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An Adaptive Battery Charging Method for the Electrification of Diesel or CNG Buses as In-Motion-Charging Trolleybuses

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***Abstract*— The decarbonization of urban bus fleets can be made by their electrification as in-motion-charging (IMC) buses which can run as trolleybuses or in battery mode. The benefit is that IMC buses can use the existing trolleygrid infrastructure where their route overlaps with it to charge the battery and operate in battery mode outside of it. Presently, the IMC battery charging power is set conservatively to the minimum of all the spare capacities of the traction substations (SSs) found along the bus route. This can render most electrification projects techno/economically infeasible as not enough energy is picked up for the battery-mode operation and long charging times at bus terminals are required. This article proposes then an adaptive charging approach that uses the locally available spare capacity under any traction SS, taking into account the limitations of the maximum SS power and the minimum line voltage. The method is proven here both theoretically and in a case study over one full year of operation of four electrified diesel/compressed natural gas (CNG) bus lines in Arnhem, The Netherlands, using comprehensive and verified trolleybus and trolleygrid models. The proposed adaptive charging method, as opposed to the present conservative method (here, Regular Charging), is shown to make one bus electrification project completely feasible and reduce the extra terminal charging time for the other lines by up to 64%.**

***Index Terms*— Adaptive charging, dc systems, in motion charging (IMC), trolleybus, urban transportation.**

I. Introduction

Electrification of urban public transport is gaining momentum, pushed by ambitious zero-emission policies. For example, almost half of the EU member states have set a 75% target for zero-emission bus sales by 2030 [1], [2]. This steep increase poses a challenge for electric transport infrastructures looking to electrify their diesel or compressed natural gas (CNG) fleets. On the other hand, the existing urban transport networks, such as trams or trolleybus grids, tend to be both oversized and underutilized in terms of their power capacity [3], [4], [5], [6], [7]. This invites investigations into using this spare capacity for sustainable electrification and charging of electric vehicle fleets without the need for major urban grid infrastructure updates and investment costs [8], [9], [10], [11], [12].

A. Trolleybuses and Trolleygrids

The trolleybus is different from a battery electric bus (BEB) in that it is an electric vehicle supplied by a catenary (overhead lines), and not by a precharged battery. For reasons such as voltage drops and faults, a dc trolleygrid is fragmented into substations (SSs) that each feed a number of sections (SCTs), as shown in Fig. 1. From the low-voltage ac (LVac), the SS (step-down transformer and a rectifier) supplies the buses on its SCTs via feeder cables (e.g., FC1 in Fig. 1), at 650–750 V dc (V_{SN}), depending on the SS and the trolleybus city. To limit over-currents, the minimum bus voltage for operation is 400 V, and the bus curtails its own power demand when under 500 V. The SCTs are from a few hundred meters up to 2 km in length, depending on the trolleygrid city. Trolleybuses typically consume about 70 kW while driving, but can reach power peaks above 300 kW while accelerating. When a trolleybus brakes, the available regenerative braking power can be as high as 200 kW. If the braking trolleybus has an on-board storage system (also known as a dual-source trolleybus [13], [14], [15], [16]), it can harvest this braking energy to be later used while accelerating. In the absence of on-board storage, this power can be shared with buses on the same SCT, on a connected SCT under the same SS busbar (Bus1 and Bus2 in Fig. 1), or wasted in on-board braking resistors [14], [15], [17]. The braking energy cannot be sent back to the LVac grid because of the unidirectional rectifiers at the SS.

B. IMC Buses

A new generation of trolleybuses, namely, the in-motion-charging (IMC) bus, combines the advantage of a trolleybus and of a BEB and is being rolled out into more cities [5], [17], [18], [19], [20], [21], [22], [23], [24]. As summarized in Table I, IMC buses run under the catenary as a trolleybus but are also equipped with an on-board battery. This battery is charged while the bus is in motion under the route segment with overhead wires (the charging corridor). This gives the IMC bus both the route and range flexibility of a BEB, but with a smaller battery size which is needed only to cover the catenary-less part of the bus route (the battery-mode operation). The IMC battery charging power is different per trolleybus city and is limited by factors such as the IMC

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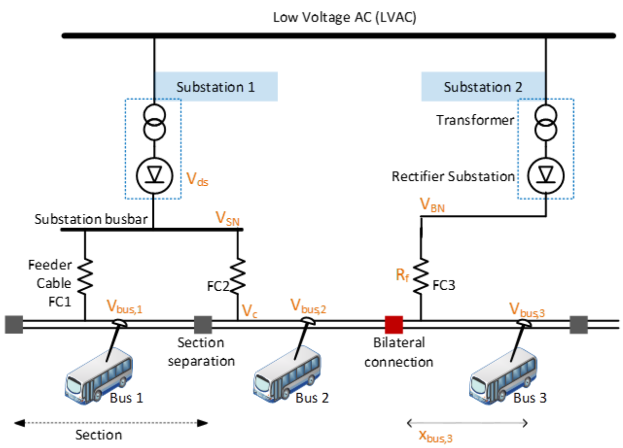

Fig. 1. Trolleygrid and its components.

battery capacity and technology, the available grid capacity, and the ratio of the battery-mode route length to that of the charging corridor. It is important to note that the IMC bus draws a lower battery charging power when standing (referred to as Π in this article) than the power it draws when moving (here, Ψ). This is not to overheat and damage the point of connection of the bus to the catenary when standing still.

C. IMC Buses for Bus Electrification

In the context of the electrification of diesel or CNG buses, replacing them with IMC buses is useful for the routes that overlap significantly with the existing trolleygrid infrastructure. In this manner, the IMC bus can charge its battery when under the existing catenary and drive in full battery mode in areas outside of it. This method better uses the existing infrastructure and reduces the battery size needed for the route in comparison to a BEB [7], [25].

