INTELLIGENT PROSUMER COUPLING BY TWO GALVANICALLY ISOLATED BATTERY STORAGE SYSTEMS

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ABSTRACT

This work presents an innovative concept to connect prosumers to the grid. The connection is achieved by two galvanically isolated battery storage systems which are switched over cyclically. Based on the permanent galvanically isolation of grid and prosumer, this concept reveals fully new options for grid-optimized operation, optimization of self-consumption and energy trades as well as improved utilization of fluctuating generation by renewables in the grid. The concept also shows important benefits compared to conventional parallel battery storages. Simulations of this intelligent prosumer coupling (IPC) concept applied to a real grid configuration verify the value of this new approach.

BACKGROUND

In the context of the German "Energiewende", the fluctuating generation by renewable energy systems (RES) increased strongly. This causes problems concerning the transmission capability of power grids. Moreover the difference between fluctuating supply and load has to be compensated.

To cover the peaks of RES, battery storage systems (BSS) for buffering energy and reducing line loads are necessary [1], [2]. We considered one BSS consisting of one battery and one inverter parallel connected to the grid. Actual developments show an increase in BSS behind the fuse for photovoltaic-systems and optimization of self-consumption [3], [4]. These can theoretically contribute to reduce line loadings in the grid, but it is subjected to the specified load profile and will be rather used for purposes of the prosumer. Thus its options for grid optimization are limited.

In this work, an innovative concept to connect prosumers via BSS is presented. We mention it as Intelligent Prosumer Coupling (IPC). The IPC concept is capable of reducing and equalizing grid loads, decoupling grid and power quality parameters from the customers and improves the utilization of RES.

The central idea of the IPC is to use two BSS, which are galvanically isolated from each other, one on the grid-side and one on the prosumer-side as shown in Figure 1. For a certain time cycle the grid-sided BSS can be charged or discharged with an arbitrary time profile by the grid. The load-sided BSS can be charged or discharged according to a load profile by the prosumer completely independent of the grid. After each cycle the two BSS are switched over. The only existing constraint is that at the moment of switch over the BSS have an agreed state of charge. Another concept where different BSS are switched over is described in [5].

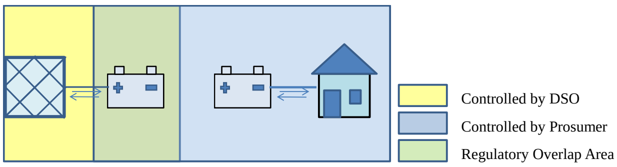

Figure 1: Intelligent Prosumer Coupling (IPC)

Figure 2 illustrates the functionality of the concept. It shows the energy content of both BSS over several cycles. In our case, the chosen cycle to switch the two batteries follows 24 hours. It can be adjusted to fulfill other operational targets and is one degree of freedom.

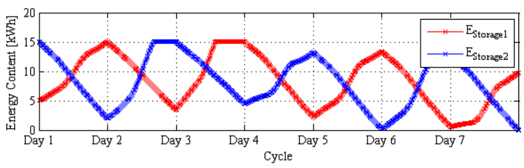

Figure 2: Energy contents of the two storages over several cycles

The IPC can be used in different ways regarding the rating, e.g. to connect loads and generations of different amounts to the grid or whole parts of the network as shown in Figure 3. The usage in medium voltage levels is also thinkable.

A fully implementation of the IPC concept in one connected grid area offers further options of variable operating voltage and frequency. On the other hand, the importance of power quality in the grid with regard to the usual customer requirements can be strongly reduced. The customer is forming his own grid where AC and DC voltage is available. The grid operator and the customer (prosumer) are only "connected" by an agreed interchange of energy packages.

In this case, power quality issues of the grid are completely decoupled from the customer demands.

