Integration of Electric Vehicles in Extreme Suburban Grids with the Support of Extended Functionality of PV Storage Systems

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***Abstract*— The change in traffic is a politically desired change from vehicles with conventional engines to electric vehicles. The number of electric vehicles and charging stations has risen during the last years. Especially in suburban residential areas, an increase in electric mobility and private charging infrastructure can be assumed. Battery capacities and charging powers will continue to enhance in the future. Charging powers will be possible up to 22 kW (AC). For this reason, approaches are necessary in order to be able to guarantee secure grid-operation even with an increasing penetration of electromobility. This paper presents the positive impact of extended functionality of PV-storage systems and in particular the provision of reactive power by them.**

***Keywords*—distribution grid, energy storage, electro mobility, reactive power control, voltage control**

I. Introduction

The current share of electromobility in the total number of vehicles worldwide is still very low at around 3 million vehicles. Many countries have ambitious targets with regards to electric mobility and the number of vehicles. In some large cities, driving bans for combustion engines and even nationwide sales bans are planned in the medium term. In addition to the political efforts of the individual states with regard to electromobility, the major automotive manufacturers have also announced a large number of electric models and an increasing proportion of electric vehicles in their sales figures. For example, Volkswagen announces 80 electric models and a 25 % share of electric vehicles in total sales in 2025 [1]. For these reasons, the number of electric vehicles will increase exponentially, reaching high overall figures in the long-term. For the year 2040, 55 % of all new vehicle registrations and a total of 550 million vehicles are forecast worldwide. This corresponds to 33 % of the global fleet [2].

Parallel to the increase in vehicle counts, the number of charging infrastructures is also increasing. Private, domestic wallboxes with charging power of up to 11-22 kW are mainly integrated into existing grids in suburban residential areas, because these areas offer very good conditions due to private homes in connection with garages or carports. Depending on social and demographic factors, the penetration of electric vehicle will be different. Therefore, electric mobility hotspots with a high number of electric vehicles can arise under certain circumstances in low-voltage grids in suburban areas. Due to the ramp-up of electric mobility and the extension of the charging infrastructure, the grid is identified as a weak point of the system. An impact on grid operation has already been proven by many investigations [3], especially in suburban areas [4] and negative scenarios like blackouts are outlined [5]. For this reason, approaches are necessary that are both appropriate for change in traffic and guarantee secure network operation.

II. Challenges in Residentials Areas

In the household sector, a change from the conventional household to the *prosumager* household with electric vehicles is taking place in suitable areas, driven by the development of the energy price and the prices for new components such as PV-storage systems or electric vehicles (EV). This change is shown schematically in the Figure 1.

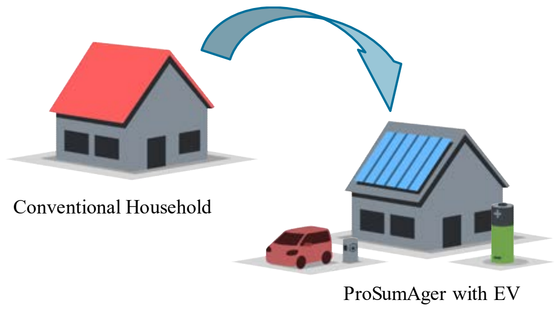

Figure 1. Changes at Household Sector

Historically, the electrical supply was mainly used for lighting in households. In recent decades, the supply has also been used for electric cooking or even electric hot water preparation. The grid was usually designed for this consumption or use. In recent years, the number of PV systems in houses in suburban areas has increased. Currently, such systems are still being installed, especially in connection with storage tanks, or existing systems are being expanded with storage tanks. At the same time, the number of electric vehicles will increase. As a result, households will become prosumagers. The portmanteau prosumager represents an extension of the term prosumer, which was already developed in 1980 [6], and consists of three parts

- PROducer: Energy is generated by an own PV system
- conSUMer: Energy is used by devices in the household or for charging the electric vehicle
- storAGER: Energy can be stored temporarily by means of a battery system

Compared to the conventional household, the new components result in a completely different behavior from the point of view of grid technology.

