NOVA Measures in Suburban Low Voltage Grids with an Inhomogeneous Distribution of Electric Vehicles

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***Abstract*— Due to the German government's policies, electric vehicles (EV) will significantly gain popularity and market share over the next few years. Great potential for electromobility exists especially in suburban areas, where a full-scale development of so-called electromobility-hotspots is most feasible. The immediate consequence of such transformation may lead to a considerable surge in power consumption and a significantly higher loading of the suburban's low voltage grid. Any inhomogeneous distribution of EV within the grid will further increase the load locally. In order to increase the number of EV that can be integrated into the electricity grid, it is necessary to further expand the low voltage grid. In this paper the grid planning principle "NOVA" is examined ensuring a cost effective and sparing use of resources when it comes to grid expansion. The effectiveness of different "NOVA" measures is monitored and compared on the basis of an increased penetration of EV with guaranteed grid stability.**

***Keywords*—distribution grid, voltage control, NOVA, electromobility-hotspots, electromobility integration, inhomogeneous distribution of electric vehicles**

I. INTRODUCTION

The number of electric vehicles (EV) worldwide has grown exponentially in recent years. At the end of 2019, the car stock was 7.2 million EV (both battery electric vehicle and plug-in hybrid electric vehicle). In 2019 alone, 2.1 million EV were sold, representing 2.6 % of all vehicle sales. [1]

The major automotive manufacturers have announced a large number of electric models and an increasing proportion of EV in their sales figures. More than 500 EV models should be available in 2022 [2]. For these reasons, the number of EV will still increase exponentially, reaching high overall figures in the long-term. For the year 2030, 28 % of all new vehicle registrations and a total of 116 million vehicles are forecast worldwide [1].

Parallel to the increase in vehicle counts, the number of charging infrastructures is also increasing. The charging processes take place especially in the private environment. Suburban areas have good conditions for electromobility due to a high proportion of owner-occupiers and commuters. For this reason, a potentially high penetration of private charging infrastructure, especially wallboxes with charging power of up to 11-22 kW, can be assumed in these grid areas [3][4]. The effects are so-called electromobility hotspots. These suburban grids are already tending to be heavily loaded [4]. Through the grid integration of private charging infrastructure, voltage range breaches and grid overloads are possible depending on the actual penetration and the respective charging behavior [5]. Without suitable measures, there is even the possibility of blackouts [6].

II. "NOVA" MEASURES

Resulting from the increasing number of EV and the ongoing extension of the charging infrastructure more and more critical grid situations are occurring. These situations manifest themselves by violating the voltage range and the valid thermal limits of the electrical equipment. [4]

The grid planning principle NOVA principle is applied to expand the grid capacity and thus preventing critical grid situations. The NOVA principle is derived from § 12 of the German renewable energy law and describes a cost-progressive process for upgrading existing electricity grids [7]. Applying NOVA to a grid extension project means to primarily consider possible grid optimization, then – if optimization is not applicable – a technical grid reinforcement and finally as a last measure grid expansion [8]. The following Fig. 1 shows this successive process.

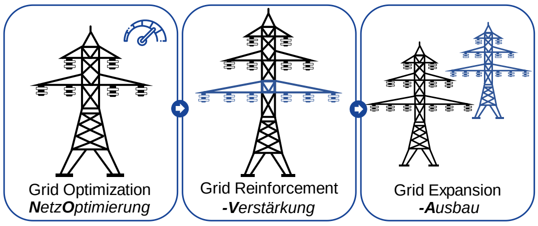

Fig. 1. Grid Planning Principle "NOVA"

Besides cost-efficiency, the goal is to operate with a minimum of intervention into grid and environment [9]. The NOVA principle is the intended method in the German grid development plan of the transmission system operators and is therefore usually used in the extreme high voltage and high voltage grid [8]. In the low voltage grid, considering the existing uncertainties regarding the user-dependent charging behavior and the resulting penetration of the EV in Germany, the step-by-step approach of the NOVA principle holds less risk potential than a conventional grid expansion [10].

A. *Grid Optimization*

Grid optimization can be achieved by changing switching states in the grid and therefore optimizing the load flow. In this paper measures for grid optimization are not considered, since only measures implemented by grid operators are taken into account and the examined suburban low-voltage grids have a lack of operability due to missing information and communications technology (ICT) systems. Other than that, a consumer-side grid optimization for electromobility hotspots such as grid-oriented charging [11] or the use of PV storage systems in the context of prosumers have already been investigated [12]. For this reason, these approaches will not be discussed in this paper.

B. *Grid Reinforcement*

The technical solutions used for grid reinforcement are categorized according to their operating principle of reducing the line impedance and line utilization or longitudinal voltage control. The following Fig. 2 illustrates this.

