GRID-INTEGRATION OF HIGH POWER CHARGING INFRASTRUCTURE

Dr.-Ing. Johannes Brombach
Innovation for ENERCON GmbH
Bremen, Germany
Johannes.Brombach@enercon.de

Dr.-Ing. Frank Mayer
Wobben Research and Development GmbH
Aurich, Germany
Frank.Mayer@enercon.de

Dipl.-Ing. (FH) Christian Strafiel
Wobben Research and Development GmbH
Aurich, Germany
Christian.Strafiel@enercon.de

Dr. Jens Winkler
ENERCON GmbH
Aurich, Germany
Jens.Winkler@enercon.de

Dipl-Ing. (FH) Alfred Beekmann
Wobben Research and Development GmbH
Aurich, Germany
Alfred.Beekmann@enercon.de

Abstract – **This paper presents a novel approach to integrate charging infrastructure in low and medium voltage grids. Technologies out of wind energy converter are used to make grid features possible which are well known from modern wind energy systems. The first chapter describes the requirements of modern charging infrastructure. The application pattern of chargers is presented, the need of renewable sources to minimize the CO_2 footprint is shown and the technical requirements will be given. In the second chapter a detailed view to the electrical grid is given, with an emphasis on integration of renewable sources and charging infrastructure. In the third chapter a modular and flexible charging system is presented with an additional support of the grid. It can be proven more charging infrastructure could be installed in an existing grid, if the system is equipped with modern grid stabilization technologies.**

Keywords – grid integration; charging infrastructure; modular charging system; storare integration

I. ELECTRIFICATION OF TRANSPORT SECTOR

Reducing local emissions and the CO_2-footprint of mobility are main drivers for the current trend towards battery electric vehicles (BEV) worldwide. With reference to the Paris climate agreement to reduce global warming to 2° C, it is obvious that the electricity used in BEV must be generated by renewable sources.

The electrification of transport will bring great challenges in terms of infrastructural expansion to our economies. Following the goal to transform a high percentage of classic combustion engine cars to battery electric vehicles means, making them suitable for different use patterns, including the need to drive long distances without having stops of several hours to charge the battery in between. Therefore the need for fast charging solutions – such as High Power Charging Stations with 350 kW per charging spot – along the main traffic routes is inevitable.

Especially grid operators have to think about new concepts, how to ensure availability of high power demands without a negative impact on the power quality of the existing distribution network. On the other hand the regulatory obligations may have to be adapted to the future needs. To design the complete grid technology according to maximum power demands (worst case) will be too conservative and therefore expensive.

Taking into account that there renewable energy sector is already a successful example for an optimization of decentralized grid use patterns and the fact that there are technologies for decentralized grid support activities and electrical storage components available, grid expansion may not be necessary in the first place or might be avoided completely.

A. *Requirements Regarding Typical Use Patterns*

One of the first questions is the typical operational profile of a car. Figure 1 shows the distribution of the daily driven distances in the USA.

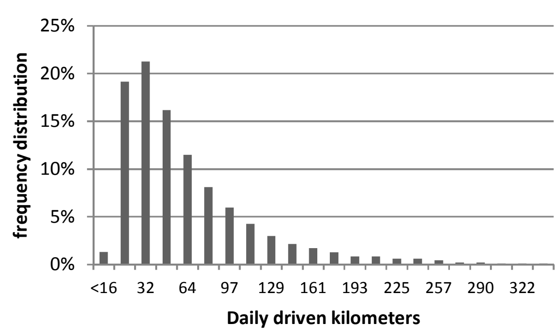

Figure 1. Frequency distribution of dayly driven distances in USA (according to [1])

The chart shows that at 75 % of the days an electric car could be loaded over night at home with a charging rate of approximately 12 km range per hour (25 kWh/100 km, 3 kW charge power). If a reload is possible at one destination (for example at work) 95 % of the days the car could be loaded at a normal plug.

