Impact Assessment of Integrating Novel Battery-Trolleybuses, PV Units and EV Charging Stations in a DC Trolleybus Network

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Abstract— **This paper deals with the challenges and solution approaches of modelling a simulation environment for a public transport system with, inter alia, battery-trolleybuses. The currently operating trolleybuses are equipped with a combustion engine in order to overcome the line free sections of the DC overhead grid. In the not too distant future, all the trolleybuses will be replaced by the novel battery-trolleybuses with the aim of pervasively electrifying the entire public transport system of Solingen, Germany. The goal of this paper is to demonstrate how the Direct Current (DC) power flow algorithm was implemented in order to consecutively reflect a detailed grid state. A constructive simulation model is developed based on technical and physical limits which are given by both battery-trolleybuses and usual trolleybuses, the photovoltaic systems and the DC overhead grid. The detailed insight of the power flow within the DC overhead grid can be regarded as a basis for future efforts in developing a smart system.**

Keywords: Battery, Trolleybus, Photovoltaic, PV, Smart, DC Grid, DC Power Flow

I. INTRODUCTION

Solingen is known for the largest operating trolleybus system in Germany, with 50 electrically driven trolleybuses which are equipped with auxiliary combustion engines and 50 additional conventional diesel buses serving the public transport system.

The project "BOB-Solingen" - the abbreviation BOB denotes the German words "Batterie-Oberleitungs-Bus" - intends to electrify the entire public transport sector by introducing a new kind of trolleybuses, which will be able to travel regardless of the vital overhead line by means of the included battery. BOB is the result of combining the recognized trolleybus technology with the latest battery technology and the intelligent charging infrastructure, creating the next generation of buses which, as a matter of fact, are able to drive on routes with no power supply by the overhead line as well.

Moreover, the project is planned to integrate charging stations for electric vehicles (EV), decentralized renewable power generators such as photovoltaic (PV) systems as well as a stationary power storage system. The stationary storage will consist of used trolleybus batteries to increase their cost efficiency by establishing a second-life utilization concept.

This paper intends to simulate and evaluate the power profiles of all operating trolleybuses as well as the planned BOB based on different possible operation circumstances (e.g. stopping or not at traffic lights and bus stops, different stopping durations, traffic influences, variation in temperature and passenger numbers). The power profiles for both the buses and additional actuators within the DC grid, such as PV systems, charging stations and stationary power storage units will be presented and discussed.

The grid state is expected to be strongly fluctuating due to the increased number of loads and feeders, some of which operate bidirectionally. Power flow calculations will be the key to point out the actual grid state in order to enable the essential intelligent grid control. Performance and capability will be presented and evaluated in this paper.

II. SMART TROLLEY SYSTEM

The future Smart Trolley System will consist of many components. In the following, the new battery trolleybus, PV units and EV will be discussed.

A. BOB

To model and implement battery trolleybuses into the simulation, power profiles of trolleybuses without an onboard-battery were created in the first step. The basis for this is [1], due to the fact that modelling an accurate trolleybus power profile, many properties of the buses (e.g. curb weight, front surface and engine power) have to be considered. In addition, as described in [1], dependencies (e.g., number of passengers, traffic and topography) must also be considered to generate a realistic power profile. As a result of all input parameters, a power profile will be generated, as shown exemplary in Figure 1. This power profile consists of four different modes (acceleration, constant speed, coasting and braking). Due to the various influences, the profile will be changed as shown in [1].

The existing model of the trolleybus is now equipped with another feature. The battery, including properties such as nominal capacity, initial state of charge (SoC), and maximum charge and discharge power, is added to the existing model. The calculated and claimed power at a specific time can then be retrieved in the simulation via the overhead line or from the integrated onboard battery. If the BOB uses the power from the overhead line, the SoC of the battery remains unchanged, provided that the battery is not charged at the same time and losses are neglected. Otherwise, the BOB gets the energy from the lithium-ion-battery, so a new reduced SoC needs to be calculated. The charging method constant current constant voltage (CCCV) is used and combines the constant-current charging method with the constant-voltage charging method [2]. The new SoC of the battery is calculated using the following formula:

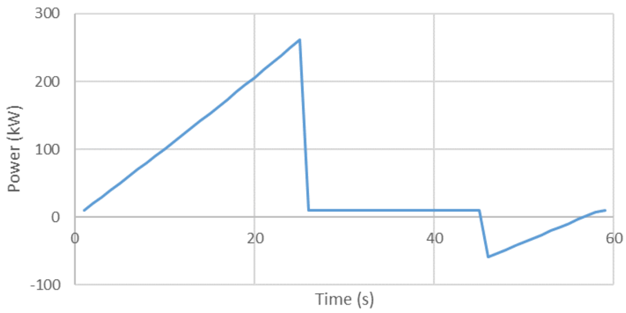

Figure 1: Standard power profile

$$SoC(t) = SoC(t-1) + \frac{1}{C_{nom}} \int_{t-1}^{t} P \, dt \qquad (1)$$

SoC is the state of charge, C_{nom} the nominal capacity and P the actual charge or discharge power. Figure 2 shows SoC over time while the BOB leaves the overhead line. The BOB drives around 10.5 minutes with the power from the battery until he reaches the overhead line and stats charging the onboard battery. The subsequent charging takes about 35 minutes.

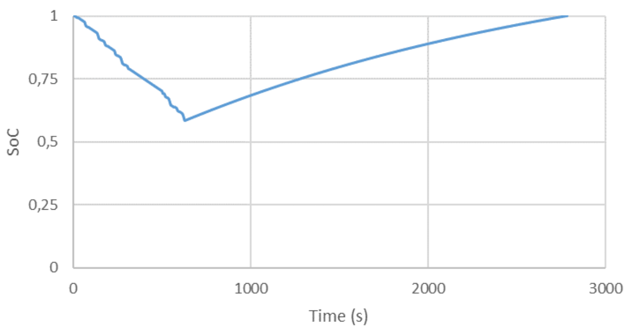

Figure 2: SoC of an onboard battery

The routes of the buses, which run outside the overhead line, are relatively short. For example, the route used here is about 1.7 km long. In order to obtain the lowest possible SoC on this short route, the outer conditions have been adjusted. Thus, for example, the temperature was set extreme low, so that the heating power of the buses is enormously high. In addition, the battery will be charged very slowly because the received energy by the overhead line is largely used for heating and driving. The remaining energy that can be obtained from the overhead line is then stored in the battery.

In the future, the regulation of the onboard battery will be implemented. For example, the maximum current that can flow through the pantographs depends on the BOB speed. This effects the charging power of the battery.

B. PV

The implementation of a photovoltaic system requires a wide range of parameters which are supposed to be delivered both as static input values and dynamic values as well. In the following, all necessary parameters and the workflow of the PV simulator will be presented. In order to simulate a realistic representation of a photovoltaic systems infeed power with regard to its place of installation the following parameters are of crucial importance: location in terms of longitude and latitude, the installed power, the day type whether its summer or winter and the orientation angles in terms of altitude and azimuth. With this information given as an input first of all the suns route from the earths point of view has to be described. The resulting radiation profile which is led by the sun can be arithmetically converted to an ideal power profile of a predefined PV system. As a matter of fact, the ideal values are badly reachable and not representative due to the disruptive factors which is why both the efficiency and a coverage of the PV systems panel must be considered. This will be taken into account by adding a cloud reduction profile in order to deliver realistic results.

The radiation profile is gained by a mathematical description of the suns position towards the earth [3]. The maximum angle between the earth and the sun regarding the radiation direction varies between

$$\delta = 23.27° \qquad (2)$$

for the 21st of June and

$$\delta = -23.27° \qquad (3)$$

for the 21st of December.

The resulting equation for determining the exact position of the earth at each time can be written as:

$$\delta = \frac{23.27°}{180} \cdot \pi - \omega \cdot k \qquad (4)$$

with δ as the axis of the earth, ω as the daily angle change and k as the number of days since or to the 21st of June.

