INTEGRATION OF A THERMAL ENERGY STORAGE AS A DYNAMIC LOAD INTO THE ELECTRICAL GRID OF AN URBAN QUARTER

Tim PLÖßER
TU Darmstadt - Germany
tp@e5.tu-darmstadt.de

Dominik MAIHÖFNER
TU Darmstadt - Germany
dm@e5.tu-darmstadt.de

Jutta HANSON
TU Darmstadt - Germany
jh@e5.tu-darmstadt.de

ABSTRACT

This paper focuses on the implementation of a thermal energy storage as a dynamic load in the electrical grid of an urban quarter. First, the electrical grid of the quarter and a use case for the thermal energy storage in the grid is presented. Then an approach to model the thermal energy storage together with a heat pump as a thermal generator is described. In this case the heat pump is directly connected to the busbar of a power supply unit. Based on an already existing thermal energy storage the necessary storage capacity is approximated. Furthermore, a control strategy is proposed to use the heat pump to decrease the transformer loading within the grid by producing thermal energy in times of high transformer loading and storing the produced thermal energy in the thermal energy storage. The proposed control strategy in conjunction with different storage sizes is used to simulate the transformer loading for a given network load based on real measurement data in order to evaluate the approach.

INTRODUCTION

The increasing share of renewable energy sources (RES) within the German electrical power supply structure leads to several new challenges for German power system operators. Currently it is possible to accommodate the volatility of RES by adapting the generation of conventional power plants. Given the fact that the German government pursues a share of RES on the total net generation up to 45 % until 2025 and up to 60 % until 2035 [1] this approach might no longer be economically feasible. One possible solution for this upcoming problem is a stronger interconnection between different energy sectors. Especially the coupling between the electrical grid and local heating grids is promising [2].

It is one of the aims of the project "EnEff:Stadt - Campus Lichtwiese" to showcase the possibility of stronger system interconnection based on real life infrastructure. Therefore, the project uses a campus of Technische Universität Darmstadt (Campus Lichtwiese) as an object of study. Due to the fact that the whole area of Campus Lichtwiese is owned and operated by the university there is an unique level of access to its information and energy infrastructure. This enables the interdisciplinary project team to create detailed models of the whole infrastructure which can be used to develop and test different concepts for a future design of the energy supply infrastructure.

One of the main aspects of the project is to create a stronger connection between the existing electrical and heat grid. As a first step, an integration of an existing thermal energy storage (TES) as a dynamic load into the existing electrical grid is discussed.

ENERGY GRIDS OF CAMPUS LICHTWIESE

As depicted in figure 2 the electrical grid of Campus Lichtwiese has two medium voltage levels: 20 kV and 6 kV. The 6-kV-level is the initial medium voltage level of Campus Lichtwiese, while the 20-kV-level is the voltage level of the upstream distribution grid operator.

In the long run, it is planned to replace the 6-kV-level entirely by an all 20-kV-grid. Currently the connection between both medium voltage levels is realized via two transformers and one identical spare transformer. The rated apparent power of each transformer is 3,15 MVA. The transformers are located at the power plant of Campus Lichtwiese which contains the main substation for both medium voltage levels. The loads of Campus Lichtwiese are mainly connected to the 6-kV-grid. During summer 2016 power flow through all low voltage transformers was measured in order to get total load of the campus without network losses of both medium voltage grids. The cumulative load based on these measurements is shown in figure 1. The load profile shows the time from Wednesday, June 15, 12:45 p.m. till Tuesday, June 21, 6:30 a.m.

As it can be seen the active power load of the grid fluctuates between 3 MW in the night and 4,5 MW during daytime.