For longer journeys and situations where a fast reload is necessary faster chargers are needed. For such situations fast loading infrastructure has to be installed at neuralgic points, for example at motorway service stations or other frequently used roads. Due to practical reasons the charging rates have to be comparable to conventional refuel of a diesel or petrol car. Today's fast charger with 50 kW could charge 200 km range in one hour, see table 1. For a daily shuttle to work (of about 10 km) this might be enough, but for more convenience the charging rates have to be much higher and the charging power has to be above 100 kW to charge up a car during lunch break. For a fair comparison to conventional cars the charging power has to be 350 kW, so a reload for a distance of 350 km additional range is made in a short brake of 15 min.

TABLE I. CHARGING RATES FOR A PREMIUM CAR WITH A POWER CONSUMPTION OF 25 KWH/100 KM AND POSSIBLE DISTANCES AT TYPICAL CHARGES

Charging source	Charging power	Charging rate (range per hour)	Range after typical charge
Home plug (AC, one phase)	3 kW	12 km/h	72 km (6 h)
Home plug (AC, 3 phases)	9 kW	36 km/h	216 km (6 h)
Fast charger (DC)	50 kW	200 km/h	350 km (3,5 h)
Fast charger (DC)	125 kW	500 km/h	350 km (42 min)
High Power Charger	350 kW	1400 km/h	350 km (15 min)

B. *Renewable Sources*

Today, in Germany about 535 TWh of electric energy are consumed per year. Also taking efficiency gains into account, this number is doubled to 1.000 TWh p.a. by 2050, as mobility and heating will successively be electrified [4]. In parallel the nuclear phase out and a future coal phase out has to be compensated with renewable sources to meet the climate goals, see figure 2.

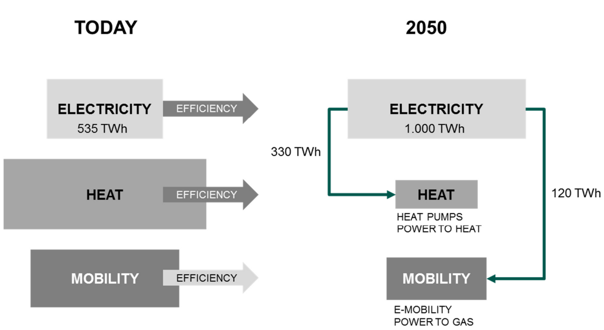

Figure 2. Expected development of energy demand [3]

In the last 20 years the renewables in Germany has doubled the energy production every seven years, see figure 3. Renewable energy production is a story for successful subsidies, because the cost of energy is today in the range of conventional power plants or even lower.

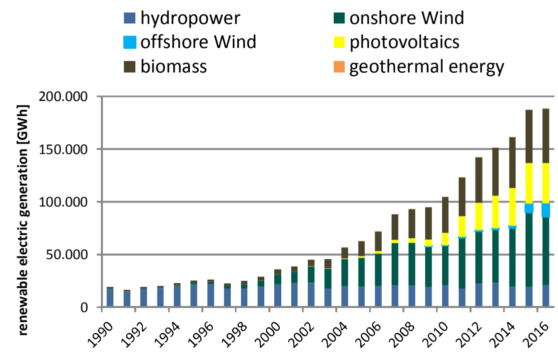

Figure 3. Development of renewables-based electricity generation in Germany [2]

Today renewables could compete with conventional power plants from the economic point of view. According to the growth rate of the last years Germany has a good chance to substitute the conventional generation and to cover the additional energy. Because of grid integration challenges political frameworks limiting the development of renewables. Recent studies show that about 13 % of the area of Germany is suited for onshore wind energy from a technological and ecological point of view. This equals a potential electric energy generation of about 2.900 TWh p.a. [5]. This shows that the technological potential for renewable resources is in line even in a densely populated country like Germany. However, decentralized renewable energy supply is also associated with technological und economic challenges. Potential solutions include an optimization of the interaction between energy producers and smart consumers like charging infrastructure and storages for a prospective establishment of Smart Grids.

Based on the potential the main challenge will be the integration of the energy. The renewable energy generation could not follow the load demand yet and simultaneity of generation based of global weather phenomena leads to high surplus of generation especially in the distribution grids, see figure 4. That very high surplus of renewable energy feed in leads also to high loads in the transmission system, because of necessary energy transports.

One solution to reduce the energy transmission and the surplus in the distribution grids could be controllable loads out of the industry, heat and e-mobility sector.