An example grid and scenarios are defined for the investigation of the impact of electromobility in connection with PV-storage systems in prosumager households.

A. Grid Selection

In order to obtain the greatest possible impact of electromobility and the PV storage system, an extreme grid with 145 households is used for the investigation. The selected grid has a critical string of 69 households [7]. This string is the main focus of the investigation because it has the greatest impact on the voltage due to the length and number of households. The remaining strings are partly combined and not examined in detail. The components PV system, storage, and electric vehicles are nevertheless considered appropriately. The grid is shown in Figure 2.

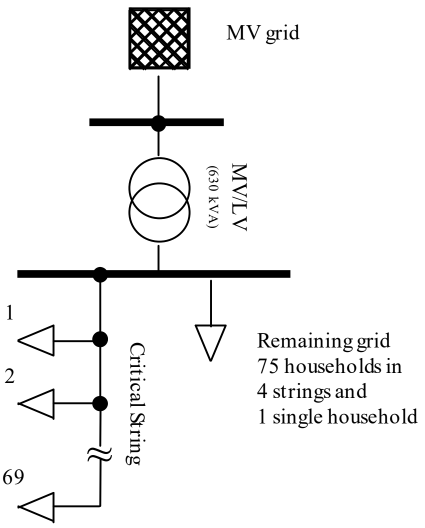

Figure 2. Selected Grid

B. Investigated Scenarios

Synthetic load profiles are used for households. A model with realistic behavior is used for EVs and their charging process [8]. The charging power is assumed to be 11 kW and battery capacities of 35 kWh for all vehicles with a recharging demand of 14 kWh (~100 km). The simulations are carried out with the simulation program DigSILENT Powerfactor and its Quasi-Dynamic-Simulation (QDSL) tool. The voltage at the slack bus is varied between 1 and 1.04 p.u. [9] and the typical voltage drop in the medium-voltage grid is considered.

In a first step, the grid is examined with conventional households as the starting point with regard to load factors and voltage behavior. For this purpose, an annual simulation is carried out and times with minimum voltage or maximum load are determined, because the grid conditions at these times are the limiting factor with regard to the number of possible simultaneous charging processes. Based on this, electric vehicles are supplemented until voltage or load limits are violated in order to determine a maximum penetration for the example grid. For the voltage, 95 % of the 10-minute averages have to be in the range $U_{n\pm}$ 10 % and all 10-minute averages have even to be in the range of U_{n+} 10 %/-15 % [10]. The load limitation is determined by the transformer with 630 kVA and cables (4x150mm²). With the help of PV-storage systems and various reactive power controls, this maximum penetration is ultimately to be increased. Impact of these approaches is finally presented.

III. Impact of Charging Processes

The simulation results of the grid only with conventional households represent the starting point for further investigations. The challenges of the extreme grid can already appear in normal operation with the voltage. In principle, eight simultaneous charging processes are possible, in which the permitted voltage limits are still adhered to. Voltages below 0.9 p.u. are within the permissible time frame. The curves for the case without charging processes and eight simultaneous charging processes with a slack bus voltage of 1 p.u. are shown in the Figure 3 as examples. Table 1 gives an overview of the voltages at the end of the critical string as a function of the voltage at the slack bus and the simultaneous charging processes, which are evenly distributed.

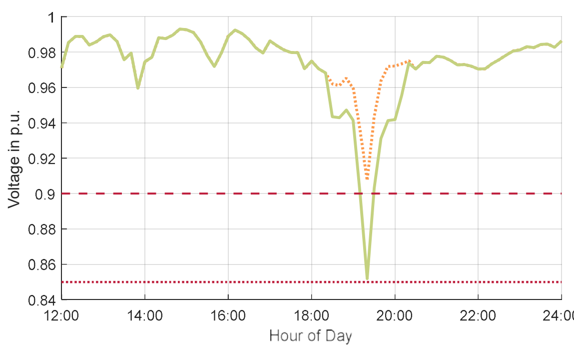

Figure 3. Exemplary voltage curves without charging processes (orange dotted) and eight simultaneous processes (green) with a slack bus voltage of 1 p.u.

