**International Journal of Engineering and Advanced Technology (IJEAT)**
**ISSN: 2249 – 8958, Volume-5, Issue-4, April 2016**

# About Electric Scooter Mobility. Aspects Regarding the Designing of a Brushless DC Motor for an Electric Scooter

**Ionuț Daniel Smărăndescu, Petre-Marian Nicolae**

***Abstract*****: *The paper deals with the electric scooter mobility in Europe and with the designing of a brushless dc motor for an electric scooter. In the first part of the paper, the context and the motivation of the theme are presented. In the second part of the paper, the electric scooters market is described. Then, the main parts equipping an electric scooter are exposed. The final part of the paper deals with the designing of a permanent magnet brushless dc motor for electric scooter propulsion.***

***Index Terms*****: *designing, electric scooter, electric scooter mobility, permanent magnet brushless dc motor.***

## I. INTRODUCTION

"*We will not stop till every car in the road is electric.*" - Elon Musk [1], [2]. This speech was given by the CEO of Tesla Motors - one of the most famous manufacturers of electric vehicles worldwide. Disregarding the strong advertising content of the preceding quotation, what is true is that, in future, more electric vehicles will share the road infrastructure with traditional vehicles.

An electric vehicle, either a car or a scooter, is often presented as an environmentally friendly alternative to the traditional mobility. This applies only considering emissions, but several factors must be analyzed to describe a full frame. Along with electric vehicles, new materials are introduced into the product lifecycle, such as permanent magnets used in brushless dc motors, or lithium, used in batteries.

"*The main interest of Eco Design is to examine the conditions for and to provide help in creating a sustainable future by improving recycling, energy savings and products well suited for its purpose.*" - Conrad Luttropp [1], [3]. With these words, it is possible to understand the perspectives that were used to carry out the entire study. There is no easy solution or an easy response to get an efficient design in terms of the environment.

This study was conducted to gain a clearer view of the electric mobility as an efficient alternative to protect the environment.

## II. THEME CONTEXT

Cities are increasingly populous and scooters are gaining ground as an alternative to cars [1], [4]. However, traditional scooters, especially those equipped with two-stroke engine, are due to exhaust gases, one of the main causes of air pollution. According to the Environmental Protection Administration, the Government of China, an ordinary scooter with two-stroke engine produces from three to seven times more pollutants per kilometer than a 2,000 cm$^3$ car [1], [5].

After an examination of the history of electric cars and electric scooters, it is interesting to note how they are not a new product. In fact, both were considered as an alternative to the internal combustion engine vehicle before the ’20s. During the ’90s, various reasons (increased fuel prices, environmental issues) led to the rediscovery of electric vehicles.

In the last fifteen years, manufacturers have made many efforts to produce electric vehicles that are comparable to traditional vehicles, in terms of performance. Most of the major car manufacturers have electric cars available through their models.

The current electric scooters market situation can be described by the following vicious cycle: high initial price → reduced attraction for customers → reduced requirement for electric scooters → lack of interest for the investors → mass production of electric scooters can not be initiated → no large-scale sales → high initial price. This situation must be changed by entering the following cycle: high interest for investors → mass production of electric scooters → large scale sales → low initial cost → increased customer satisfaction → high demands of electric scooters → high interest for investors.

The transport system of the 21st century must be environmentally friendly, efficient, intelligent and sustainable.

## III. THEME MOTIVATION

Two-wheeled vehicles have always been a practical solution for individual transport for urban areas, where the average speed for a vehicle with four wheels often falls below the speed of walking due to the number of cars and transport infrastructure. When this environmentally friendly special mobility is combined with a propulsion system, results a vehicle that substantially contributes to solving two of the most distressing problems of city dwellers and local government: transport and environmental protection.

Electric scooters now have a growing popularity, mainly due to the increase in oil prices. The battery technologies achieved significant progress, making this mode of transport increasingly more attractive to potential users.

Benefits:

**Revised Version Manuscript Received on March 09, 2016.**

**Ionuț Daniel Smărăndescu**, Department of Electrical Engineering, Energetics and Aeronautics, University of Craiova, Faculty of Electrical Engineering, Craiova, Romania.

**Petre-Marian Nicolae**, Department of Electrical Engineering, Energetics and Aeronautics, University of Craiova, Faculty of Electrical Engineering, Craiova, Romania.

