MOBILITY & VEHICLE
MECHANICS

https://doi.org/10.24874/mvm.2024.50.03.03
UDC: 621.01 (656.132+62.83):574+629.07)

PERFORMANCES OF FAST CHARGERS FOR ELECTRIC BUSES IN BELGRADE ON THE EKO2 LINE

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Received in August 2024 *Accepted in September 2024*

RESEARCH ARTICLE

ABSTRACT: The performance of the electric bus charging system is an important aspect of electric bus operation. The correct choice of power and number of chargers on the line is essential to optimize the time required to charge or top up the battery/supercapacitor, to achieve the planned transport volume. The paper will present an analysis of the operation of fast chargers, power 400 kW, from the aspect of the time required to charge and transfer the amount of electricity to the E-bus, which is achieved under regular operating conditions, during regular waiting at the terminals, on the EKO2 line in Belgrade, which was put into operation on January 24, 2022, on which 8 E-buses are in traffic.

KEY WORDS: *Performance of Chargers, Electric bus, Time of charge, EKO2 line*

PERFORMANSE BRZIH PUNJAČA ZA ELEKTRIČNE AUTOBUSE U BEOGRADU NA LINIJI EKO2

REZIME: Učinak sistema za punjenje električnog autobusa je važan aspekt rada električnog autobusa. Pravilan izbor snage i broja punjača na liniji je od suštinskog značaja za optimizaciju vremena potrebnog za punjenje ili dopunjavanje baterije/superkondenzatora, kako bi se postigao planirani obim transporta. U radu će biti prikazana analiza rada brzih punjača, snage 400 kV, sa aspekta vremena potrebnog za punjenje i prenos količine električne energije u E-bus, što se postiže u redovnim uslovima rada, pri redovnom čekanju na terminalima, na liniji EKO2 u Beogradu, koja je puštena u rad 24. januara 2022. godine, na kojoj saobraća 8 E-buseva.

KLJUČNE REČI: *Performanse punjača, električni autobus, vreme punjenja, EKO2 linija*

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Slobodan Mišanović

INTRODUCTION

Charging batteries or supercapacitors with electricity is an important aspect of the operation and organization of the bus with an electric drive. In practice, three basic strategies are used:

- Slow charging using a "plug-in" connector;
- Fast charging using a pantograph;
- Contactless charging.

The choice of electric bus charging system is determined by the type and size of the battery or supercapacitor, the requirements regarding the duration of charging, timetable and commercial speed, route lengths, kilometres operated per bus per day, the available energy capabilities of the electrical network, economics of AC versus DC charging, and the space provided for charging [1]. The most commonly applicable ways of charging electric buses are presented in Table 1 [2].

Table 1 E-bus charging method

Charging	**Charging in garage**	**Charging at the terminus**		**Charging on the line**	
		once	**both**	**In the stations**	**Dynamically (Wi-Fi)**
Slow charging	yes	-	-	-	-
Fast charging	yes	yes	yes	yes	-
Combined, (Slow and Fast)	yes	yes	yes		
Contactless	yes	yes	yes	yes	yes

In practice, slow and fast charging strategies in garages or at terminals are currently the most prevalent, while contactless charging is less common in practice. Slow charging is used exclusively for E-buses with batteries. With this concept, bus charging is performed when the vehicle is not in operation, which is often during the night period, which is why it is usually called night charging. Electric buses with a standard length of 12 m, which are charged in this way, have batteries with a large capacity of 300÷500 kWh, which enables them to have a significant daily autonomy of movement, which can be over 250 km. The power of the slow charging charger installed in the garage is usually 60÷250 kW [3] (Figure 1), so the charging process lasts between 2.5 and 4 hours depending on the degree of battery discharge, capacity, and charging power. Table 2 presents the expected electrical losses that occur in the slow charging process of the E-buses from the charging source to the drive motor [4].