The resulting angle is used to calculate the sun movement by means of spherical trigonometry for a specific position, respectively longitude and latitude. The radiation profile in turn enables the calculation of the ideal power profile with regard to the parameters: orientation angles and the installed power. The ideal power profile for a PV system simulated in July with an installed power of 120 kWp in Wuppertal, Germany is shown in Figure 3

Historical data sets – provided for the years 2016 and 2017 – taken from the aforementioned local PV systems data log were used to reach the realistic power profile. It goes without saying, that the data sets include any type of disruptive factor such as the cloud coverage. These data sets

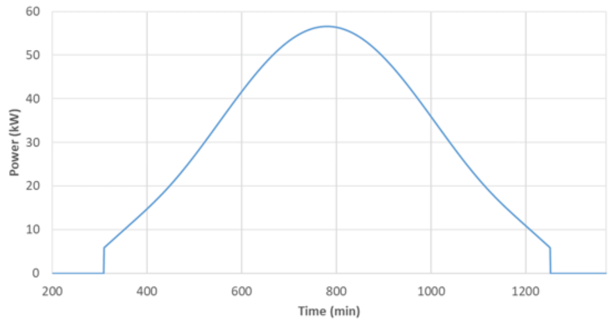

Figure 3: Ideal PV power profile

have correspondingly been compared with the respective ideal power profile for the chosen day. The result is a data set which no longer provides power values for each time step, but a reduction factor between 0 and 1 representing the differentiation between the ideal power value for a time step and the actual measured value.

These cloud reduction data sets are respectively sorted for the particular month of the raw data. By randomly choosing a cloud reduction factor set according to the month which is aimed for the simulation, a realistic power profile can be presented, as seen in Figure 4.

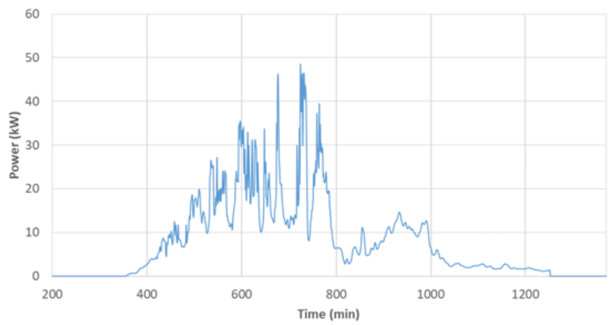

Figure 4:Real power profile

C. EV

For the consideration of EV a comprehensive simulation program is planned to be implemented. The parameters will take numerous influencing factors into account which are expected to be quite difficult to define but nevertheless of crucial importance in order to provide a realistic usage behavior to some extent. The basis for this is a distributional analysis for the following components: number of electric vehicles as a function of the number of inhabitants in small villages, small cities, big cities and metropolitan regions, maximum charge capacities as a function of number of electric vehicles and the driving profiles of different layers of society, unemployed and employed people and most recently the distribution of public EV charging stations having regard to their maximum charging power abilities.

III. Electrical Grid

Solingen's trolleybuses are supplied with DC power that is infeed by overhead grid lines, the interconnection between these lines forms a heavily meshed DC overhead grid. Multiple substations, which are distributed over the DC overhead grid, are responsible to provide the trolleybuses with required power to move them over the city region. The withdrawn power is provided from the medium voltage alternate current (AC) grid after transforming and rectifying its voltage by a step-down transformer and an AC/DC converter. Power cables are used to connect the substation DC bus bar with the over headlines. The overhead lines are divided into sections which will give the possibility of supplying parts of the lines while disconnecting one or more from them. The electrical grid topology is formed based on the bus positions, in other words, the grid topology will change continuously over time due to the moving parts that it contains, i.e., the trolleybuses. Hence, the dynamic behavior of the buses as loads causes a decisive difference regarding the calculation algorithm for the grid state. Alternating topologies can be put on a level with equally alternating admittance matrices which have to be taken into account for the power flow calculations.

A. DC Power Flow for Trolleybus Network

The differences in voltage magnitude over the DC grid nodes are responsible for mapping the power flow over the grid. In order to get the grid state, a power flow (PF) method needs to be implemented. Many approaches using the Newton-Raphson (NR) and Gauss-Seidel (GS) methods [4][5] approved to be reliable methods for solving nonlinear DC PF problems.

