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A Bilateral Substation-Voltage Tuning Approach

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Increasing the Integration Potential of EV Chargers in DC Trolleygrids: A Bilateral Substation-Voltage Tuning Approach

1st Ibrahim Diab
Electrical Sustainable Energy department
Technische Universiteit Delft (TU Delft)
Delft, The Netherlands
i.diab@tudelft.nl

2nd Gautham Ram Chandra Mouli
Electrical Sustainable Energy department
Technische Universiteit Delft (TU Delft)
Delft, The Netherlands
G.R.ChandraMouli@tudelft.nl

3rd Pavol Bauer
Electrical Sustainable Energy department
Technische Universiteit Delft (TU Delft)
Delft, The Netherlands
P.Bauer@tudelft.nl

***Abstract*—Light rail networks such as trolleybus grids have the potential to become multi-functional smart grids by using the excess capacity of the grid to implement PV systems, EV chargers, and storage. This paper offers a solution to increasing the potential for integration of EV chargers in the trolleygrid, without additional infrastructure costs, by simply tuning the nominal (no-load) voltages of bilaterally connected substations. This method shifts the load share between the two substations, creating more room for the integration of other utilities in a desired zone of the bus route. A mathematical derivation is presented, followed by a verifying case study using detailed and verified bus and trolleygrid simulation models for the city of Arnhem, the Netherlands. It is shown that by setting a substation nominal voltage from +10V compared to its bilateral substation to -10V, the substation can take, on average, as much as 7.5 percentage points less of the load share (from 45.9% to 38.4%) and see as much as 5 percentage points more of complete zero-load time (84.3% to 89.2%).**

I. INTRODUCTION

Transportation electrification is a necessary step toward sustainable societies as transport accounts for almost a quarter of total climate-change emissions [1, 2]. Trolleybuses, as a replacement for diesel buses, are making a comeback into this electric urban transport landscape, pushed by a recent advancements in battery technologies and electric mobility [3–5]. The trolleybus grid has as well the potential to go beyond its single function of powering the buses, and become a multi-functional smart grid integrating PV, EV-chargers, and storage systems, as shown in figure 1 [6–17].

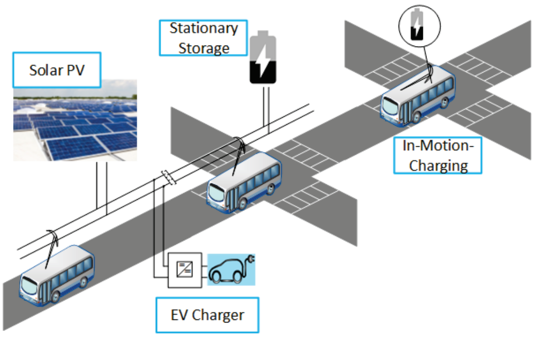

Fig. 1. The trolleygrid as an active grid with PV, EV and Storage. Both regular and In-Motion-Charging buses can operate under this grid

A. The Trolleybus Grid

Figure 2 shows the typical layout of a trolleygrid. The bus lines are divided into isolated sections of few hundreds of meters, up to 1 or 2 km, depending on the trolleygrid city. This for reasons such as faults, transmission losses, and maintenance. The power comes from the Low Voltage AC grid (LVAC) and is turned by the substations (a transformer and a rectifier system) to 600-750V DC, depending on the substation. One substation can feed one or more sections, to which it is connected via the section feeder cables (FC). In cases like the one presented in figure 2, substation 1 feeds two sections, while substation 2 feeds one. However, these sections are in fact bilaterally connected. A bilateral connection is a controllable connection between two sections that are under different substations. The consequence of this is that now Substation 1 and 2 can actually power the 3 sections shown. The substations can be idealized as voltage sources, and like in any electric circuit, the share of the power demand that each substation delivers to the circuit elements is a function of the voltages and the impedances.

