

INTEGRATION OF E-MOBILITY INTO DISTRIBUTION GRIDS VIA INNOVATIVE CHARGING STRATEGIES

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ABSTRACT

To combat the climate change, there is an ongoing shift towards a more decentralized and renewable energy system in Germany. The increasing number of volatile distributed generators and large consumers requires a coordinating smart grid system in order to avoid an expensive grid expansion. Due to the high power consumption, especially the charging process of electric vehicles (EVs) has to be controlled by a load management system. To avert a loss of acceptance for EVs, it is important to ensure that the mobility of the users is not restricted due to load control activities. This paper describes the developed EV load management add-on for an existing smart grid system whose aim is to minimize the negative effects for the vehicle users due to innovative charging strategies.

INTRODUCTION

The finiteness of fossil resources and the environmental impacts of CO₂ emissions are forcing a rethink in the energy sector. To mitigate the climate change and to limit the consumption of the resources, more and more energy – particularly electrical energy – is generated from renewable sources. Unfortunately, most of the renewable produced electrical energy is highly volatile (especially produced by wind turbines and PV systems), so the installed capacity has to be considerably higher compared to conventional power plants to generate the same annual amount of energy. Furthermore, especially the PV systems are connected to the low voltage (LV) grid which has not been designed for this purpose. Therefore, very high power flows can occur, if all renewable generators feed their maximum power at the same time which may lead to an exhaustion of the grid components' capacity or a deviation from the permitted voltage range. Additionally, a large storage amount is needed to bridge the periods of low feed-in.

Besides the electrical energy sector, the transport sector has an even higher energy demand (28% of the final energy demand in Germany [1]) which nowadays is mainly met by oil. For the above reasons, this demand has to be generated renewable in the long term too. In principle, biofuels, renewable generated hydrogen, and batteries used in EVs are eligible for this purpose. Due

to the limited acreage and the competition with foodstuffs, biofuels however will only cover a minor part of the energy required and since the efficiency of hydrogen generation is rather low, EVs are the (energetically) most appropriate option.

An increasing number of EVs causes problems for the electrical grid. EV charging stations are – as well as PV systems – mainly connected to the LV grid which has only been designed for small customers. In case of a simultaneous charging of multiple EVs in combination with an already high load, the grid could be overloaded. An additional problem is that the charging process is not time-correlated with the production from the PV systems (Fig. 1). Therefore, the mentioned off-limit conditions are not compensated, but could occur in both directions (Fig. 2).

Fig. 1 illustrates a characteristic comparison of PV feed-in and a cumulative charging load. It shows that EVs are mainly charged in the evening, but PV systems produce energy during the day.

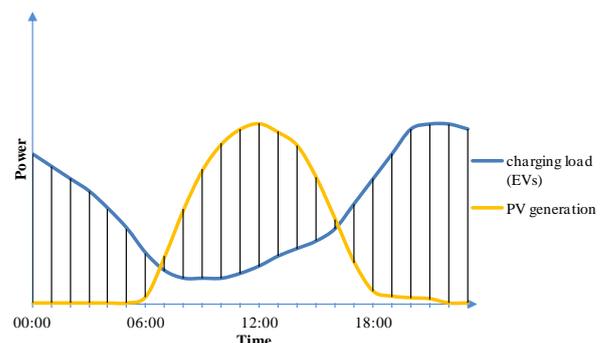


Fig. 1: Comparison of a characteristic PV generation and a cumulative EV charging load

Fig. 2 depicts the voltage curve of an uncontrolled LV grid during a sunny day with only a light load as well as the curve of an evening in case of a high load. While the high PV feed-in at daytime leads to an illegitimate voltage increase, the EV charging load in the evening causes a lower deviation from the permitted voltage range.

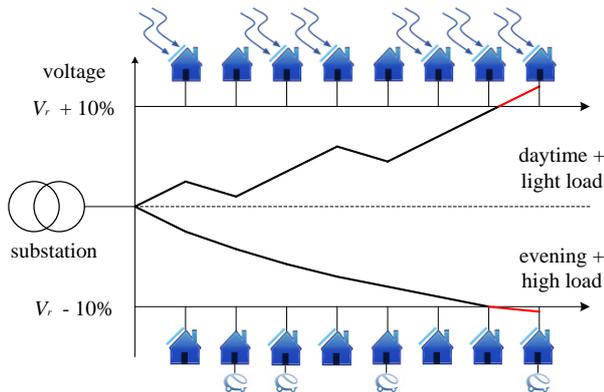


Fig. 2: Voltage curves of an uncontrolled LV grid during a sunny day and in the evening

To prevent those inadmissible grid states, there are two distinct possibilities: On the one hand, a very expensive grid and storage expansion, on the other hand, an intelligent load and feed-in management which controls generation as well as consumption (smart grid) [2]. For economic reasons, the grid operator has to keep the costs down, so the expansions should be minimized.

