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Električni avtomobil z energijsko varčno vodenim asinhronskim motorjem

The Electric Vehicle and Energy Saving Controlled Induction Motor

BORIS BIZJAK - KAREL JEZERNIK

Razvoj električnih avtomobilov postaja intenzivnejši predvsem zaradi varčevanja z energijo in problemov z onesnaženjem okolja. Prispevek pregledno predstavlja sociološke in ekološke razloge za uvedbo električnega avtomobila. Poudarjen je prikaz novih tehnologij pri razvoju električnega avtomobila: asinhronski pogonski motorji, mikroračunalniški krmilniki in nov algoritem vodenja motorja, ki omogoča varčevanje z energijo. Primerjali smo posamezne vrste akumulatorjev in predstavili avtomobil na električni pogon, ki smo ga preuredili v podjetju Mechatronica.

Ključne besede: avtomobili električni, razvoj avtomobilov, motorji asinhroni, varčevanje z energijo

Electric vehicles are a good example of how to reduce energy consumption and prevent pollution. Because of these two reasons the development of electric vehicle technology has taken on an accelerated pace.In this paper the social and ecological reasons for the introduction of electric vehicles are given. The overview includes the new technology such as induction motors, power controllers and microelectronics that provide less energy consumption. Comparisons are made between different kinds of battery, with emphasis on the lead acid one.The new product Electric Pick Up Vehicle developed and produced in Mechatronica is presented.

Keywords: electric vehicle, development of electric vehicle, induction motors, energy saving

0 UVOD

V svetu posvečamo vedno večjo pozornost varovanju okolja in varčevanju z energijo in zato postaja razvoj električnega avtomobila vse intenzivnejši.

V prometu porabimo 60 odstotkov vse načrpane nafte in plina. Ker so zaloge omejene, se pojavlja problem odvisnosti in varnosti pri oskrbi z energijo. Primerjava energijskih bilanc električnega vozila in vozila z bencinskim motorjem kaže, da električni avtomobil porabi približno 20 odstotkov manj primarne energije. Varčevanje z energijo je učinkovitejše v primeru mestne vožnje, kot pri daljših razdaljah.

Kalifornija je leta 1990 sprejela zelo znana predpisa "California Air Resource Board" in "Clean Fuels Program", ki predpisujeta, da morata biti do leta 1998 prodanih 2 odstotka avtomobilov brez emisij. To število se mora leta 2003 povečati na 10 odstotkov. Da bi omilili onesnaženje zraka z izpušnimi plini in vsaj delno odpravili vzroke t.i. tople grede, tudi druga mesta in države sprejemajo odredbe o uvajanju vozil, ki ne oddajajo izpušnih plinov.

Električni avtomobil vsebuje mnogo elementov moderne informacijske dobe, saj je informatiziran in elektrificiran. Preprosto ga je mogoče vključiti v nove cestne navigacijske, cestnovarnostne in zaščitne sisteme. Tako električni avtomobil prispeva k urejenosti in varnosti prometa.