B. Designing the Trolleygrid of the Future

The integration of EV chargers in the trolleybus network is not only an opportunity, but also a necessity for the effective integration of renewable energy source in the trolleygrid [6], by creating a base load for the RES sources. However, this multi-functionality requires sophisticated algorithms that would ensure that the bus demand is prioritized, without violating the trolleygrid operational limits. The trolleygrid has limitations on the allowable:

- *Maximum Power*, due to the substation component ratings

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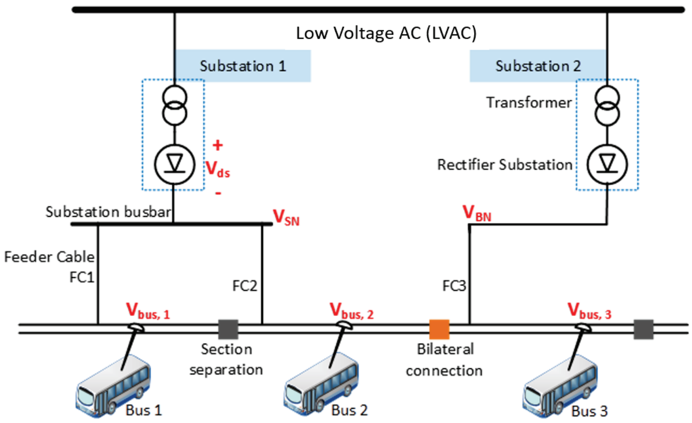

Fig. 2. The Trolleygrid and its components

- *Maximum Line Current*, due to the current-carrying capacity of the overhead cables
- *Minimum Line Voltage*, due to the bus operation limits (power curtailment under 500V, and complete shutdown at 400V [18, 19])

The presence of a bilateral connection would typically enhance the voltage and current behavior in the grid, away from the limits. This is a trivial conclusion from the existence of two voltage sources at a distance from each other. Additionally, this paper suggests that by properly tuning the substation voltage of each bilateral substation, the power limit can also be better respected, by shifting the bus load of the substation where the EV charger is installed to the other substation.

C. Paper Structure

Section I introduced the trolleygrid and the scope of this paper. Section II presents the mathematical derivations of the load power share and identifies the elements to tune to control this share. Section III presents the case study, its modelling methodology, and the results. Finally, section V offers conclusions and recommendations for future work.

II. POWER FLOW IN TROLLEYGRIDS WITH BILATERALLY CONNECTED SUBSTATIONS

A. Load Power-Share Calculations

Figure 3 shows a bus between two substations, drawing a power P_b. Its voltage is v_b and it draws a current i_b.

$$P_\mathrm{b} = v_\mathrm{b} \cdot i_\mathrm{b} \tag{1}$$

Defining the impedances as

$$R_i \triangleq R_{\mathrm{f},i} + R_{\mathrm{l},i} \quad i = 1, 2 \tag{2}$$

And assuming that the two substations SS1 and SS2 are at a voltage differential ΔV_ss of

$$\Delta V_\mathrm{ss} \triangleq V_\mathrm{s,1} - V_\mathrm{s,2} \tag{3}$$

And defining the voltage drop ΔV as the voltage drop between the bus and the second substation, SS2:

$$\Delta V \triangleq V_\mathrm{s,2} - V_\mathrm{b} \tag{4}$$

The power delivered by each substation can be written as:

$$P_1 = V_\mathrm{s,1}(\frac{\Delta V + \Delta V_\mathrm{ss}}{R_1}) \tag{5}$$

$$P_2 = V_\mathrm{s,2}\frac{\Delta V}{R_2} \tag{6}$$

Eq.1 can be rewritten as:

$$P_\mathrm{b} = (V_\mathrm{s,2} - v_\mathrm{b}) \cdot (\frac{\Delta V_\mathrm{ss} + \Delta V}{R_1} + \frac{\Delta V}{R_2}) \tag{7}$$

