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A Case-Study on Offshore Wind Power Supply to Oil and Gas Rigs

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Abstract

Electricity consumption of offshore oil and gas rigs are commonly supplied by gas turbines located on the platforms. These are expensive to operate and emit significant amounts of CO_2 and NO_x. Offshore wind farms may thus be an economic and environmentally sound option. This paper presents this possibility assuming a wind farm to be operated in parallel with gas turbines. Fuel savings and emissions reductions are quantified by numerical simulations of a case study of an offshore platform in the North Sea. It is concluded that offshore wind is an economic and environmentally sound option for supplying electricity to oil and gas rigs. The size of the wind farm and operational strategy should be carefully selected for securing technically stable and economic operation.

Keywords: Offshore wind, Isolated power systems, Fuel savings

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1. Introduction

Electricity consumption of offshore oil and gas rigs are commonly supplied by gas turbines located on the platforms. These are expensive to operate and emit significant amounts of CO_2 and NO_x. Supply from the main grid is an option, but expensive for platforms far from shore and with limited environmental benefits if not supported by non-polluting generation. Offshore wind farm technology now being developed also for deep sea can on the other hand be connected directly to the platforms, and operate in parallel with gas turbines. The wind farm will then save fuel and reduce emissions without the need for any long and expensive connection to shore.

Operational strategies and savings of fuel and emissions depending on the wind farm size are quantified by a case study of an offshore oil and gas platform in the North Sea. Logistic simulations show that operation of the wind farm in parallel with gas turbines will give significant fuel and emission reductions, especially when allowing for start/stop of gas turbines. The challenge is to find a good operation strategy that balances the number of start and stops of the gas turbines against dissipating energy and fuel savings.

Dynamic simulations have also been performed, in order to verify that frequency and voltage levels are within required limits. Results from the dynamic simulations and additional operational and economic analyses are published in [1].

The paper is organized as follows: Chapter 2 presents the characteristics of the case study power system. Chapter 3 explains the simulation model used in the performance analysis. Chapter 4 presents and discusses the results from the analysis of the hybrid wind/gas-poewr system at the case study oil platform, while Chapter 5 concludes the work.

2. Case study description

The case-study oil platform is shown in Fig. 1. The electricity demand at the case study oil platform is presently supplied by two gas turbines, with a third turbine as backup. Under normal operating conditions, the gas turbines share the load equally. The gas turbines are of the same type with 23 MW capacity and fuel characteristics as shown in Fig. 2. As seen, the fuel efficiency decreases drastically at low loads, and the fuel consumption at idle is about 20 % of the fuel consumption at full power. The power consumption over the year varies typically between 20 MW and 35 MW. The consumption is fairly constant, but can change quickly due to different motor start ups and shut downs. Since some of the loads are considered to be interruptible, it is assumed that the N-1 criterion do not need to be fulfilled under normal operating conditions; i.e. operation of the back-up gas turbine is not considered in the case study.

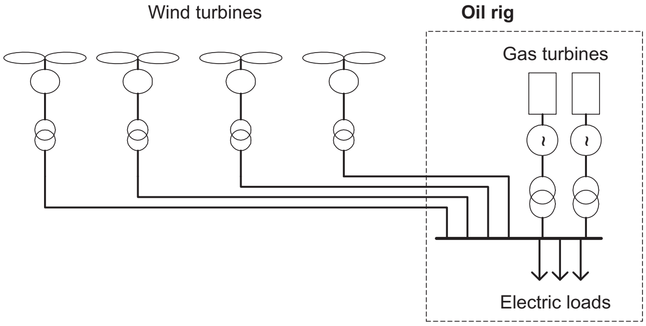

Fig. 1. Simplified illustration of oil-rig electrical system with connection of offshore wind turbines.

The wind conditions near the oil platforms are very favorable, with average wind speeds typically in the range of 10-11 m/s at turbine hub height, which theoretically gives 4000-4800 utilization hours [2]. Wind turbines can be located near the oil rig and operated in parallel with the gas turbines. If the wind power output is low compared to the electricity demand, wind would save fuel and emissions about proportional to the energy output of the wind turbines. In this case study, on the other hand, the studied wind energy penetration is significant; 4 x 5 MW wind power with 4500 utilization hours gives a penetration level of about 43 % for the present electricity consumption. With no adjustments of the gas turbine operation strategy, such high amounts of wind power may imply significant reduced operation efficiency. Therefore, a start/stop strategy for the second gas turbine is proposed in this paper (see Chapter 3) to improve the overall operation efficiency of the system, resulting in higher fuel savings.

