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# Project, design and tests of in-wheel outer-rotor PMSM for electric car application. Part 1

***Abstract**. In the paper design method, construction, of electrical machine for direct drive in the electric car is concisely presented. It is accepted that vehicle is to be driven by two machines placed in the 15 inch back wheels ring. Each machine of 5 kW power for rotating velocity 330 rpm permits three times torque overload and 70% rotational speed increase. The multi-pole synchronous machine with surface permanent magnets and external rotor is applied.*

***Streszczenie.** W pracy, w syntetyczny sposób przedstawiono metodę projektowania, konstrukcję, maszyny elektrycznej do bezpośredniego napędu samochodu elektrycznego. Przyjęto, że pojazd jest bezpośrednio napędzany dwoma maszynami umieszczonymi we wnętrzu piętnastocalowych obręczy kół tylnych. Każda maszyna ma moc 5 kW przy prędkość obrotowej 330 obr/min, oraz zapewnia trzykrotne przeciążenie momentem i 70 % zwiększenie prędkości obrotowej. Zastosowano wielobiegunową maszynę synchroniczną z powierzchniowymi magnesami trwałymi i zewnętrznym wirnikiem. (**Projekt, konstrukcja i badania silnika synchronicznego z magnesami trwałymi do bezpośredniego napędu samochodu. Część 1**).*

**Keywords**: electrical car, direct drive, permanent magnets synchronous machine, design and test of electrical machine.
**Słowa kluczowe**: samochód elektryczny, silnik synchroniczny z magnesami trwałymi, projektowanie i testowanie silnika elektrycznego.

## Introduction

In the recent years development of electrical cars has greatly increased. Nowadays all leading car manufacturers have this type of vehicle in their offer. Due to limited carrying capacity, high cost, and considerable mass of presently produced batteries most often vehicles with electrical drive are small urban cars with limited speed and range.

For the reason of high cost of electrical car on the actual stage of their development, they can be reasonably applied as a specific destination vehicles from the point of view of site of use and special equipment. For this kind of vehicle the presented in the paper electric drive machine was designed and built. Such a car could be used among the others in the separated areas in which from the ecological reasons the use of gas engine cars is banned. Besides, adopted in the car special constructional solutions as movable suspension, ability of on-board accepting and fastening a wheelchair with passenger, makes the vehicle ready both for able and disable people. To meet above functionalities and additional necessity of equipping car with several batteries the most important was to place drive machines in unused volume of wheel ring. Applying direct wheel drive has following advantages:

- Each wheel torque could be independently and quickly adjusted within the wide range that allow to achieve unique traction properties;
- Quicker elimination of wheel slip results in reduction of breaking distance;
- Elimination of gear box, differential and mechanical way of mechanical torque transmission increases efficiency and reliability of drive;
- Enlarging of cabin space.

Disadvantages are:

- Bigger machine mass and increase of unsuspended mass that may deteriorate comfort and security of passengers. Recent independent experimental tests prove those fears being baseless [1] [2];
- Danger of steerability loss as a result of one machine failure. Protection against this situation could be advanced control system or division of each machine in to independently controlled modules.

In the literature one can find numerous novel solutions of construction of electrical machines applied in vehicle drives. From the point of view of high power density and high efficiency the constructions with permanent magnets prevail [3] [4] [5] [6] [7] [8] [9] [10] [11]. Revision of drive systems presented in [10] reveals that in nowadays produced electric cars verified solutions of drive systems utilizing Induction Motors, Synchronous Motors with electromagnetic excitation and even DC Motors are still used. In most cases these are high speed motors that replace fuel engine while gear box, and conventional mechanical torque to wheel differential transmission is kept unchanged. From the data presented in [12] it is evident that as the years went by the use of permanent magnet machines increase. This is a result of higher efficiency and lower mass comparing to the others machines. Fears of car manufacturers concerning common use of Permanent Magnet Motors evoked from lack of certainty of their long time reliable operation, higher costs and possibility of cost increase due to permanent magnet market supply.

In respect to magnetic flux direction Permanent Magnet Machines are divided into machines with radial field [3] [4] [7] [8] [10], axial field [5] [11] and transversal field.