Giving:

$$R_\mathrm{b}\Delta V^2 + [R_2\Delta V_\mathrm{ss} - R_\mathrm{b}V_\mathrm{s,2}]\Delta V + [R_1R_2P_\mathrm{b} - R_2V_\mathrm{s,2}\Delta V_\mathrm{ss}] = 0 \tag{8}$$

where R_b is defined as the line impedance between the two substations

$$R_\mathrm{b} \triangleq R_1 + R_2 \tag{9}$$

Solving the quadratic equation of Eq.8 gives:

$$\Delta V = \frac{R_\mathrm{b}V_\mathrm{s,2} - R_2\Delta V_\mathrm{ss}}{2R_\mathrm{b}} - \frac{\sqrt{[R_\mathrm{b}V_\mathrm{s,2} - R_2\Delta V_\mathrm{ss}]^2 - 4R_\mathrm{b}[R_1R_2P_\mathrm{b} - R_2V_\mathrm{s,2}\Delta V_\mathrm{ss}]}}{2R_\mathrm{b}} \tag{10}$$

The power delivered by each substation can then be obtained by inserting Eq.10 into Eq.5 and Eq.6.

B. Effect of Bilateral Parameters on the Load Power-Share

1) Mathematical Derivation: Combining Eq.10 with Eq.5 and Eq.6 shows how for the same power demand and position of the load (i.e., line impedance), the share of each substation from the power delivered is a function of $V_{s,2}$ and ΔV_ss. However, it can be mathematically shown, by computing the partial derivatives, that the two parameters do not have the same effect on the power sharing when considering the typical order of magnitue of the parameters as seen in a trolleygrid.

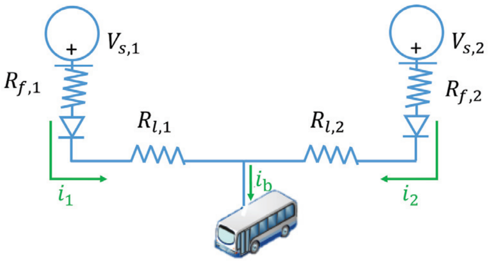

Fig. 3. Nomenclature of the parameters used to study the case of one bus powered by two bilateral substations

Firstly, in terms of $V_{\text{s,2}}$:

$$\frac{\partial \Delta V}{\partial V_{\text{s,2}}} \approx \frac{1-\dfrac{R_{\text{b}} V_{\text{s,2}}}{\sqrt{R_{\text{b}}^2 V_{\text{s,2}}^2 - 4P_{\text{b}} R_1 R_2 R_{\text{b}}}}}{2R_{\text{b}}} \tag{11}$$

For typical values of substation voltages at the order of 600-750V, i.e. $\mathcal{O}(V_{\text{s,2}}) = \mathcal{O}(10^2)$, and of line resistances at the order of 0.1Ω, i.e. $\mathcal{O}(R) = \mathcal{O}(10^{-1})$, and bus powers of $\mathcal{O}(P_{\text{b}}) = \mathcal{O}(10^5)$, it can be concluded that:

$$\frac{\partial \Delta V}{\partial V_{\text{s,2}}} \approx \frac{1-\dfrac{\mathcal{O}(10^{-1})}{\sqrt{\mathcal{O}(10^{-2})}}}{2\cdot\mathcal{O}(10^{-1})} \tag{12}$$

Leading to:

$$\frac{\partial \Delta V}{\partial V_{\text{s,2}}} \approx 0 \tag{13}$$

Which is confirmed in the next subsection.

Meanwhile, in terms of ΔV_{ss},

$$\frac{\partial \Delta V}{\partial \Delta V_{\text{ss}}} \approx \frac{-R_2 + 3\dfrac{R_{\text{b}} R_2 V_{\text{s,2}}}{\sqrt{R_2^2 V_{\text{s,2}}^2 - 4P_{\text{b}} R_1 R_2 R_{\text{b}}}}}{2R_{\text{b}}} \tag{14}$$

For typical values of difference in substations voltages of the order of tens of volts, i.e. $\mathcal{O}(\Delta V_{\text{ss}}) = \mathcal{O}(10^1)$, and the other parameters chosen above, it can be concluded that:

$$\frac{\partial \Delta V}{\partial \Delta V_{\text{ss}}} \neq 0 \tag{15}$$

Effectively meaning that tuning the absolute magnitude of the substation voltages would not have a significant effect on the load power share of each substation for any typical trolleygrid. Meanwhile, tuning the voltage difference between the two bilateral substations, ΔV_{ss}, would have a direct effect.