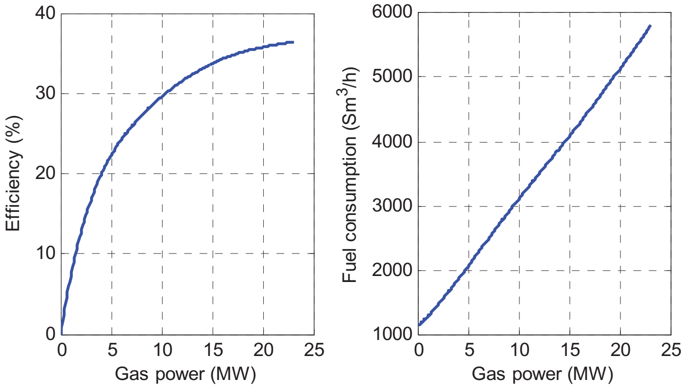

Fig. 2. Efficiency curve (Higher Heating Value) and fuel consumption curve for the gas turbines.

3. Simulation model

For simulating the operation of the combined wind-gas power system, a quasi steady-state MATLAB model has been employed. Quasi steady-state refers to types of models which simulates the system from time-step to time-step but does not take into account the dynamic characteristics of the components. Moreover, the model is a pure power balance model, and does not calculate voltages, currents and reactive power. The chosen time step size is set to 1 minute and the system is simulated for 1 year. Similar types of models are used for evaluating the performance of isolated wind-diesel power systems, see e.g. [3,4,5].

Two strategies for the combined operation of the gas turbines and wind turbines have been employed. The default operating strategy is to always run two gas turbines in parallel with the wind turbines. The wind turbines are chosen to always have priority to supply the load. This implies that no wind power is dumped except if the total wind power output exceeds the load. The gas turbines share the remaining load (load – wind power) equally, as in the case of no wind power installed. The second operating strategy, denoted “fuel saving strategy” allows one of the gas turbines to be shut down if the wind generation is sufficiently high. This strategy can take into account start-up time of the gas turbine and a minimum run-time.

By including wind power for the default operating strategy the generating capacity margin will increase, since two gas turbines always will be on (as for the no-wind case). With the fuel saving strategy on the other hand, the power system will be more vulnerable to faults when the load is supplied by one gas turbine and the wind farm. If the gas turbine trips in this case, the only power supply is from wind until the second gas turbine is online.

With the default operation strategy, the gas turbines are often run at low power when they share the remaining load in the periods with high wind speed. This is unfortunate regarding fuel consumption, since the efficiency decreases drastically at low loads. The main idea behind the fuel saving operating strategy is therefore to shut down the second gas turbine when the wind power output and one gas turbine capacity is sufficient to cover the load. However, in order to be able to supply the load in case of sudden load and wind power changes, it is necessary to take into account the start-up time of the second gas turbine. The second gas turbine is shut down at time step if the following operating condition is satisfied:

$$P_{wind}(t) + P_{gas}^{rated} > \max\left[P_{load}(t,\dots,t+t_{gas,start})\right] + \Delta P_{wind}^{margin} \cdot t_{gas,start}$$

where $P_{wind}(t)$ is the wind power output at time step t and P_{gas}^{rated} is the rated power output of the gas turbine. $P_{load}(t,\dots,t+t_{gas,start})$ is a time-series of the forecasted load from timestep t to timestep $t+t_{gas,stat}$, where ,$t+t_{gas,start}$ is the start up time of the gas turbine (5 minutes is used in the case study). ΔP_{wind}^{margin} is a margin that is added to the load in order to account for possible short-term wind power reduction.

By analysis of a representative long-term wind power time series (See Chapter 4), the margin ΔP_{wind}^{margin} is set to 0.3 MW/min pr 5 MW turbine. Thus the total wind power output of the 20 MW wind farm is assumed to not decrease more than 6 MW within the 5 minutes it takes to start up the gas turbine. This is a conservative (worst case) value used for all days of the year. If short-term forecasts of wind power variations exist, a lower margin may be used which will reduce the fuel consumption further by allowing the second gas turbine to be stopped for longer periods. If a load forecast does not exist, the load should be treated as the wind power; by adding a margin that accounts for sudden load increases. It is assumed here that the load can be 100 % accurately forecasted within the 5 min time window.

The above equation also determines the condition for start-up for the second wind turbine. Given that the wind power output never decreases more than 0.3 MW/min pr wind turbine within the time it takes to start the second gas turbine, the system will have sufficient capacity to supply the forecasted load.

