Fast inductive recharge for public transport on medium dimension electric buses: the first experience in Genoa

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Abstract

Aim of this paper is to describe the first experience in the field of the “inductive recharge” carried on by AMT (public urban transport company) in Genoa, that for this purpose has deployed a fleet of medium capacity electric buses.

The use of an inductive coupling avoids any contacts between the user and the recharge system, operating in a high level of protection and security environment. The recharge of the vehicle is carried out by the magnetic coupling of two coils that let the energy exchange to take place.

The autonomy, a fundamental parameter that has to be considered in the evaluation of a transport system like this, has demonstrated the effectiveness of the adopted recharge system philosophy: with short inductive recharge cycles carried out at the bus terminal, the battery discharge can be modulated so that the bus can always complete its mission and the main obstacle of the spreading of this type of propulsion is overcome. Data exchange between the onboard Battery Management System (BMS) and the power supply system is carried out by a wireless device that lets the module recharge with high precision.

One final subject where we focus our attention is the possible emission caused by the electromagnetic fields in the coils supplied at 20 kHz. Measurements carried out by a University Department led to extremely reassuring results.

Keywords: urban transport systems, advanced transport systems, simulation, infrastructure and maintenance, transport sustainability.
1 Inductive recharge in urban transport

The first example of inductive system in Europe concerned the French project “Praxitele” (Blosseville [4]). Each recharge station has been equipped with a system, which permits to recharge the vehicle without connectors. The vehicle recharge is possible thanks to the magnetic connection of two coils at a very little distance: the output coil is positioned in the ground and creates a magnetic field, which is picked up from the inlet coil fitted on board the bus and transformed into electrical energy to recharge the batteries on board. The coil in the ground is protected from weather and other external conditions. To get complete automatization of the inductive recharge system, the outlet coil is fixed on a mobile plate, which permits its positioning exactly under the one on board. The fast inductive recharge system presents many benefits:

• high performance and long batteries life
• batteries volume and weight reduction, due to the several recharge points
• reduced maintenance and management costs
• elimination of off-times for total batteries recharge
• higher safety due to connectors and galvanic contacts absence and to the automation of recharge procedures
• environmental immunity

Later the system has been applied from Wampfler (Germany) to particular electrical vehicles, used for tourists at the “Thermic Park” in Wakarewarewa (New Zealand) for the ITP- Charge Project.

2 The first experience in Genoa

The first Italian experience in inductive recharge system has been realized from AMT in Genoa, the local Urban Transport Company, which purchased 8 medium capacity buses Cacciamali - EPT Elfo (42 passengers, 7.48 m length), in order to fight local smog in hospital, tourist and pedestrian areas and to realize a zero emissions urban transport system with an high mission profile and low stated costs.

The “Elfo” solution is really innovative: in fact this kind of vehicle can transport 46 passengers in total - 11 seated down – but has a limited total mass

Figure 1: Elfo bus with Wampler recharge device.
(11000 kg); moreover AMT has compared the EPT bus to the ones of the previous generation and it resulted, that Elfò EPT realizes higher performances (70 km/h maximum speed and 18 km/h on a maximum road slope of 22%).

Experience in short inductive recharge cycles at terminus has demonstrated that the discharge batteries curve can be modulated to permit to end the mission, going over the main problems of electric buses; the data exchange between on board Battery Management System (BMS) and the supply device is possible through a wireless radio set and permits to module the recharge curve in the most suitable way.

The exact vehicle positioning on the coil was particularly difficult; in fact it needs very little tolerances, up to a few centimetres. At the beginning a mechanical guide system has been tested, but today a cam can be easily used from bus drives after a really short training period.

In Genoa the inductive recharge station started on February 2003 and permits the service with 4 electrical vehicles, substituting 4 thermic buses. The hardest daily service is based onto 25 routes, while theoric autonomy is up to 35 routes. Elfò system is employed onto line 518; it is 2,38 km long, with 14 stops far from each other about 170 m, with 15% maximum road slope. As far as the electromagnetic emission near the coils (supplied at 20kHz), the analysis executed by the University of Genoa has given very good results.