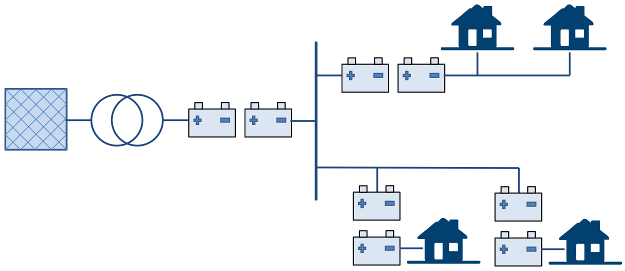

Figure 3: Possible locations for IPCs in LV grids

APPLICATIONS AND BENEFITS OF THE IPC CONCEPT

The IPC concept enables benefits for different applications and groups of interest. We differ between the three following groups of interest.

System Operator

System operators can use the grid-sided BSS of the IPC for grid-optimized operation. The buffer capacity of the storage can be independently used to equalize fluctuating load flows and feeder currents or to control the voltage and frequency. In particular, problematic load profiles of specified customers can be decoupled from the grid. The only constraint refers to the state of charge at the moment of switch over. Interactions, like voltage drop, flicker or harmonics etc. between the grid and the customer are prevented completely. Figure 4 illustrates the prosumer decoupling.

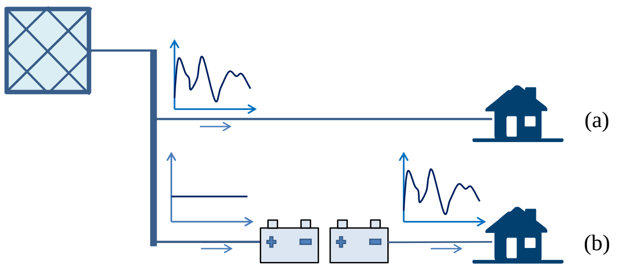

Figure 4: Coupling of loads (a) without and (b) with IPC

Energy Trader

The IPC concept opens also economic aspects of energy trading. Energy traders can sell and buy best priced energy packages from and to the energy market to and from the customer by the grid-side battery fully independent of the prosumers' load profile.
The operation points of the parallel BSS are strictly limited by the prosumers' load profile. For example, the energy trader cannot offer the maximum possible power at low electricity prices with a parallel storage in moments of high self-production (Figure 5).
Figure 6 shows another example. In this case, the prosumer is not able to sell the maximum possible power at high electricity prices with a parallel storage because the storage has to cover the prosumer's own load.

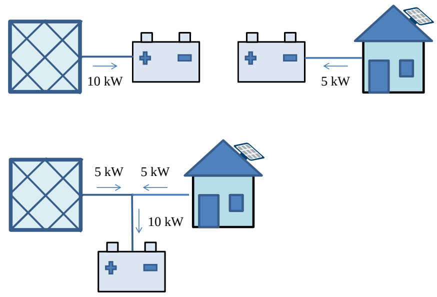

Figure 5: Limits for tradable power - Low electricity prices and high production by prosumer

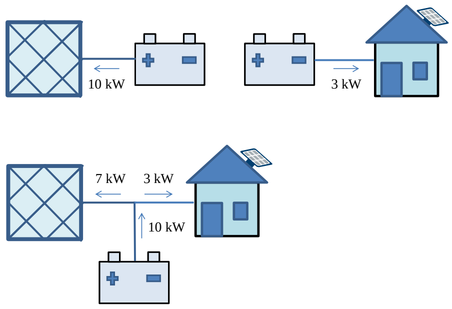

Figure 6: Limits for tradable power - High electricity costs and high load of prosumer

Prosumer

For the prosumer the IPC concept provides different benefits. First of all the prosumer can use the load-sided BSS to optimize energy self-consumption and production. The prosumer can also use the grid-sided BSS for energy trades and enables the extended possibilities of the IPC for trading energy as shown above. Moreover the prosumer is independent of power quality problems in the grid and load peaks caused by other prosumers. In the case of a fault and a supply interruption of the grid, the prosumer can be supplied uninterrupted without any switching actions. The comparison of Figure 7 shows that in case of a parallel BSS the inverter must detect the fault situation and switching actions are required. In this case, a grid-forming inverter is also needed to enable power supply for the prosumer after the disconnection from the grid.
While smart grid solutions with parallel BSS require an extensive data interchange between the smart grid control unit and the prosumers, the IPC provides a much higher IT-autarchy for customers. In the case of conventional connected loads, the instantaneous load profile must be supervised from the grid side for control, whereas in the

case of loads connected with IPC only the required amount of energy per cycle is visible at the grid side (Figure 8). So only inferences on the consumed energy are possible because no information about the required max and min power during the cycle is available. Additionally no load profiles with a high time resolution are required.

