Scenario Analyses of a Dynamic LVDC Smart-Trolleybus-Network with Battery-Assisted Traction Loads

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***Abstract*—This paper explores scenario analyses of a dynamic low voltage direct current (LVDC) Smart-Trolleybus-Network with battery-assisted traction loads. The system in question represents a complex and multi-layered solution to identify the capacity of LVDC networks in urban public transport solutions. By modelling all necessary components such as traction loads, stationary storage, PV and other miscellaneous loads, a highly complex system is generated. The goal is to determine suitable bus lines for BOB usage. The paper tries to identify how the data can be used in planning and development efforts within the project, such as scheduling of operation paths for new buses or preliminary load estimation to increase network stability and voltage quality. Results of the system are shown and different approaches to interpret the data are discussed.**

Keywords—Battery, LVDC Traction Network, Scenario Analyses, Smart Trolley System, Trolleybus

I. INTRODUCTION

With a catenary length of almost 100 km, Solingen has the largest operating trolleybus system in Germany. 50 electrically driven trolleybuses, which are equipped with auxiliary combustion engines and 50 additional conventional diesel buses are serving the public transport system. The aim of the project "BOB-Solingen" - the acronym BOB denotes the German words "**B**atterie-**O**berleitungs-**B**us" [1] – is to electrify the entire public transport sector by replacing the currently operating trolleybuses with the novel battery-trolleybuses, which combines proven trolleybus technology with the latest battery technology. The BOB creates the next generation of trolleybuses, which is able to drive on routes without the catenary, by means of the included battery. Moreover, within the project charging stations for electric vehicles (EV), decentralized renewable power generators such as photovoltaic (PV) systems as well as a stationary power storage system will be directly connected to the catenary. The stationary storage will consist of obsolete trolleybus batteries to increase their cost efficiency by establishing a second-life utilization concept. A potential analysis determined the optimal positions of PV systems and charging stations for EV [4].

To efficiently monitor and control the entire DC network, an intelligent control and management of the power flow in the overall system will be introduced. The Chair of Power System Engineering at the University of Wuppertal will develop and implement the essential automation system for the DC network to use its existing catenary infrastructure as effective as possible within its physical limitations. In order to realize an intelligent control of the network, the power flow of the current network (including the trolleybuses), as well as of the future network (including BOB) has to be modelled and simulated. By means of the simulation, critical network situations can be detected.

This paper intends to integrate the new battery-trolleybuses by replacing conventional diesel buses. Various simulated future scenarios will show the impact of the battery-trolleybuses to the dynamic network. In addition, the exchange of trolleybuses by battery-trolleybuses is simulated. Then, the scenarios are compared and evaluated. By using battery trolleybuses, the network load increases significantly, since the energy, which was previously obtained from the diesel fuel, has to be obtained from the catenary in the future. The network was not technically designed for this load and usage behavior. Network monitoring techniques will be the key to point out the actual network state in order to enable the essential intelligent network control. The aim is to predict critical network situations and to eliminate them preemptively.

II. LOW VOLTAGE DC NETWORK MODEL

The catenary with its six cross-city routes in Solingen represents the connection between substations and trolleybuses to supply them with electrical energy. For the sake of clarity, this paper does not take into account the future connected PV systems, charging stations for EV, stationary storage systems or bidirectional substations. Thus, the

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[1] battery-trolleybus

trolleybuses and the novel BOBs are the only, but also moving loads in the DC network.

A. Trolleybus and BOB Movement

Specially developed software by the authors, introduced in a different publication [1], calculates the movement of all buses for each time step over the previously defined simulation horizon. Since the buses represent moving loads, the aim of this bus movement is to determine the respective powers and positions of all buses in the DC traction network for each time step; this approach referred to as the stationary equivalent method for moving loads [3]. For the bus power calculation, the physical and technical properties of all bus types, the bus timetables, and a detailed data basis of all bus routes are obligatory. The data basis of all bus routes includes, among other things, the slope between two nodes and the node type, for instance: bus stop or curve. Generating an accurate bus power profile, four driving modes (acceleration, constant speed, coasting and braking mode [5] [6]) are required. The four different driving modes result in a constantly changing bus driving behavior over the simulation horizon. The determined mechanical power of a bus is then converted to its corresponding electrical power via the motor efficiency. The calculation of the movement from the conventional trolleybuses compared to the BOBs is identical, but different specific bus properties (e.g., the maximum bus power or mass) are used for the calculation. Charging the BOB's onboard battery increases bus power when the BOB connects to the catenary, if the battery is not fully charged. In this situation, the pantographs must conduct more current than before.

