Onboard ESU Sizing and Dynamic IPT Charging Scenarios for a Tramway Application

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Abstract

In this paper a battery based Energy Storage Unit (ESU) sizing methodology is proposed for tramway applications. At the same time, the required recharging system is also defined. For that, a tramway is modeled to define power and energy requirements. Then, the methodology is applied to obtain a set of solutions for LTO (power oriented) and sLFP (energy oriented) cell technologies, as well as, static and dynamic wireless recharging systems. The objective is to size the required system using batteries and its associated recharging system as an ESU for 15-year operation.

Introduction

Onboard Energy Storage Units (ESUs) in tramways is a current trend with multiple purposes. By employing these systems, peak power demanded and delivered from/to the overhead lines (catenary) can be reduced, improving the efficiency, and minimizing the voltage drops in the main grid [1, 2]. Furthermore, the use of ESU permits a certain range of self-sufficient operation of the tramway, providing driving autonomy to the vehicle. This has already been employed by different tramway manufacturers for catenary free operation in different locations. In these cases, the ESU is sized to fully supply the tramway power demand until the next recharging station [3, 4, 5]. On the other hand, wireless dynamic charging systems [6, 7, 8] will potentially enable ESU size reduction, as well as its degradation extending the lifetime (i.e. system powering for accelerating periods).

The objective of this paper is to present a methodology for the optimal sizing of ESU onboard a tramway considering different wireless charging stations along a city profile in a catenary free operation. For that, the tramway will be modeled, obtaining kinematics equations of the electromechanical system. Then, these expressions will be simulated with a real application data to obtain power and energy requirements. Afterwards, ESU sizing methodology will be proposed and tested with the real case-study and two battery technologies (LTO, sLFP). Apart from the ESU sizing common information inputs (i.e. recharging power, locations, degradation level), the wireless dynamic charging system influence will be evaluated with degrees of freedom of power level and length. All these potential solutions will be analysed trying to obtain the most suitable ones for the application, getting a compromise between all good solutions and each objective.

Tramway Modeling

In this section the tramway modeling will be presented. The elements of an ESU powered tramway are shown in Fig. 1. The traction controller is in charge controlling and managing the power flows. On the load side, the main elements are air-conditioner and lighting, grouped as auxiliary loads, and motor responsible for moving the tramway. On the power source side, the catenary and ESU (batteries). Note that, motor and ESU are bidirectional elements, therefore, they can act as loads and power sources depending on the circumstances. There are two main operation modes, on-grid and off-grid, in other words catenary connected or disconnected, respectively. Table I describes system configuration and assumptions according to the operation mode. As it can be seen, the ESU will be recharged in stations while the catenary is connected, and discharged during the tramway movement.

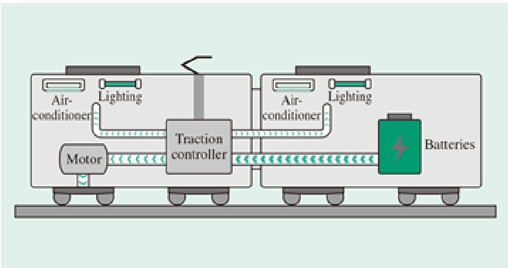


Fig. 1: Tramway main power sources and loads diagram.

Table I: Tramway operation modes.

Element	On-Grid	Off-Grid
ESU	Recharging (no grid injection)	Powering (auxiliary loads, motor)
Motor	Zero (tramway stopped)	Consuming (traction) Regenerating (braking)
Auxiliary Loads	Consuming	Consuming
Catenary	Powering (auxiliary loads, ESU)	Zero (tramway disconnected)

The motor power profiles for a trip are defined by the tramway movement equations. Figure 2 shows all the forces acting in the system [9, 10, 11], where the kinetics are defined in (1), (2), (3). The tramway mass (M_{tram}) acceleration (a) is defined by the traction force (F_T) produced by motors, drag force (F_D) due to velocity and gravity force (F_G) due to elevation (θ). The tramway traction should be evaluated in electrical kW, which can be obtained with the speed value (v). The traction power (P_T) is expressed in equation (4). Note that, the rolling resistance has not been considered in this analysis due to neglectable values in terms of power and energy requirements.