2) Validating the Mathematical Derivation: The above mathematical derivations are validated by the hypothetical case study in figure 4 where it is observed that the load sharing fraction of SS1 is more affected by ΔV_{ss}, while the substation voltage is fixed (the differences within the sets of red and sets of blue lines) than by $V_{\text{s,2}}$ while the ΔV_{ss} is constant (the differences between the curve lines holding the same marker). In the remaining part of this paper, simulations of a trolleygrid substation with actual bus traffic will allow to validate these results.

III. ARNHEM CASE STUDY

It is important to extend this work beyond a single bus on a bilaterally connected section. This is because the presence of multiple buses alters the power flow (non-linear voltage drops), and consequently, the load power shares. For this purpose, a case study is presented for two bilaterally connected sections from the trolleygrid of Arnhem, the Netherlands. The parameters are shown in figure 5. The simulation is run for a full day, in a step resolution of one second.

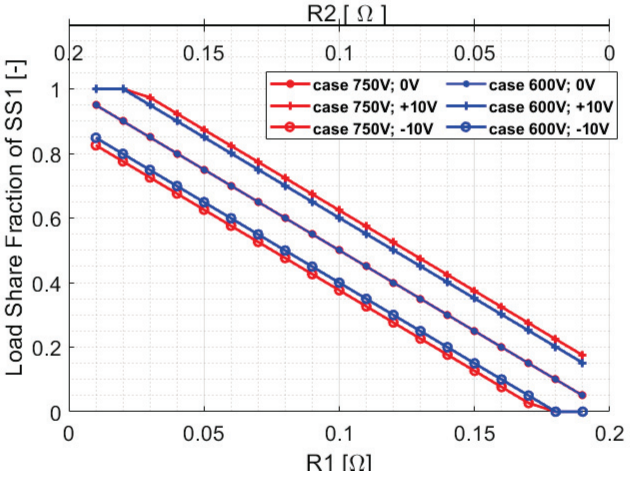

Fig. 4. Load share fraction of SS1 for different cases of [$V_{\text{s,2}}$, ΔV_{ss}] for a situation such as figure 3 with $R_{\text{b}} = 0.2\Omega$ and P_{b}=300kW. It is observed that changing $V_{\text{s,2}}$ (curves of the same marker) has a far lower effect on the fraction than ΔV_{ss} has (curves of the same color)

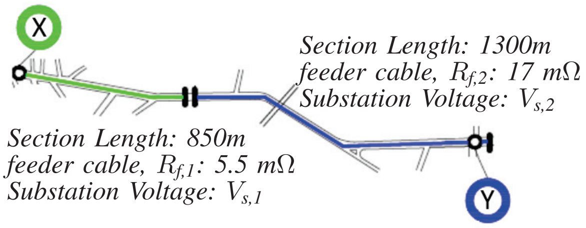

Fig. 5. Bilateral Connection: Layout of the investigated sections X and Y in Arnhem and their parameters

A. Modelling the Trolleybus Load Demand

The trolleygrid model (figure 6) begins with the creation of bus demand from measured bus velocity and power cycles, and randomized traffic and stoplight probability data.

The bus powers are given by Eq.16. While in traction mode, the bus power is simply the sum of the traction P_{tr} and the auxiliaries demand, P_{aux}. During braking, the bus power, P_{bus}, is the auxiliaries power P_{aux} plus the net exchanged with the grid P_{net}, and the excess energy P_{BR} that is wasted in the braking resistors. The auxiliaries consist of the P_{HVAC} that is a fraction (duty cycle) of the nominal HVAC power (36.5 kW), and P_{base} (taken here as 5 kW) that is the power of basic bus loads such as the doors, the screens, and the indoor lights, etc.

