Impact Assessment of Electric Vehicles on Existing Distribution Grids with Decentralized Photovoltaic Generators

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Abstract—**In the near future, the existing grids may be overloaded due to the integration of an increasing number of batteries from electric vehicles (EV). In this work, the mobility behaviors in different regions are analyzed, and the corresponding load curves are deduced for two charging concepts. The quantity of EVs as additional load in distribution grid is examined with the aid of a static load flow analysis for the different charging concepts.**

Keywords: mobility behavior; load curve; load flow analysis; absorbing capacity

I. Introduction

Due to strong political demands and technological advances, there is a growing interest in electric vehicles (EV) to replace the vehicles with combustion engine. According to the projection by RWE, from now on, the number of electric vehicles (EV) and plug-in hybrids (PHEV) will increase rapidly, and till 2020, there would be 1.5 million EVs and 1 million PHEVs in Germany [1]. The existing grids need to satisfy the growing energy demand from the introduction of battery electric vehicles in the future. On the other hand, with the development of battery technology, as mobile energy storage devices, batteries could even store excess renewable energy and provide balance energy by load management. For grid extension planning, it is especially essential to assess the potential absorbing capacity of existing distribution power grids for EVs.

First of all, the load curve of the mobile energy storage needs to be determined. It depends on its charging power, the resulting charging time, and also the time slots when the battery can be connected with grids. Furthermore, the aggregated load curve could be equalized using a controlled charging concept, but it needs extra communication and control units that may cause additional costs.

In this article, the existing low voltage grids are chosen to be modeled in detail; these grids are then augmented by additional feed-in of Photovoltaic Generators (PG) at every household. Different feed-in curves are applied to model delivery of energy during the course of the day. On the assumption that the battery may be charged only at home with two different charging concepts, the potential absorbing capacity of power grids are evaluated by load flow analysis.

II. Availability of Cars for Grids

In the ideal case, the battery should be charged directly as soon as car is parked. Obviously, it requires enough charging stations in public places, additional units such as communication and clearing systems etc. should be also assembled into the charging station. By comparison, charging at home being easy to realize in the short term [2]. In this section, the availability of electric car for the grids is analyzed in case of charging only at home.

A. Mobility behavior analysis

For the availability analysis, it has to be known the total number of registered cars in an area, the main users of these cars, how these people use the car every day, e.g. employed persons may drive to go shopping after work. Figure 1 shows the possible mobility behavior during the day; due to the assumption "charging only at home", only the trips between household and other destinations were taken into account. However, for subsequent estimation of daily energy consumption, the trips between all destinations have to be considered.

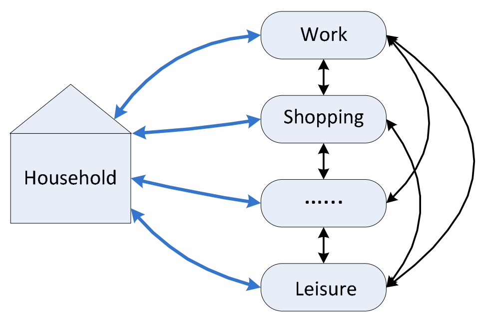

Figure 1. Possible destinations of trips during the day

The relevant statistics can be obtained from two data bases; one is the databank of state statistical office, which is directly available online [3]. The demographic structure is then determined: such as information about population density, households, registered cars, incoming and outgoing commuters, part-time and full-time employees etc. The other data base for the mobility analysis is the study "Mobility in Germany (MiG) 2002" [4]. It is a nationwide survey involving around 25,000 households. The study, which has been carried out on behalf of the Federal Ministry of Transport, Building and Urban Affairs, concerns the day-to-day travel behavior of Germans in 2002 and 2008 (available in 2010). The data, which is compiled in the course of the study will be used both as a basis for transport planning in Germany and for scientific research on daily mobility. The mobility behavior of cars is determined by many factors, such as the price of oil, the demographic development, and legal frameworks e.g. fuel taxes and the commuting allowance and the development of public transport. In the long term, the mobility behavior will change slowly [5]. The mobility behavior of cars is one of the most important criteria concerning the estimation of the load curve of electric vehicles. Therefore, following major characteristics are determined on the basis of empirical data.

