CONTROL STRATEGIES OF NETWORK CONNECTED ELECTRICITY STORAGE ELEMENTS – CASE SIMULATIONS

Antti Supponen, Sami Repo

Department of Electrical Engineering

Tampere University of Technology

Tampere, Finland

antti.supponen@tut.fi, sami.repo@tut.fi

SUMMARY

This paper presents case simulations of distributed photovoltaic (PV) generation of household customers with small grid connected energy storage. We examine a case of one actual Finnish LV network where we assume that customers have acquired a grid connected PV generators with energy storage elements. First, the effect of the various control strategies on customer load time series are simulated and finally, the network impacts compared to original loads are examined.

KEYWORDS

Electricity storage, Distributed generation, Electricity storage optimization

1. INTRODUCTION

The electricity generation of small scale PV systems is intermittent. In Finland, the peak generation of PV and peak of consumer demand do not meet. Generation peak occurs typically during midday at summertime and loading peak occurs night time at winter. It would be beneficial if customer loads could be shifted from high loading times to high generation times. Unfortunately, the seasonal variation of load and generation is not easily compensated for. Still variations within a day can be shifted with sophisticated energy storage elements or demand response functionalities. The demand response functionalities in the scope of this study could be for example electric space heating loads shifted at desired hours [1]. The energy storage element can be for example a large enough lead-acid battery or lithium ion battery pack [2],although these systems may be economically unprofitable.

In this paper we examine various control strategies for grid connected energy storage element when accompanied with PV generation for household customers. The objective is to find and define different modes of control for grid connected storage elements, define their optimization and simulate storage behavior in real LV network.

2. SIMULATION SETUP

In the case simulations an actual Finnish LV network is taken under examination. The network consists of 51 LV-connection points, most of which are detached houses. In the simulation we consider a situation that every detached house in the network would have acquired a grid connected PV system with a storage element. The composition of the simulated network is depicted in figure 1. Even though the figure shows just simplified version of the network, the model used in simulation contains all network components.

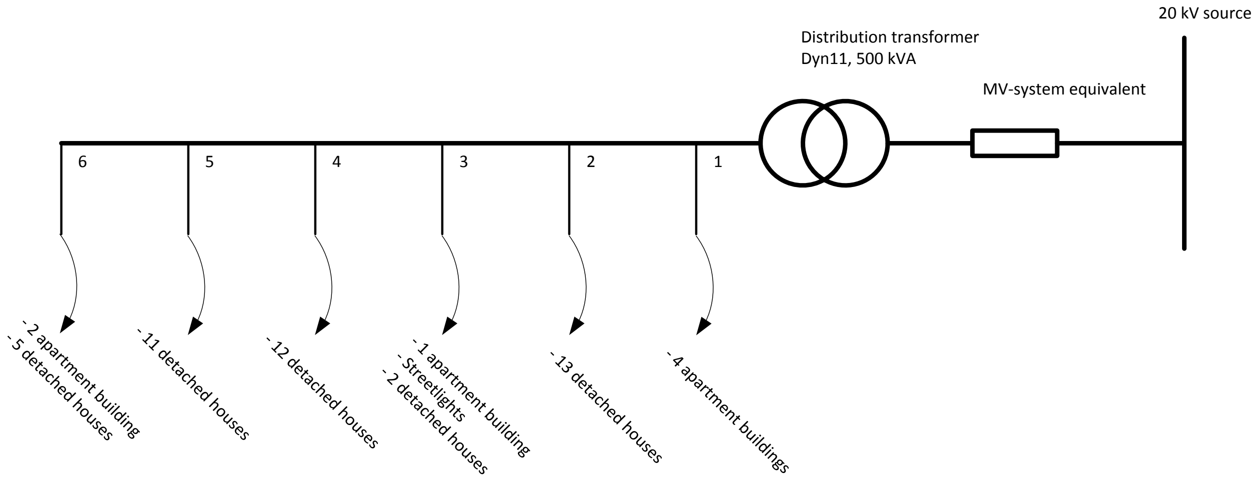

Figure 1 : Simplified diagram of simulated network

The customer loads in the simulation are based on hourly automatic meter reading (AMR) measurements from the period of 1.11.2011 to 31.10.2012. The nominal power of the PV generator is assumed to be 5 kW for each customer and the nominal capacity of the storage element 5 kWh. The structure of customer connection point is depicted in figure 2. We also assume that the customers having a PV generator and storage element also have sophisticated energy management system which is capable of either scheduling of the charging and discharging cycles of the storage element, or performing accurate demand response actions (load shifts) in order to emulate storage-like behavior.

