THERMAL OPTIMIZATION OF AN INTEGRATED LV BATTERY ENERGY STORAGE STATION

Frank VAN OVERBEEKE
EMforce – the Netherlands
vanoverbeeke@emforce.nl

Robert DE GROOT
Enexis/TUE – the Netherlands
Robert.de.groot@enexis.nl

Jan BOZELIE
Liandon – the Netherlands
Jan.bozelie@alliander.com

Han SLOOTWEG
Enexis/TUE – the Netherlands
Han.slootweg@enexis.nl

ABSTRACT

In the framework of an R&D project called "Smart Storage", Enexis has developed a boxed electricity storage system called the Smart Storage Unit (SSU). The SSU is a concrete housing in which a set of batteries and DC/AC converters is pre-assembled. After local installation, 50% of the SSU is below ground level. The thermal concept of the system has been chosen to minimise reliance on active cooling. This paper presents the design considerations, discusses the thermal balance on various time scales, and describes the chosen solution. Extensive functional and cyclic testing of the assembled system was performed in KEMA's Flex Power Grid Laboratory in Arnhem in March-April 2012.

These tests have led to modifications on the internal air flow, which have been implemented and have been put to test in December 2012. The paper presents the results and discusses the achieved performance improvements.

INTRODUCTION

The pattern of electricity consumption in residential areas is expected to change rapidly during the next decade. This is caused on one hand by the decreasing cost of PV systems, making it economically attractive for consumers to install PV systems of several kW per home, and on the other hand by the anticipated introduction of electric cars. In particular the PV systems, having simultaneous electricity production within a limited geographical area, may cause unacceptable voltage excursions in the LV distribution network. Moreover the added load variations from neighbouring LV branches may lead to overload conditions in the overlaying MV network.

One way of managing the load and generation variability is by installing electricity storage systems in MV/LV distribution stations. These systems serve as voltage regulators and peak shavers of power exchanged with the MV network. Additional benefits are:

- the mitigation of harmonic problems occurring in the network both as a consequence of multiple PV inverters and as a consequence of the increasing amount of non-linear loads;
- the option to run the local LV network in islanded mode, in case of a supply interruption in the MV network.
- Voltage regulation by reactive power control
- Improved flicker behaviour
- Improved coordination of protections in weak grids

In order to acquire operational experience with energy storage, Dutch distribution network operator Enexis has decided to develop a full-size prototype, to be installed in a network branch, which already hosts enough PV to cause reverse power flow through the MV/LV transformer.

Installing an electricity storage unit in a dense residential area, results in specific requirements on the system, one of which is that space utilization has to be minimized. In addition to this, sound emissions have to comply with strict regulations. On the other hand, both the batteries and the power electronic converters must be operated preferably within a narrow range of ambient temperature. The practical consequence of this is that thermal management, over a year in which outside air temperatures may vary from -20 to +35 °C, poses a big challenge.

These considerations have led to the development of an integrated energy storage station, of which about 50% is located below ground level. The intimate contact with the soil, in addition to the thermal buffer provided by the concrete structure of the building, leads to a design in which a stable internal temperature is achieved with minimal active cooling requirements.

Technical details of the project are presented in an accompanying paper [1].

LAY-OUT OF THE SSU

Figure 1 shows the main components of the Smart Storage System in a simplified diagram of the LV network. The green box contains the components which have been located inside the SSU:

- A 400 V distribution panel;
- Four DC/AC inverters of 100 kVA each;
- Four Lithium-ion battery sets of 57 kWh each.

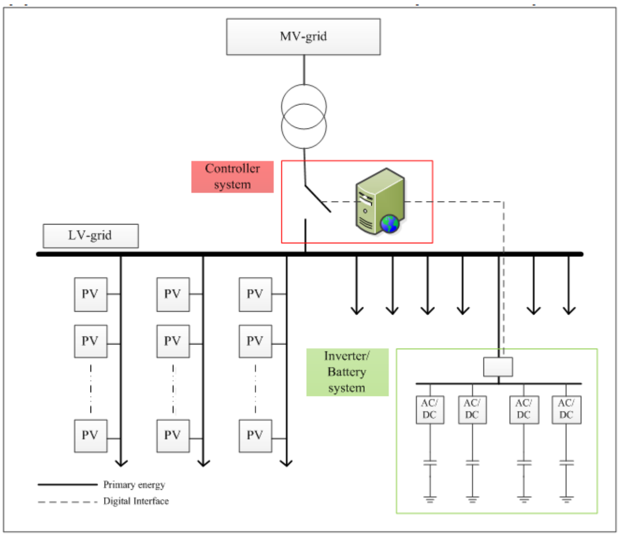

Figure 1. Simplified diagram of the LV network with the Smart Storage system (red and green boxes).

