Case study:

Cost-efficient and reliable pitch control and backup power for wind turbines with hybrid powercapacitors

1 Introduction

Wind turbines today are increasingly used to generate part of our electricity. Their operation however is subject to variable wind conditions and they also must operate in very cold to very warm weather conditions.

An important part of a wind turbine are the pitch controllers. These are used to continuously help in adjusting the blade's angle to the wind variability but also to rotate the blades to a safe position in an emergency shut-down or when the wind becomes too fierce. This is often done in conjunction by using part of the generated electricity and a battery connected in parallel. The batteries are needed because the load is very variable and dynamic requiring high power peaks. This battery is also the back-up power supply if for some reason the main power is lost. Thus, it is important that the backup power supply is always available. Both ultracapacitors and lead-acid batteries were until now commonly used as energy storage devices for the pitch control system.

Lead-acid batteries have a limited life span and have a reduced capacity at low temperatures (40% capacity left at -20°C). Furthermore, the required power is a limiting factor for the batteries. The batteries need to be replaced approximately every 3 to 5 years after installation. Ultracapacitors on the other hand have a long-life span and don't suffer from extreme temperature environments as much, but they have a low energy density (3-10Wh/kg). This results in heavy and expensive systems. A pitch backup power supply using batteries must have the capacity to perform three full load pitch adjustments. With electric double layer capacitors (EDLC's) often only one can be performed, increasing the vulnerability of the system.

This paper will discuss the replacement of lead-acid batteries with carbon-based hybrid power capacitors on a wind turbine of Shanghai Electric. We also briefly discuss how they improve on the use of EDCL supercapacitors.

2 Cost-efficiency

Each wind turbine needs 72 batteries for the three pitch backup power supplies. They have to be replaced 8 times in the 25 years of the wind turbine life. In addition, it takes 3 workdays to replace the batteries and this also means 3 days without electricity being generated.

Ultracapacitors have a cost that is approximately 6 times higher and they have to be replaced after ten to twelve years. This means that not including the cost of the replacement, they cost about 50% more. over the life of the wind turbine. In the available space one can only fit a capacitor bank with enough energy for 1.5 cycles. Since the energy storage participates in the day-to-day operations of the pitch control system, multiple cycles are consumed per day. While in theory an ultracapacitors can operate for more than 500000 cycles, the capacity decreases over their lifespan. When they no longer can deliver sufficient energy they have to be replaced.

Carbon-based hybrid power capacitors have less cycles than ultracapacitors, but a higher energy density. This means that in the given space there is room for a larger energy storage unit, the energy density being 80Wh/kg. Even at the end of life of the battery, there is still 75% of the original capacity left, while the power capability is still available. Hence the battery will probably not need to be replaced during the 25-year life of the wind turbine.

3 The wind turbine case

Figure 1 The wind turbine

A wind turbine of Shanghai Electric which originally had lead-acid batteries is retrofitted with carbon-based power capacitors. This is a hybrid technology with an activated carbon anode and a lithium compound cathode. The old system used 24 12V 12Ah batteries for each pitch control system. This is replaced with a hybrid powercapacitor battery consisting of two modules. This results in a battery of 320V and rated (at high C-rates and leaving part of the energy unused) of 6.6Ah with 2kWh energy. Each module is assembled from 128Sx3P 18650 cells. Two modules are connected in parallel.

The original lead-acid battery charger is not replaced. To prevent overcharging in float charging mode, the operational range is reduced from 352V to 330V. While strictly not necessary, the additional margin is beneficial for the lifespan of the battery. The battery voltage is kept between 327V and 329V after being fully charged. The existing charger switches periodically between the 3 batteries.

Figure 2: The six power capacitor modules used for the pitch backup power supply.