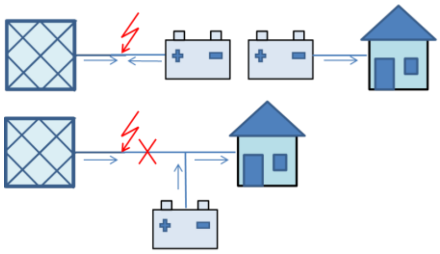

Figure 7: Uninterruptible power supply with IPC

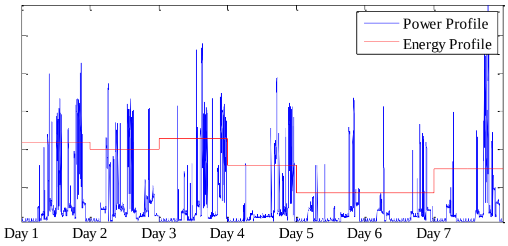

Figure 8: Comparison of power and energy profile

Integration of RES

Besides these groups, who can use the IPC for their own interests, the IPC can also be used for the overall goal of integrating RES into the existing grid. The grid-sided BSS can be specifically applied to compensate the difference between a given fluctuating generation profile and a given load profile. So the IPC has the ability to provide a full controllable load for the fluctuating generation of RES. This enables full demand side management without any constraints for the consumer. With IPCs it is possible to come from a load following operation to a generation following one.

SIMULATIONS REGARDING THE GRID OPTIMIZED OPERATION OF THE IPC

Methods

For the investigation of the grid-optimized operation of the IPC load flow calculations were carried out for each minute of one or more cycles with measured and generated load profiles. The test grid based on data from a German utility is shown in Figure 9.

The feeders 1, 3 and 5 have the same load profiles and feeders 2, 4 and 6, too. The last load of 2, 4 and 6 is a problematic commercial load which is connected by IPC. The remaining loads are common households. IPC is preferably installed at the last load of the feeder.

The batteries are modeled with fixed efficiency rates for storing and feeding, with fixed lower and upper power limits, with a lower and an upper SOC limit and a capacity limit.

The following control strategies for grid-optimized operation were implemented for the grid-sided BSS.

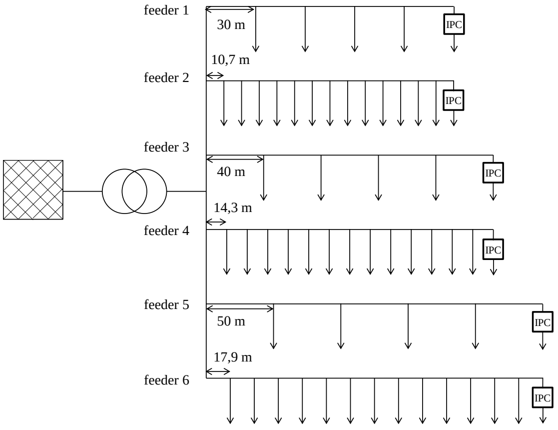

Figure 9: LV grid used for simulations

Constant Power

The grid-sided BSS charges with an average constant power corresponding to the amount of energy required by the prosumer at the moment of switch over.

Feeder Current Control

The grid-sided BSS charges in a way that the current and power of one feeder is constant. In sum one feeder requires a definite amount of energy, by using IPCs the corresponding average power can be purchased. This is done by controlling the storage in that way that the profiles of the storages in sum with the profiles of the conventional coupled loads result in the required average power, which is consumed/produced by all prosumers of the feeder.

Voltage Control

The grid-sided BSS holds the voltage on its connection point in a dead band. The BSS charges with an average power as long as the voltage lies within the dead band. If the voltage dead band is left, the storage charges or discharges with an iterative calculated power to hold the voltage inside the dead band.