CURRENT SMART GRID SYSTEM

While some approaches focus on a single component within the grid, i.e. controllable voltage regulators, the authors of the present paper prefer an integrated concept for smart distribution systems, including different components like controllable voltage regulators and controllable generation and consumption units. A fast, intelligent power flow calculation algorithm has been developed and implemented into an autonomous control unit ("Smart RTU") within the low voltage grid's substation [3], [4]. The power flow calculation is utilized for cyclic, virtually real-time supervision of the distribution grid. A sparse and competitive sensor network gathers online voltage and current measurements within the grid.

In case of an off-limit condition, a three-stage control algorithm (sorted by negative effects of a control operation) cures the violation autonomously. Fig. 3 shows the functionality of the algorithm in case of an illegitimate voltage increase (too much DG feed-in) [5].

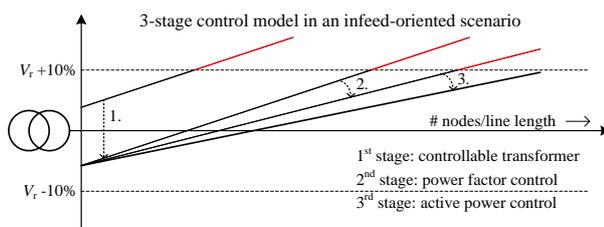


Fig. 3: Three-stage control algorithm of the smart grid system

The first stage is a reduction of the voltage at the substation by the use of an on-load controllable transformer. This reduction has no negative effect, as long as the voltage does not fall below the permitted voltage range at any node of the grid.

If this stage was not sufficient or no controllable transformer is available, the power factor control (2nd stage) will be used to lower the voltage. Although an increase of the reactive power leads to a higher current flow and therefore to increased power dissipation, at least no renewable generated active power has to be reduced. This active power control (3rd stage) is only necessary, if the voltage is still too high after stages one and two.

This 3-stage model avoids active power curtailment as long as possible. With this integrated concept, it is possible to maintain voltage quality on the one hand, and avoid critical power flow situations on the other hand. The autonomous grid control unit, with the described features of the state estimation and the control algorithm, has been implemented in several LV-grids in Germany. Field experiences with this smart grid approach have been described in recent work [2].

GRID INTEGRATION OF E-MOBILITY

Particular challenge

As mentioned, the charging process of EVs has to be controlled by a smart grid system to avoid off-limit conditions. Nevertheless, an EV load management is difficult to realize, because each intervention causes disadvantages for the user of the vehicle, due to the fact that the charging time increases. In order to avert a loss of acceptance for EVs, it is important to ensure that the mobility of the users is not restricted due to load control activities. Therefore, an intelligent load management system must be able to do both: Remedy the off-limit condition and minimize the negative effects for the users. The currently developed EV load management add-on for the described smart grid system perfectly serves that purpose.

Fig. 4 depicts the intelligent control of EV charging stations. If the load factor of the grid exceeds the limit, the most suitable vehicles are chosen to remedy off-limit conditions. To prevent the connection of further new loads, the users are informed via location based services that the capacity of this grid area is exhausted and alternative charging stations are suggested. If the load is lower than the renewable generation, the EVs are charged with maximum power and users are informed to load their vehicles in this area.

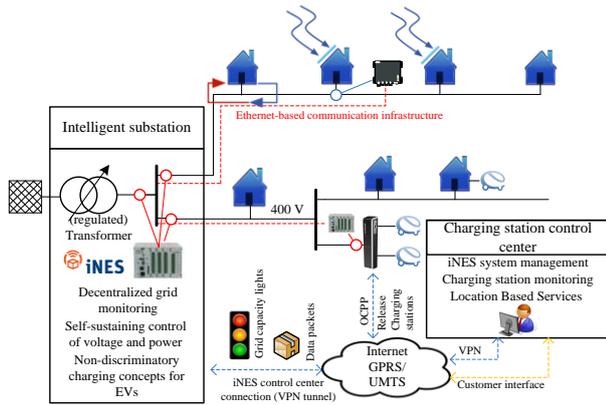


Fig. 4: Concept of the intelligent integration of electric vehicles

Selection of applicable charging stations

In case of an off-limit condition, not every charging station in the grid is appropriate to clear the actual problem. Therefore, the first step of any load management measure has to be the identification of the sensitive charging stations, because a power reduction without a positive effect on the grid state has to be avoided for the above mentioned reasons. The suitability depends on the position of the charging station within the grid, the location and in particular the type of the off-limit condition. For example, a branch overload can only be cured by charging stations which are directly fed via this cable.

