IMPACT OF VARIOUS SLOT-POLE COMBINATIONS ON AN IN-WHEEL BLDC MOTOR PERFORMANCE

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Abstract: *In this study, the optimum design of a brushless DC (BLDC) motor which is used for in-wheel light electric vehicle (LEV) propulsion is presented. The optimization work is mainly based on different slot-pole numbers which give a substantial performance improvement for that certain application. An outer rotor, 2.5kW, 150V BLDC motor which is widely implemented in light electric vehicle traction is selected. Finite Element Analysis (FEA) of the target motor design is conducted for various slot-pole combinations. By using the captured design data, the optimized motor is manufactured and tested. The test and simulation results are compared with each other to investigate the optimization approach.*
Keywords: *BLDC motor, Light electric vehicle, Slot-pole combination, Finite element analysis.*

1. Introduction

In developed countries today, alternative solutions are proposed in order to mitigate environmental pollution and to minimize fossil fuel based energy consumption. Environmentally friendly transportation is one of the most significant solutions among all others. For this purpose, it is extremely likely to observe increasing numbers of electric or hybrid cars on roads. And the most of the car manufacturers have intensified their research and development activities on this promising area [1-4].

One of the most important concepts in electric car technology is energy planning and therefore, energy efficient electric motors have utmost importance. Increasing the electric motor efficiencies and minimizing losses have become an important target for all electric power train designers. Mainly there are two benefits of using driving systems with minimum electric consumption: increasing the driving distance and decreasing the energy consumption per kilometer. It can be observed that R&D activities of car manufacturers concentrate and focus on these two beneficial topics [3-7].

Many electric motor manufacturers and vehicle manufacturers have tended to brushless motor solutions since these motors have positive features such as high efficiency, high torque, low volume and light structure especially for LEVs. On the other hand, it is still somewhat difficult to realize proper motor designs since the technology is still in the process of development, the materials are still being tested and the motor design developments are still far from being completed [7-11]. Besides, a similar situation is also valid for light electric vehicle designs which are user friendly and clean.

It is known that one of the parameters which is affecting BLDC motor efficiency is slot-pole number combination. Investigations aimed at studying this problem would come up with results that showing the importance of high efficiency motors and low energy consumption per kilometer [12].

It is obvious that the traction requirements of electric vehicles lead the designers to seek new or different electric motor topologies and structures. An in-wheel type electric bicycle motor is a prominent example of those efforts. As a LEV, electric bicycles require slim, high torque – low speed, cogging-free Recent studies and some unconventional design works are mainly on the slot-pole combinations and different winding configurations. The design developments based on recent studies have brought easily manufactured motor topologies, modular designs, more magnet utilization, low cogging motor designs etc. Those works also have indicated some important design parameters which are not designer's main concern before, such as winding inductance [13, 14].

The aim of this study is to find out the effect of slot-pole number variations on losses and its eventual impact on efficiency of LEV in-wheel BLDC motor. A finite element based computational software is conducted in the simulation study to obtain the needed data, a prototype of

Received on: 17.05.2017
Accepted on: 28.06.2017

the designed motor is manufactured and the test results are compared to calculated values [15].

2. BLDC In-Wheel Motor Simulation Study

The steps taken in this phase of study are shown in Figure 1.