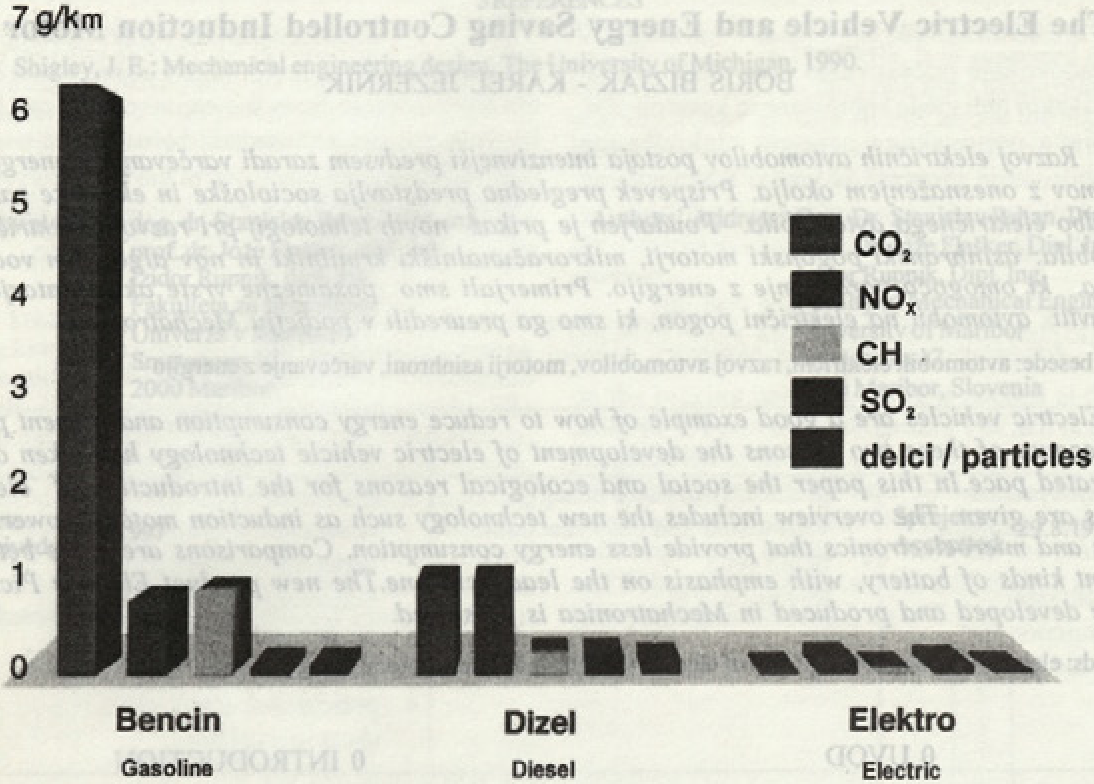
0 INTRODUCTION

In a world where energy conservation and environmental protection are growing concerns, the development of electric vehicle technology has taken on an accelerated pace.

The transportation sector uses over 60 percent of oil demand. As the resource of oil is limited, this problem is becoming the issue of national security and dependence. The energy efficiency of the electric vehicle is about 20 percent higher than the natural gas vehicle and gasoline internal combustion engine vehicle respectively. The energy saving of electric vehicles is more significant in city driving compared with that in highway driving.

In the 1990, the California Air Resource Board adoped the Low-Emission Vehicle and Clean Fuels Program. This program required a percentage of the vehicles sold in California be Zero-Emission Vehicles, or ZEVs, starting with 2 percent in 1998 and increasing to 10 percent in 2003. Due to the growing concern for air quality and the possible consequences of the greenhouse effect, some cities have set aside emissions regulations encouraging the promotions of EV's.

The electric vehicle is more intelligent, so that it can contribute to reducing traffic jams and enhance driving safety by the aid of an intelligent navigation system, radar system for crash prevention, etc. These electronic information technologies can be readily implemented in the electric vehicle system.



Sl. 1. *Svetovne emisije škodljivih plinov za različna motorna vozila*
Fig. 1. *Global gas emissions of various motor vehicles*

1 ZASNOVA ELEKTRIČNEGA VOZILA

Pomembna vprašanja, ki se pojavljajo pri uvedbi električnega avtomobila so:
- kako izdelati poceni vozilo z dobrimi lastnostmi,
- kako se izogniti velikim začetnim vlaganjem,
- kako zagotoviti učinkovito infrastrukturo.

Dinamično obnašanje električnega vozila je določeno z momentno karakteristiko pogonskega sistema in uporabljenim akumulatorjem (sl. 2).