Direct drives machines should secure:

- High torque density in the limited volume - more often the volume of wheel rings. Above requirements to the highest extend meet machines with radial flux, surface magnets placement and outer rotor. In these machines rotor thickness (in radial direction) is small. Air gap between rotor and stator radius is closest to the limited external machine radius. This assuming the high electromagnetic force produced on big radius despite limited machine length results in high electromagnetic torque;
- Capability of machine division in to separately supplied sections for limitation of range and consequences of machine failure;
- Maximal utilization of radial direction volume. This requirement to the highest extends meets machines with fractional-groves winding in form of concentrated coils placed on individual stator teeth;
- High continuous torque necessary for high loads e.g. while driving up-hill, and several times short-time torque overload necessary while accelerate. For long time overload intensive cooling utilizing liquid cooling medium should be available. For short time maximum torque overload, thermally secure magnets shouldn't undergo even fractional demagnetization;
- Adequately high winding inductances for field attenuation at high rotational speed secure permanent magnets safety during winding short circuit.

The above requirements to the highest extend meet machines with radial flux.

In case of axial flux high volumetric torque density machines there is necessity to apply double sided machines with double rotor [5] or double stator [11]. Positioning of such a machine in limited wheel space is hard due to necessity of solid fixing of wounded stator core (high torque) and using liquid cooling system. Machines with transversal field offers good volumetric torque density but their magnetic circuit space structure is hard to made using packed core of electrical sheets [9]. Solution of above problem is utilization of powder cores [6] but this new technology is not fully verified, especially from the point of view of strength in the hard car exploitation conditions. Apart of that stator of this machine couldn't be divided in to separately-supplied angular segments in order to increase reliability.

In the research work it is assumed that projected machines should allow to fulfill the following traction requirements: maximal velocity 60 km/h, mass around 1000 kg, operating velocity of 30 km/h along way of 7% inclination, ability of exiting garage with 25% roadway inclination, acceleration while starting 1,5 $m/s^2$, acceleration while passing with velocity 40 km/h – 0,5 $m/s^2$. Applying the methodology presented in [13] and taking into consideration that car is directly driven by two motors placed in the inner space of fifteen inch back wheels rings, the nominal parameters of electrical machine was defined: power 5 kW and rotational speed 330 rpm. Additionally machine has to provide three times torque overloading and rotational speed increase by 70%.

Having in mind above requirements and limitations and taking into consideration solutions of machines with radial field construction used in electric car drives [3] [4] [7] [8] [10] the multi-pole machine with surface permanent magnets and outer rotor [3] [10] was chosen. Due to substantial allowable overloads the cooling system with liquid cooling medium contacting inside channel of stator frame on which the core is infixed [10] is proposed.

### Structure of the PMSM

Machine realizes direct drive of car wheel. It is multi-pole machine with surface permanent magnets, external rotor and concentric fractional-groves winding. Stator is mounted to a car suspension system. Car wheel is screwed down to machine's rotor. Bearing system is adapted to transmitting radial forces and side forces originated from wheel – surface reaction. In the machine five main parts realizing definite functions could be distinguished: winded stator, rotor with permanent magnets, hub, cooling system and sealing system. These parts are presented on figure 1.

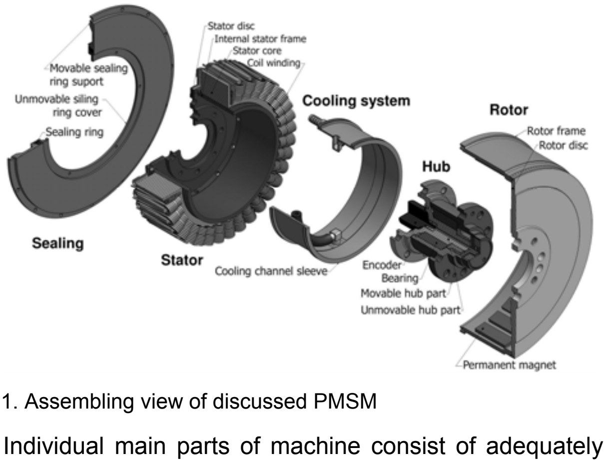


Fig.1. Assembling view of discussed PMSM

Individual main parts of machine consist of adequately linked together elements and details. Assembled main parts of machine are presented on figure 2. Stator consists of disc, internal frame and winded stator core. Frame consists of disc to which internal stator frame is welded. In the stator disc there are tapped holes for fastening machine to the suspension system, tapped holes for fixing unmovable hub parts, culvert holes through witch stator winding supply wires, signal wires from rotor position sensor (encoder), temperature sensors wires are outputted and input/output connector for cooling medium pipes. On the stator frame the stator core in form of stacked metal sheets is mounted. On straight stator teeth covered with insulation, coil winding was put on and glued. Appropriate coils are arranged in to phase belts with inputs connected to supply wires.