In addition to the operating condition explained above, it is possible to specify a minimum run-time for a gas turbine, i.e. it must have been in operation a minimum number of minutes before the turbine is allowed to be shut down again. This parameter can be set in order to reduce the number of starts and stops in order to avoid mechanical wear. However, a long minimum operating time will at the same time give higher fuel consumption, which means that there is a trade-off between number of starts/stops and fuel consumption. The minimum operating time is set to 60 minutes for this case-study to avoid too frequent start/stop operations. There has however been no attempt to find an "optimum" minimum operating time for the case-study, since this would require detailed performance and lifetime studies of the installed gas turbines.

Fig. 3 shows a simulated day with high load and high wind power output, where the second gas turbine is stopped according to the proposed fuel saving operating strategy. It is seen that as the wind picks up, the second gas turbine is stopped, causing a fast increase in loading of the gas turbine still in operation. At the end of the simulation period, it is observed that the second gas turbine is started shortly after being stopped. This happens because the same value for the capacity margin ΔP_{wind}^{margin} is used for start-up and stop of the gas turbine. Fluctuations in wind and/or load can therefore in some periods cause frequent start/stops: However, this effect can be avoided by setting the capacity margin to a somewhat higher value for shut-down than for start-up. The optimum choice of capacity margin is a trade-off between operational cost savings and mechanical wear and tear which is not addressed further in this case study.

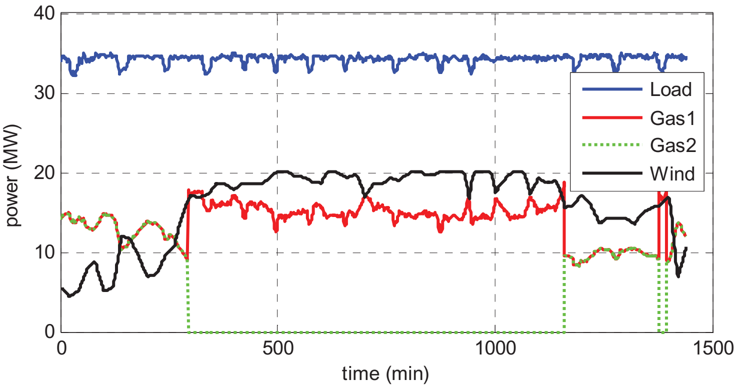

Fig. 3. Simulated wind power output and gas turbine operation during a day with high load.

4. Results

This chapter presents results for full-year simulations of the combined wind/gas supply to the example oil platform using 1-minute values for load variations and wind power as input.

A one-year wind speed time-series with 20-minute resolution from an offshore meteorological measurement station at a North Sea oil platform has been used as basis for generating synthetic wind power values. The data was provided by The Norwegian Meteorological Institute. The wind speed data is considered to have sufficient high quality for the case study. However, the oil platform itself can disturb the wind field, causing a speed-up of the wind speed, as shown in [6].

Intermediate wind speeds in the 10-minutes interval has been randomly generated using a distribution function for 10-minute variations obtained from similar wind speed series from Norway. The resolution has furthermore been increased to 1 minute using linear interpolation. Fig. 4 shows a histogram of the generated wind speed time-series. Wind speed is converted to wind power using an ideal wind turbine power curve, assuming "storm control" at high wind speeds instead of sharp cut-off and cut-in values.

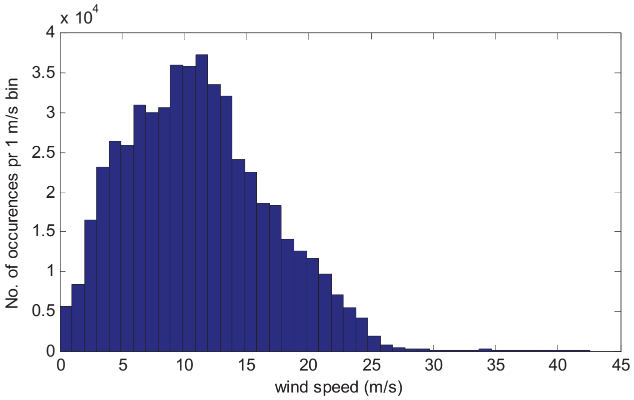

Fig. 4. Histogram of wind speed series using 1 m/s bins (data is grouped in 1 m/s intervals in the plot).