- The cost of fuel is about 25% of the one equivalent to petrol;
- Quiet far superior;
- Lack of noxious emissions;
- The batteries can be recharged anywhere there is a public network power supply (even at home);
- Reduced maintenance costs - whether for labor and consumables (eg. do not require oil changes, various filters, etc.).

Disadvantages:

- Purchase price higher than the one equivalent to the models fitted with internal combustion engines;
- Less autonomy;
- Recharge time relatively large (matter of hours).

## IV. ELECTRIC SCOOTERS MARKET DESCRIPTION

First, it is important to give a definition of the scooter. Oxford Dictionaries define scooter as follows: *"A light two-wheeled open motor vehicle on which the driver sits over an enclosed engine with their legs together and their feet resting on a floorboard."* - Oxford Dictionaries [1], [6].

Electric scooters are plug-in electric vehicles (which are loaded from an electrical outlet) with two or three wheels powered by electricity. Electricity is stored on board in a rechargeable battery, which drives one or more electric motors. Electric scooters (unlike motorcycles) have a "step-through" frame type [7].

Two-wheeled vehicle fleet in Europe amounted to over 36 million units in 2011. In the last decade the number of motorcycles and mopeds grew by more than 6 million units. The number of two-wheel vehicles in Europe increased year by year until 2010 when the vehicle market fell due to economic crisis. Considering the last 10 years, average scooters and motorcycles registered in Europe every year was 2,100,000 [1], [8].

The European country that produces most motorcycles and scooters is Italy, with over 400,000 units, followed by Germany - 110,000 and 95,000 - Spain. What must be noted is that some European brands have the production line in India or China, while some manufacturers are Japanese, so their production is almost negligible in Europe [1], [9], [10].

Considering the top ten two-wheel vehicles sold in 2012 [1], [8], seven out of ten models are from the L1 or L2 vehicle categories. The major manufacturers of two-wheel vehicles with an engine capacity of up to 125 $cm^3$ are the Italian firms Piaggio and Vespa and Japanese firms Honda Motors and Yamaha Motors.

To get an overview of electric scooters market, the report provided by Navigant Research Leaderboard [1], [11] in terms of electric scooters, states that the electric scooters market in Europe is around 2% of the traditional scooters market. The report states that the two main market areas are Asia Pacific and Western Europe. However, the two markets have different characteristics. The Asian market holds more than 99% of the global sales.

The electric scooters sold in Asia Pacific are low cost vehicles, with relatively few options and improvements. The market in Western Europe is the second world market, even if its volume is dramatically lower than in Eastern Europe.

In Europe, electric scooters have several improvements and can compete as a performance with traditional ones. However, electric scooters present on the European market are significantly more expensive than the ones with internal combustion engine.

One conducted a brief survey of the producers of electric scooters presented in the Navigant Research Leaderboard report (see Table I) [1], [11]. The idea is to highlight the differences between a model for the Asian market and one for the European market. It should be noted that in this analysis Japan is not part of the Asia market. Japanese market characteristics are similar to that of Western Europe. The main design differences between the two markets are shown in Table II.

Also, there are differences in terms of other specifications, such as the technology of braking, energy recovery technologies, autonomy, etc. These requirements differ from model to model [1], [12] - [21]. Therefore, without losing generality, it is possible to say that the main difference remains in battery technology. Lead batteries have a low price, but have low performance.

Since the purpose of the Navigant Research Leaderboard report [1], [11] is making a comparison between a scooter with traditional technology and an electric scooter, the electric scooter model is chosen for the European market. After the representative technology was selected, was made a comparison between the performance and the price of a European electric scooter and those of a traditional scooter (see Table III).