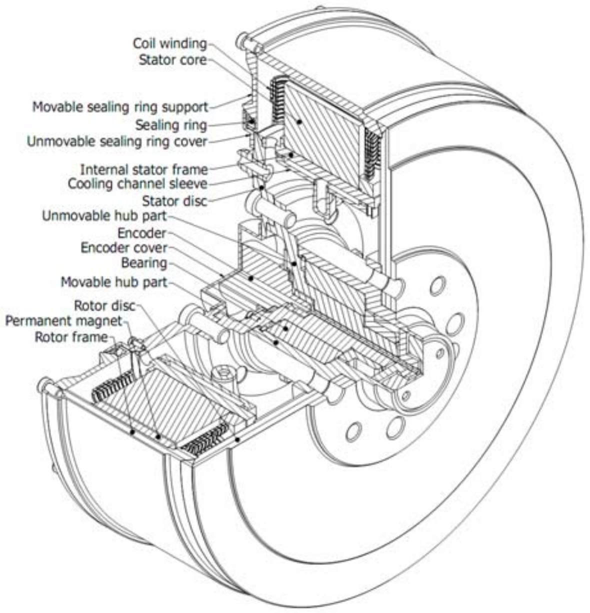


Fig.2. Main parts of the assembled PMSM

The internal side of stator disc is screwed to the unmovable hub part. Hub consists of unmovable and movable part and bearing. To the unmovable part of hub encoder is fastened. On the shaft of unmovable hub part the internal, split bearing ring, stressed and protected using special nut is mounted. In the internal socket of movable hub part the external bearing ring is mounted. Movable hub part is connected by rod through hole in the unmovable hub part with encoder shaft.

Rotor that consists of rotor disc with welded rotor frame is screwed to the movable hub part. On the internal surface of rotor frame there are uniformly distributed and glued neodymium magnets.

Cooling system is placed under the stator frame. It consists of sleeve, squeezed in to stator frame and set of pipes supplying and carrying off cooling medium. Sleeve together with internal surface of stator frame creates cooling channel of rectangular cross-section directed along stator frame perimeter.

Protection against penetration of pollutants into inside of machine is sealing system. Sealing system consists of movable ring screwed to the rotor. In the ring socket the elastic sealing V-ring is placed. To the V-ring slip lip the unmovable ring mounted on stator disc sticks. Appropriately formed rings (movable and unmovable) create together with elastic V-ring labyrinth-lip type sealing.

### PMSM design

Electric machine is the electro-mechanic converter with magnetic coupling. Precision of machine mathematical model depends mainly on precision of description of magnetic field distribution in the magnetic circuit. Depending on complexity level and accuracy of electro-magneto-mechanical phenomena description circuit and field models could be distinguished.

Circuit model is the simplest one that presents machine as a circuit of concentrated electrical, mechanical and electro-mechanical elements. These elements are defined by constant values parameters or evident functional dependences on model coordinates. During project stage, model parameters are determined on the base of calculations performed using simplified mean magnetic field distribution in the simplified magnetic circuit. This circuit contains the concentrated elements in form of magnetic voltage sources, resulted from current flow in the windings or permanent magnets and linear and nonlinear reluctances. The result of such a circuit solution are magnetic fluxes which allow only to determine mean values of flux density in the given circuit cross-sections – machine parts. The advantage of this model is very short calculating time of values of assigned constrains and machine exploitation parameters on the base of defined values of independent variables, unambiguously describing designed construction. Limited precision resulting from adopted simplifications is main disadvantage.

Field model of machine represents higher complexity description of mainly magnetic field in 2D cross-section or 3D volume of designed machine. For field modeling usually the special programs are used, which on the base of freely determined complex shape of modeled object and material properties of individual areas allows to determine using MES exact distribution of magnetic field. From this model it is possible to determine in the chosen point of cross-section or volume magnetic vector potential or flux density. Then using integral method the precise values of essential for design process parameters such as magnetic flux linked witch chosen winding and rotational torque produced in the machine are calculated. Advantage of field model is high precision of calculations, disadvantage is long calculation time and necessity of using hermetic programming environment.