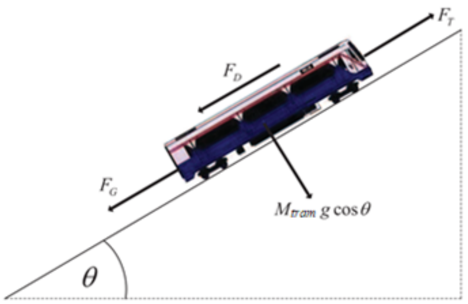


Fig. 2: Free body diagram of the tramway.

$$M_{tram} \cdot a = F_T - F_D - F_G \tag{1}$$

$$F_D = A + B \cdot v + C \cdot v^2 \tag{2}$$

$$F_G = M_{tram} \cdot g \cdot \sin\theta \tag{3}$$

$$P_T = F_T \cdot v = ((M_{tram} \cdot a) + (A + B \cdot v + C \cdot v^2) + (M_{tram} \cdot g \cdot \sin\theta)) \cdot v \tag{4}$$

The simulation parameters are shown in Table II based on tramway manufacturer data, for the case-study presented in Fig. 3. Note that, these results will represent the power and energy requirements of one coach. Usually, tramways are composed by several units. For this analysis, we assume there is one ESU per coach, being independent units. This approach helps to have a scalable solution, where total requirements can be obtained multiplying the simulation results by the number of coaches of the full tramway. Regarding auxiliary loads, it will be assumed a constant power consumption. Auxiliary loads are mainly composed by HVAC and lighting devices. Therefore, in a short trip the value is constant.

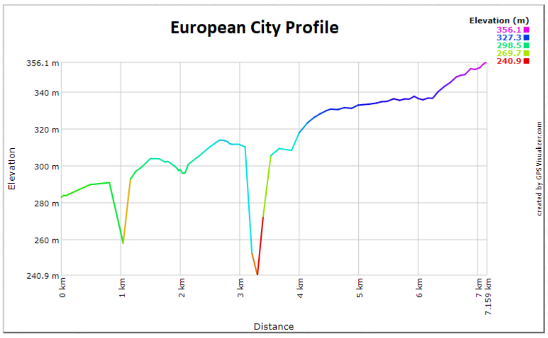
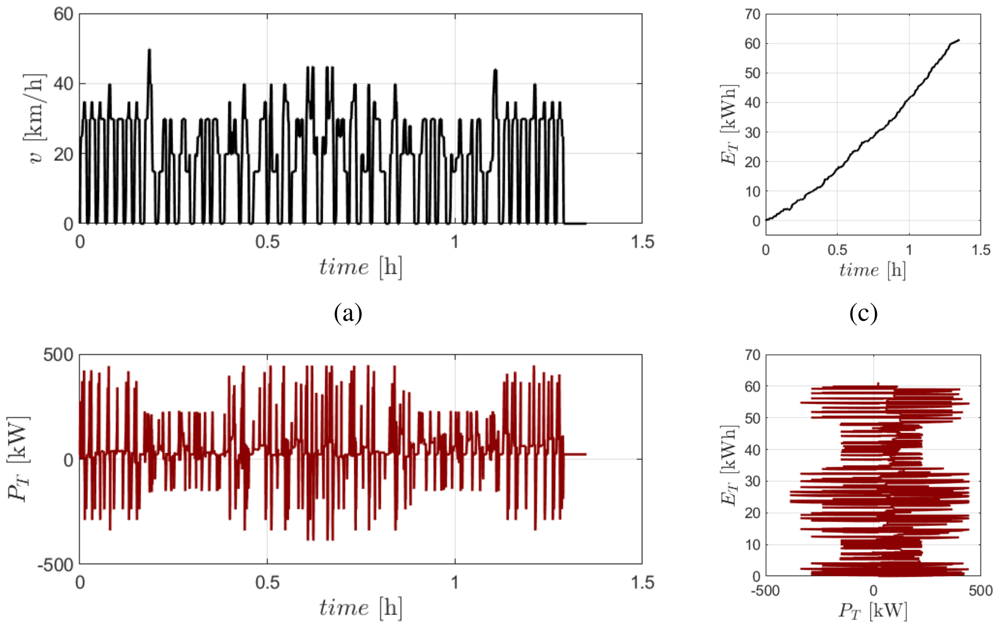


