EMPOWERMENT OF METROPOLITAN ELECTRIC TRANSPORTATION SYSTEMS: THE IMPACT ON DISTRIBUTION NETWORKS

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INTRODUCTION

The paper deals with the impact on electric distribution networks of the loads associated to the empowerment of metropolitan electric transportation systems. In particular, the first Section is devoted to the spreading trend of development of electrified transportation means for decreasing the city air pollution levels and satisfying the goals assumed by the sustainability programs. The second Section presents a software tool designed for evaluating the electric characteristics associated to the transportation system empowerment and mainly for forecasting the electric power flow and the relevant need of supply. The third Section reports some examples and applications of this program to new projects of metro transportation lines, while some comments and discussion proposals conclude the paper.

DEVELOPMENT OF ELECTRIC TRANSPORTATION PROGRAMS

The increasing needs of pollution limitation in the urban areas together with the government actions towards a sustainable development in the energy and transportation programs, push in favour of an empowerment of metropolitan electric transportation systems [1-3]. This is not only limited to collective means of transportation in the city for people, but for goods and merchandise too. While it is easy to find examples and projects for the first case, it is interesting here to refer some European experiences applied to the goods and merchandise delivery in cities and towns. This is a new area of opportunity for the expansion of metropolitan electrified transportation systems because the trucks and the vans for merchandise transportation represent the most significant polluting component in the present day traffic spectrum. In fact, some research studies on this topic are now in progress in many industrialized Countries[4-7] and also in Italy, where a co-operation between CESI and Politecnico di Milano has been established for this purpose. In 2000, the Volkswagen inaugurated, in Dresden (Germany), a new factory for car production. To solve the consequent logistic problems associated to the realization of a new productive plant in an area of the city centre, Volkswagen built a Logistics Centre located in the opposite part, out of the centre of the city [5]. From the Logistics Centre, that carries out the functions of warehouse of the materials that arrive via railway, a service of connection to the productive plant was made by means of tramway vehicles constructed purposely for goods and merchandise transportation and called “CarGotram” (see Figure 1).

Figure 1 “Elegantly and quietly the blue goods streetcar slides around the curve…”

The service, managed by DVB, is carried out on an existing line, with the construction of the connections to the logistics centre and the plant[5]. The tramway line crosses the city centre, it has a length of 4 km that is covered in approximately 15 minutes. The CarGoTram has an ability to 214.1 m³ for a 60t of capacity and a 60m of length. The structure of the CarGoTram presents 2 terminal units with drive cabin and 3 intermediate units. The cargo plan is located 1 m from the plan of the iron and sidewalls of flexible material are opened sliding on guide. Each rolling stock unit is equipped with two three-phase ac motors with rated power of 45 kW. The motor drive is cooled by air and placed under the plan [6,7]. The heads of
the rolling stock are equipped with Scharfenberg couplers, compatible with all the tramway of the net. The trams are controlled by computer and are equipped with a GPS [6].

The transport service with CarGoTram replaces until 100 travels per day of trucks in the roads of Dresden. The cost is nearly 1.5 million euro, more expensive than truck transportation, but the tram can be used over 25 years, three times longer than a truck [7].

Apart from the environmental aspects and the urban plan design that these projects involve, an important topic on the technical point of view is the electric supply of the transportation systems and the impact of these loads on the distribution network. The following section presents a software program designed for evaluating the electric characteristics associated to the electric transportation empowerment and then for sizing and optimising the electric supply system.

THE SOFTWARE SIMULATION TOOL

The simulation program permits to study the transportation system at different levels of detail, permitting its use in different stages of the project: planning of transportation plant, design of the supply system, cost optimisation.

At the planning stage, the simulation tool can be adopted for determining the sizing of the system and the definition of the investment costs thanks to the identification of the following parameters:
- timetable between the two terminal stations and among the intermediate ones,
- commercial speed,
- number of vehicles for satisfying the transportation needs,
- number of electric supply substations.

At the design stage, the simulation tool can be employed for defining the electric supply system as a function of:
- the electric drives on the vehicles (it is possible to simulate each type of electric drive by inserting as input data the electro-mechanical characteristic of the motors and the main electric parameters),
- the load cycle as a function of the scheduled timetable, of the number of the vehicles, and of the expected passenger number or merchandise weight,
- the track configuration (length, presence of curves or inclinations, number of stations and distance between them, speed limits).

In this way, it is possible to optimise, by means of the analysis of the system state variables (line drop voltage; substation current and power; absorbed energy), the following quantities:
- the supply line voltage,
- the cross-section of the line wire,
- the number, the location, the size, and the electric characteristics of the supply substation,
- the electric energy bill.

The software program can be also employed to assist the preparation of the timetable schedule at the operation stage, because it permits to determine the electric quantities variation (mainly the system electric supply power) when the train frequency or the wait-time in the stations or the speed limits on the line vary.

An interesting application of this simulation program is the analysis of the system performance in case of partial or total loss of one or more supply substations, due for example to faults, or to emergency conditions, or simply to the scheduled maintenance program. In this case the software tool permits:
- to study the operation program that guarantees the transportation service at a degraded level,
- to design a supply system that guarantees a defined level of reliability at which it is possible a full operation of the transportation service even in presence of some fault conditions.

The output data (also available in diagrams) of the simulation program permit to evaluate the system behaviour on the electric point of view, for satisfying the transportation schedule under continuity and reliability constraints. In particular, they are:
- the energy absorbed by the substations, the energy delivered to the trains, the line energy losses, the possible recovery energy given by the trains in the braking phase;
- the line voltage and its behaviour along the line with the identification of the minimum voltage point.

