Flexibility Potential of Heavy-Duty Battery Electric Vehicles Depots for Congestion Management in Medium-Voltage Grids

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***Abstract*—This paper demonstrates how flexibility from heavy duty vehicle depots can be utilized to relieve grid congestion. Through the utilisation of charging simulations alongside benchmark grid models and datasets, the impact of depot charging on the distribution network is determined. The findings indicate that depot charging can facilitate the mitigation of grid congestion during periods of substantial renewable energy feed-in. The exploitation of demand flexibility potential yields additional synergies.**

***Index Terms*—heavy-duty electric truck, depot charging, system integration, flexibility, congestion management**

I. Introduction

Flexibility represents a fundamental prerequisite for the comprehensive transformation of the energy system. In a power system increasingly characterised by volatile generation, flexible consumption technologies—such as electric mobility—facilitate the consumption of electricity during periods of high availability, notwithstanding the absence of controllable power plant capacities like gas-fired facilities. The progressive electrification of diverse sectors generates an expanding array of such opportunities, culminating in the fact that electric mobility currently accounts for 750,000 (1.6 %) vehicles in Germany [1]. The accelerated proliferation of electrified alternatives within distribution networks, specifically heat pumps and electric vehicles, exerts mounting pressure on electricity grids, necessitating mechanisms for grid operators to regulate consumption at the low-voltage level, as exemplified by §14a of the German Energy Industry Act (ger.: EnWG) [2]. A framework for the continued deployment of these technologies, despite constrained grid capacities, has been established by the European Union through flexible connection agreements (FCA) [3], subsequently incorporated into German legislation via §8a "Flexible grid connection agreements" of the Renewable Energy Sources Act [4]. Nevertheless, two primary objectives must be realised to provide a functional basis for this implementation. Firstly, substantial digitisation and rigorous modelling of the electricity grid infrastructure are essential to obtain precise longitudinal data regarding grid utilisation. The second pillar for executing optimal consumer-oriented grid operations, predicated on flexibilities, involves the precise characterisation of these flexibilities and their inherent systemic constraints. Heavy goods vehicle depots constitute both a significant opportunity and a formidable challenge in this context, owing to their projected high-volatility load profiles. Utilising a heavy goods vehicle depot as a primary case study, this paper demonstrates how flexibility derived from a system subject to operational restrictions and grid congestion—induced by renewable energy—can be harmonised to exert a grid-relieving effect.

This work was performed within the project BELLE (03EMF0506C), funded by the German Federal Ministry for Digital and Transport and the project SYMBIOSE (72002678), funded by the European Comission and the Hamburg Investment and Development Bank.

II. Methodology

The objective is to ascertain the manner in which the depot charging of heavy-duty Battery Electric Vehicle (hdBEV) can be integrated into the energy system such that it not only avoids the necessity for additional grid expansion but also alleviates the state of the grid. To facilitate this analysis, grid topology is required alongside plausible load and generation values, in addition to cumulative charging loads representing the depot demand. Depots are simulated through the application of a charging management simulation tool. The network benchmark tool SimBenchis utilised for the grid topologies, as well as the generation and demand time series. Results are generated through power flow calculations with the mentioned input data. The results are then analysed considering grid state in terms of voltage quality. How the components described here work together is shown in Fig. 1 and a detailed descriptions of these are provided in the subsequent sections.

A. Charging Simulations

The simulation tool generates individual hdBEVs characterised by specific charging capacities, battery specifications, energy requirements, and operational schedules. Data sources pertaining to vehicle specifications and scheduling are derived from Will and Ocker [5] and have been rigorously validated against empirical datasets. Identical vehicles with