Taking into account above considerations machine design was realized in the iterative way. The first stage of calculations was formulated as optimization task using circuit model. The results of optimization task solution were basic machine dimensions. Next on the base of worked out parametric field model MES 2D based on motor cross-section and adequately prepared calculation series the precise values of chosen parameters, calculated in simplified way in the first stage of calculations are determined. Verification concerns:

- Maximal values of magnetic field created by rotor permanent magnets linked with phase belt;
- Nominal value of rotational torque;
- Synchronous inductances;
- Angular permanent magnet width for which torque ripples are minimal.

On the base of parameters differences between circuit and field models correction coefficients are detrmined for circuit model and the first stage of calculations is repeated. Process is continued until relative parameter differences calculated in the first and second stage are smaller that adopted precision e.g. 0,1%.

**Project calculations based on circuit model**

Formulation of project calculations based on circuit model in form of optimization task requires definition of set of independent variables, objective function and set of constraints.

The following set of independent variables is adopted:

(1) $$x = [d_{si}, d_{sy}, d, d_{ri}, d_{re}, l, b_d]$$

where: $d_{si}$ –stator internal diameter, $d_{sy}$ – stator yoke diameter, $d$ – stator internal diameter, $d_{ri}$ – rotor core internal diameter, $d_{re}$ – rotor core external diameter, $l$ – stator stack length, $b_d$ – stator tooth width.

As a criterion of estimation of different construction variants, the active material costs, that is magnet, winding, rotor and stator core costs are accepted. This function should be easy modified to the form defining volume or mass of active materials or total cost of machine. Defined in this way objective function can be expressed as:

(2) $$f(\mathbf{x}) = \sum_{i=1}^{4} c_i \gamma_i V_i(\mathbf{x})$$

where: $c_i$ – cost of unit mass, $\gamma_i$ – specific mass, $V_i(\mathbf{x})$ – volume of material, as a function if independent variables. In the above formula index $i$=1, 2, 3… stands subsequently for: magnet, winding, stator core, rotor core.

The most important part of first stage project calculations is constrains definition. It is accepted that designed machine is characterized by nominal parameters: : $P_N$ - power, $n_N$ – rotational velocity, $U_N$ – supply voltage, $\eta_N$.- efficiency. Remaining constraints could be divided in to constraints concerning directly independent variables and constraints arranged in form of inequality sets that depends on set of independent variables, additional requirements that machine has to fulfill, material and constructional and others parameters which values are constant.

Constrains concerning directly independent variables, define lower and upper ranges ends to which values of independent variables belongs. For defining ranges ends the following parameters are used. They are easy to determine on the base of machine spatial and technological constrains:

$d_{\mathrm{remax}}$ - maximal external rotor diameter;
$d_{\mathrm{simin}}$ - minimal internal rotor diameter;
$l_{\mathrm{max}}$ - maximal stator core length;
$l_{\mathrm{min}}$ - minimal stator core length;
$h_{\mathrm{ysmin}}$ - minimal stator yoke height;
$h_{\mathrm{mmin}}$ - minimal magnet height;
$h_{\mathrm{yrmin}}$ - minimal rotor yoke height;
$b_{\mathrm{dmin}}$ - minimal tooth thickness;

Part of remaining constrains are in form of inequality:

(3) $$W_{dmin} - W_{obl}(\mathbf{x}) \le 0 \text{ or } W_{obl}(\mathbf{x}) - W_{dmax} \le 0$$

where: $W_{dmin}$ – given minimal value of parameter, $W_{obl}(\mathbf{x})$ – calculated value of parameter, $W_{dmax}$ – given maximal value of parameter.

Last part of constrains are defined in form (3) on the base of given values: minimal efficiency equal to nominal efficiency, maximal temperature difference between channel wall and cooling medium, maximal value of magnetic flux density in the magnet, that secure magnet from demagnetization, maximal winding current density, minimal stator tooth height, minimal magnet height, minimal stator yoke height, minimal rotor yoke height, maximal value of fill up of grove cross-section with copper coefficient, maximal value of supply voltage for nominal rotational velocity.

Fully defining project task requires following set of constant values of constructional, material and others parameters.