**Table I. Top Ten Producers of Electric Scooters.**

| Company | Targeted market | Country where the scooters are manufactured | Manufactures and scooters with internal combustion engine |
|---|---|---|---|
| Jiangsu Xinri E-Vehicle Co. [12] | Asia | China | No |
| Vmoto [13] | Asia + Europe | Australia | No |
| SYM [14] | Europe | Taiwan | Yes |
| Vectrix [15] | Europe | U.S.A. | No |
| Terra Motors [16] | Europe | Japan | No |
| Govecs [17] | Europe | Germany | No |
| Yamaha [18] | Europe | Japan | Yes |
| Peugeot [19] | Europe | France | Yes |
| iO Scooter [20] | Asia + Europe | Australia | No |
| BV Nimag (Nimoto) [21] | Europe | Holland | Yes |

**Table II. Europe / Asia comparison.**

| Aspect | EU market model | Asia market model |
|---|---|---|
| Battery technology | Lithium | Lead acid |
| Battery recharging time | 3-5 h | 6-8 h |
| Weight | 100-120 kg | 120-140 kg |
| Maximum speed | 50-65 km/h | 45 km/h |

**Table III. Performance comparison: electric scooter ordinary scooter.**

| Aspect | Electric scooter | Internal combustion engine scooter |
|---|---|---|
| Recharging point | Home outlet / work | Gas station |

| | | |
|---|---|---|
| Recharging time | 3-5 h | 10 min. |
| Weight | 100-120 kg | 90-100 kg |
| Maximum speed | 50-65 km/h | 60 km/h |
| Autonomy | 65 km | 250 km |
| Average fuel consumption | 3,3 kWh/100 km | 3,3 l/100 km |
| Buying price | 5400 $ | 2700 $ |
| The fuel costs after 50,000 km | 345 $ | 3341 $ |

## V. MAIN SUBASSEMBLIES EQUIPPING AN ELECTRIC SCOOTER

Figure 1 depicts the electrical schematic of a drive system for an electric scooter, in the embodiment with permanent magnet brushless DC motor.

### *A. Accumulator Batteries*

Traction motors for electric scooters are, usually, powered from batteries, which - essentially - are formed by grouping of several electrochemical elements in various connections.

Accumulator batteries can be placed either in the space below the scooter’s saddle or the scooter’s floor, covered by the elements of the bodywork and secured by means of special supports that allow disassembly easy to replace and ensures appropriate restraint, including the situation where the scooter overturns [22].

Most electric scooters from today are powered by rechargeable lithium-ion batteries, but there are models that use nickel-metal.

The manufacturer of scooters Z Electric Vehicle pioneered the use of silicate lead / sodium batteries (a derivation of the traditional lead acid battery invented in 1859) that are comparable as performance with lithium batteries, but at a lower cost [7], [23].

The currently used traction batteries can be divided into two broad categories:

- Lead-acid accumulators which represents about 95% of current traction batteries;
- Alkaline batteries and other types, which represents about 5% of actual traction batteries.

The lifespan of a battery is its ability to support as many charging and discharging cycles without losing its properties. Table IV presents a comparison between different battery technologies used to power electric scooters [1], [24].

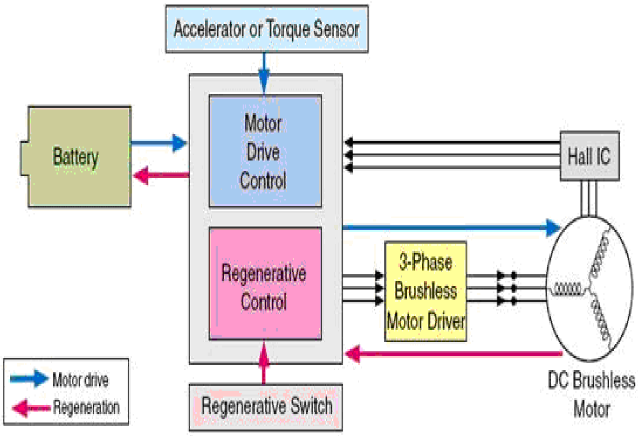

**Figure 1. Electrical scheme of the drive system for an electric scooter.**

**Table IV. Comparison of Battery Technologies.**

| Battery technology | Specific energy | Lifespan | Energetic efficiency |
|---|---|---|---|
| Lead-acid | 35-50 | 500-1000 | 80% |
| NiCd | 40-60 | 800 | 75% |
| NiMH | 75-95 | 75-1200 | 70% |
| Li-ion | 114 | 1000 | - |
| Na/S | 100 | - | - |

### *B. Electronic System for Battery Charging*

The electronic system for battery charging must ensure a full and correct charging of the traction batteries in a safe way and in a reasonable amount of time (under 10h - to ensure the possibility of using the scooter over the entire range, each day) [34].

