FEM-Based Study of Induction Machines for Electric Trucks

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Abstract—**The paper presents a study concerning the performance developed by induction motors destined for motorization of heavy electric vehicles such as trucks. Taking into consideration the imposed restrictions, one presents, in a comparative manner, the main geometrical parameters which come of the classical design algorithms. A special attention is dedicated to the winding design, since it has to ensure two synchronous speeds corresponding to 16 and 8 poles respectively. Finally, a FEM-based analysis is performed to put in view specific torque and slip values such as rated, start-up and pull-out ones. Conclusions regarding obtained results and future optimization actions are prefigured.**

Index Terms— **induction machine, design, FEM based analysis**

I. INTRODUCTION

Social and economical mutations evinced in the last decades induce mandatory reorganization of both automotive and railroad transport. The technical facilities used in their construction got forward continuously. Electric traction based on three-phase alternating current is increasingly used due to its superiority as concerns the way the traction power is transmitted. The first locomotive with static frequency converter comes from 1970 [1]. Concurrently, the producers have tested different solutions for hybrid and fully electric cars, trucks, subway vehicles and tramways or other utility vehicles. Mainly the following purposes are in discussion: decrease of factory overheads and costs of long maintenance; increase of operating safety and reliability; higher vehicle efficiency. Accomplishment of these purposes should be accompanied by technological advancements as regards the electric motors, static converters and overall driving technique.

Concerning the rotating electric motors, significant progress proved the brushless motors with their increasing per unit power and flexibility of supply voltage value. An electric traction system contains a static converter (with GTO or IGBT thyristors) which feed an A.C. electric motor (cage induction motor, permanent magnet brushless motor, switched reluctance motor). The operation of this electric drive must be situated in a certain speed range, with constant and high value torque. On the contrary, for higher speeds, the operation takes place for constant power. The specific operation conditions come from a special electronic control. Generally, the traction motors have to fulfill the following requirements: high torque at low speed, high instant power, high power density, high efficiency over wide speed and torque ranges, high reliability and robustness, low cost, fast torque response. A very realistic solution consists in the direct drive system (i.e. drive of axle or wheel without use of any gears) which offers many benefits that must be considered: no gear noise, no gear maintenance, no gear energy losses etc.

The majority of researchers consider the Permanent Magnet Brushless Motors as the most proper solution for this kind of applications due to certain advantages such as high efficiency, reduced volume for increased torque, superior performance in steady-state and transient operation (especially for low speeds). Anyway, more and more opinions claim that the induction motors, with special design, represents a cheaper and reliable solution as propulsion element in road transport (buses, trucks, middle tonnage vehicles) [2].

The main purpose of this paper is to offer some arguments in support of the use of the induction motors as driving mechanism for middle to heavy-duty trucks employed in USA where the preoccupation for such solution is ascending.

This paper is an initiatory approach, which is focused on the analysis of distinct induction machine types capable to meet the requirements of a truck propeller. The design takes as main constraints, the values of the maximum developed torque (for start-up) and the mechanical power corresponding to long term operation for a certain speed. An important constraint is imposed by the supply source, which is represented by a battery of storage cells. It has a limited and generally constant voltage with a rigid volt-ampere characteristic. The discharge time and current must be controlled carefully.

Since the solution based on D.C motors is more and more avoided mainly due to reliability and maintenance difficulties, is the use of A.C driving systems a valuable solution but which requires a frequency converter. Practically, this device placed between D.C. source and A.C. electric motor increases the costs but ensures a more flexible driving system. A convenient conformation of the speed to exploitation conditions is possible if the system allows the recuperation of some energy during braking.

Finally, the electric motor must fulfill the toughest constraint related to dimensions (diameter and length) and weight. These requirements represented for the authors of this study one of the main challenges.

II. MAIN COMPONENTS OF TRUCK MOTORIZATION

The application with the smallest power in road traction from USA uses as energy source a battery of storage cells of 125 kWh. It has 240 $LiFePO_4$ cells, each of them with a capacity of 160 Ah. The series-connection of the cells provides 1000 V. The maximum long term discharge current is of 500 A and for normal temperature, the maximum discharge current is of 1600 A in 10 seconds and for each minute. For safety and flexible operation, every 15 cells are hosted by a mechanical module (with a rated voltage of 48V). There are also automatic couplings and commutation and safety equipment. The battery is controlled by an individual unit (battery management system – BMS), which uses a microcontroller for each cell and a central unit. The system should keep a coequal voltage value of the cells and a strict control of the temperature. The technology of these batteries is up-to-the-minute one, but discharge under 2.9 V or overload above 4.1 V lead to immediate downfall of the battery. These conditions require, consequently, a complex control system.

