INTELLIGENT LOCAL GRIDS FOR HIGH PV PENETRATION

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1. Introduction

There is a pressing need to accelerate the development of low-carbon energy technologies in order to address the global challenges of energy security, climate change and economic growth. Regarding the energy supply networks the focus is changing. In the past the grids of the different voltage levels and their tasks were clearly separated. Most of the system ancillary services were located at the transmission level. With more and more generation capacity connected to the medium and low voltage networks the need arises to involve these network levels in the network operation. And the focus is broadened further not only considering the network but also the connected units, from the bulk power plants, the distributed generation, storage, electric vehicles and smart, “grid friendly” household appliances. In the future smart grid scenario all system levels and all connected units will play an active part in the operation of the system. And system ancillary services will be delivered by all voltage levels (Braun, 2007). The possible change from one network level to others is shown in the table 1. Bullets are indicating that a service is provided by one network level only; circles are indicating that more than one level is or will be involved.

Tab. 1: Provision of power system ancillary services by different network levels (based on (Braun, 2007))

Ancillary Service	Active Voltage Level					
	Today			In Future		
	EHV, HV	HV, MV	LV	EHV, HV	HV, MV	LV
Frequency Stability	○	○		○	○	○
Primary Reserve	●			●	○	○
Secondary Reserve	●			○	○	○
Tertiary Reserve	●			○	○	○
Voltage Stability	○	○		○	○	○
Compensation of Losses	○	○		○	○	
Black Start/ Network Restoration	●			○	○	○
System Coordination	○	○		○	○	○
Operational Management						
Commercial Balancing of Renewables	●			○	○	
Providing Balance Energy		●			○	○

One example for the involvement of the LV level in frequency stability is the new German LV interconnection guideline. Today about 18 GW PV is installed in Germany, most of it in local grids. To avoid load steps too big for the European rotating reserve the distributed generators connected to LV are no longer forced to disconnect at once in the case of over-frequency, but to reduce the feed-in power following a defined slope (VDE, 2011).

Frequency and in distribution networks also voltage stability is challenged when energy surplus occurs. One approach towards this challenge is to monitor network areas and to give incentives for energy consumption when surplus is generated. But power distribution systems are designed for uncoordinated and stochastic load characteristics. This design is challenged on local level by distributed generation driven by the weather conditions, especially PV, but also heat-led CHP, and future intelligent appliances coordinated by central price signals. Voltage limits as well as limits of the loading of the electrical equipment have to be considered (Gwisdorf et al., 2010). Linking both, local generation and local demand, could represent an intelligent answer to this challenge (Nestle et al., 2009).

The PV power surplus and the demand flexibility within a local network cell were analyzed. The demand side management (DSM) and control concept for the pilot installation is presented. The aim of the pilot installation is to match generation and demand within the network cell as far as possible in order to minimize network losses and to help keeping the voltage limits.

2. Situation in Local Grids – an Example

For a local network cell in a small town near Kassel, Germany, the energy balance was investigated with high PV power generation on the one hand and electrical heat demand on the other hand. For the electrical heating today there are off-peak heating systems installed and can be used for DSM, in future they are expected to be replaced amongst others by electrical heat pumps. Typical for the distribution system operator (DSO) in this region is the topology of a closed tripod (see figure 1) serving the demand in the center of the network cell.

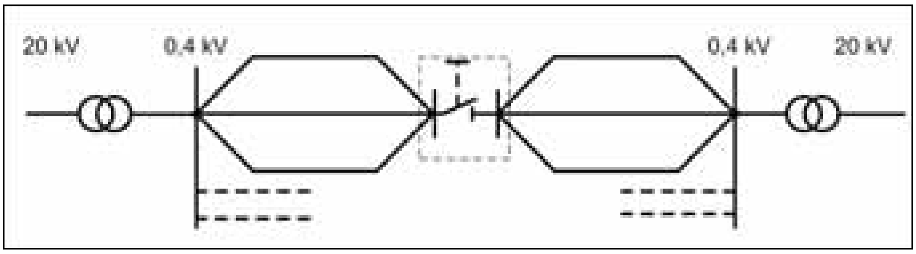

Fig. 1: LV network cells built by closed tripods following the planning guidelines of the regional DSO

If the local conditions allow, each network cell is "mirrored" by another cell and the bus bars for closing the tripods are located in the same cable cabinet (grid sectioning in figure 2). Both cells can be connected e.g. for maintenance purposes. In our example the local grid is fed via two secondary substations (630 and 400 kVA). In figure 2 the LV network cell of the 630 kVA substation is shown as single line diagram. To compensate for the voltage drop along the feeder the voltage level on the LV side of the transformer is set to 102.5 %. The cell comprises 133 customers (households and agriculture) with an average consumption of 4408 kWh per year and additionally 14 off-peak electrical heating systems. Currently there are 9 PV roof systems installed with a total capacity of 217 kW. There are some big PV power plants on barns but also several ones on dwellings. All houses and the PV systems are connected by 3 phase, 400 V cables. The cross section of the cable along the street is 4x150 mm^2; for the house lateral it is 4x50 mm^2.