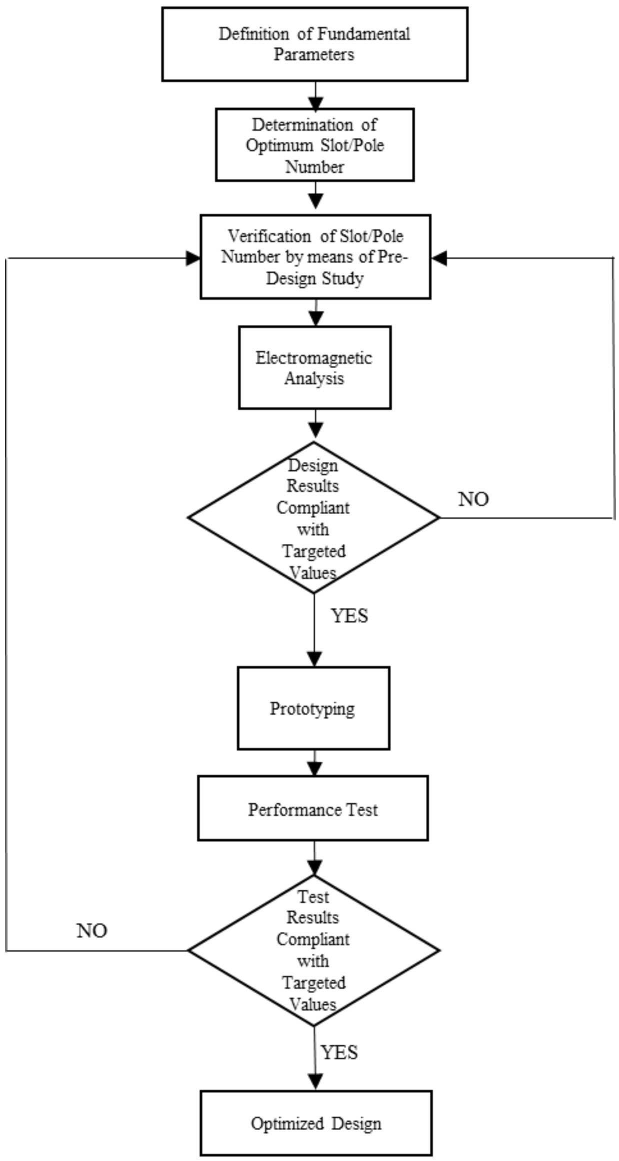


Figure 1. Design procedure of BLDC in-wheel motor

Firstly, the fundamental parameters and constraints of LEV application are defined. Then, a proper pole number depending on the motor rated speed is chosen and a corresponding slot/pole number which is enabling the required torque production is assigned for the design work. A pre-design study is realised by an electrical machine design configurator, i.e. ANSYS RmXprt. The qualified designs are investigated by the detailed electromagnetic FEA analyses to obtain more accurate results. The design is improved by using an algorithm loop which is providing a convergence to the targeted design values.

2.1. Simulation Study on Various Slot/Pole Combinations

The initial constraint of the simulation study is the constant output power, i.e. 2.5 kW. All design criteria in Table I are considered by means of their impacts on the motor performance. Other constraints are; 90 °C steady state operation winding temperature, slot fill factor in the range of 60-70%, air gap length of 1 mm, current density of 6 A/mm^2. In the light of these parameters, the slot/pole combinations of 24/18, 24/20, 36/24 and 36/30 which are suitable for in-wheel BLDC motor structure are investigated by means of FEA study. FEA is rather useful particularly for divergent slot/pole combinations [3, 15-17]. For the electromagnetic analysis ANSYS Maxwell software package is used and the results obtained are presented in Table 2.

Table 1. In-wheel BLDC motor design parameters

Parameter	Value
Output Power [W]	2500
Rated Voltage [V]	150
Rated Speed [min^{-1}]	900
Weight of Vehicle [kg]	350
Outer Diameter of Wheel [mm]	320
Type of Steel	M27_26G
Type of Magnet	NdFeB38

While investigating various designs that have different slot/pole numbers, not only the values in Table 1 are kept constant but also the slot structure, magnet geometry, air gap, slot fill factor, friction and wind losses are kept the same.

The total loss value and the related efficiency values' variation with slot/pole number, which sets the main background of the study is shown in Figure 2. It has been found that the armature copper loss exhibited a maximum for the 36 slot/28 pole configuration and the core iron loss was the worst in 36 slot/30 pole configuration with respect to other cases.

Induced current density variation, which is one of the most significant parameters in motors that decides whether the motor should be cooled by natural or forced convection is given in Figure 3. In this study, it is observed that none of the slot/pole configurations need cooling system.