One full load pitch adjustment requires 88Wh ($E=1.2\times P\times t = 1.2*(14.7kW*15s + 33.5kW*3s)$), with 1.2 being a safety margin. The pitch actuators have 14.7kW motors, and the load is sustained for 18s. The battery has sufficient energy to perform multiple full load pitch adjustments (18 have been measured in a test). To assure a smooth operation at low temperatures, the battery has 2kWh energy, because at -20°C (when the heater is not working) the battery has 60% of the original capacity left, with the capacity being recovered by self-heating in higher current operations. Another reason is to counteract the voltage decrease at low temperature. The pitch control system requires a minimum voltage of 252 V to still be able to operate and bring the blades to a safe position.

The cells have a life span of 20000 cycles which in combination with the higher energy density is sufficient for the whole lifespan of the wind turbine. Even when they have only 75% capacity left, they can still deliver the power.

4 Pre-installation simulations

In order to validate the proposed powercapacitor battery, battery load simulation are performed with a full pitch load profile as shown in figure 2 (3s at 33.5kW, 15s at 14.7kW and 60s of rest). The full load can be repeated seventeen times.

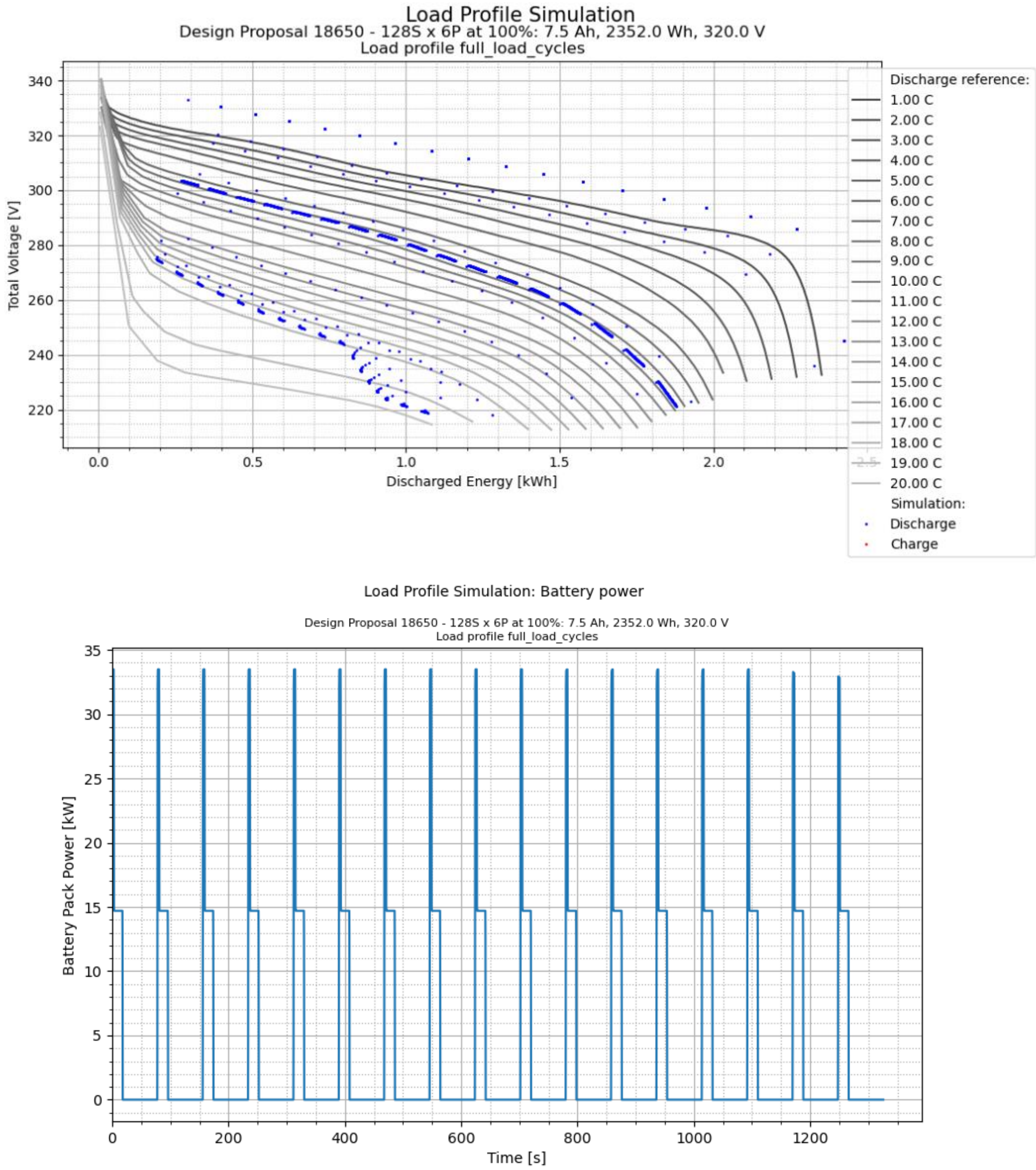

Figure 2 Load profile (power) and Voltage-Energy map simulating 17 full load pitch adjustments.

The battery in the pitch backup power supply is limited in charging voltage. This reduces the potential capacity with 12%, thus the starting state of charge (SoC) used is 88%. This also takes into account that the battery is not always at 100% SoC (due to its contribution to the continuous pitch control).

The results of the simulation show that the load profile can be performed 17 times in full. The figure below shows that the load can be applied 7 times until the minimum required voltage of 252V is reached, even if the battery has energy to spare. Keeping in mind that real batteries deviate from ideal batteries, the simulations are close to the later-on performed measurements.

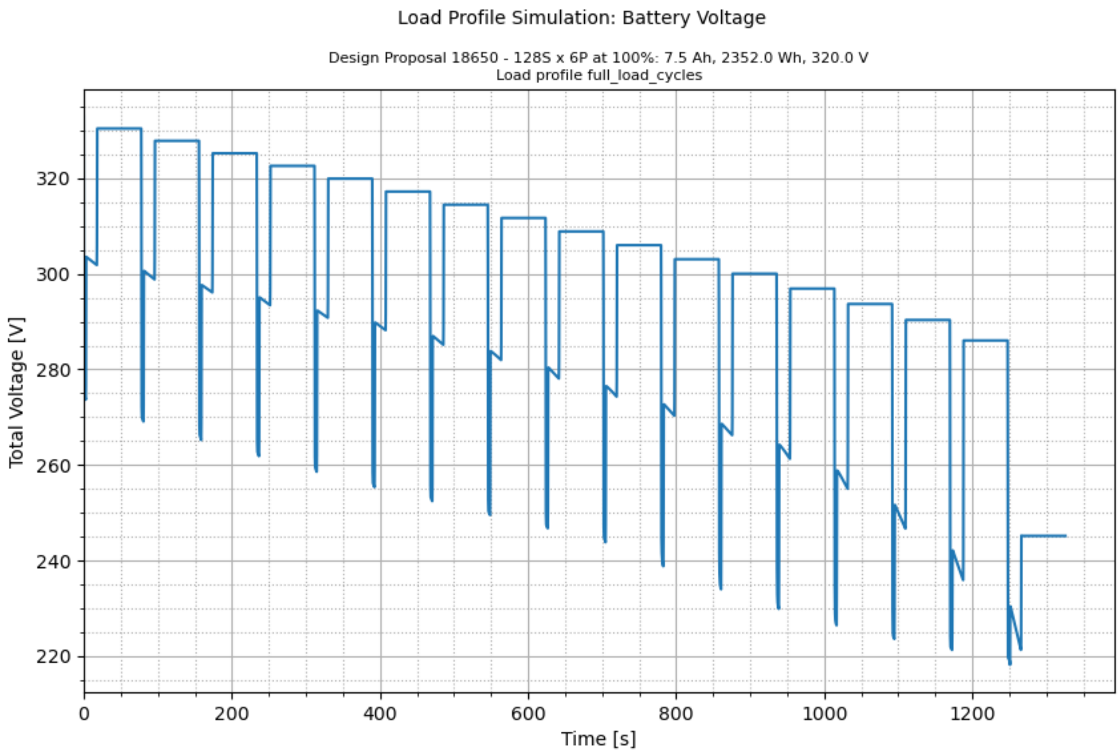

Figure 3 Voltage evolution for the profile in simulation

5 Tests

Before installation a series of tests were performed to confirm that the new batteries are suitable as backup batteries. The tests done on the modules are:

- A discharge test at 1C (3.3A) at 25°C.
- A charge and discharge test at 8C (24.6A) at 25°C.
- A discharge test at 1C (3.3A) at -20°C.
- A discharge test at 8C (24.6A) at -20°C.
- A constant power discharge test of the batteries.
- Tests with a simulated full pitch load.

These tests are performed on the modules before the final assembly. This means that the cells are not yet encapsulated in silica gel. There is also no cooling provided to the cells except by natural convection of the surrounding air in the room. The temperature is measured using a thermal camera.

5.1 Room temperature capacity test

To test the initial capacity of the modules, a battery module is discharged with a constant current of 1C (3.3A) at room temperature 25°C. After this test the voltage is 274V, the initial capacity is 3.4Ah, the energy is 1046Wh, and the temperature of the module has increased with 5.4°C. This test took 62 minutes to discharge the module.

Table 1: Test results of the 1C capacity test at 25°C.

Temperature 25±5°C	Initial capacity (Ah)	Effective energy (Wh)	Temperature rise (°C)
Module #1	3.42	1051.01	5.2
Module #2	3.41	1047.99	5.5
Module #3	3.49	1069.66	5.5
Module #4	3.43	1054.74	4.8
Module #5	3.41	1040.03	5.4
Module #6	3.31	1011.70	5.9
Average	3.41	1045.85	5.38

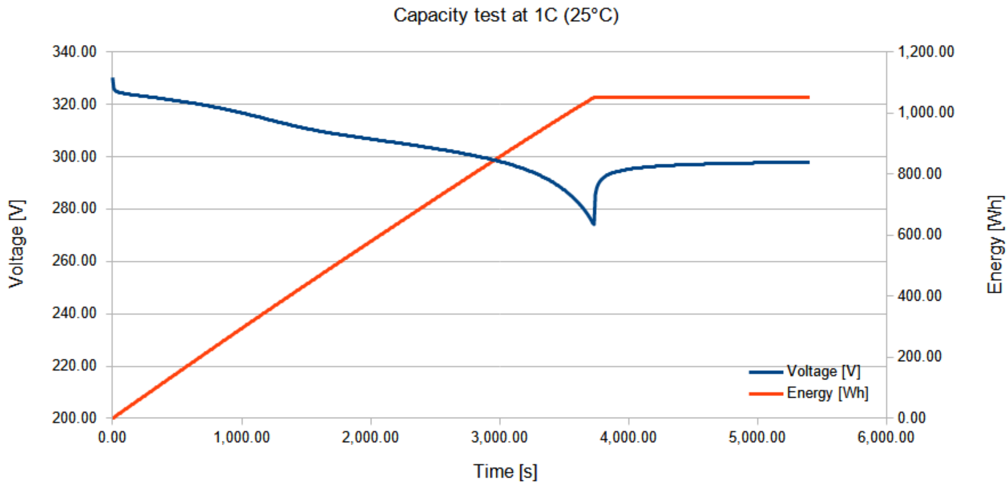

Figure 4 capacity test at 25 °C

5.2 Room temperature charge & discharge test at 8C

To test the battery near nominal motor load (14.7kW), the battery modules are charged and discharged at 8C (26.4A). The start of the test is at room temperature. After a full discharge at 1C, the modules are charged with a current limit of 8C. After charging the battery is discharged with a constant current at 8C. After charging the temperature has increased with 4.8°C and after the discharging the temperature increased with 22.7°C. At this C-rate the capacity is 3.3Ah and the effective energy is reduced to 890Wh (85%).