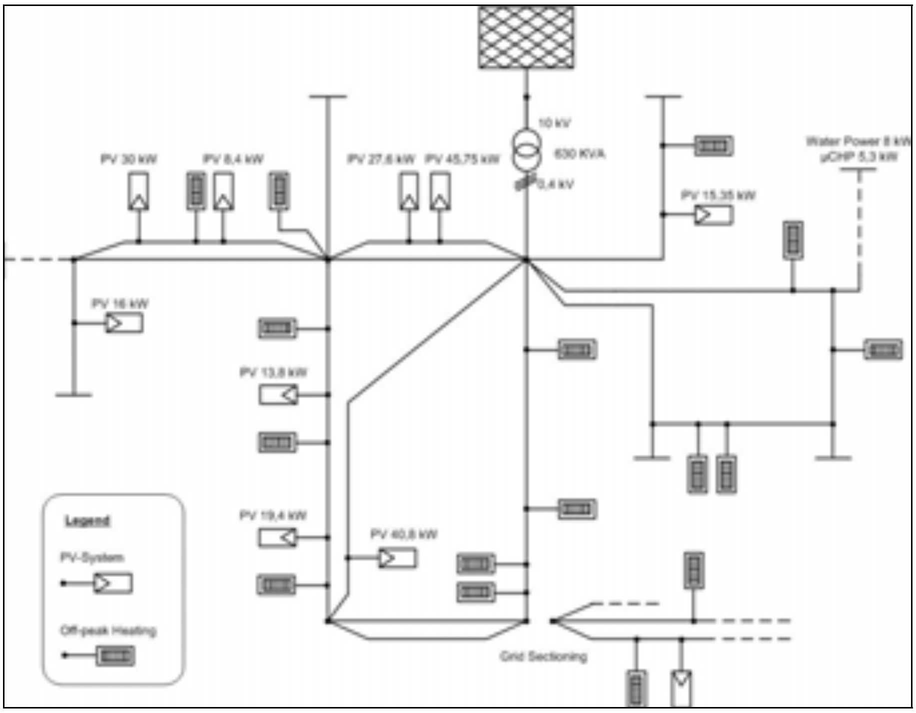

Fig. 2: Single line diagram of the investigated LV network cell (3 phase, 400 V) with currently 217 kW PV power installed

3. Current and Future PV Feed-in and Local Demand

3.1. Description of the Simulation Parameters

For the assessment of the grid different parameters were simulated with the grid simulation tool DIgSILENT PowerFactory (see table 2).

Two different cases were investigated regarding the installed PV power. Today 217 kW are installed, investigated was the case of 270 kW installed PV power, this is the already announced capacity, and the case of 488 kW, when all roofs in the network area are used for PV. The power flow over the transformer was investigated.

Tab. 2: Survey of the performed simulations

Simulation	Installed PV power	Time Period	Objective/ Investigation
Power Flow	270 kW, 488 kW	summer week and winter week	power flow direction
Voltage Profile	270 kW, 488 kW	summer and winter week	voltage profile at the substation and at the weakest network point
Power Flow	270 kW, 488 kW	summer day and winter day	power flow direction, electricity demand for heating
Voltage Profile	488 kW	winter day	Voltage profile at the substation with DSM

In preparation of the voltage profile simulations the voltage path of the network for a sunny summer day at noon (for the voltage rise) and a winter day in the evening (for the voltage drop) were investigated and the weak points of the network identified. In the further course the voltage level was simulated at two characteristic points, the low voltage bus bar of the secondary substation and the weakest point in the network cell regarding the voltage rise. This point is on a network branch where the resistance of a single cable is higher than of the tripod which consists of two loops. In figure 2 it is on the left where the 2 PV (30 and 16 kW) power plants feed in. The aim must be that the voltage at the weakest point is still within the allowed band ± 10 % U_N according to EN 50160 and the voltage rise caused by in-feed not higher than 3 % according to the interconnection rules (VDE, 2011).