Also we assume that the consumer (or the automation system) has an accurate method for forecasting day-ahead consumption and production. With these assumptions the optimization problem reduces into finding the proper time series for storage output power.

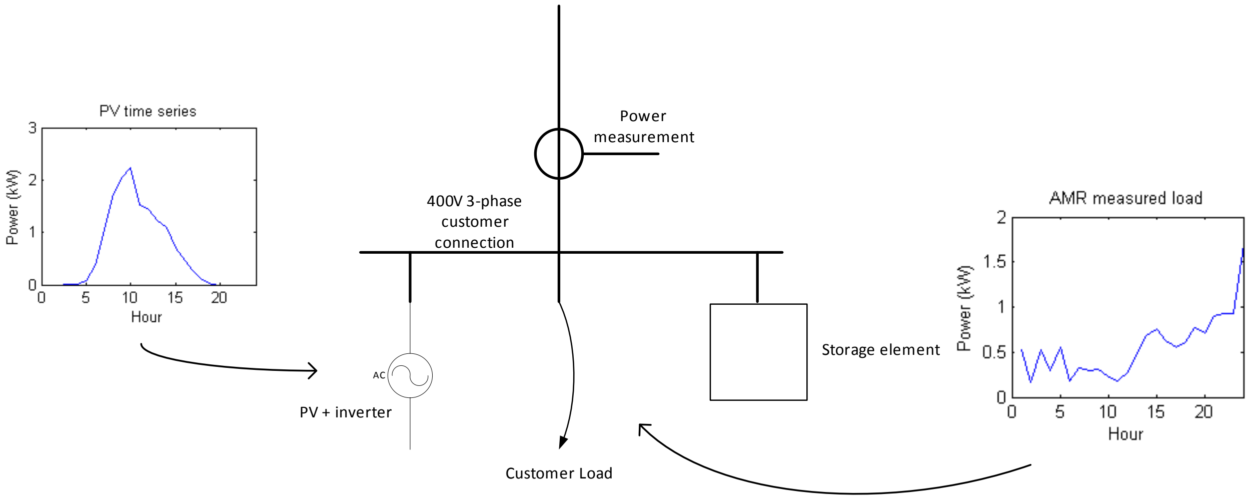

Figure 2 : Customer connection in simulation

3. EXAMINED CONTROL STRATEGIES

3.1 Case 1 – Local load peak shave (LLPS)

When a customer has a large enough grid-connected PV array there are hours in day when power flows from customer connection to the LV grid. At these hours PV generates more power than customer consumes (when averaged over hour). Customer receives some compensation from the energy injected to network but the compensation is generally smaller than the price of consumed energy. Therefore it would be beneficial from customer's point of view to use excess energy locally at connection point.

In simulation case 1 we assume that customer has some incentive to attempt minimization of load peak, which would be valuable service from distribution system operators' (DSO) point of view [3]. Essentially, in this simulation customer attempts to charge the storage element during generation hours, and then utilize the stored energy during hours of peak load. typically occurring at evening or nighttime.

3.2 Case 2 – Price driven control utilizing excess production (PDC-EP)

Simulation case 1 examines a control strategy which would be beneficial principally only to the DSO. In case 2 we examine a control strategy which takes customers' point of view. The idea of the price driven control is that we assume that the customer's electricity is priced hourly. This means meaning that the electricity price will vary during day. Now it is beneficial for the customer to consume electricity at low priced hours and not to consume at high priced hours. Still, in case 3 we assume that we do not want to use electricity from the grid in order to charge the storage element. Only locally generated energy is used in charging, and discharging is done on high priced hours.

Price in the simulation is assumed to be given day-ahead basis. The hourly prices for next day are known previous day. Price of electricity in the simulation is elspot price for Finland during the simulation period.

3.3 Case 3 – Price driven control without limits (PDC-NL)

Case 3 examines similar control strategy as in case 2. Only difference is that we allow charging of the storage element even if there is no local production. This would mean that customer will maximize utilization of storage element in order to minimize his/her electricity cost. In this case we allow charging of the element during consumption and even discharging during generation hours.

4. OPTIMIZATION PROBLEMS OF THE SIMULATION CASES

The core of this simulation study is to optimize the charging and discharging cycles of the storage element. In different simulation cases the goal of the simulation varies from either peak load minimization of the connection point to cost minimization of electricity consumption.