In addition, the buses have an integrated power control of the engine. This ensures that the bus voltage does not drop further in certain cases. If the voltage at the pantograph drops below a defined voltage level, the power reduction of the bus motor occurs. A reduction of the existing bus engine power comes into force. If the voltage drops below the minimum operating voltage of 400 V (BOBs: 380 V), the motor switches off automatically. A future paper will explain this relationship in more detail.

B. Low Voltage DC Traction Network

Due to the high number of intersections, the DC network, which has a nominal voltage of 660 V_{DC}, forms a heavily meshed network. Twenty-two substations feed the DC network from the upstream 10 kV medium-voltage network, and each catenary line mostly has a cross-section of 100 mm². The maximum power output of one substation is 1 MW. An already created database of the existing catenary and its power supply lines for a calculable traction network serves as the starting point for the power flow calculation. In addition, each bus connected to the catenary represents a further network node, this implies that the conductance matrix has to be recalculated for each time step since a new interconnection of all components is established [2] [3].

The substations operate unidirectionally, which means that they cannot feed back to the upstream AC network. If the regenerated bus power during the braking mode is higher than the consumed energy in the whole DC network, then the voltage rises to its maximum. Also, the voltage at the pantographs of a bus increases to the maximum operating voltage and the braking resistor converts the generated braking energy into heat. This happens, for example, in the morning, when only one trolleybus drives under the catenary, while the other buses are still in the bus depot. The simulation does not consider these buses until they start their daily timetable.

III. INTEGRATION OF BATTERY-TROLLEYBUSES

For the integration of BOBs into the DC network, three scenarios are considered to show how the network could develop. The simulation monitors the entire network status by calculating all powers, voltages, and currents for each time step. The first scenario corresponds to the situation before the extensive rollout of the new technologies, meaning no BOBs driving under the catenary. Since the first BOBs will travel on a specifically selected bus line, the second scenario is a transition to the third scenario. To achieve the integration of as many BOBs as possible into the present trolleybus network, an analysis of the bus lines helps to find out which bus routes the BOB can drive on without stopping as a result of a totally discharged battery. By not considering charging stations for electric vehicles, photovoltaic or stat. storage systems in the overall system, the analysis focuses exclusively on the buses. The simulation offers a large number of input parameters, which in turn have a big influence on the trolleybus system. Input parameters that generate random influences on the system are considered to be constant to compare all scenarios. This includes a constant ambient temperature of 18°C over the simulation horizon, so the ambient temperature does not rely on historical data. The waiting times at traffic lights and bus stops as well as the number of persons in each bus, which implies a constant bus mass, are further randomly generated parameters in the simulation, which are kept constant in this paper. Besides, there are currently three different trolleybus types in Solingen. A randomly chosen division of the bus types is kept identical for all three scenarios on the individual bus routes resulting in comparability under the individual simulations. The following analysis in all scenarios relies on a typical Monday.

A. Scenarios

1) Scenario I:

The first scenario consists exclusively of trolleybuses and diesel buses. Since the diesel buses do not receive power via the catenary, the simulation does not consider them. The simulation executes the aforementioned bus movement for each of the 46 trolleybuses and starts the DC power flow calculation – including the recalculation of the conductivity matrix - after each bus movement. Thus, this scenario represents the current network situation. In addition, this scenario provides the possibility to identifying weak spots within the DC network.

2) Scenario II:

The second scenario involves the integration of the bus line 695, given the fact that the BOB will definitely travel this line in the future. Partially, the BOB is currently traveling, e.g. for test drives, already the bus line 695. The simulation takes into account and simulates the 46 conventional trolleybuses and 5 BOBs needed for bus line 695.

