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PROTOTYPE OF ELECTRIC BUS OF AMZ KUTNO

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Abstract

The article discusses the prototype bus AMZ Kutno electrically driven. The aim of the project prototype electric powered bus was appointed a consortium consisting of AMZ Kutno and Department of Vehicles and Fundamentals of Mechanical Engineering of Technical University of Lodz. As a subcontractor prototype solutions involved: for battery power BMZ Gliwice, and for the control system ENIKA Lodz. The prototype bus with complete drive system is an entirely polish construction. The paper presents assumptions for the construction of a prototype electric drive system. It describes the criteria for the selection of the engine. Was analysed the available parameters of electric motors. Adopted electric motor is discussed in detail in terms of its performance characteristics. Required performance characteristics of electric motor shown in figure. The considerations taken into account and the aspect of the selection of the inverter and the microprocessor control system control the amount of energy in batteries and supercapacitors, depending on the instantaneous energy demand and the expected driving performance. Was compared the parameters of available batteries and set them the necessary capacity. It has been specified parameters of adopted battery pack. Was described the role and selection of supercapacitors in energy recuperation system provided. The assumptions were supported by the necessary calculations.

Keywords: *electric bus, electric drive system, electric motor, inverter, microprocessor control system, pack of batteries, batteries management system, supercapacitor, energy recuperation system*

1. Introduction

The share of transport in the broad sense of global CO2 emissions to the atmosphere is approximately 14% of total emissions. Road transport is responsible for around 70% of emissions. These values are in relation to the EU countries are respectively 28% and 71% [5]. However, CO2 emissions and greenhouse gases emitted into the atmosphere by transport, compared with emissions of these gases by industry does not seem to be so significant, that government programs to reduce CO2 emissions by 2025 for passenger cars, impose important requirements is the automotive industry (Fig. 1.).

According to the estimates of the European Commission savings by reducing fuel consumption, will be higher than the cost of CO_2 reduction to the assumed level of approximately 95 g / km [6]. Of course, these restrictions will also apply to trucks and buses. At the same, time the highly urbanized areas of the city, now there is a need to reduce noise and emissions of waste gas. For this reason, vehicles employing a growing interest in alternative sources of supply. For vehicles of this type are both hybrid cars and electric powered.

