Development of Electronic Equipment for Trolleybuses with Autonomous Power Source

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***Abstract* — In this paper we present the development of a system with autonomous power source for trolleybuses. These newly developed rechargeable batteries powered system are supposed to allow a trolleybus to move away from grid lines for significant distances. Here we present the energy consumption measurements for a trolleybus' on a route during one day. According to these measurements, the power rechargeable batteries chemistry will be chosen, and an efficient and reliable electric system will be developed.**

***Keywords* — Trolleybus with autonomous power source, rechargeable battery, LiFePO4, charge balancing.**

I. Introduction

Trolleybuses with autonomous power source became a common interest in scientific and social circles in the recent years. First models of trolleybuses with autonomous mode were developed in the late 90's. At the time, autonomous mode could be used for a few km at low speed. Old technology for creating compact and powerful chargeable batteries was the cause. Low efficiency of traction and large weight of the trolleybus also decreased the possibilities for developing trolleybuses, which could drive away from the supply lines.

Urban electric transport has evolved alongside modern technologies in power and control electronics. Performances of IGBT transistors and powerful microprocessors allowed implementation of powerful and efficient control methods for efficient and high energy density electric motors, such as the asynchronous motor [1]. The evolution of chargeable batteries was also substantial. The modern alkaline-based batteries can withstand 4000 charge-discharge cycles or even more, and hold power of thousands W/kg [2, 4, 5, 6]. As result, now there are trolleybuses that can drive over 60 km outside the grid lines [3].

"Informbusiness" company team decided to develop a system for trolleybuses with autonomous power source to allow electric public transport a higher mobility inside and outside a town. Such a possibility will allow trolleybuses to reach further without the need to implement complete infrastructure.

The aim of this paper is to research the energy consumption of a trolleybus during a full day functioning, and determine and implement the appropriate chargeable batteries for a working system. For the data collection was used a trolleybus type VMZ-5298 (fig.1), with an 180kW asynchronous traction motor TAD-3 and electronic control system series SDMC-103-03 (fig.2).

Fig. 1. VMZ-5298 trolleybus.

Fig. 2 SDMC-103-03 electronic control system.

II. Research of Trolleybus' Energy Consumption

To start the research in choosing the power of batteries that need to be implemented in a trolleybus, data on energy consumption of the traction system was collected on a trolleybus during a workday. Besides the traction system, a trolleybus has many low voltage devices that consume energy. Devices such as heaters, lights, compressors and hydraulic systems must also be taken into consideration when calculating the necessary battery power.

The data (tab.1) was measured on trolleybus route №7 in Chisinau. The length of one lap in this route is 16,7 km. The trolleybus, on which this data was taken, is the upper mentioned VMZ-5298. This trolleybus is driven by a 180 kW asynchronous motor and electronic control system with vector control, the SDMC-103-03.

The possibility of regenerative braking provided by the control system raises significantly the overall efficiency of the trolleybus. From 323 kWh taken from the supply grid during 10 and a half hours; almost 100 kWh was recovered with regenerative brakes. The SDMC-103-03 raises the efficiency of the trolleybus with an average 30%.

The data shown in tab.1 depicts the nonlinearity of the energy consumption rated to load and duration of the route. The main reason for that is the human factor; the driver may act differently on the same route depending on situation.

For further research, we took the data of energy consumption gathered by RTEC, from a ZIU-9 trolleybus. One of the oldest and least energy efficient trolleys available in Chisinau (tab.2).

TABEL I. Energy consumption of electrical devices in a trolley at maximum load

Symbol	Index	Value
$Ec_{traction}$	Traction system, kW*h/km	1.33
P_{comp}	Compressor, kW	1
P_{hyd}	Hydraulic booster, kW	2
P_{heat}	Heaters, kW	20
P_{light}	Lightning, headlights, kW	0.2
V	Average speed, km/h	25
S	Length of route without grid lines, km	10
E_{summer}	Energy consumption in summer, kW*h	29.1
E_{winter}	Energy consumption in winter, kW*h	45.2

Total energy consumption for seasons was calculated from the energy consumption of the traction system, compressor of the pneumatic brakes, hydraulic steering booster, heaters (in wintertime), the lights inside and headlights. The calculated energy value is for a 10 km long route outside the grid lines, travelled at 25km/h.

The compressor and hydraulic booster work nonstop, so their energy consumption depends on the time spent on travelling the route.

The heaters are taking into consideration only in wintertime, in same amount as the compressor and hydraulic system.

