Hybrid Auxiliary Power Supply System for Offshore Wind Farm

Xing Huang 1, Yao Chen 2
1 BEZIT Park Block 103 Level1, Jixianqiaobei Road, NO.10, Chaoyang District, Beijing, China. Post Code: 100015
2 Forskargränd 7, SE-721 78, Västerås, Sweden

1 helen-xing.huang@cn.abb.com
2 cathy-yao.chen@se.abb.com

Abstract. Diesel Generators (DG) are commonly adopted to supply the critical auxiliary loads for Offshore Wind Farm (OWF) during islanding operation. To reduce fuel consumption, avoid over-sizing of DG, and further enable a smooth resynchronization to main grid, a hybrid Auxiliary Power Supply (APS) system is designed with a combination of DGs, Wind Turbine Generators (WTGs), and battery Energy Storage System (ESS). Different from the typical industrial solution, this hybrid APS system uses not only DGs, but also WTGs to supply part of the auxiliary load when there is wind blowing for reducing fuel consumption and the corresponding refuelling works; moreover, the wind turbine converters can provide reactive power for balancing the charging power from the cable array inside the OWF, so as to avoid the oversizing of DG itself. ESS are also introduced to further reduce the dependence on the DGs. With enough capacity of ESS, it is even possible to remove DGs while still be able to fulfil the requirement on auxiliary load supply during islanding mode.

In this paper: firstly, the cost effectiveness of such hybrid APS is discussed via techno-economic analysis; secondly, two types of hybrid APSs with coordinated hierarchical control architectures are introduced, as well as the control strategy design for both centralized and distributed controllers; thirdly, simulation models are developed in MATLAB/Simulink, where two types of models are included. They are phasor-type model for centralized control strategy verification, and average-type model for distributed control strategy verification. The performance of hybrid APS models is validated under typical working scenarios, and the simulation results show that the control strategy has no high requirement on the communication speed between central controller and distributed controllers.

1. Introduction

As defined in the GL Rules for Classification and Construction IV (Industrial Services for Offshore Technology) [1], for all offshore installations, an independent emergency source should be provided, which is used for electrical power supply to the wind turbine auxiliary load, when the main power supply fails, and the supply time period should meet the requirement from half an hour to 4 days for different loads. Similarly, the German Transmission System operator has set a requirement of APS system to provide power for 12 hours or even longer time under extreme emergencies [2]. It can be noticed that, the original UPS system installed in wind turbine is not enough to meet these requirements.
To fit this requirement, usually DGs are installed as the major power supply under emergencies. However, using DGs only for APS has disadvantages:

- Firstly, fuel consumption is unavoidable. Take one export cable failure as an example, for a 500MW OWF, the fuel consumption can be as high as 1000tons per year. Given the diesel price at 150USD/bbl\(^3\), the fuel cost is above 1MUSD per year.

- Secondly, according to Reference ([2]), the DGs have to be oversized to cover both the active power and reactive power demands. Take a 500MW OWF with 82 WTs for example. In the worst case, the DGs have to be oversized by above 200%.

- Thirdly, the DG requires additional space and weight (e.g. 2x50 tons\(^4\)) in the platform for fuel storage, on top of that, periodical maintenance and refuelling are needed.

In order to solve these problems, this paper proposed a hybrid APS system with two alternative solutions, as shown in Figure 1. Different from typical industrial solution, this hybrid APS uses not only DGs, but also WTGs to supply part of the auxiliary load when there is wind blowing for reducing fuel consumption and the corresponding refuelling works; moreover, the wind turbine converters can provide reactive power for balancing the charging power from the cable array inside the OWF, so as to avoid the oversizing of DG itself. ESS can also be introduced to further reduce the dependence on the DGs. With enough capacity of ESS, it is even possible to remove DGs while still be able to full fill the requirement on auxiliary load supply during islanding mode.