The energy stored in the batteries ensures a transit of 100 km (city and expressway). The trucks have to perform the so-called deep delivery (department store to railway station or general store). The next model, of higher power, will need batteries with a 2-3 times higher capacity. To give space to the new equipment, the chassis and the cab must be remodeled. These trucks will operate in a similar way to trains, with special designated points for recharging. The battery allows 3000 recharge cycles, each cycle of half an hour. The battery price is of 550 USD/kWh including the BMS. Considering all the costs, the total operation price is around 0.62 USD/ litter diesel. One appreciates this solution as a profitable business. The customer is a company from Minnesota, Fil-Mor Express.

Fig. 1 presents a general view of the chassis of the truck Freightliner (Mercedes) provided with an electric motor MBT10 produced by Electroputere (the motor was designed for subway vehicles).

In Fig. 2 one can see the place where the electric motor is positioned. It has to be mentioned that the first tests run in the laboratory from *Center for Automotive Research, The Ohio State University USA,* using the electric motor produced by Electroputere with the following parameters: rated voltage – 400 V, rated frequency – 50 Hz and synchronous speed – 1500 rpm (2p=4). The tests have been stopped due to certain drawbacks such as: the Romanian company stopped the production of these motors or anything similar; the starting torque is below the limit value of 5000 Nm; the motor weight exceed 900kg which is unacceptable. All these elements determined a new beginning in finding a new solution capable to satisfy as many as possible constraints.

Fig. 1 Lateral view of the truck chassis

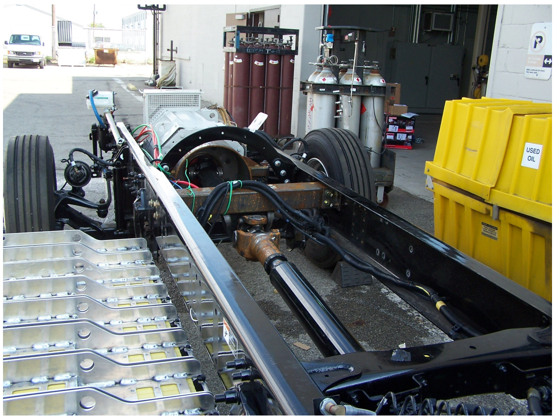


Fig. 2 Chassis view with the place occupied by the induction motor

III. DETERMINATION OF GEOMETRICAL PARAMETERS FOR INDUCTION MOTOR

The initial requirements asked for an electric motor no greater then 0.6 m in diameter and 0.65 m in length. As regards the developed torque, a value of 5000 Nm at start-up has to be accomplished. A stator winding capable to ensure two distinct pole numbers is accepted as well, but the ratio is not imposed. For steady-state operation corresponding to 3500 rpm, the motor has to deliver a minimum power of 150 kW. Obviously, an efficiency value of minimum 90% is required. The maximum stator current is limited to 2000 A.

On the basis of these requirements, a design and a FEM simulation have been performed for determination of operation characteristics. For the beginning, four distinct variants have been designed: cage winding made of copper and with round bars; double cage rotor winding (round upper bars and rectangular operating cage) made of copper; hybrid double cage winding (rectangular bars made of aluminum for starting cage and rectangular bars made of copper for operating cage); deep bars made of aluminum. Excepting the first solution, regular round bars cage, the other three types satisfied the requirements concerning torque and power values and efficiency level, but they did not represented a significant progress as concerns total weight and consumption of active materials.

Subsequently, the investor-producer has imposed new requirements as regards the dimensions of the electric motor, 0.55 m in diameter and 0.5 m in length, the other requirements remaining unmodified.