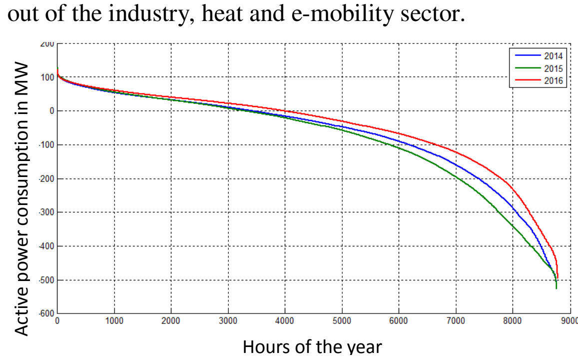

Figure 4. Annual load duration curve for a rural distribution network with high regenerative feed-in (negative is feed in)

C. *Technical Requirements*

As mentioned in the previous chapters, the power consumption of a charging system is very variable. On the one hand the moment a car is connected to a charger is undefined and on the other hand the charging power and the charging characteristics are different between possible BEVs, see Figure 5.

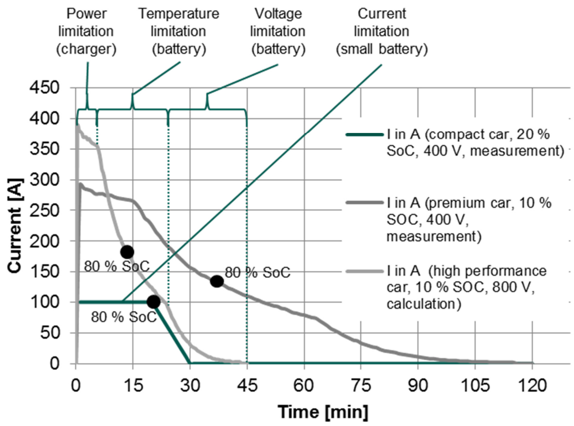

Figure 5. Current over time of different cars on a high power charger

Small BEVs limit the charging current to a defined value until a maximum voltage is reached. Since this moment (app. 80 % State of Charge, SoC) the voltage is limited. This charging characteristic is comparable to mobile phones or tablets (constant current-, constant voltage loading). Faster charging systems are designed to charge a battery with higher currents and high voltage – the limitation is caused by the maximum power at the grid side converter of the charger (constant power loading). With high charging currents the batteries warm up fast, so after a few minutes the limitation is caused by the maximum battery temperature before the constant voltage charging starts.

Especially the adopted charging characteristic of the high performance car (maximum charging power 350 kW) shows the challenge to design cost efficient charger and grid connection. The maximum power is used only a few minutes and an infrastructure designed for this performance would be only partly used for most of the time. With a mix of different customers (compact cars, premium cars and sports cars) at a loading point, the utilization factor is even lower, see Table 2. For that reason the system doesn't have to be designed for 100 % of the sum of chargers power.

TABLE II. SIMULTANEITY FACTORS WITH MIXED USE OF A CARGING STATION WITH DIFFERENT LENGTH OF STAY

Scenario of length of stay	Simultaneity factor
Continuous charging 10-80 % SoC, 1 minute to change car	36 %
Continuous charging 10-100 % SoC, 5 minute to change car	17 %
Continuous charging 30 min, 1 min. to change car	29 %
Continuous charging 60 min, 1 min. to change car	17 %

D. Market outlook

One future market for fast power chargers are the gas stations along the motorways. The number of publicly accessible charging points will grow along the number of electric vehicles. For Germany the national platform for e-mobility (NPE) expected for the year 2020 a demand of 70.000 public charging points and 7.100 fast charging points, which enables long journeys on motorways. The NPE recommends a 10,000-charging point program, jointly funded by the private sector and public sector, in order to expand the loading infrastructure as required [6].

Another big market for charging infrastructure could be the public transport sector. A lot of public transport companies in Europe have decided to change to battery powered electric busses in the cities. This applications requiring charging power of 150 kW at night, a power of 350 kW is demanded for a recharge during a normal break and for a short stop the power can go up to 750 kW with special pantographs on the roof of the busses.

