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Innovative hybrid energy system for stable power and heat supply in offshore oil & gas installation (HES-OFF): system design and grid stability

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Abstract

This paper presents an innovative hybrid energy system for stable power and heat supply in offshore oil & gas installations (HES-OFF). The hybrid concept integrates offshore wind power with gas turbines and a H_2 energy storage solution based on proton exchange membrane fuel cells and electrolysers. The objectives are: 1) improve the environmental performance of offshore installations by maximizing the exploitation of offshore wind and partially decarbonizing the gas turbines by co-feeding H_2; 2) minimize the negative effects that wind power variability has on the electrical grid frequency stability. This study presents a first assessment of the HES-OFF concept performance using an offshore platform in the North Sea as case study. The results show that the HES-OFF concept: 1) cuts CO_2 emissions up to 40 % when compared to the reference case but requires large H_2 storage capacity to fully exploit wind power throughout the year; 2) allows higher wind power penetration without infringing on the grid frequency requirements.

Keywords: offshore energy, hybrid system, energy storage, system design, grid stability.

1. Introduction

Due to the long-term character of the energy transition and the many technical limitations to replace fossil fuels with renewable energy sources (RESs), hybrid energy systems (HESs) with energy storage (ES) can be affordable alternatives. The choice of the HES configuration and its specification depends on the availability of RESs and the general purpose of the system. Optimum design can be achieved through comprehensive analyses and optimisation of layouts and the size of system components.

Offshore oil and gas (O&G) production is likely to increase in the near future and thus its related CO_2 emissions. In Norway, the petroleum sector is the main contributor to greenhouse gas emissions, making up 27 % of the total emissions in 2018 (Statistics Norway, 2018). Several options to reduce the carbon footprint of the O&G sector have been investigated (Riboldi and Nord, 2017), including the electrification of offshore facilities (Riboldi et al., 2019). The utilization of RESs is a very promising opportunity, though there are challenges for their efficient exploitation offshore.

This article presents the concept of an innovative hybrid energy system for stable power and heat supply in offshore oil & gas installation (HES-OFF), which considers wind energy along with H_2 ES using a proton exchange membrane (PEM) fuel cell (FC) and electrolyser (EL) system.

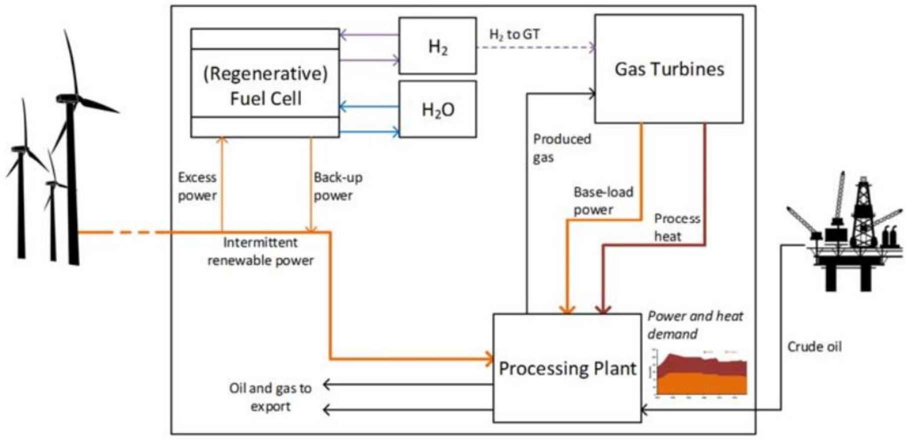

Figure 1. Schematic of the HES-OFF system proposed.

2. The HES-OFF hybrid concept

The HES-OFF concept consists of a HES integrating an offshore wind farm, stacks of PEM FC and EL for ES and back-up power supply, and a gas turbine (GT). The ES is further integrated with the GT, where the possibility to co-feed H_2 is envisioned. Fig. 1 depicts the HES-OFF system layout.