3) Scenario III:

The third scenario is divided into two sub-scenarios. The first sub-scenario (scenario IIIa) includes the 46 trolleybuses and 69 diesel buses, which the simulation replaces now as BOBs. The additional buses used at peak times generate this high number of diesel buses. Since many diesel bus lines have a high amount of catenary-free sections, not all routes are suitable for the BOB usage. The BOBs, with the help of the integrated on-board battery, have a range for overcoming catenary-free sections of 25 km. This range is not sufficient for the majority of the diesel bus routes. Therefore, the simulation in the first sub-scenario IIIa does not consider the real battery capacity, but simulates an infinite battery capacity for the BOBs. Subsequently, an evaluation takes place in order to clarify which routes are suitable for the application of BOBs.

The second sub-scenario (scenario IIIb) simulates, in addition to the 46 trolleybuses, only the appropriate BOB routes. Based on these simulations, future power demands on the DC network can be defined and upcoming weak spots can be identified and eliminated as a preventive measure.

B. *Identification of suitable bus lines for BOB usage*

To identify suitable bus lines for the BOB usage, another simulation replaces all diesel buses with BOBs, but under the assumption of real battery capacity. By assuming the real battery capacity of a BOB, it is possible to check which BOBs successfully manage to complete the daily schedule without lowering the battery charge level to 0 %, stranding outside the catenary. The routes where the BOB can drive on without stopping because of a discharged battery are therefore suitable for BOB usage in the future. Even increasing the onboard battery size can be a solution.

IV. RESULTS

Below is a discussion of the results of the simulation study. The network monitoring focus on the claimed power of the substations and the resulting voltages on the buses. In addition, the state of charge of the onboard BOB battery comes into focus to identify the appropriate bus lines for BOB usage.

A. *Scenario comparison*

The first comparison (Figure 1) shows the cumulated power profiles of all substations of the previously discussed scenarios, using 15-minute averages. It can be seen that scenarios I and II do not differ significantly, but as expected, the claimed power of all substations is higher in the second scenario than in the first one.

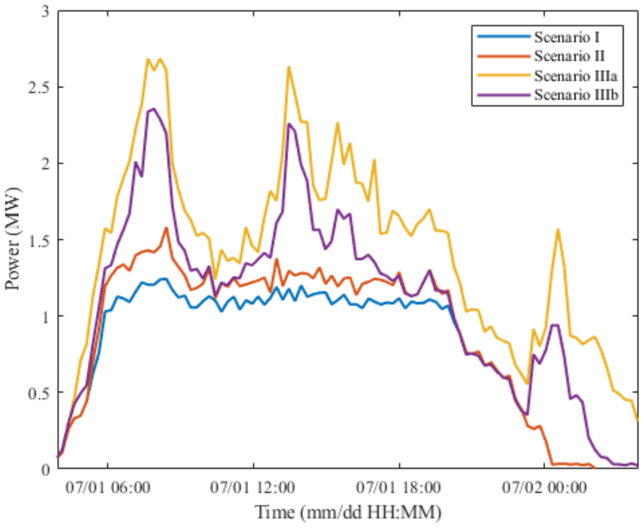

Figure 1: Cumulated power profiles of all substations (15-minutes-average)

The third scenario shows a rapid power increase. In the early hours of the morning and the afternoon, there can be found a particularly large number of passengers (students and commuters), which is why more buses are used at these peak times. The peak load in the afternoon decreases slowly until the evening and a new phenomenon occurs. In the late evening, many BOBs drive back to the bus depot and simultaneously, with their reduced state of charge connect themselves to the catenary. This results in a pronounced charging peak in the evening and at night. As expected, the load in scenario IIIb is lower than in scenario IIIa, since only the suitable diesel bus lines are replaced by the BOBs. However, the cumulated load partially doubles up.