Table 2: Test results of the charge and discharge test at 8C.

Temperature 25±5°C	Discharge capacity (Ah)	Effective energy (Wh)	Charging temperature rise (°C)	Discharging temperature rise (°C)
Module #1	3.30	898.12	4.8	22.7
Module #2	3.30	885.42	4.8	22.7
Average	3.30	891.77	4.8	22.7

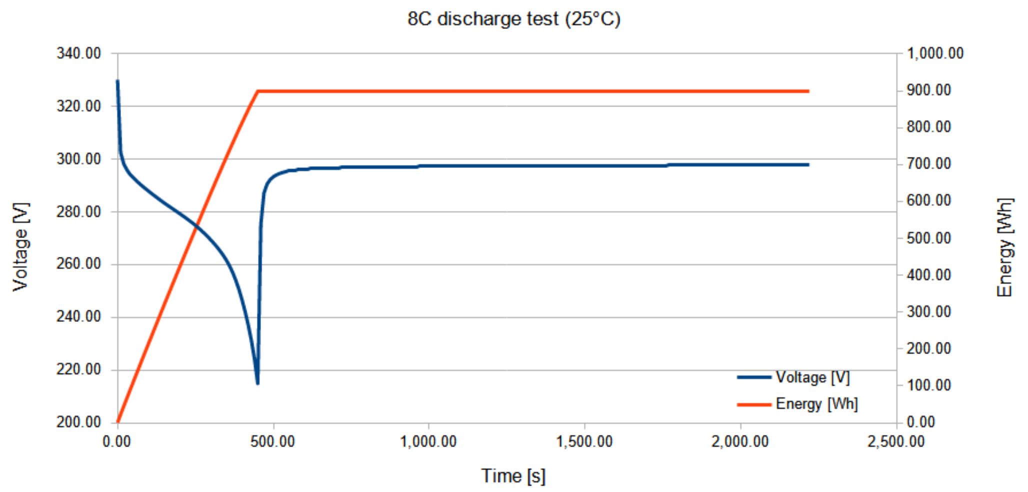

Figure 5 Discharge test at 8C and 25°C

5.3 Low temperature discharge test at 1C.

The tested modules were placed for 16 hours in a temperature-controlled box at -20°C. Afterwards the modules were discharged with a constant current of 1C (3.3A). During the test the temperature has increased with 15.6°C. The capacity at this temperature is reduced to 2.93Ah (85%) and the effective energy is reduced to 795Wh (76%). Part of the energy is restored because of the self-heating of the cells.

Table 3: Test result of the modules discharged at -20°C.

Temperature 25±5°C	Effective capacity (Ah)	Effective energy (Wh)	Temperature rise (°C)
Module #1	2.93	785.74	15.5
Module #2	2.93	804.79	15.7
Average	2.93	795.26	15.6

