Flash Recharging Tram Catenary-Free: Impact Analysis on Italian Distribution Networks

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***Abstract*—The development of new sustainable mobility solutions and the constraints about air quality in urban areas are outlining the new guidelines about energy policies. This paper considers a catenary-free tram solution based on an innovative recharging system, "flash" along the path and "slow" at the end. The vehicle, equipped with ultra-capacitors, is able to complete each "flash" charge within thirty seconds. This situation can significantly impact electrical distribution networks that, if not adequately equipped and managed, may be subjected to violations of voltage and current constraints. The paper describes the methodology developed for analyzing the impact of this new transport technology on Italian electricity distribution networks, simulating its application in a metropolis scenario and in a rural one, and finally giving an evaluation of its potential replication.**

Keywords- Distribution Network, Tram, Impact of EV Charging.

I. INTRODUCTION

The need to face climate changes, to increase energy independence and to improve the competitiveness of industry, is encouraging European countries to undertake energy policies aimed at reducing greenhouse gas emissions, increasing the exploitation of Renewable Energy Sources (RES) and promoting energy efficiency [1][2][3]. At global level many initiatives are leading the modern society towards the electrification of transports. In this context the purpose of reducing traffic and improving air quality in densely populated areas has encouraged several cities to introduce measures to counter the access of private vehicles to urban centers, whereby electric vehicles are generally exempt. Vehicle manufacturers are therefore encouraged to invest in high potential and impact technologies, not only about transport systems, but also about the electro-energetic systems. This document considers a catenary-free (without catenary) tram model based on a flash charging system along the path and "low" at the end. The ultra-capacitors equipment gives the possibility to complete each "flash" charge within thirty seconds.

The system, in many ways similar to the e-Bus Rapid Transit (e-BRT) in Geneva (TOSA project) [4], has recently been implemented on the longest chain tram line in the world (20 km, 23 stops) in the city of Huai'an (China) [5]. Routes of this extension can significantly impact electrical distribution networks that, if not adequately equipped and managed, may incur voltage and current violations, as well as cause of secondary substation transformers overload with consequent reduction in their reliability. This paper considers the use of this kind of tram within the framework of the Italian distribution networks in two case studies: a city and a rural area. In order to gain greater significance in the analysis, local public transport tracks linking urban areas close to peripheral historical centers have been firstly examined, often hosting long-distance transport terminals (airports, railways stations, etc.). In case of "rural" trails, usually characterized by a weaker electrical grid and more dispersed topology, the recharge process may be of greater interest for the purpose of the discussion. However, it should be noted the also in rural areas, bus stops are located near to populated sites (so rather close so nodes of the electric grid).

The paper is organized as follows: Section II describes the flash recharging catenary-free technique, with a description of the methodology and the related choices; Section III reports the two considered cases studies. Section IV concludes with overall considerations and future possible extensions.

II. FLASH RECHARGING CATENARY-FREE TECHNIQUE

The current framework of the Italian electricity distribution network is characterized by a growing role of distributed generation based on renewable sources. Their large diffusion is also related to phenomena of unpredictability and balancing problems and in the operation of electric networks (i.e. overcurrent, overvoltage events). On the other hand, by the load side, it is to be noted the influence of the recharging of electric vehicles, which allows increasing the share of consumption covered by renewable sources. In this context, non-catenary technology represents an advanced system usually adopted for trolley buses [4] or light rail [5]. The system is characterized by the use of dedicated routes, fast travel times, and high frequencies. The most significant advantage of the non-catenary system is the relative flexibility of the track (in comparison to traditional ones). In any case, as for other vehicles, it is necessary to set up a dedicated DC and AC/DC conversion feeding infrastructure.