However, the obvious challenge with IMC buses is that they require significantly more power from the available catenary for their battery charging, which on average can be up to 6× per km that of a conventional trolleybus [4], [7], [24]. This constitutes a major hurdle for the implementation of IMC buses as some congested areas of the trolleygrid cannot handle the additional demand of an IMC bus and its battery.

D. IMC Battery Charging Schemes: Regular and Adaptive Charging

Presently, an IMC bus has a fixed charging power duplet throughout its operation (Ψ while moving, and Π while standing still, as explained earlier). This charging power is chosen and fixed in a very conservative way according to the expected spare capacity of the *most congested* SS on the IMC bus route. This leaves the other, less-congested zones with underutilized spare capacity that could have allowed an extension of the battery-mode operation and/or reduced the required charging corridor length. This is referred to in this article as *regular charging.*

This article suggests an *adaptive charging* approach that changes the battery charging power duplet (Ψ, Π) depending on the spare capacity of the trolleygrid SS it is currently under (see Fig. 2). This spatial condition can be easily implemented

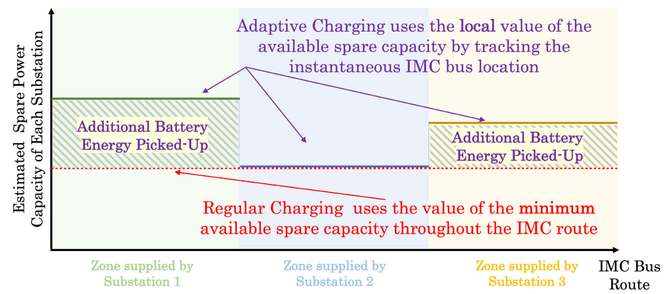

Fig. 2. Illustrative example of the different IMC battery charging methods presented in Section I-D.

by making use of the existing GPS signal found on most buses or of an integral of the bus velocity to estimate its position on the route.

E. Article Contributions

This article offers the following contributions.

1) The proposition of new charging methods for IMC trolleybus batteries, namely, the adaptive charging method that can offer more room for the integration of IMC buses and reduction of infrastructure size and costs and of bus battery charging times.
2) A theoretical proof of concept, analytical quantification, and detailed technical feasibility case study of a new charging method (adaptive charging) for the electrification of diesel/CNG bus lines as IMC buses using the existing infrastructure.
3) Analysis of maximum SS powers and minimum line voltages using comprehensive and verified bus traction and auxiliary load models and trolleygrid models, as well as accounting for both the standing and moving charging powers of IMC buses, for the study of the impact of bus electrification on the existing infrastructure, unlike the insufficient and yet typical energy and power analyses found in literature when studying transport grids.

F. Article Structure

The article started with an introduction to trolleygrids and IMC buses. Next, the adaptive charging method is introduced and its benefits are quantified with a theoretical proof of concept. Sections III–V offer the methodology and the results of a case study of the suggested charging method, for a full-year operation of four electrified diesel bus lines in Arnhem, The Netherlands. Finally, Section VI presents the conclusions and future works.

II. Advantages of Adaptive Charging: Theoretical Proof of Concept

A. Definition of Variables

Consider a charging corridor of length L_{ch} (km) for an IMC bus that needs to cover a battery-mode route length (one way) of L_{BM} (km). The IMC bus can charge Π (kW) for the time t_s (h) when it is standing still, and Ψ (kW) for the

TABLE I
COMPARISON OF DIFFERENT TROLLEY AND IMC BUSES WITH AND WITHOUT ON-BOARD ENERGY STORAGE SYSTEMS (OESS) [4], [7], [24], [25], [26]

	Trolleybus (no OESS)	Trolleybus with OESS	IMC bus - Regular Charging (Conventional)	IMC - Adaptive Charging (This paper)
Source for bus power	From the catenary	From the catenary and OESS	From the catenary	From the catenary
Route flexibility	No	Limited (if available OESS energy is sufficient)	Yes	Yes
Typical Battery size	N/A	Few kWhs	Tens of kWh	Tens of kWh
Harvesting of braking energy	Only for auxiliaries	Auxiliaries and battery	Auxiliaries and battery	Auxiliaries and battery
Battery charging from catenary	N/A	No	Yes; fixed charging value *for the whole trolleygrid*	Yes; fixed charging value *under each substation*

time t_{m} (h) it is in motion. The battery round-trip efficiency of charging/discharging is η and the bus consumes a specific energy of e in kWh/km. The total trip time, Δt (h), is

$$\Delta t \triangleq t_{\mathrm{s}} + t_{\mathrm{m}}. \tag{1}$$

In terms of the total average velocity under the charging corridor, $\overline{v}$, the charging corridor length can be expressed as

$$L_{\mathrm{ch}} = \overline{v} \cdot \Delta t. \tag{2}$$

While in terms of the average *moving* velocity, $\overline{v}_{\mathrm{m}}$, which excludes the instances of zero velocity, the charging corridor length can be expressed as

$$L_{\mathrm{ch}} = \overline{v}_{\mathrm{m}} \cdot t_{\mathrm{m}}. \tag{3}$$

B. Quantification of the Benefit of Adaptive Charging With the Case of One Congested and One Uncongested Zone

Using the above parameters, it can therefore be written that the battery energy balance between the total charged energy (energy picked-up under L_{ch}) and the total discharged energy (energy discharged during the remaining part of the trip L_{BM}) in the terms of the above variables

$$\Pi \cdot t_{\mathrm{s}} + \Psi \cdot t_{\mathrm{m}} = L_{\mathrm{BM}} \cdot \frac{e}{\eta} \tag{4}$$

or

$$\Pi \cdot L_{\mathrm{ch}}\left(\frac{1}{\overline{v}} - \frac{1}{\overline{v}_{\mathrm{m}}}\right) + \Psi \cdot \frac{L_{\mathrm{ch}}}{\overline{v}_{\mathrm{m}}} = L_{\mathrm{BM}} \cdot \frac{e}{\eta}. \tag{5}$$