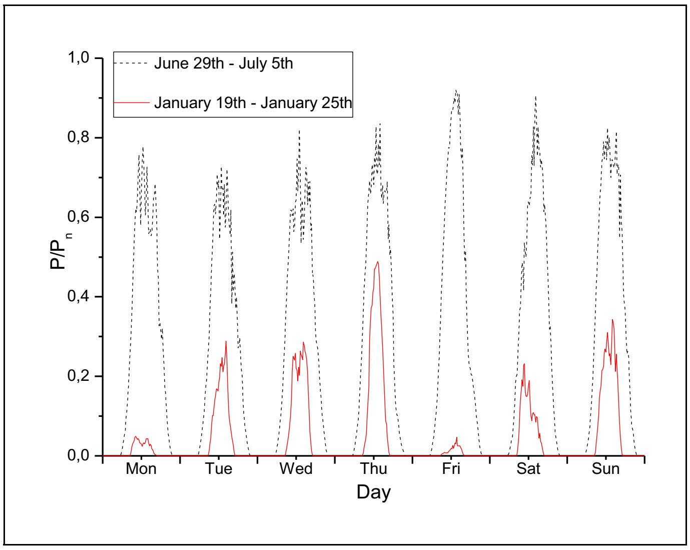

Fig. 3: PV generation per unit of the investigated summer and winter week

All simulations were performed for two different seasons, one week in winter and one in summer. For the summertime June 29^{th} until July 5^{th} was chosen when it was warm enough so that the heating could be switched off (lowest mean temperature of a day 20.3 °C). In wintertime the selected period is January 19^{th}

until January 25th. In both weeks there is one day with almost no clouds at all, i.e. maximum PV input. Figure 3 shows the PV generation profiles in dependence of the rated power of the selected summer and winter week.

Besides PV energy production the different kinds of loads have to be considered. In this paper it is mainly distinguished between the loads of a household and the off-peak-heating using standard load profiles published by the DSO. 14 off-peak-heating are installed having a specific load profile per daily mean temperature. Table 3 shows the outdoor temperatures from January 19th to January 25th.

Tab. 3: Mean outdoor temperatures during the selected winter week

Date	Temperature / °C
January 19th	3.8
January 20th	2.4
January 21st	-1.0
January 22nd	1.8
January 23rd	3.2
January 24th	2.6
January 25th	0.1

Usually the off-peak heating systems are charged during the night. On very cold days the heating can be recharged at daytime, but during the expected peaks of the household consumption around 9h, 12h and at the beginning rise in the evening it is required to totally switch off. This is not regarded as necessary for the actual peak of the evening rise, because the peak of the rise in the evening is expected to be counterbalanced by the decrease of the consumption of commercial and industrial customers.

4.1. Simulation Results

The voltage level at the low voltage bus bar of the transformer between June 29th and July 5th for 270 kW and 488 kW installed PV power was investigated. The result is shown in figure 4. The low voltage bus bar of the transformer was set to a level 1.025 p.u which is reached by the curve during the night. During daytime the curve is mainly influenced by the PV profile. There are a lot of fluctuations except on July 3rd, when the sky was almost clear. Reverse power flow during day time leads to a voltage raise up to 0.7 % (1.032 p.u.).

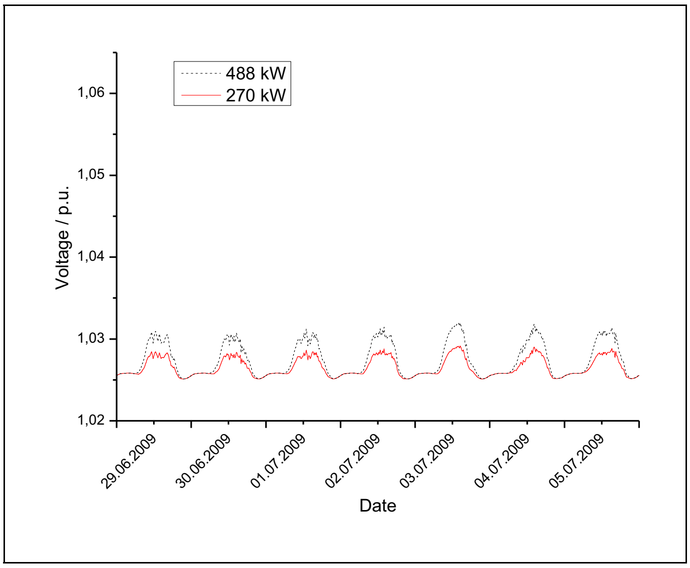

Fig. 4: Voltage at the transformer during summer with 270 and 488 kW installed PV power