Table 2 Electrical losses in the charging process with "slow" charging

System component	Efficiency coefficient (η)
Charger	0.95
Battery charging (battery internal resistance)	0.95
Battery discharge (battery internal resistance and cable losses)	0.93
Inverter	0.97
Electric motor	0.95
Total for the whole system	0.77

Figure 1 Slow charging, charger "Winline" (2x125 kW) [3]

One of the problems in the application of this charging concept is that if several buses are charged at the same time during the night or the day, they occupy a large working space in the depot and engage a large amount of power from the public distribution network at the same time. For the operation of a large number of electrically powered buses with this concept, significant investments are needed in the adaptation or construction of charging areas and chargers [3].

Fast charging of electrically powered buses can be done at stations along the route of the line or, more often, at the start/end stations (terminus) on the line where the E-bus is in operation, as well as at the depot where the vehicle parks and prepares for the next day. Electric buses with a standard length of 12m, with this charging concept, have lithium-titanium batteries (LTO) with a capacity of 60÷90 kWh [5] or a supercapacitor with a capacity of 20÷40 kWh [6]. Compared to electric buses with slow charging, this type of E-bus has limited autonomy, so they are used on predefined lines, where chargers are installed most often at the terminus so that the vehicle is recharged during the planned stay at the starting station.

Charging is done through a pantograph installed on the roof of the bus, which is activated at the place intended for charging. The average charging time is 3÷10 minutes and is performed after every completed half revolution (one direction), revolution (both directions), or more revolutions, depending on the capacity of batteries or supercapacitors, operating conditions, and power of the fast charging system. The power of the fast charging system installed at the terminus is usually 150÷600 kW [7,8,9]. Fast charging of electric buses is often called opportunity charging, given that depending on the battery capacity and operating conditions, the battery discharge can be of different intensity, so the optimal moment of battery charging is determined in this way, which is most often determined by SOC (State of charge) value between 30÷40%. Recharging this type of E-bus in the garage can be done via a pantograph (fast charging) or the vehicle is equipped with a plug-in connector for slow charging. In this way, there is a combined charging of the vehicle. Table 3 presents the expected electrical losses occurring in the fast charging process via the E-bus pantograph, which uses a supercapacitor as an electrical energy storage system, viewed from the charging source to the drive motor [10].

Table 3 Electrical losses in the charging process with "fast" charging

System component	Efficiency coefficient (η)
Charger+pantogarf	0.95
Internal resistance UC and cable losses	0.97-0.98
Inverter	0.97
Electric motor	0.95
Total for the whole system	0.85

Figure 2 Fast charging,Charger, "Gemamex" (400 kW)

Compared to the slow charging system, in the case of fast charging using a pantograph, there is a smaller loss of electricity from the charging source to the drive electric motor. Charging of electric buses can also be done in a non-contact way, which is based on the principle of electric energy transfer using magnetic induction. The primary windings are embedded in the substrate, most often at the terminus. The secondary windings are installed on the E-bus (Figure 3) [11].