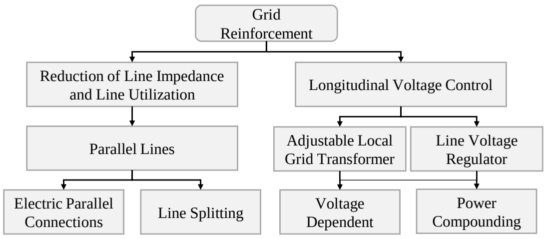

Fig. 2. Chart of the Technical Solutions used for Grid Reinforcement

1) Parallel lines: In order to reduce the line impedance, parallel lines are used. The concept of parallel lines can be differentiated into electric parallel connections as well as installing an extra line and splitting up the already existing one, thus creating two lines [13]. The explained concepts of this parallel cabling are always based on a uniform wire cross-section. Fig. 3 illustrates these concepts.

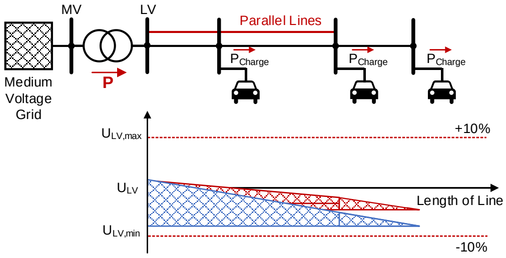

Fig. 3. Improvement of the voltage ratio in a load case due to an electric parallel line; based on [14]

When installing an extra line and splitting up the existing one, the new line is connected to the rear line section. This reduces the current flow per line, resulting in a reduced thermal load [14]. Accordingly, with this concept the line impedance at the respective connection point remains unchanged. When using the concept of adding an extra line with an electric parallel connection – *electric parallel lines* – besides the thermal load also the line impedance is reduced due to the increased wire cross-section – with uniform wire cross-section the line impedance is even reduced by its half.

2) Adjustable local grid transformers (AGT): In the context of longitudinal voltage control, two options are considered: adjustable local grid transformers (AGT) and line voltage regulators (LVR). The AGT is installed within a medium to low voltage substation and replaces the regular transformer. Following this, the secondary voltage level can be adjusted during normal operations without an interruption of the power supply [14]. The voltage regulation is based on the change of the transformer's ratio via an on-load tap-changer in discrete steps. In general the tap-changers are installed on the primary side of the transformer because of the lower nominal current [15]. The installation of an AGT and its possibility to change the voltage ratio decouples the low voltage grid from the medium voltage grid [13]. Therefore, voltage deviations occurring on medium voltage level can be compensated by the AGT. Thus, the total voltage range of U_N ± 10 % according to DIN EN 50160 can be used on low voltage level [13][16]. Fig. 4 shows the use of an AGT to adjust the voltage level due to high load caused by charging EV in order not to violate the permissible voltage range in accordance with DIN EN 50160.

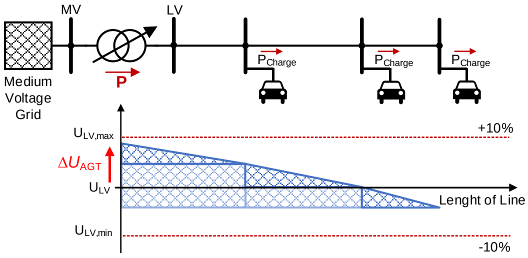

Fig. 4. Adjustment of the voltage ratios due to an AGT; based on [14]

3) Line voltage regulator (LVR): The functionality of the LVR essentially corresponds to the AGT and therefore is only briefly explained. The place of installation of the LVR within the grid in the considered line is variable depending on the location of a critical voltage level [14]. Hence, the LVR enables a change of the voltage ratio on the secondary side of the line d due to changing the transmission ratio. Fig. 5 illustrates this in a peak load case.

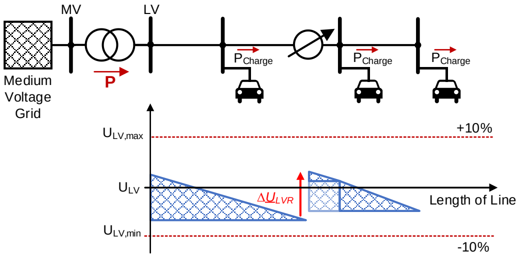

Fig. 5. Adjustment of the voltage ratio due to a LVR; based on [14]

Moreover, Fig. 5 shows that the LVR increases the voltage level to avoid violating the voltage range. Unlike the AGT, the LVT does not provide a galvanic isolation between input and output voltage [15]. Other than the, the LVR enables an individual voltage regulation for each phase. However, only the absolute value of the line voltage can be adjusted, not the voltage angle [15]. The LVR can be realized as voltage control system either with or without step control. In this paper only LVR with step control are considered.

4) Control Concepts: Two control concepts are examined for switching operations of the AGT and the LVR. The voltage-dependent control concept measures the voltage on a specified grid node and compares it to a preset setpoint. Based on these parameters a voltage difference is calculated and compared to a tolerance band. If the voltage difference exceeds the tolerance band, a switching command is triggered. In addition, the control concept of power compounding is considered. This concept is based on varying the voltage set point depending on the load of the AGT or LVR. Therefore, the given voltage set point changes depending on the apparent power flow over the AGT or LVR. [14]

C. *Grid Expansion*

The final measure of the NOVA principle is the grid expansion. The grid expansion provides the replacement of currently installed transformers or cables with larger dimensioned electrical equipment. Therefore, the larger dimensioned equipment holds higher current carrying capacity as well as thermal load limits. Other than that, within the grid expansion structural changes such as building and / or connecting another substation are possible. However, the effectiveness of these measures is already well known and therefore does not need to be further investigated [13]. In addition, these measures initiating a structural change are cost-intensive and therefore not in accordance to the cost-progressive process of the NOVA principle [7].