In figure 5 the voltage profile at the weakest point of the network cell regarding feed-in is demonstrated. The highest voltage level is on July 3rd around noon at about 1.06 p.u. The limit of the voltage rise according to the interconnection rules is exceeded, but not yet the 10 % corridor around the nominal voltage according to EN 50160. But in the usual network planning the voltage of the whole distribution system is assumed to be actively controllable in the HV/MV substation only. Therefore the 10 % corridor is split between the MV and the LV network with a remaining 5 % voltage band for the LV network including the voltage drop over the secondary substation. So the voltage raise of 6 % interferes with the usual network operation.

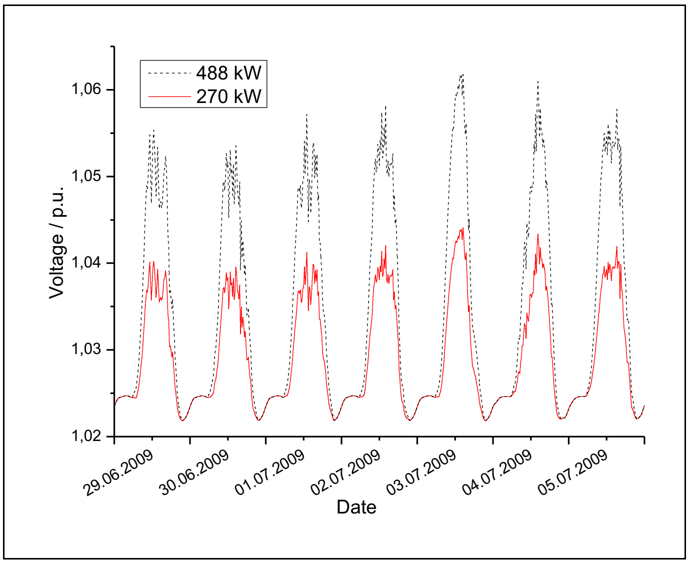

Fig. 5: Voltage profile at the weakest point of the network cell during summer with 270 and 488 kW installed PV power

The power flow over the secondary substation was also investigated. Figure 6 shows the power flow over the transformer in the summer week with the two different cases of installed PV power, 270 and 488 kW, positive power meaning back feed from the network cell to the MV network. On every day there is a big surplus during daytime.

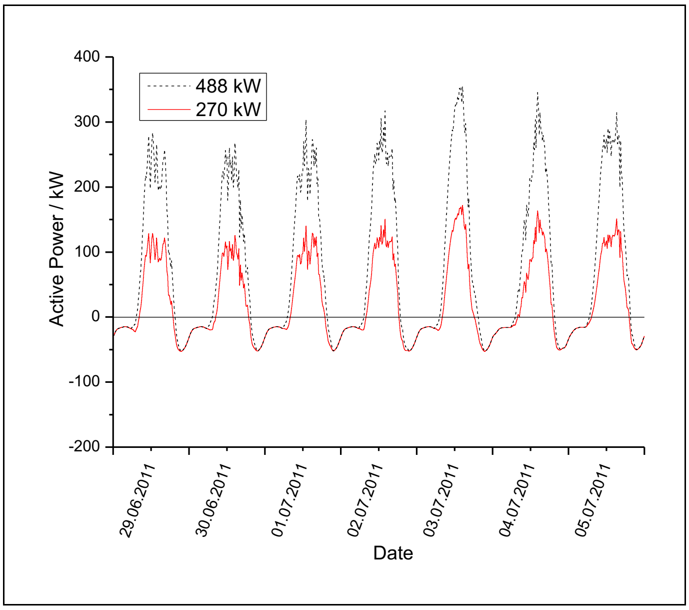

Fig. 6: Power flow over the transformer in summer with 270 and 488 kW installed PV power

Figure 7 shows the power flow over the transformer during the selected winter week. Only on Thursday there is a surplus for 270 kW installed PV power. Monday and Friday were very cloudy, so there is only a slight difference between the installed power of 270 and 488 kW.