Characteristics:

- Supply voltage: 220 V AC, single phase, 50Hz;
- Circuit type: thruster rectifier controlled by a measurement and charging control circuit;
- The maximum current flow: 3 A DC;
- Limiting the maximum charging voltage.

### *C. Control System of the Brushless DC Motor*

For the brushless DC motor control is necessary to know precisely, at any time, the rotor’s position. The necessary information to determine the rotor’s position against the stator, is given by the position sensors (Hall sensors). Based on this information, we know how to command the inverter’s transistors that feeds the motor’s phases [25].

In order to be effective in command and control, the three-phase brushless DC motor requires a three-phase inverter (the half bridge) generating a sinusoidal signal (6-step control). Also requires that the electronic switching of the motor’s phases to respect and maintain synchronism between the rotor flux and the stator flux (magnetic flux). Generally, the control circuit of such engines use one or more position sensors which give the information needed to determine the rotor’s position and thus preserves the synchronization between the two flows [26].

### *D. The Brushless DC Motor*

Currently, there are various technologies available for electric motors. However, most suitable for electric scooters is the brushless DC motor with permanent magnets. The main feature of this engine is the high specific energy. A high specific energy means an engine with low weight [1], [27].

The brushless DC motors replaces the motors with with brushes in many applications, due to lower energy consumption, increased reliability and low maintenance.

Brushless DC motors were required in electric drives with low power, but the control complexity for wide speed ranges and the high cost of specialized control circuits have limited their spread worldwide.

In the last decade, the continuous development of technology in various fields and the production of permanent magnet brushless dc motors led to the emergence of economically effective solutions for a wide spread of variable-speed applications [28], [29].

*Published By:*
*Blue Eyes Intelligence Engineering*
*& Sciences Publication Pvt. Ltd.*

## VI. ASPECTS REGARDING THE BRUSHLESS DC MOTOR DESIGNING

In the following are presented some aspects from the designing of a permanent magnet brushless dc motor, ideal for use in a drive system for an electric scooter [26], [30]. Selecting a specific configuration of a brushless DC motor depends on the application requirements. In this case, a permanent magnet machine with radial flow and inside rotor was elected.

Number of phases, poles, stator notches and windings configuration are determined depending on where the motor runs. The number of magnetic poles depends on several factors such as inertia, the magnetic material, the effect of ripple and speed of rotation. Stator yoke thickness is reduced by half if the number of magnetic poles doubles. For a given amount of current and at a certain rotor diameter, the total diameter of the motor can be reduced by increasing the number of poles:

$$h_{rr} = h_{rs} = \frac{B_g \cdot D_r \cdot \pi}{2 \cdot 2 \cdot p \cdot B_{iron}}. \qquad (1)$$

Table V presents the calculated parameters for the brushless DC motor.

With a certain thickness of the radial magnet, the air gap induction can be calculated by:

$$B_g = \frac{B_r}{1 + \mu_r \cdot \frac{g_e}{l_m}} , \qquad (2)$$

where the effective air gap is defined as:

$$g_e = g_c + \frac{l_m}{\mu_r} , \qquad (3)$$

and $g_c$ is the air gap in the the notches area.

The inner diameter of the stator is:

$$D_{is} = D_r + 2 \cdot (l_m + g) . \qquad (4)$$

Stator teeth height is:

$$b_{is} = (\pi \cdot D_{is} \cdot B_g)/(Q \cdot B_{iron}). \qquad (5)$$

To build a compact motor, a high current density ($S_1$) is not desirable. The load of the machine must always be less than the maximum allowed current ($S_{max}$) in order to prevent demagnetization of permanent magnets:

$$S_1 = \frac{3}{2} \cdot \left( \frac{2 \cdot T}{\pi \cdot D^2 \cdot B_g \cdot L \cdot k_w} \right) \text{ A/m}, \qquad (6)$$

$$S_1 < S_{\max} = \left[ \frac{\sqrt{2} \cdot g_c \cdot k_{w1} \cdot (B_g - B_D)}{2 \cdot D \cdot \mu_0 \cdot \sin\alpha} \right] \cdot p \text{ A/m}, \qquad (7)$$

where $B_D$ is the induction demagnetization limit and $\alpha$ is half of the magnet opening in electrical degrees.