The "Trolleybus Optimization Système Alimentation" (TOSA) system, designed for bus lines but similar in its modularity to the rail one, is based on power-driven vehicles whose batteries are recharged along the path at flash recharging stations in a range of 1÷4 stops. The battery is then recharged through a pantograph and a short charge of fifteen seconds. The vehicle can then proceed to the next section of the route. The process, launched in Geneva in 2013 on bus line between the airport and the Palexpo, has exceeded all expectations and the municipality has already ordered another twelve vehicles. From the technical point of view, the system is made up of a combination of ultra-capacitors and high capacity batteries. Ultra-capacitors, thanks to their high power/energy ratio, can act as buffers to support batteries in a repetitive charge and discharge process and under stress conditions due to elevated road gradients.

A. *The Methodology*

In order to carry out an assessment that could be reliable in case of lack of available data, some hypotheses were made concerning various aspects, from the vehicle type to the layout of the electric network in relation to the considered path. It was then assumed that the flash recharging stations would be positioned at each stop, assuming the near coincidence with nearby MV/LV substations. Additionally, the public national geographic informative portal [6], recording the geographic extent of the road and of the electricity distribution network, gives the opportunity to identify the involved substations comparing them with the desired road path. The close proximity between electric networks and bus stops in urban areas allows to plan charging points without any special changes in the electrical grid topology (Figure 1).

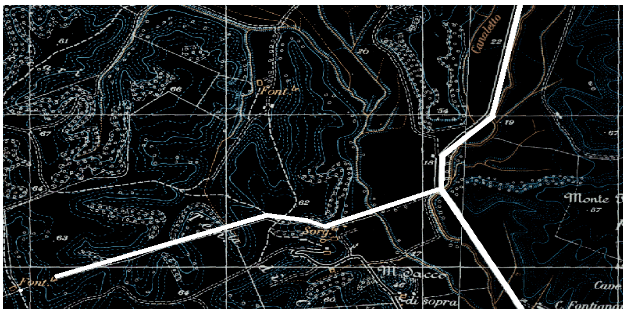

Figure 1: The considered distribution network in a geo-overview [6].

B. *Vehicle Type*

For compatibility with the TOSA technology, it was considered a 36-m long vehicle with flash-charging solution at the stop (like CRRC HADDB infrastructure system of Huai'an) at 600 V_{DC} (like vehicle model Alstom Citadis X05 305 [7]). The capacity of the vehicle is about 250 passengers for a density of four passengers / m^2.

C. *Charging Infrastructure*

The charging infrastructure, based on an accumulation system between the power supply and the connector at the selected stop, is assumed as follows:

- At stop (LV network side): 55 kVA / 400 V_{AC};
- At stop (vehicle side): 600 kW / 600 V_{DC};
- At terminal (LV network side): 430 kVA / 400 V_{AC} (in some case with a specific substation);
- At terminal (vehicle side): 400 kW / 600 V_{DC}.

III. Case Studies

A. *Urban Case*

For this analysis, the procedure has been applied to a suburban area in Rome, located in the suburban area between the city center and the airport. The conversion of existing bus lines to trams tracks (model TOSA) was conceived, suitable for a path connecting the two urban poles. The area comprises sixteen stops for an extension of approximately 10 km, covered by three transport lines (23, 89, and 808) under two HV/MV substations (Table I).

Table I. Bus Stops & Involved Substations

Station	*Bus Line*	*Distance (km)*	*HV/MV substation*
Malagrotta	23[a]	0	Raffinerie
Casale Bruciato	23	0.6	Raffinerie
Podere S. Pietro	23	1.3	Raffinerie
Podere C. Murata	23	1.7	Raffinerie
Podere Lungarina	23	2	Raffinerie
Podere P. Rotondo	23	2.3	Raffinerie
Idrocarburi	23	2.9	Raffinerie
Civico 248	23	3.5	Raffinerie
Pisana	23, 89, 808	5.5	Ponte Galeria
Civico 181	23, 89, 808	6.4	Ponte Galeria
Moratelle	23, 89, 808	6.7	Ponte Galeria
Pitentino	23, 808	7	Ponte Galeria
Domus de Maria	89, 808	7.9	Ponte Galeria
Portuense	23, 89, 808	8.3	Ponte Galeria
Ex Dazio	89[a]	8.7	Ponte Galeria
Eiffel	89,808[a]	10.2	Ponte Galeria

a. Bus terminal

The electrical network object of the case study is characterized by:

- HV/MV substations' nominal power: 25 ÷ 50 MVA;
- MV/LV substations' nominal power: 250 kVA (at terminal supposed upgraded to 630 kVA);
- Two involved 20 kV MV feeders;
- Feeder's unique nominal current rate: 240 A;
- Other parameters estimated by the defined model.

All lines are considered as upgraded with the TOSA technology. The path (Malagrotta – Eiffel) has an estimated travel time [8] of about thirteen minutes during all hours within the week (Figure 2).

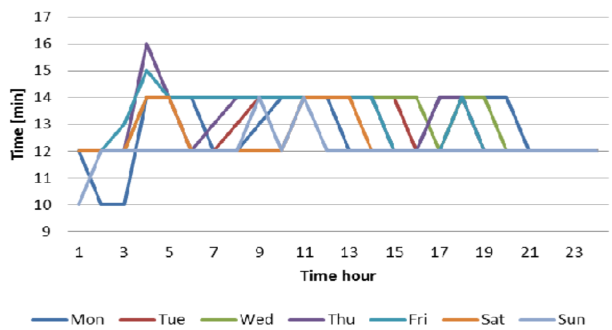

Figure 2: Urban test case scenario – Path travel time.

The service hours of the lines considered (Table II) show a high concentration of vehicles at some MV/LV stops (Pisana, Civico 181, Moratelle, Portuense) from 9am to 12pm and from 15am to 8pm.

TABLE II. WEEKDAY BUS TIMETABLE AT A STATION

Pisana (Eiffel destination)			
23	*89*		*808*
	5.40		5.35
6.00	6.10	6.40	every 15’
7.05	7.15	7.50	every 15’
8.05	8.25		every 15’
9.05	9.00	9.35	every 15’
10.05	10.10	10.45	every 15’
11.05	11.20	11.50	every 15’
12.05	12.30		every 15’
13.05	13.00	13.40	
14.05	14.10	14.40	
15.00	15.20	15.50	every 15’
16.00	16.30		every 15’
17.05	17.10	17.50	every 15’
18.05	18.30		every 15’
19.05	19.10	19.50	every 15’
20.05	20.30		every 15’
21.05	21.05	21.40	every 20’
22.05			every 30’
23.00			23.40

The stop at the terminal, lasting about ten minutes, is compatible with the “slow” charging process. Simulation on the electric network, carried out in DIgSILENT environment, was performed considering a full day of service on the selected route; Due to reduced bus frequency, pre-festive and holiday days have not been considered since they are related to minor impacts of charging on the power grid. Load profiles were calculated at the charging stations throughout the day. Different load peaks, linked to simultaneous recharge of vehicles operating in the opposite direction, modify the existing profile, determined by the estimated standard power profile (Figure 4).

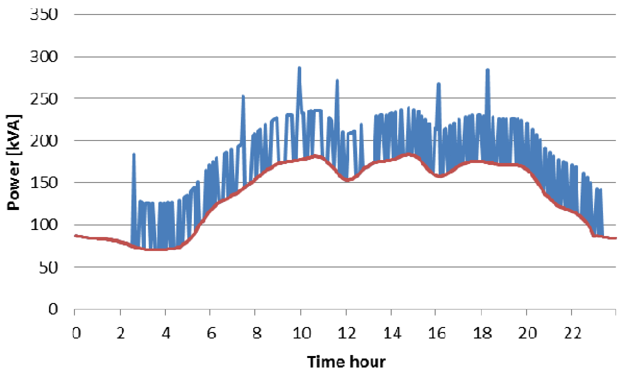

Figure 3: Daily load profile at “Pisana” stop (red-baseline: estimated, blue-spiked: calculated).