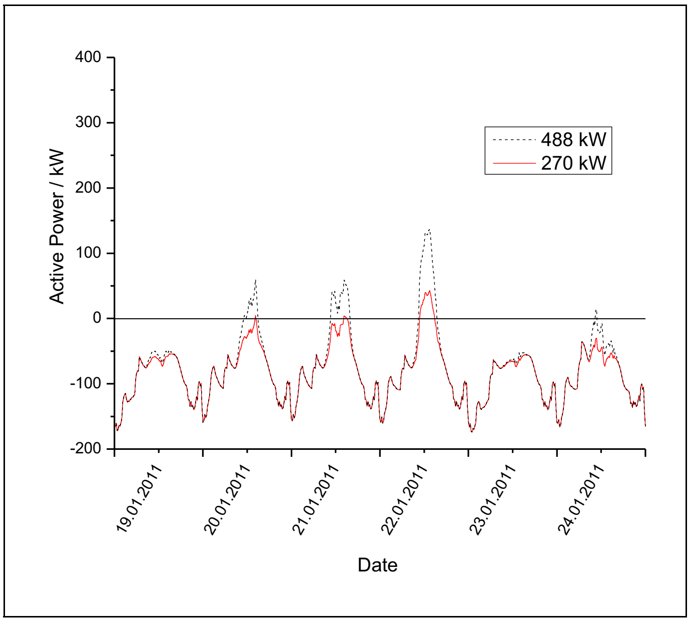

Fig. 7: Power flow over the transformer during winter with 270 and 488 kW installed PV power

5. Domestic Load-shifting

A distribution system operator (DSO) can look at distributed generation as troublemaker only, or make use of their capabilities and actively include them in the network planning and operation. Opportunities can arise from the postponement of grid re-enforcement in heavily loaded network areas, reduction of losses and contributions to peak reduction or control energy. But this requires either a very good coupling of generation and demand through control and demand side management (DSM), or, in contrast, the de-coupling of generation and demand by storage. Both can as well be used in combination.

5.1. Thermal Storage

Thermal storage to de-couple local generation and local demand of electrical energy has a certain potential to raise the energy efficiency and to help keeping the voltage limits in low-voltage networks. Many appliances in buildings, dwellings and offices, employ electrical energy for heating or cooling regarding thermal building conditioning, hot water preparation or freezers and refrigerators. Frequently used electrical systems for heating and cooling are CHP units, heat pumps, refrigeration machines and off-peak heating systems. On the one hand these systems lead to higher electrical energy demand, on the other hand they carry the potential to balance on a daily basis the fluctuating generation from PV and wind. CHP units driven by the electricity demand can be used to compensate for gaps due to changing weather conditions, if the thermal storage is adequately designed. Heat pumps and refrigerating machines, in contrast, can be actively used when the network cell generates power surplus. Traditionally off-peak heating in Germany is used to fill the “night valley” of energy demand to optimize the operation of base load power plants. They were installed beginning in the 1970ies and are in some areas still in operation. In 2004 there were in Germany in 1.44 mio. flats electrical heating system installed with an energy demand of 35 TWh (Frey, 2007). Off-peak heatings are directly controlled by the DSO and can nowadays be re-used to balance local renewable energy generation and local demand (Degner et al., 2010). In Germany off-peak heating systems in buildings with more than five flats in Gemany have to be replaced by other heating systems within ten years, and it is expected that this will happen also for smaller buildings. But in the whole the electrical energy demand used for heating purposes is expected to grow. The future heat demand of well insulated dwellings will be very low leading to an advantage of electrical heating systems like heat pumps. Electrical heating systems are expected to partially replace gas and oil fueled boilers. Long-term energy concepts expect a share of 40% of all heating systems for electrical heat pumps by 2050 in the sector of private households (Schmid, 2010). These heat pumps can be utilized as thermal storage in local grids. The local controllable storage capacity could be enlarged considering e.g. room air conditioners or the batteries of solar home systems and electric vehicles.

5.2 Balancing surplus from renewables using thermal storage

In order to shift loads to another time there must be a surplus when energy is supposed to be fed in back to the MV grid. In this case thermal storage should be linked with PV power generation to consume local generated power locally.

In figure 8 the sunniest day of the selected winter week is considered. Negative power means feed-in from the grid, positive power means back feed from the LV network cell. The green marked area shows the surplus which is generated by the installed PV power plants. The red filled area represents the heat demand.