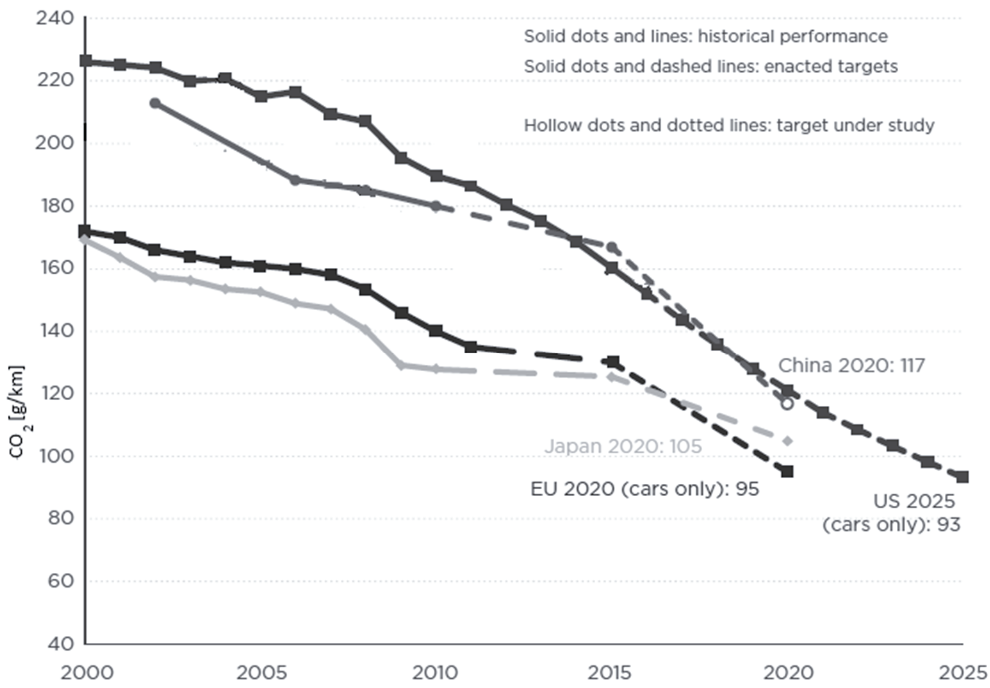

Fig. 1. Government programs to reduce CO2 emissions by 2025 [6]

2. A prototype electric bus of AMZ Kutno

The aim of the project prototype electric powered bus was appointed a consortium consisting of AMZ Kutno and Department of Vehicles and Fundamentals of Mechanical Engineering of Technical University of Lodz. As a subcontractor prototype solutions involved: for battery power BMZ Gliwice, and for the control system ENIKA Lodz. The prototype bus with complete drive system is an entirely polish construction.

For the proposed bus adopted:

- electric drive,
- total mass m_c = 18 000 [kg],
- its own mass m_w = 11 500 [kg],
- dimensions (H x W x D) 3250x2400x8950 [mm],
- expected range S = 250 – 350 [km],
- speed v = 50 [km/h] = 13.9 [m/s].

3. The drive system

From the characteristics of an electric motor that, with proper control, it is possible to produce a full torque starting from the zero speed. This solution allows you to reduce the number of mechanical components such as the clutch and gearbox, which results in lower vehicle weight and a real cost reduction. The electric motor drives the wheels of the vehicle through the fixed ratio main gear and differential. The need to be fitted to the vehicle a battery, eliminate the previously obtained weight reduction.

Mass of prototype electric vehicles with heavy batteries, should not exceed the weight of the vehicle with conventional drive, at a comparable range of both vehicles. Block diagram of the electric power train with respect to the other elements shown in Fig. 2.

In order to ensure the recovery of braking energy in the system, the use of supercapacitors was done. The complete drive system includes motor / generator, energy storage (batteries and supercapacitors) system, power electronics (inverter) and microprocessor control system.

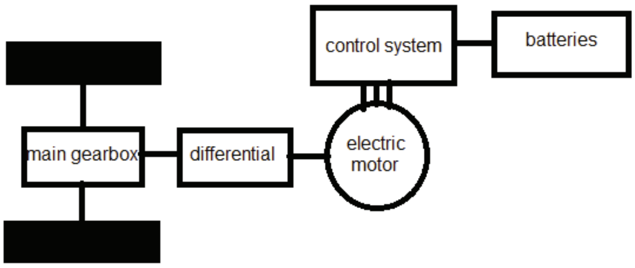

Fig. 2. Block diagram of the electric drive bus

4. Electric motor

The required engine power was based on (1):

$$N_{max} = (W_t + W_p + W_w) \times v = 165.8 \text{ [kW]}, \tag{1}$$

where:
W_t – motion resistance – 1765.8 [N],
W_p – air resistance – 931 [N],
W_w – slope resistance (for a 3% slope) – 9235.1 [N],
v – max speed of the vehicle –13.9 [m/s].

Due to the inclusion in the calculation of the resistance of the hill was the engine of 165 kW has considerable excess capacity. For this reason, further considerations are omitted power demand of 10 kW to supply additional bus system (compressor, power steering pump, heater).

The required power needed just to overcome resistance to motion will be:

$$N_r = (W_t + W_p) \times v = 37.5 \text{ [kW]}. \tag{2}$$

A maximum engine speed determined from the equation (3):

$$n_{max} = \frac{v30i_g}{r_k\pi} = 1690 \text{ [rpm]}, \tag{3}$$

where:
i_g – main gear ratio – 6.3,
r_k – radius of the wheels of the vehicle – 0.495 [m].