Additional dimensions:

$\alpha_e$ – relation of magnet angular span to angular pole pitch,

$\delta$ - air gap thickness, [mm]
$h_{d1}$ – tooth height above winding, [mm]
$b_{iq}$ – grove insulation thickness, [mm]
$d_{lm}$ – magnet length increment in respect to stator packet length, [mm]
$d_{lr}$ – rotor core length increment in respect to magnet length. [mm]
Winding parameters:
$m$ – phases belt number,
$p$ – pole pair number,
$Q$ – stator groves number.

Moreover in the design task the set of material parameters of magnet and stator core and coefficient set describing additional power losses is utilized.

Programmatic realization of optimization task was executed in Matlab environment using fmincon procedure. Taking in to consideration requirements resulting from procedure functionality, computer based realization of optimization problem solution required creation of adequate Matlab programs and scripts.

**Program for given criterion values calculation** in form of Matlab function file. This function calculates the cost, mass or volume of active materials values.

**Program for constrains values calculation** in form of Matlab function file. This function calculates the inequality constrains values. In reality that requires to perform complete machine electromagnetic calculations, for given sinusoidal waveforms of induced voltages and currents. Calculations could be systematized in the following way:

a- Calculation of maximal value of magnetic flux produced by magnets linked with phase belt, rotational induced voltage for nominal rotational speed and assumptions that there is one bar in the grove, mechanical losses, ideal power and maximal grove mmf.

b- Calculation of maximal flux density leading to magnet demagnetization, originated from winding mmf for maximal overload, critical flux density that doesn't lead to the permanent magnet demagnetization, depending on magnet operational point and boundary of demagnetization characteristic linearity, and conditional determination of first constrains.

c- Calculations of dimensions and grove cross-section, current density, losses, efficiency, temperature difference between channel wall and cooling medium, winding inductance for one bar in the grove.

d- Calculation of bars number in the grove and normalized bar cross-section on the base of maximal value of supplying voltage for nominal rotational speed and given machine overload and control procedure.

**Supervising program for calculation course control** in script form that enable:

- introduction of nominal data, data that define constrains set, additional data and parameters for given values, control data – procedure options, data concerning magnetization characteristics of magnetic materials, loss characteristics, coordinates of boundary points of magnet magnetization characteristic and linearity boundary that depends on given magnet temperature,
- define of starting point, which could be new starting point defined by set of starting values of individual variables or results of solution of former optimization task,
- start of program of optimization task solution,
- perform of project calculations on the base of set of optimal values of independent variables,
- save calculation results in a file.

**Project calculations based on field model**

Calculated in the previous stage of basic machine dimensions allow to create field model of designed machine. Model was created assuming that magnetic field distribution doesn't change along machine length. For such assumptions field task is reduced to determination of magnetic vector potential z-coordinate in the nodes of net that discretize motor cross-section. To speed up calculations the symmetry conditions are utilized. As a result only the smallest non-repeated fragment of machine cross-section is modeled.

To uniform calculation environment field model was prepared using Matlab calculation tool in form of special text files using commands interpreted by professional program MES. This way of calculations organization allows for automatic preparation and solution of single or series of field tasks. Results of single task solution is determination of magnetic field distribution in the machine cross-section with precisely mapping shape for real, adequately adopted current values in the individual winding belts for given rotor position. For known field distribution, on the base of adequately defined surface or linear integrals the parameters that were approximately determined on the base of circuit model are calculated. As it was mentioned before using field model the subsequent parameters are verified:

**1. Maximal value of flux linked with winding belt**.

This is a magnetic flux created by machine rotor magnets that is maximally linked with winding belt. This flux is calculated on the base of single field task solution for zero values of stator belts current and for rotor position that secure maximal coupling of magnet flux with given (e.g. first) winding belt. This rotor position is called direct-axis in respect to first belt axis. Another characteristic rotor position is quadrature-axis position. In the quadrature-axis position in respect to given belt axis, magnets flux coupled with this winding belt is equal to zero.

Magnetic field distribution, created only by magnets for direct-axis rotor position in respect to first belt in the half of machine cross-section is presented on figure 3. Black dots mark teeth on which coils belong to the first belt are placed. Those coils connected in series create winding belt. End of 1st coil is connected to end of 2nd coil, next beginning of 2nd coil is connected to beginning of 3rd coil and so on.