**Table V. Calculated parameters of the brushless DC motor.**

| **Parameter** | **Symbol** | **Value** | **Parameter** | **Symbol** | **Value** |
|---|---|---|---|---|---|
| Number of phases | $m$ | 3 | Induced voltage | $E_{ph}$ | 11,9 V |
| Number of poles | $p$ | 4 | Rotor diameter | $D_r$ | 20 cm |
| Number of notches | $Q$ | 12 | Diameter + air gap | $D$ | 22,5 cm |
| Air gap | $g$ | 0,5 cm | Stator inner diameter | $D_{is}$ | 23 cm |
| Torque | $T$ | 4 Nm | Stator outer diameter | $D_{os}$ | 52,8 cm |
| Air gap induction | $B_g$ | 4 T | Tooth height | $b_{ts}$ | 3 cm |
| Motor's active length | $L$ | 30 cm | Copper surface | $A_{cu}$ | 32,5 $\text{cm}^2$ |
| Notch height | $h_s$ | 10 cm | Magnet thickness | $l_m$ | 1 cm |
| Number of conductors per notch | $n_s$ | 28 | Stator yoke height | $h_{rs}$ | 4,4 cm |
| Speed | $\omega_m$ | 7500 RPM | Rotor yoke height | $h_{rr}$ | 4,4 cm |
| Current density | $J$ | 10 $\text{A/cm}^2$ | Maximum current load | $S_{max}$ | 85,1 kA/m |
| Conductor diameter | $A_{conductor}$ | 1,1 cm | Charging current | $S_1$ | 47,5 kA/m |

The active length of the motor is calculated as:

$$L = \frac{3 \cdot T}{\pi \cdot D^2 \cdot B_g \cdot S_1}. \qquad (8)$$

The number of conductors from the notch is:

$$n_s = \frac{Z}{3 \cdot p \cdot q}, \qquad (9)$$

where Z is the total number of conductors and is given by:

$$Z = \frac{3 \cdot T}{D \cdot L \cdot I \cdot B_g \cdot k_w}. \qquad (10)$$

The torque constant derives from the previous formula:

$$k_T = \frac{T}{I} = \frac{1}{3} \cdot (Z \cdot D \cdot L \cdot B_g \cdot k_w) \text{ Nm/A} \qquad (11)$$

The induced voltage can be approximated by the equation:

$$E_{phase} = g \cdot n_s \cdot D \cdot L \cdot \omega \cdot k_w \cdot B_g \qquad (12)$$

Stator teeth surface area based on the height of the notch:

$$A_{notch} = \frac{\pi}{Q} \left[ \left( \frac{D_{iz}}{2} + h_s \right)^2 - \left( \frac{D_{iz}}{2} \right)^2 \right] - b_{iz} \cdot h_s \qquad (13)$$

The surface of a conductor and the surface of a single conductor from the notch:

$$A_{cu} = A_{notch} \cdot k_{fill}$$
$$A_{conductor} = \frac{A_{cu}}{n_s} \qquad (14)$$

The outer diameter of the stator results as:

$$D_{os} = D_{is} + 2 \cdot (h_s + h_{rs}) \qquad (15)$$

The distribution of the windings is performed differently for each combination of poles / slots. Thus, for the studied case, the windings are distributed as shown in the figure below (Figure 2).

Table VI shows the coils phase distribution.

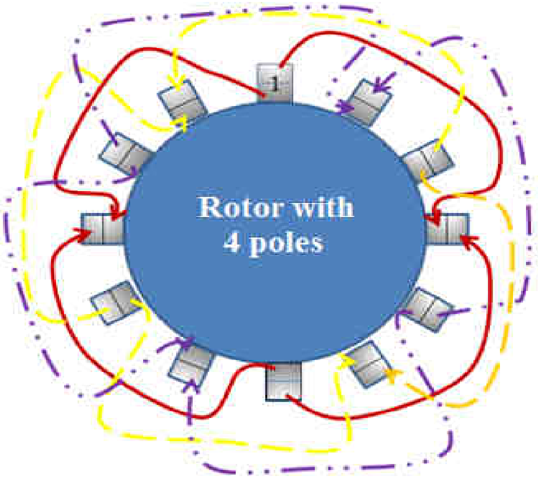

**Figure 2. Windings distribution (Phase A - red, Phase B – yellow, Phase C - blue).**

**Table VI. Coils Phase Distribution.**

| **Coil Number** | **Coil Angle** | **Phase A** | | **Phase B** | | **Phase C** | |
|---|---|---|---|---|---|---|---|
| | | In | Out | In | Out | In | Out |
| 1 | 0 | 1 | 4 | 5 | 8 | 3 | 6 |
| 2 | 0 | 1 | 10 | 5 | 2 | 3 | 12 |
| 3 | 0 | 7 | 4 | 11 | 8 | 9 | 6 |
| 4 | 0 | 7 | 10 | 11 | 2 | 9 | 12 |