III. INVESTIGATED SCENARIOS AND METHODOLOGY

This section outlines the framework for simulating the influence of electromobility in suburban grid areas. Quasi-dynamic simulations using DIgSILENT PowerFactory are utilized to analyze the impact of the EV on the grid. Based on these power system analyses, statements can be made about future planned but not yet realized network expansion measures in the sense of the NOVA principle, considering current or future loads caused by EV.

A. *Considered Grids for Suburban Electromobility Hotspots*

The investigation on the effectiveness of NOVA measures are conducted on the basis of two suburban low voltage grids. In order to cover possible voltage fluctuations in upper grid levels, a reduced input voltage of 0.95 pu is assumed. The grids are based on the type networks in [17] for *normal* and *extreme suburban grids* synthesized from real low voltage grid areas. For the investigation the grids are divided into two areas: the *critical string* and the *rest of the grid* [12]. The critical string is characterized by its considerable length and its high number of house connections. Accordingly, its influence on voltage stability is greatest in the suburban grids. The rest of the grid has less influence on voltage stability and the load of the cables. Therefore, these grid strings are not examined in detail and some households respectively their loads (including EV) are aggregated (see Fig. 6). The parameter constellation of the extreme grid is chosen accordingly, ensuring that the equipment loads and voltage ratios within the simulations are at least equal to or better in 95 % of the existing suburban low-voltage grids in Germany in comparison to the extreme grid [17]. Fig. 6 illustrates the extreme grid with its total 145 households.

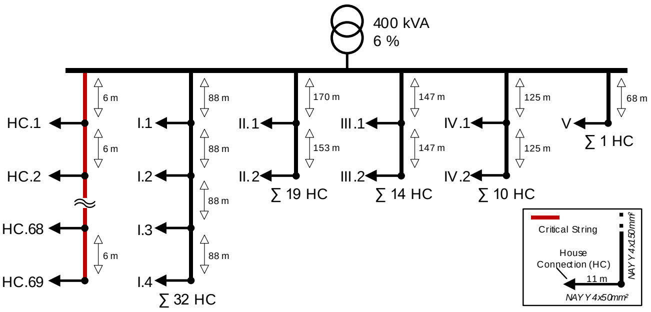

Fig. 6. Extreme suburban grid; based on [17]

The *normal grid* with a total of 146 households replicates the most frequently occurring network structures of suburban settlement structures, with a normal, average parameter constellation [17].

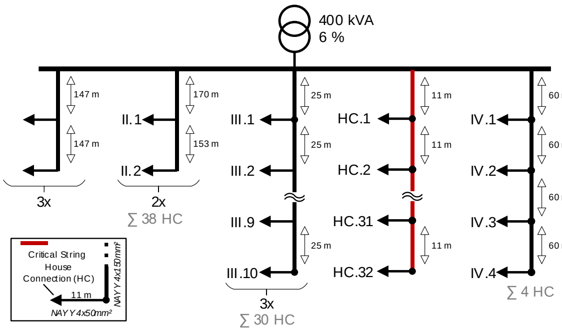

Fig. 7. Normal suburban grid; based on [17]

B. *Load Profiles, Charge Profiles and Simulation Period*

The used synthetic load profiles for households are based on high-resolution time series developed in the course of the dissertation of [18]. Households consisting of two to six persons are considered. The number of the respective household sizes within the grid is chosen based on statistical population data in German suburban areas [19]. The household load profiles are then randomly assigned in the grid.

In this paper two different load profiles for EV are considered. The first charge profile – *overnight charger* – is generated based on the specific weekly mileage of 308 km in suburban areas [20]. This results in an annual mileage of 16,060 km. The average mileage in Germany in 2019 was 13,602 km [21]. Overnight charging is accordingly to [22] seen as a focus for private charging points. Therefore, the loading period of this profile is spread over the night (10pm to 5am) to simulate a realistic user behavior. The second charge profile – *extreme charger* – represents a clearly above-average weekly mileage of 580 km. Thus, it represents a seasonally weekly mileage, which can occur e.g. in the Christmas season while visiting relatives. Furthermore, an average energy consumption of the EV of 25 kWh per 100 km is estimated. This reflects the general trend towards more powerful vehicles with higher specifications [23]. Moreover, the charging power is considered with 11 kW because according to [24] and [25], this charging capacity will become the standard for three-phase charging with a current of 16 A. To demonstrate a worst-case scenario, the simultaneity of one is assumed for the charging processes of the EV.

A simulation period of one week is chosen for the verification of the voltage quality criteria applicable according to DIN EN 50160 [16]. The week is selected according to the largest possible load case in the data basis.