The calculus of main geometrical dimensions took into consideration the imposed rated values: (IM8) P_N=150 kW, U_N=380 V, n_{1N}=450 rpm, f_{1N}=60 Hz, $\cos\varphi_{1N}$=0.72, η_N=0.9, p_1=8. The stator inner diameter is calculated with the well known expression [3,4,5]:

$$D = \sqrt[3]{\frac{2p}{\pi\lambda}\cdot\frac{60S_i}{n_{1N}C}} = 0.45m \qquad (1)$$

where: $\lambda = 5.5; C = 300\cdot 10^3 J/m^3; S_i = 231.500VA$

The form factor value, λ, (ratio of ideal length and polar pitch) has a much higher value as the scientific literature recommends (λ=5.5 in comparison with λ=2). This option leads to the ideal length:

$$l_i = \frac{60\cdot S_i}{k_f k_{B1}\alpha_i \pi^2 D^2 n_{1N} 10^2 A_c B_{\delta c}} = 0.48m \qquad (2)$$

The constraints regarding the volume are accomplished. The linear current density has an exaggerated value as well, A_c=50000 A/m. Likewise, the air-gap flux density, $B_{\delta c}$=0.9T. Consequently, a special ventilation system (by air or water) is compulsory. The final solution is expected during the experimental tests.

The stator slot number is Z_1=48, which gives a number of slots per pole and per phase of q_1=1, for p=8, and q_1=2, for p=4, respectively. The air-gap width is δ=1 mm, but for experimental model a thinner air-gap is to be expected (0.75-0.5 mm).

The rotor slot number is Z_2=34 and depends on Z_1, number of poles and diameter value. The slots are in rectangular shape and they are placed deep inside rotor body for a significant unsymmetrical current distribution at start-up and an increased starting torque. Main geometrical dimensions and details regarding the slots and yokes are presented in Fig. 3.

The solution with closed rotor slot is possible since the laser techniques are used for blanking. The model IM8 has obviously over values for magnetic loads and consequently it is proper for start-up (high load torque) and short term operation (dozens of seconds).

The next step of the study consisted in calculus of the rated quantities for a machine with p=4 (IM4) but with the geometrical dimensions calculated for IM8. The purpose was to obtain acceptable electromagnetic loads. The following values have been obtained: P_N=270 kW, U_N=600 V, n_{1N}=900 rpm, f_{1N}=60 Hz, $\cos\varphi_{1N}$=0.78, η_N=0.9, p_1=4. This time resulted: C=280000 J/m^3, λ=2.7, A=50200 A/m, B_δ=0.812 T.

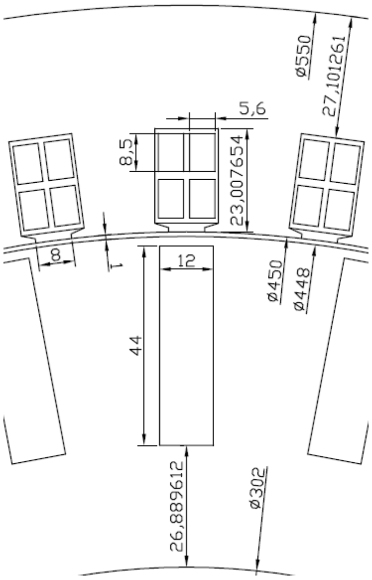


Fig. 3 Geometrical dimensions, slot detail

IV. SIMULATION STUDY OF THE INDUCTION MOTOR

A first set of characteristics obtained by means of the FEM-based simulation (FLUX2D package) looks for the M=f(s) dependences (torque versus slip) for the following cases (Fig.4):

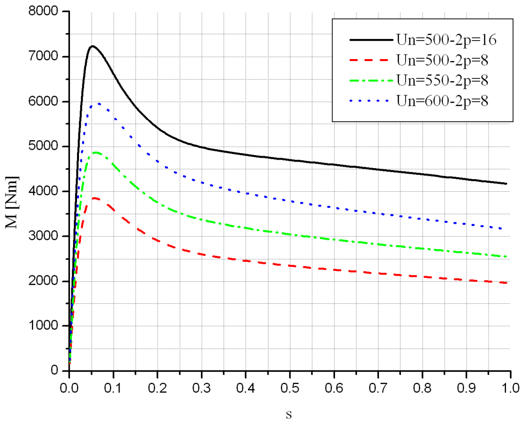


Fig. 4 Torque-slip characteristics

- IM8 machine with 500 V supply voltage (a value with approx. 25% greater then U_N);
- IM4 machine with 600V, 550 V and 500 V supply voltage, respectively.

