HYBRIDIZATION OF TROLLEYBUSES – MEANS FOR INCREASING THE TRANSPORTS FLEXIBILITY AND REDUCTION OF THE POLLUTION

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This paper presents the means for choosing the optimal solution for the lack of autonomy of a trolleybus. It covers a wide range of supply systems that assure the function of a trolleybus without the grid. The proposed method brings balance between the economic and technological perspective and takes into account the specific power, mass, pollution, price, maintenance, etc. The starting point of the paper is the current state of research for hybrid buses followed by the means for extending the solution to trolleybus and the multi-criteria analysis involved in choosing the optimal power source.

Keywords: power source system, hybrid trolleybus, eco-friendly, multi-criteria analysis

1. Introduction

In our society pollution reduction should be a concern for all the economy sectors. Transportation is one of them, and the public transport is a major one. Its means: buses, trolleybuses and trams have a negative impact over the urban areas.

To function all this vehicles need a power source which, for now, is represented by oil, in a considerable ratio.

Oil, the backbone of global contention, has not ended its role yet, but besides its being disputed as combustion pollutant, it also enters the age where its exploitation becomes more and more difficult. We live in the era where, as statistics show, oil exploitations achieve their maximum and which follows is the depletion of reserves.

For this situation some poor choices regarding public transportation also contributed. In the '50s, in several regions such as Latin America and USA [1],

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and later in other regions [2], electric transport was replaced by vehicles with internal combustion engines (ICE). The flexibility provided by these won the race.

Time showed that the advantages of ICE engines are partial, because of the pollution they cause. Suzuki Foundation demonstrated that 8% of the traffic related deaths are caused by pollution, diesel engines being responsible for a lot of diseases, such as: asthma, pneumonia, other breathing diseases, cancer, heart diseases [3].

The increasing power demands accelerated after each economic or any other natural crisis, require additional new resources for the transport system. Among them, renewable power sources are preferred and increasingly applied.

A big step for a pollution free environment is providing the public transportation with eco-friendly power sources.

At this time there are several projects aiming at developing an eco-friendly bus. The main strategies for the power source that will equip this type of bus involve high power and high voltage battery packs, fuel cells (FC) or combination of them.

The main advantages of a power source based on battery packs are analyzed in [4] – [16]. The major programs, in Europe, that propose as the main power supply the FC are: Hy FLEET: Cute Project [17] and CHIC. Hy FLEET: CUTE – defined as the largest project in the world with buses on hydrogen, started in January 2006 and ended in December 2009. The project managed: 47 buses with FC and ICE, 8 hydrogen stations, out of which 6 with on-site production, 31 industries, government and academic institutions. The European Commission was a major co-financer [17]. The cities included in the program were: Amsterdam, Barcelona, London, Luxembourg, Madrid, Hamburg and Reykjavik. After the program ended CHIC program started with the objective of implementing this type of transport to the designated cities.

In this context of introducing non-polluting means for transport, there is also an ascendant trend for developing trolleybuses, particularly in areas where electric power production is made in non-polluting plants (hydro-plants, wind power plants, photovoltaic power stations etc.). There are several cities in Europe like Bologna and Castellon [1] and also in Romania, such as Bucharest and Craiova [2], which extended their trolleybuses fleet or acquired one for the first time.

Treating the pollution problem as a hole, the trolleybus has a big advantage over the bus, namely the noise. The electric motor of the trolleybus produces less noise and vibration than the ICE of any bus.

Compared with buses, the trolleybuses are twice more economical, as they need only 10.8 MJ/km as compared to 24MJ/km needed by the buses [18]. On the other hand the presence of the overhead power lines and the lack of autonomy represent the downsides of them. All this disadvantages can be limited or eliminated by: sharing the overhead power line with the street light, creating a dedicated power line at the road axis, developing smart grids [1] or by deploying auxiliary power sources [19].

This paper addresses the technical challenges for developing the optimal auxiliary power source for a trolleybus (Trolleybus Extra Supply System – TESS). The paper is organized as follows: section 2 presents different technologies that can be used for TESS, section 3 describes the feasibility factors from the economical point of view, section 4 presents the steps needed for choosing the optimal TESS by multi-criteria analysis and section 5 shows a case study for two different solutions of TESS based on battery packs and FC.

2. Developing TESS

For trolleybuses the electric traction is not something new as is for buses, or other vehicles in general [1], [18] – [20].

Moreover the improvements of the electric motors, inverters and cc-cc converters made possible to maximize the space allocated for the passengers while maximizing the power/mass ratio.

All this improvements open the way to tackle the lack of autonomy problem by developing TESS.