TABLE I. OVERVIEW VOLTAGES

Voltage at slack bus in p.u.	Minimum voltage at the end of the critical string in p.u.		
	Number of simultaneous charging processes		
	0	*4*	*8*
1,00	0,910	0,876	0,852
1,02	0,924	0,900	0,882
1,04	0,952	0,922	0,906

In addition to the charging processes in the critical string, there are also simultaneous charging processes in the remaining grid whose impact on the voltage in the critical strand is almost non-existent. These charging processes only have an impact on the load of the transformer. The maximum load of the transformer is 78.04 % in the worst case of the critical string and 18 additional simultaneous charging processes in the remaining grid. Thus, the transformer offers a sufficiently large reserve for additional charging processes.

IV. PV-STORAGE SYSTEMS AS APPROACH

The households with the charging points are supplemented with a PV-storage system. The storage capacity is assumed to be 8 kWh because in 2017 the average capacity was 7.1 kWh with an upward trend [11]. The maximum power of the battery inverter is set at 10 kVA.

Whereas in a conventional household there was only a power purchase from the grid, the power flows in prosumager households are more complex, which results in a correspondingly different grid-technical behavior. Figure 3 shows all power flows that are possible. In principle, the electric vehicle could also offer further power flows. However, these are not included because the focus is on the impact of the PV-storage system. For the storage, a model was developed in PowerFactory which includes the active power behavior (charge and discharge on the basis of a power-dependent characteristic) as well as different reactive power controls which are investigated.

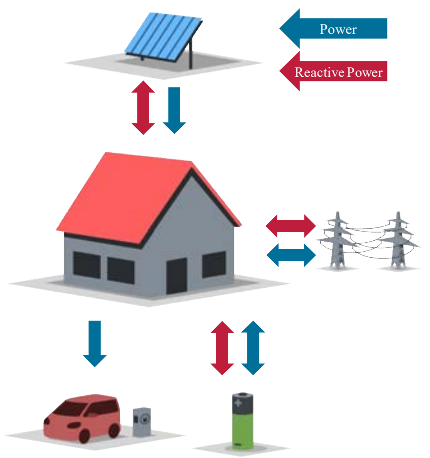

Figure 4. Powerflows in a Prosumager-Household with EV

The day with the lowest voltage is used as the basis for further investigations of the approaches in order to be able to present the impact of the chosen approaches as clearly as possible. With the first approach, the storage can only be charged by the PV system. With the help of the stored energy, the electric vehicle can be charged in the evening to relieve the load on the grid as far as possible. During the charging process, the storage is regarded as a load and is operated with a power factor cos φ= 1 [12]. A power factor is defined for the discharge case, which has to be between 0.9 overexcited and 0.9 underexcited for systems with an apparent power greater than 4.6 kVA. In the case of lower apparent power, the limit is 0.95 [13].

The use of storages to shave the feed-in peak at midday and the consumption peak in the evening hours can relieve the load on the grid [14]. However, this approach becomes problematic in the winter months with short days or days with bad weather. On these days the storage can only be charged a little or not at all. The problem mentioned is illustrated by an SOC annual graph in Figure 4. This clearly shows the low usage at that time. During these periods, electric vehicles must continue to be charged completely from the grid, which results in a corresponding load.

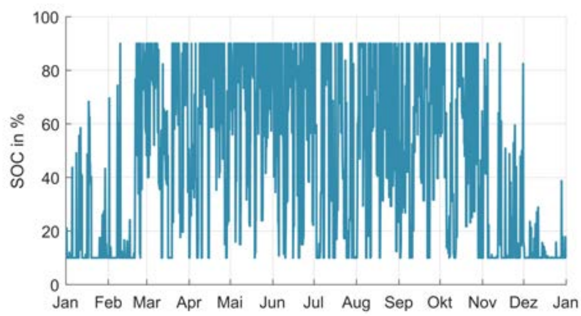

Figure 5. SOC of Example Storage

The day investigated is a day without generation from the PV systems, which is why the storage cannot be used. The PV storage system can therefore not relieve the grid with regard to the charging of the electric vehicle. For this reason, the provision of reactive power is attributed greater importance as a voltage-stabilizing measure, which is why further control approaches are being investigated.