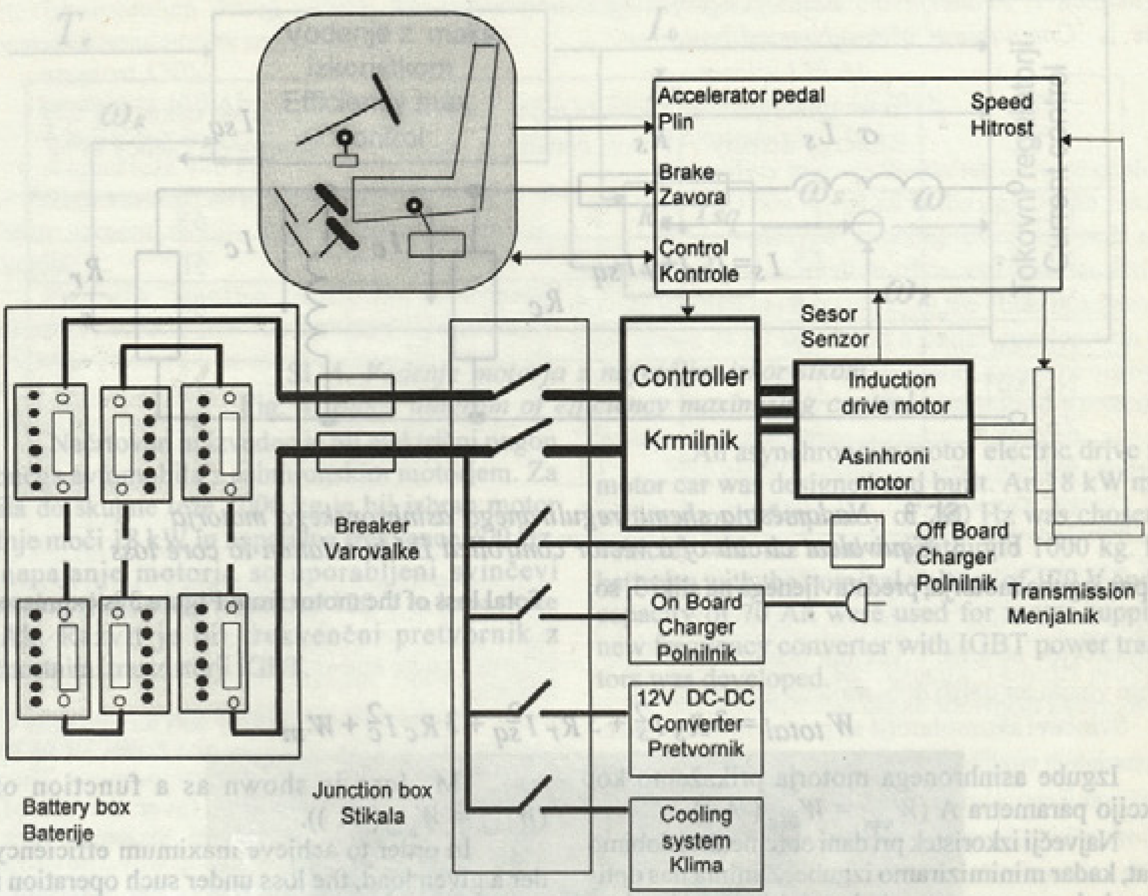
Uporabljene tehnologije so različne: elektrika, elektronika, avtomatika in kemija. Električno vozilo sestavljajo karoserija, električni pogonski del, akumulator za shranjevanje energije in sistem za upravljanje z energijo akumulatorjev. Važna lastnost in kriterij za izbor komponent je največji izkoristek sistema za vse obratovalne razmere vozila, posebej za majhne hitrosti in majhne momente.

1 CONCEPT OF THE ELECTRIC VEHICLE

The key issues in the successfully commercialized electric vehicle are:
- how to produce low cost good performance electric vehicles,
- how to leverage the initial investment,
- how to provide an efficient infrastructure.

The dynamics of an electric vehicle is mainly characterised by the torque characteristics of the power system and by the battery used (Fig. 2).

The technology involved is diverse: electrical and electronic engineering, mechanical and automotive engineering and chemical engineering. The electric vehicle system is an integration of vehicle body, electric powertrain, battery and battery management. An important characteristic and selection criterion is the overall efficiency of the drive for all operation points, especially at low speeds and low torques.