C. *Performance Indicator of NOVA Measures*

The effectiveness of a NOVA measure is determined by an increase in the maximum number of EV that can be connected to the grid while charging simultaneously with guaranteed grid stability. The connected number is limited by the applicable voltage limits (DIN EN 50160) and load limits of the electrical equipment. The following Fig. 8 illustrates this.

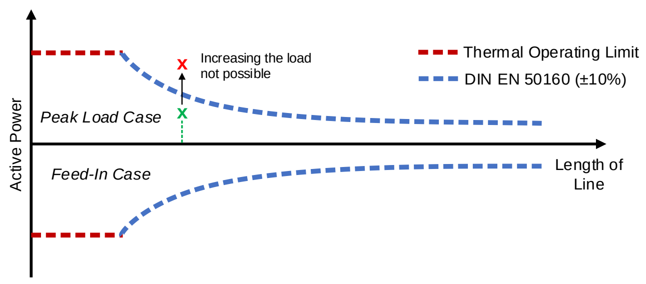

Fig. 8. Identification of triggers for critical grid situations using limit curves in the case of load and feed-in; based on [13]

During the simulations in the first step the maximum number of EV in the critical string is determined. Then, based on the penetration of EV in the critical string, EV are added to the rest of the grid and grid stability is checked again. If grid stability cannot be assured, the number of EV in the critical string is reduced by one. Consequently, the penetration rate of EV is the same in the critical string and the total grid.

D. *Positioning of the EV*

The maximum possible number of EV connected to the grid depends heavily on the positioning of the EV in the grid. Two methods are used to position the EV: homogeneous positioning and inhomogeneous positioning. Using homogenous positioning, the EV are distributed evenly in the critical string. The inhomogeneous positioning considers a rear positioning with the incremental addition of EV starting from the last household in the critical string.

IV. INITIAL GRID STATUS

In this section, the influence of electromobility on the initial status of the extreme and normal grid is examined. This is done by using four different scenarios, arising from two charge profiles and two positioning methods.

A. *Extreme Grid – Initial Status*

Table I illustrates the maximum possible penetration of EV in the initial extreme grid per scenario determined on the basis of quasi-dynamic simulations and assuming simultaneous charging of EV.

TABLE I. EXAMINATION RESULTS OF THE INITIAL STATUS OF THE EXTREME GRID

Charge Profile		Overnight Charger		Extreme Charger	
Positioning		Inhomog.	Homog.	Inhomog.	Homog.
Limiting Factor / Criteria		0.85 pu	0.90 pu	0.90 pu	Cable load
Penetration Rate		14.5 %	15.9 %	7.6 %	11.7 %
Number of EV	Total Grid	21	23	11	17
	Critical String	10	11	5	8

When using the overnight charger profile, higher penetration rates are achieved than using the extreme charger profile. This is due to the nightly loading period represented in the extreme charger profile which is normally a weak load phase. Therefore, during these periods greater capacities in the voltage range as well as cable and transformer utilization are available for the charging process of the EV. When using the extreme charger profile, the penetration of EV is significantly lower due to the higher power consumption.

Furthermore, from an inhomogeneous distribution of the EV follows a clearly smaller penetration rate. In the case of an inhomogeneous distribution using the overnight charger profile, violations of the permissible voltage range limit a higher penetration. These violations manifest themselves by the occurrence of at least one voltage value which is lower than 0.85 pu – *0.85 pu criteria* – and therefore contradict the standard DIN EN 50160. The voltage values used are calculated on the basis of ten-minute averages. Within the extreme charger profile and inhomogeneous distribution, the permissible number of ten-minute averages per week lower than 0.9 pu – *0.9 pu criteria* – is exceeded thus also contradicting DIN EN 50160. In addition, in the case of a penetration rate higher than the one stated in Table I, more than 5 % of a week's ten-minutes averages would fall below the lower limit of the voltage range of U_N -10 %.

The maximum permissible period for violations of the voltage range on the basis of ten-minute average values in one week is 8.4 hours. Since no lower deviations of the voltage range occur in the extreme grid without EV, 8.4 hours cannot be exceeded when using the overnight charger profile because the total charging time is lower. Using the extreme charger profile however follows a high load duration. Therefore, in scenarios using extreme charger profile violations of the 0.9 pu criteria predominate in terms of voltage range violations.

In the case of homogeneous positioning of the EV, regardless of the selected charge profile, the permissible equipment load limits the penetration rate. More specifically, it is the thermal limit of the used cable within the first line section of the critical string – connecting the bus bar to the first household.

B. *Normal Grid – Initial Status*

In the context of the determination of the grid capacity of the normal grid, it is revealed that in all scenarios the permissible equipment utilization of the local grid transformer limits a higher EV penetration rate. Therefore, with regard to the intended investigation of NOVA measures, the local grid transformer is upgraded to 630 kVA rated apparent power. According to [17], this is the largest rated apparent power used in suburban grid areas. The following Table II illustrates the maximum possible EV penetration rate while ensuring that all voltage and thermal limits are not exceeded.