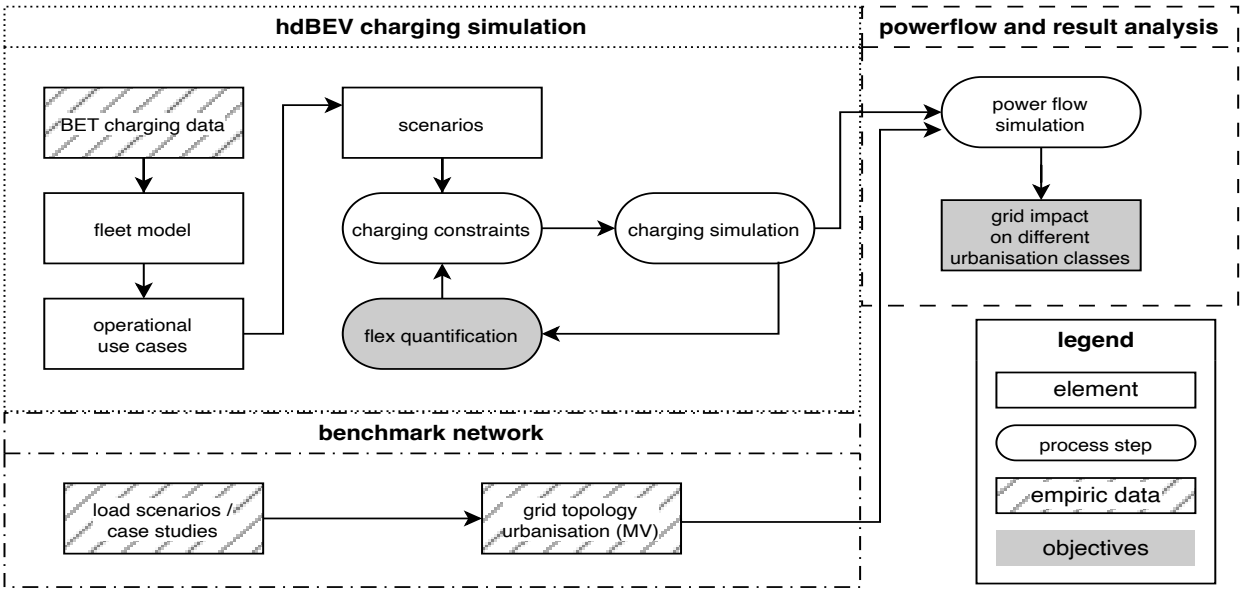


Figure 1: components used in this work and how they interact

uniform schedules are synthesised, incorporating probability-driven variations in departure and arrival timestamps. These

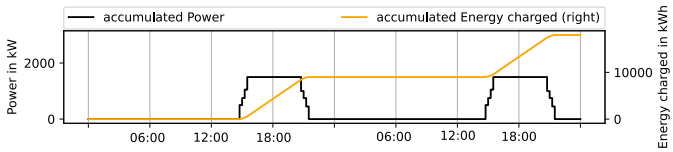


Figure 2: Depot profile snippet of 48 hours

parameters result in the fleet model depicted in the upper-left quadrant of Fig. 1. The facility described herein represents a depot for refuse collection vehicles, which informs the operational use case. The depot is represented by a scenario that delineates the specifications and constraints of the charging infrastructure alongside the maximum aggregate load. Consequently, comprehensive charging simulations can be executed. Fig. 2 illustrates the load profile of the charging process derived from the simulation. The charging process remains unmanaged, commencing upon the connection of the vehicle at the depot at approximately 15:00. The hdBEVs conclude their charging cycles at approximately 21:00, well in advance of their scheduled departure at 07:00. The intervening duration is therefore available for flexibility utilisation.

Flexibility is constrained by the operational schedule; specifically, arrival and departure times are immutable. In this context, flexibility constitutes the combination of curtailable load and the duration by which it can be deferred. The tool generates time-series data for each individual hdBEV and the resultant depot load. A more comprehensive exposition of the methodology is provided by Decher and Schäfers [6]. When implementing case studies within the benchmark network tool, the maximum cumulative charging power of the depot is utilised.

B. network benchmark tool

Grid topology and time-series data are utilised from *SimBench* networks. SimBench aims to provide network topologies encompassing both load and generation values and "is intended as a benchmark to test, publish and compare methods and algorithms for various use cases [...]. The use cases include the fields of grid planning, operation and simulation." [7, p.2]

SimBench classifies itself as a "benchmark dataset with multiple voltage levels and data of time series and study cases to compare innovative solutions of multiple use cases based on power flow analysis" [8, p. 5 Table 2] In this scholarly work, the primary focus lies on the medium voltage (MV) level. Consequently, the subsequent description focuses on the features specifically related to MV. SimBench provides its methodology to synthesise network topology, which results in four distinct MV basis grids. These differ in general network topology, such as open ring or mesh, as well as in their constituent components, and are intended to represent Urbani-

Table I: key characteristics of hdBEV depot

	unit	value
no. of vehicle	-	30
max. charging power	kW	50
battery capacity	kWh	400
max. cum. power	MW	1.5
departure	-	07:00
arrival	-	15:00
demand per hdBEV	kWh	300

sation Characteristics. The four Characteristics are rural, semi-urban, urban and commercial, which can be studied in detail, alongside the methodology, in Meinecke et al. [9].

