Investigation of the electromagnetic field in electric and hybrid cars

R Hristov*, S Stefanov and P Kostov
Faculty of Mechanical Engineering and Technologies, Technical University of Varna, 1 Studentska Street, Varna 2010, Bulgaria
* corresponding author: rosen.hristov@tu-varna.bg

Abstract. Electric and magnetic fields are present everywhere electricity flows. In electric vehicles, passengers sit very close to electrical system with significant power, usually for significant period of time. The relatively high currents achieved in these systems and the short distance between power devices and passengers mean that the latter are exposed to the relevant magnetic fields. In view of this, it is important to study the values of electromagnetic field parameters on board electric vehicles to ensure compatibility with international standards. The measurements were performed inside the four conventional vehicles under the standard condition. Data of international and Bulgarian standards for safe levels of electromagnetic fields are given. After the measurements, it was established that these levels were not exceeded.

1. Introduction
This report will present a study of electric and magnetic fields (EMF) exposure inside electric vehicles and hybrid vehicles. The purpose of the report is to present the parameters of electromagnetic environment inside different vehicles and to compare them with the requirements of international and Bulgarian standards. The task of the study is to determine whether the vehicles in question have negative effect on the human body through their non-ionizing radiation. It is assumed that the new cars are in the norm, this should be checked by their manufacturers. We decided to measure on cars that have been in operation for several years to see if there is any significant increase in electromagnetic radiation.

The definition of a kind “What is an electromagnetic field” can also be found in the science world. For instance, Einstein defined a field as “regular, geometrical curvature of space” [1]. Electromagnetic fields can be either time constant or time varying. If the sources which produce electromagnetic fields are not varying in time, the electromagnetic fields themselves are also time constant. To reduce the magnetic field inside the compartment, some car manufacturers choose to integrate the inverter into electric motor and the power management system into the battery system [2].

There have been other publications on EMF and noise research in recent years [3,4,5], but we are expanding the number of measured points in the car. Fields in non-hybrid cars were higher at the front seats, while in hybrid cars they were higher at the back seats [6].

2. Experimental setup
2.1. General Design of Electric Vehicle
Unlike the complex and low-efficiency design of vehicles with internal combustion engines, electric vehicles have extremely simple system, consisting mainly of drive and power supply module. Control is much simpler, and the natural features of electric motors effectively replace the expensive and
complex systems, such as: ABS braking system, off-road drive, speed differentiation when cornering, etc. Moreover, the reversing mode of operation of electric motors allows the use of unnecessary inertia to generate energy and to charge the batteries.

Electric vehicle efficiency depends mainly on the right choice and design of its electrical system. If we have to compare individual components of electric vehicle and those of conventional one, we may say that the batteries play the role of a tank. They store energy, which will be converted later on into some mechanical motion. The high voltage battery, which is the heaviest electrical component of the vehicle, is located very low below the passengers. Most electric vehicles have front-axle drive and the battery modules are located in the floor between the front and rear axles. This configuration provides a lot of free space for passengers, large trunk, and very low centre of gravity, which improves the overall stability of the vehicle (Fig. 1)[7].

![General design of electric vehicle](image)

**Figure 1.** General design of electric vehicle.

Battery is the key component of electric vehicle for the following reasons:

- vehicle take-off run depends almost entirely on the battery;
- this is the heaviest electrical component;
- this is the most expensive electrical component.

The torque is provided by electric motor. Two types of electric motors, which together form a third type of electric motor, are mainly used in production of passenger cars:

- permanent magnet motors;
- induction motors;
- motors with variable magnetic resistance.

It is more appropriate in this case to call them electric machines instead of motors, since they can generate electricity when the vehicle is not moving. This mechanism is called energy recovery/ regeneration or regenerative mode (recuperation).