In this paper: firstly, the cost effectiveness of such hybrid APS system is discussed via techno-economic analysis; secondly, the hierarchical control architecture of the hybrid APS system is introduced, as well as the control strategy design for both centralized and distributed controllers; thirdly, simulation models are developed in MATLAB/Simulink and the performance of the hybrid APS system is validated under typical working scenarios.

![Figure 1 Diagram of Hybrid APS](image)

2. Techno-economic analysis

The techno-economic analysis in this report mainly focuses on the cost saving generated by hybrid APS solution. Cost saving analysis results show that, this hybrid APS solution is able to achieve rational economic benefits for OWF, compared with original APS (only DG for APS). Detailed calculations are introduced briefly in Appendix A. Some basic conclusions for this hybrid APS solution are summarized here:

- **Alternative I - Hybrid DG + WTG:**
  This solution demonstrates rational economic benefits in terms of both capital cost saving and life time maintenance cost saving. Take a 500MVA OWF as an example. The final capital cost saving is around 14.6MUSD, which is around 4% of electrical system cost. Assuming WTGs can share 50% of auxiliary power, the annual maintenance cost saving is in the range of 76.5~645.4kUSD per year considering different transmission technology and shipment distance,
which is around 1% of annual operation and maintenance cost for a HVDC VSC OWF. The total life time cost saving of this hybrid APS in 30 years is in the range of 17~34MUSD, as shown in Table 1.

Furthermore, sensitivity study shows that, the increase of fuel price will bring significant economic benefit for hybrid APS on maintenance cost saving in the following years. Assume ~38% increase of fuel price to 2040, the maintenance cost saving of the new hybrid APS solution can increase ~25%. Solutions like multi-substations and platforms can help to decrease the unavailability of OWF, thus save the maintenance cost for fuel and refuelling. However it will introduce a much higher capital investment as well, which is less cost effective than the hybrid APS solution in this perspective.

- Alternative II - Hybrid ESS + WTG:
This solution only demonstrates higher economic benefits on life time maintenance cost saving, with little contribution to capital cost saving. Also take the 500MVA OWF as an example, this solution can save annual maintenance cost in the range of 152~1290kUSD per year considering different transmission technology, as shown in Table 1, while the capital investment is more or less the same. This is due to that the application of ESS can avoid the fuel consumption and refuelling requirement, however the capital cost of battery is also high.

In this case, the sensitivity study on battery price is done for the economic analysis of ESS+WTG solution. The prediction from DOE shows fast decrease of battery price in the following years. Compare with the price in 2010, the battery price may decrease to 10% in 2030. [3] Along with this decrease, the total life time cost of a 500MVA offshore wind farm may decrease to 11 million USD. The decrease of battery price will make the hybrid ESS + WTG solution more attractive.

Table 1 – Cost Saving (CS) results of a 500MW OWF with distance to shore from 50km to 300km

| Capital CS | Alternative I - Hybrid DG + WTGs | Alternative II - Hybrid ESS + WTGs |
|-----------|---------------------------------|----------------------------------|
| HVAC      | 15 MUSD                         | ~ 0 kUSD                         |
| HVDC LCC  | [76, 135]                       | [78, 162]                        |
| HVDC VSC  | [420, 645]                      | [152, 270]                       |
| HVAC      | [154, 324]                      | [842, 1290]                      |
| HVDC LCC  |                                  |                                  |
| HVDC VSC  |                                  |                                  |
| Annual Maintenance CS (kUSD/Year) |                          |                                  |
| Total Life CS MUSD/20Years | [17, 20] | [27, 34] | [3, 6] | [17, 26] |

3. Control strategy development
Two types of systems have been developed to design the coordinated control strategies for the hybrid APS system, as illustrated in Figure 2(a) where the APS consists of both centralized DG and distributed WTGs, and (b) where the APS consists of distributed WTGs with ESS and optionally centralized ESS. Both system adopt hierarchical control architecture. Details control strategy is introduced below.