TABLE II. EXAMINATION RESULTS OF THE INITIAL STATUS OF THE NORMAL GRID

Charge Profile		Overnight Charger		Extreme Charger	
Positioning		Inhomog.	Homog.	Inhomog.	Homog.
Limiting Factor / Criteria		Transform. load	Transform. load	0.90 pu	0.90 pu
Penetration Rate		34.3 %	34.9 %	21.2 %	32.2 %
Δ Extreme Grid		+19.8 %	+18.4 %	+13.6 %	+20.5 %
Number of EV	Total Grid	27	27	17	25
	Critical String	11	11	7	10

Based on the more homogeneous grid structure and parameter constellation, the normal grid already allows a relatively high penetration rate in the initial status compared to the extreme grid. Due to the smaller number of households, there is no overloading of the first line section in the critical string.

When using the overnight charger profile, the permissible thermal limit respectively the transformer overload restricts the grid capacity for EV. Considering the scenarios using the extreme charger profile, voltage range violations namely the 0.9 pu criteria limits higher penetration rates. In order to further increase the grid's capacity, it is necessary to take measures for voltage regulation and to increase the capacity of the local grid transformer even further.

V. IMPACT OF NOVA MEASURES ON EXTREME GRID

In this section, the effectiveness of the NOVA measures used to increase the extreme grids capacity for EV is analyzed. For this purpose, the measures respectively the achieved penetration rate is compared and thus the most effective measure in the extreme grid is identified. The maximum possible number of EV in the critical string of the extreme grid is always determined with ensured grid stability. The resulting penetration rate same applies for the rest of the grid. Fig. 9 illustrates the comparison of the NOVA measures.

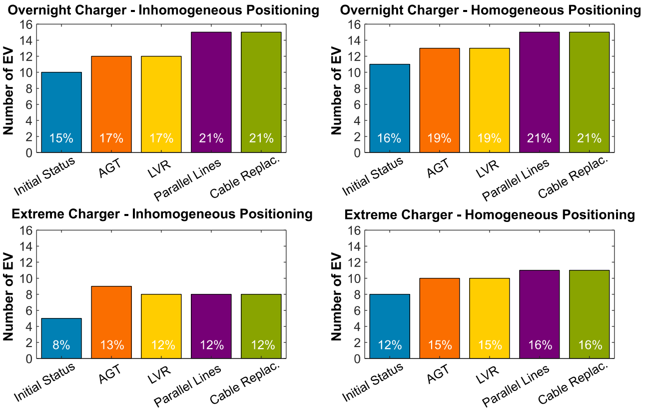

Fig. 9. Comparison of the NOVA measures used in the extreme grid; representation of the grid-stable number of EV and the resulting penetration rate

In addition, Table III specifies the limiting factor of the penetration rate depending on the selected NOVA measure.

TABLE III. LIMITING FACTORS FOR HIGHER PENETRATION RATES IN THE EXTREM GRID DEPENDING ON THE NOVA MEASURE

Charge Profile		Overnight Charger		Extreme Charger	
Positioning		Inhomog.	Homog.	Inhomo.	Homog.
Initial Status		*0.85 pu*	*cable load*	*0.90 pu*	*cable load*
NOVA	AGT PC	cable load	cable load	cable load	cable load
	LVR PC	cable load	cable load	0.90 pu	cable load
	Parallel Lines over 2/3 of Crit. String	transform. load	transform. load	0.90 pu	0.90 pu
	Cable Replacem. 240 mm²	transform. load	transform. load	0.90 pu	0.90 pu

The penetration rates shown represent the most effective variants of each NOVA measure and are explained along with the limiting factors in more detail in the following sections.

A. *Grid Reinforcement – AGT*

In the case of a grid reinforcement using an AGT, the control concept of power compounding is the most effective and therefore the most suitable technical variant. In the case of the AGT with power compounding – as in the case of the voltage-dependent control – a higher penetration rate is limited by the current-carrying capacity respectively the thermal limit of the first line section in the critical string. An improved voltage ratio reduces this cable load due to the reduced power loss and therefore highers the transmission capacity. Using power compounding leads to improved voltage maintenance, more precisely a higher voltage level compared to a voltage-dependent control. The following Fig. 10 illustrates this.

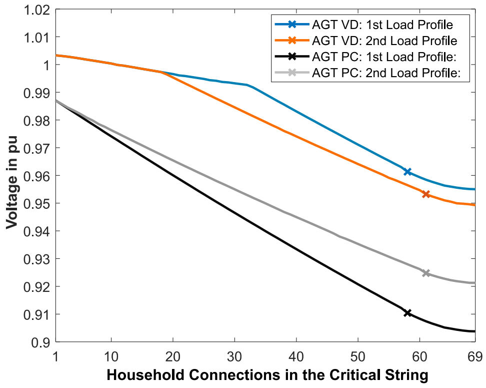

Fig. 10. Comparison of the voltage curves of the different control concepts of an AGT on the basis of the occurring minimum voltage values in the critical string with inhomogeneous distribution of the EV

Therefore, due to the AGT, even under inhomogeneous positioning violations of the voltage range can successfully be avoided. Thus, making full use of the permissible equipment limit of the cable. The cable load of the first line section on average is reduced by about 4 % compared to the voltage-dependent control and by about 11 % compared to the initial status.