The results validate the possibility of obtaining a starting torque value greater then 4000 Nm with IM8. As regards IM4, the supply with 500 V determines a rated operation at s=0.02 where the rated torque is of 2700 Nm, active power – 270 kW, efficiency – 0.92 and cosφ - 0.76. The starting torque is obviously small, approx. 2000 Nm, but can be increased to 3000 Nm for a higher supply voltage (with 20%).

To obtain p=8 (IM8) is necessary to connect in series four winding sections per phase (Fig. 5). The IM4 machine requires a different connection of the sections. The change of poles number is traditionally accomplished with a mechanical controller or with micro contactors.

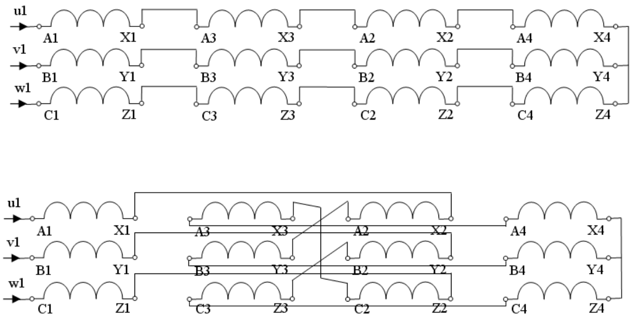
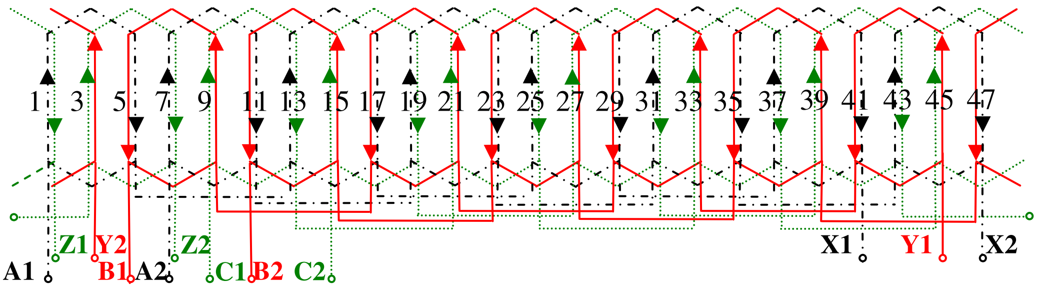


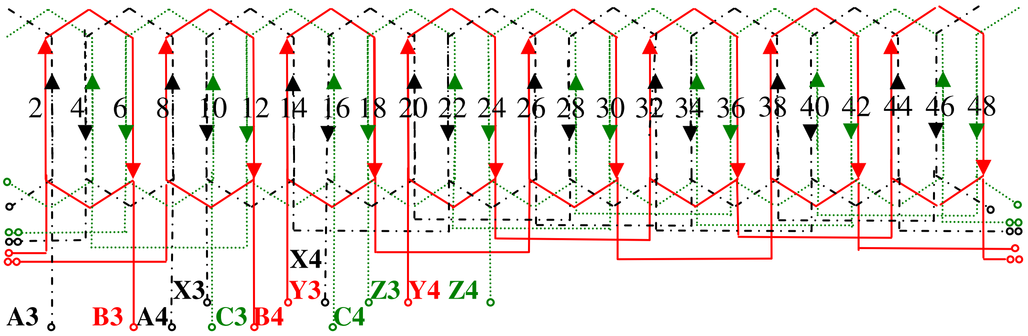
Fig. 5 Connections of the winding sections
p=8 (up), p=4 (down)

Details upon the stator winding are presented in Fig. 6. When p=8, the series connection of the sections correspond to Fig. 6a (odd sections) and Fig. 6b (even sections). The winding has long pitch for p=8 (y=4, τ=3), and short pitch for p=4 (y=4, τ=6). To obtain p=4, an original connection type was necessary (*intercalation* of sections from distinct phases – Fig. 6c). One connects each 4 coils of a phase with equidistant position on the stator periphery (with two turns per slot). Thus, one obtains a coil *group*. Each phase contains four coil groups.