The duration curves for the load and the power output of the 4 x 5 MW wind turbines are shown in Fig. 5. Also shown is the minute-to-minute net load (load – wind), which is the resulting load that must be covered by the gas turbines. It is seen that during a few periods, the minimum load is lower than the wind power. In these periods, the wind power output must be reduced, e.g. by pitching the blades, resulting in dissipated wind energy.

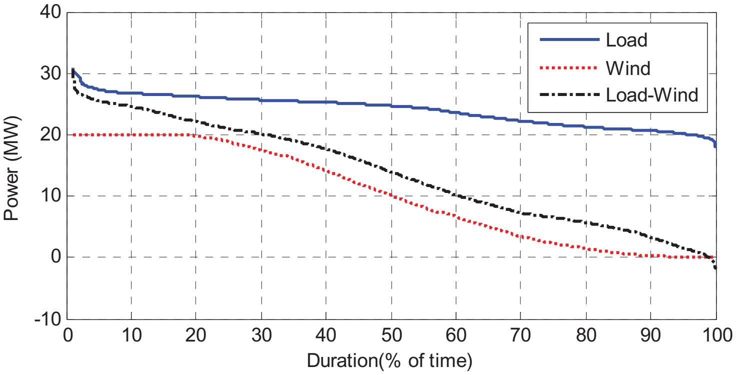

Fig. 5. Annual duration curves of load, wind power and net load (Load-wind power).

For the default operating strategy, both gas turbines are always in operation, and they will supply half of the net load each. With 20 MW wind installed, the default operating strategy gives many hours of operating the gas turbines at low loading, with increased mechanical wear and low efficiency as a result. From the net load duration curve it can be deducted that the both gas turbines operates below 5 MW as much as 40 % of the year. By allowing start/stop of the second gas turbine, as shown in Fig. 6, the periods with low loading of the gas turbines are reduced significantly. The other gas turbine is then operated at below 5 MW for only 15 % of the year, while the second gas turbine is switched off for 65 % of the time. Between day 200 and 250, when the load is stable at about 20 MW, the second gas turbine is not started.

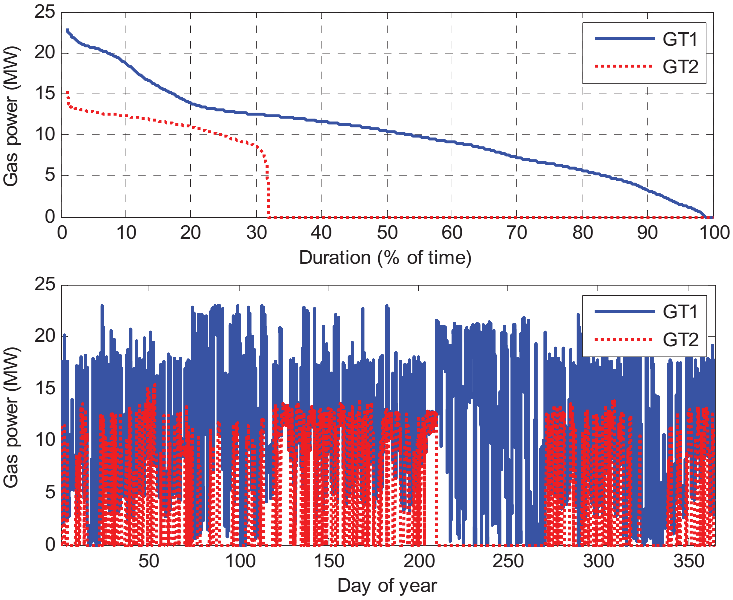

Fig. 6. Annual duration curves (upper) and time-series of simulated power output (lower) of the gas turbines operating together with 20 MW offshore wind using the fuel saving operation strategy.

Annual results are presented in Table 1 to Table 3. The start/stop operating strategy increased the fuel efficiency from 25.6 % to 30.1 % which is observed to be close to the average efficiency for the case with no wind. To obtain this operational benefit, the second gas turbine must be switched off and started 543 times of the year, i.e. 1.5 times pr day in average. Further studies are needed to assess if this leads to unwanted mechanical degradation and reduced lifetime of the gas turbines.

Table 1. Yearly power consumption and generation.

Operation Strategy	Wind MW	Demand GWh	Wind GWh	Gas GWh	Dumped power GWh
Default	0	210.32	0.00	210.32	0.00
Default	20	210.32	89.85	120.47	0.03
Fuel savings	20	210.32	89.85	120.47	0.03

Table 2. Wind fraction of energy supply, dumped wind energy, avg. gas efficiency and number of start-ups of the 2. gas turbine over a year.