V. ADVANCED REATIVE POWER SUPPLY

With the original provision of reactive power by means of a fixed power factor, the provision of reactive power is very limited and demand-oriented control is not possible. For this reason, a voltage-dependent reactive power supply was included as a possibility in the application guideline in 2018 [13].

A. Voltage-Rated Characteristic Q(V)

The approach of a voltage-dependent reactive power supply for PV systems has already been extensively investigated [15]. The characteristics used are shown in Figure 6. It has a death band of +/- 3% and a rise range of 4% each.

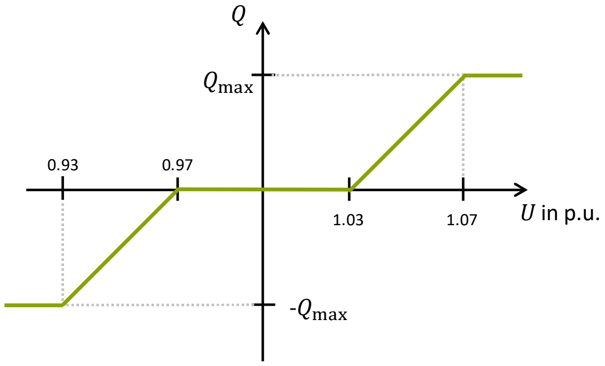

Figure 6. Q(V)-Characteristic

Based on this voltage-dependent characteristic, the storage systems can be operated at the operating points in the marked areas in Figure 7. This allows the reactive power to be adjusted according to demand.

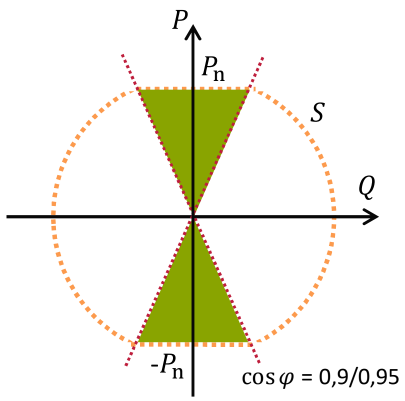

Figure 7. Operating Points for a Q(V) control

For the provision of reactive power, however, active operation with regard to power is necessary (charging or discharging of the storage). For this reason, this reactive power control cannot bring any improvements to the extreme day, under consideration, just like the control, according to current standards.

B. *STATCOM Mode*

The STATCOM mode represents an extension of the Q(V) control. With this approach, reactive power can also be provided at times without charging or discharging. The characteristic shown in Figure 6 also applies to this approach, but with the difference that outside of +/- 7% the reactive power can be further increased. Unlike the Q(V) control, STATCOM mode can provide reactive power even if the storage is neither charged nor discharged as shown in Figure 7. The power has priority and the apparent power is limited. The maximum possible reactive power for the operating points results from the following equation:

$$Q_{\max,\text{current}} = \sqrt{S_{\text{nominal}}{}^{2} - P_{\text{current}}{}^{2}} \qquad (1)$$

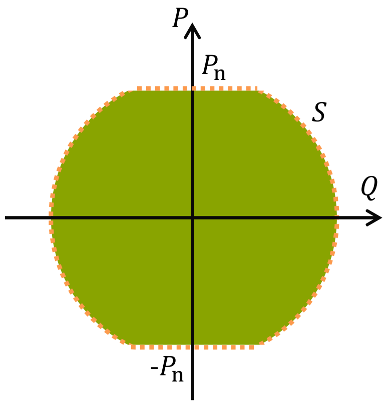

Figure 8. Operating Points during STATCOM Mode

The improvements in the voltage at the end of the critical string due to the STATCOM mode are shown in Table 2 for the investigated cases. In these investigations, it is assumed that a small amount of residual energy from the previous day is still present in the storage, but this is not sufficient to charge the respective vehicles.