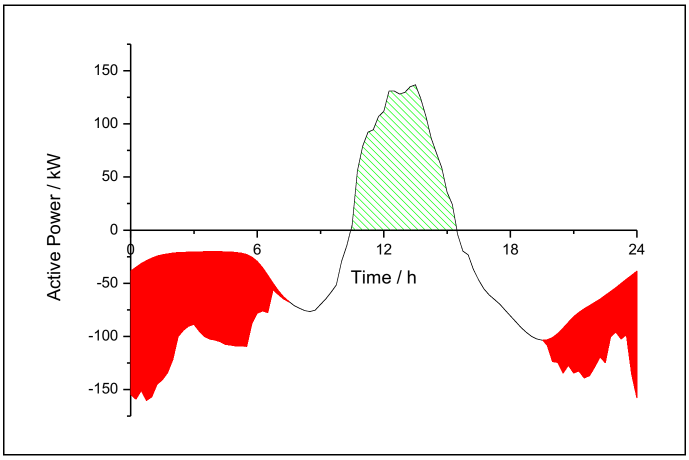

Fig. 8: Power flow over the transformer on January 22nd, 488kW installed PV power. Light green shaded area PV surplus, red filled area heat demand.

The energy balance in table 4 says that more energy is needed for heating than surplus is produced during the day. That means it is possible to use the total PV surplus for the off-peak heating if the charging is shifted from the night to periods with PV generation. Considering heat pumps the electrical energy will be used more efficient and the demand for heating will be lower. To utilize the whole PV surplus the scope of the DSM has to be broadened beyond heating systems in the future. This applies also for the summer case.

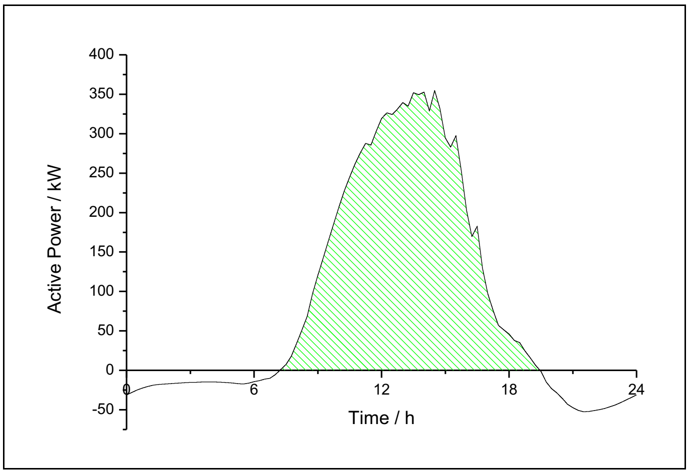

Fig. 9: Power flow over the transformer on July 3rd, 488 kW installed PV. Light green shaded area PV surplus.

The same simulation was done for the sunniest day of the selected summer week, July 3rd. Surplus begins at around 7h and lasts until 20h. But there is no heat demand. To use this surplus locally other appliances than heating systems have to be involved in the energy management like freezes or room air conditioners.

Tab. 4: Energy balance on July 3rd of PV and heat demand

	PV surplus / kWh	heat demand / kWh
July 3rd	2322	
January 22nd	460	809

Table 4 shows the values of the marked areas in figure 8 and figure 9 representing the PV surplus and the heat demand on July 3rd and January 22nd.

6. Demand Side Management

6.1 Control Concept

Fraunhofer IWES is developing one possible building block of the future smart grid: a bidirectional energy management interface (BEMI) (Nestle et al., 2009). The BEMI is the technical core component of the presented control concept. It is located at the point of coupling between the grid and the building and takes local decisions on the operation of loads and generators owned by the end-user. The decision is based on local available information about the current status of the different units and on central information given as tariff profile. This tariff profile is built with input from the energy markets, the weather forecast and the expected load. Depending on the communication scheme the tariff profile can be adapted once a day or every hour. The possible interaction of the BEMI with the markets, the DSO and the end-user is shown in figure 10.