B. Comparison of availability of cars in typical regions

Three typical regions are selected to investigate: urban area (A), small town (B), rural area (C). Population structure and the corresponding main-user structure of vehicles are estimated based on the two databases; missing actual demographic data can be estimated using general data from the study MiG 2002, such as the specific number of students. On the basis of data from the study, in accordance with the mobility behavior, inhabitants can be roughly divided into four groups: employed persons with car; unemployed person with car, students with car, and apprentices with car. For instance, with high percentage about 90 % of full-time employees in rural area belong to the first group; 60 % of retired persons are part of the second group; the percentage is varied for different regions. In general, the total number of persons with available cars is about 10 %-15 % more than the total number of registered cars. Coincidentally, in the selected area C, the total of four groups approximately equals to the total number of registered cars.

The usage of cars for each group is investigated in the following: e.g. when people as driver start leaving home; different destinations of trips during the day; when they will be back home, etc. Thus, the number of drivers from each person group as well as the mobility behavior for each purpose of the trip should be determined. The trips, whose transport is motorized individual traffic (MIT), are selected hourly for the calculation of the non-availability of cars for local grids concerning different purposes of trips. If the person as driver is mobile by day, main purpose should be determined by means of comparing the number of trips for different purposes at first. Furthermore, the probability, that the mobile driver may use the car for other purposes, is estimated. For instance, for the persons of group 1, the main purpose of the trip may be driving to work on weekdays and driving for leisure on the weekend. Students and apprentices have similar mobility behavior as unemployed and employed persons respectively [6]; therefore, inhabitants are classified following only into two groups. In addition, mobility behavior depends also significantly on the following factors: region, season, and type of days. With consideration of these factors, the specific availability of cars can be estimated. Altogether nine characteristics are used to describe the availability of cars in different periods. Figure 2 shows the availability of cars over the course of time (on weekday during winter in selected areas).

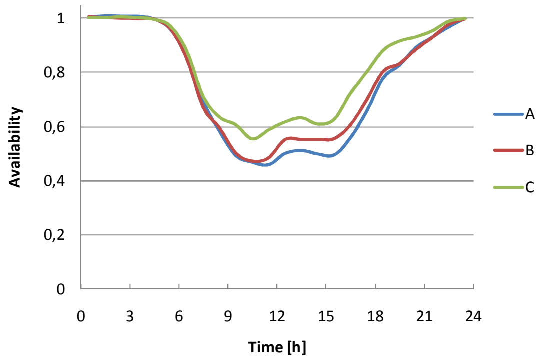

Figure 2. Time-related availability of cars

Around 6 am, employed persons start leaving home, around 12 pm., only 45 - 60 % of cars are available; availability of cars fluctuates at midday due to the mobility behavior of group 2 actually; the curve indicates also the when the mobile person (as driver) might stay at home; mobile persons (as driver) in urban city stay rather outside during the day. Moreover, based on the characteristics, time-related available energy and power can also be estimated.

III. LOAD CHARACTERISTICS OF THE BATTERY

A. Evaluation of daily energy consumption

In the previous section, the time-related availability of cars for local grids has been derived. In order to analyze the load characteristics of batteries, it is necessary to know how long the battery can be connected to the grid; which is related to the specific daily energy consumption of cars. Thus, estimation of the daily mileage of each group is necessary. The daily mileage for each group depends especially on the number of MIT-trips and trip distance, purpose of the trips and also on season, region etc. For instance, car mileage of group 1 and group 2 in winter on weekdays in rural area are about 37 km and 21 km, respectively. The average car mileage for two groups is determined and applied to each car, which is determining to calculate the charging duration. The charging duration is evaluated on the basis of following assumed technical characteristics of battery:

- Battery capacity 35 kWh;
- Energy consumption 20 kWh/100km;
- Linear working area - state of charge always between 30 % and 80 %.