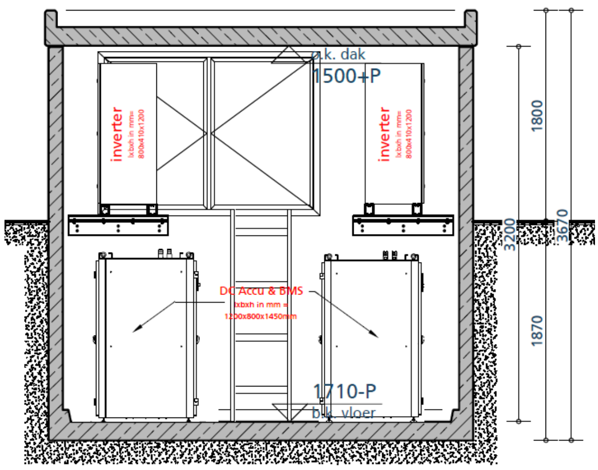

Figure 2. Sketch of the interior lay-out of the SSU.

The SSU box has been designed and assembled by the company Alfen. A cross-sectional sketch is depicted in **Figure 2**. The sketch shows the concrete housing with two of the four battery units on the floor. The inverter belonging to each battery is placed vertically above its battery, on a steel bridge structure and at such a height, that the inverter can be accessed via an outside door after the SSU has been placed in its final position. The inverter doors are not shown in the sketch. A view through the access doors of the inverters can be seen in **Figure 3**.

Staff access of the SSU is possible via another door and a small stairway. These are also indicated in Figure 2. A view of the interior through the staff access door has been depicted in **Figure 4**. The cubicles on the "basement" floor are the battery units. Above each battery unit an inverter cubicle can be seen. The tubes are the air inlet channels of the inverters. The box on the far end, with the transparent window, is the interconnection panel for the incoming 400 V cables.

THERMAL REQUIREMENTS

Design criteria

The thermal design was based on the assumption that the SSU is in operation continuously and that the batteries perform one full discharge/charge cycle per day. In order to make a worst-case calculation, it was further assumed that this cycle would be concentrated in one interval of discharge of one hour at 46 kW per battery, followed immediately by an interval of charging during 2 hours at 23 kW per battery. During the rest of the 24-hour period the system then remains grid-connected without absorbing or supplying a significant amount of power.

The mass of the concrete structure is more than 16 tonnes, resulting in a heat capacity of 4.5 kWh/K. In particular the sub-ground section of 50% provides the thermal buffer stabilizing the internal temperature, so that an active cooling system has to be rated only for the average thermal load over a 24-hour period.

The average thermal load of the SSU thus calculated is 2252 W. This is exclusive of the effect of solar irradiation during the day, however this should have a small effect on the interior, being absorbed by the concrete of the box. In order to remain on the safe side, the cooling system (air conditioner) was nevertheless rated for a heat load of 5000 Wth.

Active cooling

In order to save on the cost and losses of an active cooling system, the initial plan was to use outside air to cool the interior of the SSU, with a provision to switch to internal circulation whenever the internal temperature would fall below 10 ºC. However the use of outside air would result in considerable condensation on the inner walls of the SSU and was therefore abandoned, the risk of water accumulating on the floor of the SSU and condensation in the electronics being unacceptable.

Therefore it was decided to design the SSU as a closed box and to remove any excess heat from the interior using an air conditioning unit. This unit not only cools the inside air but also dehumidifies it, so that any remaining condensate is removed from the SSU. The air conditioner has a setpoint of 25 ºC.

Internal circulation

Most of the heat load in the SSU is produced in the batteries and in the inverters. In a battery the losses are distributed evenly over the whole battery system, so that the temperature rise is quite uniform. Moreover, the battery cells themselves have sufficient heat capacity to absorb the dissipation of the specified cycle and the losses can be transferred gradually to the air inside the SSU. Forced cooling of the battery systems was not deemed necessary for the specified thermal cycle.

In an inverter the losses occur very localized, in particular in the IGBTs. This heat must be removed immediately by forced ventilation. The ventilation systems of the inverters are used also to mix the air inside the SSU. In this way hot spots in the SSU are avoided and the moving air has an improved heat exchange with the concrete walls.

THERMAL TESTING

Tests in FPG Lab

The Smart Storage system was tested extensively in the period 26 March – 10 April 2012 at DNV KEMA's Flexible Power Grid Laboratory (FPG Lab) in Arnhem. This laboratory offers the unique possibility to test this grid-connected system to its fully rated power of 400 kVA in all modes of operation, both charging and discharging, at an arbitrary frequency, level of reactive power, and harmonics. As a part of this test sequence, a full day of thermal cycling has been performed. During this test the concrete box was located fully above ground on the laboratory floor.