Sl. 2. *Shema električnega avtomobila*
Fig. 2. *System configuration of electric vehicle*

2 ENERGIJSKO VARČEN POGON

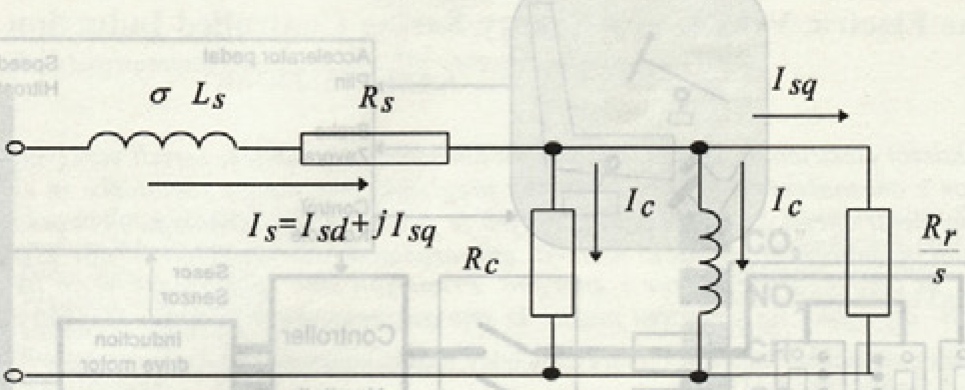
Ker je uskladiščena energija električnega vozila omejena, je doseg vozila odvisen od izkoristka pogonskega sistema.

Asinhronskemu motorju je mogoče spreminjati vrtilni moment in s tem vrtilno frekvenco z magnetilnim in momentnim tokom. V energijsko varčni shemi vodenja smo ugotovili, da je primerno spreminjati obe krmilni veličini (oba tokova) v področju vrtljajev nad sinhronimi. Največje izkoristke asinhronega pogona pri spreminjanju električne energije v mehansko dosežemo, če se razmerje tokov $A = I_{so}/I_{sq}$ spreminjamo v odvisnosti od zahtevane trenutne obremenitve motorja T_e. V motorju so opazne izgube v bakrenih navitjih, prav tako izgube v železu motorja.

2 ENERGY SAVING POWERTRAIN

Efficiency is one of the important factors for the EV driving motor because the cruising distance per battery charge needs to be improved.

The torque, and consequently the speed, of an asynchronous motor can be changed by two control values: the magnetizing and the torque current. It has been established in the energy saving control scheme that it is reasonable to vary both control values (i.e. both currents) in the power control domain above the synchronous speed range. The best efficiency of the drive in the electromechanical conversion is achieved if the ratio of currents $A = I_{so}/I_{sq}$ varies as a function of the actual motor load T_e. In this way the losses of the copper windings are included. Equally important is also the contribution of iron losses.



Sl. 3. *Nadomestna shema reguliranega asinhronskega motorja*

Fig. 3. *Equivalent circuit of a vector controlled IM in relation to core loss*

Skupne izgube motorja, predstavljenega na sliki 3, so:

Total loss of the motor from Figure 3 is expressed by:

$$W_{total} = 3 R_s I_s^2 + 3 R_r I_{sq}^2 + 3 R_c I_c^2 + W_m \quad (1).$$

Izgube asinhronega motorja prikažemo kot funkcijo parametra A ($W_{total} = W_{total}$ (A)).

Največji izkoristek pri dani obremenitvi dobimo takrat, kadar minimiziramo izgube. Zanima nas optimum glede na parameter A, kar dobimo z odvodom $dW_{total} /dA = 0$:

IM loss is shown as a function of A ($W_{total} = W_{total}$ (A)).