In addition to grid topologies, SimBench provides comprehensive time-series data. The resultant outputs comprise time-series representing the contemporary state regarding both topology and demand [10]. With respect to future projections, SimBench aims to synthesise time-series that engender grid states necessitating intervention. Consequently, the data approximate existing network conditions, thereby facilitating research into multifaceted objectives. Of particular significance are the developmental scenarios (fut.0, fut.1, fut.2) encompassing both grid topology and (demand and generation) time-series, alongside associated case studies [7]. Inasmuch as these scenarios are designed to provoke situations requiring remedial action – specifically the violation of operational constraints such as voltage bands or line and transformer loading – they are highly efficacious for evaluating the impact of depot charging within MV networks. Furthermore, these case studies align demand and generation profiles with specified parameters to deliberately precipitate critical grid states that mandate operational response.

In the context of the objectives of this study, SimBench incorporates Electric Mobility (EM) through two distinct methodologies. At the extra high voltage (EHV) level, EM is integrated within the industrial and transport profile. Nevertheless, in this specific instance, transport pertains exclusively to public transport. Regarding voltage levels beneath EHV Battery Electric Vehicle (BEV) are categorised as commuting vehicles. Consequently, the profile reflects passenger cars charged at domestic or professional premises. HdBEV, however, are excluded from all stages of SimBench, regarding both en-route and depot charging. [10]

SimBench *Case Studies* are combinations of load and Distributed Energy Resources (DER) generation states expressed as a fraction of the maximum possible values. The case studies are therefore defined by the factor p for load and generation. Beside time series data, data of the high DER generation and low load case study ℓPVare used in this work. The resulting bus voltages over feeder length for ℓPV are visualised in Fig. 3a.

Regarding its applicability to the objectives delineated in this treatise, SimBench's own predefined use cases merit consideration. The most pertinent use cases here are *Local Congestion Management (DSO11)* and *Foresighted Operation Management (DSO7)*[11, Tab.3.1ff]. Consequently, given that it employs reproducible methodologies for time-series analysis, case studies, and network synthesis, as well as future developmental scenarios to evaluate network operational approaches, SimBench is eminently suitable for assessing the impact on congestion management, as the aims of this research align precisely with the SimBench use cases.

In the described analyses case study ℓPV is used and for time series analyses a period between the 7th and 14th of February of a SimBench reference year (i.e. time steps 3648 to 4320). In this period occur high fluctuation of bus voltages.

Table II: key characteristics of used grid

		commercial net topology		
	unit	fut.0	fut.1	fut.2
topology		Open ring, MV single busbar		
Rated Voltage	kV		20	
Nodes		107	110	111
DER		PV, Wind, Hydro, Biomass		
Transformer	MVA		2x40	
load	MW	37.1	39.9	49.9
generation	MW	16.6	28.6	35.1
storage	MW	0.0	3.1	23.1

C. Assessing Depot Charging Impact

It is postulated that bus voltages in closer proximity to the rated voltage and exhibiting reduced distribution enhance the resilience of the grid state against congestion arising from either demand or DER generation. The subsequent section delineates these indicators and the methodology employed for their calculation. To evaluate the impact of depot charging on distribution grid (DG), the per-unit system for voltage is utilised as a primary indicator, as it is established for every bus within the power flow calculation. The indicator resolves to $U_r = 1\,pu$, with the rated voltage being $U_r = 10\,kV$ or $20\,kV$ respectively in MV. This value is computed for every bus during the power flow calculation in accordance with Equation 1. The boundaries for U_{pu} must be identified to ascertain whether U_{pu} remains within the permissible voltage band. SimBench data stipulates upper $\left(U_{pu}^{max}\right)$ and lower boundaries $\left(U_{pu}^{min}\right)$ for every bus, typically employing standard values of approximately $\pm 5\,\%$. Utilising these boundaries, every $U_{pu} \geq 0$ is situated within a relative scalar ranging from 0 to 100, where 0 corresponds to $U_{pu} = 1$ and 100 corresponds to the upper boundary; similarly, for $U_{pu} < 0$, values range between -100 and 0, where -100 represents the lower boundary. Equation 2 represents the calculation of the resulting voltage within band B_{pu}, which constitutes the percentage deviation from the rated voltage U_r. The alteration in the voltage band of U_{pu} when a depot charging load is connected to the grid serves as the indicator for assessing the influence of depot charging. If the deviation of U_{pu} from unity is smaller with depot charging than without, it is deemed to be supporting the grid. The deviation is calculated in percentage points using Equation 3.