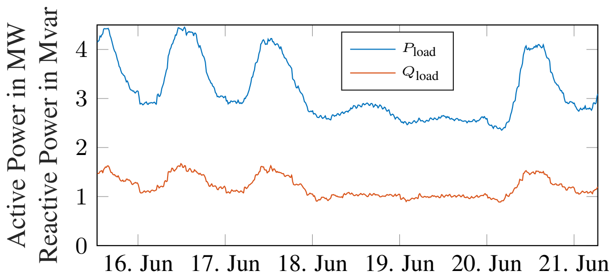

Fig. 1: Total electrical load of Campus Lichtwiese in summer 2016 measured at LV-side of MV-/LV-transformers

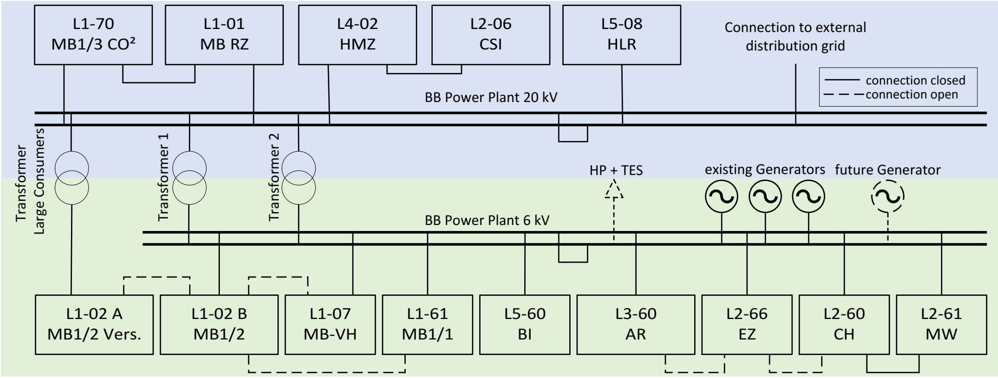

Fig. 2: Overview of the electrical grid structure of Campus Lichtwiese including both medium voltage levels

Besides the electrical grid there also exists a district heating grid on Campus Lichtwiese which is used to supply all buildings with the required heat. The comparison between heat and electrical energy consumption of the whole university for the year 2014 is shown in figure 3. According to network operator Campus Lichtwiese consumes roughly half of the depicted amount. As it can be seen the electrical consumption is relatively steady at around 5 GWh per month during the whole year while the heat demand fluctuates significantly between 1,5 GWh in August and 16 GWh in February. Because of the steady demand of electrical energy it is assumed that the load profile shown in figure 1 is valid throughout the whole year.

The power generation at Campus Lichtwiese contains three existing combined heat and power plants (CHP) with a rated apparent power of 2,4 MVA each, which are directly connected to the 6-kV-level. The CHPs are used to generate electricity as well as heat for the district heating grid. Currently, the generators are heat-led and power factor controlled ($\cos(\varphi) = 0,98$). Based on the shown heat consumption this leads to very different utilisation of the CHPs throughout the year. During summer only one of the three CHPs is running to supply the necessary heat. During winter all three CHPs are running constantly. As the thermal power of the CHPs is not sufficient to provide the necessary heat for the campus, six additional gas fired hot water boilers with an individual thermal power of 10 MW are used in times of peak demand. As shown in figure 2, it is planned to install another identical CHP. This will increase the total generation to around 8 MW ($P_{th} \approx P_{el}$). During winter it can be expected, that all four CHPs will run full time to provide the necessary heat. During fall it is valid to assume that generators can provide the necessary heat during night times and the hot water boilers are only needed during daytime.

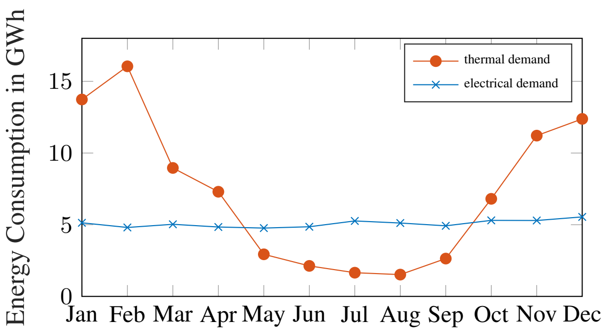

Fig. 3: Thermal and electrical energy consumption for Campus Lichtwiese during the year 2014

Currently, one TES exists which is used as a buffer storage for the CHPs. For the purpose of this paper the existing storage and its parameters are used as reference to simulate the connection of additional heat pumps (HP). Data of the existing TES is given in table 1.