## VII. CONCLUSIONS

The emergence of scooters in urban transport has occurred since the period immediately following the Second World War. Low maintenance cost and agility in handling mattered a lot in a crowded city, making the use of the scooter a very good solution.

Along with the development of power electronics and with the introduction of new legislations regarding pollution, the major vehicle manufacturers have turned their attention towards endowment vehicles with electric motors.

The implementation of the solution with the permanent magnets brushless DC motor in the electric scooter drive system, was taken after it was found by manufacturers that it meets most of the requirements, namely: the size / weight / speed ratio got it to impose over the other types of engines; simplicity of construction; smooth engine operation under extreme conditions; possibility of speed control in a wide range of speeds.

## REFERENCES

1. Braconi Dario, „Green two-wheeled mobility-Material Hygiene and life cycle analysis of an electric scooter", Dissertation, Stockholm, Sweden, 2014.
2. http://www.teslamotors.com/en_GB/about/executives/elonmusk.
3. http://www.kth.se/en/itm/inst/mmk/forskning/forskningsenheter/systemkomponentdesign/ecodesign.
4. Colella Wh. G., „Market prospect, design features, and performance of a fuel cell powered scooter", *Journal of Power Sources*, 2000.
5. Electric motorcycle development action plan", *EPA, Environmental protection administration*, 1998.
6. http://www.oxforddictionaries.com/definition/english/scooter.
7. https://en.wikipedia.org/wiki/Electric_motorcycles_and_scooters.
8. The motorcycle industry statistical overview, *ACEM*, 2013.
9. Environmental annual report", Honda, 2013.
10. Corporate Social Responsibility report", Piaggio, 2013.
11. http://www.navigantresearch.com/research/navigant-research-leaderboard-report-electricscooters.
12. Jiangsu Xinri E-Vehicle Co., http://english.xinri.com.
13. Vmoto, http://www.vmoto.com.
14. Sym, http://www.sym-global.com/index.
15. Vectrix, http://www.vectrixitalia.it.
16. Terra Motors, http://www.terra-motors.com.
17. Govecs, http://www.govecs.it.
18. Yamaha Motors, http://www.yamaha-motor.eu/it/prodotti/scooter/index.aspx.
19. Peugeot scooter, http://www.peugeotscooters.it.
20. iO scooter, http://www.io-scooter.com.
21. Nimag B.V. (Nimoto), http://www.nimoto.nl/contact.
22. http://www.icpe.ro/ro/d/2/p/scuter-electric.
23. Billings Randy, „Z Electric Vehicle Introduces New Model 5000 Scooter", *EV World.com*, 9 May 2012.
24. Sullivan J.L. and Gaines L., „Status of life cycle inventories for batteries", *Energy Convension and Management*, Vol. 58, pp. 134-148, 2012.
25. http://vega.unitbv.ro/~ogrutan/Microcontrollere2011/5-motoare.pdf.
26. Brushless DC motors - three phased", *Electronica AZI*, web access: http://electronica-azi.ro/2004/07/08/motoare-de-curent-continuu-fara-peri-trifazate (in romanian).
27. Larminie J. and Lowry, J., "Electric machines and their controllers", *Electric Vehicle Technology Explained*, Chapter 6, Second Edition, 2012.
28. ***https://ro.wikipedia.org/wiki/Motor_electric_de_curent_continuu_f%C4%83r%C4%83_perii.
29. http://www.scrigroup.com/tehnologie/electronica-electricitate/Motoare-de-curent-continuu-far73164.php.
30. Fransua Al., Măgureanu R., Câmpeanu A., Condruc M., Tocaci M. – "Machines and electric drive systems", Ed. "Tehnică", Bucharest, 1978 (in romanian).