$$U_{pu,i} = \frac{U_i}{U_r} \tag{1}$$

$$B_{pu,i} = \frac{U_{pu,i} - U_{pu,i}^{min}}{U_{pu,i}^{max} - U_{pu,i}^{min}} \cdot 200 - 100 \tag{2}$$

$$B_{pu,i} \in \{x \in \mathbb{R} \mid -100 \leq x \leq 100\}$$

$$\Delta B_i = \left|B_{pu,i}^{D}\right| - \left|B_{pu,i}^{R}\right| \tag{3}$$

with

$i :=$ bus index

$D :=$ elements of scenario with depot load

$R :=$ elements of the reference scenario

The initial stage involves quantifying the implications of the depot load. To accomplish this, the depot load is integrated into the feeder exhibiting the highest average ΔB. Manifestly, the impact is contingent upon the extant net load and its proportionality to the overall generation. The selected feeder possesses a generation surplus in ℓPV that corresponds approximately to the magnitude of the depot load. Utilising this specific configuration, the resulting impact is substantial and illustrative for analytical purposes. Upon alternative feeder, the observed effect remains consistent, albeit with diminished amplitude. Fig. 3 delineates the impact of the depot load, which is coupled to the designated bus. Under identical grid conditions, the depot load successfully mitigates the deviation of the bus voltages from the theoretical optimum.

Within this scholarly work, the variation in deviation from the optimum, expressed in percentage points, signifies whether the voltage under depot load conditions aligns more closely with the optimum than in its absence, predicated on the assumption that proximity is of greater consequence than being above or below said value.

To assess the dispersion of the bus voltages, the standard deviation σ across the bus voltages is rigorously measured. For the purpose of a straightforward comparison, the discrepancy between the deviations is calculated (Equation 4).

$$\Delta\sigma = \sigma^D - \sigma^R \tag{4}$$

A negative value indicates a reduction in the standard deviation. Such a result is interpreted as a lower dispersion of bus voltages.

III. Results

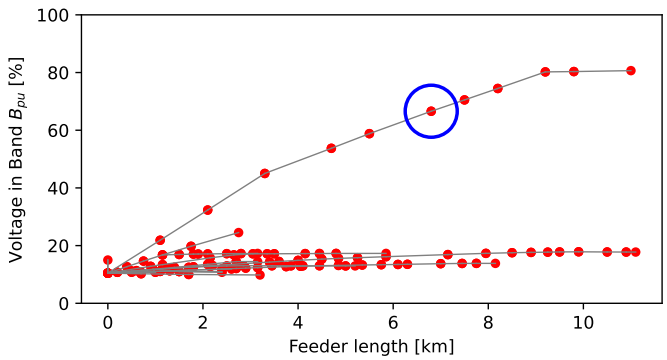
In order to compare the impact of depot charging across the prospective developmental scenarios (fut.0, fut.1, fut.2), the load, generation, and storage states from the case study "ℓPV" are utilised. The average modification of the voltage in band $\Delta\bar{B}$ on the feeder associated with the depot load is illustrated in Fig. 4. Specifically, the difference for every bus of the reference power flow compared to the one with the depot load within the same scenario is calculated, and subsequently, the average per scenario across the considered buses is determined. Since the compared values are expressed as percentages within the voltage band, the values in Fig. 4 are represented in percentage points. It is observed that across all three scenarios, the voltages on the feeder as well as the voltages throughout the entire MV grid segment decrease with the introduction of a depot load. The overall average movement towards the nominal voltage (blue) is not as significant as that observed on the feeder (orange). This occurs because bus voltages on other feeders are influenced indirectly only through the common coupling point, namely the bus at the substation. However, as the voltage on the common bus drops slightly, all other bus voltages experience a minor decrease as well. Nevertheless, the overall average remains primarily driven by the buses located on the same feeder as the depot load. Across all buses, the voltages shift closer to the nominal voltage by 3 to 4 percentage points within the voltage band. On the feeder, the average change reaches up to 25 percentage points. Fig. 5 compares the dispersion of bus voltages with and without the depot load using box plots. In this particular plot, all buses are considered regardless of whether they are situated on the same feeder. The increase in the number of buses across the scenarios—as indicated in Table II—is negligible. In all comparisons, the outliers are notably reduced, whilst the mean and median move closer to 1.0 when the depot is connected. Given that the case study is characterised by high DER generation and low load, this outcome is to be expected.

