \right\} \\
V_{\text{min}} &\leq \left| V_{i,t} \right| \leq V_{\text{max}} \\
\theta_{\text{min}} &\leq \angle V_{j,t} - \angle V_{j,t} \leq \theta_{\text{max}}
\end{align*}

4. Results and Discussion
The proposed energy management model is validated on a 6-bus system, as shown in figure 2. The line impedance data is provided in [16]. The system base power and base voltage are 10 kVA and 230 V, respectively. The PV system and tidal turbine of rated output power of 5 kW are considered for analysis. The forecasted power outputs of these RESs are presented in figure 3.

![Figure 2. 6-bus system architecture.](image)

![Figure 3. Forecasted power outputs of the PV system and the tidal marine turbine.](image)

The investment and O&M costs of PV system and tidal turbine are provided in Table 1. The investment and O&M costs of Li-ion battery are 200 €/kWh and 20 €/kW-yr, respectively. The discount rate is 4% and degradation coefficients of RESs are assumed to be 2% each. The project life time of PV system and tidal turbine is 20 years, while it is 4 years for Li-ion battery. RV of Li-ion battery is considered 40% of its investment cost. The depth of discharge and rated capacity of Li-ion battery are assumed 50% and 10 kWh, respectively. The charging and discharging efficiency are 0.9 each. The active power output range of DG is 1 to 9 kW, while reactive power varies from -1 to 7 kVAR. The operating cost coefficients, $a, b, c$, of DG are 0.35, 0.3, and 0.01 respectively [17]. The upper and lower limits for buses voltages are 1.05 pu and 0.95 pu, respectively. The developed energy management model for a stand-alone marine MG is solved by primal-dual interior point algorithm in Python using GEKKO package [18, 19].
Table 1. Renewable energy sources cost parameters.

| Energy Source     | Investment cost (€/kW) | O&M cost (€/kW-yr) |
|-------------------|------------------------|--------------------|
| PV system         | 1930                   | 22                 |
| Tidal Turbine     | 3500                   | 140                |

The active power scheduling profiles of Li-ion battery and DG are presented in figure 4. During high demand periods, energy sources cannot meet load demand that leads to load-shedding, as shown in figure 5. At hours 19 and 20, power outputs of the tidal turbine and the PV system are low. Therefore, the battery discharges and the DG provides its rated power to meet load demand. The battery energy profile is presented in figure 6. The battery charges in low demand periods to provide power at load ends during high demand periods. The buses voltage profiles, given in figure 7, clearly show that they are operating in defined stability range.

Three cases are considered to study the loss of power supply probability (LPSP), which is defined as the ratio of undelivered demand to the total load demand [20]. In case 1, only DG is considered. DG, PV system and tidal turbine are considered in case 2, while case 3 also includes Li-ion battery. Table 2 shows that the LPSP in case 3 is very low, thereby proving that RESs operation with DG and storage controls load-shedding effectively.
Table 2. LPSP analysis.

|        | Case 1 | Case 2 | Case 3 |
|--------|--------|--------|--------|
| LPSP   | 0.182  | 0.038  | 0.014  |

5. Conclusion
In this paper, a stand-alone microgrid in a marine context was proposed to meet energy demand of islands. A case study of Ouessant island, located in Bretagne (France), was considered for the proposed stand-alone microgrid system. It includes a PV system, a tidal turbine, a diesel generator, and Li-ion battery. The proposed energy management model has shown promising results in achieving optimal decision strategies of hybrid energy sources. It reduces operating cost of the microgrid, while satisfying system technical constraints. Due to the noncontinuous availability of diesel fuel, loss of power supply probability is higher when only DG is considered. This probability is considerably decreased with the integration of renewable energy sources and battery storage systems.

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