Table 2. In-wheel BLDC motor design parameters

Slot/Pole	**24/18**	**24/20**	**36/24**	**36/28**	**36/30**
Average Input Current [A]	18.622	18.297	18.448	18.762	18.435
Armature Current Density [A/mm^2]	4.086	3.903	3.949	4.224	3.857
Frictional and Windage Loss [W]	36.791	37.007	34.751	28.049	30.815
Iron-Core Loss [W]	172.7	175.87	190.6	165.46	195.6
Armature Copper Loss [W]	83.765	32.146	41.838	120.52	38.649
Total Loss [W]	293.26	245.02	267.19	314.03	265.06
Output Power [W]	2500.1	2499.5	2500	2500.2	2500.2
Input Power [W]	2793.3	2744.5	2767.1	2814.3	2765.2
Efficiency [%]	89.502	91.072	90.344	88.842	90.415
Rated Speed [min^{-1}]	1313.3	1320.9	1241.6	1004.8	1102.7
Rated Torque [N.m]	18.178	18.071	19.228	23.762	21.651

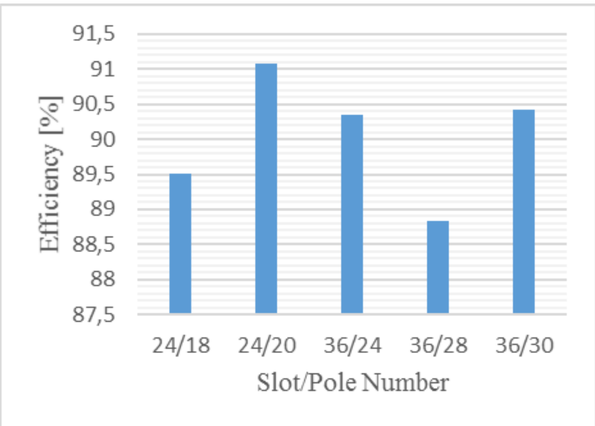


Figure 2. Impact of slot/pole number variation on efficiency

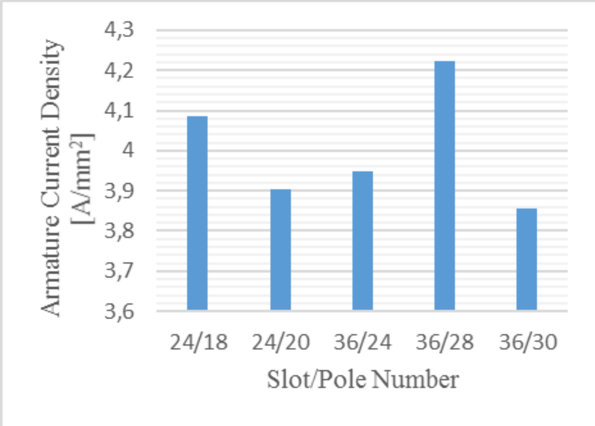


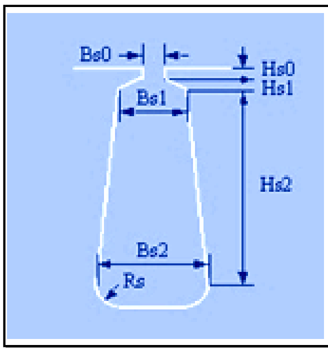
Figure 3. Impact of slot-pole number variation on current density

When the simulation results are assessed (Table 2), 24 slot/20 pole configuration stands higher than all other configurations both in terms of induced conductive current density and efficiency values.

2.2. Simulation Study for Various Slot/Pole Combinations

As a result of various slot/pole combinations, the simulation of 24/20 type motor is singled out as an outstanding candidate of prototype motor, then the impacts of differed slot dimensions on the efficiency of motor is investigated. An example of optimized stator slot sizing is given in Figure 4. In this design study, slot fill factor is chosen an admissible value of 70% and the constant output power is considered.