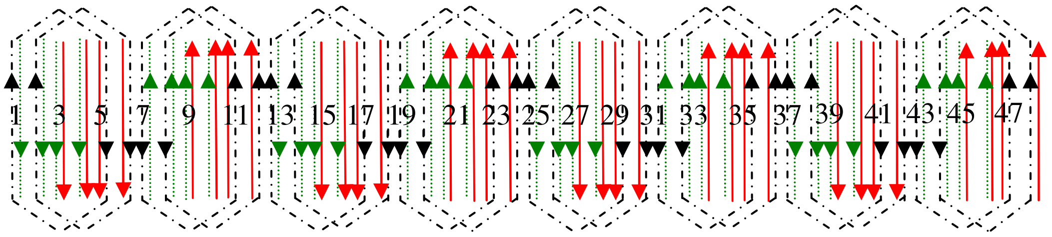
The solution adopted for the winding allows more options for the supply system. One can use one, two or four distinct converters.



a) Connection of odd winding sections, p=8



b) Connection of even winding sections, p=8



c) Current density distribution, p=4

Fig. 6 Details of the winding for variable pole number (16/8)

The proposed winding connection diagram offers a high flexibility and adaptability to the D.C supply source, which itself contains modules with a 48 V supply voltage value. The final solution should be further adopted.

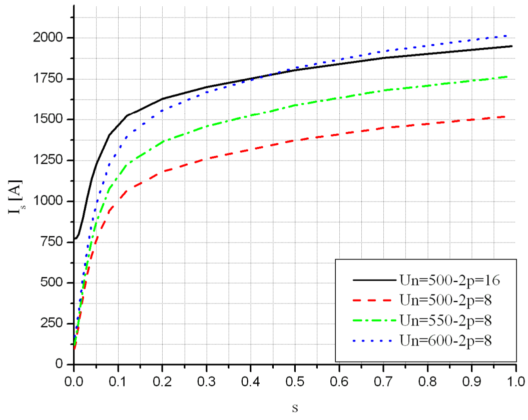


Fig. 7 Stator current versus slip characteristics

Fig.7 and Fig. 8 present the variation of stator currents and stator current densities with the slip.

Fig. 9 to 11 show the air-gap magnetic flux density (corresponding to a pole pair) and the content in high order harmonics. The fundamentals have values around 0.8 T.

Fig. 12 and Fig. 13 present the same flux density waves along the entire air-gap.

Finally, Fig. 14 shows the flux density color maps corresponding to the four analyzed cases. The maximum value does not go beyond 2T.