Within this energy system, the GT operation meets the process heat demand and supplies base-load power to a processing plant. Wind turbines (WTs) provide the remaining load. The FC and EL stacks smooth out the intermittent wind power output by: 1) storing excess power in the form of gaseous H_2 when production is larger than demand; 2) providing back-up power on the contrary. This HES is expected to reduce CO_2 emissions from an offshore facility due to: 1) enhanced exploitation of RESs; 2) clean fuel to GTs; 3) improved operational strategy of the GTs.

3. Modelling framework

Two main areas of the modelling activity are distinguished, namely (1) process components and (2) offshore grid modelling. The general intention is to pre-screen the feasibility of the HES-OFF concept and to assess the potential reduction of CO_2 emissions.

3.1. Process components

The HES-OFF process components are modelled in MATLAB and are presented below.

GTs: Two types of gas turbines are considered for the study, namely a GE LM2500+G4 (rated power 32.2 MW) and a GE LM6000 PF (rated power 41.9 MW). To simulate the GTs, two data-defined models are used. Those are based on performance curves retrieved from tabulated data and assess the effect of changing working conditions as well as off-design operation. The models were validated against the Thermoflow library (Thermoflow Inc, 2016). The performance of the LM2500+G4 model was further checked against real operational data by Riboldi and Nord (2018), showing good agreement, and used in previous publications (e.g., Riboldi and Nord, 2017).

FCs&ELs stacks: The models used in this study are based on zero-dimensional, static models of PEM FC and EL stacks, which describe the electrical domain of cells. The FC stack model is based on Spiegel (2008), improved and tuned according to Dicks et al. (2018). The EL stack model is based on Zhang et al. (2012) with further improvements based on Millet (2015). The output of the model is the overall performance of the FC and EL stacks as a function of load expressed in MJ/kgH_2 and kgH_2/MJ, respectively. The obtained results reflect the state-of-the-art for high capacity PEM systems on the market. **WT:** The conversion of wind speed into power was simulated through the power curve of the Hywind Scotland WT (Nielsen, 2018). The wind speed distribution throughout a year was based on the measurements from a platform in the North Sea made available by the Norwegian Meteorological Institute (reported in Korpås et al., 2012).

3.2. Offshore grid

A surrogate model of the electrical grid (Alves et al., 2019) was developed in Simulink. It evaluates frequency dynamics using Eq. (1):

$$\dot{\omega} = \frac{P_a - k_d \omega^2}{2H_{GT}\omega} \qquad (1)$$

$$P_a = P_{GT} + P_{FC} + P_{WT} - P_{EL} - P_{LD} \qquad (2)$$

where ω is the frequency in per unit[1] (pu), the model state and output; P_a is the net accelerating power in pu and the model input; H_{GT} and k_d are model parameters, defined as the equivalent inertia constant in s and the equivalent damping constant of the plant in pu/pu. Base values are: $\omega_b = 2.\pi.60$ rad/s; $P_b = 44.7$ MW.

P_a is defined by Eq. (2) where P_{GT}, P_{FC}, P_{WT}, P_{EL}, P_{LD} are respectively the power in pu of GT, FC, WT, EL and loads. The model from Eq. (1) is extended to include PID controllers for the GT, FC and EL (Alves et al., 2019 and Sanchez et al., 2017). Those keep the grid frequency at its rated value. The choice of controller parameters follows the magnitude optimum criteria as outlined by Papadopoulos (2015).

4. Results

The developed methodology was tested on a case study: an offshore facility in the North Sea, for which an estimation of the energy requirements throughout its lifetime was made available by the operator (18 years). To ease the analysis, the power and heat supply demand was discretized: 1) Peak (2 years): 43.6 MW electrical power, 14.0 MW heat power; 2) Mid-life (4 years): 35.2 MW electrical, 11.0 MW heat; 3) Tail (12 years): 32.9 MW electrical, 8.0 MW heat.

4.1. Long-term system design

The long-term analysis sizes the components of the HES by: 1) ensuring that power and heat demand is always met; 2) maximizing the reduction of CO_2 emissions; 3) removing one GT; 4) avoiding waste of wind power.