II. TODAY AND FUTURE GRID REQUIREMENTS

Anticipating the additional amount and characteristics of electricity demand in future from BEV charging, especially distribution grid operators have to think about new concepts to minimize impacts on their electric networks [7]. Regulatory frameworks may have to be adapted to future needs. As an example, the current approach, to design the entire grid infrastructure for worst case maximum power demands will be too conservative and expensive. Figure 6 show the transformation process in the electric energy supply system including the integration of renewable energy systems and charging infrastructure.

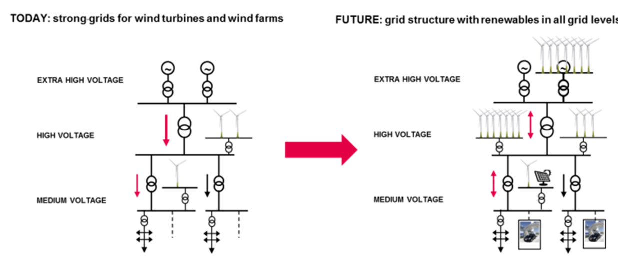

Figure 6. Transformation of the electricity grid

The main goal, to cope with the power demand in areas where the grid is weak and without investing in new infrastructure, can be achieved by supporting the grid voltage through an adequate infeed of reactive power. Therefore the ability of a BEV charging infrastructure is necessary to provide auxiliary services to the grid.

Figure 7 shows a classification of the different auxiliary services from wind power plants. These features can be fulfilled by charging infrastructure as well by using a full converter as an active front-end to the grid.

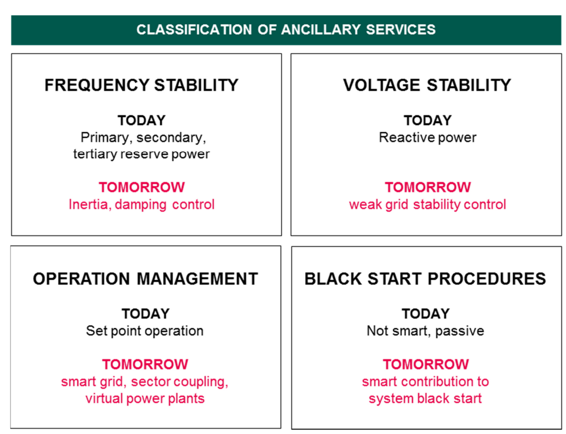

Figure 7. Classification od auxillary services of charging infrastructure based on wind power plants today and in the future (red)

A. *Voltage Stability*

In distribution grids at medium voltage level the feed in or the use of active power has an impact onto the voltage profile in the grid. With a step transformer a voltage regulation at the sub-station from high voltage to medium voltage is possible. That technology has two disadvantages:

- The reaction time of the controller is in the range of minutes. A voltage dip due to fluctuating feed in or consumption could not be compensated.
- The regulation is only at the terminal-level and not within the grid. Hence the controller has to calculate the worst case voltage inside the grid and has to adjust the terminal voltage in a way that all voltages within the grid are in the allowed voltage range.

Because of that most renewable sources have to stabilize the voltage at the point of connection. That is done with reactive power to compensate the self-inflicted voltage drops.

In case of failures with an under voltage in a grid all energy sources have to feed in a reactive current for voltage stabilization nowadays (fault right through capability).

B. *Frequency Stability*

In Europe the transmission grid operator has the responsibility to regulate the grid frequency. For that reason renewable energy systems have to reduce the feed in power in critical situation when the frequency in the grid is too high. Another possibility is an active frequency regulation, if the power is set under the available power of a renewable system.

In case of under frequency events an automatic load shedding is activated. Therefore complete medium voltage outputs are disconnected to reduce the grid load.

In future it is important that also big loads do an active frequency support in failure situations or even to sell reserve power. More important is loads do not disconnect themselves in case of under voltage or over frequency events (fault right trough) to avoid power surplus in the transmission system or – after an undefined reconnection of the loads – an energy shortage.

C. *Other Requirements*

Other requirements for a safe operation of transmission and distribution grids with high penetration of charging infrastructure are the possibility to define limits for power consumption of the charging stations or to define maximum power gradients. The possibility to provide information for grid operator could be helpful for a safe operation.