Fig. 3: Tramway route elevation profile.

Table II: Simulation parameters.

Parameter	Description	Value
M_{tram}	Tramway mass (coach+passengers)	12000kg
A	Mass coeff.	$2.965kg$
B	Track coeff.	0.46
C	Aerodynamic coeff.	0.005
g	Gravitational accel.	$9.81m/s^2$

Fig. 4a presents the speed profile. It represents a tramway completing a full round trip, go and back six times per day. Fig. 4b presents the power profile for the full trip. Maximum acceleration power is 447kW and minimum braking power is -387kW. The sign criterion is positive for acceleration power values, and negative for braking situations. It has been assumed that in braking mode the energy will be stored by the ESU and used afterwards, increasing system efficiency. Also mention that this power has been delivered through the catenary, being the coach continuously connected to the grid. Finally, the electrical requirements can be represented as power versus energy requirements. This graph illustrates visually the limits of the ESU sizing, in other words, what are the bounds of the sizing study, as well as what are the power requirements for each SOC of the ESU. Fig. 4d shows the results for the city tramway. This is because the easiest solution to power the tramway is to install an ESU covering all the requirements of all the stations (-387kW+447kW and 61.2kWh). That solution is not optimal due to the over sizing and lower efficiency, which would require an installation of a huge ESU in every single coach. The objective is to reduce this sizing, satisfying tramway requirements, while the efficiency is only slightly decreased.



(a) (c)

(b) (d)

Fig. 4: Case-study: (a) speed profile, (b) power profile, (c) energy profile, (d) power vs. energy diagram.

ESU Systems Sizing and Associated Recharging System Definition

In this section the ESU sizing methodology will be presented, applied to the real case-study and the results analyzed.

ESU Sizing Methodology

The methodology is presented in Fig. 5. Steps 1 was completed in the previous section. Step 2 defines the recharging strategy (i.e. power level, recharging locations, etc.). Step 3 and step 4 are composed by the first round of simulations considering the State Of Charge (SOC) control, series/parallel cells configuration and ESU lifetime at the Beginning Of Life (BOL). The second round of simulations is carried out in step 5, considering the ESU End Of Life (EOL). Finally (step 6), the results are validated and system configuration evaluated in terms of mass and size. It has to be mentioned, the lifetime and system performance will be defined by the capacity and internal resistance degradation, decreasing the storage capacity and increasing thermal requirements. The sizing criteria is presented in Table III.

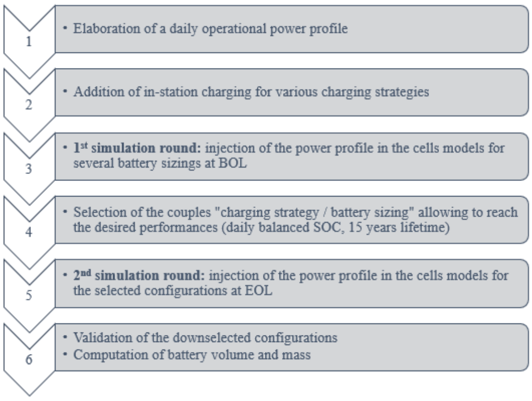


Fig. 5: Sizing methodology.

Table III: Sizing criteria.