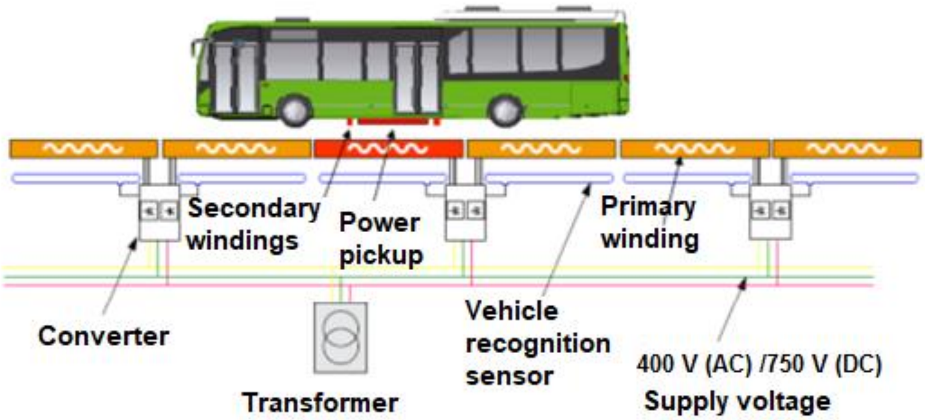

Figure 3 Contactless charging E-bus

Upon encountering the E-bus on the base where the primary is placed, the sensors recognize the E-bus, after which it is possible to turn on the system and contactless transmission of electricity, i.e. charging the battery on the vehicle. This process lasts 5÷8 minutes depending on the capacity of the battery and the power of the charger, which is 400÷600 kW. With this charging system, there is a greater loss of electrical energy from the charging source to the drive electric motor, given the greater number of components that make up the charging system. Further development of fast charging technology for electric-powered buses will lead to the development of technology for charging vehicles in motion, which will enable the E-bus to charge the battery or supercapacitor in the zone of certain stations via a wireless network (Connection). The world's leading manufacturers of electric bus charging systems are Siemens, ABB, Shunk, Jema Energy, Ekoenergetyka.

1 CITY LINE EKO 2

City line EKO2 (Sports Center M.G. Muskatirovic-Belgrade Waterfront) was put into operation on January 24, 2022. After the introduction of the EKO 1 line in 2016, it represents the continuation of the introduction of electric-powered buses into the Belgrade public transport system. The average length of the line is 7.1 km. There are 15 stations in direction "A" and 16 stations in direction "B". The average inter-station distance is 450 m. The line according to its spatial position is a diametrical line that connects parts of the city with a high degree of attraction: Kalemegdan, Trg Republike, Terazije, Trg Slavija, Nemanjina Street, Belgrade Waterfront (Figure 4). There are 10 electrically powered buses 12 m long, manufactured by Higer, KLQ6125GEV3 (Figure 5), which use a supercapacitor with a capacity of 40 kWh as an electrical energy storage system. Charging the E-bus is done using a mobile pantograph that is placed on the roof of the vehicle. The technical characteristics of E-bus Higer KLQ6125GEV3 are shown in Table 4 [10].

Figure 4 Line EKO2 in Belgrade

Figure 5 Higer KLQ6125GEV3

Table 4 Technical characteristics, Higer KLQ6125GEV3 [10].

	Higer KLQ6125GEV3, Production 2021
Length/width/height	12000/2550/3680 mm
Curb weight	12190 kg
Passengers	90+1
Doors	3
Max.speed	70 km/h
Ultrarcapacitor	AOWEI 40 kWh
Charging time	Max 5 minutes
Traction motors	1DB2016 6NBO6, permanent magnet
Power	160 kW/230kW
Max. Torque	2500 Nm
Inverter	DC/AC 600-720 V
Traction control	Siemens ELFA 3

2 FAST CHARGING INFRASTRUCTURE ON THE EKO 2 LINE

When defining the new EKO2 line in Belgrade, a necessary condition was the possibility of installing fast chargers at the terminus of the Sports Center- Milan G. "Muskatirovic" (Figure 6) and "Belgrade Waterfront" (Figure 7). At both terminals, there are two 400 kW AC/DC fast chargers, which are powered by 2 MW transformer stations, which are located near the chargers.

Figure 6 Fast chargers, 2x400 kW, terminus Sports Center

Figure 7 Fast chargers, 2x400 kW, terminus Belgrade Waterfront

Table 5 Technical characteristics of chargers

Producer	Gemamex
Input Voltage AC	3X380 V
Max. Power	400 kW
Max. Output current, DC	500 A
Max.Output Voltage, DC	750 V
Charger efficiency	97%
Pylon Height	4.5-4.6 m
Trafo, AC	Dalcom, 2 MW

Given that there are two fast chargers and charging points at each terminus, it is planned that these terminuses will be used in the future for new lines on which electric buses will operate, since one charger at each terminus is sufficient for the EKO2 line.

3 THE METHODOLOGY OF DATA ACQUISITION

Data acquisition to analyse the performance of fast chargers on the EKO2 line was carried out during the charging process at the terminal by collecting data via the S-CAN network of the E-bus using a LAPTOP computer or using the CARMON-ABRITES application for real-time data collection.