Finally,

$$L_{\mathrm{BM}} = \frac{\eta \cdot L_{\mathrm{ch}}}{e \cdot \overline{v}_{\mathrm{m}}}\left[\Psi + \Pi\left(\frac{\overline{v}_{\mathrm{m}}}{\overline{v}} - 1\right)\right]. \tag{6}$$

Consider the charging corridor consists of a congested SS zone and an uncongested zone. In an adaptive charging scenario, accounting for two different charging power duplets (Ψ, Π), the energy balance of (4) can be rewritten as

$$\left(\Pi_{\mathrm{c}} \cdot t_{\mathrm{s,c}} + \Pi_{\mathrm{u}} \cdot t_{\mathrm{s,u}}\right) + \left(\Psi_{\mathrm{c}} \cdot t_{\mathrm{m,c}} + \Psi_{\mathrm{u}} \cdot t_{\mathrm{m,u}}\right) = L_{\mathrm{BM,A}} \cdot \frac{e}{\eta} \tag{7}$$

where c and u subscripts refer to the congested and uncongested zones, respectively, and $L_{\mathrm{BM,A}}$ is the battery-mode route length obtained by adaptive charging. The net additional benefit in the achievable battery-mode distance obtained from adaptive charging over regular charging, ΔL_{BM}, is in the difference between (6) and (7).

Indeed, by defining the ratio of the congested to uncongested velocities as ϕ, ΔL_{BM} can be expressed as

$$\frac{\Delta L_{\mathrm{BM}}}{L_{\mathrm{u}}} = \frac{\eta}{e \cdot \overline{v}_{\mathrm{m,c}}}\left[(\phi\Psi_{\mathrm{u}} - \Psi_{\mathrm{c}}) + \left(\frac{\overline{v}_{\mathrm{m,c}}}{\overline{v}_{\mathrm{c}}} - 1\right)(\phi\Pi_{\mathrm{u}} - \Pi_{\mathrm{c}})\right]. \tag{8}$$

This value is always larger than zero since, by definition, $\phi \in [0, 1]$ and thereby $\phi\Psi_{\mathrm{u}} \in [\Psi_{\mathrm{c}}, \Psi_{\mathrm{u}}]$. Moreover, $\overline{v}_{\mathrm{m}} \geq \overline{v}$, also by definition. Consequently, the benefit ΔL_{BM} is a sum of strictly positive terms and is thereby always strictly positive, and adaptive charging will always lead to an increase in the potential for picked-up energy by the battery. Looking at values of the typical order of magnitude for a trolleybus (see the case study later), it can be shown that the length of the added battery mode can be at the order of a few L_{u}, i.e., in the range of kilometers. This can have significant implications on reducing the length of the charging corridors or increasing the length of the battery-mode SCTs, as well as on the economical and technical feasibility of the bus electrification projects.

C. Generalization of the Results for N SCTs

When multiple SCTs are involved, such as in Fig. 2, the net increase in the feasible battery-mode operation distance, $\Delta L_{\mathrm{BM},N}$, can be obtained by an extension of (8) to N SSs as

$$\Delta L_{\mathrm{BM},N} = \frac{\eta}{e}\sum_{i=1}^{N}\frac{L_i}{\overline{v}_{\mathrm{m,c}}}\left[(\phi\Psi_i - \Psi_{\mathrm{c}}) + \left(\frac{\overline{v}_{\mathrm{m,c}}}{\overline{v}_{\mathrm{c}}} - 1\right)(\phi\Pi_i - \Pi_{\mathrm{c}})\right] \tag{9}$$

where the subscript "c" is reserved for the most congested SS among N SSs, i.e., the one with the least spare capacity. The same analysis as the one that followed (8) can show here as well how the benefit described by (9) is also always strictly positive.

To revisit Fig. 2 as a way of an example, the three SSs shown have three spare capacities for charging: Ψ_1 for SS1 (relatively high), Ψ_2 for SS2 (relatively low), and Ψ_3 for SS3 (relatively medium). For simplicity, the standing charging powers (for example, Π_1) are not mentioned here but their design choice follows this same process.

TABLE II

COMPARISON OF THE ADAPTIVE (THIS ARTICLE) AND REGULAR IMC CHARGING METHODS

		IMC Charging Power
Adaptive Charging	**SS1**	Ψ_1
	SS2	Ψ_2
	SS3	Ψ_3
Regular Charging	**For all three SS**	$\min(\Psi_1, \Psi_2, \Psi_3) = \Psi_2$

Table II shows this charging powers' decision process. The adaptive charging method uses the locally available spare power capacity, which increases the amount of picked-up energy relative to the regular charging method. The latter is more conservative and is the method currently used in all IMC applications. The regular charging method uses the minimum of the spare capacities throughout the network, which leaves out a lot of unharvested spare capacity. Fleets using regular charging can be upgraded to adaptive charging by tracking the bus position by methods such as GPS tracking, a velocity-measurement integral with a lookup table, or others.

III. Advantages of Adaptive Charging for a Full Bus Line: The Arnhem Case Study

To quantify the total benefit of adaptive charging for a fleet of operating buses, Sections III–V present the results of a case study of the electrification of four bus lines in the Dutch city of Arnhem.