Another requirement is the power quality. Especially power electronics with passive rectifiers are problematic. The ideal load from grid produces perspective is a single sinusoidal current.

III. High Power Charging Infrastructure with Advanced Grid Features

As shown in the last chapters a future charging infrastructure has to be expendable, flexible with the division of the output power of the single charging points and it has to have advanced grid features. With experience of grid integration of big wind power plants a modular charging system is presented.

A. *Status Quo*

As can be surveyed most ‘quick’ charging points – with the exception of charging network of up to 120 kW chargers of only one OEM - only offer a charging capacity of 50 - 60 kW (DC, CCS or CHAdeMO), meaning that charging and thus waiting times still exceed one hour, provided the battery capacity exceeds 50 kWh.

At all known systems the input circuit is a passive rectifier and there is no possibility to change the phase angel of the input current. From grid perspective all available charging infrastructures are classic constant power loads, comparable with laptop power adapters. This implies that the power consumption is not dependent on grid conditions (like voltage and frequency). In case of any voltage or frequency problems in a grid standard charging infrastructure will not support stabilizing voltage or frequency. With fluctuating load and higher charging power in future it is important to think about strategies for an effective use of the grid infrastructure (similar to wind power plants).

B. *New Approach for High Power Charging Infrastructure*

The experience of the integration of big wind energy converters is used to develop the fast charging solution presented in this paper. The same platform for the grid connection is used hence most grid supporting features for big wind energy converters are also available for the charging system, see figure 10 in chapter C.

A pilot recently introduced at the 2017 Hannover Trade Fair represents one approach of future quick charging solutions. It is based on already existing technology that is used for connecting DC battery outputs of energy storage systems to AC grids. The key components of this power conversion system are inverter technologies, which have been used in wind turbines for more than 30 years.

It is apparent that by exploiting the opportunities of power electronics drawing power from the grid can be done very smooth and also completely balanced. The current flow from the supply grid used to charge vehicles is then nearly sinusoidal so it minimizes harmonic effects during fast charging. Reactive power is fed into the grid in parallel, to help maintaining a normal grid voltage at the connection point. The project task was that the newly developed system must be compatible with global grid guidelines and requirements relating to grid feed-in quality. The result is that connection is possible at a low- or medium-voltage connection point designed for rapid charging and to minimize the influence on grid voltage. The aim is to enable a higher percentage of installation compared to passive systems.

The main component of the high power charging BEV station presented in this paper is a set of two inverters with a total nominal active power of 600 kW. The maximum capacity of reactive power is 500 kVar. That system is used to connect a variable number of charging points.

Based on an intermediate DC link the available power is distributed to power converter units. These units are galvanically isolated and perfectly correspond to the power demand of DC fast charging of today’s BEV. Required voltage and current for the charging processes are given by the battery management systems of the BEV. By choosing between parallel or serial operation of the internal converter units the nominal voltage can be adjusted up to 1000 V and the current can be regulated up to 350 A on a 1000 V basis, or up to 500 A on a 500 V basis. By an intelligent power distribution system, a power of up to 350 kW can be routed to each of the charging ports. Beside the advantage to provide reactive power a cost minimal over installation of charging infrastructure behind this system is possible. Following the calculation of Table 2 in most cases that is possible with no performance reductions on the chargers side.

In Fig. 8 some examples of actual power distribution to four charging points with one power station are shown. Each time a BEV is connected to one charging points of the charging station, the battery management system (BMS) of the car will build up communication to the charging station and based on the requirements of the BMS and the driver of the car the charging process will be started.

Figure 8. Examples for the fully flexible power distribution of ENERCON's High Power Charging Station

To have a power of 600 kW available at the grid point of contact (POC) the typical connection point will be to the medium voltage (MV) grid. In Fig. 9 a possible configuration of the standard charging solution is depicted. The POC on the MV-grid could be e.g. a shared POC with a wind farm, to have the physical availability of renewable energy at the same location. In other cases the renewable energy could be available in the grid just by balance sheet.