Figure 8 Data acquisition using a laptop computer

Figure 9 Current values of voltage and current on the supercapacitor in real-time on the EKO2 line

Downloaded data: current (A), voltage (V), and state of charging of supercapacitor SOC (%) are exported to an EXCEL file, with a base frequency of 0.25 s. It should be noted that electric buses on the EKO2 line are charged with electricity after each turn on the line (Direction "A"+direction "B"), where the vehicles run about 14.2 km. On several measurements, data acquisition was performed even after completing one-half turn, i.e. after running in one direction.

4 RESULTS OF THE DATA PROCESSING AND DISCUSION

Figure 8 presents a graphic representation of the downloaded data at the "Belgrade Waterfront" terminus, on February 10, 2023, in the period from 07:09:47 to 07:14:15 [12].

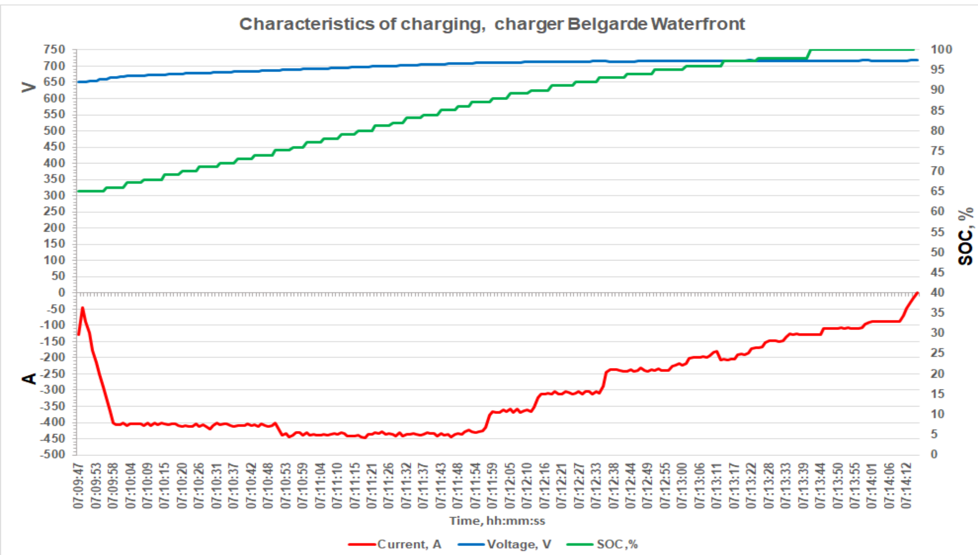

Figure 10 Current values of charging current (A), voltage (V) and SOC (%) on the E-bus supercapacitor

For the given example, in the period of charging, which was 04:28, 15.875 kWh of electrical energy was taken from the charger to the supercapacitor. The charging phase begins with the activation of the mobile pantograph located on the roof of the vehicle and its connection with the contact conductors of the charger located on the supporting pylon. After that, the interface connection is established and this phase lasts about 5÷10 seconds on average. After that, the filling phase begins. The current strength of the DC charging current (A) that charges the supercapacitor is regulated depending on the voltage reached on the supercapacitor. It can be seen from the Figure 10 that in the initial phase of charging, the instantaneous current reaches maximum values in the range of 400÷451 A, at voltage values of 650÷700 V. When the voltage on the supercapacitor reaches the value of 700 V, there is a rapid drop in the instantaneous charging current, so that for the value of the reached voltage of 720 V, the current value of charging is about 80 A, which reaches the charge of the supercapacitor of 100%, and the completion of the charging phase by the automatic disconnection of the charger and the pantograph of the vehicle. The maximum charging current was 451 A, the maximum charging power was 314.6 kW, the minimum power at the beginning of charging was 29.9 kW, and the average charging power during the entire phase was 212.3 kW. At the start of charging, the current charge level of the supercapacitor was 65.2% and the voltage value was 650 V. At the end of charging, a voltage of 720 V was reached, i.e. the charge level of the supercapacitor was 100%. To see as realistically as possible the performance of the fast chargers on the EKO2 line at the terminals "Belgrade Waterfront" (BW) and "Sports Center Milan G. Muskatirovic" (SC), data acquisition was performed during the filling process on a sample of 19 measurements. After processing the collected data, the performance of the charger is shown in Table 6 [12].