The thermal test was not intended to verify the calculated performance as presented before, but to stress the system to its limits and to verify that the individual subsystems and components can cope with such stresses and are appropriately switched off by their thermal protections. Furthermore the test was used to verify internal temperature rises in the inverters as part of a design review.
For that reason a repetitive thermal cycle was defined corresponding to the maximum currents specified for the inverter or the battery:

- Discharge with 100 kW per battery until minimum State of Charge (SOC) is attained;
- Charge with 30 kW per battery until 90% SOC is attained.

The duration of one cycle is thus approx. 30 minutes discharging and 1 hour, 45 minutes charging. The cycles are repeated in a continuous sequence.

Figure 3. Two inverter cubicles as seen through a side door of the SSU.

Figure 4. Interior of the SSU as seen through the main access door.

Figure 5. The SSU after installation on site in Etten-Leur.

A typical graph of the results is shown in **Figure 6**. The dark blue curve shows the air inlet temperature of one of the inverters and the brown curve the outlet air temperature of the same inverter.

The test starts at 08:48 at an SOC of 88%. Immediately a steep increase of the ceiling air temperature is caused by the output air of the inverters. The dip at 8:57 is caused by the inverter ventilators switching to a higher speed. At 9:13 the system is switched from discharging to charging, which occurs at a much lower power level. During the next discharging interval some of the inverters are switched off by an internal thermal protection. After a few minutes they restart automatically, resulting in an overall longer discharge period and less temperature difference between charging and discharging.

It can be observed that the ceiling temperature follows more or less the inverter outlet temperature until 13:30. At that point the SSU was opened for a short inspection, during which the air outlet direction of the air conditioner was modified. This resulted in improved internal circulation.

At approx. 14:30 the test is stopped because the overtemperature protections acted too often. The air conditioning unit is unable to maintain the internal temperature, which is obvious in view of the total internal dissipation being higher than 5000 W even during charging. Once the system has been stopped, the inside air temperature at 1.5 m height (red trace) drops quickly and remains hovering around its setpoint temperature 25 ºC.

After the tests several points of improvement were identified:

- Place the internal air heat exchanger in the top centre of the SSU to improve its effectiveness.
- Improve the circulation of outside air through the condensor of the air conditioner.
- Mount longer air inlet channels on the inverters to avoid contamination of the inlet air by hot outlet air, and to improve the air circulation in the SSU.

These improvements were implemented during the months following the test period. After implementation the FPG lab was not available for this project anymore. The SSU was modified in a workshop which did not have a suitably rated power supply connection for thermal tests. These were therefore made after commissioning of the system on its final location.

Tests on final location

In the fall of 2012 the system is installed and commissioned on its destined location in the village of Etten-Leur. Once put in place (see **Figure 5**), the box has a very small environmental impact. In December the SSU is available for the thermal test, which is performed on 6 December. Due to a technical problem with one of the battery units, the test is performed with three out of four batteries and inverters.
On the 6th of December the outside temperature starts around 3 ºC in the morning and rises to approx. 6 ºC at noon. Prior to the tests the system has been running at low load (< 10 kW/battery) for more than 24 hours. The internal temperature of the concrete wall inside the SSU when starting is 12 ºC and the inside air temperature at 1.5 m above floor level is 17 ºC.