TABEL II. Energy consumption of the trolleybus' traction system during a work day

Lap	Time	Duration, min	Consumption, kWh		Regenerative Braking, kWh		Load, % of max
			Counter	One lap	Counter	One lap	
1	7:24-8:25	61	27.7	27.7	8.5	8.5	70
2	8:25-9:20	55	54.5	26.8	17.3	8.8	80
3	9:20-10:14	56	79.5	25	25.4	8.1	80
	Break			0			
4	11:10-12:03	53	104.6	25.1	32.8	7.4	60
5	12:03-12:58	55	130.5	25.9	40.9	8.1	50
6	12:58-14:01	63	164.7	34.2	47.2	6.3	50
7	14:01-15:06	65	187.1	22.4	59.5	12.3	90
	Break			0			
8	15:47-16:45		211.4	24.3	67.6	8.1	60
9	16:45-18:06	81	237.2	25.8	75.9	8.3	80
10	18:06-18:55	49	264.8	27.6	85.2	9.3	80
11	18:55-19:40	45	288.8	24	92.6	7.4	70
12	19:40-20:30	50	312.2	23.4	98.9	6.3	20
	Parking						
	Total	633	323	-	99.5	=	223.5

In the winter the headlights must be on the entire time, if the vehicle is moving, without consideration to time of day. In the summer, the lights work for an average of 4 hours per day: in the evening and in the morning. It is calculated for the situation when the it is dark and the lights function for the whole time the trolley is away from supply lines.

$$E_{summer} = Ec_{traction} \cdot S + (\mathrm{P}_{hyd} + \mathrm{P}_{comp} + \mathrm{P}_{light}) \cdot \frac{S}{v} \quad (1)$$

$$E_{winter} = Ec_{traction} \cdot S + (\mathrm{P}_{hyd} + \mathrm{P}_{comp} + \mathrm{P}_{light} + \mathrm{P}_{heat}) \cdot \frac{S}{v} \quad (2)$$

III. Battery Choice and Development of Electric System

Having an estimated energy value, which the trolleybus needs for a 10 km range autonomous drive, we can look for the suitable rechargeable battery and develop a supply system.

The main criteria by which the battery chemistry is chosen are [2,4,5,6]:

- Energy density (Wh/kg, Wh/l)
- Power density (W/kg)
- Voltage
- Power requirements and duration
- Cycle life
- Temperature (and management)
- Self discharge
- Maintenance
- Safety
- Cost
- Physical dimensions
- Charger characteristics and requirements
- Environmental (& recycling)
- Reliability

It is very important that in automotive applications the batteries have high power and energy density. The trolleybuses need higher power to operate than regular vehicles. The graph in fig.3 [4] shows the high power Li-Ion batteries to be most suitable for autonomous electric public transport.

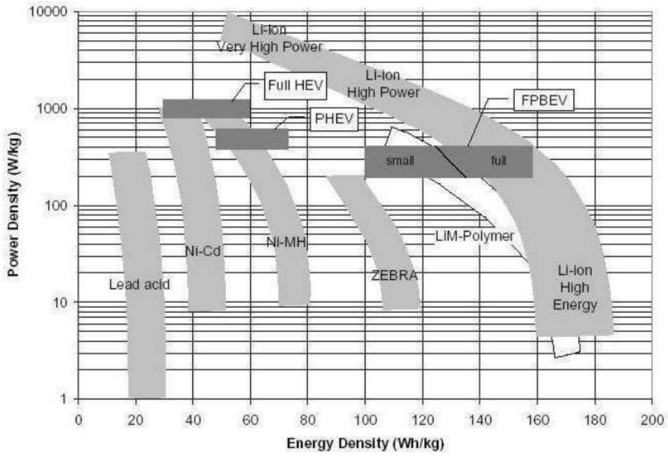

Fig. 3 Power and energy density of existing rechargeable batteries.

TABEL III. Tab.3 Li-Ion battery types specifications

Specifications	$LiCoO_2$	$LiMn_2O_4$	$LiFePO_4$	$LiNiMnCoO_2$
Voltage	3.60V	3.80V	3.30V	3.60/3.70 V
Charge limit	4.20V	4.20V	3.60V	4.20V
Cycle life	500–1,000	500–1,000	1,000–2,000	1,000–2,000
Operating temperature	Average	Average	Good	Good
Specific energy	150–190Wh/kg	100–135Wh/kg	90–120Wh/kg	140-180Wh/kg
Charging rate (C-Rate)	1C	10C, 40C pulse	35C continuous	10C
Thermal runaway	150°C (302°F)	250°C (482°F)	270°C (518°F)	210°C (410°F)
Cost	Raw material high (cobalt)	Raw materials moderate	Manufacturing cost high	Raw materials moderate
In use since	1994	1996	1999	2003
Notes	Very high specific energy, limited power; cell phones, laptops	High power, good to high specific energy; power tools, medical, EVs	High power, average specific energy, safest lithium-based battery	Very high specific energy, high power; tools, medical, EVs

Considering the characteristics of Li-Ion rechargeable batteries, the $LiFePO_4$ (LFP) based one seems to be most suitable. It has higher power to cost ratio, good energy density, a long life cycle, and is the safest. High charging rate also makes the LFP battery standout. Safety is one of the highest priorities when dealing with passenger safety, especially considering the power at which they will be operating.