The charging power could keep constant up to state of charge of 80% using the typical charging method "constant current constant voltage", after that, the charging power decreases with increasing state of charge, it leads to longer charging duration. By setting the limit to 30%, the battery cannot be discharged deeply to ensure the long-term durability [7]. The standard charging plug for cars has been defined in Europe, the battery can be charged using single/three phase voltage, the charging power is limited to 3.5 kW (1~) and 11 kW (3~) concerning the nominal current 16 A per phase according to DIN 61851-1 in Germany.

B. *Load curve under different conditions*

Subsequently, the time-related load characteristics for every household are determined. There are also nine load curves; Figure 3 shows the load curve on weekdays in winter using single/ three-phase voltage. Logically, the battery can be quickly recharged with 11 kW, thus, power demand is lower at the beginning of the night. However, the peak value of load curve is higher and appears earlier than with single-phase connection.

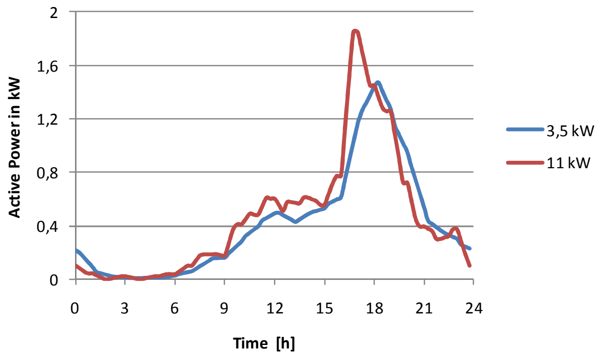

Figure 3. Load curve for charging with single- and three phase voltage

Figure 4 illustrates the load curves for each household according to single phase charging (3.5 kW) on weekdays in winter in different regions; peak load in the small town (B) and rural area (C) is higher than in selected urban areas (A) due to the larger number of cars per households; load curve is noticeable higher in the small town at midday.

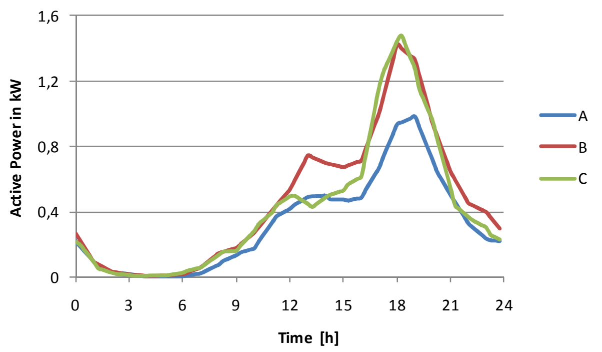

Figure 4. Load curve of battery in different regions

Due to similar mobility behavior, the resulting load curves of batteries are also the same on workdays, therefore, load curve only at the weekend (including Monday and Friday) have been selected to illustrate. Figure 5 describes the load curve only over the weekend in winter regarding single phase charging. There is almost no more power demand from battery during the night before 6 am. The peak load on weekdays is distinctly higher than at the weekend since most people do not have to work, on the other hand, mobile persons stay rather at home.