In order to achieve maximum efficiency under a given load, the loss under such operation must be minimized. Therefore, we solve it for A through $dW_{total} /dA = 0$:

$$\frac{dW_{tot}}{dA} = \frac{d(3R_s I_s^2 + 3R_r I_{sq}^2 + 3R_c I_c^2 + W_m)}{dA} \quad (2),$$

$$A = \frac{I_{sq}}{I_o} = \sqrt{\frac{R_s + R_m}{R_s + R_r}} \quad (3).$$

Tako lahko izpišemo izraze, ki zagotavljajo največji izkoristek reguliranega asinhronega motorja:

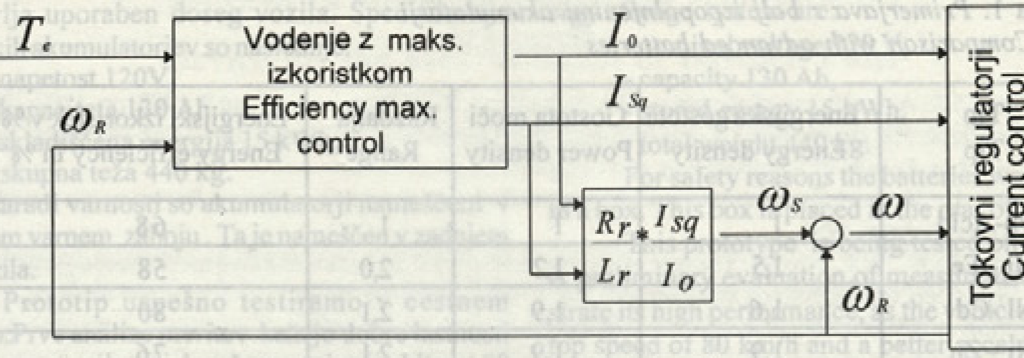
So the solution which maximizes the IM efficiency is obtained:

$$I_o^* = \sqrt{\frac{T_e}{3pL_m A}} \quad (4),$$

$$I_{sq} = \frac{T_e}{3pL_m I_o^*} \quad (5).$$

Optimalno shemo vodenja asinhronskega motorja lahko predstavimo v obliki blokovnega diagrama na sliki 4.

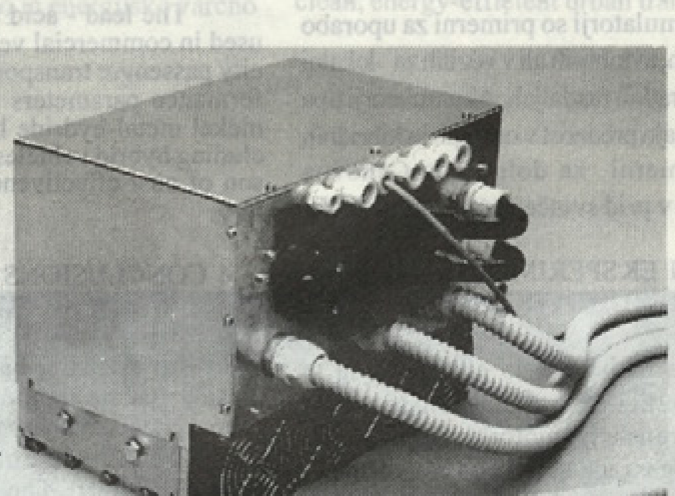
Figure 4 shows the block diagram of efficiency maximizing control of IM.



Sl. 4. *Vodenje motorja z največjim izkoristkom*
Fig. 4. *Block diagram of efficiency maximizing control*

Načrtovan in izveden je bil električni pogon osebnega avtomobila z asinhronskim motorjem. Za vozila do skupne teže 1000 kg je bil izbran motor srednje moči 18 kW in napajalne frekvence 200 Hz. Za napajanje motorja so uporabljeni svinčevi akumulatorji imenske napetosti 120 V in kapacitete 70 Ah. Razvit je bil frekvenčni pretvornik z močnostnimi tranzistorji IGBT.

An asynchronous motor electric drive for a motor car was designed and built. An 18 kW motor with a supply frequency of 200 Hz was chosen for vehicles with the total weight up to 1000 kg. Lead batteries with the nominal voltage of 120 V and the capacity of 70 Ah were used for motor supply. A new frequency converter with IGBT power transistors was developed.