This justifies the choice of engine with low speeds.

The maximum motor torque should be less than the instantaneous torque resulting from the force of adhesion between the wheel and the ground. Assuming the adhesion coefficient μ = 0.8 and the strength of the rear axle as 70% of the total weight of the bus (180,000 N) obtained:

$$P_\mu = 0.7 \text{x} 180000 = 126000 \text{ [N]}. \tag{4}$$

Thus, maximum torque:

$$M_\mu = P_\mu \frac{r_k}{i_g} = 8047 \text{ [Nm]}. \tag{5}$$

Given the predicted friction was considered applicable engines:

– asynchronous motor ENI-ZNAP/TB/165 – cage, 400 V, three-phase, 165 kW, weight 770 kg, fed with frequency converter – speed control range from 0 to 1200 rev/min. , with constant torque 1400 Nm and from 1200 to 3100 rev/min at constant power, cooling realized by own fan mounted on the motor shaft , rated current 293 A,
– engine STDa250-4B, cage, 400V, three-phase, 125 kW, weight 475 kg, rated torque of 622 Nm, rated speed 1918 rev/min., rated current 219 A, the overload factor 3,

LSM280 motor, synchronous permanent magnet (PMSM), 600 V, 155 kW, weight 350 kg, speed control range from 0 to 1200 rev/min. at constant torque 1400 Nm and from 1200 to 3250 rev / min at constant power, the overload factor of 1.9.

The considerations were taken into account engine type BLDC (brushless DC motor).

However, due to the availability of this type of engine with high power, its price and the high cost of the control system, abandoned this solution. In addition, it is considered that [2]:

– knowledge of these engines is as yet limited,
– common solutions are mainly low-power systems ,
– high speed BLDC motor would cause the need for additional gear in order to reduce them.

Engines ENI-ZNAP/TB/165 and STDa250 -4B is a proven asynchronous traction drives. Unfortunately, there may not be regarded as a more modern construction.

In turn, the motor PMSM motors are characterized by [8]:

– highest efficiency of all types of electric motors,
– maximum attainable current ratios of the rated torque and maximum torque to the engine weight,
– high current overload torque.

In addition, allowed to get low ripple torque motor shaft and allow achieving high dynamics and precision of the control drive.

Meanwhile the SLAM 280 motor with maximum torque of 1400 Nm, gives than 5-fold surplus of torque in a typical traffic conditions, which will also retained more than 2-fold reserve at 2 –fold the electric motor overload. Therefore, to drive a prototype electric bus was adopted LSM 280 motor. The operating characteristics of the engine are shown in Fig. 3.

In the first control zone, the motor PMSM is operated at a constant ratio of voltage to frequency, that is, at a constant magnetic flux. Torque on the motor shaft is approximately linearly dependent on the current supply. At constant current, the torque value is also constant.

With speed, n_b voltage value reaches the maximum value. This value is limited by the possibilities of the inverter. In order to maintain the maximum voltage and increase the engine speed, it is necessary to weaken the magnetic flux. In the second regulation zone, assuming that the motor is powered by a constant value, the power is approximately constant [3].