A. Modeling Methodology

The case study simulations make use of the following.

1) Traction and auxiliaries' bus demands and velocities, of 1-s resolution, for a full year of trolley operation, extrapolated from a set of measurements from the trolleygrid in Arnhem (previously detailed by the authors of this article in [3] and [11]).
2) A randomized bus scheduling extrapolated from the bus timetables and delay probabilities to account for the stochastic nature of the bus position (detailed in [3]).
3) A comprehensive and verified nodal grid model that calculates, among other parameters, the minimum line voltage and maximum SS power demand (detailed in [3]), as opposed to the traditional energy approach or current-source modeling approach found in the literature.

The bus traffic and power are modeled using velocity data obtained from measurements in the city of Arnhem, made available by the HAN University of Applied Sciences [17]. As shown in Fig. 3 and explained in [3], these measurements offer a more realistic study of a trolleygrid. This is particularly important with IMC since the charging power, as explained earlier, is lower when the bus is not moving. The bus velocities are combined with the bus timetables and random delays to create realistic bus traffic around the city. The traction demand for the bus is calculated from the bus velocity and route slope data according to [17], [27]. During winter months, the demand by the bus auxiliaries, mainly heating, ventilation, and air conditioning (HVAC), can be as high as the traction load [17], [28]. This can be shown by the energy demand (integral of measured trolleybus powers) in Fig. 3 where the total HVAC demand of 17.95 kWh accounts for half of the bus total demand of 36.11 kWh during an 11.60-km trip. The HVAC system of the Hess bus used in Arnhem operates using a duty cycle over a period of 5 min. For these simulations, the HVAC demand is derived from the ambient temperature and the empirically fit HVAC system lookup table for Arnhem as found in [29]. The Kiepe IMC500 bus is used for the simulation, capping the bus power, P_{bus} at 500 kW. Otherwise, this bus power is given as a sum of the traction or braking power, P_{tr} or P_{BR}, the HVAC power, P_{HVAC}, the auxiliary base loads, P_{base}, and the battery charging power, P_{batt}

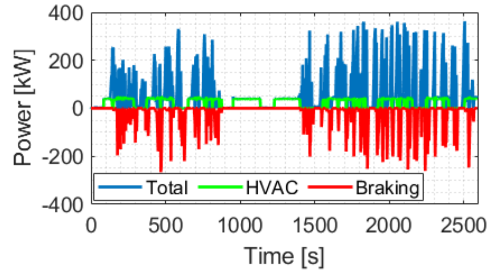

Fig. 3. Measurement example of the total, HVAC (heating), and braking bus power. The data are for a full trip on trolleybus line 1 in Arnhem, The Netherlands, on a winter day.

$$P_{\text{bus}} = \begin{cases} P_{\text{tr}} + P_{\text{HVAC}} + P_{\text{base}} + P_{\text{batt}}, & \text{if traction} \\ P_{\text{BR}} + P_{\text{HVAC}} + P_{\text{base}} + P_{\text{batt}}, & \text{if braking.} \end{cases} \quad (10)$$

B. Case Study Definition: Bus Lines and Trolleygrid Limits

The Dutch city of Arnhem is taken as a case study for this article. The city has six trolleybus lines fed by a trolleygrid of 18 SSs that cater to 40 SCTs. The SSs have a rated power limit of 800 kW, except for the Arnhem Central Station (ACS, SS 4) which has an increased capacity of 1800 kW by the time of this research.

Four diesel bus lines in Arnhem, namely, lines 4, 13, 29, and 352, are suggested as candidates in this article for electrification. As summarized in Table III, these lines have routes that are independent of each other, other than the unavoidable exception of the ACS.

As mentioned earlier, the two obstacles to the integration of IMC buses are the SS power and line voltage limitations. Small power peaks are commonly withstood by transformers, and for this study, a limit of 1 h/year (3600 s) of operation up to 150% of the rated SS power is deemed acceptable. This number is close to a daily 10 s of such an operation that is currently reported in measurements on the Arnhem grid. No value above this is accepted. On the other hand, a minimum line voltage between 450 and 500 V is not welcomed since it means curtailment of the bus power, yet still is acceptable if the voltage is not lower than that. This means that no voltage under 450 V would be accepted because the grid's lower operational limit is 400 V as mentioned in Section I.

These limits of the SS power demand, P_{ss}, as a function of its rated power and of the minimum line voltage, $V_{\min}$, are

TABLE III

FOUR STUDIED DIESEL BUS LINES IN ARNHEM, WITH THE TROLLEYGRID SSs AND SCTs THAT THEY CROSS MARKED WITH A CHECKMARK. ALL BUS LINES PASS THROUGH SCT 5 OF SS 4 WHICH IS THE ACS

Bus	Route under	L_{BM}	SS	1		2			3		4			5			9	10	12	
Line	the catenary	(one-way)	SCT	2	3	14	15	16	12	36	5	6	8	17	18	35	25	22	23	24
4	ACS-De Praets	5.6 km								✓						✓				
13	ACS-Graaf Ottoplein	1.4 km			✓					✓	✓	✓								
29	ACS-Velp	25.2 km					✓	✓		✓	✓		✓	✓			✓			
352	ACS-Oosterbeek	12.1 km	✓	✓						✓								✓	✓	

summarized in the following equations, respectively,

$$P_{ss}\begin{cases} \leq 100\% \text{ rated}, & \text{Acceptable} \\ > 100\% \& \leq 150\% \text{ rated}, & \text{Acceptable up to} \\ & \quad 3600 \text{ s per year} \\ > 150\% \text{ rated}, & \text{Not Acceptable} \end{cases} \quad (11)$$

$$V_{min}\begin{cases} \geq 500 \text{ V}, & \text{Acceptable} \\ < 500 \text{ V} \& > 450 \text{ V}, & \text{Acceptable} \\ & \quad \text{although undesired} \\ \leq 450 \text{ V}, & \text{Not Acceptable.} \end{cases} \quad (12)$$

C. Suggested Adaptive Charging Power Levels

The different IMC charging powers' levels are as follows.