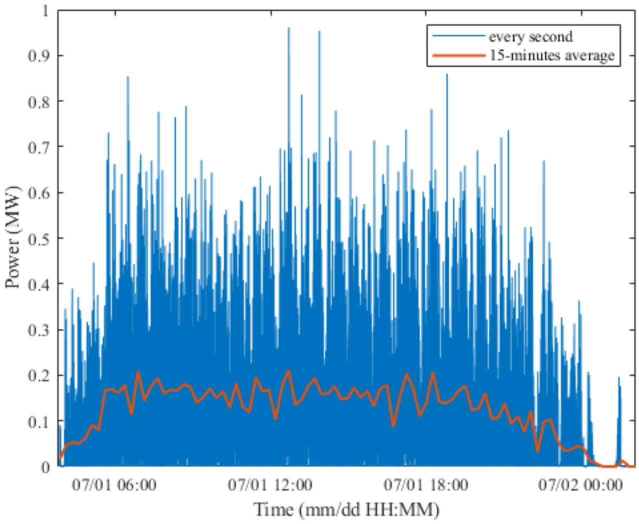

Figure 2: Power profile comparison of one substation (scenario I)

Figure 2 additionally shows a simulation comparison of the power profile of one substation in scenario I. While Figure 1 shows the 15-minute averages, the network is monitored every second. Here, a comparison is made between the 15-minute averages and every second generated simulation values. Due to the very high volatility, the power of the substation varies within a few seconds between the minimum (0 MW) and maximum feed-in power (1 MW). The 15-minute average results show in comparison feed-in power up to 200 kW. As explained above, most substations have a maximum output of 1 MW. As a result, at certain times in scenarios II and III, the maximum power of a substation may be exceeded.

Figure 3 shows a monitored comparison of the average bus voltages of all moving buses of the different scenarios. The focus is once again on the 15-minute averages of the individual simulations. The additional power demand in scenario II shows a voltage drop from scenario I to scenario II. In scenario IIIb, there is a rapid voltage drop at around 08:00 am, which, however, correlates with the power profile of Figure 1. At midday, the average bus voltages in scenario IIIb are slightly elevated compared to the first scenario.

This can be attributed to the fact that in the third scenario altogether more buses drive than in the first two scenarios. During lunchtime, many of these BOBs added in the third scenario are located in certain places on the network (mainly at the bus depot), so they artificially increase the average voltage because they have the nominal voltage of 660 V. In the afternoon, a similar situation arises as in the morning. Due to the additional loads in the DC traction network, the voltages drop on average. Towards evening, the same phenomenon occurs as during lunchtime. In summary, the bus voltages sometimes worsen significantly by adding more buses. As a result, buses sometimes have to reduce their motor power as explained before.

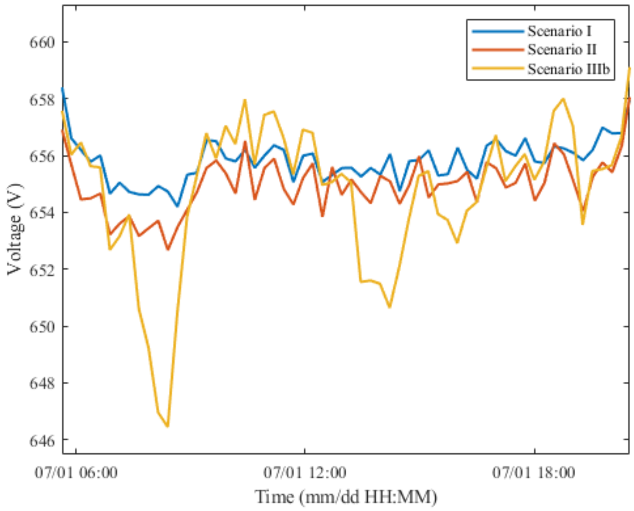

Figure 3: Bus voltage profile comparison (15-minutes-average)

Since the voltage profile of a bus is very volatile, similar to the power profile of a substation (Figure 2), the average voltage (15-minutes average) does not show how often the integrated voltage-driven bus power control is used. Figure 4 illustrates this fact and shows how quickly the voltage on a bus can drop because the buses can switch between braking and acceleration within seconds. The bus voltage depends heavily on the bus position in the DC network as well as on the total network load.