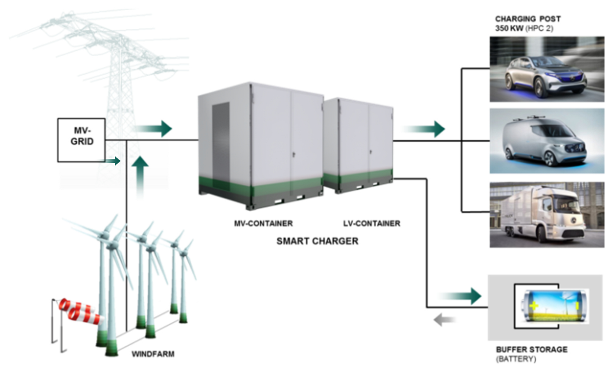

Figure 9. Possible configuration of future HPC 2 charging station

The MV-container – as depicted in the figure – can also be a standard MV-station, comparable to the stations that are already available in the grid of a specific operator. In a standard configuration – based on BMS of currently available BEV – one Low Voltage (LV)-Container with four charging points are proposed. This can be modified to the needs of the specific operator. More important than just adaptability is the characteristic expandability. For future needs the system can be expanded modularly by additional LV-Containers, transformers with a higher power or e.g. battery buffer storage.

C. *Integration of Additional Buffer Storage*

In case the grid connection did not have the necessary power capacity there is an option to install a buffer storage system at the spot of the charging station. A battery system enables the grid connection to be used 24/7 drawing just as much power as the grid can deliver to keep the buffer storage full. When a vehicle arrives for charging the instantaneous high power demand this can be provided directly from the grid whereas further demand served from buffer storage.

Additionally buffer storage can be used for ancillary services, too or for local peak shaving of a renewable feed in. With that multi-purpose option an additional business case for storage application could be developed.

D. *Advanced Grid Features*

From distribution and transmission grid perspective many grid features are possible with a charging system, comparable with modern wind power plants, see figure 10. Also features like the integration of DC-loads like hydrogen generation systems are conceivable. Especially the last option could be interesting to combine smoothing the power consumption and generate hydrogen for fuel cell cars at the same station.

One of the main challenges for the grid operator having high power charging stations installed in his medium or low voltage network is to maintain a suitable voltage level for all connected customers. Especially randomly used charging power will cause fast and high gradients in the voltage. To counteract the problems of the voltage fluctuations the charging station offers the ability to feed reactive power to the grid and to limit the active power gradients. In order to have a convenient solution for mitigation of voltage fluctuation problems the station offers various strategies to control the reactive power support. Starting from the infeed of constant reactive power over power factor control up to Q(U)-control, just to give some examples. All these different strategies can be directly parametrized in the control system of the charging station or operated via standard remote control systems from the control center of grid operator.

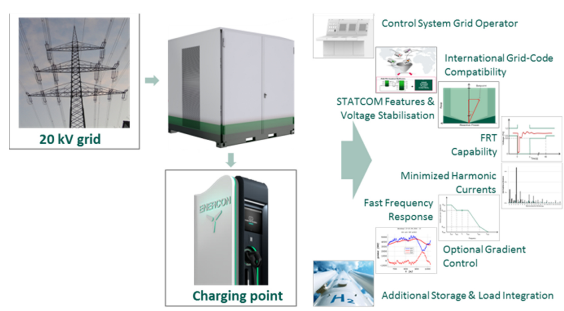

Figure 10. Possible grid features of modern charging infrastructure

As an example for the voltage support the voltage distribution in a medium voltage grid has been simulated, see figure 11. Three voltage distributions are illustrated: in black a simulation without any charging infrastructure installed, in blue a standard charging station installed and in red a charging station feeding reactive power and having a voltage controller installed.

It can be shown – even with an addition of highly fluctuating load – the charging station could stabilize voltage profile in the grid, compared to a grid without charger with voltage support. Thus, beside the compensation ability of the charging station on the network, the charging station achieved an active improvement of the grid.