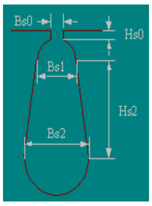
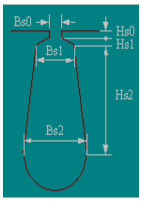
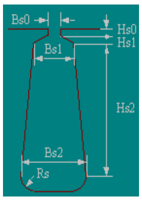
The investigation of different slot dimensions is given in Table 3. The stator tooth width, slot opening, slot height and slot width are taken as constants and the slot type is changed solely. Type-3 in Table is chosen due to its lower loss and higher efficiency values.



Stator Slot Sizing [mm]
hs0 (mm): 1.5
hs1 (mm): 1
hs2 (mm): 10
bs0 (mm): 5
bs1 (mm): 18.8279
bs2 (mm): 16.1949
Rs (^{0}) : 0.3

Figure 4. Stator slot sizing

Table 3. Different slot dimensions

	Type 1	Type 2	Type 3
			
Average Input Current [A]	18.2969	18.4405	18.1867
Armature Current Density [A/mm^2]	3.90272	3.91225	3.91193
Frictional and Windage Loss [W]	37.0072	40.8065	40.2617
Iron-Core Loss [W]	175.87	196.092	156.862
Armature Copper Loss [W]	32.1458	29.5163	31.2289
Total Loss [W]	245.023	266.415	228.353
Output Power [W]	2499.51	2499.66	2499.65
Input Power [W]	2744.53	2766.07	2728
Efficiency [%]	91.0723	90.3685	91.6293
Rated Speed [min^{-1}]	1320.88	1453.86	1434.84
Rated Torque [N.m]	18.0702	16.4183	16.636

2.3. Detailed Investigation of 24/20 Slot/Pole Arrangement

The detailed electromagnetic analysis of the selected slot/pole type, i.e. 24/20 is conducted in this phase of study by using Maxwell analysis software. The magnetic flux distribution and flux lines of the designed motor are given in Figure 5 and 6. The utilization of magnetic core is defined by the proper flux distribution within some specific limits. The near saturated sections whose flux density is around 2T are shown in the edges of teeth only. Also as shown in Figure 6, the flux lines exhibit a smooth and homogenous distribution as expected.