Based on the load profile shown in figure 1 and the increased electrical generation the loading of the MV-/MV-transformers will also change. The change can be seen in figure 4, which shows the simulated transformer loading for three and four generators based on the load profile of figure 1 for one week during October, which means that all generators are running full time. As it can be seen the loading increases from around 40 % during the day and around 55 % during the night to 70 % and 90 %, respectively.

Because of the decreasing load in the 6-kV-grid it can be assumed that the loading of the transformers will increase even further in the future. Thus, there is a need to manage the increase in transformer loading in order to guarantee a save and stable operation of Campus Lichtwiese. One possibility to lower the loading of the transformers during the

Table 1: Parameters of the existing TES

Parameter	Value
Volume	125 m^3
maximum temperature	95 °C
minimum temperature	60 °C
Heat capacity C_{TES}	145 kW K^{-1}
static losses U_{TES}	0,028 kW K^{-1}
energy content	5,075 MWh

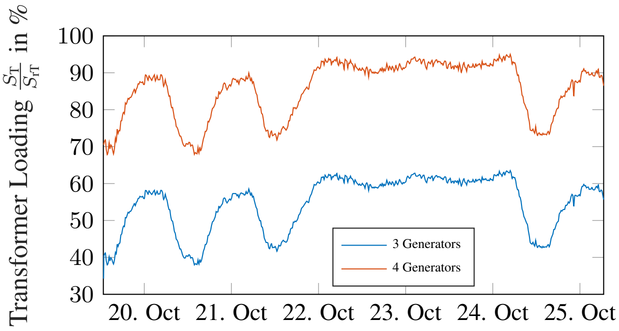

Fig. 4: Impact of additional generator on the transformer loading

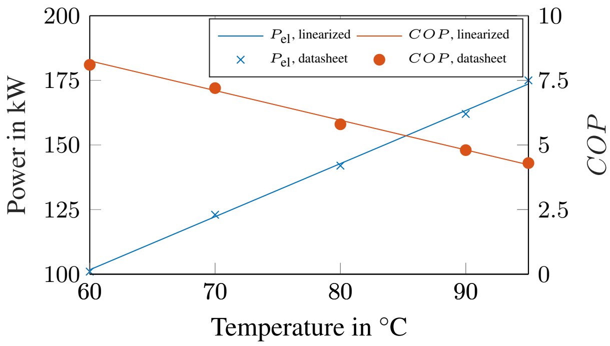

Fig. 5: Linearized values for electrical power and coefficient of performance (COP) for the heat pump (HP) based on [4]

night is to use the surplus electrical generation of the CHPs to generate thermal energy with heat pumps and store the thermal energy for the daytime. With this method loading of transformers during night can be decreased and the generated heat can be used to reduce the usage of gas fired boilers, also reducing the overall CO_2-emissions.

MODELLING APPROACH

Based on the measured data of the low voltage loads of Campus Lichtwiese a series of load-flow calculations is conducted for the period of time shown in figure 4. Load-flow calculations are executed with the MATLAB package MATPOWER [3]. After each time step the state of charge (SOC) of the TES is calculated and used to determine the power consumption of the HP which is used to couple the TES with the electrical grid. Grid, HP, TES and Controller modeling is described in the following sub sections.

Electrical Grid

The modelling of the electrical grid is done according to information provided by the network operator. The loads within the grid are placed on the low voltage side of each MV-/LV-transformer and are based on the measured data. The electrical side of the HP is modelled as a load directly connected to the 6-kV-level busbar of the CHPs, see figure 2.