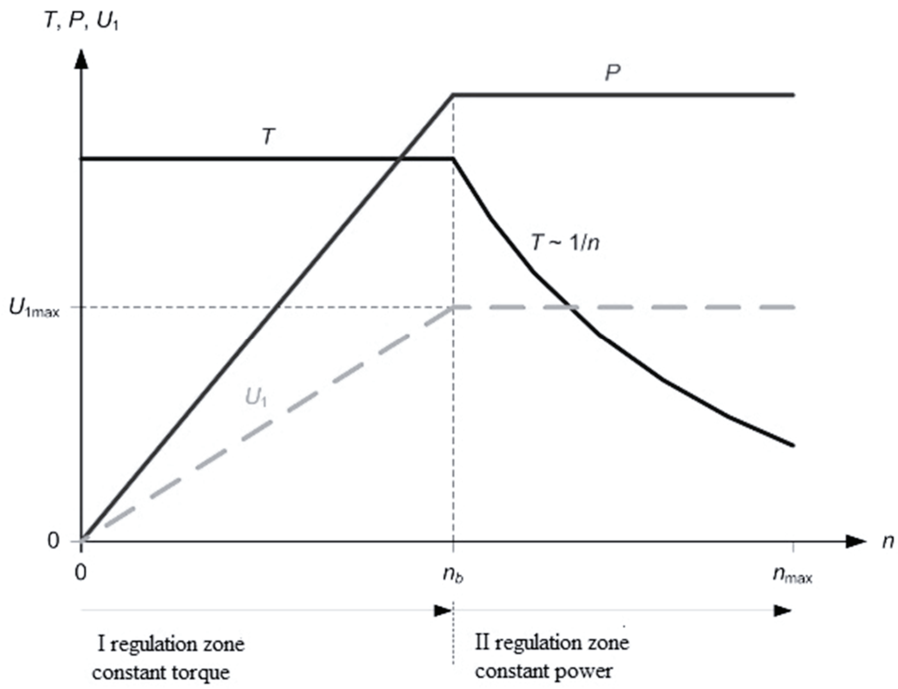

Fig. 3. Operating characteristics of PMSM motor (T – torque, P – power, U_1 – supply voltage, n – rotary speed) [3]

5. The inverter and microprocessor system.

At a speed higher than the rated (zone II regulations) operating point of the engine is limited by the maximum power of the engine and mechanical characteristics is limited hyperbole constant power. The inverter power the engine should be quadrant, it means that the mechanical characteristics of the drive (speed as a function of load torque) should include the four quadrants of the coordinate system. Such work of inverter must ensure the microprocessor control system. Work of engine in the second zone adjustment, Fig. 3, complicated control system due to the increased power consumption. Resignation from high rotation speed range (control zone II) simplifies control, but the effect is that the motor vehicle would be oversized i.e. too big and too heavy. When designing the vehicle to drive typically urban, please note that the vehicle speed is limited by the urban road traffic regulations to 50 km/h. This range should cover the first speed control zone. Therefore, our drive in the second zone of the regulation would be sporadic worked and the balance of the total energy consumption should not play a significant role. Motor with permanent magnets placed inside the rotor has two components synchronous moment: the moment of the magnet and reluctance torque. To take full advantage of these moments must be supplied the algorithm to the converter that allows adjustment of the phase angle indicating the position of the stator current with respect to the magnetic axis of the rotor. Electric motor and inverter form a complete set. The main task of the microprocessor system shown in Fig. 4 is steering of the transistor keys of power electronics system by measuring the current drawn (dotted lines) through the phases of the motor and on the basis of the position of the rotor relative to the stator. Moreover, the microprocessor system controls the amount of energy in batteries and supercapacitors, depending on the momentary demand of the vehicle's kinetic energy, which means that during braking of vehicle or driving down a hill, is possible to recuperation (recovery) of energy.

During braking of the vehicle for a drive system, in a short time will be a large amount of energy delivered to the system. The adoption of this energy from batteries is practically impossible, without affecting their durability. The microprocessor system has the task of directing the energy in the first place to supercapacitors, further limiting the battery charging current to a safe level for their durability. Necessary energy to continue driving of the vehicle should be taken first from supercapacitors, in order to make room for the adoption of energy during the next braking, second from batteries.

