POTENTIAL ANALYSIS FOR THE INTEGRATION OF RENEWABLES AND EV CHARGING STATIONS WITHIN A NOVEL LVDC SMART-TROLLEYBUS GRID

M. Wazifehdust, D. Baumeister, M. Salih, M. Koch, P. Steinbusch, M. Zdralle
Chair of Power System Engineering
University of Wuppertal
42119 Wuppertal, Germany
wazifehdust@uni-wuppertal.de

S. Mour
SWS Netze Solingen GmbH
42655 Solingen, Germany
s.mour@netze-solingen.de

C. Troullier
Stadtwerke Solingen GmbH
42655 Solingen, Germany
c.troullier@sws-solingen.de

ABSTRACT

The ongoing practical integration of renewable energy systems in power supply as well as alternative drives in the transport sector are of major importance to cope with the climate change. Both are addressed within this paper, since the major goal of the project at hand – which will be presented in the following – is firstly, the replacement of conventional trolleybuses with auxiliary combustion engines by fully electric driven battery-trolleybuses and secondly, the implementation of photovoltaic (PV) systems and electric vehicle (EV) charging stations within the respective overhead grid. In order to ensure a reliable operation despite the increased number of loads a comprehensive monitoring and control system is required to avoid overloads. Furthermore, the control system is supposed to manage the battery charging for the new battery-trolleybuses to secure a sufficient state of charge for the sections without overhead lines. Since the positions for PV systems and EV charging stations are not determined yet, it is of crucial importance to figure out at which locations the aforementioned components can operate the most grid supportive, respectively, the less grid harming. This paper intends to demonstrate how the optimal placement and sizing can be reached.

INTRODUCTION

The city of Solingen uses the largest Low Voltage Direct Current (LVDC) overhead trolleybus system in Germany. The presented power grid operates on direct current with a nominal voltage of 660 V and is supplied by 22 substations. However, not all of the local bus routes are operated by trolleybuses, because they are confined to the overhead grid and can only leave for line free sections with the help of the equipped diesel engine. Future plans aim to replace all ordinary trolleybuses with novel battery-trolleybuses in order to electrify the entire public transport. This part is only one of many within the joint research project "BOB Solingen". The term BOB is derived from the German abbreviation for "Batterie-Oberleitungs-Bus".

Within the project there are also plans to connect PV systems and EV charging stations to the LVDC overhead grid. Research suggests that direct integration of DC power components into such a grid can save up to 20% energy and furthermore improve on power quality, increase system reliability and reduce system costs [1]. Due to the fact that the main purpose of the LVDC grid is to supply the existing trolleybuses with energy, system stability and load have to be analysed as criteria to determine the optimal placement and sizing for the potential integration of PV and EV applications. The existing grid does currently not have the capability of refeeding any energy into the superordinate medium-voltage grid, due to the fact that all substations are operated unidirectional.

For this purpose, a simulation model has been created to represent the entire overhead grid and its actuators, such as buses [2], PV generators and EV charging stations [3]. Commonly used power flow algorithms have been adapted to be utilized in a LVDC grid with unidirectional substation rectifiers. In this paper, two different methods are proposed for determining the optimal placement and sizing for PV generators and EV charging stations in the LVDC grid.

LOW VOLTAGE DC GRID MODEL

The overhead lines, which provide the power to operate the buses, are distributed throughout most of the city forming a heavily meshed DC grid. For the purposes of this paper, a test grid is planned, see Figure 1. A timetable for trolleybuses or BOB, that describe buses movement over the test grid, is defined as well. With the help of a DC power flow approach, the differences in voltage magnitude over the test grid nodes will be determined [3]. The grid nodes are divided into two types, where the source nodes are V-controlled and all other nodes are P-controlled. The DC power flow process works sequentially since it has to be performed for each time step and each change in a voltage or power profile for each node in the grid, over the total simulation time.