Control

The operation of the HP is based on the SOC of the TES and the loading of the transformers. If the loading of the transformers exceeds 85 %, the HP is activated and delivers thermal power based on the current temperature of the TES. The HP is shut down, if the SOC reaches 100 % or if the loading of the transformers drops below 79 % while the HP is still running. If the HP is shut down because of the SOC, then the HP will be kept out of operation until the SOC reaches 80 % again.
To reduce total CO_2-emissions the stored thermal energy is released when the gas fueled boilers would be needed. In the simulation this is the case between 9 a.m. and 7 p.m. during weekdays. Because there is no detailed information about heat demand during the day, it is assumed that between 9 a.m. and 7 p.m. one of the six hot water boilers is needed to supplement the CHPs. This assumption is based on the information provided by the district heat grid operator. Accordingly, up to 120 MWh of thermal energy can be replaced by the TES during the day. For simplification it is assumed that the TES discharges a constant amount of thermal energy during this time frame. The released thermal power is based on the size of the TES.

Heat Pump

In order to be used within the district heating grid, the temperature within the TES must reach the flow temperature (95 °C). The return flow of the district heating grid is supposed to be the source for the HP. The average temperature of the return flow is 55 °C.

Based on the given requirements and based on an analysis of the currently available industrial high temperature heat pumps the model *IWHS 640 ER3* from Ochsner Energie Technik has been chosen. The nominal thermal power of one device is 640 kW and electrical power ranges from 125 kW to 175 kW based on the temperature of the heat sink [4]. Because the electrical power consumption of one single HP is too small compared to the nominal power of the transformers two of the specified HPs are used in parallel in order to provide the necessary power consumption of up to 350 kW.

In general, the relationship between the electrical power consumption of a HP and the corresponding thermal power production is given by the coefficient of performance (COP) [2]:

$$P_{th} = COP \cdot P_{el}. \quad (1)$$

The COP as well as P_{el} for a single HP is depending on the temperature of the temperature sink of the HP [4]. In this case the TES is the heat sink of the HP, this means that both values vary throughout the simulation. The data sheet provides data for fixed temperature points which are shown in figure 5. For the simulation it is necessary to know the values of COP and P_{el} for each temperature point. Therefore linear regression is used to calculate the values for each temperature point:

$$P_{\text{el,lin}} = 2{,}05\,\text{kW}\,°\text{C}^{-1} \cdot T_{\text{TES}} - 21{,}54\,\text{kW}, \tag{2}$$

$$COP_{\text{lin}} = -0{,}11\,°\text{C}^{-1} \cdot T_{\text{TES}} + 15.15. \tag{3}$$

Based on the initial temperature of the TES (2) and (3) are used in conjunction with (1) to calculate the relevant parameters of the HP for each load-flow calculation. The nominal power factor of the HP is 0,85 [4].

Thermal Energy Storage

Based on figure 4 it is possible to determine two different storage size requirements for the TES. First, it can be seen that during the week the TES must be able to store energy for up to 12 hours for the night. If it is also desired to decrease the loading of the transformers for the entire weekend, then the TES must be able to store energy equivalent to about 60 hours of HP operation. Because the temperature of the TES changes based on the stored energy, the thermal power of the HP also changes. In order to calculate the necessary storage capacity of the TES the median temperature (72,5 °C) is used to calculate the thermal energy. For the 12 hour time period 20,6 MWh are calculated, which means that the TES needs to be 4 times bigger than the existing TES. For the 60 hour time period during the weekend 103,2 MWh are generated which means that the storage needs to be 20 times bigger than the existing TES. The relevant parameters of table 1 are multiplied correspondingly.

The modelling of the used TES is based on [5]. The TES is assumed to be ideally mixed. This means that a homogeneous temperature throughout the whole storage is assumed. The stored energy within the TES is calculated as follows:

$$\begin{aligned} H_{\text{TES}}(n) =& H_{\text{TES}}(n-1) + \eta_{\text{ch}} \cdot H_{\text{HP}}(n) \\ &- \frac{H_{\text{Load}}(n)}{\eta_{\text{dis}}} - H_{\text{loss}}(n). \end{aligned} \tag{4}$$