B. *Grid Reinforcement – LVR Power Compounding*

In the context of the LVR, the control concept of power compounding is most effective, as this has already been proven to be more suitable in the case of the AGT. Moreover, the positioning of the LVR in the string to be controlled has a significant influence on the effectiveness of the voltage control. The LVR can avoid all voltage range violations regardless of its positioning in the string, which confirms the effectiveness of the voltage regulation. Therefore, the optimal position of the LVR throughout all scenarios is immediately after the busbar before the beginning of the first cable section. In this position, the LVR can reduce the load of the cables as already stated in the context of the AGT.

The investigations reveal that in three of the four scenarios considered, the permissible current carrying capacity of the cable in the first line section limits the grid absorption capacity. The exception is the scenario with the overnight charger profile and inhomogeneous positioning. In this scenario, an undercutting of the voltage range occurring outside of the critical string in the rest of grid limits the grid capacity.

C. *Grid Reinforcement – Parallel Line*

As part of the grid reinforcement by means of parallel lines, the extension over half, two thirds and three quarters of the length of the critical line was investigated. Similar to the existing line, a NAYY 150 mm² cable is used for the parallel line. Thus, the line impedance can be reduced by 25 %, 33% or 38 %. The addition of an extra line with parallel connection to the existing line over a length of two thirds of the critical string is the optimal technical variant of this grid reinforcement. Longer parallel lines do not increase the possible penetration of EV, as other factors limit the network absorption capacity.

With the addition of a parallel line in the case of the grid reinforcement, critical cable loading in the first line section can be completely prevented, regardless of the scenario. In the case of the overnight charger profile, the limiting factor is the permissible operating load of the local transformer during the simulated overnight charge. When using the extreme charger profile, the 0.9 pu criteria according to DIN EN 50160 is the limiting factor. However, it must be noted that the voltage range violations do not occur solely in the rear area of the critical string, but also at the end other strings in the rest of the grid.

The creation of two lines by adding an extra line e.g. over two-third of the length and then splitting up the already existing one is not recommended. With inhomogeneous positioning no improvement in penetration rate for EV can be determined. This is due to the fact that in the extreme grid, the influence of the length of the parallel cabling and the resulting lower longitudinal impedance is dominant over the influence of the reduced line losses on the voltage drop in the critical string by splitting up the string and therefore the power flow.

D. Grid Expansion – Cable Replacement

In the course of the grid expansion, the replacement of the existing cable routes by cables with cross-sections of 240 mm² and 400 mm² is being considered. As a result, the line impedance in the critical string can be reduced by 28 % or 47 % compared to the originally used cable cross section of 150 mm². The use of a cable cross-section of 240 mm² proves to be the best technical solution, since larger cable cross-sections do not lead to any improvement in the grid absorption capacity for EV.

Fig. 9 shows that the same penetration rate of EV results when using parallel lines as for the grid expansion with cable replacements. Other than that, the same limiting factors are identified as for grid reinforcement using parallel lines. As explained in this context, the limiting factors are independent of a further reduction of the line impedance. Instead, measures for voltage regulation in the entire grid area, e.g. in the form of an AGT together with higher rated apparent power, are necessary for a further increase in the penetration rate of EV.

E. Technical Comparison of the Applied NOVA Measures

For a technical comparison of the NOVA measures, Table IV shows the percentage increase of the penetration rate in the critical string of the extreme grid.

TABLE IV. COMPARISON OF THE NOVA MEASURES ON THE BASIS OF THE INCREASE OF PENETRATION RATE OF EV IN THE CRITICAL STRING OF THE EXTREME GRID

Charge Profile		Overnight Charger		Extreme Charger	
Positioning		Inhomog.	Homog.	Inhomo.	Homog.
NOVA	AGT PC	+20 %	+18.2 %	**+80 %**	+25 %
	LVR PC	+20 %	+18.2 %	+40 %	+25 %
	Parallel Lines over 2/3 of Crit. String	**+50 %**	**+50 %**	+60 %	**+37.5 %**
	Cable Replacem. 240 mm²	**+50 %**	**+50 %**	+60 %	**+37.5 %**

In three of the four scenarios considered, the NOVA measures of parallel lines and cross-sectional enlargement of the cables form the optimum for increasing the grid capacity. Both measures simultaneously enable an increased current carrying capacity and voltage stabilization due to the impedance reduction. Thus, these measures provide suitable solutions for the limiting factors of the cable load in the first line section and the voltage range violations which occur in the initial status of the extreme grid.