1) **No IMC:** Keep the studied buses as diesel buses.
2) **IMC—No Charging:** Transform the diesel buses into IMC buses, but do not charge the battery under *this* specific SCT. This means that the bus only consumes traction and auxiliary power from the catenary and $\Pi = 0$ kW and $\Psi = 0$ kW.
3) **Π; Ψ kW:** All the four studied bus lines electrified, and charging the battery at Π kW while stopped and Ψ kW while moving. The different duplets are studied in this article, according to the existing and future IMC charging powers from European cities [7], [24].

The ***IMC—no charging*** suggestion is a key feature of the adaptive charging method where the IMC bus completely refrains from charging under a congested SCT of the trolleygrid but still runs as a trolleybus rather than in battery mode. To highlight an example, Fig. 4 shows one day of operation of SS1 with the significant reduction of almost all power violations by switching to the no-charging mode, yet still operating as a normal trolleybus and not depleting the battery.

IV. GRID POWER AND VOLTAGE ANALYSIS: FULL YEAR WITH IMC BUSES CHARGING AT $[\Pi; \Psi] = [100 \text{ kW}; 150 \text{ kW}]$

A. Yearly Power Demand Analysis

Table IV shows the simulated yearly power demand on the Arnhem SSs with the electrified IMC buses charging at $[\Pi; \Psi] = [100; 150 \text{ kW}]$. To simulate the most demanding conditions for the SS power and line voltage, regenerative power sharing between buses will be excluded as well as bilateral connections.

SSs 1, 3, and 12 are already ruled out on the basis of their excessive power breaches as set by (11). These SSs can

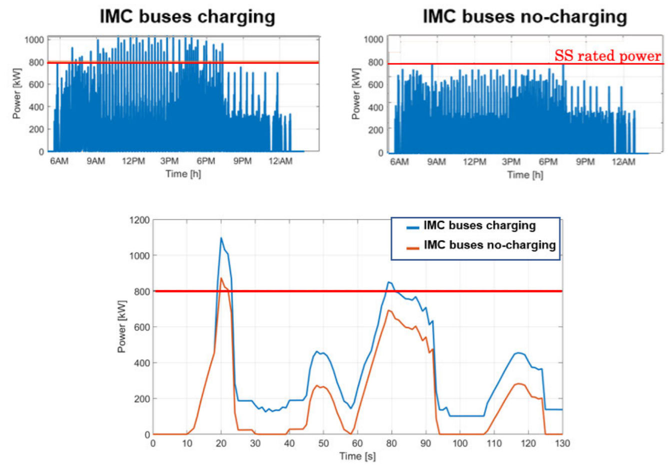

Fig. 4. One-day simulation of SS1 power demand including IMC bus line 352 both when the IMC buses are charging at 150 kW (top left) and in no-charging mode (top right). A zoom-in on 2 min of operation (bottom) shows how the no-charging mode of adaptive charging can reduce both the severity and the number of power breaches.

probably still benefit from the electrification as IMC buses with no-charging mode. This means that an IMC bus running under these SSs would pick up less energy and would need to compensate for it elsewhere. However, this is still a major advantage over regular charging as the latter would have deemed the whole electrification project unfeasible when faced with this information. Further investigations of these lines are then conducted in Section V of this article.

On the other hand, SSs 2, 4, 5, 9, and 10 are capable of integrating these electrified bus fleets, and at these battery-charging powers, as no unacceptable breach levels were flagged. In the next section of this article, these SSs will be investigated to see whether they can handle an even higher IMC charging power.

First, however, a voltage study is conducted to look at possible violations of the minimum line voltage limits.

B. Yearly Minimum Voltage Analysis

If a trolleybus sees the low voltage of 500 V, the on-board power control will intervene [30] and curtail its demand. This results, for example, in the bus HVAC system shutting off and the bus not being able to accelerate. At 400 V, the power to the bus is completely shut off.

For this analysis, any occurrence of the minimum line voltage below 500 V is undesired, and the limit of 400 V is a serious violation. Comparing this to a situation with IMC buses (see Figs. 5 and 6), it can be noted that SCTs 2 and 22 of SSs 1 and 10 now also have voltage drops below 500 V. While

TABLE IV

YEARLY NUMBER OF POWER DEMAND BREACHES ON EACH SS OF THE CASE STUDY SIMULATIONS (WITH IMC BUSES CHARGING AT [Π; Ψ] = [100 KW; 150 KW]). THE UNACCEPTABLE BREACHES, ACCORDING TO (11), ARE MARKED IN RED

		Substation							
		1	2	3	4	5	9	10	12
Total yearly number of Rated Power Breaches [s]	>100% but ≤ 150%	91708	3093	24031	0	190	0	11	3806
	>150%	14	0	1974	0	0	0	0	0
Acceptable Breaches as per Eq.11?		**No**	Yes	**No**	Yes	Yes	Yes	Yes	**No**
Next Study Suggestion*		Try IMC-no charging	Higher Power	Try IMC-no charging	Higher Power	Higher Power	Higher Power	Higher Power	Try IMC-no charging