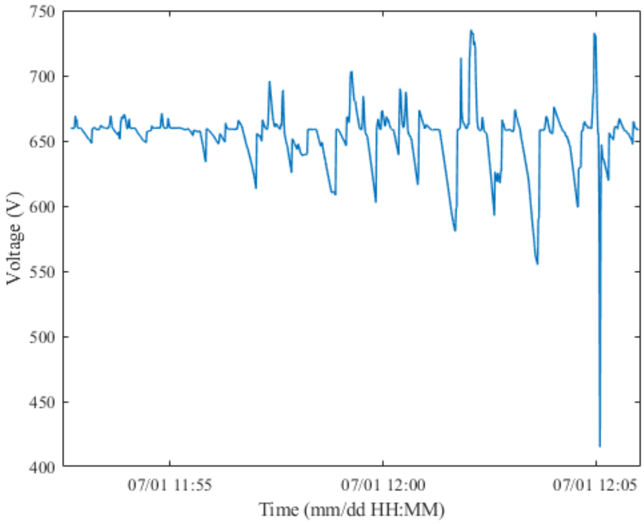

Figure 4: Voltage profile of one bus (every second)

Finally, Table I shows how the losses behave considering the number of used buses operating. The table summarizes the usage of trolleybuses and BOBs. The already explained burned breaking energy in the table arises in network situations when regenerative breaking power cannot be utilized by other buses and is therefore burned. Adding buses to the DC network increases the load of the entire network, resulting in fewer situations where the braking energy of one or more buses cannot be used. Thus, the average burned energy of a bus decreases as the buses in the trolleybus network increase. In addition, a comparison of the system losses takes place. The results also show that by adding buses, the summed system losses, which are composed of the line losses and the burned braking energy, increase. With a high number of buses in the network, braking buses are likely to find a consumer for the recovered energy. Furthermore, the current must overcome a shorter distance in the network in these situations. Even if more power is flowing throughout the network, system losses per bus can be reduced.

TABLE I: LOSSES COMPARISON

		Scenario			
		I	***II***	***IIIa***	***IIIb***
Bus number	trolleybuses	46	46	46	46
	BOBs	0	5	69	43
Summed "burned" braking energy (kWh)		58.83	54.93	41.23	56.50
Average "burned" braking energy (kWh)		1.28	1.08	0.36	0.63
Summed system losses (MWh)		1.60	1.80	3.46	2.54
Average system losses per bus (kWh)		34.69	35.39	30.07	28.58

B. *Identification of suitable bus routes for BOB usage*

BOBs have a limited battery capacity and are unable to operate all bus lines while keeping the state of charge of the battery capacity above 0 %. A simulation that replaces diesel buses with BOBs with real battery capacity (effective energy content: 45 kWh) shows which routes the BOB can drive. The maximum range that the BOB can drive with the onboard battery, while it is not connected to the catenary, depends largely on the topographical conditions. The elevation profile of the individual routes is required and stored in a database. Figure 5 shows the city of Solingen. Yellow indicates the catenary, while gray represents the diesel bus routes without catenary. The 22 substations that feed the DC traction network from the 10 kV medium-voltage network are also visualized.

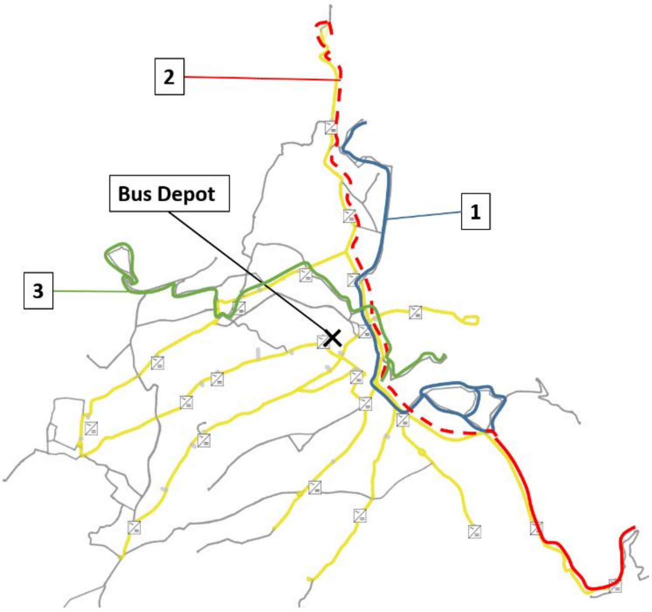

Figure 5: Low Voltage DC Network and additionally catenary-free diesel bus routes

The following examines three bus routes by way of example.