DC grid nodes can be divided into two types, where one can control the injection or absorbing of power, while the others are responsible for the DC bus voltage. In the P-Controller node, power is agreed and the voltage is to be calculated, while the V-Controller hold a constant DC voltage value and bus power amount is modified to match the power within P-Controller nodes.

In order to form the grid power equation, Kirchhoff's current law can be applied for each node, i.e. the injected current at node i is the sum of all other currents flowing to the other connected $(n-1)$ nodes, assuming that the total number of nodes in the grid is n. The DC current $I_{dc,i}$, which is injected in node n can be written as:

$$I_{dc,i} = \sum_{\substack{j=1 \\ j\neq i}}^{n} I_{dc,ij} \tag{5}$$

where $I_{dc,i}$ is the DC injected current in node i, and $I_{dc,ij}$ is the DC current flowing from node i to j. The current $I_{dc,ij}$, which is flowing from node i to j, is calculated as follows:

$$I_{dc,ij} = \frac{1}{R_{ij}}\left(V_{dc,i} - V_{dc,j}\right) \tag{6}$$

$V_{dc,i}$ and $V_{dc,j}$ are the node voltages at node i and j respectively, as well as, R_{ij} is the branch resistance that is between node i to j. Therefore, equations (5) and (6) can be rewritten as:

$$I_{dc,i} = \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{1}{R_{ij}}\left(V_{dc,i} - V_{dc,j}\right) \tag{7}$$

Or in matrix form:

$$\begin{bmatrix} I_{dc,1} \\ I_{dc,2} \\ \vdots \\ I_{dc,n} \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1n} \\ G_{21} & G_{22} & \cdots & G_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ G_{n1} & G_{n2} & \cdots & G_{nn} \end{bmatrix} \begin{bmatrix} V_{dc,1} \\ V_{dc,2} \\ \vdots \\ V_{dc,n} \end{bmatrix} \tag{8}$$

Where all non-diagonal elements in the conductance matrix are equal to:

$$G_{ij} = G_{ji} = \frac{-1}{R_{ij}}, i \neq j \tag{9}$$

And the diagonal elements are the sum of the absolute values of the row:

$$G_{ii} = \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{1}{R_{ij}} \qquad (10)$$

When there is no link between node i to j, the conductance value G_{ij} is set to zero in the conductance matrix.

Node power $P_{dc,i}$ is the respective power resulting from the DC node voltage $V_{dc,i}$ and the DC node current $I_{dc,i}$:

$$P_{dc,i} = V_{dc,i} \cdot I_{dc,i} \qquad (11)$$

From equations (7), (10), and (11) the grid power equation can be expressed as:

$$P_{dc,i} = V_{dc,i} \sum_{j=1}^{n} G_{ij} V_{dc,j} \qquad (12)$$

As mentioned before, the DC grids nodes are either P-Controller or V-Controller, i.e., power or voltage is known in a node. In this case, equation (12) will form a set of non-linear equations which can be solved using NR or GS methods [4][5].

The simulation process in this paper is handled by NR methods. Results will be presented and evaluated.

B. Simulation Program

The investigated DC grid involves several substations, where the voltage is down streamed and converted from AC to DC, connected by meshed overhead lines. The loads, which are in our case the trolleybuses, have a dynamic behavior concerning the position and magnitude. The simulation tool is meant to handle the trolleybuses, and BOBs movements and power consumptions, as well as the additional actuators within the grid, e.g. PV and EV. A power flow calculation for the available power and voltage values at the nodes of interest within the DC grid, e.g., substations, PVs, EVs, trolleybuses, and BOBs is performed. Afterwards the actual grid state will be pointed out as all voltages over the grid nodes and power flows in-between them are defined.

The flow of the simulation process can be illustrated in Figure 5.

At the beginning of the simulation, the starting time with the aimed operating duration for buses are set, followed then by reading the input data which includes traffic and electric information of the grid. Once all data are imported in the program, a model representing the real world electrical grid is build up, PV and EV power profiles are generated for the pre-set time duration. The traffic network will include buses movement paths. Last part to be initialized is the buses model, two different models are to be built, one for trolleybus and the other for BOB. The bus model will generate the bus movement over the traffic network and hold the power and position within the DC grid [1].