*see example results in Figure 7

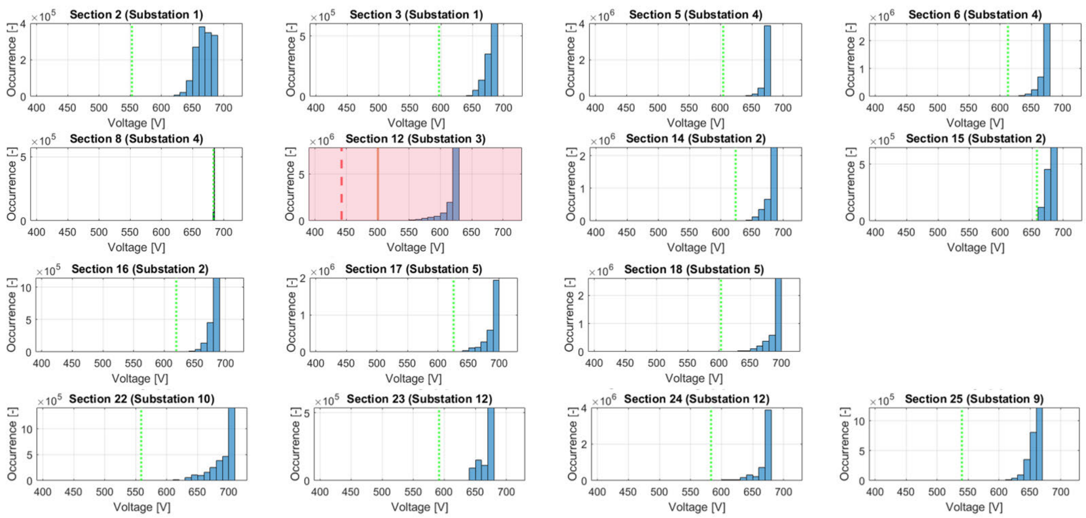

Fig. 5. Histogram of the yearly minimum line voltage on each SCT in this study for the present trolleygrid (without IMC buses). The lowest recorded voltage is indicated by a green dotted line if the limit of 500 V of (12) is not exceeded, and a red dotted line otherwise. Also per (12), orange-colored plots flag an unwelcome yet tolerated operation, while red-colored plots flag an unacceptable operation (IMC charging not feasible).

this is undesired, it is still feasible according to (12).

The minimum voltage of SCT 12 of SS 3 drops even further to the minimum of 400 V. SS 3, therefore, does not seem to allow the electrification of bus line 29. This is already an expected result as this congested SS caters to all six conventional trolleybus lines in Arnhem.

No other SSs are then excluded by the 150-kW charging scheme and the chosen SSs can be studied for higher charging powers. If a higher charging power is chosen in the end for an SS, it is worth keeping in mind that a possible voltage under 500 V would then first momentarily curtail the battery charging power, and not the bus traction power, and is thereby acceptable although undesired outcome as it affects seconds of battery charging rather than a shutting down of the bus. This justifies why the voltage analysis is not repeated in the upcoming SCT.

V. ELECTRIFICATION OF BUS LINES WITH ADAPTIVE CHARGING PER SS

A. Analysis for Different IMC Charging Powers

The results of other IMC charging powers are presented in Fig. 7. The power demand throughout the day is shown in blue, while the SS limit (i.e., 800 kW for all SSs except SS 4 which is built for 1800 kW) is indicated with a red dashed line. Across the board, an increase in power demand can be observed when looking from left to right. For SSs 2, 9, and 10, this power demand increase is relatively small. On the other hand, SSs 1 and 4 show drastic increases in power demand.

Battery charging of IMC buses waiting for their next trip at Arnhem CS even causes the power demand for SS 4 to constantly be above zero from early in the morning to at least 7 P.M. SSs 3, 5, and 12 show power demands that do increase quite a lot but this mostly shows up as short peaks instead of a constant increase.

This indicates that SSs 2, 9, and 10 could supply the buses with a higher charging power to compensate for a decrease in charging power on other SCTs.

The suggested adaptive charging approach is summarized in Table V, by adopting the highest possible charging power at each SS according to the power and voltage limitations described earlier. Regular charging is the most conservative, as previously explained, and adopts the most conservative charging power of any SS on the bus route throughout the whole route. The first IMC bus line considered is bus line 4, which passes under SSs 4 and 9. It can be seen that SS 9 can take charging powers up to 500 kW without exceeding the power demand limit too often. However, these charging powers are so far unachievable with the available bus technology. For SS 4, the limit is [100; 150 kW]. If needed, bus line 4 can shift thereby the battery charging from under SS 4 to under SS 9.