Parameter	Value
Capacity Ageing	40% degradation (15-year lifetime)
Resistance Ageing	150% increasing (15-year lifetime)
Balanced SOC	1% tolerance (daily)
Balanced Temperature	1% tolerance (daily)

Real Case-Study Approach

For this application two battery technologies are considered (LTO and sLFP), see Fig. 6 and Fig. 7 and their main characteristics (Table IV). Both cells are currently used for railway applications. LTO ones are more oriented to power applications than sLFP ones. However, both ones are suitable for the application for the power levels obtained in the modeling section. For each cell technology, the number of cells in series was chosen to allow to reach a standard railway traction voltage (600V minimum), being 360S for LTO (612V-972V) and 216S for sLFP (606V-832V). Finally, several parallel configurations will be evaluated, for LTO (4P, 6P, 8P, 10P) and for sLFP (4P, 6P, 8P, 10P, 12P, 14P).

Fig. 6: SAFT VL45EFe cell (sLFP), VL47EFe precursor.

Fig. 7: SAFT LP31MTi cell (LTO).

Table IV: Cell Characteristics.

Cell Name	Format	Capacity (Ah)	Energy (Wh)
LP31MTi	Prismatic	31	70
VL47EFe	Cylindrical	47	132

Regarding the recharging system, the operational cycle selected for the study is repeated 6 times per day (8h working and 16h resting approximately). And this profile will be applied 320 days per year. Recharging configurations are presented in Table V and Table VI, showing all the configuration inputs for the sizing. The static charger is used when the tramway is stopped (only station catenary). On the other side, the dynamic wireless system will support acceleration processes (right after the station). Both systems can be installed in the same station. The number of charging stations indicates what is the total of recharging points in the route, from no charging points (0 stations) to all the stations (42 stations).

Table V: Static wired charging system.

Charging Stations	Power Level	Night Charge
0, 7, 14, 21, 28, 35, 42	100kW 200kW 300kW	100kW (optional recharge)

Table VI: Dynamic wireless charging system.

Charging Stations	Power Level	Path Length
0, 7, 14, 21, 28, 35, 42	100kW 200kW 300kW	15m 30m

Results

Once the methodology is applied with discrete input values and ESU constraints, a family of solutions is obtained. Therefore, an analysis is required to evaluate most representative and valuable results in terms of ESU size (series/parallel cells) and required recharging system (dynamic wireless and static systems). This analysis has been completed for each technology individually, and then compared.

Starting with LTO cells, the results are shown in Fig. 8. In Fig. 8a for each sizing the minimum number of stations and recharging power requirements (dynimac and static systems) is presented. As it can be seen, if a wireless dynamic recharging system is introduced there are two effects. The ESU size or number of stations can be reduced. There are two interesting solutions for this application. If 28 stations with 200kW of static recharging systems are selected, just to add a 100kW dynamic wireless recharging systems reduce the required ESU from 10P360S to 6P360S. On the other hand, there are no solutions for only static recharging systems at 100kW, but adding a wireless system at 100kW allows to have a feasible 42 stations solution.

Secondly, the wireless recharging system length also determines optimal solutions. In this case (Fig. 8b), if the length is increased the ESU size can be reduced. However, the most interesting conclusion is that longer solutions make it possible to have lower number of stations. As an example, if the wireless system length is increased up to 30m with an static system of 100kW, required stations are reduced from 35 stations down to 28 or 21 stations (depending on the ESU size), not being feasible before for 15m solutions.