3 System potentiality evaluation

Following first application at 518 bus line, AMT has decided a strategic plan for the evaluation and the diffusion of electric buses with inductive recharge system; the necessary study has been executed in collaboration with Enterprise S.a.s.. Thanks to such study, it has been possible to analyse this service in a very
peculiar way, in order to point out realistic scenes, able to satisfy either users or firm needs. A wider use of electrical buses is now planned and it will be realized step by step by AMT, accordingly available financing; this development fit very well to AMT target, that is to apply, where possible, this kind of service, which has a very low environmental impact.

The followed method of analysis, validated during many on-site tests, permits a prompt reply to several questions: in fact the system “electrical buses + fast inductive recharge” can get a wide success only if each new required service is carefully evaluated and justified at all.

3.1 Selection of suitable lines

Before to go ahead with the study, the whole AMT urban lines, which have the right characteristics for Elfo buses service, has been defined; it has been observed the plane-altimetric profile, the main location of terminus and the compatibility of buses 7,5 m long with the current demand for transport (Messina and Trevisan [3], Carnevali et al. [2]). In detail, the first group of bus lines has been defined and focused; among them, the ones of main interest and the number of recharge points, have been defined. The equipped terminus must be optimised comparing to the diffusion on the territory and the possibility of using them quite immediately onto different bus lines.

The analysis has permitted to write down a document including all important data to each bus line and particular details obtained from the bus line running. It has been focused 18 bus lines of main interest with an even distribution onto municipal territory of Genoa. Then, it has been elaborated a methodology including a first group of evaluation criteria:

- vehicles compatibility to street layout according to plane-altimetric profile
- compatibility to bus depots location
- connection with main important location (hospitals, railway stations etc.)
- existence of important touristic/historical centre or areas with a high air and loud pollution
- even distribution in municipal territory
- transport demand level (high enough to justify such investment)
- vehicle service compatible to electrical traction bus lines, as regard to transit times and to stop times, necessary to a partial battery recharge
- transferring distances between terminus or depot and recharge station not too long
- not heavy traffic jam

To evaluate the number of vehicles needed on each line the equation is:

\[ N = \text{int sup} \left( \frac{T}{C} \right) \tag{1} \]

where \( C \) is time (in minutes) between departures, \( T \) is total time of each route in minutes, \( N \) is medium number of running vehicles, \( L \) is line length in km, \( D \) is distance from depot.
3.2 Multicriteria analysis

After focusing the first group of suitable bus lines and a consistent analysis about the electrical traction with inductive recharge at terminus, it has been applied a multicriteria analysis to obtain the final selection. All data have been determinate according the priority of express elements in homogeneous way with the minimum lost of information. Each parameter got a weight accordingly the importance of each one, into a quite real scene. Values and weight considered several parameters, such as compatibility with the AMT service planes, street profile, distance from depot, site attractiveness, environmental situation, traffic jam, transport demand, possibility of build equipped terminal and number of employed vehicles.

3.3 On-site activities

It was necessary to organize several tests, to get a sample of experimental data wider than the one already obtained by AMT and to realize the simulation cycles: the validation of the realized model has been performed comparing experimental data to the simulated ones. Before to start the tests, it has been focused some standard criteria in order to equalize the results and to obtain idoneous, comparable and careful data. Following strategies has been applied:

- during all the tests the “worst” vehicle has been used;
- only drivers with a great experience in such vehicles have been used, to obtain valid and homogeneous data;
- vehicles have been charged with a ballast of suitable weight (about 3000 kg, obtained considering passenger weight around 75 kg and 40 on board passengers) and material (sand bags);
- during the tests, all bus stops has been executed in order to reproduce the real situation of acceleration and breaking. Sometimes, when it was possible, test bus has followed a bus really on service, to better reproduce the real service conditions.