(a) Centralized DG and distributed WTGs
In Figure 2(a), three different connection modes of WTGs are defined:
- Mode 1 (White): only the auxiliary loads of WTG are connected to the collection grid, which can be seen as a pure load in the islanding system;
- Mode 2 (Blue): both wind converter and the auxiliary loads are connected, which can be seen as a reactive power source in the islanding system;
- Mode 3 (Green): the whole WTG is connected to the collection grid, which can be seen as an active/reactive power source in the islanding system.

Two layers of control coordination are defined, considering the active and/or reactive power contribution from the WTGs based on the wind conditions.
- First tier coordination between DG and WTG: aiming to balance the power while still maintaining the minimum fuel consumption. The input factors include acceptable frequency/voltage variation range, wind speed, etc., the possible outputs include power/voltage references for DG, active/reactive power commands for group of WTGs, etc.
- Secondly tier coordination among multiple WTGs: Since the total capacity of WTGs of an OWF is far larger than the auxiliary loads, the WTGs should be selectively switched on, to take care of the active/reactive power commands allocated by the first tier coordination and meanwhile achieve optimal efficiency within WTGs and the collection grid. The input factors include generator type, location, WTG condition, etc., the possible outputs include on/off and active/reactive power commands for multiple WTGs, etc.

In Figure 2(b), also three connection modes of WTGs are defined:
- Mode 1 (Green): WTG+ESS connected, where circuit breakers CBWmb1 to CBWmb3 are closed;
- Mode 2 (White): WTG+ESS disconnected I, where only CBWmb2 and CBWmb3 are closed;
- Mode 3 (Blue): WTG+ESS disconnected II, where circuit breakers CBWmb1 to CBWmb3 are open.

Correspondingly, two layers of controllers are designed and coordinated: central level controller which is located in the offshore platform, and distributed level controller which is located in the individual WTG.
- Central controller to determine the connection mode of the multiple WTGs/ESSs according to the wind speed, wind turbine conditions, loading level and the layout of the OWF.
- Distributed controller to determine the control mode and corresponding control references for individual WTG/ESS according to the connection mode and system stabilization requirements.

There are three control modes:
- Active/reactive power (P/Q) mode
  WTG in P/Q mode can operate as current source, and provide active and reactive power for the auxiliary load, but cannot establish the system voltage and frequency in islanded mode.
  Two sub-control modes are included: with or without droop characteristics in P/Q mode.
  With droop characteristics shown in Figure (3), multiple power sources can operate.
together in an autonomous way. Without droop characteristics, the distributed controller will receive active and reactive power references from central controller.

- **Voltage/frequency (V/f) mode**
  WTG in V/f mode can operate as synchronous voltage source with Primary Frequency/Voltage Regulation characteristics, which is similar to the droop characteristics shown in Figure (3). Central controller will send voltage and frequency references to the distributed controller in WTGs.

- **Resynchronization mode**
  WTG in resynchronization mode can operate as synchronous voltage source with Secondary Frequency/Voltage Regulation characteristics, which can be used to regulate the system frequency/voltage, and finally help the wind turbine to be re-synchronized & re-connected to other voltage source (i.e. utility grid) with little or even zero power injection, which is called seamless resynchronization. In this mode, central controller will send additional frequency/voltage offset to distributed controllers in WTGs, so that their droop characteristics are modified, and the system frequency/voltage are modified in sequence.