The discretized lifetime energy demand of the offshore installation is considered, where each year is simulated with an hourly resolution. Table 1 reports the input parameters varied to define a design.

[1] per unit (ou) is a system for expressing values in terms of a reference or base quantity.

The storage strategy adopted ensures a net-zero balance of H_2 at the end of the year and the storage size is determined by the largest variation in the storage level. At first the design is tested over one year without ES.

Table 1. Input parameters for the long-term system design

INPUT PARAMETERS	
GT type	GE LM2500 or LM6000
Max. GT load	95 %
Min. GT load	40 %
Max. H_2 in GT	20 % vol.
Wind turbine	Hywind Scotland
Wind farm size (MW)	12-18-24

Table 2. Input parameters for the short-term grid stability analysis

INPUT PARAMETERS	
H_{GT}	1.85s for LM2500 1.8s for LM6000
k_d	7 pu/pu
GT PID controller	Kp = 3.8, Ki=1.6, Kd=0, Td=100
EL / FC PID controllers	Kp = 0, Ki=0, Kd=6, Td=50

In case of a net deficit of power (typical of peak years), the strategy: 1) evaluates total H_2 needed; 2) when possible, increases GT load and uses extra power to produce H_2; 3) stops when reaching a maximum storage level; 4) stops when reaching overall H_2 needed. In case of a net surplus of power (typical of tail years), the strategy: 1) evaluates total H_2 produced due to surplus power; 2) when possible, decreases GT load and use fuel cells to produce power; 3) when the level of H_2 storage reaches a maximum, uses H_2 in the GT; 4) if some H_2 is still unused, sends H_2 to GT. Table 3 and

Table 4 shows results obtained for the small and large GTs, respectively.

The designs of the HES-OFF concept reduce CO_2 emissions both compared to the reference case (only GT) and to the basic integration of wind power (GT+WIND). The lowest cumulative CO_2 emissions are obtained by the HES-OFF designs based on the small GT (LM2500). However, those are also characterized by extremely large (possibly unfeasible) sizes of the H_2 storage and fail to remove one GT. Conversely, the HES-OFF design based on the large GT obtain a more limited CO_2 emission reduction but with more acceptable sizes of the H_2 storage and with a single GT.

The size of the H_2 storage is given in kg of H_2 as the storage technology is not specified. Cryogenic option has been ruled out because of the significant energy requirements. H_2 storage in gaseous form has been considered as more appropriate for this application. The very large volumes connected with this option would require a storage on the seabed. Some technologies have been qualitatively investigated such as the utilization of gas balloons (Pimm et al., 2014), gas pipes and underground formations (Kruck et al., 2013). Additional analyses are planned to identify the most promising option.

Table 3. Output results of the HES-OFF concept based on the LM2500 GT

INPUTS		**Only GT**	**GT + WIND**			**HES-OFF**		
GT type		LM2500	LM2500	LM2500	LM2500	LM2500	LM2500	LM2500
No. GT		2	2	2	2	2	2	2
Max. GT load	%	90 %	90 %	90 %	90 %	95 %	95 %	95 %
Min. GT load	%	40 %	40 %	40 %	40 %	40 %	40 %	40 %
Wind farm size	MW	-	12	18	24	12	18	24
OUTPUTS								
Size H_2 storage	kg	-	-	-	-	175334	81605	71062
Size EL stacks	MW	-	-	-	-	6	6	6
Size FC stacks	MW	-	-	-	-	4	4	4
CO_2 emissions	Mt	3.51	2.71	2.42	2.25	2.50	2.27	2.09
Max. frequency	Hz	60.00	60.15	60.23	60.31	60.12	60.19	60.25
Min. frequency	Hz	59.22	59.02	58.91	58.79	59.13	59.04	58.95
Max. dP/dt GT	%/s	1.52	1.88	2.11	2.33	1.68	1.86	2.03