The optimization has to consider the functioning of the storage element. Naturally, the storage cannot discharge before some energy has been charged into the element, or the storage cannot charge over specified capacity. Additionally the nominal power of the storage element may limit the magnitude of charging and discharging. The transient constraints of storage usage are not considered as the resolution (step length) of the simulation is relatively long. In following chapters the objective functions and optimization constraints are discussed in detail.

In this study we examine a period of one year which is divided into 24 hour segments. The optimization is done independently for each 24 hour segment in the year. The optimizations for these simulations were executed with Optimization Toolbox of Matlab (fmincon).

4.1 Case 1

The optimization problem in local load peak shave is given by minimization of f_{target} given by (1), which is the sum of squares of the connection point's hourly power time series. The vector **B** represents the mean hourly powers of the storage element during the optimization period. Negative values in **B** mean discharging, and positive values means charging of the storage. n is the number of optimizable variables (in this case hours in the optimization period). The vector **P** represents the mean hourly powers of the connection point (Load + PV) without the battery during the optimization period. Negative value in **P** means the power is being injected to the network and positive means that power is being drawn. D is the desired load level, which in these optimizations is set to be 0 (scalar).

$$f_{target}(\mathbf{B},\mathbf{P},\mathrm{C}) = \sum_{k=1}^{n}\left(\mathrm{D} - (\mathrm{P_k} - \mathrm{B_k})\right)^2 \tag{1}$$

4.1.1 The constraints given by battery capacity

The capacity of the storage element sets certain limits to its charged and discharged hourly energies. When we assume that charging and discharging losses and the idle state losses of the storage element are negligible, the capacity constraint can be given in following for: The sum of hourly energies cannot be more than the capacity in the storage at the beginning of the simulation at any hour. Also the inverse sum of hourly energies cannot exceed the charged capacity at any hour.

The first constraint makes sure that the storage element isn't overcharged during simulation and the latter ensures that there is enough charged capacity when the storage is being discharged. (2) gives the capacity dependent limits in matrix form.

$$\begin{bmatrix} 1 & & & & \\ -1 & & & & \\ 1 & 1 & & & \\ -1 & -1 & & & \\ \vdots & \vdots & \vdots & \ddots & \\ 1 & 1 & 1 & \dots & 1 \\ -1 & -1 & -1 & \dots & -1 \end{bmatrix}_{(2n\ x\ n)} \mathbf{B} \le \begin{bmatrix} \mathrm{C_0} \\ \mathrm{C_{max}} - \mathrm{C_0} \\ \mathrm{C_0} \\ \mathrm{C_{max}} - \mathrm{C_0} \\ \vdots \\ \mathrm{C_0} \\ \mathrm{C_{max}} - \mathrm{C_0} \end{bmatrix}_{(2n\ x\ 1)} \tag{2}$$

In this C_0 is the initial capacity of the battery before optimization and C_{max} is the maximum energy capacity of the storage element.

4.1.2 Constraint from remaining capacity

If the optimization is done with constraints above, the storage element will be empty after optimization period if daily generation is less than daily consumption. Sometimes it is beneficial to “save” some energy for the next optimization period. This adds one more constraint to optimization given by (3). C_r is minimum remaining capacity requirement defined.

The usefulness for this constraint is somewhat questionable, as the need to “save” capacity is hard to estimate. The problem of how much capacity should be kept in reserve from one period to another is not considered in this study and thus we have assumed that $C_r = 0$ for all simulation cases.

$$[1 \quad 1 \quad 1 \quad \cdots \quad 1]\,\mathbf{B} \le [\mathrm{C}_0 - \mathrm{C}_\mathrm{r}] \tag{3}$$

4.1.3 Limits

The limit vectors ($\mathbf{L}_{max}$ and $\mathbf{L}_{min}$) define the maximum and minimum values of every hourly power of the storage element during optimization period (i.e. the values of **B**). In this simulation case the storage element should only charge when there is local generation. Also the storage element shouldn’t charge more than the local generation is able to provide at given hour. The discharge is limited to hours of positive demand, and to nominal power of the storage element.