1 Eng.: battery-trolleybus
The test grid including several nodes which are joined by branches forms a meshed grid that reflects the real grid in rated means. The nodes will represent the switches, crossings, balancing bridges and dead-end disconnections from the real world grid, on the other hand, the overhead lines and the infeed cables are revealed as the branches in the test grid. The branches resistance and current capacity are divided into two groups. The first group of branches that represent the infeed’s cables has $0.1 \, \Omega/km$ and a maximum current of $600 \, A$, the second group that represents the overhead lines has $0.2 \, \Omega/km$ and $400 \, A$ maximum current capacity.

**Trolleybuses and BOB**

The operation of 5 trolleybuses within the test grid is determined within a proposed timetable that reflects a real one with its routes and stop stations. The buses routes will embrace a possible traffic station, e.g. traffic light, junction, and curve. The speed limit on the roads was taken in consideration as well. With all the variations of the buses operating, based on the timetable and technical specifications of the trolleybuses or the BOBs, a power profile will be modelled [3].

**SELECTION OF APPLICABLE PV SYSTEMS**

The following chapter deals with the optimal placement and optimal sizing of PV systems. For bidirectional substations, the generated power can be transferred to the medium voltage network. Since only unidirectional substations are considered, the sensitivity analysis – which will be described and used in the following chapter – cannot adequately simulate the voltage increase at the substations. Therefore, new methods for placement and sizing have been developed.

**Placement**

The strategy for determining the optimal placement for PV systems is divided into five steps:

1. **Elimination of Substations**
   In the first step, all substations, PV systems and EV charging stations will be removed from the DC grid. Substations are assumed to be P-controlled nodes with 0 W. The result is an empty LVDC grid (Figure 1).

2. **Adding Power Supplies**
   In the second step, power supplies are added and connected to selected nodes. These feeders behave exactly like substations and are shown in Figure 2 as possible PV systems (red). This step is done to display the feed-in potential for each node. Since PV systems cannot be connected to all nodes (e.g. switches), only selected nodes are considered.

3. **Run Simulation**
   The DC Grid will be simulated for the given period of time and the buses run according to the stored bus timetables. The output is the feed-in power for the selected nodes.

4. **Zone of influence**
   Choosing the optimal locations that are in a defined distance to each other, a zone of influence of the PV system was defined. To determine the zone of influence for each DC node, three different methods were developed. The first method considers only the length of the overhead lines starting from the considered node.

**Selection of Applicable PV Systems**

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Assuming that the influence range is 500 m, the zone of influence for each node is shown in Figure 3. Starting from each node, the next 500 meters in each direction are considered. All nodes that do not exceed the maximum length are added to the influence area. A major disadvantage of this method is that different cross sections of the overhead line have no influence on the zone. The other two methods take into account the resistance.

The second method calculates the zone of influence due to a maximum voltage difference. The aim is to calculate a maximum resistance from a given voltage difference. Subsequently, the zone is not determined by length but by the maximum resistance. Each branch of the overhead line receives a resistance value which is composed of the length of the branch and the specific resistance. To calculate the maximum resistance, some parameters have to be known. Figure 4 shows a circuit in which a PV system feeds in and a load is connected via the overhead line, which has an unknown resistance. In order to not exceed the specified voltage difference, the largest PV system of the grid is considered to be the feeder. The current \( I \) is calculated with the maximum infeed power of the PV system \( P_{PV} \) and the given voltage \( V_{PV} \). Based on the given voltage difference \( \Delta V \), the voltage at the load \( V_{Load} \) and the maximum resistance \( R \) can then be calculated. Now the procedure is equivalent to the first method. The zone of influence is determined by the resistance rather than the length.

\[
I = \frac{P_{PV}}{V_{PV}} \quad (1)
\]

\[
V_{Load} = V_{PV} - \Delta V \quad (2)
\]

\[
R = \frac{\Delta V}{I} \quad (3)
\]