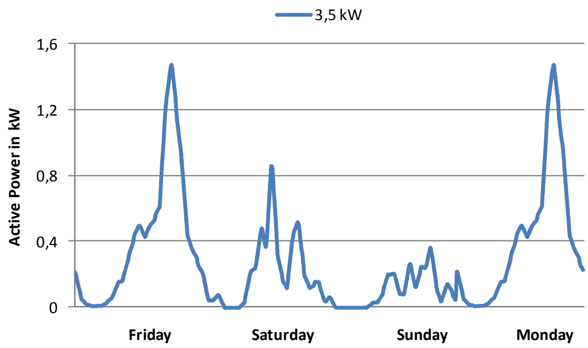

Figure 5. Load curve of battery at the weekend in winter

C. *Standard load profiles and aggregate load curve*

The daily basic load of households is described using standard load profiles [8]; the standard load profiles (SLP) consist of a set of daily load curves with a resolution of 15 minutes. One profile comprises nine different curves, considering three seasons (winter, summer, transition period) as well as three day types (weekday, Saturday, Sunday). These SLPs are designed for different types of customers, namely households, agriculture etc; only the household profile H0 is considered. Apart from the day type, this profile uses a correction factor for each day according to the season [9]. The coefficients of this function are changeable so that it can be adapted to apply in different regions, and the following function is used in this work, the dependent and independent variable indicate the correction factor and ordinal day number. Its value oscillates roughly between 1.25 in winter and 0.75 in summer. The raw form of SLPs is standardized to a yearly consumption of 1000 kilowatt-hours (kWh), corresponding to the area underneath the 365 daily load curves.

$$y = -3.92e\text{-}10\ x^4 + 3.2e\text{-}7\ x^3 - 7.02e\text{-}5\ x^2 + 2.1e\text{-}3\ x + 1.24$$

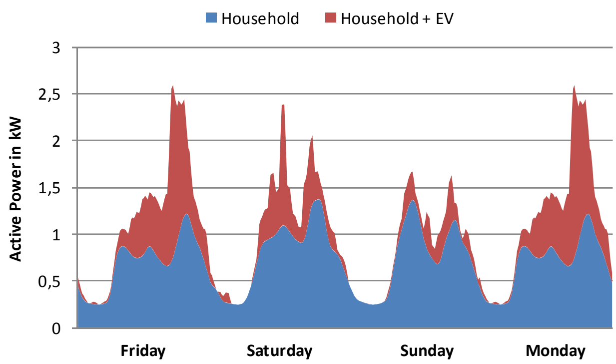

Figure 6. Aggregate load curve using three phase charging connection

The peak power demand of batteries using three phase voltage occurs earlier than the peak load of households; in contrast, the peak load with 3.5 kW appears almost at the same time. Thus, the aggregate peak load is lower using three phase battery charging in spite of higher charging power.

Corresponding different day types in winter, the aggregate load curve according to three phase charging (11kW) at the weekend in selected rural area is shown in Figure 6**.** With high penetration of electric cars, the aggregate peak power demand in the evening increases significantly, while low load during the night remains almost unchanged. The aggregate peak load at midday on Saturday is as high as in the evening on weekdays. As mentioned in section 2, the additional load is actually caused by mobile persons (driver), who use electric cars daily; on the other hand, the load curve of households depends mainly on the consumer habits and the peak load might occur only when the consumer is at home, that means, more persons in the household, load may be higher; in this way, that is easy to understand, why the aggregate peak load in the evening on weekdays is almost double as basic peak load of household, e.g. battery is recharged during cooking. Avoiding overload of the existing grids may be possible only with low penetration of electric cars, which should be examined according to the current operating condition of grids.

D. Controlled battery charging

To increase the penetration of electric cars without grids extension, the controlled charging of batteries is worth to be considered, namely, the batteries may be charged mainly during the night; meanwhile, the basic load curve could be partially equalized. In the present work, a controlled charging concept is proposed to meet the following conditions:

- Charging not during peak load periods;
- Charging finished before 6 am on the following day.

At first, the load curves of battery and household are selected corresponding to the day type. If the battery cannot be fully charged in the evening on the same day, it may be recharged in the following night; however, the aggregate load in the night should be lower than the limit value, which depends on the peak load on the next day. Thereby, the absorbing capacity of grids would be enhanced; however, the control units cause expenses or additional costs.