TABLE II. OVERVIEW VOLTAGES WITHOUT AND WITH STATCOM MODE (EIGHT CHARGING PROECESSES)

Voltage at slack bus in p.u.	Minimum voltage at the end of the critical string in p.u.	
	Without STATCOM	***With STATCOM***
1,00	0,852	0,867
1,02	0,882	0,890
1,04	0,906	0,912

This approach allows more simultaneous charging operations to take place and thus more electric vehicles to be integrated into the grid. The households for which further charging processes have been added in these studies also have PV storage systems. In addition to the increase in the critical line, the number of charging processes in the rest of the grid is increased identically. In the case of a slack bus voltage of 1 p. u., the number of simultaneous charging processes in the critical strand can be increased from eight to twelve. In the other two cases, more can take place due to higher voltages. In these cases, however, overloads of more than 100 % in the critical string are possible due to the high initial load without electric vehicles. The slack bus voltage of 1 p. u. will only be investigated in the following because this case limits the capacity of the grid.

VI. MULTIPLE-USE OF STORAGE

In addition to the reactive power supply in STATCOM mode, the multiple-use of the storage system is a supplement. The storage system is not only charged from the own PV system, but can also be charged from the grid, e. g. at times when local wind turbines fed into the grid. In this application, the storages can also be used at times when it was not possible in normal operation. Multiple-use is considered by a larger initial value of SOC. For this reason, a large part of the charging power for the electric vehicles is provided by the storage systems. Grid consumption can be significantly reduced. Figure 9 shows the impact of the approach. The number of simultaneous charging processes was doubled in the critical string from eight to 16 compared to the scenario without PV storage system. The minimum voltage is increased from 0.852 p. u. to 0.885 p. u. with the support of the investigated approach, despite an increase in charging processes. From around 8 p.m. onwards, the voltage in the investigated approach is slightly below the original voltage, because at this point the storages are already almost completely discharged.

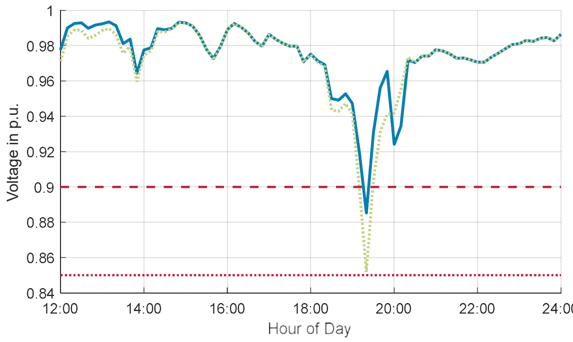

Figure 9. Voltage with eight charging processes (green dotted) and voltage with investigated approach and 16 charging processes (blue)

Due to the improved voltage curve, additional charging processes are also possible in principle. A total of 30 simultaneous charging processes are possible in the critical strand. At the same time, 35 additional charging processes take place in the remaining grid. This limitation is caused by the stored energy in storage systems. Additional charging processes are possible with an increase in storage capacities. The comparison of the cases is shown in Figure 13.

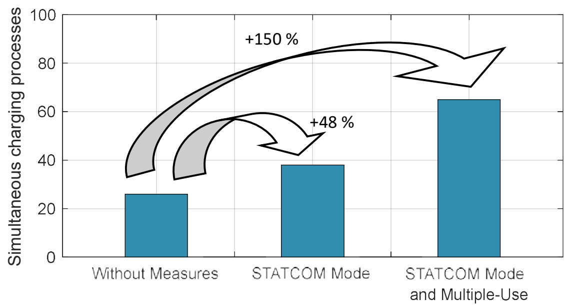

Figure 10. Number of EV in the Cases Investigated

VII. Losses

From a technical point of view, the approaches presented offer good opportunities for the grid integration of electric vehicles. For plant operators, however, additional costs for the approaches are an important factor from an economic point of view. As a result of the provision of reactive power, especially in STATCOM mode, losses occur in the battery inverter. The losses are in addition to the normal charging and discharging losses. In order to determine these losses, a real single-phase battery inverter was operated on many operating points as shown in Figure 8. The reactive power was adjusted in several steps up to the maximum apparent power of 3.3 kVA. The losses as a function of the set points are shown as a heatmap in Figure 11. Due to the battery used, only operating points up to 2 kVA could be reached. A linear dependence on the set apparent power is recognizable and the efficiency is about 92 %. The charge and subsequent provision of the energy or discharge therefore has an overall efficiency of 85 % without storage losses within the battery.