Figure 4: Circuit diagram of a PV infeed with load

The last method calculates the area of influence based on the maximum losses. As before, the influence zone is to be determined on the basis of a maximum resistance, which is calculated over the given relative losses. It is considered the same circuit as before. This allows the current to be calculated again (1). Given the relative losses \( v \), the absolute losses in the resistance can be determined. Then, based on the resistance, the losses and the current are calculated. The further procedure for the determination of the influence zone is exactly the same as with the second method.

\[
P_{Losses} = P \times v \quad (4)
\]

\[
R = \frac{P_{Losses}}{I^2} \quad (5)
\]

4. Comparison with ideal PV power profile

In the fourth step, the theoretically usable energy of the PV system can be calculated on the basis of the ideal PV power profile and the feed-in power of one node (Figure 5). In addition, it is possible to determine the energy that needs to be provided by another source. A possible shading of the PV system was not considered.

Figure 5: Comparison with ideal PV power profile

5. Selection of Nodes

In the last step, the nodes to which the PV systems should be connected have to be selected. The feed-in power of the nodes is summed for each influence zone and then checked which node has the largest feed-in potential.

Sizing

In order to determine an optimal size for a PV system for the selected nodes, all feed-in powers of a zone of influence were added to get a feed-in power profile of every zone. Then several ideal PV power profiles with different peak powers were created. These were compared with the feed-in power profile of a zone. As a further input parameter, a utilization factor was defined, which indicates the percentage of fed-in energy to the generated energy of the PV system. The feed-in power profiles are compared with all PV power profiles and a utilization factor is determined for each comparison. The calculated utilization factor closest to the given utilization factor determines the size of the PV system.

SELECTION OF APPLICABLE EV CHARGING STATIONS

To identify the optimal positions for EV charging stations, another approach is needed. It is technically possible to use the power-flow calculation inside the DC grid model with varying load at predetermined locations to solve the problem, but the computational effort is time intensive. Instead of pure power flow calculations an adapted sensitivity analysis approach is used as described in [4]. A sensitivity matrix \( S \) is used to linearize the problem. The
sensitivity matrix is created modifying the existing admittance matrix of the grid by adding the internal admittances of all existing slack nodes and afterwards inverting it.

\[ S = (Y_{mod})^{-1} \]  

(6)

By varying the load at a specific location a change in current \((\Delta I)\) can be estimated. The change in current considers two different time steps.

\[ \Delta I = I_1 - I_2 \]  

(7)

The current is calculated as shown in equation (8).

\[ I_x = \frac{P_x}{V_x} \]  

(8)

The current deviation can be calculated by combining equation (7) and (8) which is shown in equation (9).

\[ \Delta I = \frac{P_1 \cdot V_2 - P_2 \cdot V_1}{V_1 \cdot V_2} \]  

(9)

The error which is given by the estimation of the voltage can be reduced by the following adaptations:

\[ \text{reqmt.} : V_1 \approx V_2 \]

\[ \Delta I = \frac{P_1 - P_2}{V_1} \]  

(11)

Another improvement can be done by adding the prior voltage change for each calculation step.

\[ \Delta I = \frac{\Delta P}{V_{\text{start}} + \Delta V} \]  

(12)

To calculate the current adaption, equation (16) can be used. \(P_1\) and \(V_1\) are derived from the actual grid state calculated by the power flow method, while the power adaption is indirectly considered with \(P_2\) and the sensitivity matrix \(S\).

\[ f_1 = P_{xy} \cdot S_{yy} \]  

(13)

\[ f_2 = 2P_{4y}S_{yy}V_{iy}^2 - 4P_{2y}S_{yy}V_{iy}^2 - V_{iy}^4 \]  

(14)

\[ f_3 = 2S_{yy}V_{iy} \]  

(15)

\[ \Delta I_y = \frac{-f_1 - f_2 + f_3 + f_4}{f_3} \]  

(16)

Based on the change in current a voltage difference \((\Delta V)\) can be calculated with equation (17) using the sensitivity matrix. The new voltage distribution \(V_{\text{sense}}\) can be determined by subtracting the voltage difference from the starting voltage \(V_{\text{start}}\) as shown in equation (18).

\[ \Delta V = S \cdot \Delta I \]  

(17)

\[ V_{\text{sense}} = V_{\text{start}} + \Delta V \]  

(18)

The linearity causes an error that increases with the power difference used to calculate the current change. To decrease the error a new grid-state can be calculated with power-flow to give a new operating point for further iterations of the sensitivity analysis.