$$P_{\text{bus},j} = \begin{cases} P_{\text{net},j} + P_{\text{aux},j} + P_{\text{BR},j} & \text{if braking} \\ P_{\text{tr},j} + P_{\text{aux},j} & \text{if traction} \end{cases} \quad j = 1..N_{\text{bus}} \tag{16}$$

$$P_{\text{aux}} = P_{\text{HVAC}} + P_{\text{base}} \tag{17}$$

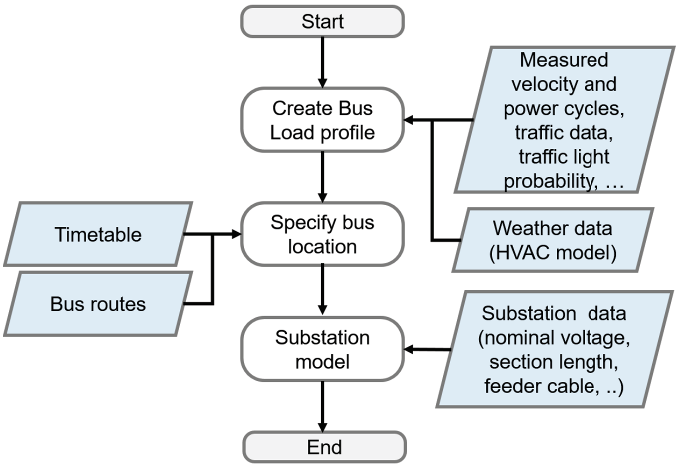

Fig. 6. The trolleygrid model flowchart

The HVAC simulation model is based on a thermodynamic heat exchange model, its output is per-second power of the bus of the requirements to meet the inside cabin comfort conditions for the passengers. The HVAC model takes into account the conductive and convective heat transfer load (between the cabin and the external environment), the heat exchange due to the forced air ventilation and air circulation (air quality requirement), the air ventilation due to the opening of the doors for passenger transit (air exchange with the external environment), the direct, diffuse and reflected solar radiation heating of the bus external surfaces, and the metabolic heat gain from the passenger bodies.

Once the bus powers is known, the position of the bus loads under the trolleygrid is derived from the timetables and bus routes and the previously randomized traffic data.

B. The Trolleygrid model

The grid model is based on the backward-forward sweep method [20]. The model takes into account the line impedance, feeder cables, parallel line connections (for impedance reduction), as well as the existence of a bilateral connection.

The model starts by reading and sorting the positions and powers of all the buses on the supply zone. As explained in Eq.18, at the first iteration step, k, the current at each node, n, is the power of the node divided by the substation nominal voltage V_{SN}, as an initial guess. At later iterations, with a voltage assigned to each node, the current is obtained by dividing the power of each node by its voltage. The total impedance between two nodes n and n-1, $R_{n,n-1}$, is obtained by Eq. 19 from the equivalent impedance model in [18]. The model takes the feeder cables into account as well, as this is an important step in the calculation of the voltage level at the connection point of the bilateral connection to the section. This voltage, V_{c}, is given by Eq.20. If the substation is supplying power, this voltage is equal to the substation voltage, V_{s}, minus the voltage drop across the feeder cable resistance R_{f}. If the substation is not supplying power, the voltage is equal to the substation nominal voltage plus any voltage blocked by the rectifier diodes, V_{ds}.

The bilaterally connected substation is modelled as a virtual bus with regenerative braking. The value of the regenerative braking is iterated until the virtual bus voltage matches the bilateral substation bus voltage. This complete trolleybus grid model is explained in detail and verified by the authors of this paper in [18].

$$I_{\mathrm{n}} = \begin{cases} P_{\mathrm{n}}/V_{\mathrm{SN}} & k=1, \quad \& \quad n \neq \mathrm{SN} \\ P_{\mathrm{n}}/V_{\mathrm{n}} & k \neq 1, \quad \& \quad n \neq \mathrm{SN} \\ -\sum_{n \neq \mathrm{SN}} I_{\mathrm{n}} & n = \mathrm{SN} \end{cases} \tag{18}$$

$$R_{n,n-1} = \rho \cdot |x_n - x_{n-1}| \tag{19}$$

$$V_{\mathrm{c}} = \begin{cases} V_{\mathrm{SN}} - R_{\mathrm{f}} \cdot I_{\mathrm{SN}} & i_{\mathrm{SN}} > 0 \\ V_{\mathrm{SN}} + V_{\mathrm{ds}} & i_{\mathrm{SN}} = 0 \end{cases} \tag{20}$$