Before starting with the buses movements routine, a pre-set of conductance matrix G is made, where it will be based on the fixed topology of the DC grid, in other words, no presence of any bus in the DC grid is to be found. Power values for PV and EV are collected as they will be joined afterwards with the power from the bus movements. With each time step from the total operating duration, one bus or more will be moved, producing by each act new power values and new positions. With the new location of the buses, a new DC grid topology can be presented, leading the pre-set G matrix to be rebuilt to include all new values of the grid

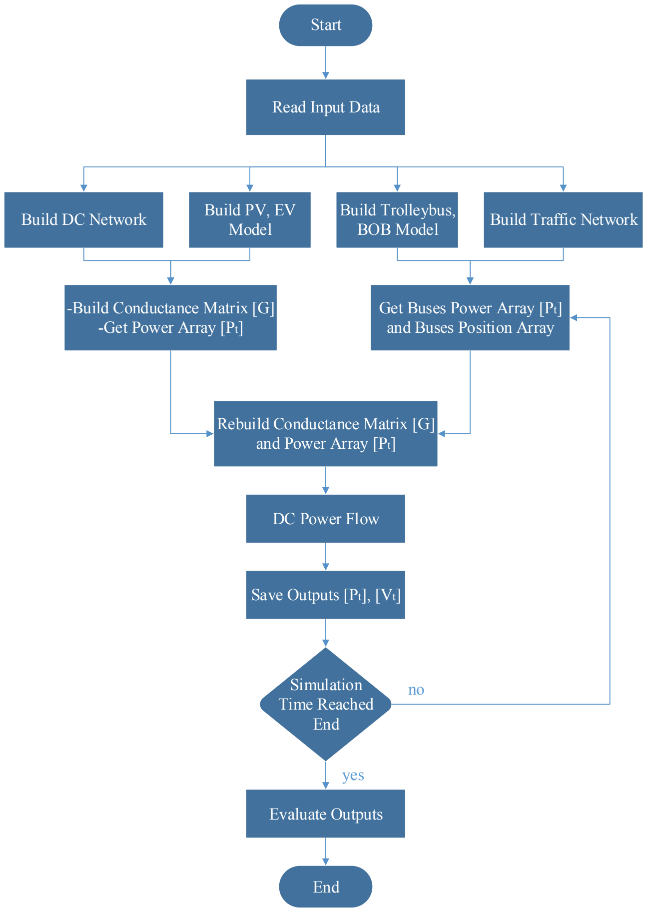

Figure 5: Flow chart of the simulation program

branches and nodes, due to the fact that present buses in the DC grid represent additional nodes which will fit in-between nodes of one of the grid branches, causing that branch to be divided into two or more branches, depending on the number of buses that are present in-between the branch nodes.

The power flow calculation is set with the new G matrix, which represents the instant grid topology, and the power from PVs, EVs and buses. One more thing which is needed to complete the required input value is the voltage value of the substations. The output of the power flow calculation will be saved and the simulation will continue with the process until the required duration is fulfilled.