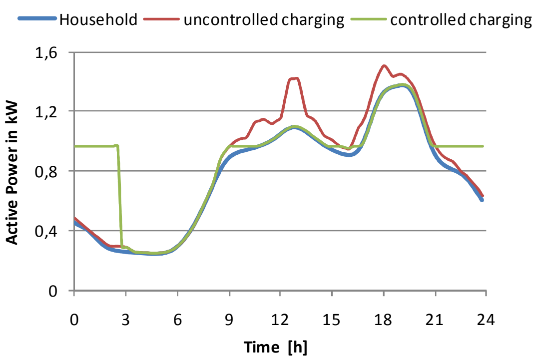

Figure 7. Comparison of load curves (controlled and uncontrolled charging)

Assuming that 25 % of registered cars are replaced by electric cars, Figure 7 depicts the aggregate load curve on Saturdays in winter according to the controlled charging concept (with three phase connection). The blue curve indicates the load curve of households; the red load curve is for uncontrolled battery charging, the green load curve has been determined by complying with the abovementioned conditions, batteries are recharged in the evening with the limited constant charging power; since the batteries cannot be fully recharged on Friday, the higher load still occurs early in the morning on Saturday.

IV. LOAD FLOW ANALYSIS

The following investigation has been carried out only for the selected rural area (C). An existing distribution grid in this area has been selected to evaluate its absorbing capacity for electric vehicles. Potential future photovoltaic installation has already been estimated for this rural area [10]. With the aid of static load flow analysis, the quantity of electric vehicles as additional load in distribution grid will be examined concerning three phase battery charging. Following models have been used to simulate the network, the household customers and the photovoltaic (PV) units. All investigations have been carried out with a commercial software system for network planning.

A. Grids

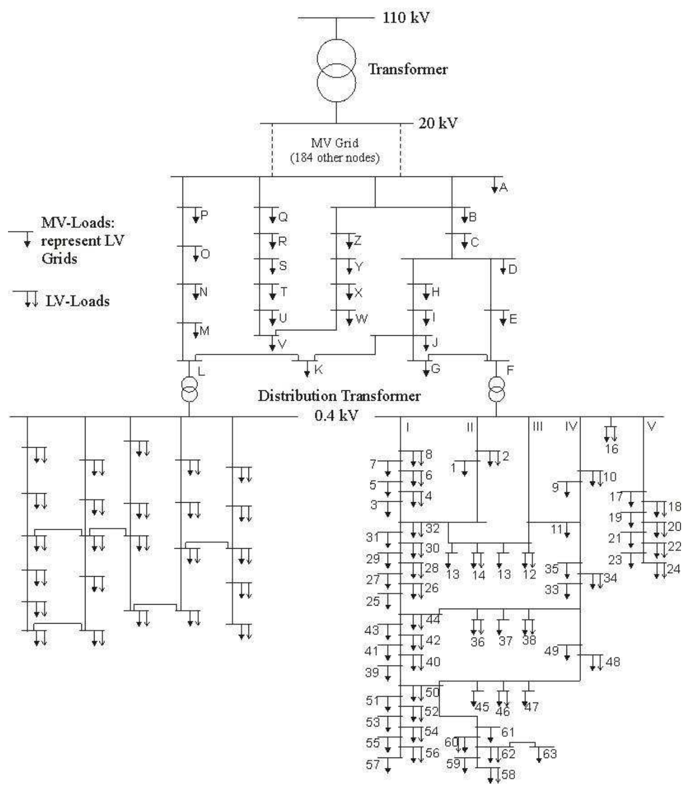

Figure 8. Power grid with its 63 loads

The research for this paper is based on one low voltage (LV) network covering several streets of a small town in

Germany. It is part of a medium voltage (MV) network ranging over a mainly rural area. The LV network consists of 63 household loads and 1.5 kilometers of lines where 100% is implemented as cable.

The annual peak power amounts to 365 kVA which corresponds to 90% loading of the 400 kVA distribution transformer. Approximately 67 % of the loads are connected in meshed structure; the rest is connected in a radial structure to the substation. Fig. 8 shows the LV grid topology with its 5 feeders and 63 loads in detail.

B. Consumers

In this model, loads represent household customers. Due to the lack of additional information, they are all assumed equal concerning peak power and load profile. In the given network, the peak power of the substation is known by measurement. It is divided by the number of connected consumers to obtain peak power at household level. Power factor is considered constant over all households with 0.95 inductive. Hence, all 63 customers are assumed to follow exactly the same load curve. Concerning the measured power and household size of the selected rural area, it can be estimated that each customer contains four households. Finally, the values of the household load profile H0 are normalized so that its maximum value equals to the peak power of one household. Considering batteries as additional loads of each household, the developed aggregate load curves for two charging concepts in the section 3 have been utilized. The simulation has been carried out, on the supposition that battery is recharged only using three phase connection.