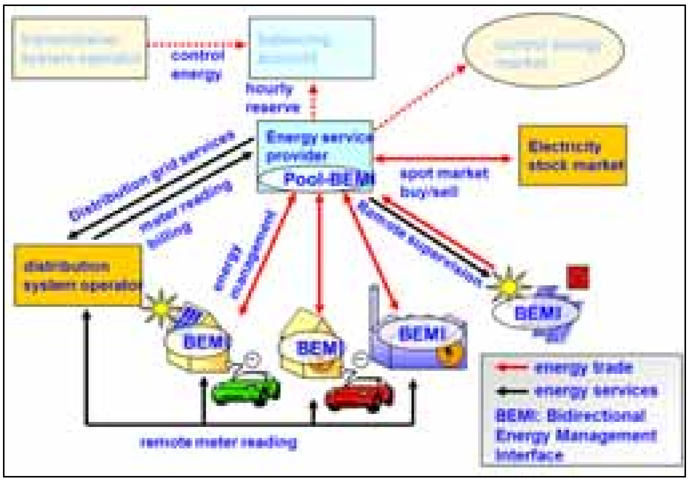

Fig. 10: Possible interaction of the energy management system Pool-BEMI/ BEMI

In a pilot installation beginning early 2012 the DSM potential of off-peak heating systems and freezers will be tested. Additionally a time-of-use tariff will be generated to investigate the impact on the user behavior. The information of the user will focus on the use of washing machines, dryers and dish washers.

To realize the DSM a BEMI system is used. It is located in the customer's premises and takes local decisions on the operation of the freezer and the off-peak heating system. The decision is based on local information about the current status of the appliances and on central information i.e. a time variable tariff. The tariff information is provided by a higher instance the so called Pool-BEMI monitoring the network area. The tariff takes into accounts predicted weather and load conditions and is sent day-ahead to the user interface of the end-user. In figure 11 the local management system is shown.

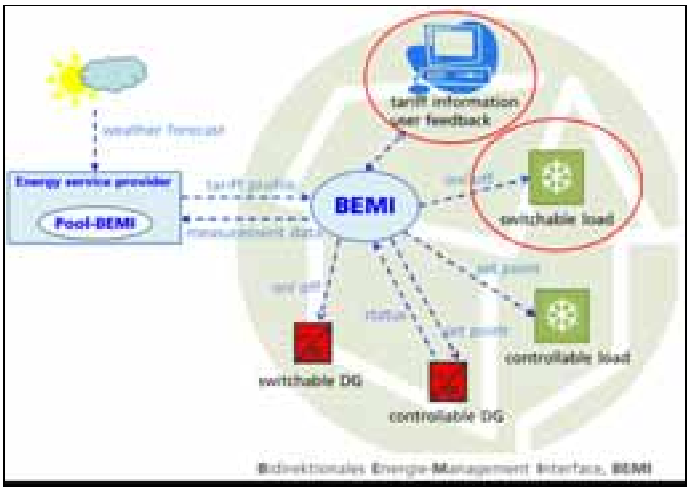

Fig. 11: DSM approach in the planned pilot installation

6.2 Incentives

The end-user should be motivated to support the grid operation actively and use energy when it is best from the point of view of the DSO. The incentive to reach such a behavior will be set by a time-of-use tariff and an information campaign. The consume pattern and the expected generation was analyzed with the aim to develop tariff zones that foster the matching of local demand and local generation. In the time periods where PV surplus is expected the tariff is reduced. The reduction is carried out in two steps. The distribution of the tariff levels is shown in table 5. Tariff level C is the general price for electricity that will be reduced to level B and level A according to the expected PV surplus in this network cell.

Tab. 5: Time-of-use tariff with three levels to foster the matching of local demand and local generation

Weather forecast	Sunny and slightly overcast		Clouded and rainfall
Time	March – Sept.	Oct.-Feb.	all-seasons
0 h – 8 h	Tariff level C	Tariff level C	Tariff level C
8 h – 10 h	Tariff level B	Tariff level C	Tariff level C
10 h – 15 h	Tariff level A	Tariff level B	Tariff level C
15 h – 17 h	Tariff level B	Tariff level C	Tariff level C
17 h – 24 h	Tariff level C	Tariff level C	Tariff level C

Each network cell, i.e. each network area downstream a secondary substation, can be provided with an individual tariff. But it has to be further investigated, whether different tariffs in one municipality will be accepted by the customers.

6.3 Benefits

The presented power balancing has two main benefits, raising the hosting capacity of the local grid for renewables and reduction of network losses.

Matching local generation and local demand supports keeping the voltage limits. For the presented winter day, Jan 22^{nd}, all of the PV surplus could be consumed by the electrical heating. Shifting the charging of the heating systems to the time when PV surplus occurs was simulated and the result on the voltage is shown in figure 12.

The generated PV power is consumed in the network cell. The network cell does not feed-back and therefore is not raising the voltage at the MV grid. And in the LV network cell also the used voltage band is narrowed. The same effect can be utilized in summer when the voltage management is more critical but other appliances of the end-user must be involved.