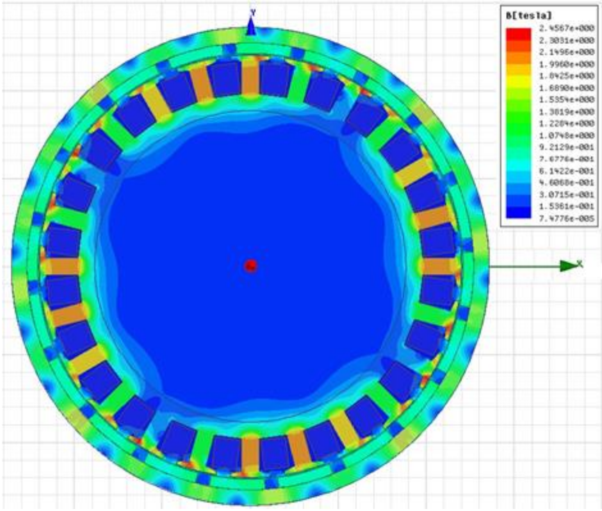


Figure 5. Two dimensional flux density distribution of prototyped 24/20 motor

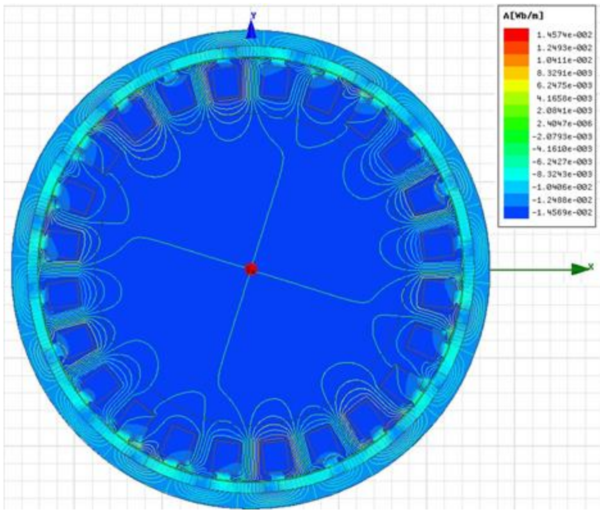


Figure 6. Flux lines of prototyped 24/20 motor

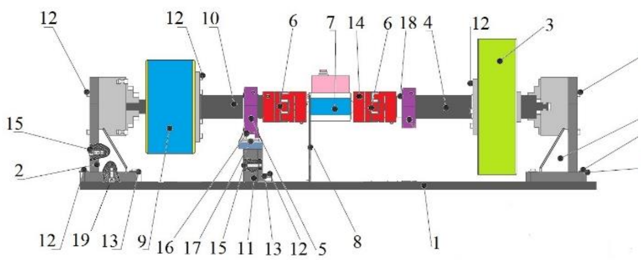
3. Prototyping and Experimental Study

For the stator manufacturing, the defined electrical steel material (M27-26G) is used by the help of simulated results. The stator structure is obtained by laser cutting method to eliminate any edge impurity. Total number of 56 laminations are stacked and fixed properly. The stator with completed winding fabrication is shown in Figure 7.

According to the admissible current density values, the conductors placed in stator slots are chosen with the cross sectional area of 2.2 mm^2. The slot fill factor is determined as 65% which is an adequate value for prototype fabrication. Also another important issue to be dealt with is the winding overhangs which are particularly large for alternate tooth wound motors. So the overhangs of stator windings are kept up to a proper limit which is ensuring the slimmer motor structure.

Figure 7. Stator with completed wound

A test setup is formed by using a loading mechanism which is consisting of an adjustable eddy current braking and a BLDC motor controller and required measurement devices. The test setup also uses a loading generator instead of eddy current brake. Braking device, eddy current brake or generator, is connected to the test motor via a torque transducer. In the eddy current brake, the loading power is dissipated on aluminum brake disc. In the generator case, three phase terminal voltages of the generator are rectified by a three-phase bridge rectifier and the output of the rectifier is supplying an adjustable loading resistor bank. The principal schema of test setup with the loading generator is given in Figure 8. Also in Figure 9 The photograph of test setup up with PM eddy brake loading mechanism is shown.



Part Number	Name of Part	Part Number	Name of Part	Part Number	Name of Part
1	Bottom Plate	8	Holder of Transducer	15	Bolt
2	Holder	9	Load	16	Bolt
3	In-Wheel BLDC Motor	10	Flange of BLDC Motor	17	Distance Ring
4	Flange Connection	11	Wedge of Bearing	18	Stay Bolt
5	Bearing	12	Bolt	19	Connection Device
6	Flange Coupling	13	Distance Ring		
7	Torque Tranducer	14	Bolt		

Figure 8. Structure of test setup

Due to the higher accurate precision measurement requirements, all parts of the test bed are designed, assembled and calibrated precisely. 2.5 kW, 150 V in-wheel motor is supplied via a BLDC motor driver which is designed especially for testing purposes. The motor performance is captured for various loadings and different terminal voltages and the overloading tests are also conducted. The discrete and continuous adjustable resistors are used to adjust proper accurate loading, i.e. output power values. The no-load current and no-load speed of the tested motor are measured as 2.1 A and 1016 min^{-1} consecutively.

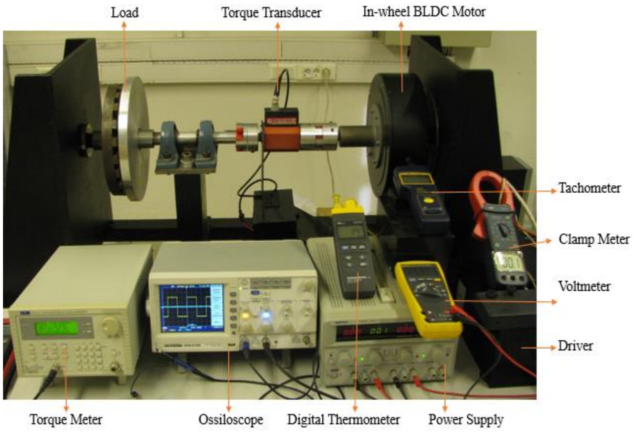


Figure 9. Test setup

The heating test is conducted by using the winding resistance increase method and also by capturing some certain temperatures via the temperature sensors in the motor. Also input power is measured by using a power analyzer which is giving the reliable values of input power measurement. In Figures 10,11 and 12, the simulated and measured values of efficiency versus shaft speed, output power versus shaft speed and shaft torque versus input current are presented, respectively.