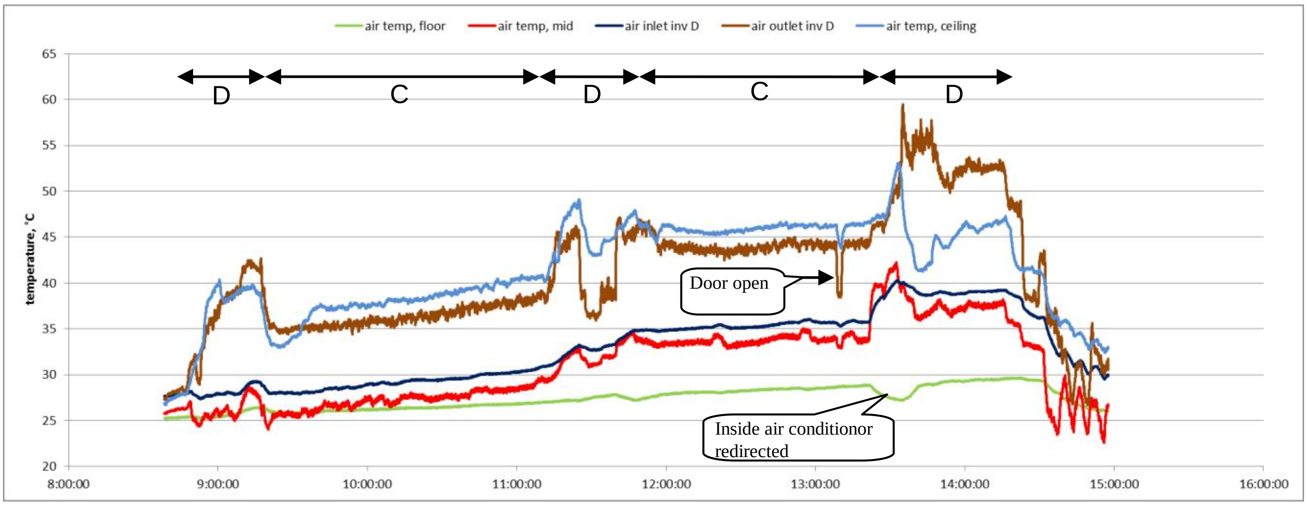

Figure 6. Temperatures measured in the SSU during the thermal test on 5 April 2012. Periods of charging are indicated by "C" and periods of discharging by "D".

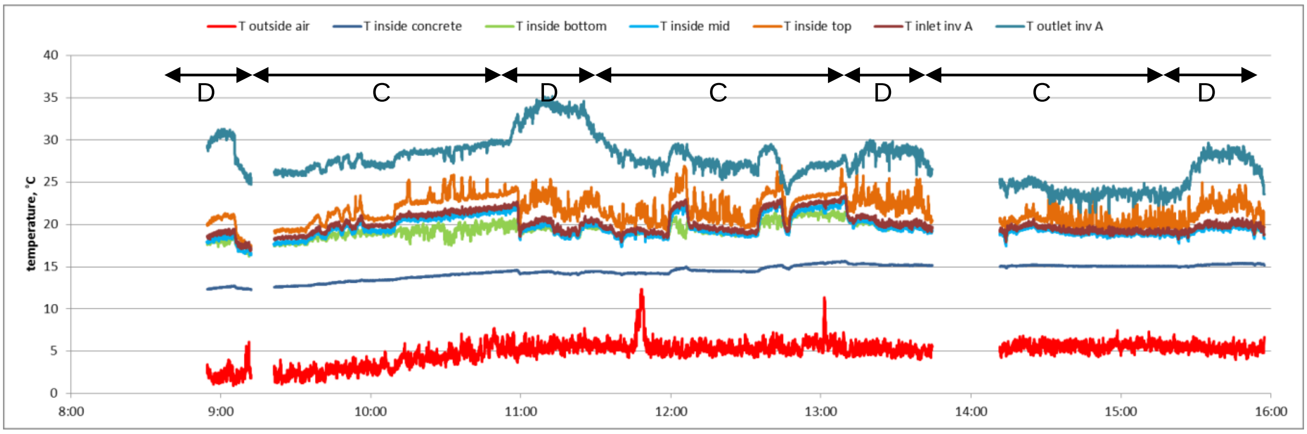

Figure 7. Temperatures measured in the SSU during the thermal test on 6 December 2012. Periods of charging are indicated by "C" and periods of discharging by "D". Missing parts of the temperature recordings were caused by irregularities with the datalogger settings.

The test starts at 08:25 and ends at 15:55. This period covers four discharge and three charge intervals as indicated in **Figure 7**. One of the inverters is regularly switched off caused by a spurious transducer failure, so that this inverter has executed approximately one half cycle less than the other two, and has partially operated out of synchronism with the other two. It is concluded that the maximum temperature difference between the inside air and the concrete wall is approximately 10 °C, and that the air temperature close to the ceiling is much lower than the inverter outlet temperature because of the improved internal circulation. Although fewer inverters are in operation, the overall improvement compared with the tests on 5 April is obvious.

CONCLUSION

The internal air circulation of the integrated storage system described in this paper has been optimised. It was demonstrated that the losses during a high power discharge/charge cycle can be effectively absorbed by the thermal inertia of the concrete box. By placing the system partially underground, it has a very modest environmental impact while the thermal stabilization of the earth adds to the temperature stability of the system. This may be particularly attractive in countries having high temperature differences between day and night.

ACKNOWLEDGMENT

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REFERENCE

[1] R.J.W. de Groot, F. van Overbeeke, A.J.M. Schouwenaar, J.G. Slootweg, 2013, "Smart Storage in the Enexis LV Distribution Grid", this conference, paper 0583.