The voltage limits (0.95 to 1.05 p.u.) in each charging condition, even in the presence of two or more simultaneous charging vehicles at the same network portion, are not violated, being near the rated ones (Figure 5 and Figure 6).

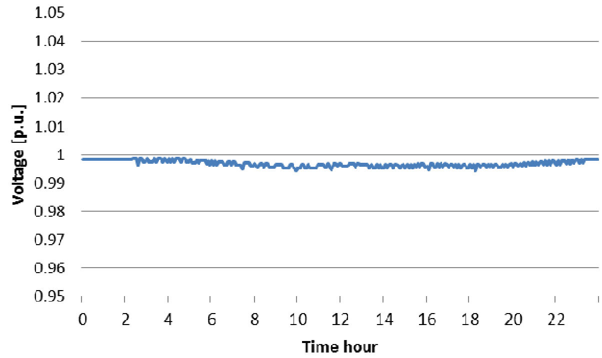

Figure 4: Calculated daily voltage profile at “Pisana” stop.

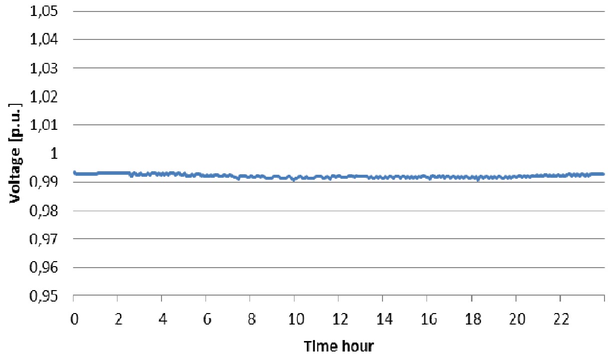

Figure 5: Calculated daily voltage profile at “Malagrotta” terminal.

Charging profiles compared to the peak and minimum annual [11] overheads of the secondary cab transformer in the acceptable range (Figure 7).

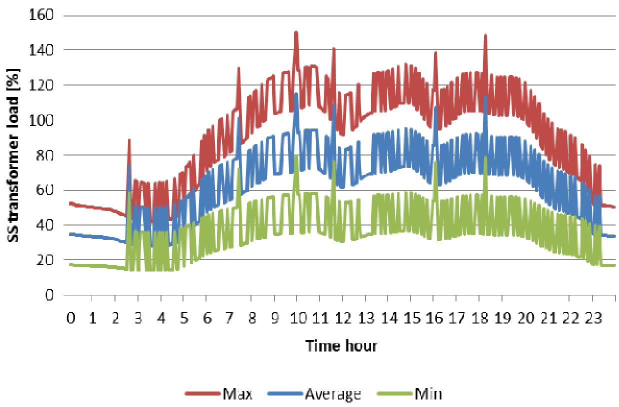

Figure 6: Daily MV/LV transformer load profile at “Pisana” stop.

B. *Rural Case*

The second case study is focused on a rural area in the northern Italy, related to the dismantled internationally Valmorea railway linking Malnate and Stabio (Switzerland). Currently, the future of this area, after a period of tourist exploitation, is still undefined despite an approved project of a light tram/subway realization. Due to its characteristics of both electrical and route type, completely different from the previous case, a series of simulations were carried out in order to estimate the impact of the implementation of a non-catenary flash recharge line in this area. The considered track (5 km, single rail) includes three stations (Malnate, Cantello and Valmorea) referring to a HV/MV substation and to several MV/LV secondary substations (Figure 7, Figure 8).