The campaign calendar had been defined according need to park vehicles into the closer depot, to create groups of test lines and to begin each test with an idoneus state of battery charge. The most interesting parameter to evaluate suitability of electric traction is obviously the electric consumption for each bus line. To measure this parameter, the state of charge (SOC), red onto a proper indicator, considered quite reliable, has been taken as reference together with the transit time and relevant distances.

3.4 Test data analysis

Together with the AMT preliminary analysis, the study of data got during the on-site test, permitted to select the first group of lines. Following it is described a simulator, validate onto experimental test, which has permitted, in any case, to preview consumption data. From the compared analysis of available data for bus lines, it has been observed a quite little difference between empty or full load vehicle (included into a range of 1,2 - 1,6), depending from plane-altimetric
profile, bus stops number or other kind of slowdown, starting state of charge of traction battery. This data, which has been uniformed for all bus lines, has been used to make the definitive choice.

4 Simulation activity

Simulator functioning is based on the dynamic equation, which describe the motion of a vehicle, generally describing in (2) (Perticaroli [1]):

\[ T - R = m \frac{dv}{dt} + \sum_{i} k_i j_i \frac{d\omega}{dt} \]  

(2)

\( T \) is breaking or traction force, \( v \) is vehicle speed, \( m \) its total mass and \( R \) is the data including all factors contrary to motion. The last equation factor includes the acceleration of all the rotating masses, each one with an inertness motion \( J_i, k_i \) represents proportionality coefficient between the angular speed \( \omega \) of the equipment \( "i" \) and vehicle speed \( "v" \). The data relating to rotating masses is hard to calculate, so that it has been preferred to correct mass \( m \) with a specific \( E \) coefficient, generally included into a 0.5 - 1.5 range. The motion equation is also modified as shown in (3):

\[ T - R = \left[ m_p + m_v (1 + \varepsilon) \right] \frac{dv}{dt} \]  

(3)

where \( m_p \) represents passengers mass and \( m_v \) only the vehicle one.

To calculate \( R \), different factors have been considered, which characterize the opposition to vehicle motion (4). First element \( R_D \) represents friction typical of the vehicle, the friction between wheel and street and drag forces. This data could be penalized in particularly situation. This is synthesized in the Davis equation as follows:

\[ R_D (v) = a + b v + c \left( 1 + \xi \right) v^2 \]  

(4)

To arrange total counting of the motion resistance, the Davis equation has been modified adding other two components (slope and curve ray). A vehicle driving on a not plane street is subject to a gravity acceleration, which could better or worst the drive. To calculate the motion resistance, a data proportional to bus line slope has been introduced; this value is red from simulator as input and it becomes positive when vehicle is driving up, negative when it is driving down the street. So, the equation of resistance used from simulator is the following:

\[ R = \left[ (7.6 + 0.056 \cdot v) \cdot (m \cdot 9.81) + 0.018 v^2 \cdot S e z \right] + m \cdot 9.81 \cdot 10 \cdot (\pm i) \]  

(5)

where \( i \) represents street slope, and \( m \) is the total mass \( (m_p + m_v) \).
It is to emphasize, that street slope and curve ray are directly bounded and referred to vehicle total mass, because of its influence on the entity of represented data. Furthermore these terms are multiplied for specific coefficients, in order to guarantee dimensional consistence.

For each point, breaking and traction forces \( T_v \) are inserted in an appropriate matrix, which is contained in the file of relevant data. Now active and passive forces operating on vehicle are known; the only unknown quantity in the motion equation is the acceleration:

\[
\frac{dv}{dt} = a = \frac{T-R}{m + m_p(1 + \varepsilon)}
\]  

(6)

When acceleration in the instant “\( i \)” is known, the speed and the position in the next instant is:

\[
v_{i+1} = v_i + a_i \Delta t
\]

\[
x_{i+1} = x_i + \frac{v_{i+1} + v_i}{2} \Delta t + \frac{1}{2} a_i \Delta t^2
\]

(7)

\( \Delta t \) is the temporal range; an integration range of 1 second represents a very good compromised between calculation speed and precision results.