In order to establish the optimal TESS we consider the following hypothesis: the trolleybus has a low range route and the driving time is alternated by breaks, the slope of the route is no more than 5%, the off grid periods during a route are less than 50% of the entire route.

Based on the research done for the development of an eco-friendly bus we considered several technologies for TESS such as (Fig. 1): motor-generator group systems, high power and high voltage battery packs, double-layer capacitors, FC and combination of them.

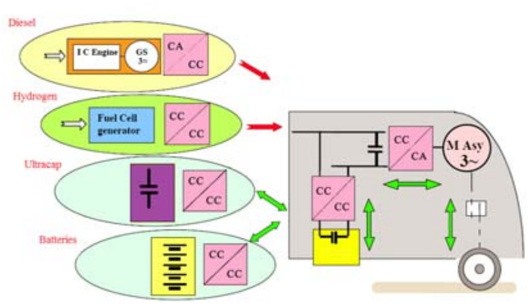

Fig. 1. Different power sources for a trolleybus

From all the possible TESS technologies the motor-generator group system is the most prone to environmental pollution, but we kept this solution assuming that the fuel used is eco-friendly (vegetable oils).

Unlike the battery pack needed in an eco-friendly bus which requires high energy density for assuring long range autonomy, the battery pack for TESS requires high voltage and high specific power for electric traction. In this context and considering the safety issues the most promising battery technologies are: Ni-MH and $LiFePO_4$.

The ultra-capacitors can be a solution on their own by absorbing and providing the current peaks from and to the grid, but most likely they will be used in combination with other power sources like battery packs [21] and FC [22].

Among all the FC technologies the Proton Exchange Membrane (PEM) is the most adequate solution for public transport because it provides high power density, low operation temperature, relatively high service life and a good dynamic behavior and efficiency [7].

The first step in the developing process for TESS should be the development of the model for the power source used. Based on a discharge profile from the designated route and using the available power source models [23] – [27] it is very easy to obtain the parameters of the source. Among them the most important ones, which also represent the multi-criteria entries, are:
T1: specific power – indicates the loading capability of the source and is expressed as power – to – mass ratio [W/kg]; T2: mass – the total weight of the system [kg]; T3: estimated life – the number of years of service until replacement [years]; T4: concentration of each pollutant (if any).

After the characteristics of TESS are established they should be analyzed from the economic point of view.

3. The economic perspective of TESS

Despite the advantages electric vehicles provide, they also face several limitations that prevent the large scale implementation of them. Some of these include battery cost and infrastructure [28]. In [29] and [30] it is proven that the high cost of the battery discourages potential buyers. Furthermore, charging stations are rare than gas stations which impose drivers to use longer routs in order to arrive at their destination.

The mentioned limitations are relevant only for private electric vehicle owners. The electric public fleet vehicles face less of these challenges [28]. They can implement Vehicles-to-Grid technologies (V2G) which can bring revenues for the fleet owner. Theoretically the electric vehicles can be plugged in for the entire time when they are not in use, enabling them to collect revenues for the storage capability provided to the electric grid [28]. This technology has been established as a source of income for the participant on frequency regulation market [31] [32].

There are several studies [28], [33] which calculate the total income and expenses produced by a single electric vehicle per year, and in all they report that the vehicle generates profit.

The economic analysis of TESS considers the initial investment and the cost to operate and maintain it. For this purpose we establish a series of criteria such as: E1: the total cost, E2: the cost-per-kilometer to operate TESS, E3: the cost-per-kilometer for maintenance and E4: the cost-per-kilometer to neutralize the pollutants (if any).

The total cost to implement TESS includes the cost for all the source components and also for any other auxiliary devices needed for it to operate like the charger for the battery pack or the hydrogen station for the FC.

The cost-per-kilometer to operate (CPKO) TESS is composed of the cost for fuel for the motor-generator group, the electricity needed to charge the battery or the hydrogen needed by the FC.

The cost-per-kilometer for maintenance (CPKM) includes the cost for the parts that are replaced and the labor hours to install them.

The cost-per-kilometer to neutralize (CPKN) the pollutants is represented by the cost of the auxiliary systems used in order to meet the eco-friendly criteria.

4. The multi-criteria analysis

The multi-criteria analysis (MCA) is a decision-making instrument when a single evaluation criterion is not sufficient [34].The advantages of MCA over other approaches [15], [22], [35], [36] are represented by the large number of criteria involved and its versatility.

The MCA operates with several concepts among which the most important ones are: options, criteria, performance matrix, score and weight.

The options are the elements that are subjected to comparison or hierarchy. From these the MCA will choose the solution, the option that best fits all the criteria.

The criterion is the measure against which the options are evaluated. Each criterion measures a relevant aspect of the options and is independent of other criteria.