Figure 6: Potential locations for EV charging stations

This process is repeated until a set load-maximum is reached, or the minimum operating voltage of the grid is breached.

RESULTS

The placement and sizing for PV systems was performed by an adapted load flow algorithm allowing the replacement of the proposed PV systems with new infed sources in order to compare their infed profiles with the respective PV profiles.

Based on an improved sensitivity analysis a method was implemented to calculate placement and sizing of EV charging station using only voltage information. The results for the mixed sensitivity analysis show a small error while reducing computational effort.

Applicable PV Systems

For the test grid, four optimal locations for PV systems were determined with the presented method. Nodes 16, 12, 22 and 6 have been proved to be particularly suitable. These nodes have the largest feed-in potential and can feed the most energy into the grid. With a closer look at the bus timetable, the chosen nodes can be confirmed, because these nodes are on the heavily traveled routes.

Consistent with the optimal placement, the largest PV systems will be placed at the chosen nodes. The maximum feed-in capacity depends extremely on the input parameters. With a utilization factor of 90 % and relative losses of 5 %, 100 kWp can be fed in at selected nodes.

Applicable EV Charging Stations

Using the proposed sensitivity analysis approach, testing was conducted within a test network. Figure 6 shows all potential charging points, which were analysed and sized according to the method implemented. Each node is iteratively increased in 6 steps of 22 kW until a maximum of 132 kW is reached. To compare the aforementioned methods, 3 different simulations were performed. It was possible to deduct a reduction in simulation time from only using power flow by 29.7 % using sensitivity analysis for
each step and 27.24 % using the mixed approach, doing 2 steps of sensitivity analysis and one step power flow, alternating twice. The simulation time for each method and realized reduction of computational effort are shown in Table 1.

<table>
<thead>
<tr>
<th>Simulation Mode</th>
<th>Simulation Time [s]</th>
<th>Time reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Power Flow</td>
<td>143.090</td>
<td>0</td>
</tr>
<tr>
<td>Pure Sensitivity</td>
<td>100.557</td>
<td>29.72</td>
</tr>
<tr>
<td>Mixed Approach</td>
<td>104.115</td>
<td>27.24</td>
</tr>
</tbody>
</table>

Table 1: Simulation time by method

The average deviation of voltage using the two different approaches was calculated to see if the proposed method can be used in future applications. Figure 7 shows the average voltage deviation for all time-steps in each node-candidate analysed. Using pure sensitivity analysis, the average voltage error reaches a maximum of 1.96 % at the most unstable node inside the test-network.

**Figure 7: Average voltage deviation for pure sensitivity analysis**

Figure 8 shows the results for average voltage deviation for the mixed approach. The maximum average voltage deviation error can be reduced to 1.481 %, a reduction of 24.44 % compared to pure sensitivity analysis, while simulation time is only increased by 3.54 %.

**Figure 8: Average voltage deviation for mixed approach**

For the test grid, four optimal locations for EV charging stations were determined with the mixed approach for the sensitivity analysis. Nodes 5, 6, 7 and 11 and have been proved to be very suitable due to the fact that higher installed powers do not violate the voltage limits in the simulation.

**CONCLUSION AND FUTURE WORK**

Within this paper two methodical approaches for evaluating the grid reserve capacity have been introduced. The impact of integrating renewable power sources as well as charging stations for electric vehicles needs to be quantified in order to figure out the ideal positions. The approaches at hand foresee an automated power variation accompanied by respective position changes for both systems.

In this approach only voltages are analysed and further work has to take branch current capacities, that are a major factor in sizing the charging stations, into consideration.

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**REFERENCES**