Sl. 5. *Krmilnik asinhronskega motorja za električna vozila*
Fig. 5. *Induction motor controller for EV*

3 AKUMULATORJI

Današnji pogonski akumulatorji imajo manjšo energijsko gostoto in gostoto moči kakor naftni derivati. Najbolj je razširjen akumulator v električnih vozilih je brez dvoma svinčen. Ima gostoto energije 33 Wh/kg in gostoto moči 94 W/kg, ter je dobra osnova za relativno primerjavo z bolj izpopolnjenimi akumulatorji (preglednica 1).

3 BATTERIES

The energy and power densities of batteries are generally much smaller than those of petroleum distillates. The lead-acid battery is without doubt the best-known battery introduced in electric vehicles. For the benchmark Pb-Acid batteries with energy and power density of 33 Wh/kg and 94 W/kg respectively, a comparison with advanced batteries is shown in Table 1.

Preglednica 1. *Primerjava z bolj izpopolnjenimi akumulatorji*
Table 1. *Comparison with advanced batteries*

Tip Tip	Energijska gostota Energy density	Gostota moči Power density	Razdalja Range	Energijski izkoristek v % Energy efficiency in %
Pb-Acid	1	1	1	68
Ni - Fe	1,5	1,2	2,0	58
Ni -Cd	1,6	1,9	2,1	80
Ni - Zn	1,9	1,9	2,1	76
Ni -MH	1,7	2,1	2,3	76
Zn - Br	2,2	0,6	2,1	75
Na - S	2,5	1,1	3,4	91
Li -FeS$_2$	4,0	4,0	4,0	80

Značilen primer izpopolnjenih akumulatorjev so nikelj-metalhidridni (Ni-MH). Prednost tega tipa akumulatorjev se kaže v večjem dosegu in pospeševanju vozila ter daljši dobi trajanja akumulatorja.

Svinčevi akumulatorji so primerni za uporabo v komercialnih vozilih, avtobusih ali v vozilih za lokalni prevoz potnikov na kratkih razdaljah. Akumulatorji tipa nikelj-metalhidrid imajo prednost v osebnih in hibridnih vozilih, ter so primerni za dolge poti.Cenovna primerjava se izteče v prid svinčenega akumulatorja.

4 SKLEP IN EKSPERIMENTALNI REZULTATI

Obširne tržne raziskave so pokazale, da je najprimernejši pogonski sistem sistem za naše vozilo sestavljen iz asinhronskega motorja tip DOMEL 2AD.132 in 3 faznega tranzistorskega pretvornika . Motor je konstruiralo in izdelalo podjetje DOMEL Železniki, pretvornik IGBT je konstruiral Inštitut za robotiko Univerze v Mariboru. Celotno vozilo je bilo konstruirano in testirano v podjetju Mechatronica Štajerskega tehnološkega parka.

Motor tehta 55 kg, krmilnik pa 11 kg. Imenska moč motorja je 18 kW in dosega moment 90 Nm. Krmilnik napajamo z akumulatorsko napetostjo 120V.

Pogonski sistem je v sprednjem delu vozila. Krmilnik z integriranim polnilnikom je nameščen nad elastično vpetim motorjem, ki je neposredno spojen z menjalnikom.

Akumulatorji so bili izbrani tako, da sta doseg vozila in doba trajanja akumulatorjev največja. Akumulator je izdelek podjetja Vesna iz Maribora in ga sestavlja 20 kosov 6 V celic. Svinčevi hermetični akumulator je bil izbran tako, da smo dosegli optimum med izbrano težo in skladiščeno energijo, ki

The Nickel metal-hydride (Ni -MH) batteries are a most popular advanced batteries. The advantages of the nickel metal-hydride battery are shown in larger range and acceleration, as well as its longer lifetime.

The lead - acid battery has advantages when used in commercial vehicles and buses, or in inner-city passenger transport for short journeys. The performance parameters tend to favor the use of the nickel metal-hydride battery in passenger cars, including hybrid vehicles for a long way.The comparison of cost-effectiveness favors the lead-acid battery.