Results

Exemplarily scenarios with Feeder Current Control are presented in this paper. Figure 10 shows the feeder currents and voltages at the last node of each line without IPCs in the grid.

Especially feeder 2, 4 and 6 show significant peaks in current and voltage, caused by the commercial loads mentioned above which are not connected by IPCs in this case.

Figure 11 shows the simulation results with IPCs at each feeder. In addition to the currents and voltages, the energy content of the storages is depicted.

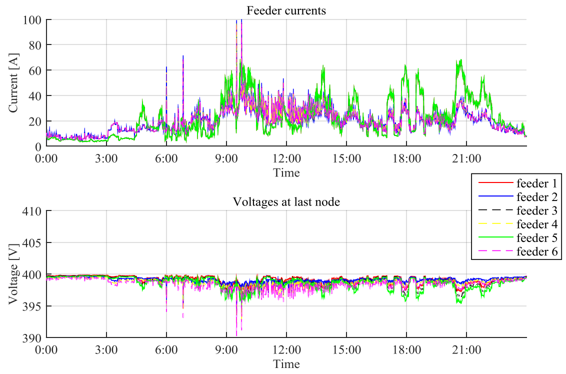

Figure 10: Feeder currents and voltages without IPCs

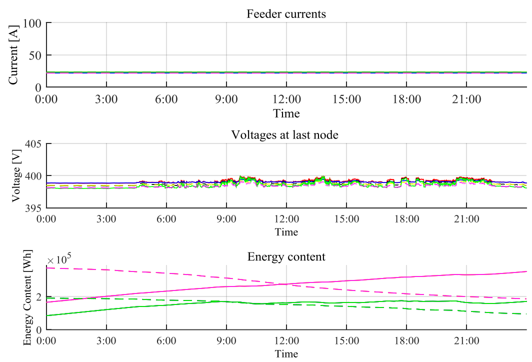

Figure 11: Feeder currents and voltages with IPCs

Table 1: Loading of Transformer

	Maximum load [kVA]	Utilization Factor
Without IPC	345.6	0.274
Constant Power	228.1	0.423
Line Current Control	124.8	1

One can see that the feeder current can be smoothed completely by only one IPC per feeder. The curves for energy content depict that the BSS do not charge constant and even discharge in some moments (green line) to reach the goal of constant feeder currents. It can be seen that with only a part of the loads connected with IPC the maximum loading of the lines can be strongly reduced. Also the loading of the transformer can be reduced, that means a lower power rating of this equipment is possible and the utilization factor tends to one (Table 1).
Further investigations with a typical PV-penetration at the prosumers were carried out. Figure 12 shows the currents and voltages without use of IPC. Due to back feed by the prosumers in the feeder 5 and 6 high negative currents and voltage rises can be observed.
Figure 13 shows the simulation result of the scenario with PV-penetration. It can be seen that the feeder currents can be nearly completely equalized again. Because of the extreme back feed caused by the prosumers in feeder 5 and 6 the BSS in these have to buffer a much higher amount of energy to achieve the goal of a constant feeder current. Hence the BSS in feeder 5 reaches its upper capacity limit (green line at 15:00), so the constant current cannot be provided for a short period of time.