1) Bus line 695 (blue):

The first bus line has a catenary share of about 27%. After the BOB starts in the northern part of the route and drives about 4.5 km to the south without receiving power from the catenary, it connects to the catenary near the city. From this time on, the BOB can recharge its battery until it leaves the catenary after another 2.5 km. The second catenary-free part of this bus line is between 3.5 and 5 km long.

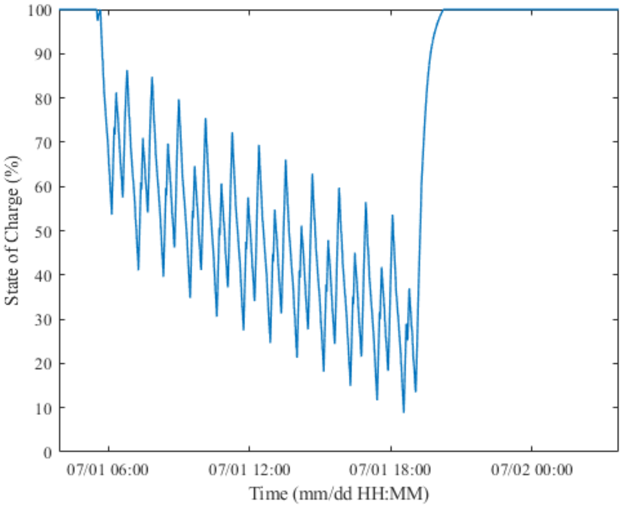

Figure 6: State of charge of the built-in bus battery on bus line 695

Figure 6 shows the state of charge profile of the integrated BOB battery. At the start, the BOB drives off the bus depot. After the BOB travels the bus line 695, the characteristic state of charge profile is established. In each bus cycle, the BOB loses about 3 to 5 % state of charge, which means that the catenary-free amount of this route is very large and the BOB cannot fully recharge the needed energy. However, the BOB can drive a certain number of driving cycles without running the risk of completely discharging the battery. There will also be a charging point installation on the northernmost part of this bus line so that the bus can recharge after each cycle. Accordingly, a waiting time at the end of the cycle is necessary. Figure 6 does not consider this charging point.

2) Bus line 683 (red):

The second bus line runs almost solely under the catenary, as this line is a trolleybus line, which is therefore commonly used by trolleybuses. However, a diesel bus travels the lower part of the route (dashed red line in Figure 5) which the simulation replaces with a BOB. In the southern area the BOB drives without catenary (about 1.5 km), whereby the state of charge of the battery decreases only by less than 5 % (Figure 7). This bus line is suitable for BOB use. Since in the future no articulated buses will travel this route, the use of further diesel buses is likely, since the previous BOBs are all articulated buses. New battery-assisted rigid buses, which are also to be integrated in the future, can solve this problem.

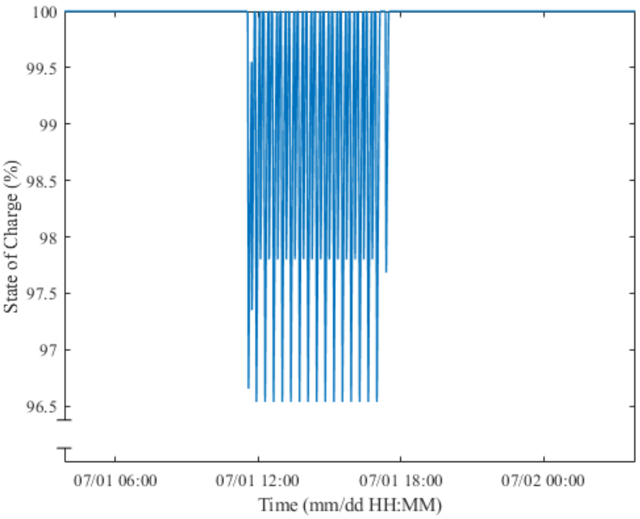

Figure 7: State of charge of the built-in bus battery on bus line 683

3) Bus lines 698 & 692 (green):

The green line in Figure 5 shows the combination of two bus lines (698 and 692). At present, diesel buses drive this exact combination, so it is worthwhile to analyze them more precisely. The huge amount of catenary-free sections of the combined bus lines means that the BOB does not manage a large number of bus cycles. By longer waiting times beneath the catenary to enable the BOB more charging time or by installing another charging point at the end of a bus line, this combined bus lines can theoretically be suitable for BOB usage. Likewise, an increased battery capacity can remedy the situation. More than twice the battery capacity is needed to cover the entire day.