Time series analyses are conducted because the states of load, generation, and storage, as well as the depot load, undergo fluctuations. Fig. 6 illustrates the voltage variation on the feeder across all three future scenarios. This represents the calculation visualised in Fig. 4 for each time step, specifically focused on the feeder and interconnected as lines for each development scenario. The depot exhibits no charging load during periods where the lines are equal to zero. Additionally, the net load (defined as load minus generation plus storage) on the feeder is plotted for each scenario. A positive impact is anticipated in states characterised by a negative net load, signifying a generation surplus. This condition persists in every time step: the minimum voltage per-unit consistently remains above 1.0. Nonetheless, time steps with positive $\Delta\bar{B}$ occur within the two development scenarios. The rationale is that in certain time steps, the combination of load, generation, and storage usage results in voltages that are predominantly proximal to the rated voltage. This occurs because SimBench introduces additional load to the time series in these two scenarios, which generally leads to reduced floating within the voltage band. During these time steps, the utilisation of flexibility would shift charging loads and subsequently achieve lower values for ΔB as well.

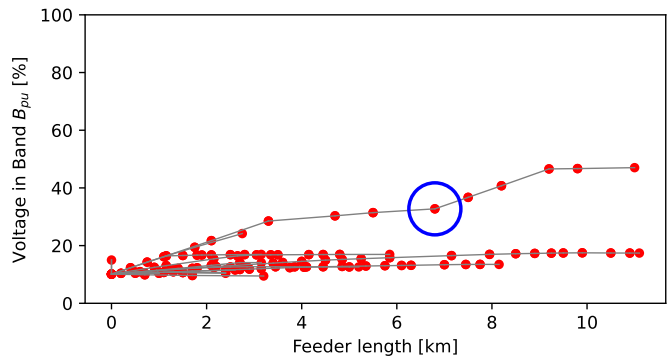
As demonstrated in Fig. 7, the loading of both transformers and lines does not exceed 100 % in any of the time steps. With the depot load connected, the maximum line loading across all time steps reaches 67 % for both future scenarios and 40 % in the reference scenario. The transformer loading remains below 15 % in the reference and future 1 scenarios and increases to 21 % per cent in the future 2 scenario.

IV. Discussion

The results demonstrate that highly fluctuating loads, such as the depot charging of hdBEV, are indeed capable of enhancing the resilience of a DG. In the examined use case of waste collection, the load profile exhibits synergies with DER generation at the MV level, even in the absence of flexibility utilisation. The escalating charging load during the afternoon reduces both the bus voltage distribution and the deviation from the rated voltage across most time steps in all development scenarios. In no scenario are the loading limits surpassed. Naturally, certain limitations exist: The grid states utilised in this research are primarily driven by DER generation, which generally leads to bus voltages exceeding the rated voltage. In these states, higher loads are capable of



(a) Result of Case Study "ℓPV"