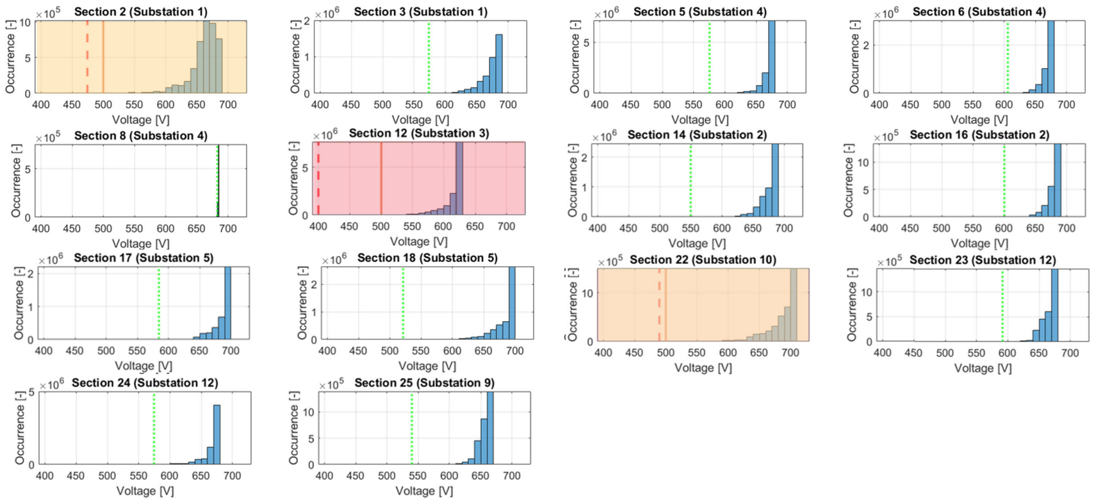

Fig. 6. Histogram of the yearly minimum line voltage on each SCT in this study for the present trolleygrid (without IMC buses). The lowest recorded voltage is indicated by a green dotted line if the limit of 500 V of (12) is not exceeded, and a red dotted line otherwise. Also per (12), orange-colored plots flag an unwelcome yet tolerated operation, while red-colored plots flag an unacceptable operation (IMC charging not feasible).

TABLE V

COMPARISON OF THE ADAPTIVE (THIS ARTICLE) AND REGULAR IMC CHARGING METHODS FOR THE STUDIED BUS LINES IN ARNHEM AND THE MAXIMUM POWER THAT CAN BE DRAWN [Π STANDING; Ψ MOVING] FROM THE SSs THAT SUPPLY THEM. AS EXPLAINED IN SECTION I-D, THE REGULAR CHARGING METHOD USES THE MOST CONSERVATIVE CHARGING POWER THROUGHOUT THE WHOLE BUS ROUTE

		Line 4	Line 13	Line 29	Line 352
Adaptive Charging ([Π standing; Ψ moving])	**SS1**				No Charging
	SS2		[200;300kW]	[200;300kW]	
	SS3			No Charging	
	SS4	[100;150kW]	[100;150kW]	[100;150kW]	[100;150kW]
	SS5			[100;150kW]	
	SS9	[200;500kW]			
	SS10			[200;300kW]	
	SS12				No Charging
Regular Charging ([Π standing; Ψ moving])	**For any SS on the route**	[100;150kW]	[100;150kW]	No Charging	No Charging

Bus line 352 passes under SSs 1, 4, and 12. As SSs 1 and 12 show power limit breaches even at low charging powers, the charging power should be shifted to another SCT. However, SS 4 cannot compensate for more than 150 kW of charging. For this IMC bus line, no solution can be found without an increase in the SS capacity or the installation of small stationary storage that can momentarily relieve the SS by assisting in load coverage.

As can be seen from the first four columns of Table VI, the picked-up energy, while increased with adaptive charging, is not sufficient for the full catenary electrification of lines 4, 29, and 352.

In case the electrification of the diesel lines is not feasible using only the charging corridor, an additional opportunity charger at the end-of-line can be used to help charge the battery from its current state, E_b, to its needed energy level for the trip, E_{trip}. For this, adaptive charging also has the advantage of reducing the charging time.

B. Adaptive Charging as a Way to Reduce Charging Times

To increase the total battery energy, E_b, to its needed energy level for the trip, E_{trip}, the additional charging time needed at an opportunity charger, t_{op}, for a charging session at a power, P_{op}, and total converter + battery efficiency of η_{op} is

$$t_{op} = \begin{cases} \dfrac{E_{trip} - E_b}{\eta_{op} \cdot P_{op}}, & \text{if } E_{trip} \geq E_b \\ 0, & \text{otherwise.} \end{cases} \quad (13)$$

When a charger of 100 kW is installed, the suggested adaptive charging scheme presented in Table V leads to the results in Table VI. It is seen that the method proposed in this article can reduce the charging times needed at the terminals by up to 64%, or almost 40 min.

The electrification of diesel line 13 is feasible with both regular and IMC charging and is highly urged to be implemented to offset the carbon emissions of the present diesel buses. Bus line 4 can require as little as 5.6 min of opportunity charging when using the here-suggested adaptive charging method. This time window can be easily worked into the bus timetables and delays, as opposed to the 15.4 min needed with regular charging. Bus lines 29 and 352 are not as promising, unfortunately, as significant opportunity charging time is still needed even with adaptive charging. However, it is important to note that bus 29 would pick up no energy under the regular charging method, needing thereby to be electrified as a full BEB if an electrification project is underway. With adaptive