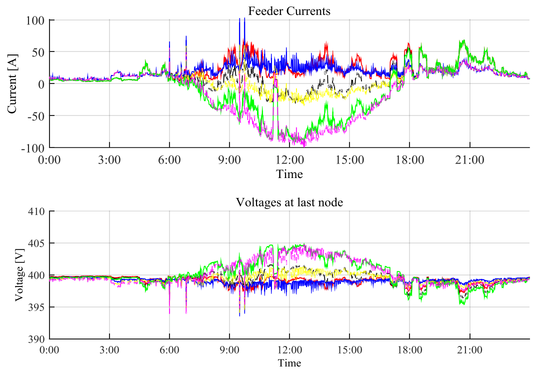

Figure 12: Simulation Results with PV and without IPCs

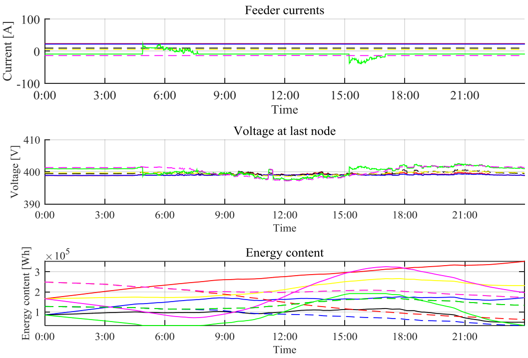

Figure 13: Simulation Results with PV and with IPCs

Moreover simulations over several cycles were carried out, e.g. one week like in Figure 2. They show that the storages have to be a bit more oversized for real applications than in the one cycle simulations.
Additional simulations with a predefined fluctuating generation profile show that the usage of generation by RES can be improved significantly by the use of IPCs.
Furthermore scenarios with different ratios of IPC-connected prosumers and different charging strategies were considered. All scenarios show that only a small part of prosumers connected via IPCs reduces the line and transformer loads and improve their degree of utilization.

COMPARISON TO PARALLEL BATTERY STORAGE SYSTEM

Finally the IPC concept is compared to the concept of parallel connected BSS. Figure 14 opposes the two concepts.

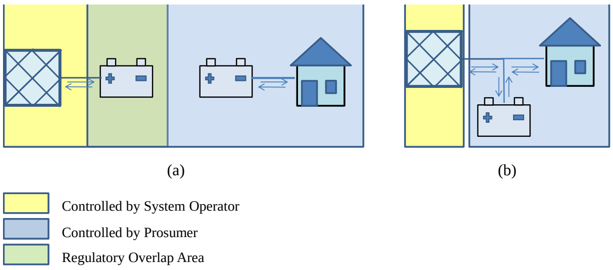

Figure 14: Comparison of the IPC concept (a) and a parallel BSS (b)

The IPC concept comprises one BSS which is fully under control of the prosumer and one BSS which can be assigned to a new regulatory role. It may be used by the system operator, the energy trader or prosumer based on mutual agreements.

The parallel BSS is normally used and controlled by the prosumer or third-party owner of the BSS to optimize self-consumption or provide primary control energy triggered by the grid operator. A direct access of the grid operator or energy trader is hard to be realized.

The respective simulations have shown that theoretically the parallel BSS concept is able to reach the goals of the above mentioned charging and grid loading strategies as the IPC concept. But from practical point of view, the IPC concept includes decisive benefits. In general, the IPC concept is reducing the necessary demand of control and rate of data exchange comparing to the parallel BSS.

Furthermore the IPC does not only provide balancing energy for the grid but also decouples galvanically problematic loads from the grid. In a line with X loads and N BSS

- The parallel concept:
  - Controls X loads with N BSS
- The IPC concept (it needs two BSS!):
  - Decouples $N/2$ problematic loads
  - Controls $X - N/2$ loads with $N/2$ BSS

Additional advantages that cannot be provided by a parallel BSS are as follows:

- Fully prevention of interactions between grid and prosumer by galvanic decoupling
- Very high IT-autarchy for prosumers
- Uninterruptible energy supply without action of disconnection
- Enhanced possibilities for energy trade

The drawback of the higher necessary capacity of the IPC will be partially relativized by consideration of the cyclic aging of the batteries. It can be assumed that the two BSS of the IPC only perform one half cycle of charging or discharging after each switching (24 hours) of the two BSS. The parallel BSS performs charging and discharging each day. Hence the cyclic lifetime of the IPC can be nearly twice higher than that of the parallel BSS.

CONCLUSION

This paper outlines an innovative concept for coupling of prosumers and grids via two BSS. The IPC concept shows important benefits for prosumers, system operators, energy traders and integration of RES. The concept can be used for different applications and with different charging strategies of the grid-sided storage. The grid-optimized operation is investigated in detail based on a low voltage test grid with different charging strategies for the IPC. The results of the load-flow calculations show that the grid can be unloaded with a small ratio of IPC-connected loads compared to scenarios without IPCs. Comparative simulations show that grid-optimized operation modes can also be realized with parallel BSS. Considering the additional advantages of the IPC compared to the parallel BSS the IPC represents an interesting alternative for different applications or combined applications.

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