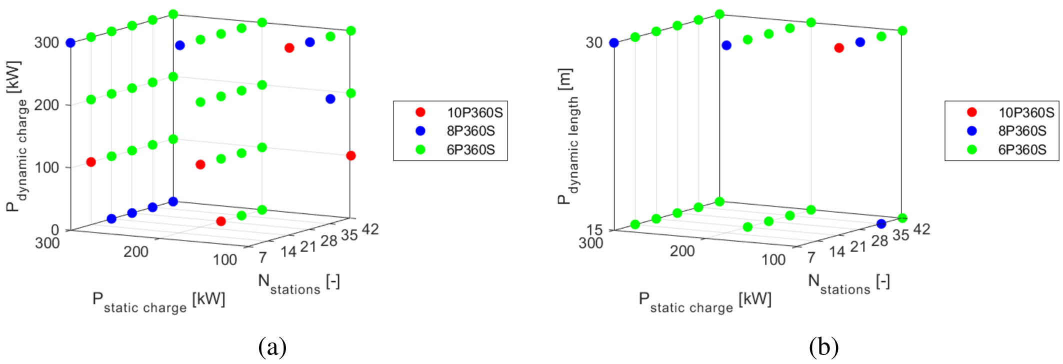


Fig. 8: LTO cells sizing results: (a) wireless charger power, (b) wireless charger path length.

Regarding sLFP cell solutions presented in Fig. 9, the conclusion is the same. Among all ESU sizing solutions, there is a clear trend where adding wireless dynamic recharging system reduces significantly the ESU size. For example, if a 14 stations and 300kW of static recharging system is selected, the required ESU size is reduced from 12P360S down to 8P360S only adding a 100kW wireless recharging systems.

In this case and compared to LTO cells technology, there are ESU solutions for all the wireless recharging systems lengths. Then, if the length is increased the ESU size is reduced. As an example, in a 21 stations and 100kW static system solution, the ESU required size is reduced from 12P360S down to 8P360S.

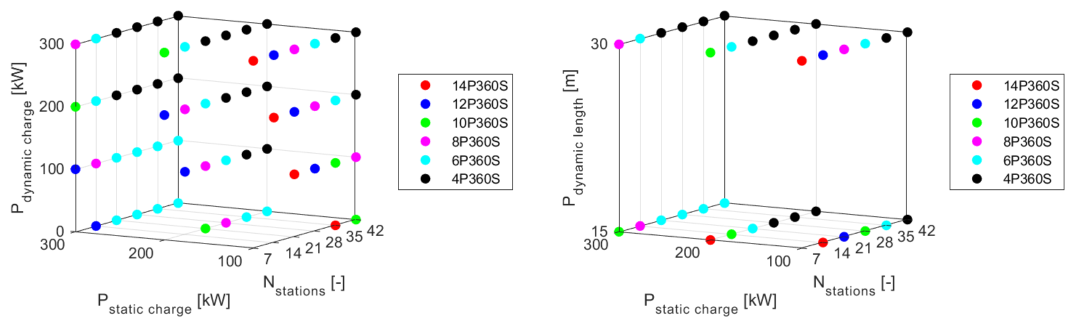


Fig. 9: sFP cells sizing results: (a) wireless charger power, (b) wireless charger length.

Finally, if both ESU cell technologies are compared the sLFP has an advantage in terms of optimizing the infrastructure. It is possible to perform the profile with a smaller number of charging stations and/or less powerful ones, which is expected because the tram profile studied is more energy-oriented. In terms of volume and weight onboard the tramway, the LTO has an advantage due to its prismatic format which allows to reach a better integration factor. Note that the volumes and weights presented here would be impacted by the thermal management needs of the current ESU. Having smaller batteries (be it sLFP or LTO) would also mean a smaller cooling system, minimizing the impact on the tramway architecture. Depending on the objectives at system level, sLFP cell will minimize infrastructure costs and LTO will minimize impact on the tramway (e.g., retrofit of an existing tramway). It is interesting to note that, if eventually power needs to be increased, LTO would become a more favored solution as it is a power-oriented cell and can accommodate very fast charge or discharge sequences.