![Figure 3 P/f and Q/V characteristics under P/Q control mode](image)

4. **Simulation verification**
   Take hybrid APS solution with ESS and WTGs for example. To verify the performance, two types of models are developed in MATLAB/Simulink.
   - **Phasor-type model**
     This model is used for centralized control strategy verification, as shown in Figure 4(a). Four WTGs with ESS are modeled as controllable power sources, connected to the cable array modeled with reactance and capacitance, which are then connected to the platform. In order to simplify the internal modeling and primary control for WTG and ESS, which will be address by the average-type below. Both WTG and ESS in phasor-type model are controllable power sources. And the three-phase series RLC branch is inserted just as a high resistance to avoid two current sources connected directly. And corresponding measurement and PI control methods of WTG and ESS are also the same with the average-type model.
   - **Average-type model**
     This model is used for distributed control strategy verification, as shown in Figure 4(b). Two WTGs with ESS as well as their control systems are developed, which are connected to the power source. As we mainly focus on the control strategy design of grid-side WTG/ESS, the influences caused by motor-side wind turbine converter or energy storage equipment are ignored here. This model is designed according to the mathematical equations in dq synchronous rotating reference frame, and is connect into the OWF collection grid by using controllable voltage source blocks.
Figure 4 Simulation model for hybrid ESS+WTG APS system control strategy verification

Figure 5 exemplifies one simulation case from the centralized control strategy under the scenario of wind speed changes. The central controller decides the connection mode (CM) of individual WTG according to the wind speed and the WTG availability, as shown in Figure 5(a). The active/reactive power references from the WTGs and ESSs are computed and adjusted in order to balance the load from the auxiliary systems and the cable array, as shown in Figure 5(b) and Figure 5(c). The total simulation time period is set to 100s, which can be divided into five time period as listed below:

- \( t \in [0s, 10s] \), all WTGs in connection mode 3, because the WTGs are not ready for operation yet. Thus the output power of WTG1 is zero, while ESS1 supplies 100% of local load.
- \( t \in [10s, 20s] \), all WTGs in connection mode 2, because wind power is not high enough to balance local auxiliary load and ESS charging demand. Since the wind speed is only 3m/s, \( P_{WTG} \) is only about 70kW, and consequently \( P_{ESS} \) is reduced to 10kW. WTG1 can fully compensate reactive power need from auxiliary load, so that the \( Q_{WTG} \) increases to 60kVar, and \( Q_{ESS} \) reduces to zero;
- \( t \in [20s, 60s] \), all WTGs in connection mode 1, because the wind power is high enough to balance local power demand, but the required number of wind turbine to balance the substation level power demand is not less than the available wind turbine for grid connection. WTG1 starts to connect to cable array as the first wind turbine, and at steady-state, \( P_{WTG} \) is 166kW when the wind speed is 4m/s, and increase to 207kW when the wind speed increases to 4.3m/s. Besides, WTG1 takes care of balancing the reactive power demand of the small grid, which means \( Q_{WTG} \) is 675kVar, including about 735kVar capacitive charging power from the two cables, and also 60kVar inductive power from the local auxiliary load.
- \( t \in [60s, 80s] \), only WTG1 and WTG2 are needed to operate as connection mode 1, because the wind speed is further increased, so that only two WTGs can fully compensate the substation level auxiliary load and ESS charging demand.
- \( t \in [80s, 100s] \), only WTG1 is needed to operate as connection mode 1, because the wind speed has further increased so that only one wind turbine is needed to connect to the cable array.
Figure 5 Simulation results from the phasor-type model

Figure 6 exemplifies the other simulation case from the distributed control strategy when WTG with ESS is in islanding mode operation from the beginning, through black-start and local system restoration get re-connected back to the grid. The V/f and P/Q control modes can be switched between WTG and ESS smoothly, and the re-connection to the grid is seamless with little power injection to grid. The total simulation time period is set to 60s, which can be divided into four time period as listed below:

- \( t \in [0s, 16s] \), Black Start Operation. Firstly, to build the system voltage and frequency, ESS1 and ESS2 are started with no load, and then supply the auxiliary load by closing the corresponding Circuit Breakers (CB). In this case two wind turbines are in Mode3. Secondly, to save the energy consumption of ESS, WTG1 and WTG2 are started in Mode2.