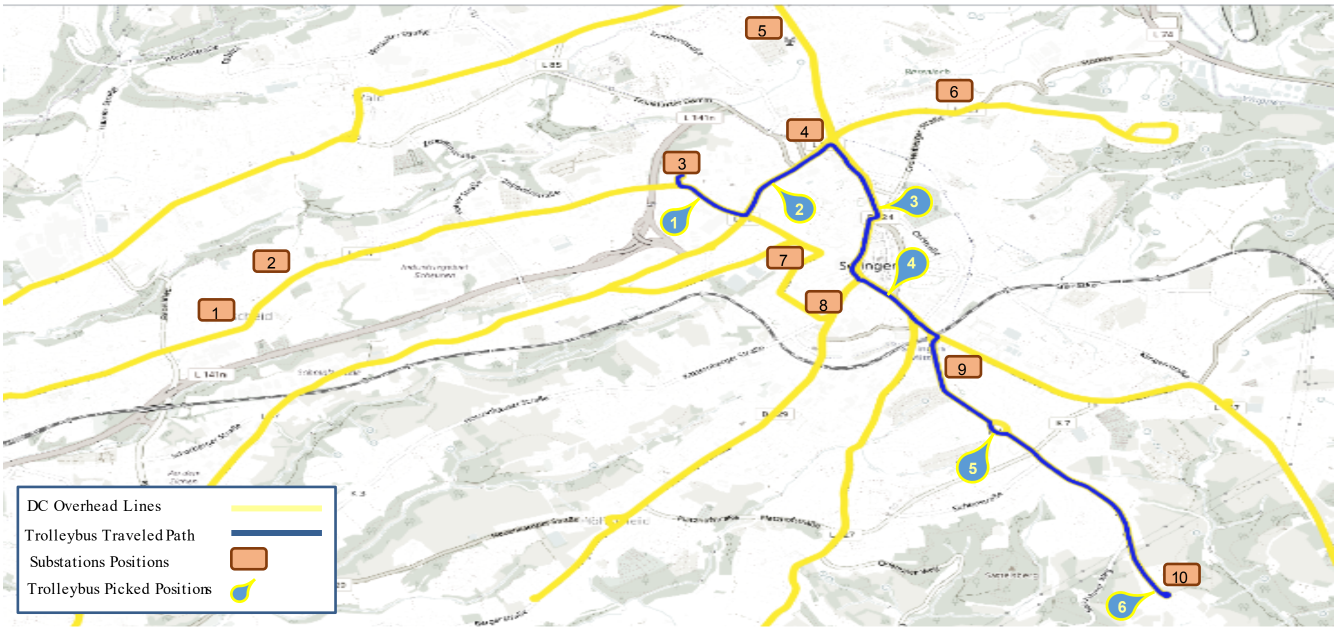

Figure 6: The DC overhead lines grid with a trolleybus traveled path

C. Results

In this section, apart from the results of the simulation program will be illuminated and discussed as voltage and power value over the DC grid nodes are clearly revealed. In order to verify the simulation output, one trolleybus operation over a distance of almost 6 km will be discussed. Afterward a BOB operation will be clarified where its action with batteries outside the DC grid and recharging them when reconnecting to the grid are illuminated.

Figure 7: Trolleybus power and voltage profile referenced to the bus crossed distance

Figure 6 illustrates the movement of a trolleybus under a part of the overhead DC grid, other parts of the gird are showed as well. Substations, which are influenced by the bus operation, are pointed out and randomly numbered. Gradual points over the crossed distance by the bus are marked and numbered sequentially after the distance from the point of start. The trolleybus power and voltage profile can be shown in Figure 7, in [1] the method to generate the mentioned power profile was carried out with deep details. The output that was expected from the simulation program can be seen in this voltage profile, as all its values were calculated by the power flow process in the simulation. The lowest voltage value can be seen at point 5 where the bus is approximately in a middle way between substation 9 and 10 with high power demand. Highest voltage is always 100% of the nominal voltage value, it cannot exceed this value due to the fact that the substations in the grid are one direction suppliers, i.e., the power that can be produced from the braking operation, causing a rise in bus voltage, will be directed into a braking resistors onboard the bus. The voltage will be held at maximum 1 P.U. when the bus brakes.