The controller is used to control the electric motor. It determines the speed at which the electric motor will rotate. Its purpose is the same as that of the carburettor. The controller doses the fuel supplied to it, depending on the speed, which we want to move with. In our case, the supplied fuel is voltage from the batteries. The power electronics control module has several subsystems and each of them has control function. When the vehicle is charged by the mains - 230 [V], the rectifier converts alternating current...
(AC) into direct current (DC), which is fed into the high voltage battery. DC-DC converter is responsible for lowering high voltage (e.g. 400 [V] of a three-phase grid) to low voltage of 12 [V].

The inverter controls electric machine speed and torque, converting direct current from the battery into AC three-phase current for the electric machine. When the vehicle is in the energy recovery (braking) phase, the inverter performs reverse conversion, from 3-phase AC to DC.

2.2. Methods used to measure electromagnetic field (EMFs)

Emissions from electric vehicles are completely different from the exposures of power lines, which arise greatest concern in society. EMFs in electric vehicles are characterised by complex and wide frequency spectrum and specific wave patterns. The information obtained from the measurements in this work will allow determining the specific characteristics of electromagnetic field that could be harmful to human body. The careful determination of electromagnetic fields inside the vehicle under different operating conditions, obtained from their field measurements, can provide information, which is important to reduce the exposure. Based on the presented location of electrical components and to measure and evaluate the exposure to EMF, the following methodology was used. Each passenger's and driver's seat in the vehicle's body was measured at three points: at the level of lower limbs (feet), at the level of torso (seat pan) and at the level of head. Points have been selected at the level of the limbs due to the close location of the batteries in the floor of the electric vehicle interior (See: figure 1); the same applies to the points selected at torso levels.

Schematically selected measurement points are presented in figure 2. The presented diagram shows that the measured EMF exposure values are personal for each passengers and driver seat, thus locating the areas with the highest values, which will be indicated and compared with the standards for EMF exposure limit values.

Figure 2. Diagram of the points where measurements were made [8]. The diagram is additionally processed.

2.3. Instruments Used in the Study. Measured Parameters

EMF 450 device was used for this purpose (see figure 3) This device measures simultaneously and displays magnetic field, electric field and radio frequency force and has three orthogonal sensors. The parameters and types of measurements are expressed in units of electric and magnetic field and power density. This device is very suitable for measurements of power lines, electrical appliances, industrial
devices, mobile phones, base stations and microwave ovens. The device is delivered fully tested and calibrated and, when used properly, provides reliable results.

Figure 3. EMF 450

The following physical characteristics were measured to describe the exposure to electromagnetic fields:

- Electric field strength (E); [Vm-1] (Volt per meter).
- Magnetic flux density (B), measured in micro tesla, [μT].

Standards for EMF exposure levels and ordinances existing in Bulgaria. Limit values. (ICNIRP, IEEE, Ordinance No RD-07-5 of 15 November 2016)

For the purpose of this study, the approximate frequency range where the electromagnetic fields generated by electric vehicles irradiate should be determined. Most electrical systems, including electric vehicles, are characterised by time-varying electrical quantities. Many magnetic field generators are located in these vehicles. The elements of electronic control, inverters, switches, etc. supplement traction drive and battery. According to the modern technologies for production of electric vehicles, electromagnetic fields generated by electric vehicles represent relatively wide frequency spectrum, from 0 [Hz] (at rest) to about 1 [MHz]. For this reason, standard limit values in the range of these frequencies need to be set.

On a world scale, there are standards for the levels of EMF exposure to which the human body can be exposed. World organisations develop these standards in accordance with research and conclusions drawn from these developments. Two of these organisations are presented here - these are ICNIRP and IEEE.

ICNIRP (International Commission on Non-Ionizing Radiation Protection). It provides scientific advice and guidance on the impact of non-ionizing radiation on human health and its impact on environment, and develops and proposes measures to protect people and environment from harmful exposure to the aforementioned radiation.

ICNIRP has established the following exposure limit values for the entire body in Guidance on Exposure Limits for Variable Electric and Magnetic Fields (100 [kHz] to 300 [GHz])[8].

For frequency range 0,1-30 [MHz] - E (electric field strength [V / m]) 660/f 0.7. H (magnetic field strength [A / m]) 4.9 / f. As f - frequency in [Hz].