C. PV units

The potential for PV installations is approximately one kilowatt-peak (kWp) per inhabitant for the respective town. The yearly output has been estimated according to measured values of solar irradiation and the system efficiency. The measured data set consists of one single curve of about 35 000 quarter hourly values for one whole year.

Using cautious assumptions, for the following simulations, a PV system with 10 kWp is installed on every second roof obtaining a yearly output of 900 kWh per kWp and year. Only active power feed-in is considered, i.e. the power factor equals to 1. PV feed-in depends heavily on the weather.

D. Results

The impact of integration of batteries into grids on the system, especially the loading of critical components like cables or transformers, as well as possible voltage violations have been examined according to the following criteria:

- Avoiding overloading of distribution transformer, cables, and overhead lines;
- Voltage variation between ± 10% of rated voltage at each node.

Several simulations were carried out to examine the absorbing capacity of the selected existing distribution grid for two charging concepts. The penetration of electric cars depends mainly on the rated capacity of the distribution transformer of this grid. According to above-mentioned criteria, 20% and 32% penetration of electric vehicles in regard to the total number of registered cars in the selected region is determined concerning uncontrolled and controlled charging concept respectively.

The graphs presented in this paper show the third week in January and the second week in June as they comprise the value of maximum household consumption and maximum PV feed-in, respectively. Current, power flow and loading of the transformer and cables have been simulated.

In the following figures only active power flow are presented. Furthermore, loading of cables has not been critical during the simulation. In order to present characteristic voltage profiles, the nodes 57 has been selected for connecting the most distant load in the meshed topology. Furthermore, the 0.4 kV main bus bar is selected because its voltage profile is mainly imposed by the MV level where no PV feed-in is considered.

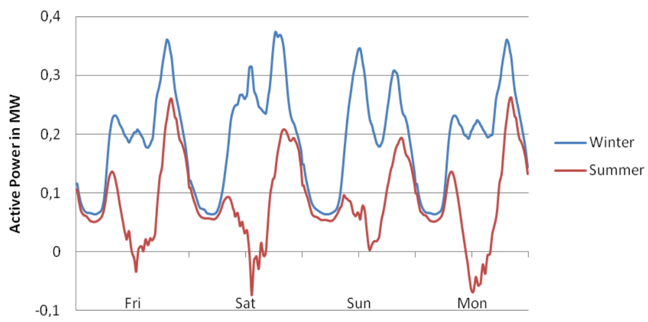

Figure 9. Active power flow into LV grid (via transformer)

As shown in Figure 9, with 20 % penetration of electric vehicles using uncontrolled charging, the peak power demand in the evening in summer is lower than in winter due to the correction factor for standard load profiles indeed. The peak active power demand is about 374 kW for those 63 households in the evening on Saturday in winter; meanwhile, the transformer is fully loaded. At midday in summer, active power can be fed into the MV-grids via transformer due to the decentralized PV generators; hence, in these situations the voltage is higher at that moment.

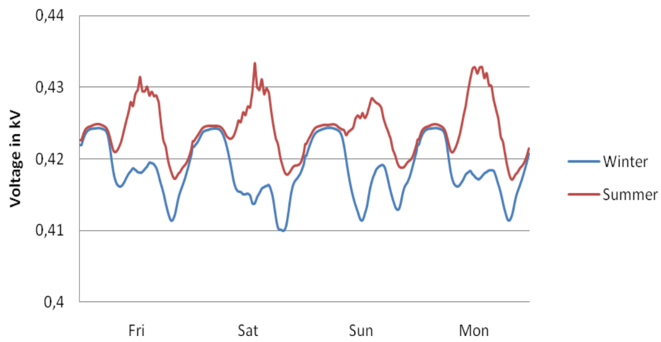

Figure 10. Voltage profiles for 0.4 kV main bus bar

As shown in Figure 10, the peak voltage is about 433 V. Avoiding a peak voltage above 440 V, the traction battery can be considered to be utilized as electrical storage to absorb the excess energy in due time and meet the peak demand in the evening. In this case, the available energy and power of batteries, which depend on the mobility behavior of mobile persons, need to be examined.