Operation Strategy	Wind MW	Wind fraction %	Dumped wind %	Gas efficiency %	No. of starts
Default	0	0.00	0.00	31.50	0
Default	20	42.72	0.04	25.64	0
Start/stop	20	42.72	0.04	30.13	543

Table 3. Fuel savings, emission reductions and operational cost savings due to wind power.

Operation Strategy	Wind MW	Fuel Mill. Sm^3	CO_2 1000 tonnes	NO_x tonnes	Cost Mill. €
Default	20	18.06	39.72	270.83	4.23
Start/stop	20	24.45	53.79	366.76	5.73

It is estimated that 20 MW wind annually gives 24 Mill. Sm^3 fuel savings, 54 000 tonnes CO_2 reductions and 367 tonnes of NO_x reductions. With a CO_2-tax of 0.09 €/ Sm^3 (approx. 39 €/tonne CO_2) , NO_x-tax of 2.2 €/kg and a gas price estimate of 0.11 €/ Sm^3, the annual operational cost savings from 20 MW installed wind are estimated to be 5.73 Mill. €. Since 20 MW wind power is estimated to generate 90 GWh/year (see Table 3), the resulting specific operational cost savings of wind power in this case study becomes approximately 64 € pr MWh produced wind power. This is significantly higher than present average electricity spot marked prices as shown in Fig. 7, emphasizing that power supply to oil and gas rigs is promising early market for deep sea offshore wind farms. In Fig. 7, historical Norwegian natural gas prices has been used for 2006-2008, while the case study estimate of 0.11 €/ Sm^3 is used for 2009 (this is close to the actual market prices as of Nov. 2009). Taxes for CO_2 and NO_x are kept constant. The cost savings are compared with historical yearly average spot prices at the NordPool spot (Oslo and Denmark-West areas) and the APX Netherlands power exchange. The compared values should be handled with care since factors such as wind power support schemes, grid connection costs and balancing costs are not considered. Moreover, future prices and emission taxes are highly uncertain. Nevertheless, it is clearly seen from the figure that the economical value of wind power is higher at the oil platform than at the spot markets for the assumptions of this case study.

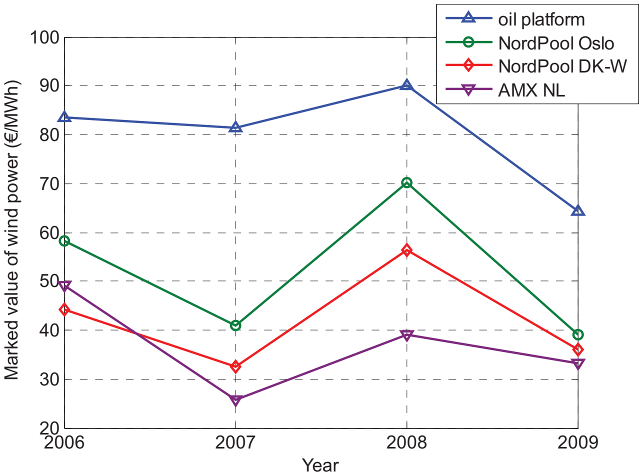

Fig. 7. Economic value of wind power supply to the oil platform using historic data for natural gas prices, compared with spot market prices for selected areas around the North Sea.

5. Conclusions

This paper have presented the possibility of operating a 4 x 5 MW offshore wind farm in parallel with gas turbines for power supply to a real operating oil and gas field centre, with a resulting wind energy penetration level of about 40 %.

Two operation strategies for the gas turbines was evaluated; a default strategy where both turbines shared the remaining load equally and a fuel saving strategy where one of the turbines were allowed to shut-down according to specified criteria. Simulations of a full year, representing 2009, resulted in 53 790 tonnes CO_2 reductions, 367 tonnes NO_x reductions and 24 Mill. Sm^3 fuel gas reductions. The fuel saving strategy showed significant benefits over the default strategy; the average gas turbine efficiency increased from 25.6 % to 30.1 %. However further assessments can be carried out to study the effect of on/off switching on the performance and lifetime of the gas turbine. With the present natural gas fuel price, NO_x tax and CO_2 tax at the field centre, the cost savings due to wind were estimated to be 5.73 Mill. €/year, corresponding to 64 €/MWh wind generation.

It is concluded that offshore wind is an economic and environmentally sound option for supplying electricity to oil and gas rigs. The size of the wind farm and operational strategy should be carefully selected for securing technical stable and economic operation.

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