The stored energy of the TES for each time step ($H_{\text{TES}}(n)$) depends on the stored energy of the TES for the previous time step ($H_{\text{TES}}(n-1)$), the amount of energy provided by the HP ($H_{\text{HP}}(n)$), the amount of energy which is extracted from the TES ($H_{\text{Load}}(n)$) and the losses of the TES ($H_{\text{loss}}(n)$). The amount of energy which is provided by the HP is calculated based on the thermal power for the current time step according to (1) and the amount of time which passes each discrete time step $\Delta t = 1\,\text{min}$. Thus, the amount of thermal energy which can be extracted from the existing TES is given by:

$$H_{\text{load}}(n) = P_{\text{th,TES}}(n) \cdot \Delta t. \tag{5}$$

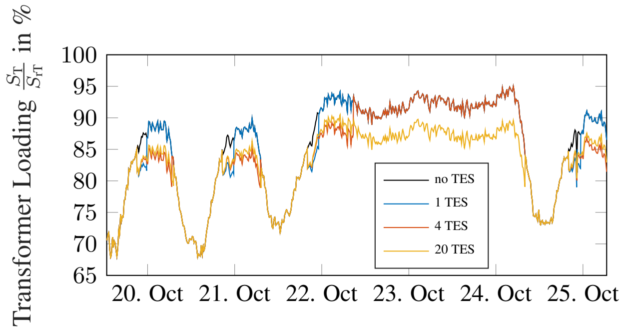

Fig. 6: Transformer loading for four different scenarios with four combined heat and power plants (CHPS)

The value of $P_{\text{th,TES}}$ depends on the size of TES and is set to 500 kW for the existing TES. The losses of TES are given by the following equation:

$$H_{\text{loss}}(n) = U_{\text{TES}} \cdot (T_{\text{TES}}(n) - T_{\text{amb}}(n)) \cdot \Delta t. \tag{6}$$

The values of the ambient temperature are based on measured data acquired on Campus Lichtwiese. The values η_{ch} and η_{dis} describe the charge and discharge efficiency. For simplification and in accordance with [5] both values are chosen to be 95 %.

Simulation Scenarios

Simulations are done for four different scenarios: the first scenario is the base scenario and utilizes no TES at all. This scenario is used to evaluate all following scenarios. Additionally, simulations are done for the existing TES (*1 TES*), a TES which is big enough to last for one night during the week (*4 TES*) and a TES which is dimensioned to last for a whole weekend (*20 TES*).

RESULTS

Figure 6 shows the transformer loading for the defined time period within all four scenarios. The amount of time in which the transformer loading can be reduced depends on the size of TES. It is not possible to reduce the transformer

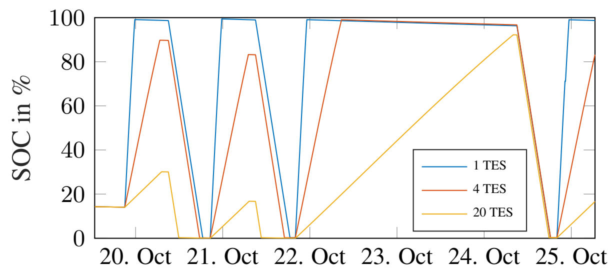

Fig. 7: State of charge of the thermal energy storage (TES) during the simulation

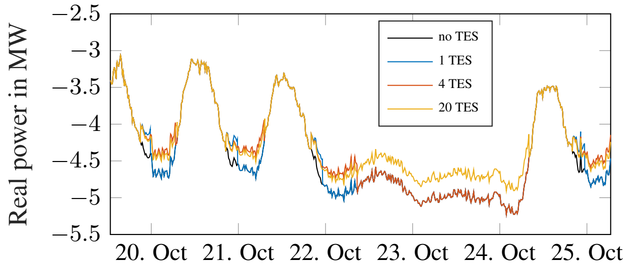

Fig. 8: Power exchange between the Campus Lichtwiese grid and the upstream distribution grid

loading for one whole night during the week, if the existing TES is used. With *4 TES* it is possible to reduce the transformer loading for a whole night without any issues, but it is not possible to reduce the loading for the whole weekend. In order to achieve this, *20 TES* are required.