A standard instrument for MCA is the performance matrix. Each row of the matrix is occupied by an option and each column comprises of an evaluation criterion. The values that are passed in each cell represent the performance of an option for a particular evaluation criterion.

The score represents the value of each option. Usually they are standardized to a scale between 0 and 100 points, where the best value receives 100 while the others receive scores proportional to their value per best value ratio.

The weight assigned to each criterion is the percentage value to highlight its importance. The sum of the weights must add up to 100%.

Based on the concepts previously defined the elements used by the MCA for establishing the optimal TESS are: **options:** the motor-generator group, the battery pack, the ultra-capacitor, the FC; **criteria:** T1 – E4. In order to obtain a balanced solution between the technological and economic factors each of these categories will receive 50%. The distribution of the weights within each category is presented in Table 1.

Table 1

The distribution of the weights for the MCA

	Criteria	Weight
Technology	T1	13%
	T2	10%
	T3	12%
	T4	15%
Economic	E1	12%
	E2	12%
	E3	12%
	E4	14%

The distribution of the weights was done so it will emphasize the eco-friendly aspect of TESS.

5. Case study

In order to demonstrate de advantages of our proposed method we present a case study to determine the optimal TESS for a trolleybus from Bucharest. The starting point of the study is based on a discharge profile (Fig. 2), obtained from a trolleybus equipped with two electrical motors of 120 kW each.

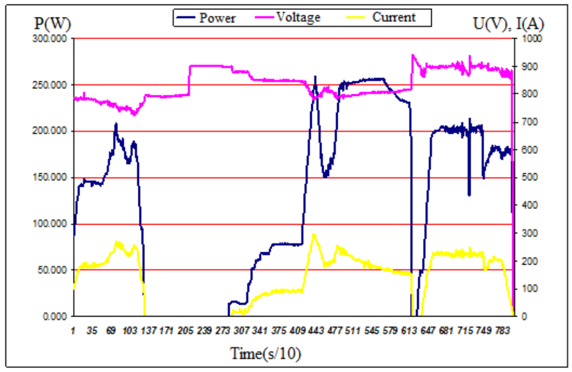

Fig. 2. Discharge profile for a trolleybus from Bucharest

In this study we only considered two options for TESS: a battery pack of $LiFePO_4$ cells (option 1) and a FC with a Li-Ion auxiliary battery (option 2).

To determine the technical characteristics for the two options we used a third order RC network battery model which we proved to be the best model for a $LiFePO_4$ battery for EV applications in [37] – Fig. 3 and a generic model for FC and Li-Ion battery from MATLAB®/Simulink® environment – Fig. 4.