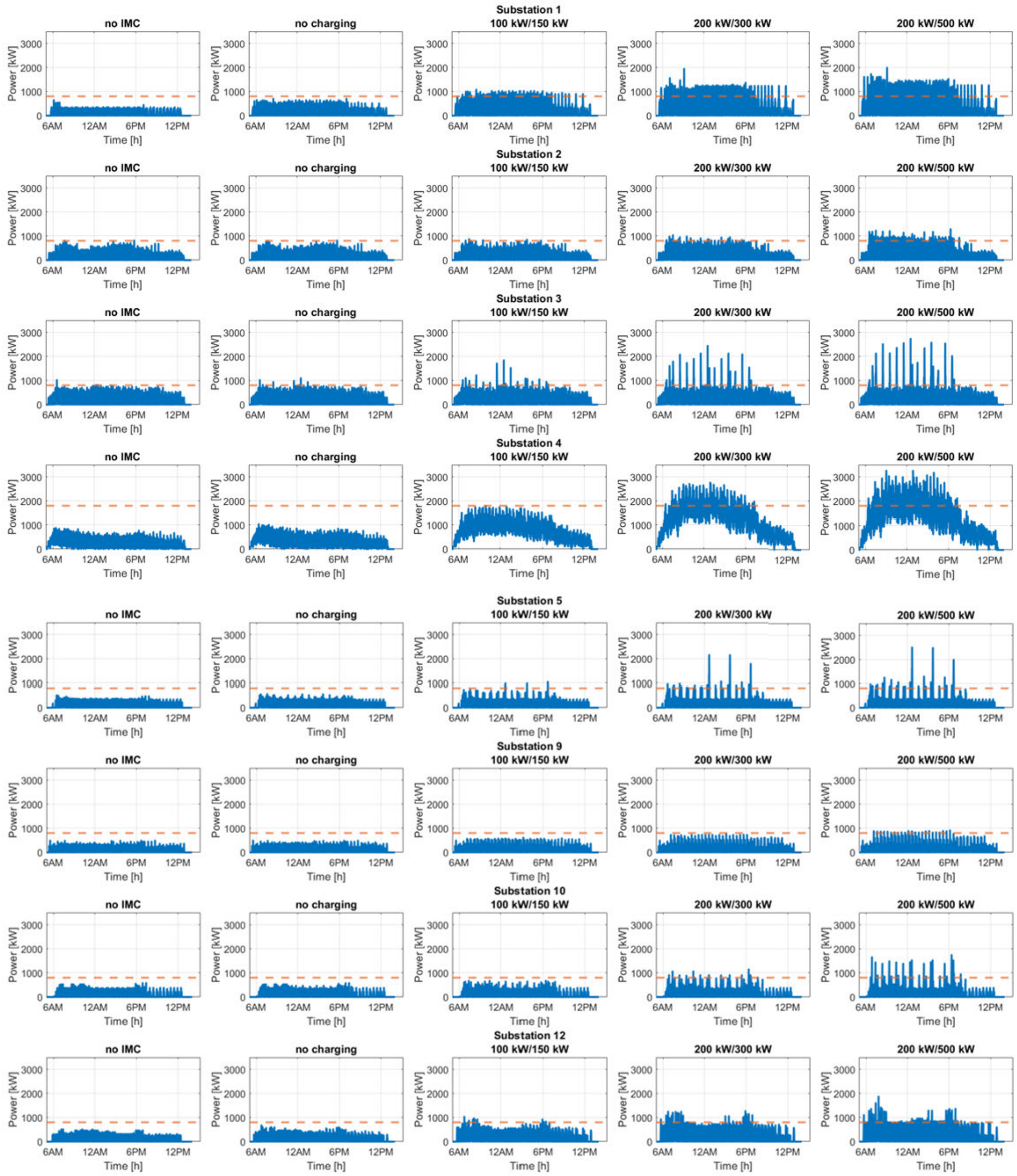

Fig. 7. Closer look at the SS power demand on a regular weekday schedule for five IMC battery charging schemes.

TABLE VI

Comparison of the Energy Picked Up by the IMC Battery, Route Feasibility, and Extra Charging Time Needed for Adaptive Charging (This Article) or the Conventional Regular Charging Methods, With $e = 3$ kWh/km [7]

Bus Line	Energy needed for a battery-mode round trip (=2*$L_{\text{BM}} \cdot e$)	Feasible energy pick-up (Integral of the battery charging power curve when adopting the values in table V)		Additional time needed at an opportunity charger (Eq. 13 with P_{op}=100kW, η_{op}=0.94)		
		Regular Charging	Adaptive Charging	Regular charging	Adaptive Charging	Time saved
4	33.8 kWh	9.6 kWh	25 kWh	15.4 min	5.6 min	64%
13	8.3 kWh	16.2 kWh	26.2 kWh	0 min	0 min	N/A
29	151.3 kWh	0 kWh	59.5 kWh	96.6 min	58.6 min	39%
352	72.6 kWh	0 kWh	2 kWh	46.3 min	45.1 min	3%

charging, more than a third of its energy demand can be picked up from under the existing catenary, translating into a reduction by up to a third of the needed battery capacity. This brings benefits in costs, space, and traction energy from the reduced battery mass. Line 352, on the other hand, is limited by its congested SSs, and a new, more sophisticated and instantaneous charging scheme is urged for a future investigation.

VI. Conclusion

This article suggested the electrification of diesel or CNG buses as IMC trolleybuses that make use of the existing trolleygrid infrastructure. For that aim, an adaptive charging method for the IMC battery was also introduced that can better use the spare trolleygrid capacity.

In a theoretical proof of concept, adaptive charging proved that it can extend the range of the IMC bus operation by a few kilometers.

The suggested charging scheme was also tested in a case study of the electrification of four diesel bus lines in the city of Arnhem, The Netherlands, using comprehensive and verified trolleybus and trolleygrid models for one year to analyze the power and voltage violations in the grid. One of the four lines was achievable without any need for additional grid extensions. For the other three lines, an opportunity charging point was needed, and the adaptive charging method proved indeed to be superior to regular charging, with terminal-charging times reduced by as much as 64%, or up to 40 min. One of the four studied lines (bus line 352) was completely unachievable with regular charging, and unfortunately, the adaptive charging method was not enough either and could only pick up 3% of the required energy for the battery-mode trip. This is because the route of this bus had mostly congested SSs that did not allow any IMC battery charging, but did allow for the electrification of the buses in any case. Still, the IMC no-charging electrification can mean that the bus can be decarbonized and with a reduced battery size since it runs as a trolleybus under the charging corridor, and not in battery mode.

Overall, the adaptive charging offered significant reductions in battery mass, cost, and volume when compared with a project of electrification by full BEBs.

Finally, a more instantaneous charging scheme is necessary for a future investigation of bus lines with a number of no-charging zones.

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