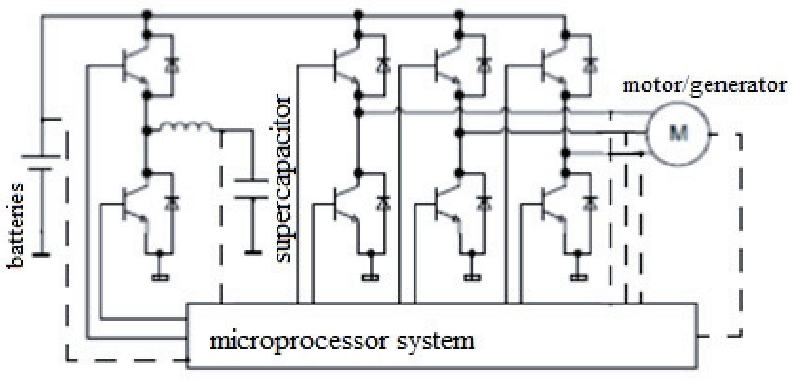

Fig. 4. Mechatronic system of electric vehicle [1]

6. Batteries

The basic problem in the design of electric drive vehicle battery is an appropriate choice. Adverse factors in the case of the battery is low power density, problems with taking large momentary currents, high quality requirements as to the value of the charging current and voltage, large mass and relatively low durability (number of cycles of charging-discharging). For the comparison batteries, data are shown in Tab. 1.

Tab. 1. Comparison of traction batteries (data from the period 2008 – 2010) [4]

	Pb Lead-acid	NiCd Nickel-cadmium	NiMH Nickel-metal hydride	Li-Ion Lithium-ion	Polimer Li-Ion Lithium-polymer
Specific energy [Wh/kg]	45	40-80	60-120	100-200	200
Specific power [W/kg]	212	125-200	220	120-300	350
Nominal cell voltage [V]	2	1.25	1.25	3.6	3.6
Maximum load current	5C	20C	5C	3C	3C
Internal resistance [mΩ]	<100 12V Module	100-200 6V Module	200-300 6V Module	150-250 7.2V Module	200-300 7.2V Module
Operating temperature [ºC]	-20-60	-40-60	-20-60	-20-60	0-60
Fast-charge time [h]	8-16	1	2-4	2-4	2-4
Characteristics of discharge voltage	Heavily sloped	Sloped	Slightly slope	Almost horizontal	Almost horizontal
Cycle life (up to 80% capacity) [cycles]	200-300	1500	300-500	300-500	300-500
The self discharge (1 month in temp 20 ° C) [%]	5%	20%	30%	10%	10%
Duration of service	3-6 months	30-60 days	60-90 days	Not required	Not required
The cost of 1 kWh [$ U.S.]	50-100	430	280	180	90

A comparison of the basic parameters of the batteries used in vehicles, it appears that, rechargeable Li-Ion best meet the current criteria of traction, which is reflected in many prototypes of electric cars. In order to ensure evenly charging and discharging of the battery and because of the need to adopt in a very short time large amounts of energy during recuperation, used advanced control system (BMS-Batteries Management System).

For urban driving cycles based on [7] it's possible to read the amount of energy required to travel 250 km, which amounts to 310-424 kWh/250 km. These data show that, despite the different cycles, urban traffic needs similar energy E_{sr} for the specified section of the road. It should be noted that these results correspond to the dynamics of the cars. For a city bus, received parameters above should be considered excessive, around twice.

The minimum required amount of energy from the battery to the range S = 300 km, vehicle speed v = 50 km/h and a power of 37.5 kW necessary to overcome motion resistance is:

$$E_{ak} = \frac{S}{v} N_r = 225 \text{ [kWh]}. \tag{6}$$

Assuming an axle efficiency $\eta_\mu = 0.95$ and efficiency of the electric motor $\eta_z = 0.9$, the power absorbed by the motor from the batteries will be:

$$N_{ak} = \frac{N_r}{\eta_\mu \eta_z} = 43.8 \text{ [kW]}. \tag{7}$$

Adopted lithium-ion batteries – 180 packets x voltage 3.2 V = 576 V, 400 Ah capacity. The energy stored in the battery is E_{ak} = 576 x 400 = 230.4 kWh permissible laden mass of 2500 kg. For voltage battery pack U, and the power consumed by the motor from the batteries specified by equation (7) the current consumption from the battery is:

$$I_{ak} = \frac{N_r}{U} = 76 \text{ [A]}. \tag{8}$$

Taking into account the battery capacity C = 400Ah, possible vehicle driving time t will be:

$$t = \frac{C}{I_{ak}} = 5.2 \text{ [h]}. \tag{9}$$

An actual coverage of a bus moving at a maximum speed of v = 50 km/h according to the relation (10) reaches the value:

$$S_r = vt = 260 \text{ [km]}. \tag{10}$$

This confirms the validity of the assumptions.

7. Supercapacitors

The advantage of a drive equipped with a supercapacitor is the ability to drive without power from the primary network (battery). Energy stored in the supercapacitor with capacitance C [F] and a voltage U [V] can be determined from the relationship:

$$E_s = \frac{CU^2}{2} [J]. \tag{11}$$

As is apparent from equation (11) the size of the energy stored is dependent on the capacity and voltage. Thus, the same amount of stored energy can be obtained by using one large-capacity capacitor and the low voltage and the capacitor pack, which capacity is low, operating at a higher voltage. The advantage of this second solution is less weight and dimensions of the assembly. The prototype should be applied to the package of supercapacitors.

Due to the diversity of urban cycles, often with different and unique dynamic parameters in real traffic crossing the city, the choice of capacity supercapacitors determined from the condition, that it should allow for the accumulation of the kinetic energy of the vehicle during braking. Assuming driving speed limit of 50 km/h is obtained capacity of supercapacitors:

$$E = \frac{mv^2}{2} = \frac{18000x13.9^2}{2} = 1739[kJ] = 0.483\ [kWh]. \tag{12}$$

Given the above, it was assumed supercapacitors BMOD0063 Maxwell with a capacity of 63 F, 125 V voltage, energy density of 2.3 Wh/kg, connected to a battery. Assuming 4 modules connected to pack to obtain: Umax = 500 V, C = 15.75 F, Es = 0.55 kWh, the power density P_w = 3.6 kW/kg and short load current up to 6900 A. Durability of module is 1 000 000 cycles, and weight 60.5 kg.

References

[1] Glinka, T., Fice, M., Setlak, R., *Hybrydowy napęd pojazdu miejskiego*, Maszyny Elektryczne, Nr 75, s. 95-100, 2006.

[2] Goryc, Z., *Metody sterowania silników BLDC,* Prace Naukowe Instytutu Maszyn, Napędów i Pomiarów Elektrycznych Nr 66 Politechniki Wrocławskiej, Studia i Materiały, Nr 32, 2012.

[3] http://www.auto-elektryczne.pl/nap281d-elektryczny.html.

[4] Krasucki, J., Rostkowski, A., *Projektowanie hybrydowych elektrohydraulicznych układów napędowych,*. Wydawnictwo Naukowe Instytutu Eksploatacji Maszyn, Radom 2010.

[5] Menes, E., Słoński, D., *Energochłonność i emisja dwutlenku węgla generowana przez transport krajów tworzących Unię Europejską,* Kwartalnik Naukowy ITS Transport Samochodowy, Nr 2, 2010.
[6] Mock, P., *Reducing CO2 and fuel consumption from new cars: Assessing the near-term technology potential in the EU,* pdf, http://www.theicct.org/reducing-co2-and-fuel-consumption-new-cars-eu, January 2013.
[7] Pawelski, Z., *Napęd hybrydowy dla autobusu miejskiego,* Monografie Politechniki Łódzkiej, 1996.
[8] Rossa, R., Król, E., *Regulacja prędkości obrotowej w napędzie elektrycznym e-kit dedykowanym do elektryfikacji małych samochodów osobowych i dostawczych*, Zeszyty Problemowe, Maszyny Elektryczne, Nr 4, 2012.