$$\mathrm{L}_{\mathrm{min,k}} = \begin{cases} \mathrm{P_k} & ,if \quad -\mathrm{P_{battery,nominal}} < \mathrm{P_k} < 0 \\ -\mathrm{P_{battery,nominal}} & ,if \quad \mathrm{P_k} < -\mathrm{P_{battery,nominal}} \\ 0 & ,if \quad 0 < \mathrm{P_k} \end{cases} \tag{4}$$

$$\mathrm{L}_{\mathrm{max,k}} = \begin{cases} \mathrm{P_{battery,nominal}} & ,if \quad 0 < \mathrm{P_k} \\ 0 & ,if \quad 0 > \mathrm{P_k} \end{cases} \tag{5}$$

4.2 Case 2

In the second simulation case the objective was to minimize electricity cost during the simulation period. The objective function for the optimization is again minimization of f_{target} which is now given by (6). The c_{load} and c_{gen} are hourly prices of consumed and generated energy, respectively. P_{Net} is the sum real power measured at customer connection point.

$$f_{target}(\mathbf{B},\mathbf{P}) = \sum_{\mathrm{k}=1}^{\mathrm{n}} \left(f_{price}(\mathrm{P_k} - \mathrm{B_k})\right)$$
$$f_{price}(\mathrm{P_{Net}}) = \begin{cases} \mathrm{P_{Net}} \times \mathrm{c_{gen}} & \mathrm{,if} \quad \mathrm{x} < 0 \\ \mathrm{P_{Net}} \times \mathrm{c_{load}} & \mathrm{,if} \quad \mathrm{x} \ge 0 \end{cases} \tag{6}$$

Otherwise the constraints concerning the charging and discharging cycles are same as in case 1. The physical characteristic of the storage element remain unchanged, thus constrains given by (2) remain. And as the objective is still to utilize only the excess production of the PV generation, the constraints given by (4) and (5) still apply.

4.3 Case 3

In the final simulation case the objective is to minimize electricity cost during the simulation period, as in case 2. Thus the objective function is same (6). Now the charging and discharging is only limited by the nominal power of the storage element (7). Otherwise constraints to simulation are same as before (3).

$$L_{min,k} = -P_{battery,nominal} \quad (7)$$
$$L_{max,k} = P_{battery,nominal}$$

5. NETWORK IMPACTS

In figure 3 the effects of optimization on the net power of one customer are depicted. The figure shows considerable flattening of the consumption profile when peak shaving control is applied (1st image from top). Whereas purely price based control of the storage seems to increase demand peaks for the customer (last image from top). This is to be expected as it is most beneficial for the customers to maximize the utilization ratio of the storage element and shift as much energy from expensive hours to cheap ones as possible. The picture between former represent the combination of the other two cases, for most of the time it is beneficial not to charge the storage during hours of surplus generation as the energy is more expensive during those hours. The vertical dashed lines represent the optimization segments.

In figure 4 the cumulative energy costs for one customer for the simulation period is shown. The costs do not include taxes or energy retailer's commission, only the cumulative cost calculated from hourly energy prices. It can be seen that from economical point of view the customer should maximize the utilization of the storage. This however can cause severe problems in the network if majority of customer would do this, as is shown later on.