C. Arnhem Case Study Results

The simulations were run for Arnhem for a full day, for the worst case scenario of a high traffic schedule with a high HVAC demand. The day chosen is an October day, using a baseline of 690V as $V_{\mathrm{s},2}$. The results are tabulated in Table I where it can be seen that the power share of substation 1 can change by up to 7.5 percentage points by the tuning of the substation voltage difference. Additionally, the substation would see almost 90% of its day as a zero load period, available completely for EV charging.

TABLE I. SUMMARY OF RESULTS OF LOAD SHARE FRACTION AND ZERO-LOAD TIME FOR THE SS1 IN THE CASE STUDY OF FIGURE 5 FOR DIFFERENT VALUES OF ΔV_{ss}

ΔV_{ss}	**Average Load Share Fraction**	**Daily Zero-load time**
+10V	45.9%	84.3%
+5V	48.0%	84.4%
0V	46.0%	87.3%
-5V	43.4%	88.9%
-10V	38.4%	89.2%

A closer look at the results is presented in figure 7 for the half an hour span between 8.30 am and 9.00 am. The zero load instances can be observed. With ΔV_{ss} of 10V, for example, SS1 is engaged most of the time for more than 50% of the load, and during moments where it had not been previously engaged in supplying the load. It is especially interesting to note the peak demand moments before 9:00 am where SS1 had no share of the power demand, leaving it completely to SS2, and then in the case of +10V, became engaged in more than half of the load. This again, shows the benefit of this method. It is worth noting, however, that this load shifting will also have an effect on the recuperation of braking energy and the transmission losses. A more detailed study into the expected benefits or losses is urged.

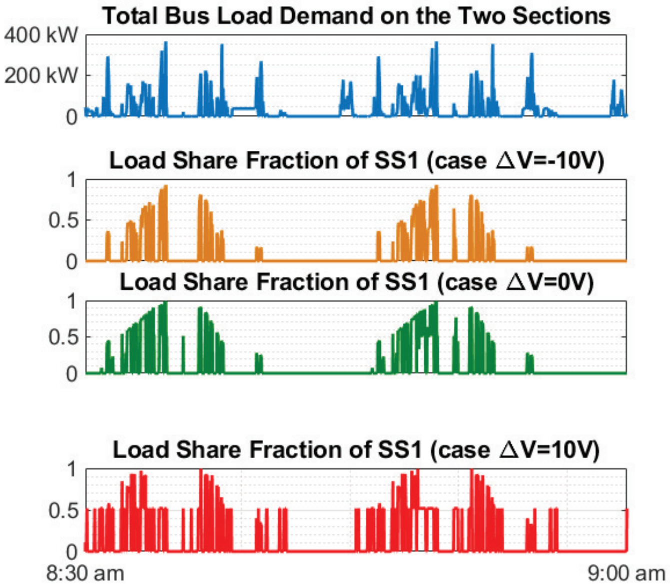

Fig. 7. A closer look at the load share fractions between the two bilaterally connected substations based on different values ΔV_{ss} for 30 minutes during the day

IV. CONCLUSIONS

This paper suggests a method of increasing the integration potential of EV chargers in trolleygrids by properly choosing the substation voltage levels for bilaterally connected substations. The idea is that a simple tuning of the voltage of two bilateral trolleygrid substations can positively shift the load distribution between them and offer more room for the integration of other functionalities. The results presented in the case study of Arnhem, The Netherlands, verify the mathematical derivations suggesting this claim. Further work is recommended in studying the grid with an implemented EV charger to see the new effect on the transmission losses and power limits of each substation, and finding an optimal voltage differential between the two substations. Furthermore, work is urged on the study of the effect the new substation voltage could have on the recuperation of the bus braking energy and the bus transmission losses.

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