An exception forms the scenario using the extreme charger profile and inhomogeneous positioning of the EV. In this case, due to the high loads that occur in the rear line section, a measure for active voltage regulation in the entire grid area is necessary. The AGT represents the only effective technical solution. When looking at the measures for longitudinal voltage control, the AGT and the LVR achieve the same improvement in the penetration rate in three of the four scenarios. This reflects the influence of the inhomogeneous grid structure of the extreme grid respectively the influence of its critical string. Accordingly, the advantage of the AGT as a central voltage regulation is only reflected when using the extreme charger profile and inhomogeneous positioning. In this respect, the following Fig. 11 illustrates the voltage curve resulting from the different NOVA measures.

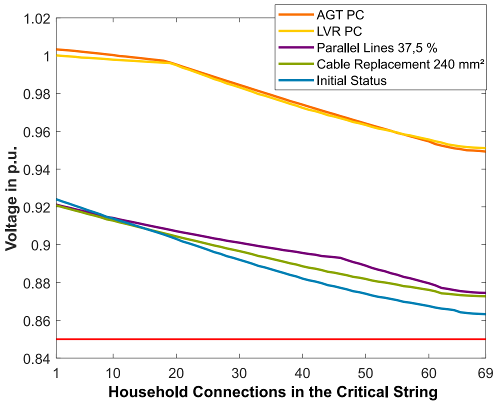

Fig. 11. Comparison of the NOVA measures on the basis of the voltage minima along the critical string of the extreme grid; using the extreme charger profile and inhomogeneous distribution of the EV

The increased voltage quality (see Fig. 11) resulting from the use of an AGT or an LVR is not reflected in the grid capacity due to the limiting factors shown in Table III. Instead, in the extreme grid, the occurring problems with the equipment limits must first be solved in order to fully benefit from voltage maintenance.

Overall, the use of electrical parallel lines and cross-sectional enlargement of the cables on average of all scenarios provides the greatest increase in the penetration of EV in the extreme grid with a 400 kVA transformer. For a better differentiation of these NOVA measures, the relevant investigations using the overnight charger profile are repeated with a larger dimensioned transformer with 630 kVA. The results are listed in Table V.

TABLE V. SIMULATION RESULTS OF THE USE OF AN AGT OR PARALLEL LINES WHEN USING A TRANSFORMER WITH 630 KVA

Charge Profile		Parallel Lines		Cable Replacement	
Positioning		Inhomog.	Homog.	Inhomog.	Homog.
Limitting Factor / Criteria		0.85 pu	cable load	0.85 pu	cable load
Penetration Rate		23.5 %	30 %	23.5 %	23.5 %
Number of EV	Total Grid	34	42	34	34
	Critical String	16	20	16	16
Δ 400 kVA	Num. EV	1	5	1	1
	Penetrat.	+10 %	+50 %	+ 10 %	+ 10 %

The results show that a differentiation based on the scenario with homogeneous positioning of the EV is now possible. Here a higher penetration rate can be achieved by using the parallel line. This is due to the greater impedance reduction and current carrying capacity of the electrical parallel connection.

In summary, due to the basic idea of the NOVA principle, the grid reinforcement is always to be preferred to the grid expansion, if the resulting grid capacity is the same. Accordingly, the parallel line over two thirds of the existing line is identified as the most suitable NOVA measure for the extreme grid with a 400 kVA local transformer. When using a larger dimensioned local transformer, in the case of the overnight charger profile it is shown that the grid stable penetration rate can be further increased by means of a parallel line compared to the cross-sectional enlargement of the cables. Therefore, the recommended NOVA measure in the extreme grid are parallel lines, which can be confirmed independently of the rated value of the local transformer.

VI. Impact of NOVA Measures on Normal Grid

The insights gained from the extreme grid have been incorporated into the investigations of the normal grid. Accordingly, the same most effective variants of technical solutions of NOVA measures are identified. The optimal length of the parallel line is 37,5 % of the extent of the critical string. The following Fig. 12 illustrates the achieved penetration rates in the critical string depending on the NOVA measures used.

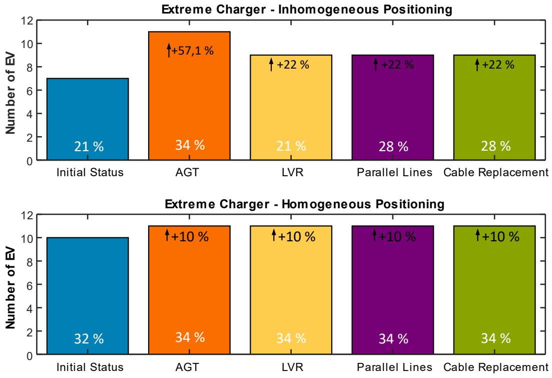

Fig. 12. Comparison of the NOVA measures in the normal grid

In the scenarios of the overnight charger profile, on the basis of the investigated NOVA measures no increase in the penetration rate of EV compared to the initial status can be achieved. The limiting factor in form of the permissible overload of the transformer is decisive for this. In this context, the following Table VI illustrates the limiting factors for a higher penetration rate in the scenarios of the normal grid.

TABLE VI. Limiting Factors in the Normal Grid for a Higher Penetration Rate in Dependence of the NOVA Measure.