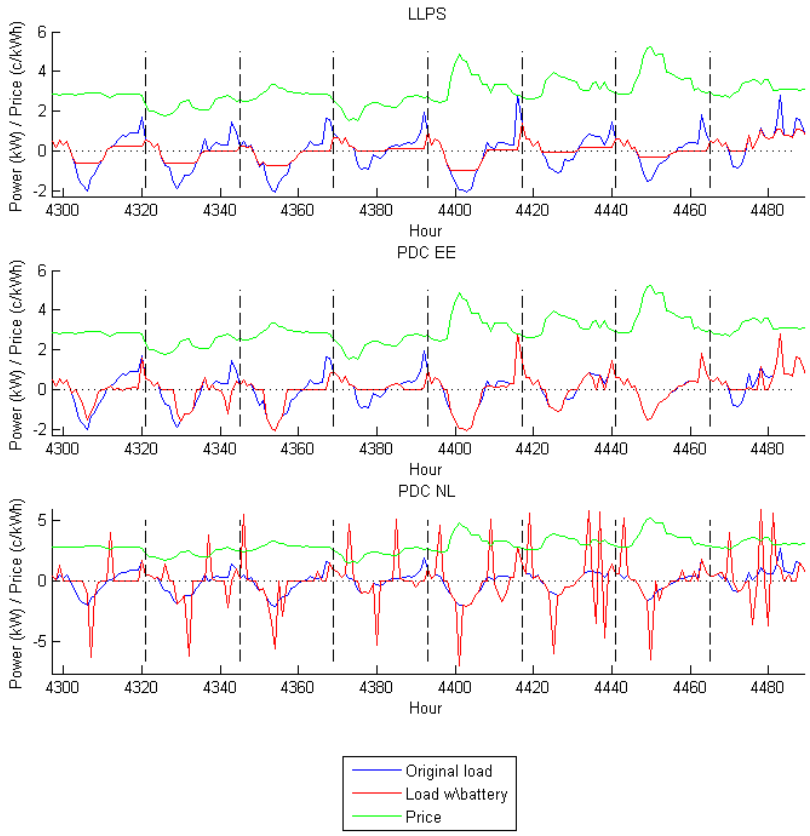

Figure 3: The effects of storage usage on customer net power during 28.4. – 5.5.

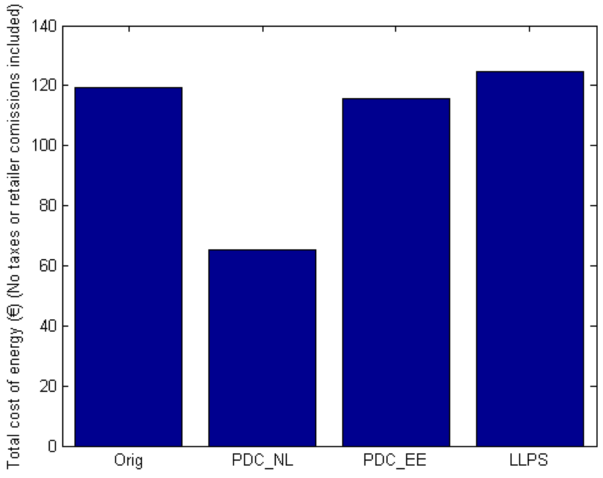

Figure 4 : Changes in energy costs for one customer.

After the optimization task a power flow simulation for every hour of the year is run. Power flows are calculated using OpenDSS [4] simulation software. The effect of storage use on peak demand and generation in the whole LV network is shown on table 1. It can be seen that peak shaving and utilization of excess energy in cost minimization (Cases LLPS and PDC EE) do not effect on the peak demand of the network. This is reasonable as the demand peak of the year typically takes place during wintertime. At winter there is essentially no surplus generation for the peak shaving or cost minimization.

However on the peak generation there is a considerable effect. The peak shaving naturally decreases the generation peaks as the objective function (1) values the charging of the storage at the hour of peak generation over any other hour. The excess energy cost minimization causes rise in the peak generation. This is because at some hour it is most beneficial to use the storage to feed the grid, for example when the hours of daily surplus generation is followed by really expensive hour. Then it is more beneficial to sell energy at the expensive hour than to use it to compensate for own usage afterwards.

The cost minimization with full storage utilization will cause the peak demand and generation to rise in the network. This is because of multiple consumers attempting to minimize their electricity cost by shifting loads into same cheap hours, and at the same time attempting to feed energy to grid when electricity is expensive. The cumulative effect of this will cause significant rise on peak generation and demand.

Table I : Peak demand and generation in different simulation cases

Case	Original	LLPS	PDC EE	PDC NL
Peak demand (kW)	473	473	473	574
Peak generation (kW)	72	37	142	283

In the figure 5 network voltages and currents are shown during the same period as depicted in figure 3. The figure shows that cases 1 and 2 do not really cause problems from networks point of view. All voltages and line currents are inside acceptable ranges. In the case 1 the aim of the control is to minimize demand and generation peaks which aim to decrease voltage variation in the network, and as can be seen from the figure the voltage drops at high demand hours have dropped. It is clear though that case 3 will cause serious voltage drops and possibly overloads in network components.