IEEE (Institute of Electrical and Electronics Engineers)

The institute approves the limit values in IEEE Standard for Safe Human Exposure Levels for Electric, Magnetic and Electromagnetic Fields from 0 to 300 [GHz]” (IEEE Std C95.1™-2019) [9].

For frequency range 0.1-1.34 [MHz] E (electric field strength) - 614 [V / m]. H (magnetic field strength [A / m]) 16,3/f. As f - frequency in [Hz].
In Bulgaria, similar standards have been approved and entered in force with Ordinance No RD-07-5 of 15 November 2016 on the Minimum Requirements for ensuring Health and Safety of Workers at Risks related to Exposure to Electromagnetic Fields [10]. It is issued by Minister of Labour and Social Policy and Minister of Health, published in State Gazette No 95 of 29 November 2016, and is in force from 1 March 2017. The ordinance is based on Directive 2013/35 / of the European Union. Due to the low and extremely low frequencies at which the electric vehicle is irradiated, the lowest values of magnetic flux density - B and electric field strength - E are taken into account for frequency range from 1 [Hz] to 1 [MHz] by the above-mentioned Ordinance. The values referred to in this Ordinance have been used in this study.

As regards magnetic flux density, the Ordinance has set the following exposure limit values:
- In the range from 1 to 8 [Hz] - 200,000 to 3125 [μT];
- In the range from 8 to 25 [Hz] - 3125 to 1000 [μT];
- In the range from 25 to 300 [Hz] - 1000 [μT];
- In the range from 300 [Hz] to 3 [kHz] - 1000 to 100 [μT];
- In the range from 3 [kHz] to 1 [MHz] - 100 [μT].

As regards electric field strength, the Ordinance has set the following exposure limit values:
- In the range from 1 to 25 [Hz] - 20,000 [V / m];
- In the range from 25 to 50 [Hz] - 20,000 to 10,000 [V / m];
- In the range from 50 to 1.64 [kHz] - 10,000 to 305 [V / m];
- In the range from 1.64 [kHz] to 3 [kHz] - 305 to 167 [V / m];
- In the range from 3 [kHz] to 1 [MHz] - 170 [V / m].

2.4. Tested Vehicles

For the purpose of the study, the electromagnetic fields in three electric vehicles and a hybrid vehicle were measured. The vehicles tested are of the following brands and models and have the following technical characteristics (Table 1).

| No | Brand and model | Vehicle type | Drive          | Power | Working voltage |
|----|-----------------|--------------|----------------|-------|-----------------|
| 1  | Kia Soul        | electric     | front-wheel    | 81 [kW]| 375 [V] DC      |
| 2  | Nissan Leaf     | electric     | front-wheel    | 80 [kW]| 400 [V] DC      |
| 3  | Smart           | electric     | rear-wheel     | 55 [kW]| 375 [V] DC      |
| 4  | Toyota C-HR     | hybrid       | front-wheel    | 60 [kW]| 201,6 - 600 [V] DC |

3. Experimental Results from EMF Measurement in Electric Vehicles and Hybrid Vehicles

Spot measurements were made while the vehicle is at rest (is not moving), with the engine running and idling in a standby mode in an insignificant background field (at rest), and at different vehicle speeds - 10, 25, 35, 50 [km / h] and in reverse mode (in motion) of the engine. EMF values are measured at each of the four seats indicated in figure 2 - a total of 12 points. At each seat, the instrument was stationary at all specified points, so as to measure the levels of the electromagnetic fields and the location of their highest values.

The exposure to electromagnetic fields in the studied electric vehicles and hybrid vehicles has the following highest values according to the tests:
- Magnetic flux density – B (figure 4).
  - Vehicle 4 moving with 35 [km / h] - at the rear right seat in point 1 (at floor level) - magnetic flux density reaches a value of 2 [μT];
Vehicle 1 (in reverse mode, at the driver's seat in point 1) - magnetic flux density reaches a value of 1.27 [μT];

Vehicle 3 (moving with 25 [km / h] in point 3) - magnetic flux density reaches a value of 0.9 [μT]

The average mean of the highest readings Bmax (trend lines) do not exceed 1 [μT].