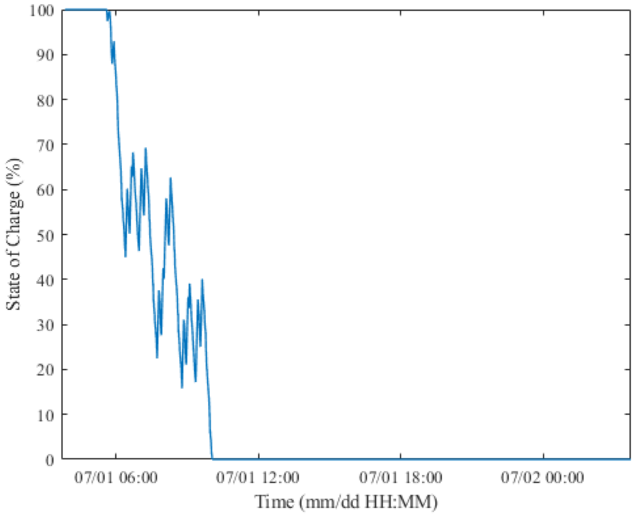

Figure 8: State of charge of the built-in bus battery on a combined bus line (698 & 692)

4) Other bus lines:

The green line in Figure 5 shows the combination of two bus lines (698 and 692). An extensive analysis has shown that the BOBs can replace the diesel buses in 43 of 69 cases, but it is not possible to switch a whole bus line from diesel buses to a single BOB. Exceptions are the aforementioned bus lines 695 and 683. However, the higher number can be explained by the fact that many additional diesel buses travel at rush hours in order to manage the work and school traffic.

V. CONCLUSION AND FUTURE WORK

The paper showed how the load on the substations will develop in the future. Bus voltage and power profiles show the consequence of a worsened network state. Not shown limit violations increase significantly by adding BOBs into the system. An analysis of different future scenarios shows how BOB usage is possible. Many diesel bus lines do not offer a switch from diesel buses to BOBs, but the additionally used diesel buses during peak hours are suitable. These drive usually less than 25 km, whereby a charge of the onboard battery at the bus depot is sufficient. A restructuring of the bus lines is necessary to integrate more BOBs.

The simulation shown in this paper monitors all buses in each simulated time step. Furthermore, the simulation offers the possibility to perform live monitoring and forecasting for the DC network. Figure 9 shows the required procedure. After successfully reading of all measurement data and setting the buses to their correct position, the simulation starts to simulate a forecast.

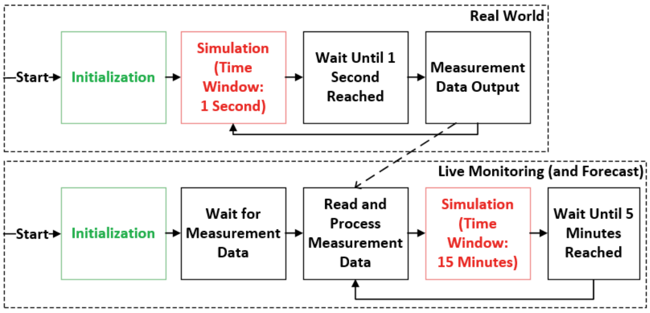

Figure 9: Live Monitoring (Flow diagram)

Future papers will focus on optimizing the forecast. For example, the duration and number of forecasts will be evaluated. In addition, functions are provided to detect threshold violations and implement an intelligent control strategy to eliminate critical network situations preemptively. An adaptation of the simulation takes place in order to execute the control commands of the control strategy.

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