In summary, this methodology enables to obtain a family of feasible ESU solutions suitable for the case-study, but not being possible to chose a single solution. For this selection more factors must be considered in further steps (i.e. engineering, budgeting, infrastructure limitations, etc.). However, this methodology defines the best ESU sizing for the number of stations and recharging systems (static and dynamic). Note that, a small 100kW wireless dynamic recharging system allows to reduce the number of stations and ESU size, as it has been concluded.

Conclusions

In this paper, a tramway has been analytically modeled in order to obtain the power and energy requirements for a real application. The objective is to size the required system using batteries and its associated recharging system as an ESU for 15-year operation. For that, it has been proposed an ESU sizing methodology where the constraints are defined by the ESU cells safe operation (capacity/resistance ageing and SOC/temperature balance).

This methodology has been applied to a real case-study using LTO and sLFP cells for the tramway. Recharging system is composed by static and dynamic wireless systems with different power levels, lengths and number of stations. A set of solutions has been obtained for both ESU technologies, being both suitable for the application. sLFP (energy oriented) cells have an advantage in terms of optimizing the infrastructure and LTO (power oriented) cells for a better integration. Mention, small wireless dynamic recharging system allows to reduce number of stations and ESU size, being a key for the final solution.

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References

[1] L. Mir, I. Etxeberria-Otadui, I. P. de Arenaza, I. Sarasola, and T. Nieva, "A supercapacitor based light rail vehicle: system design and operations modes," in *2009 IEEE Energy Conversion Congress and Exposition*, 2009, pp. 1632–1639.

[2] J. J. Mwambeleko and T. Kulworawanichpong, "Battery and accelerating-catenary hybrid system for light rail vehicles and trams," in *2017 International Electrical Engineering Congress (iEECON)*, 2017, pp. 1–4.

[3] A. Rujas, I. Villar, I. Etxeberria-Otadui, U. Larrañaga, and T. Nieva, "Design and experimental validation of a silicon carbide 100kw battery charger operating at 60khz," in *2014 IEEE 15th Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2014, pp. 1–7.

[4] V. I. Herrera, H. Gaztañaga, A. Milo, A. Saez-de Ibarra, I. Etxeberria-Otadui, and T. Nieva, "Optimal energy management and sizing of a battery–supercapacitor-based light rail vehicle with a multiobjective approach," *IEEE Transactions on Industry Applications*, vol. 52, no. 4, pp. 3367–3377, 2016.

[5] J. J. Mwambeleko, U. Leeton, and T. Kulworawanichpong, "Effect of partial charging at intermediate stations in reducing the required battery pack capacity for a battery powered tram," in *2016 IEEE/SICE International Symposium on System Integration (SII)*, 2016, pp. 19–24.

[6] I. Villar, A. Garcia-Bediaga, U. Iruretagoyena, R. Arregi, and P. Estevez, "Design and experimental validation of a 50kw ipt for railway traction applications," in *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018, pp. 1177–1183.

[7] A. Avila, A. Garcia-Bediaga, U. Iruretagoyena, I. Villar, and A. Rujas, "Comparative evaluation of front- and back-end pfc ipt systems for a contactless battery charger," *IEEE Transactions on Industry Applications*, vol. 54, no. 5, pp. 4842–4850, 2018.

[8] F. Gonzalez-Hernando, U. Iruretagoyena, M. Arias, and I. Villar, "Dynamic ipt system with lumped coils for railway application," in *2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)*, 2017, pp. P.1–P.9.

[9] P. Li and M. Mitchell, *Chapter 2 - Railway Industry Overview*. AREMA, 2003.

[10] Z. Tian, N. Zhao, S. Hillmansen, S. Su, and C. Wen, "Traction power substation load analysis with various train operating styles and substation fault modes," *Energies*, vol. 13, no. 11, 2020. [Online]. Available: https://www.mdpi.com/1996-1073/13/11/2788

[11] K. Mongkoldee, U. Leeton, and T. Kulworawanichpong, "Single train movement modelling and simulation with rail potential consideration," in *2016 IEEE/SICE International Symposium on System Integration (SII)*, 2016, pp. 7–12.