Table 6 Performance of chargers on the EKO2 line in Belgrade

Charger, location	Date	Start of charging (hh:mm:ss)	End of charging (hh:mm:ss)	Duration of charging (mm:ss)	Duration of charging (ss)	Energy taken (kWh)	Average charge power (kW)	SOC start (%)	SOC end (%)
BW	19.9.2022	08:28:22	08:31:39	03:17	197	11.690	212.55	73.2	100
BW	19.9.2022	05:48:40	05:52:05	03:25	205	11.153	194	74	100
BW	19.9.2022	07:11:28	07:15:05	03:37	217	12.506	206.52	72	100
BW	10.2.2023	05:49:08	05:54:02	04:54	294	19.897	242.68	56	100
BW	10.2.2023	07:09:47	07:14:15	04:28	268	15.875	212.30	65.2	100
SC	27.2.2023	06:30:35	06:35:08	04:33	273	13.650	199.01	67.2	100
BW	27.2.2023	05:54:34	05:59:32	04:58	298	17.461	210.9	59.2	98
BW	6.3.2023	23:18:06	23:23:34	05:28	328	21.237	228.3	54	100
SC	6.3.2023	11:49:36	11:51:53	02:17	137	6.722	174.77	85.2	100
SC	6.3.2023	06:29:20	06:33:16	03:56	236	12.268	185.77	73.2	100
SC	7.3.2023	18:34:09	18:38:27	04:18	258	18.927	263.01	57	100
SC	8.3.2023	06:30:44	06:33:05	02:21	141	10.020	253.74	74	97
BW	8.3.2023	07:08:28	07:11:40	03:12	192	10.568	204.38	74	98
BW	8.3.2023	16:34:01	16:37:20	03:19	199	15.301	273.35	62	96
BW	8.3.2023	09:47:46	09:51:34	03:48	228	10.533	236.29	65.2	98
SC	9.3.2023	17:24:11	17:28:06	03:55	235	18.244	278.54	57.2	100
SC	11.4.2023	17:14:17	17:15:58	01:41	101	7.229	254.59	81.2	97.2
BW	11.4.2023	16:34:13	16:35:20	01:07	67	4.107	217.28	86	95.4
BW	20.4.2023	11:14:12	11:16:49	02:37	157	11.582	264.5	69.2	95.2
Average value				**03:35**	**215**	**13.10**	**226.97**		

After processing the downloaded data, it follows that the mean time of charging the E-bus at the terminus is 03:35 (3 minutes and 35 seconds), while the mean value of the electricity with which the supercapacitor is charged is 13.10 kWh. The average charging power is

226.97 kW. The amount of electricity with which the supercapacitor will be charged (recharged) during the charging phase depends on its discharge, which is directly related to the total electricity consumption of the E-bus during operation on the line and the charging time.

The most significant influencing factor on the total electricity consumption of the E-bus is the use of the passenger and driver space heating system during the winter period of operation and the use of the passenger and driver space cooling system during the summer period of operation. From Table 6, it can be seen that the highest value of supercapacitor charging energy via the fast charger at the Belgrade Waterfront terminus was 21.237 kWh (March 6, 2022) and 19,897 kWh (February 10, 2022) during the winter period of operation.

If the electrical energy of charging is analysed as a function of the achieved charging time, a significant correlation dependence of these two quantities is reached, as shown in Figure 9 [12].