Table 4. Output results of the HES-OFF concept based on the LM6000 GT

INPUTS		**Only GT**	**GT + WIND**			**HES-OFF**		
GT type		LM6000	LM6000	LM6000	LM6000	LM6000	LM6000	LM6000
No. GT		2	2	2	2	1	1	1
Max. GT load	%	90 %	90 %	90 %	90 %	95 %	95 %	95 %
Min. GT load	%	40 %	40 %	40 %	40 %	40 %	40 %	40 %
Wind farm size	MW	-	12	18	24	12	18	24
OUTPUTS								
Size H_2 storage	kg	-	-	-	-	10010	8014	11824
Size EL stacks	MW	-	-	-	-	4.0	4.0	6.6
Size FC stacks	MW	-	-	-	-	1.1	1.1	1.1
CO_2 emissions	Mt	2.92	2.48	2.36	2.30	2.45	2.32	2.23
Max. frequency	Hz	60.00	60.15	60.23	60.31	60.14	60.22	60.30
Min. frequency	Hz	59.21	59.02	58.90	58.78	59.06	58.92	58.75
Max. dP/dt GT	%/s	1.05	1.30	1.46	1.61	2.49	2.88	3.32

4.2. Short-term grid stability analysis

This step verifies if each proposed design of the long-term analysis: 1) is stable from the frequency stability perspective (Kundur et al., 2004); 2) complies with industry requirements (IEC, 2015) for frequency deviations (± 2%) during normal operation conditions; 3) complies with technical specifications of GT ramp rates.

For that, it simulates the offshore grid model presented in section 3.2. Inputs are obtained as following: 1) P_{GT}, P_{FC}, and P_{EL} are results from the long-term analysis of the process model and are assumed as constants; 2) P_{WT} and P_{LD} are results from analyses of 1-year long datasets of wind speeds and loads sampled every minute and are assumed as variables. These datasets are stored in an NTNU repository and are not publicly available. To reduce total simulation time, two synthetic time series reflect the worst-case scenarios of operation during the offshore platform lifetime. Those are 3-minutes long and contain the most sharp and common positive and negative variations of P_{WT} and P_{LD}. Parameters for the short-term grid stability analysis are reported in Table 2.

The bottom part of Table 3 and

Table 4 presents the obtained results. Note that as the wind farm size increases: 1) the frequency deviations increase and, in the extreme cases (24 MW wind farm), the minimum frequency limit (58.8 Hz) is always violated, except for the LM2500 HES-OFF concept; 2) the rate of change of power (*dP/dt*) of the GT increases, which translates into increased actuation of the governor and consequently additional wear and tear. The HES-OFF concept contributes to decrease frequency deviations and GT ramp rates. Note that, in the LM6000 HES-OFF concept with 24 MW wind farm, the minimum frequency limit can be respected if the FC increases to 1.6 MW. This shows the importance of considering grid requirements in the design phase of a HES.

5. Conclusions

The HES-OFF concept was presented and tested on a case study. Six configurations were assessed using two GTs of different rated power. Long- and short-term analyses verified the HES potential to reduce CO_2 emissions and to provide a stable offshore grid. The HES-OFF concept demonstrated the ability to reduce the cumulative CO_2 emissions of an O&G platform not only compared to a reference case using only GTs but also compared to a concept integrating GTs and WTs without ES. The designs based on the small GT return the highest CO_2 emission reductions (between 29 % and 40 % depending on the wind farm size) but are unable to remove one of the GTs and involve very large H_2 storage capacity. Conversely, the designs based on the large GT return lower CO_2 emission reductions (between 16 % and 24 % depending on the wind farm size) but use a single GT and more limited H_2 storage capacity. It is also shown that the addition of ES helps reducing the frequency variations in the offshore grid. The minimum frequency specification is generally met by the HES-OFF solutions but at 24 MW wind capacity for the large GT. However, an increase in the FC stack size would allow the frequency to be within the required limits. Not least, GTs ramp rates are reduced as well, with potential advantages in terms of decreased wear, tear and maintenance requirements. Further work in this ongoing research project envisions the development of more complex models, optimization of the HES and validation by means of hardware-in-the-loop simulation.

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