In order to make a selection of applicable charging stations, the type of the off-limit condition has to be detected first. In case of a deviation from the permitted voltage range, the influence on the voltage at the affected node has to be determined. If a branch overload exists, the influence on the current flow is the decisive factor.

To identify the individual influence of a control measure at a specific charging station on the voltages of the other grid nodes, a sensitivity analysis is suitable. This analysis can, for example, be implemented on the basis of the admittance matrix; the current flow to all nodes (\vec{i}_N) is only depending on the admittance matrix (\mathbf{Y}) and the voltage at the nodes (\vec{u}_N). Since the current flow is proportional to the power consumption, also the relevant connection of voltage and power consumption is described.

$$\vec{i}_N = \mathbf{Y} \cdot \vec{u}_N = \begin{pmatrix} i_{N1} \\ \vdots \\ i_{Nn} \end{pmatrix} = \begin{pmatrix} \sum Y_{N1} & \cdots & -Y_{1,n} \\ \vdots & \ddots & \vdots \\ -Y_{n,1} & \cdots & \sum Y_{Nn} \end{pmatrix} \cdot \begin{pmatrix} u_{N1} \\ \vdots \\ u_{Nn} \end{pmatrix} \quad (\text{I})$$

The admittance matrix only describes the grid at the LV-level, but significant voltage drops are also caused by the transformers. The voltage drops caused by the

superordinated MV-grid could be neglected, because its admittance is comparatively small. Therefore, the admittance matrix has to be extended to include the internal resistances of the feeding transformers.

$$\mathbf{Y}_{ext} = \begin{pmatrix} \sum Y_{N1e} & \cdots & -Y_{1,n} & -Y_{1,T1} & \cdots & -Y_{1,Tn} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ -Y_{n,1} & \cdots & \sum Y_{Nne} & -Y_{n,T1} & \cdots & -Y_{n,Tn} \\ -Y_{T1,1} & \cdots & -Y_{T1,n} & \sum Y_{NT1} & \cdots & -Y_{T1,Tn} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ -Y_{Tn,1} & \cdots & -Y_{Tn,n} & -Y_{Tn,T1} & \cdots & \sum Y_{NTn} \end{pmatrix} \quad (\text{II})$$

In order to receive the influence of a load change on the voltage of another grid node, equation (I) has to be solved for the voltage \vec{u}_N ; but previously, the extended admittance matrix has to be reduced by the lines and columns of the new transformer nodes, because the voltages at these nodes are determined by the superordinated grid. [6]

$$\mathbf{Y}_{red} = \begin{pmatrix} \sum Y_{K1e} & \cdots & -Y_{1,n} \\ \vdots & \ddots & \vdots \\ -Y_{n,1} & \cdots & \sum Y_{Kne} \end{pmatrix} \quad (\text{III})$$

Thus, the reduced admittance matrix \mathbf{Y}_{red} meets the originally admittance matrix \mathbf{Y} , with the exception of the changed row sums of the slack nodes. In contrast to the originally admittance matrix, \mathbf{Y}_{red} is not singular, so equation (I) can be reformulated to:

$$\Delta \vec{u}_N = \mathbf{Y}_{red}^{-1} \cdot \Delta \vec{i}_N \quad (\text{IV})$$

Here, $\Delta \vec{u}_N$ stands for the voltage drop up to this node and $\Delta \vec{i}_N$ for the current drain at the considered node. The resulting sensitivity matrix \mathbf{Y}_{red}^{-1} indicates how much the voltage at a node is affected by a change of the current drain at another node. In this way, the influence of a control measure at any charging station on the voltage of any node can be identified and suitable stations can be selected.