2. Electric field strength – E (figure 5).

Vehicle 3 in a standby mode in point (2) at the driver's seat - electromagnetic induction reaches a value of 12 [V / m];

Vehicle 4 moving with 25 [km / h] in points 1 and 2 - with 35 [km / h] in point (1) and with 50 [km / h] in point (1) - electromagnetic induction reaches values of 10 [V / m] at the rear right seat;

Vehicle 3 moving with 35 [km / h] in point 2 at the driver's seat - electric field strength reaches a value of 9 [V / m].

All other readings have values of 7 [V / m] or smaller ones. The trend lines (average means) of the highest readings Emax do not exceed 8 [V / m].
Conclusions
The results of the study are compared with those referred to in the standards recommended in Ordinance No RD-07-5 of 15 November 2016 on the Minimum Requirements for ensuring Health and Safety of Workers at Risks related to Exposure to Electromagnetic Fields.

The study indicates the measured readings of EMF exposure. They range from 0 to 2 [μT] (Vehicle 4) for magnetic flux density $B$, with average values not exceeding 1 [μT]. Compared to the limit values set in Ordinance No RD-07-5 of 15 November 2016 - 100 [μT], they are only 2% of the lowest reading required by standard. As regards electric field strength $E$, the measured values vary between 3 and 12 [V / m] in different modes and in motion, with the average values of the peaks not exceeding 8 [V / m]. In this case, the Vehicle 3 showed the highest results. Compared to the lowest possible limit values specified in the above-mentioned Ordinance, namely 167 [V / m], the measured peak readings are 7.19% of the lowest values specified in the standard.

Acknowledgments
This work received funding from the Technical University of Varna under project KD3 with a project leader Assoc. Prof. PhD R. Hristov.

References
[1] Prša M and Kasaš-Lažeti K 2018 IOP Conf. Ser.: Mater. Sci. Eng. 294 012001
[2] Ionescu V, Săpunaru A, Popescu M and Popescu C 2019 Magnetic field constraints in the...
passenger compartment of electric vehicles *IEEE ISGT-Europe* (Bucharest, Romania) pp 1-5

[3] Gumiela J, Sitnik L and Sztafrowski D 2019 Measuring identification of electromagnetic field emissions in electrical cars *Przegląd Elektrotechniczny* vol 95 issue 12 pp 128-131

[4] Gombarska D, Smetana M and Janousek L 2019 high-frequency electromagnetic field measurement inside personal vehicle within urban environment *12th International Conference on Measurement* (Smolenice, Slovakia) pp 223-6

[5] Kang Q, Gu P, Gong C and Zuo S 2019 Test and analysis of electromagnetic noise of an electric motor in a pure electric car *SAE Technical Paper* 2019-01-1492

[6] Hareuveny R, Sudan M, Halgamuge M, Yaffe Y, Tzabari Y, Namir D and Kheifets L 2015 Characterization of extremely low frequency magnetic fields from diesel, gasoline and hybrid cars under controlled conditions *Int. J. Environ. Res. Public Health* 12 1651-66

[7] Group 1 Nissan Retrieved from https://www.group1nissan.co.za/nissan-leaf-electric-vehicle/

[8] Moreno-Torres P, Lafoz M, Blanco M and Arribas J 2016 *Passenger Exposure to Magnetic Fields in Electric Vehicles* INTECH pp 47-52

[9] ICNIRP Statements-Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz) 2020 Health Physics 118(5) pp 483-524

[10] IEEE Standard for Safety Levels with Respect to Human Exposure to Electric, Magnetic, and Electromagnetic Fields, 0 Hz to 300 GHz in IEEE Std C95.1-2019 (Revision of IEEE Std C95.1-2005/ Incorporates IEEE Std C95.1-2019/Cor 1-2019) pp 1-312