- \( t \in [16s, 32s] \), Local System Restoration. To help the auxiliary power supply for OWF, central controller may select several WTs (\( \geq 1 \)) to form a local islanding system, which means to pick several WTs to work in Mode1. Assume WT1 and WT2 are both selected to be in Mode1, then WT1 will build the voltage of AC collection grid firstly, and WT2 will re-synchronize and re-connected to the AC collection grid by using Re-synchronous control method.

- \( t \in [32s, 48s] \), Seamless Grid Connection Operation. When the grid power is recovered, WT1 and WT2 should switch from islanding mode to grid-connected mode. To realize the seamless switch with less influence to the auxiliary power supply, and provide the OWF restoration with fast re-connection speed, the central controller will coordinate the WTs in a bottom-up way: firstly, WT1 and WT2 are in Mode2 to support their own AS load; secondly, central controller
closes the CB to recover the voltage of AC collection grid; and thirdly, each WTs control their own WTG/ESS to re-synchronize and re-connected to the collection grid.

- $t \in [48s, 60s]$, the distributed controllers control WT1 and WT2 to transfer from the emergency control mode for auxiliary power supply to normal grid-connected mode for wind power generation. At $t=52s$, ESS1 will stop working, while ESS2 will switch into P/Q control without Droop characteristics for power charging. At $t=54s$ WTG1 and WTG2 will switch into P/Q control without Droop characteristics.

5. Conclusions

A hybrid APS system for OWF with DG+WTGs or ESS+WTGs is provided, which uses WTGs and/or ESS to supply critical auxiliary loads, so that the power capacity of DG and its fuel consumption can be reduced or even replaced. A hierarchical control system with two levels are proposed thereafter, to realize the coordination of multiple devices in the OWF. Simulation results show that the designed control strategy can deal with different cases while still maintaining the stable operation of OWF; the wind power can be fully utilized to share the power demand for both auxiliary loads and ESS charging. Plus, the control strategy has no high requirement on the communication speed between central controller and distributed controller.
References
[1] GL. Rules for Classification and Construction, IV Industrial Services, Offshore Technology, Electrical Installation, Aug. 15th, 2007.
[2] Joakim Berggren, “Study of auxiliary power systems for offshore wind turbines - an extended analysis of a diesel gen-set solution,” Master thesis, Univ. Uppsala. June 2013.
[3] Annual Energy Outlook 2013, reported by DOE/EIA, 0383, 2013.

http://www.eia.gov/forecasts/aeo/pdf/0383(2013).pdf
[4] Lazaros P. Lazaridis. Economic Comparison of HVAC and HVDC Solutions for Large Offshore Wind Farms under Special Consideration of Reliability, Master Thesis, KTH Electrical Engineering, 2005.

Appendix A – Cost Saving Analysis
The essential objectives of the hybrid APS solution is to reduce the cost of offshore wind farm, in terms of both capital cost and O&M cost. This paper takes a 500MW offshore wind farm as an example. The economic analysis results show that: By using DG+WTG solution, the capital cost saving for electrical systems can reach 4%, and the O&M cost saving can reach 1%. By using the ESS+WTG solution, the capital cost remains the same, however the O&M cost saving can be doubled to ~2%. Calculations will be introduced briefly in the following sections.

Cost saving analysis
Capital cost saving includes two parts: diesel generator cost saving, and offshore platform cost saving due to avoid oversizing of diesel generator set.

This paper found that, the total capital cost saving of one 500MW offshore substation platform = Platform Cost Saving + DG Set Cost Saving = 14,225kUSD +360kUSD =14,585kUSD.

Given the cost of 0.58MEUR/MW for the electrical system for offshore wind farm, for a 500MW offshore wind farm, the total cost for the electrical systems is 290MEUR.

It can be calculated that by using the hybrid APS solution, the cost of electrical systems can be reduced by 14.6MUSD/290MEUR x 100% = 4% (exchange rate to be 1EUR=1.3USD).

For ESS+WTG solution, the capital cost saving from diesel generator set, fuel tank and offshore substation is roughly the same to the capital investment for the battery ESS system (22MUSD).