Figure 7 shows the SOC for the different scenarios. The SOC of the existing TES reaches a SOC of 100 % after 3 hours and 44 minutes. This means, that it is not possible to use the existing TES to decrease the loading of the transformers for one whole night during the week. *4 TES* reach a maximum SOC of 90 % during week nights and a SOC of 100 % after 12 hours and 41 minutes during the weekend. *20 TES* reach a maximum SOC of 30 % during week nights. After the whole weekend the SOC reaches 92 %.

The power exchange between the upstream distribution grid and the grid of Campus Lichtwiese is shown in figure 8. It can be seen that during the time of HP operation the feedback of active power into the upstream distribution grid is reduced by the amount of power the HP needs to generate the thermal energy.

Figure 9 shows the amount of reduction in total network losses within the grid. The reduction is achieved by the fact that the power which is delivered by the CHPs is used directly on the 6-kV-level bus bar of the power plant. The reduction reaches values between 5 and 8,7 % depending on the power consumption of the HP. During the simulation time the following amounts of thermal energy were fed back into the district heating grid during the day: 13,39 MWh (*1 TES*), 49,08 MWh (*4 TES*) and 126,19 MWh (*20 TES*). Based on a conversion factor of 202 g/(kW h) [6] this leads to a total reduction of CO_2-emissions of 2704 kg, 9915 kg and 25 491 kg respectively.

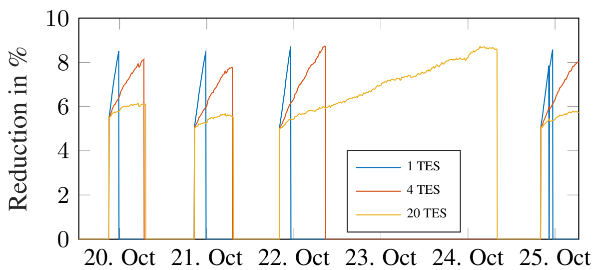

Fig. 9: Reduction of the network loss for different sized TES

CONCLUSION

In the course of this paper a modelling approach to implement a thermal energy storage as dynamic load within an electrical grid is introduced. The presented approach is used to include different sized TES into the electrical grid of Campus Lichtwiese. A control strategy coupling electrical and heating grid to reduce the loading of the transformers between the 6-kV-level and the 20-kV-level has been evaluated. It is shown that the currently existing TES is not sufficient for the planned control strategy and that the storage capacity of the TES has to be increased four times to achieve reduction of transformer loading for 12 hours. If the loading has to be decreased during a whole weekend the TES needs to be 20 times bigger. Sector coupling as shown in this paper proves as a fruitful option for both electrical and heating grid to promote the integration of RES and reduce overall CO_2-emissions.

ACKNOWLEDGEMENTS

This research has been funded by the German Federal Ministry of Economics and Technology (BMWi) in the project EnEff:Stadt - Campus Lichtwiese.

REFERENCES

[1] BMWi, 2011, *EEG-Novelle 2016 - Fortgeschriebenes Eckpunktpapier zum Vorschlag des BMWi für das neue EEG*, BMWi, Berlin, Germany, 2-3.

[2] Nabe et al., 2011, *Potenzialen der Wärmepumpe zum Lastmanagement im Strommarkt und zur Netzintegration erneuerbarer Energien*, BMWi Vorhaben Nr. 50/10, Ecofys Germany GmbH, Prognos AG.

[3] R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, 2011, "MATPOWER: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education", *IEEE Transactions on Power Systems*, vol. 26, no.1, 12-19.

[4] Ochsner Energie Technik, 2014, *IWHS R3: Hochtemperatur Industrie-Wärmepumpen*, datasheet, Austria.

[5] Steen et al., 2015, "Modeling of thermal storage systems in MILP distributed energy resource models", *Applied Energy*, vol. 137, 782-792.

[6] P. Icha, 2013, *Entwicklung der spezifischen Kohlendioxid-Emissionen des deutschen Strommix in den Jahren 1990 bis 2012*, Umweltbundesamt, Dessau-Roßlau, Germany, 7-11.