During the drive diagrams defining procedure, the code provides punctual calculation of mechanical power “\( P_{mecc} \)” related to the vehicle, which could be obtained in the instant “\( i \)” according the following relationship:

\[
P_{mecc,i} = T(v_i) v_i
\]

(9)

The value corresponding to electrical power “\( P_{ele} \)” could be obtained considering the electromechanic output of vehicle energetic chain “\( \eta \)”, and the one related to auxiliary services on board “\( P_{aux} \)”. Equations in the close form could be given, which are relevant to breaking (11) or traction phase (10), in order to calculate the electric power in instant “\( i \)”.

\[
P_{ele,i} = P_{mecc,i} \frac{\eta(v_i)}{\eta(v_i)} + P_{aux}
\]

(10)

\[
P_{ele,i} = P_{mecc,i} \eta(v_i) - P_{aux}
\]

(11)

During breaking phase, the so calculated electric power does not represent the really regenerated one, bounded to batteries receptivity, but the total available one. Regarding evaluation of SOC it has been elaborated an ad hoc model, which
is based onto evaluation of weighted energetic flows and also onto SOC decline (12).

\[ SOC_{i+1} = f(i_{batt}, SOC_i) \]  

(12)

4.1 Results

After simulation, several graphics have been realized, describing the most important parameters such as plane-altimetric profile of all lines (to observe immediately possible criticises) and the medium consumption (in terms of SOC). The obtained results have showed very much alike to the one obtained during on-site activities, confirming the model precision. Following figure shows an example of plane-altimetric profile and of state of charge (SOC) trend concerning to a “normal” route using as first value 75%.

Figure 4: Plane-altimetric profile (left) and discharge curve (right) for a typical route (bus line 54).

The following pictures show the supposed speed profile for a typical route of bus line 54.

Figure 5: Bus line 54 speed profile.

The following graphic shows battery current. Positive values typically mean currents and energies during breaking phases.
The graphic below shows simulation result of a very significant morning working time. It has been prudentially fixed at 95% battery charge at the start from depot; the depot has been considered about 4 km far from the terminus and the transferring consumption has been consequently evaluated in 10%. As consequence first SOC value is about 85%. Stop times at equipped terminus are not indicated; generally they are about 10’ (only in one case 5’) and they are enough to execute recharge cycles. We can observe now, that bus line is in a state of energetic balance.

Finally it has been summarized characteristic values of the simulated bus line:

- route length: 2 km
- max slope: 8%
- medium speed: 12,5 km/h
- transit time: 10’
- medium SOC: 91,5%
- consumption: 1,1 kWh/km

Studying another urban bus line, number 57, Genoa - Nervi, it has been observed that it is quite impossible to end the assigned route in respect of the above mentioned transit time, since battery charge falls under 40% at the 4th route (figure 10, left). It has been however demonstrated, with a further simulation, that this service can be arranged foreseeing a longer stop at terminus (up to 20’), that means 3 vehicles are necessary (figure 10, right). In this case there is a substantial maintenance of batteries charge during an unlimited range of time, also obtaining an optimal theoretic use of them, as suggested by literature.
5 Conclusion

Inductive recharge technology of batteries traction for electrical buses at terminus is nowadays strong and consolidated.

Starting from already available data, which are based on a preliminary tests campaign based on bus line 518, an instrument to choose a first important set of lines of main interest has been defined. Technical consideration and other technical strategic target of the examined project have permitted to elaborate a multicriteria evaluation table. Following test campaign had therefore permitted to get several and important information about the considered bus lines.

Subsequently a simulator settled onto assembled experimental data has been created, which permits to foreseen in a quite precise way the “electrical bus + fast recharge battery” system performance.

For all these cases, it has been possible suppose and analyse different scheme of service, optimising vehicles performances through the correct employ of inductive fast recharge systems.

References