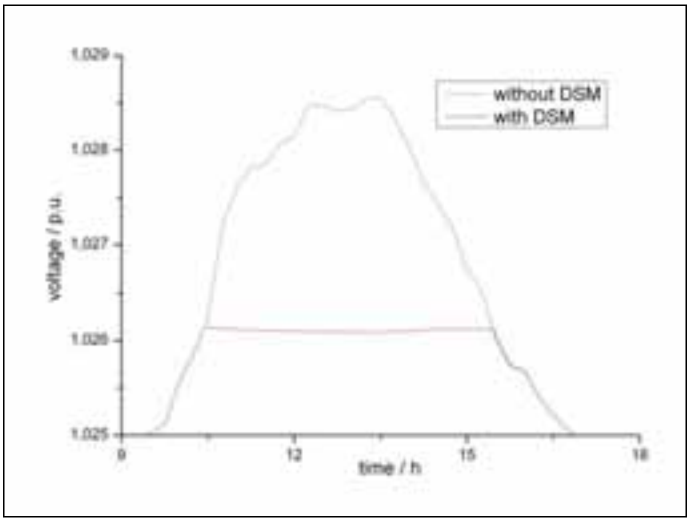

Fig. 12: Voltage rise at the transformer LV bus bar on Jan 22nd with and without DSM

Regarding the network losses we will first consider the case without DMS. On a day when PV surplus occurs it will be transported from the network cell where it is generated to a neighboring network cell where the demand prevails. Losses in the secondary substation of the first network cell, losses for the transport as well as losses in the neighboring secondary substation are to be considered. Each part can be estimated with 1 %, summing up to 3 %. Thus the effect of loss reduction by distributed generation does not occur, when the generation cannot be consumed near the generator without passing a substation. Transportation losses are not avoided. Only the direction of the energy flow is changed.

In spite of the PV energy surplus there will be energy demand in the network cell when no PV generation is available. This demand will be served by the central power system. We can assume another 3 % losses for this energy transport.

Transportation losses can be avoided twice, if generation and demand are locally and temporally matched: first during PV energy surplus and second for demand without PV generation.

7. Conclusions

In this paper the potential for demand side management for the operation of the local grid was investigated. Simulations of a concrete network cell show that voltage limits could be reached when more and more PV installations are set up. The BEMI control scheme for demand side management in local grids was presented. In a 100 % scenario electrical energy from renewables will be used for serving parts of the heat demand also. Considering this demand in an energy management system can foster keeping the voltage limits, raising the hosting capacity of local grids for renewables and reducing network losses. Simulations for a concrete network cell show how thermal storage can utilize local PV power surplus. The operational voltage range in the network cell is narrowed and voltage rise in the MV grid avoided. Shifting local demand to periods of local generation raises the overall energy efficiency of the system by avoiding transportation losses twice.

8. Acknowledgements

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9. References

Braun, M., 2007, Technological Control Capabilities of DER to Provide Future Ancillary Services, in: International Journal of Distributed Energy Resources, Vol. 3 No. 3, July-September 2007, pp. 191-206

Degner, Th., Heckmann, W., Gonzales, F. G., Krause, M., Meyer, R., 2010, Intelligentes Verteilnetz –

Lastmanagement und dezentrale Erzeugung, in: Kongressbeiträge VDE-Kongress 2010, Leipzig, Germany, 2010-11-08

Frey, G., Schulz, W., Horst, J., Leprich, U., 2007, Studie zu den Energieeffizienzpotentialen durch Ersatz von elektrischen Strom im Raumwärmebereich, Study for co2online, Saarbrücken, Germany, 2007

Gwisdorf, B., Stepanescu, S., Rehtanz, C., 2010, Effects of Demand Side Management on the Planning and Operation of Distribution Grids, in: Proceedings of the Innovative Smart Grid Technologies Conference Europe, 2010 IEEE PES, Gothenburg, Sweden, 2010-10-11.

Nestle, D., Ringelstein, J., Selzam, P., 2009, Einbindung von Stromkunden in ein intelligentes Verteilnetz, in: ETG-Fachbericht 118, Internationaler ETG-Kongress 2009, Düsseldorf, Germany, 2009-10-28.

Schmid, J. (Editor), 2010: Energiekonzept 2050, Report of Fachausschuss „Nachhaltiges Energiesystem 2050“, ForschungsVerbund Erneuerbare Energien, Berlin, Germany, Juni 2010

VDE, 2011, VDE-AR-N 4105, Generators connected to the low-voltage distribution network – Technical requirements for the connection to and parallel operation with low-voltage distribution networks.