Maintenance cost saving
Maintenance cost saving also includes two parts: fuel cost saving, and refuelling cost saving.

Calculation shows that, the fuel cost saving for a 500MW OWF with distance to shore from 50km to 300km is:

- In the range of [55.0, 80.3] kUSD/year for HVAC transmission technology;
- In the range of [55.9, 96.5] kUSD/year for HVDC LCC transmission technology;
- In the range of [303.2, 384.4] kUSD/year for HVDC VSC transmission technology.

The refuelling cost saving for a 500MW OWF with distance to shore from 50km to 300km is:

- In the range of [21.4, 54.5] kUSD/year for HVAC transmission technology;
- In the range of [21.7, 65.6] kUSD/year for HVDC LCC transmission technology;
- In the range of [117.9, 261.1] kUSD/year for HVDC VSC transmission technology.

It should be noticed that all figures listed above are obtained with an assumption that only 50% of the energy can be supplied by WTGs.

Given the cost of 1.5MEUR/MW for 20 years of O&M cost for offshore wind farm, for a 500MW offshore wind farm, the total cost for O&M in 20 years is 750MEUR.

Take 500MW offshore wind farm with HVDC VSC transmission technology, and 100km distance to shore for example, it can be calculated that by using the hybrid APS solution, the cost of operation and maintenance can be saved about 20years x (319.4kUSD + 126.8kUSD) / 750MEUR x 100% = 1% (exchange rate to be 1EUR=1.3USD). Considering the increase of the fuel price and labor cost, the costing saving percentage will go higher.

For ESS+WTG solution, since fuel consumption will be totally removed, the total maintenance cost saving will be doubled compared with DG+WTG solution.
Sensitivity analysis

To cope with the potential inaccuracy of input parameters, the economic evaluations about five input parameters are concluded here:

- **Fuel price**
  
The situation of fossil fuels running out quickly will lead to the increasing of fuel price in the following years. To 2040, this fuel price increasing may lead to around 38% increase, and makes the OWF annual maintenance cost saving of this new hybrid APS solution increase around 25%.

- **Fuel tank size**
  
  A small tank can lead to a smaller annual maintenance cost for OWF, but will increase the capital cost for platform. Based on the analysis results, 50~150Ton is relatively optimal size of fuel tank for a 500MW OWF with distance from service station to offshore substation platform 100km.

- **WTGs power contribution**
  
  The more power contribution from WTs means more cost saving for the OWF. In this case, the OWF operator should choose the WTGs contribution with higher priority than DG sets for APS.

- **Unavailability of OWF with multi-substations**
  
  Multi substations and platforms can help to decrease the unavailability of OWF, save the diesel consumption, and the maintenance cost for fuel consumption and refuelling. But it does not increase the total lifetime cost saving due to high capital investment. Take double substations and platforms (2*350MW OWF) as an example, about 30% decrease of total lifetime cost saving is shown, compared with single substation and platform topology (1*500MW OWF).

- **Shipment distance per refuelling operation**
  
  As the fast operation vessel is rented at a time unit of 24hrs, the rent time of vessel will change in step-wise. In this way, if the increase of rent time has not been step changed, exp. from 1 day to 2 days for one refuelling operation, the total life cost saving of OWF will not change rapidly with difference only within 1%; if the rent time of vessel has been step increased, exp. from 1 day to 2 days for one refuelling operation, then the total life cost saving of OWF will change rapidly with difference around 10%.

- **Battery Price**
  
  Besides the evaluation results above, which are suitable for both DG+WTG solution and ESS+WTG solution, battery price is one key parameter for the economic analysis of ESS+WTG solution. The prediction of DOE shows the fast decrease of battery price in the following years. Compare with the price in 2010, the battery price may decrease to 10% in 2030. Along with this decrease, the total life cost of a 500MVA offshore wind farm may decrease to 11 million USD. This decrease of battery price will make the hybrid ESS + WTG solution more attractive.