Ultimately, any high power application requires building a battery source consisted of multiple single battery cells (fig.4).

Moreover, to have a long life power source, all the batteries must be controlled to have an equal state of charge, otherwise the life of a single battery deters much faster than the other ones. That is the reason for every battery cell to have its' own charging monitor circuit (fig.5) and an overall balancing system (fig.6) [7, 8].

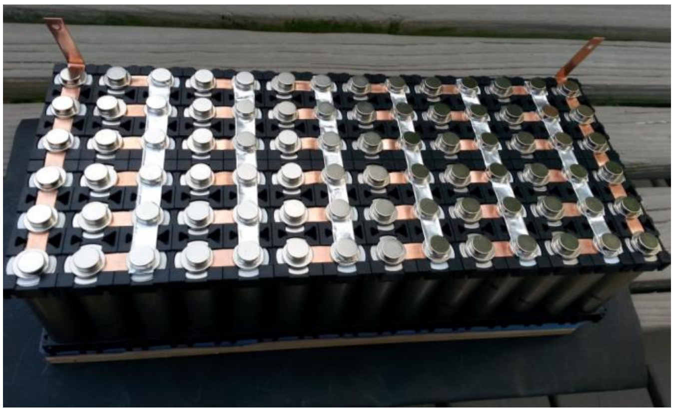

Fig. 4. Battery cells connected to form a system.

Fig. 5. Battery monitorfing system (BMS).

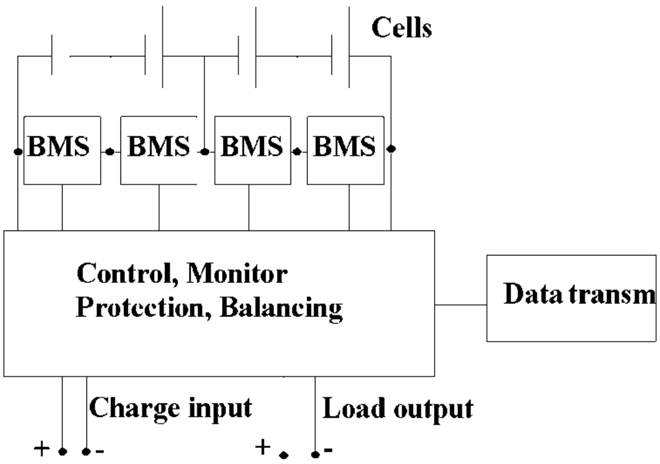

Fig. 6. Cell charge balancing system diagram.

In order to attain the necessary 550VDC, we must use multiple LFP battery cells. One cell works best at 3.3 -3.6V, so about 160 cells should be enough for making the closest replace to standard gridline power source. As the market presents itself [8], one can find a big range of battery power, including 100 Ah. 100 Ah multiplied by 160 and by rated 3.3V gives 52.8kWh. If we relate to the calculations in tab.2, we can see that it is enough to travel 20km without supply lines even in wintertime.

Having all the information, it is possible now to start developing a traction system with autonomous power source. We will continue developing the electric drive system for traction with asynchronous motor and electronic equipment series SDMC-103-03, according to shown on fig.7 structure.

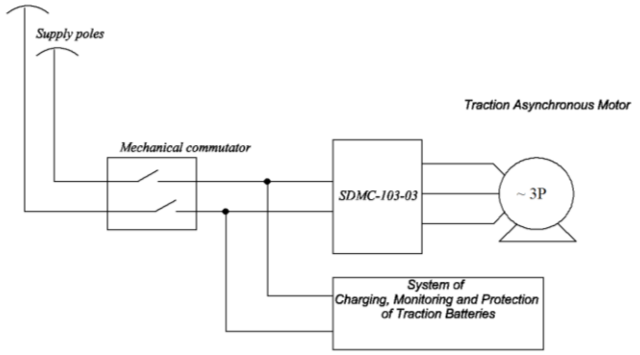

Fig. 7. Power system with autonomous power source for traction with asynchronous motor.

IV. Conclusions

The growth of prices on fossil fuel and degrading state of environment make the public electric transport to stand out as solution to many problems.

Now that modern technology allows it, trolleybuses with autonomous power source and electric buses are becoming a part of solution in electric public transportation.

Concluding from upper-mentioned research and arguments the "Informbusiness" company team is ready to design a system of electronic equipment for trolleybuses with autonomous power source. Once tested and implemented on a larger scale, trolleybuses with autonomous power source can help expanding the network of public transportation without the previously necessary infrastructure.

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