In case of a branch overload, the change of the current flow due to a control measure is the determining factor. The current flow depends on the voltage difference between the beginning (U_B) and the end (U_E) of the cable and its impedance (Z).

$$I_{BE} = \frac{\Delta U}{Z} = \frac{U_B - U_E}{Z} \quad (\text{V})$$

Since the impedance can be assumed to be constant, the change of the current flow only depends on the change of the voltage difference.

$$\Delta I_{BE} \sim \Delta \Delta U = \Delta U_B - \Delta U_E \quad (\text{VI})$$

Because ΔU_B and ΔU_E could be determined with help of the sensitivity matrix, the influence of a control measure on the current flow via any branch can be identified and appropriate charging stations can be selected.

Smart charging concepts

From the group of sensitive charging stations, those with the lowest consequences for the users have to be chosen for load management measures. An important aspect is that the selection is non-discriminatory, meaning that not the same charging station is selected every time, just because it is positioned at a grid bottleneck (especially relevant for home charging stations). With these targets in mind, five charging concepts were developed, each with its own advantages and disadvantages, which are briefly explained below.

First Come – First Serve

According to this concept, the vehicles are charged in the chronological order of their grid connection time. If necessary, the power of the latest connected vehicle is reduced. This concept is easy to understand for the customers, it does not need any status information from the vehicle and guarantees a fast charge of the first connected vehicles. Unfavorable is the fact that long waiting periods for the last connected vehicles could be generated, so they would be not operational for a significant time. To realize this concept, the charging stations only have to transmit the connection time.

Equal distribution of the available power

The available power is distributed uniformly among all charging stations. This way, waiting periods are avoided and very short distances could be covered after a short charging time; again, no status information from the vehicle are necessary. Main negative factor is that a complete charge may take a long time. From the technical point of view, the charging stations must be able to control the charging power dynamically.

Preferred charging of fully discharged vehicles

If the remaining range of a vehicle is below a minimal level, its charging power will not be reduced. Therefore, all vehicles are operational for average trips in a minimal time. Again, the disadvantage is the long complete charging time. This concept needs the state of charge and the battery capacity of the connected vehicle.

Combination of preferred charging and First Come – First Serve

Both discharged and long connected vehicles are preferred. This Combination limits the loading time to a defined maximum and keeps the advantages of the “preferred charging of fully discharged vehicles”. Here, state of charge, battery capacity and connection time are needed.

Prioritization according to the planned length of parking time

The user enters the time of his next planned trip. Therefore, the load management system can ideally distribute the available power, so the vehicles are then fully charged when needed. If the user additionally enters the length of his next trip, the distribution can be realized even superior. To ensure a truthful reporting, however, flexible electricity prices or other (financial) incentives are required. Otherwise the users would possibly enter very short parking times. Furthermore, this concept leads to an extra effort for the users and restricts the option of spontaneous trips.

Current feasibility

Present charging stations are not able to read status information (such as state of charge, battery capacity etc.) from the vehicle. This requires an advanced communication link between the charging station and the vehicle which is still being developed within the ISO 15118 protocol. For this reason, the more complex but also more intelligent concepts (which need status information) cannot be used until its introduction.

Outlook

The above mentioned concepts are only able to cure off-limit conditions caused by an excessive load, but nowadays an illegitimate voltage increase due to a high PV feed-in is the major problem. Therefore, in order to harmonize the decentralized generation and the e-mobility power consumption, also charging concepts which are able to increase the current charging power are necessary. This could, for example, be realized by throttling the charging process to a limited power maximum until a higher load is needed. Another option is to limit the state of charge (if the user does not need the entire range) and to fully charge the battery only if the renewable feed-in is too high.

In any case, those concepts necessarily involve disadvantages for the users which have to be compensated (financially). In order to gain acceptance for these measures, it is important to create a (financial) incentive system.

CONCLUSIONS

The present paper shows the necessity of a smart grid system in order to prevent an expensive grid and storage expansion. Due to the high power consumption, particularly the charging process of electric vehicles has to be controlled by such a system. Thereby, it is important to ensure that the mobility of the users is not unnecessary restricted by load control activities and negative effects are minimized.

To achieve this objective, only charging stations which can influence the current off-limit condition should be controlled; a possible selection method based on sensitivity analysis has been presented. From all suitable stations, those with the lowest consequences for the users have to be chosen for load management measures. Therefore, five charging concepts were developed which each place different requirements on the charging infrastructure.

It has also been shown that (financial) incentive systems have to be created, in order to ensure a truthful reporting (e.g. for the "Prioritization according to the planned length of parking time" concept) or to realize concepts which can increase the current charging power.

NOTIFICATION

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