4 CONCLUSIONS AND EXPERIMENTAL RESULTS

An extensive market research led to the conclusion that the appropriate powertrain consisted of a three phase asynchronous motor DOMEL 2AD.132 supplied by a 3-phase transistor inverter Mechatronica type JR01.I001. The motor was deigned by the DOMEL Železniki company, the electronic inverter by the Institute of Robotics at the University of Maribor. The entire EV was built and tested by the Mechatronica company of Styrian technological park.

The motor has a weight of 55 kg and the controller of 11 kg. The nominal motor power is equal to 18 kW and its maximum torque reaches 90 Nm. The controller is supplied by a direct voltage of 120 V.

The drive system has been located in the front of the vehicle. The controller has been placed upon an elastic support, and the motor - located under the controller - was directly coupled to the gear box.

The type of energy storage system was selected to maximize the range of the vehicle and also the lifetime. The battery-patch consisted of 20 pieces of 6V, 130 Ah elements made by Vesna Maribor. It was selected as the most suitable choice because of its optimum storage capacity in relation to its weight and its ability to provide high peak currents for a reasonable time period. The specifications of the enzagotavlja uporaben doseg vozila. Specifikacije pogonskih akumulatorjev so naslednje:

- napetost 120V,
- kapaciteta 130 Ah,
- skladiščena energija 15 kWh,
- skupna teža 440 kg.

Zaradi varnosti so akumulatorji nameščeni v posebnem varnem zaboju . Ta je nameščen v zadnjem delu vozila.

Prototip uspešno testiramo v cestnem prometu.Prve analize meritev kažejo dobre lastnosti električnega vozila, saj dosežemo največjo hitrost 80 km/h in pospeševanje vozila je boljše kakor pri sorodnem avtomobilu z bencinskim motorjem. Med testiranjem v urbanem naselju smo dosegali do 75 km prevožene poti.

Električni pogonski sistem je na visoki tehnološki ravni, vendar akumulatorji še niso razviti do ustrezne tehnološke ravni, imajo relativno majhno energijsko gostoto in so pretežki. Kljub temu ima električni avtomobil nesporno uporabnost kot urbano prevozno sredstvo, tako danes kakor v prihodnosti. Uporaben je kot ekološko čisto in energijsko varčno prevozno sredstvo.

ergy storage system are:

- nominal voltage 120 V,
- capacity 130 Ah,
- stored energy 15 kWh,
- total weight 440 kg.

For safety reasons the batteries were enclosed in a box. This box is placed in the rear of the vehicle.

This prototype is being tested on roads now. A preliminary evaluation of measurements demonstrate its high performance, as the vehicle achieves a top speed of 80 km/h and a better acceleration performance than the corresponding gasoline-powered counterpart. In urban traffic conditions the tests demonstrate that the range is about 75 km.

The electric drive system is at an advanced technological level, but the batteries haven't been developed yet to the required level as they have a relatively small power density and are to heavy. Nevertheless, the value of electric vehicles for urban transport cannot be doubted and their widespread use in the future is expected. Electric vehicles provide a clean, energy-efficient urban transport alternative.

Sl. 6. *Eksperimentalno vozilo*
Fig. 6. *Experimental car*

4 LITERATURA
4 REFERENCES

[1] Chan, C.C.: An overview of electric vehicle technology. IEEE Proc., vol. 81, no 9, 1993, pp. 1202-1213.

[2] Jezernik, K. , D. Drevenšek, J. Korelič: Robust VSS induction motor control for electric vehicles. University of Maribor, Faculty of Electrical Eng. and Computer Science, 1997.

[3] Bizjak, B. , K. Jezernik: Gospodarno krmiljenje vrtljajev asinhronskih motorjev. Posvetovanje o varčevanju z energijo, Radenci, 1996.

[4] Barron, M.B. , W.F. Powers: The role of electric controls for future automotive mechatronic systems. IEEE/ASME transactions on mechatronics, Vol. 1, No. 1, 1996, pp. 80-88.

[5] Leonhard, W. : Control of electric drives. Springer-Verlag, Berlin, 1984.

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