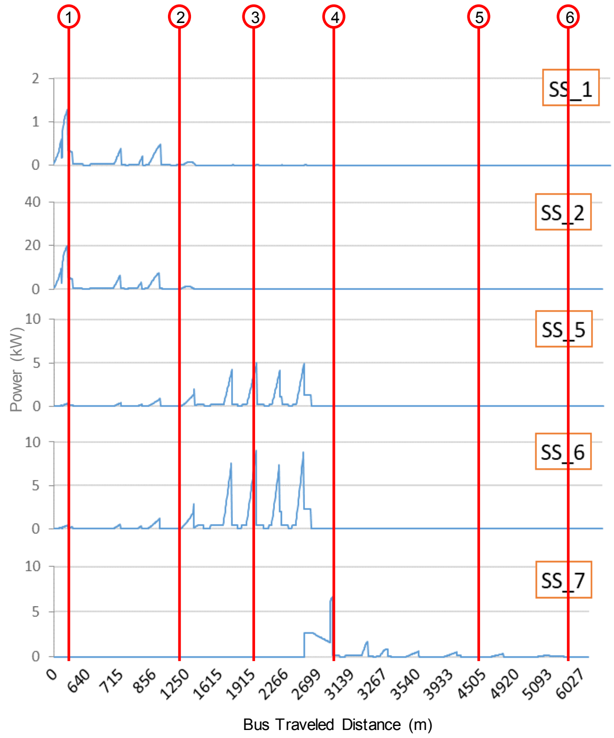

Figure 8:Substation power profile referenced to the trolleybus crossed distance

Figure 8 and Figure 9 shows the calculated power in ten chosen substations, the amount of the power in 1, 2, 5, 6, and 7 is very small as their position relatively far from the derived path, as shown in Figure 8. The other five substations, which are showed in Figure 9, share the highest demand, depending on the bus position with respect to them. For example, when the bus is at point 4, a very small amount of power is supplied by substation 7, more value provided by 8 and 9.

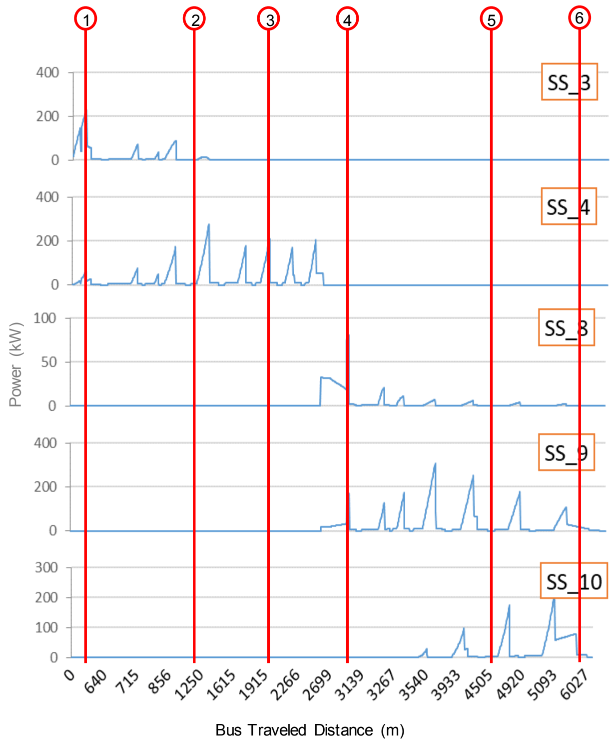

Figure 9: Substation power profile referenced to the trolleybus crossed distance

The BOB model was tested in the simulation program. The onboard battery trolleybus operated outside the DC overhead lines cutting a distance of 1.7 km for around 10 minutes. The battery SoC dropped to almost 60% since the outdoor temperature was adjusted for typical winter conditions. By this, a sufficiently low SoC was reached in order to obtain the charging modes impact. The time for charging the battery to its maximum capacity was about 35 minutes. The charging started immediately as the BOB reconnected with the overhead lines. The consumed power has been increased slightly by the new bus.

From the first look, the grid seems to be capable of handling the operation of one BOB without impacting the existing grid infrastructure. The aforementioned risk might rise dramatically with an increasing number of BOB in the grid.

IV. Conclusion And Future Work

Within this paper a methodical approach of modelling a public transport system was introduced by adding new components to the trolleybus network. A first impact on grid stability has been achieved, but further simulations are needed to validate. Adding battery trolleybuses destructively influences the grid stability due to the fact that additional energy from the overhead is consumed instead of receiving the same energy from the diesel combustion engine.

For the future, a further developed simulation environment with bidirectionally operating substations and enhanced models for the BOBs and the EV charging stations is planned to be implemented. The integration and reliability of the EV charging stations depends basically on the given information. The simulation model in progress will enable to make reliable statements whether EV charging stations are reasonable at specific positions in the Smart-Trolleybus-System or not. The sense of purpose will be regarded with consideration of the EV charging stations capability to relieve the DC overhead grid. In order to implement bidirectionally operating substations a steadily enhanced model for the DC power flow needs to be developed, since this case example is not that common. The further development of the BOBs basically depends on real measured values helping to validate the aforementioned simulation model.

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