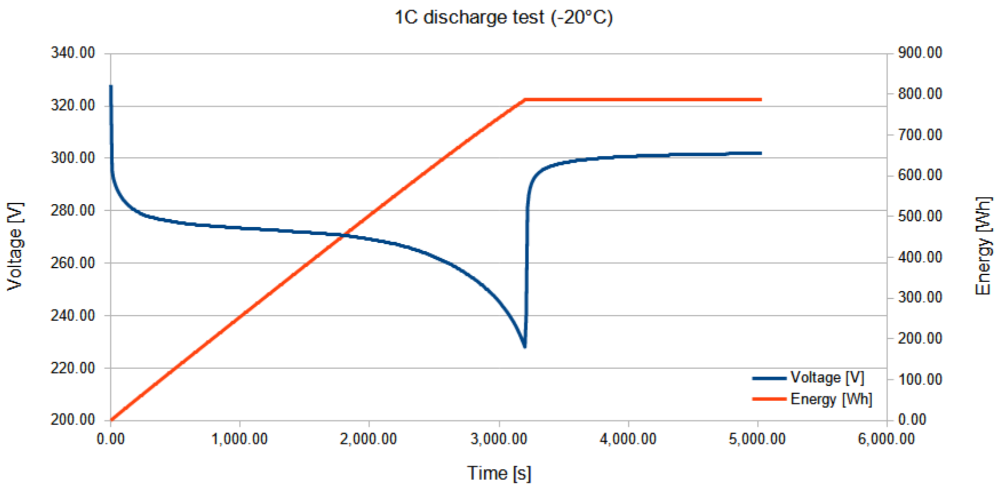

Figure 6 Discharge test at 1C and -20°C

5.4 Low temperature discharge test at 8C

The modules were placed for 16 hours in a temperature-controlled box at -20°C and discharged with a constant current at 8C (26.4A). The capacity under these circumstances is reduced to 2.77Ah (81%) and the effective energy is reduced to 607Wh (58%). The modules regain a significant part of the energy because of self-heating. Note also that as a result also the voltage is re-established.

Table 4: Test results for an 8C discharge at -20°C.

Temperature 25±5°C	Effective capacity (Ah)	Effective energy (Wh)	Temperature rise (°C)
Module #1	2.57	557.66	35
Module #2	2.96	656.13	35
Average	2.76	606.89	35

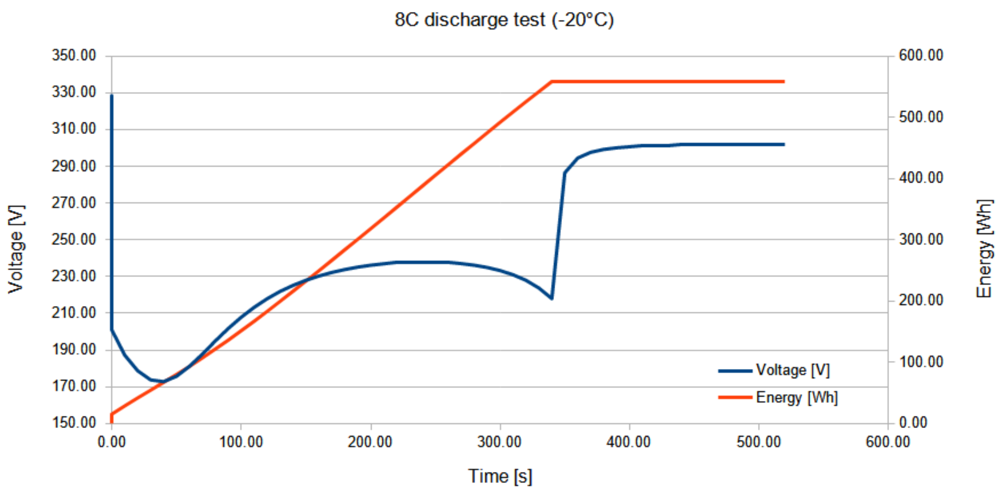

Figure 7 Discharging test at 8C and -20°C

5.5 Constant power test

For this test two modules are connected in parallel. The battery is then discharged with a constant power of 2.3kW, taking 52 minutes to complete. After the test the voltage was 267V and 2018Wh energy was discharged.

5.6 Post-installation tests

Following installation on the wind turbine, functional tests have confirmed the validity of the powercapacitor solution. An emergency shutdown took 19.8 second sand could be repeated 5 times. At all times did the voltage remain between the specified values.

6 Conclusion

The pitch backup power supply batteries are replaced with carbon-based hybrid power capacitors. The new batteries passed all the tests. There is sufficient margin in the modules, hence the capacity could be decreased with about 30%

One important characteristic of the power-capacitor batteries is that energy is recovered by self-heating in low temperature environments. In addition, they can remain installed over the whole lifetime of the wind turbines, The use of hybrid powercapacitors, combining high power capability with a high energy density, safety, long cycle life and capability to operate at low temperatures decreases the operational cost (close to zero maintenance) and also increases the operational energy output of the wind turbines.

For more information:

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