Analogously, at the node 57, the voltage is also higher at midday in summer; however, the voltage is even below 400 V in the evening in winter.

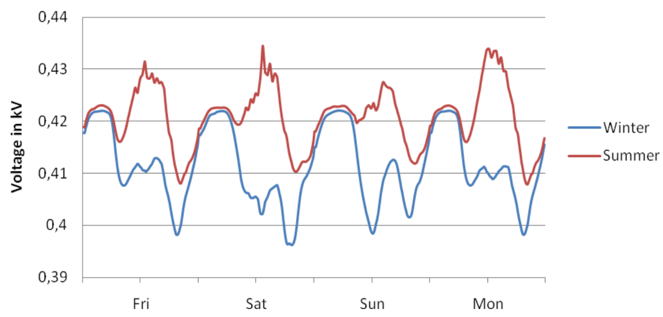

Figure 11. Voltage profiles at node 57

The critical voltage occurs either at midday around 1 pm in summer or in the evening around 7 pm in winter. Concerning controlled charging concept, the battery should be recharged mainly during the night, thus, the controlled battery charging has almost no influence on the critical voltage. On this account, the voltage profiles for controlled charging not shown in the figure.

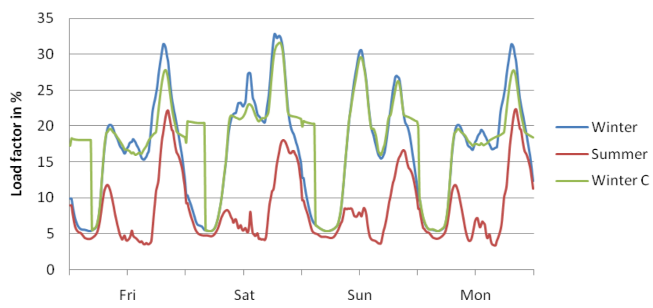

Figure 12. Load factor of cabel F-I

Figure 12 illustrates the time-related load factor of cable FI. The green curve (winter C) indicates the load factor in the course of time concerning the controlled battery charging; the peak value of load factor is about 33%. Actually, the load factors of the other cables are also below 45%. At midday in summer, the load factor is even below 10%; obviously, cable is not the critical component for integration of EVs into the selected grids.

V. Conclusions

In the present work, the mobility behavior analysis has been carried out on the basis of the study "Mobility in Germany 2002", and the resulting availability of electric vehicles for distribution grid in different regions has been determined on the assumption that batteries can be recharged only at home. However, using electric vehicles as a replacement for vehicles with combustion engine may lead to the change of mobility behavior [11]. The consequent feedback effect for availability has not been considered.

Concerning two different charging concepts, the Load profiles of battery have been generated for single and three phase charging. The aggregate peak load of household depends mainly on the mobility behavior of mobile persons. The absorbing capacity of the selected existing grid for traction battery has been assessed with regard to two charging concepts. In case of uncontrolled three phase charging, 20 % penetration of electric cars can be achieved; the penetration increases by 12 % regarding controlled three phase charging, the load curve can also be partially equalized. The distribution transformer is the critical component of the selected gird for EV integration. Similarly, the absorbing capacity of the other distribution grids in the selected rural area can also be assessed.

Given the technological progress, installed power of new distributed generation units can exceed consumption. This effect is particularly visible for photovoltaic systems as peak generation is in the middle of the day, while peak consumption occurs mainly in the evening. Batteries of EVs could be utilized to cover the peak power demand and to balance short-term stochastic feed-in of decentralized photovoltaic generators [12]. However, the required control units may cause additional costs.

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