Charge Profile		Overnight Charger		Extreme Charger	
Positioning		Inhomog.	Homog.	Inhomo.	Homog.
Initial Status		*transform. load*	*transform. load*	*0.90 pu*	*0.90 pu*
N O V A	AGT PC	transform. load	transform. load	transform. load	transform. load
	LVR PC	transform. load	transform. load	0.90 pu	transform. load / 0.90 pu
	Parallel Lines over 37,5 % of Critical String	transform. load	transform. load	0.90 pu	transform. load / 0.90 pu
	Cable Replacement 240 mm²	transform. load	transform. load	0.90 pu	transform. load / 0.90 pu

In summary, the optimal NOVA measure in the normal grid is the grid reinforcing measure of the AGT and its possibility of central voltage regulation of the entire grid area. As a result, the permissible equipment load of the transformer can be fully utilized and the highest possible grid-stable penetration of EV can be achieved. In addition, based on the limiting criteria described above, it is recommended that when replacing the conventional transformer with an AGT, a larger dimensioning should be checked at the same time. The approach of improving the voltage conditions solely in the critical string by LVR, parallel lines, or cross-sectional enlargements has a limited effect on the normal grid. This is due to the more homogeneous grid structure compared to the extreme grid with regard to the length of the lines and the distribution of the households.

VII. Influence of Inhomogeneous Distribution of EV on Central Voltage Control Concepts

The electrification of the mobility sector may result in highly inhomogeneous grid structures [15]. Central control concepts for voltage regulation, such as the use of an AGT, can reach their limits in these scenarios. Thus, the effects of inhomogeneous loads caused by electromobility on the control capability of the AGT are examined using the extreme grid. A distinction is made between grid-wide inhomogeneity and inhomogeneity within the string. The greatest possible inhomogeneity within a string results from the scenario in which the entire load from the electromobility is connected at the end of the critical string. In the scenario of the highest grid-wide inhomogeneity, only the critical string is equipped with EV. In the critical string the EV is evenly distributed. Fig. 13 compares these two forms of inhomogeneity.

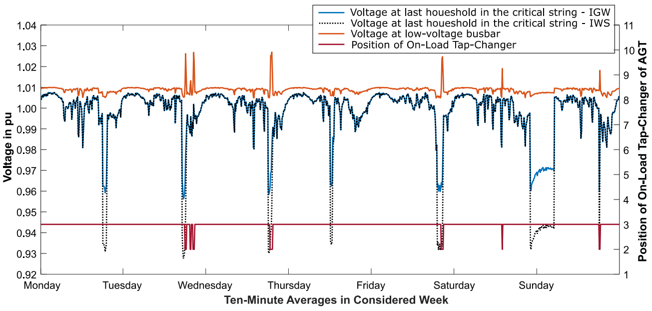

Fig. 13. Comparison of the influence of grid-wide inhomogeneity and inhomogeneity in the string on the controllability of the AGT with power compounding control concept.

As shown in Fig. 13, no difference in the control behavior of the AGT between grid-wise inhomogeneity and inhomogeneity within the string can be detected. Furthermore, it can be seen that no voltage range violations occur. The voltage setpoint is constantly maintained at the measuring point of the local control, the low voltage busbar. In addition, the AGT reliably regulates the voltage fluctuations that occur due to the reduced input voltage and the load caused by charging EV. An increase in the penetration rate and thus inhomogeneity in the grid area would increase the switching activity of the AGT with a power compounding control concept. However, this is not possible within the applicable equipment and voltage limits, since the maximum number of EV determined in the initial status is already used. A grid reinforcement or extension would reduce the line impedance and thus the actual incentive for a voltage regulation. Consequently, only if equipment limits are ignored it is possible to create scenarios in which the AGT does not correctly detect a voltage range violation at the end of the critical string due to its local setpoint at the voltage busbar.

Thus, within the permissible equipment limits the central voltage regulation respectively the AGT is able to avoid all voltage range violations independent of the form and extent of the inhomogeneity. The controllability of the AGT is therefore not restricted by inhomogeneous loads caused by electromobility.

VIII. CONCLUSION

In extreme grid structures, due to a large number of connected households and long line lengths voltage drops and thus voltage range violations as well as high cable utilization limit the grid capacity. Accordingly, technical solutions are needed, which increase the thermal limit and stabilize the voltage respectively reduce the line impedance. Consequently, parallel lines are identified as the most suitable NOVA measure for extreme grids. In this context, the optimal length of the parallel lines has to be determined depending on the voltage range violations in the rest of the extreme grid in order to avoid over-dimensioning. In normal, homogeneous grid structures, the most effective NOVA measure to grow the number of EV is by using an AGT for central voltage regulation as the undervoltage problem is dominant and limits the transmission capacity. Moreover, attention must be paid to sufficient dimensioning of the transformer. Apart from that, AGT are invariably able to handle loads caused by electromobility and centrally adjust the voltage level accordingly, as long as all of the grid’s electrical equipment is operating within its limits. Therefore, the controllability of the voltage regulation is not affected by inhomogeneous nor uneven loads, regardless of where those loads occur within the electric grid.

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