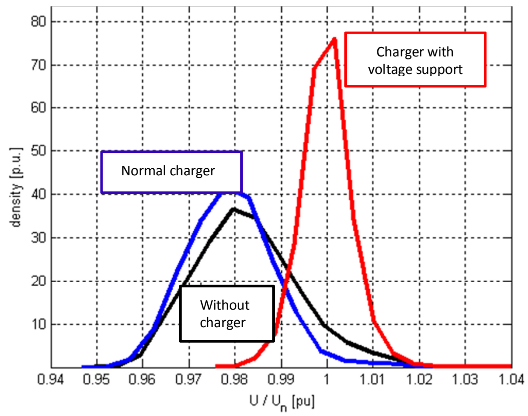

Figure 11. Simulated spread of voltage in a local grid with different charging station options

Furthermore to the voltage support also reactive and active power management could be important for advanced grid integration, respectively an optimal utilization of existing grid infrastructure.

Figure 12 shows a grid with loads, charging systems, wind power plants and a voltage problem at the end of the line and a load problem at the transformer in the substation. The voltage problem could be solved with reactive power from one charging station. With a feed in of reactive power from the upper charging point and with a temporally reduction of active power (for example with a storage or extra charging power) the current flow over the transformer can be minimized to solve the utilization problem in the substation, because of renewable energy feed in. This example proves that intelligent loads in combination with renewable sources could optimize the grid integration of both, charging infrastructure and wind power plants.

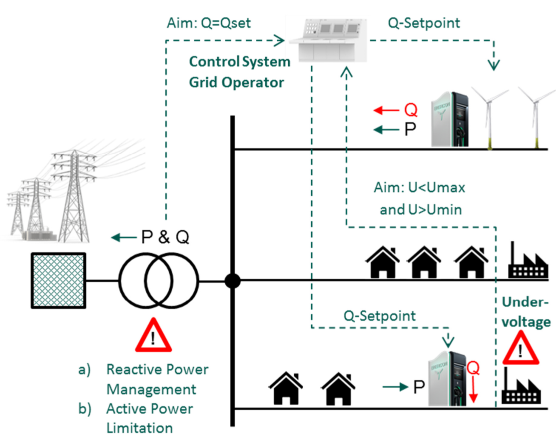

Figure 12. Medium voltage grid with voltage problem at the end of the line and a load problem at the transformer

IV. Conclusion and Outlook

One main challenge for the electrification of the transport sector is the integration of charging infrastructure in the existing grids. A grid expansion based on the maximum power of the fluctuating load profiles is neither technical nor from an economic meaningful.

The paper shows a novel approach of a flexible, expendable and grid supporting charging infrastructure. The shown system could charge up to a range of 350 km in 15 minutes. Thus a charging process is comparable with a diesel or petrol refill. Only with this acceleration of charging times longer journeys without long pauses are possible with an electric car.

Additionally the presented system minimizes voltage and current impacts on the existing grid and avoids expensive grid expansion. This has been achieved by well-known technologies and experiences with the grid integration of wind power plants.

Finally a flexible and cost minimal system was designed. On the one hand the charging power can be distributed flexibly to the charging points, which reduce the costs of the power electronics. On the other hand the system could be expended by more charging power or more charging points, if necessary. Extensions could be easily integrated in the existing system.

The presented system helps to solve economic and technical challenges for the electrification of the transport sector. With the experience of many years of wind farm grid integration a cost minimal integration of charging infrastructure in existing grids is feasible.

References

[1] Solar Journey USA: "Assessment of Electric Cars' Range Requirements and Usage Patterns based on Driving Behavior recorded in the National Household Travel Survey of 2009", Rob van Haaren, Columbia University, December 2011

[2] Federal Ministry for Economic Affairs and Energy (BMWi): Erneuerbare Energien – Zeitreihen Erneuerbare Energien" Historic data about the development of renewable energies in Germany. Erneuerbare Energien (in German). Accessed September 2017.

[3] Fraunhofer Institut für Solare Energiesysteme ISE: "Jahresbericht", Freiburg 2017

[4] Fraunhofer Institut für Windenergie und Energiesysteme IWES: „Geschäftsmodell Energiewende", Norman Gerhardt et al., Kassel 2014

[5] Umweltbundesamt: „Potenzial der Windenergie an Land", Insa Lütkehus et al., Dessau 2013

[6] National platform for e-mobility (German: Nationale Plattform Elektromobilität): http://nationale-plattform-elektromobilitaet.de/themen/ladeinfrastruktur/, accessed September 2017

[7] European Distribution System Operators for Smart Grids: „Future-Ready, Smarter Electricity Grids", 2016