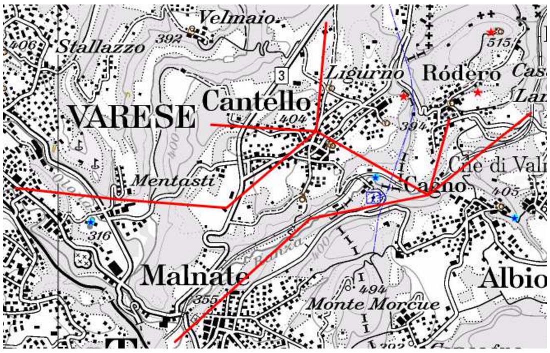

Figure 7: The considered distribution network (source Swisstopo).

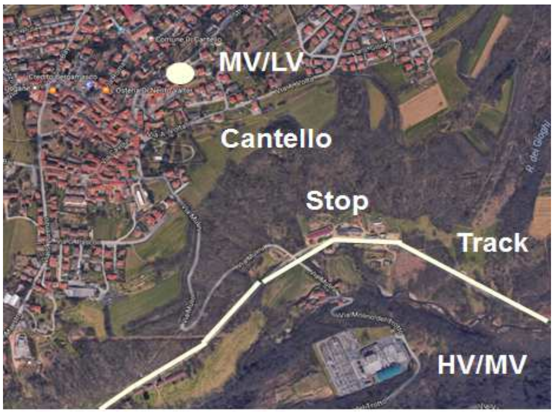

Figure 8: The considered track in comparison with the HV/MV site and a MV/LV one.

The estimated characteristic parameters were therefore:

- HV/MV substation's nominal power: 20 MVA;
- MV/LV substations' nominal power ratings: 250 kVA;
- Two involved MV feeder;
- Total electric network's branches length: 7 km;
- Rated voltage: 15 kV;
- Rated current: 240 A;
- Other features similar to the previous case.

The presence of a single rail that excludes the presence of more vehicles and the time travel (5 minutes for the Italian section, 11 minutes for the entire route) makes it compatible with the use of only one shuttle with a cadence frequency of about 30 minutes.

TABLE III. LAST RAILWAY TIMETABLE (STABIO DESTINATION)

Malnate	**10.23**	**14.49**	**19.04**
Cantello	**10.30**	**14.55**	**19.10**
Valmorea	**10.35**	**15.00**	**19.15**
Stabio	10.40	15.05	19.20

In this context, the load profile, characterized by its greater linearity, could minimal affect the voltage profile (Figure 9) thanks to the likely electric proximity to the HV/MV substation (Figure 8).

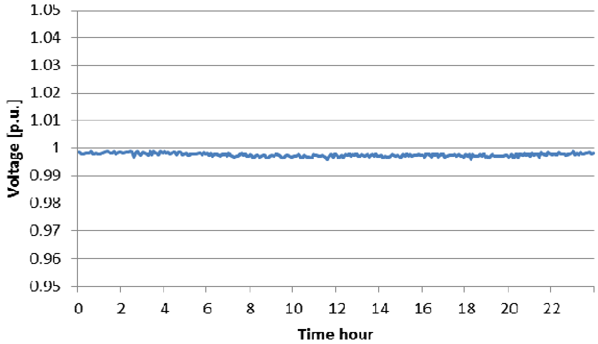

Figure 9: Daily voltage profile at "Cantello" stop

Likewise, the MV/LV substations' transformers load profiles are not so particularly affected, being, for the conditions outlined above, well below network limits.

IV. CONCLUSIONS

The potential application of a non-catenary flash recharge tram system has been assessed on some case studies representing the Italian electric distribution network considering different aspects (geographic area, traffic flows, etc.). Simulations have demonstrated a limited impact on the operation of grids; a more in-depth analysis on the specific case has to be carried out to complete a full evaluation. In any case, distribution networks do not seem to represent an obstacle to the widespread use of this solution, being in general stops in proximity of notable loads and adequate infrastrucutres. Following actions of this activity will address further considerations about the convenience across different areas and frameworks, using more sophisticated transport models and detailed grid data.

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