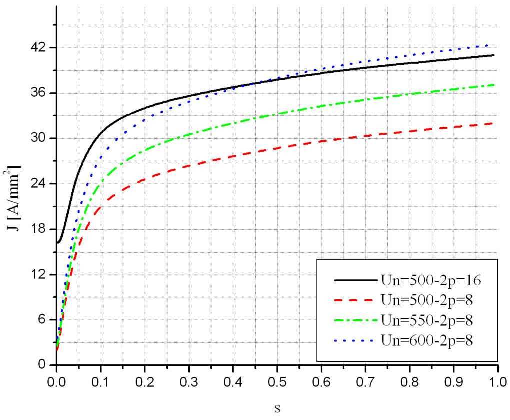


Fig. 8 Stator current density versus slip characteristics

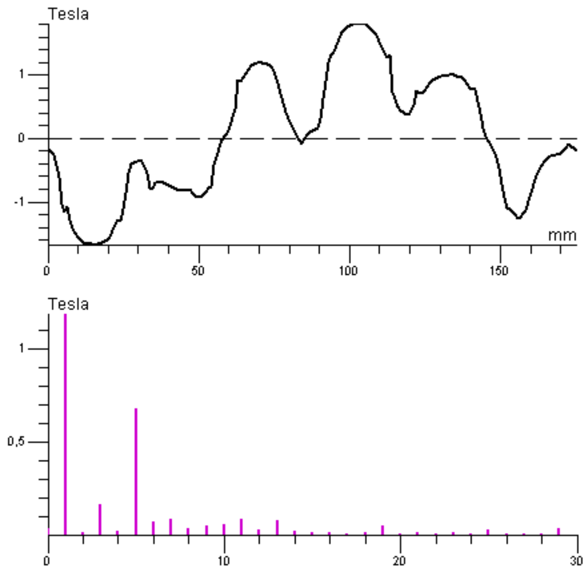


Fig. 9 Air-gap flux density and content in high order harmonics, U=500V, p=8

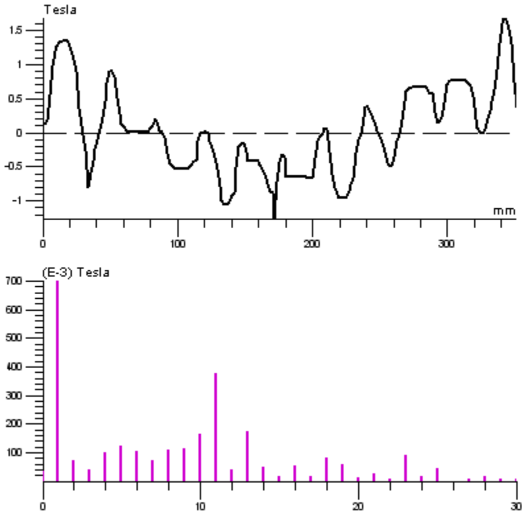


Fig. 10 Air-gap flux density and content in high order harmonics, U=500V, p=4

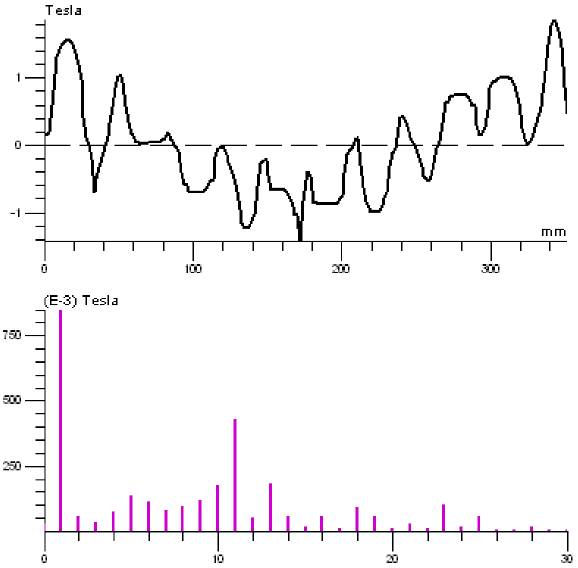


Fig. 11 Air-gap flux density and content in high order harmonics, U=600V, p=4

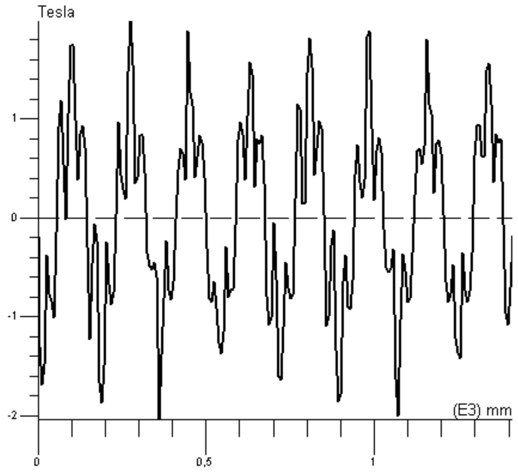


Fig. 12 Air-gap flux density, U=500V, p=8

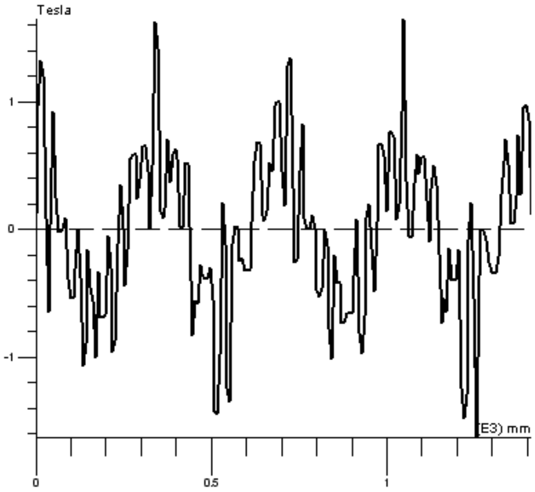


Fig. 13 Air-gap flux density, U=500V, p=4

V. CONCLUSION

The use of induction motors in automotive electric traction is a viable solution due to its superior technical and economical performance in comparison with gasoline engines.