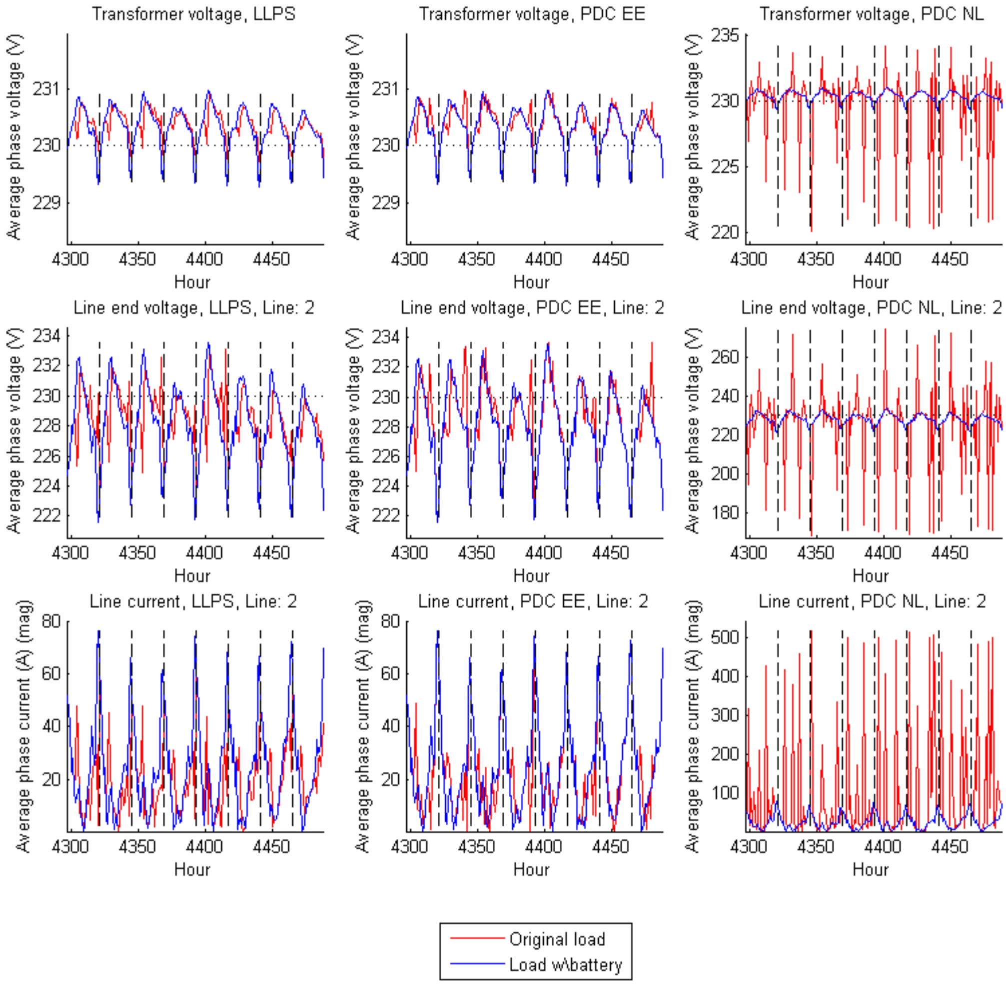

Figure 5 : Voltages at transformer, voltages the end of line 2 and the currents of line 2 in different simulations

6. CONCLUSION

In this paper a method for storage element optimization is shown and applied. The optimization problems and their constraints are examined and explained for three different optimization goals. The storage behaviour was then simulated with a model of real LV network and with consumption measurements from actual customers.

The network impact evaluation suggests that customer driven control may cause problems for DSO, as the DSO would want to keep the demand peaks as low as possible. Instead the customer would want to maximize his/her savings by shifting as much demand on the cheap hours as possible, which would inevitably lead to higher demand peaks. The conflict of interest between customer optimizations and DSO's interests is thus clearly visible. The model of customer behaviour can be used to evaluate proper dynamic grid tariff structures in order to give customer a real monetary incentive to limit demand peaks.

7. ACKNOWLEDGEMENT

The research leading to these results has received funding from the European Union's seventh framework program (IDE4L project FP7-SMARTCITIES-2013 under grant agreement 608860) and the Smart Grids and Energy Markets (SGEM) program.

BIBLIOGRAPHY

[1] Mubbashir A., The Role of Electric Space Heating in Demand Response, M.Sc. Thesis, 2012, Aalto University, Department of Electrical Engineering, 72 p.

[2] Divya K.C., Østergaard J., Battery energy storage technology for power systems—An overview, Electric Power Systems Research, Volume 79, Issue 4, April 2009, Pages 511–520

[3] Delille G, Francois B., Malarnge G., Fraisse J., ENERGY STORAGE SYSTEMS IN DISTRIBUTION GRIDS: NEW ASSETS TO UPGRADE DISTRIBUTION NETWORKS ABILITIES, CIRED 20th International Conference on Electricity Distribution, Prague, 8-11 June 2009 Paper 0493

[4] OpenDSS homepage, http://smartgrid.epri.com/SimulationTool.aspxs, 2.6.2014