The program is mainly addressed to metropolitan traction systems supplied in dc, but application to dc railroad lines is also possible. A modified version is also available for single-phase ac railroad systems.

The program is made with the software language Visual C++ and can run under Windows or MS DOS environment.
For the validation of the simulation tool a measurement campaign was made on the line B of the subway of Rome. The data relevant to the transportation system and the experimental conditions during the measurement process are reported in [8]. The comparison between the actual absorbed power measured at the different substations and the ones calculated by the simulation program presents a maximum error of 4%. This light difference is due to some data difficult to set, as the mechanical resistance of the vehicle during curves or the passenger load. To estimate the error due to the evaluation of the passenger number, it is worthy to consider that a variation of 10% in the passenger load generates a variation of 2% in the average value of the absorbed electric power. Anyway the above mentioned level of error found during the validation process [8], is fully acceptable at the design stage of the transportation system or during the verification process.

EXAMPLE OF APPLICATION

The example refers to the project of a new light metro system in the town of Cagliari, in the Sardinia Island. This new metro line completely on surface consists in the electrification of an existing rail track between Repubblica Square and Monserrato Station and it will empower the electric transportation system of Cagliari. The total length of the metro line is 6.362 km and the operating schedule of the service expects nine stations (two terminals and seven intermediate stations) with a deposit for control and maintenance located close to the Monserrato terminal station.

The maximum number of vehicles present on line is 6 and the maximum train frequency corresponds to a time interval between two consecutive vehicles of 312 s. The maximum speed limit is 70 km/h and it is reduced to 20 km/h in correspondence of intersections with roads and of track switches. The estimated commercial speed is 21 km/h.

The vehicle characteristics are the following:
- nominal voltage: 750 V dc,
- maximum voltage: 900 V dc,
- minimum voltage: 500 V dc,
- number of motors: 4; with rated power of each motor equal to 70 kW,
- vehicle weight: 35 t,
- maximum number of passengers: 201,
- vehicle weight at full passenger charge: 48.7 t,
- vehicle length: 28 m,
- maximum acceleration: 1.1 m/s²,
- operational deceleration during the service: 1.2 m/s²,
- auxiliary services’ absorbed power: 56.5 kW,
- electric traction efficiency (drive and motor): 0.87,
- mechanical efficiency: 0.95.

The electromechanical characteristic of the motor during the traction phase is inserted as input data by means of the values torque-speed provided by the drive constructor.

The application of the software tool to these data, taking into account some environmental constraints and some conditions related to the availability and reliability of the connection with the electric MV network, gives as result the following characteristics for the supply system.

- Substation SSE 1 that supplies the line of the metro in two points: directly at the progressive distance 2192 m, and by means of a feeder 730 m length at the progressive distance 1460 m. This latter is necessary to guarantee the respect of the minimum line supply voltage limit in the worst cases of train power absorption.

- Substation SSE 2 located at the terminal Monserrato and supplying the deposit, too.

In particular, it is interesting to analyse the currents delivered by the substations and the variation of these currents during the scheduled train circulation on line. As an example,
Figure 3 reports the current relevant to the substation SSE 1, as results from the simulation program.

The worst condition corresponds to four vehicles that are departing from the most distant stations with reference to the supply points, and two vehicles running between intermediate stations. In this case the current delivered by SSE 1 is 2.8 kA (see Fig. 3) and the one delivered by SSE 2 is 1.57 kA. The relevant maximum absorbed power by the substations are reported in Table 1.

**TABLE 1. Maximum and average absorbed power for the substations SSE 1 and SSE 2.**

<table>
<thead>
<tr>
<th></th>
<th>SSE 1</th>
<th>SSE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum power [kW]</td>
<td>2240</td>
<td>1258</td>
</tr>
<tr>
<td>Average power on dc side [kW]</td>
<td>800</td>
<td>460</td>
</tr>
<tr>
<td>Average power on ac MV side [kW]</td>
<td>980</td>
<td>600</td>
</tr>
<tr>
<td>Average apparent power on MV side [kVA]</td>
<td>1030</td>
<td>630</td>
</tr>
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</table>

In Table 1, the average power associated to the transportation schedule are reported as results of the simulation process. These data are important for defining the economical contracts with the electricity distribution Company. The complete design of the supply system must take into account the necessity to resort to standard sizes for the transformer-converter units and the possible degraded conditions in which it is necessary to guarantee the full transportation service:

- loss of one MV line supplying the substations,
- fault or maintenance turn-off on one of the transformer-converter units in the substation.

The simulation results brings to these conclusions:

- Substation SSE 1: n. 3 transformer-converter units, 1.5 MW each;
- Substation SSE 2: n. 2 transformer-converter units, 1.5 MW each.

In SSE 2 an additional 1.5 MW unit is also located for the deposit supply.

**CONCLUSIONS**

The increasing political and economical support towards the empowerment of electrified transportation systems in urban areas generates the need to evaluate the relevant impact on the electric distribution network. A simulation software for this purpose is proposed in the paper. Starting from the track and vehicle data and implementing the transportation service constraints, it is possible to estimate the best location of the new sub-stations for system supply and the relevant size. The software tool permits to take also into account some emergency conditions due to transportation system faults or to electric supply programs set by the distribution Company.

The simulation program was validated thanks to several experimental investigation performed on the line B of the metro of Rome and the example here reported refers to the design of the new light metro line of Cagliari.

The time-domain simulation permits, in particular, to point out the absorbed current waveforms with the relevant peaks. These latter are very important for a correct design of the protection devices and for verifying the respect of the Standard allowed overcharges. In the case of the transformer-converter units adopted in the example, these limits are: overcharge of 50% for 2 hours and 200% for 1 minute, as indicated in the CEI EN 146-11 Standard.

**REFERENCES**