A careful design of the electric machine, concerning the geometrical dimensions, accompanied by a special stator winding and a supply system which includes static converters can together satisfy the constraints imposed by traction systems.

The results offered by the FEM simulation confirm widely the validity of proposed solution.

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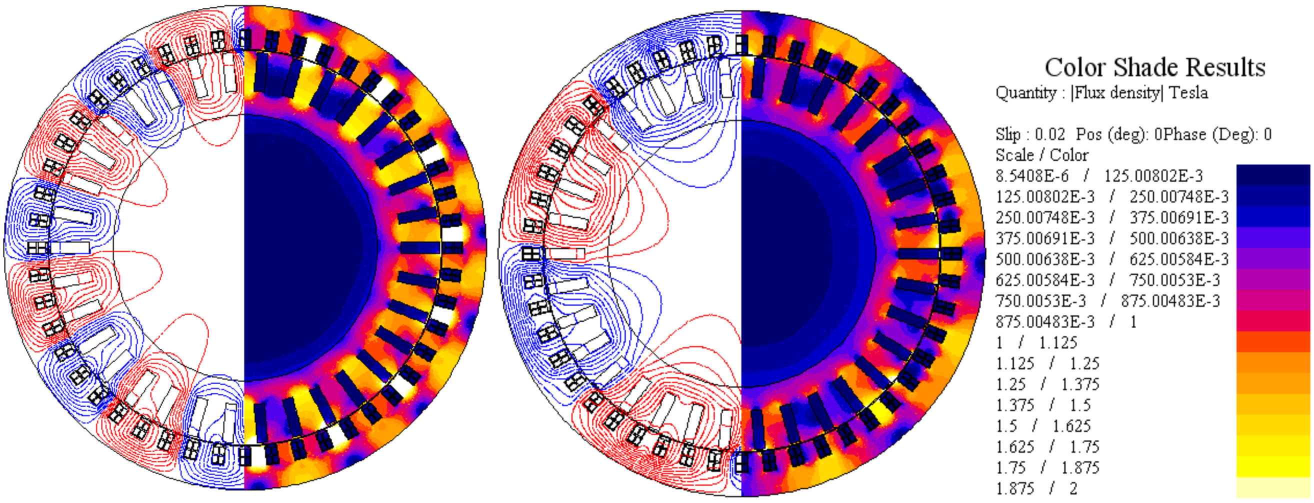
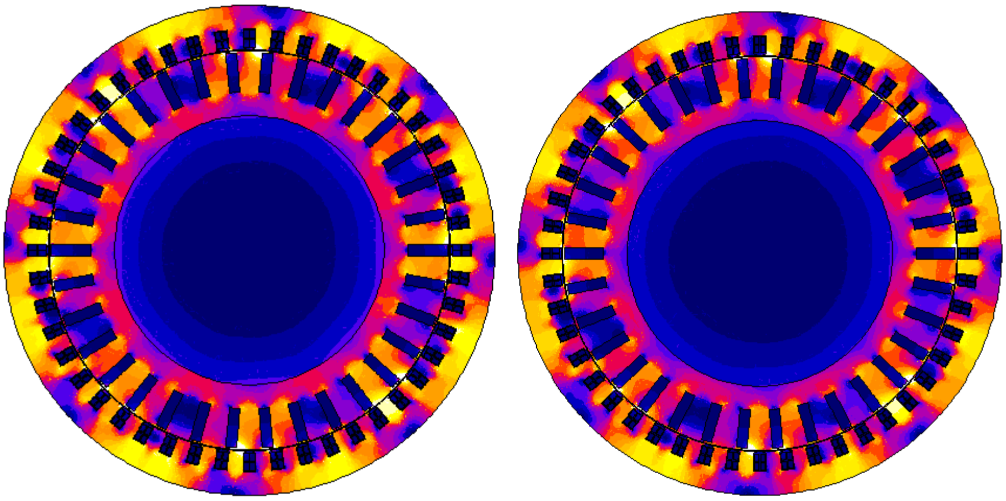


a. U=500V, p=8

b. U=500V, p=4



c. U=600V, p=4

d. U=550V, p=4

Fig. 14 Flux density color maps