(b) Depot load applied to a bus on the most affected feeder

Figure 3: Feeder length over bus voltage in future 0

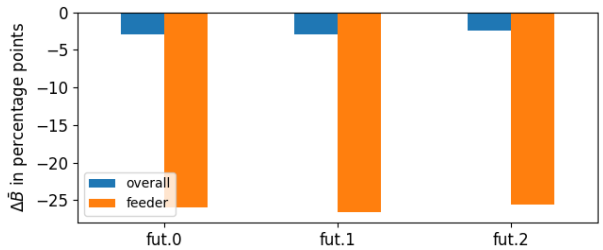
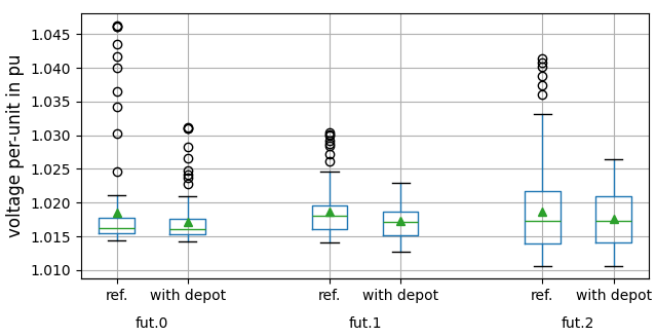


Figure 4: Change of distance to rated voltage through depot load for case study ℓPV



$\Delta\sigma \cdot 10^{-3}$: -3.66 -2.30 -1.24

Figure 5: scatter of bus voltages with and without depot load for case study ℓPV

shifting the bus voltages closer to the rated voltage. In grid topologies with less DER, the required charging power must be supplied from the higher voltage level, causing bus voltages to decrease further.

The primary factor to consider is that depots are, in most instances, already established and will be transitioned to EM. Consequently, the connected bus cannot be selected freely. However, this work illustrates the potential to include hdBEV depots as grid-supportive entities when placed in context with other entities, even with existing connection points.

Main requirements include the capacity to transmit signals between those responsible for grid steering and depot operators, which also necessitates the determination, forecasting, and planning of grid states as well as depot demands. Additionally, these must be embedded within regulations and market mechanisms.

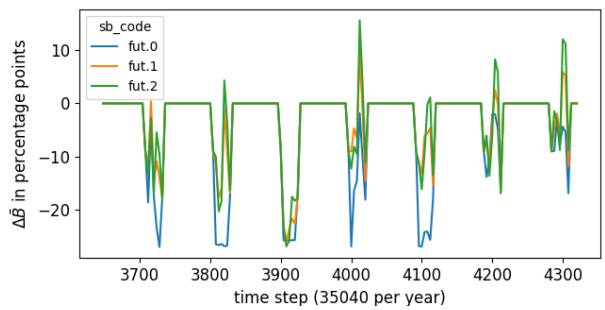


Figure 6: $\Delta\bar{B}$ through depot load in time series analysis over one week focused on the branch

V. Conclusion and Outlook

It can be demonstrated that the depot-based charging of hdBEV possesses the potential to assist in managing congestion at the MV level. Naturally, the majority of depot loads are unlikely to be new constructions solely dependent upon their connection to a specific MV bus. However, the results indicate that depots exhibit a significant synergy with DER, even in the absence of utilising flexibility potential.

Further research may determine whether the employment of flexibility enhances the network's capacity to integrate loads and DER to a greater extent. Other hdBEV use cases, such as distribution and line-haul operations, ought to be rigorously evaluated. The anticipated additional impact of bi-directional charging should also be subjected to further investigation.

Author contributions: S.D.: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing, Visualization. M.G.: Writing section I, Review H.S.: Review, Supervision, Project administration,

Funding acquisition. Language improvement with kagi translate.

Competing interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

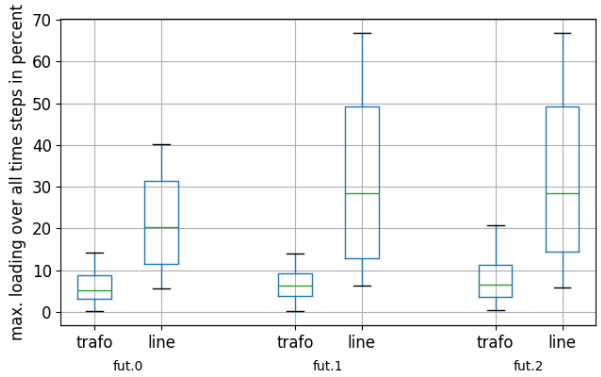

Figure 7: Maximum transformer and line loading over all time steps