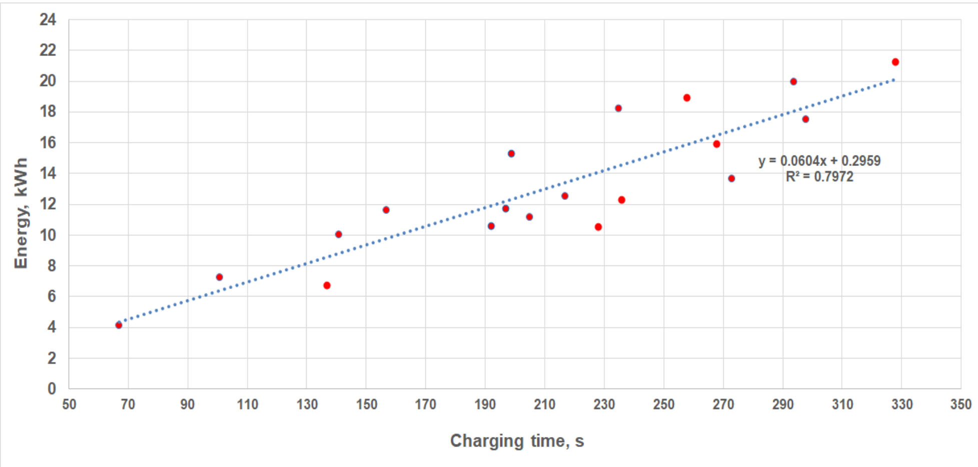

Figure 11 Dependence of charging energy and charging time on chargers, line EKO 2

The correlation dependence between charging energy and charging time has a significant linear dependence where the coefficient of dependence is R^2=0.797. Knowledge of the aforementioned charger performance, above all the dependence on the charging energy and the required charging time, is significant from the point of view of the organization of the operation of electric buses on the EKO2 line to optimize the waiting and charging time at the terminus. Considering that the prescribed time for the bus to stay at the terminus when changing the direction of movement is 5 minutes, it follows that it is optimal that the time of refuelling the vehicle via the charger should be within the stipulated time of staying at the terminus, i.e. under 5 minutes.

From the examples in Table 6, it is proven that the specified criterion is fulfilled, which practically means that from the point of view of the organization of the work of vehicles on the EKO2 line, it is recommended that the E-bus be topped up after each turn at one of the terminuses. Recharging the E-bus after driving in one direction (half a turn) is not recommended, considering that the capacity of the supercapacitor is 40 kWh and that its discharge, in that case, is relatively small and also decreases without the necessary activation of the movable pantograph mechanism located on the roof of the vehicle. In the case of E-bus operation, if 2 turns were made, the charging time would be between 7 and 8 minutes, which is more than the prescribed 5 minutes of staying at the terminus and would have an impact on the realization of the planned timetable.

5 CONCLUSION

The performance of fast chargers for electric buses represents an important segment of the planning, organization, and exploitation of the operation of vehicles on the line. The correct choice of the number and power of fast chargers results from the available possibility of connecting to a transformer station the expected consumption of electric energy of the E-bus on the selected line and the number of vehicles in operation. The best case is that the required charging time is less than 5 minutes, based on which the strategy of charging vehicles at the terminus can be defined, i.e. whether charging will be performed after each realized direction of movement, one or two half-turns. Based on the charging time, the amount of electricity that will be stored in the supercapacitor via the fast charger can be predicted.

The analysis of the performance of fast chargers on the EKO2 line in Belgrade proves that they meet the set criteria in terms of the time required for charging and the transfer of the amount of electricity that is achieved during the charging phase between the distribution network, the charger and the supercapacitor of the vehicle. The chosen strategy of charging the E-bus after each completed turn is justified, given that the charging time is under 5 minutes, which guarantees the realization of the planned bus schedule on the line.

6 CONCLUSIONS

During the 1600-hour UV aging process, we conducted mechanical tests on samples taken at various time intervals. Our goal was to assess how resistant each compound is to UV radiation and to what extent they change. Samples I and III were the most sensitive to UV radiation, while Samples II and IV were less affected. We recommend further development of the formulation used in Samples II and IV for the windshield sealing material.

Overall, this study demonstrates the varying levels of UV resistance among the tested rubber compounds. By identifying the compounds that show greater resilience, manufacturers can focus on optimizing these formulations for enhanced durability in real-world applications. The findings also highlight the importance of continuous testing and material development to ensure the longevity of rubber materials exposed to UV radiation in transportation settings.

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