In analysis of the test results, an agreement is shown between the tested and the calculated values of motor performance. Thus, the comparison of the tested and simulated results verifies the validation the design study.

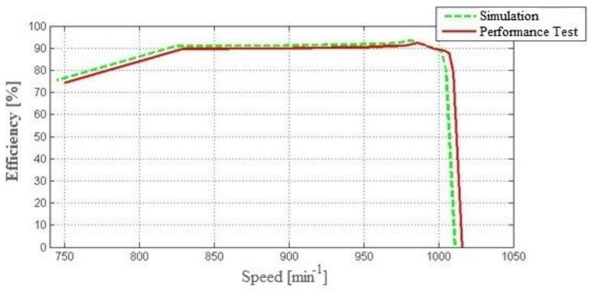


Figure 10. Efficiency versus shaft speed.

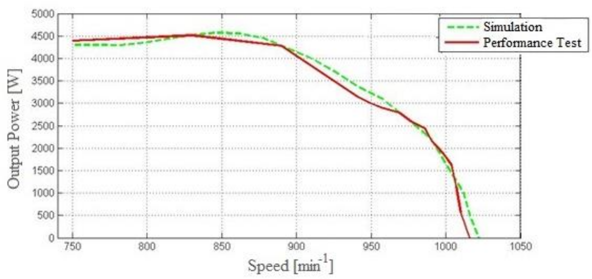


Figure 11. Output power versus shaft speed.

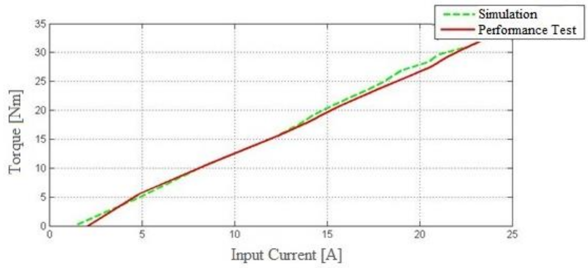


Figure 12. Shaft torque versus input current.

4. Conclusions

In this study, the impact of various slot-pole combinations on an in-wheel BLDC motor is investigated by means of simulations and tests. The motor structure is particularly designed for a direct driven LEVs. For proper propulsion of LEVs, the motor has some certain performance requirements including efficiency. The design study is based on slot-pole variations and their effect on preferential performance parameters such as shaft torque, speed and efficiency. An electromagnetic FEA software is used for designing purposes. After a search study, the selected slot-pole arrangement is analysed in detail and also its effect of motor structure is investigated substantially. A prototype of optimized motor design is manufactured and tested according to the focused design parameters. The simulated and measured values are in agreement which shows the validation study and initial approach to the design work. The study also shows the importance of unconventional slot/pole combinations and design topologies to get rid off cogging torque and to satisfy higher efficiencies. Furthermore, slim motor designs with shorter winding overhangs and segmented stator designs which enable fast and cost-effective manufacturing are only possible by means of some certain slot/pole combinations.

ACKNOWLEDGMENT
This work was supported by the Institute of Pure and Applied Sciences at Marmara University in Turkey through Grants under Projects FEN-C-DRP-110412-0096.

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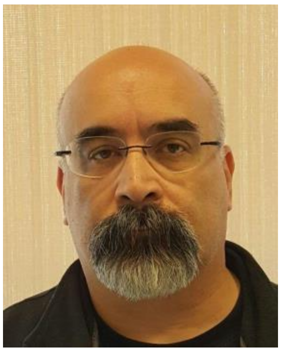

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