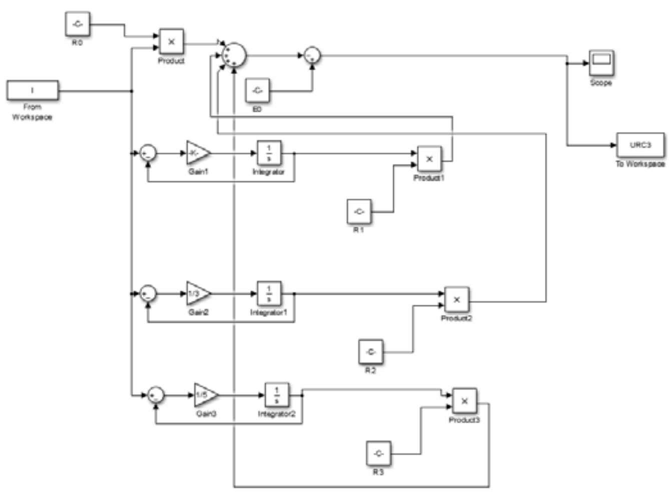

Fig. 3. The model for TESS option 1

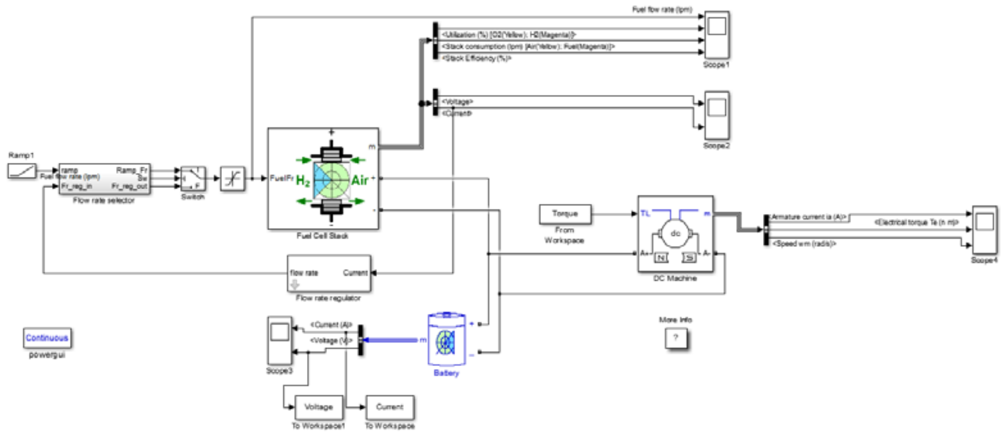

Fig. 4. The model for TESS option 2

Based on these models we could establish that for the proposed discharged profile it is needed a $LiFePO_4$ battery with the rated voltage of 900 V and rated capacity of 112 Ah (cca. 100 kWh sored energy) for option 1 and for option 2 a 50kW, 625Vdc FC with PEM and a Li-Ion battery with the rated voltage of 800 V and rated capacity of 25 Ah (cca. 20 kWh sored energy).

These values were obtained through try and error in order for TESS to match the grid voltage that powers up the trolleybus motors (at the same current) – Fig. 5.

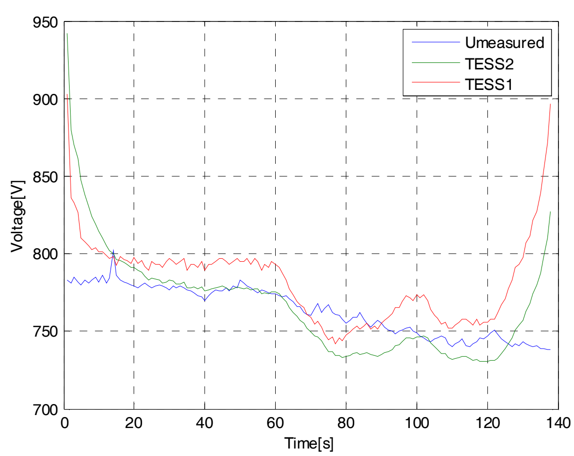

Fig. 5. The output voltage for TESS option 1 and 2

Once the technological characteristics of the two TESS solutions were established based on their stored energy and keeping the proportion with the prices for CPKO and CPKM indicated in [28] and [33] we calculated the economical parameters involved in the MCA. In the cost for TESS 1 is also included the charger, while in the cost for TESS 2 the hydrogen station price is not included. All the parameters are synthetized in Table 2.

Table 2

The values for the parameters used for the MCA

	Parameter	TESS 1	TESS 2
Technology	T1: Specific power [kW/kg]	0.1148	0.099
	T2: Mass [kg]	870.40	702.46
	T3: Life [years]	9	12
	T4: pollution	0	0
Economic	E1: cost [$]	67 000	250 000
	E2: CPKO [$/km]	0.0501	0.776
	E3: CPKM [$/km]	0.124	0.497
	E4: CPKN [$/km]	0	0

Based on the values from Table 2 and on the weights from Table 1 we determined the performance matrix of the MCA – Table 3.

Table 3

The MCA performance matrix

	Criteria	Value	**Total**
TESS 1	T1	13	**66.07**
	T2	8.07	
	T3	9	
	T4	0	
	E1	12	
	E2	12	
	E3	12	
	E4	0	
TESS 2	T1	11.21	**40.18**
	T2	10	
	T3	12	
	T4	0	
	E1	3.21	
	E2	0.77	
	E3	2.99	
	E4	0	

Analyzing the values from Table 3 it can be observed that while the FC solution (TESS 2) has superior technological characteristics with a technological score of 33.21 points greater than 30.07 obtained by TESS 1, overall the optimal solution is TESS 1 which combines good technological characteristics with a low price.

6. Conclusions

Considering the multitude of existing solution for a hybrid power source for a trolleybus choosing the optimal one is not an easy task. In this paper we address this problem from a complex point of view which include technological characteristics of the source such as: specific power, mass, estimated life, concentration of each pollutant (if any) and also economic indicators: cost, the cost-per-kilometer to operate, the cost-per-kilometer for maintenance and the cost-per-kilometer to neutralize the pollutants (if any). All this parameters are process using a multi-criteria analysis and in the end the optimal solution is determined.

The proposed method is oriented to establish the most eco-friendly solution, but considering the versatility of the multi-criteria analysis it is very easy to create other scenarios by modifying the weights involved in the performance matrix. In this way the method can be very easy turned into choosing the most economical solution or the best technological one.

To prove the method viability we performed a case study for a trolleybus from Bucharest and we establish that the optimal solution for assuring its functionality without the grid is an extra power source composed of a 900 V and 112 Ah $LiFePO_4$ battery pack. This power supply combines good technological characteristics with the lowest price.

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