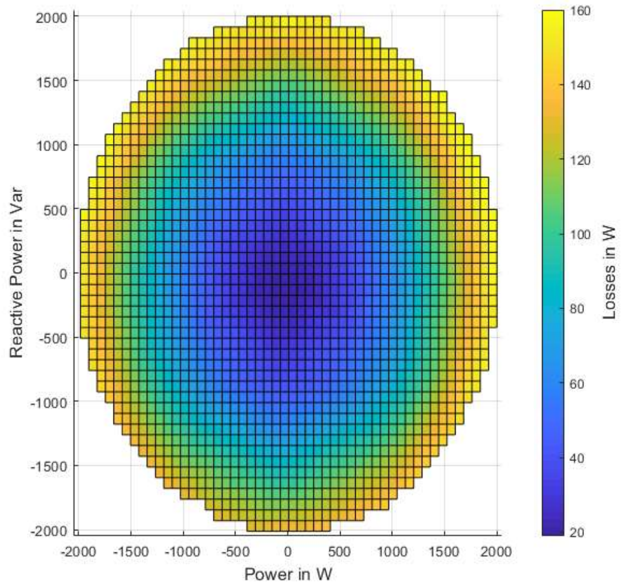

Figure 11. Power Loss of the Battery Inverter (measured)

The reactive energy requirement at the end of the critical string is 3.54 kVarh in STATCOM mode. With additional multiple use, the requirement is 0.76 kVarh. This requirement is lower because the voltage drop during charging process is reduced due to the provision of active power from the storage. This results in a loss energy of 0.22 kWh at STATCOM mode during the charging process. Due to the lower reactive power supply in the expansion with multiple use, the loss energy in this case is 0.05 kWh. In addition, losses occur as a result of the charging and discharging of the storage system. Due to the efficiency, 1.18 kWh grid consumption is required to effectively obtain 1 kWh for charging the electric vehicle. Multiple use is therefore uneconomical and appropriate incentives should be created for this type of operation. However, this approach can prevent a cost-intensive grid expansion.

VIII. Conclusion

The investigated extreme grid offers the possibility of a 18 % penetration rate of simultaneous charging processes without measures. This low penetration is due to the already low voltage during normal operation in the case considered. By a higher slack bus voltage of 1.02 or 1.04 p.u. the penetration can already be minimally increased.

PV storage systems basically represent an approach for increasing the number of possible charging processes. However, operation according to the current standards does not bring always any improvement because the storage system cannot be used completely or possibly not at all, especially on winter days. The provision of voltage-stabilizing measures in the form of reactive power is also not possible in this case due to the behavior required by the guidelines. For this reason, extended functions are necessary.

A battery inverter with STATCOM mode can provide a remedy. Depending on the voltage, this provides reactive power, even if the storage is neither charged nor discharged. This approach enabled the penetration of the investigated grid to be increased from 26 to 38 vehicles or 26 %.

Another function is the multiple-use of the storage. With the help of this function, the penetration could be increased to 65 simultaneous charging processes or 45 % in conjunction with STATCOM mode. It can be assumed that with such a number of electric vehicles the simultaneity is considerably less than one. Therefore, the number of actual electric vehicles in such a grid area will be higher than the number of possible simultaneous charging operations.

Overall, PV-storage systems with the extended functions can make a good contribution to the grid integration of electromobility and grid expansion can be prevented. For this, however, appropriate incentives must be created, because these approaches result in increased losses in the battery inverter and thus with higher costs.

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