Flux linked with $k$-th winding belt, assuming that each coil has only one turn is calculated on the base of two-dimensional magnetic field distribution in the cross-section of motor from dependence:

$$\psi_k = n_s l_{fe} \sum_{i=1}^{2Q/ns/m} sA_{ki} 10^{-3} \quad (4)$$

where: $n_s$ – number describing multiplication of modeled fragment In whole machine, $Q$ – number of groves, $A_{ki}$ – mean value of vector potential component in the cross-section area of $i$-th side of consecutive coil in the group of $k$-th belt, $s$ = 1 when current flows in to $i$-th side of coil, $s$ = -1 when current flows out from $i$-th side of coil, $l_{fe}$ – stator core length in mm.

**2. Nominal value of rotational torque**.

This is the maximal value of electromagnetic torque for nominal current. Torque is calculated on the base of solution of single field task. In this task currents in the belts are determined by chosen instant of time from one period of sinusoidal currents arrangement which amplitude is equal to maximal value of nominal current. While assigning current distribution in the belts these instants of time are chosen in which current in given belt reaches maximal value. Ten rotor could be positioned in respect to the axis of that belt. Torque has maximal value in quadrature-axis position of rotor in respect axis of belt with the maximal current value. For the maximal value of current in the 1st belt, quadrature-axis rotor position is shifted by 90 electrical degree in respect to direct-axis position presented on figure 3.

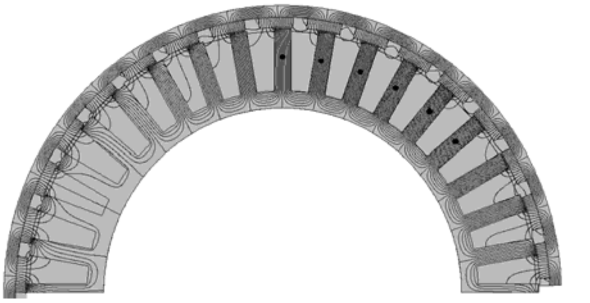

Fig.3. Magnetic field distribution created by magnets in the half of motor cross-section

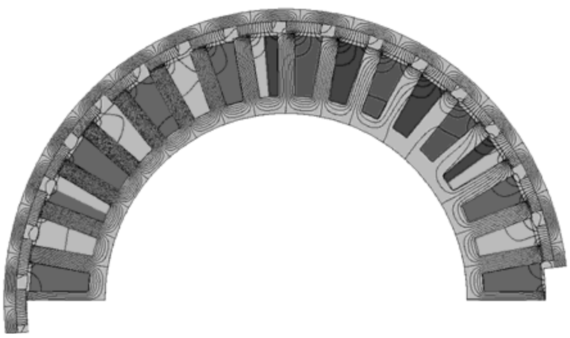

Fig.4. Magnetic field distribution for calculated nominal value of rotational torque

Value of electromagnetic torque $T_e$ in any rotor position is calculated on the basis of two-dimensional magnetic field distribution in the motor cross-section from dependence:

$$T_e = n_s r^2 l \int_0^{\vartheta_s} \frac{B_n(\vartheta, r) B_t(\vartheta, r)}{\mu_0} d\vartheta \tag{5}$$

where: $r$ – radius of curve in the air gap – path of angular density of tangent force integration, $l$ – machine length, $\vartheta_s$ – angular span of modeled part of machine, $B_n(\vartheta,r)$, $B_t(\vartheta,r)$ – normal and tangent component of flux density in respect to curve of radius *r* in the position described by angle $\vartheta \in (0,\ \vartheta_s)$, $n_s$ – as in (4).

**3. Synchronous inductance**s.

In the circuit model the synchronous inductances, defined as ratio of maximal value of flux linked with winding belt, produced by currents of all stator belts to maximal value of current in the direct-axis or quadrature-axis position are used. Included in inductance definition conditions for current flow in the quadrature-axis rotor position are the same as for nominal torque calculation in the previously. Therefore quadrature synchronous inductance (index q) could be calculated on the base of field distribution presented on figure 4. This inductance is calculated using formula (6) in which flux produced by currents, linked with 1[st] winding belt is the difference of the resultant flux (produced by currents and magnets) and flux produced only by magnets (for zero values of currents):

$$L_q = \frac{1}{i_m}\Big(\psi_{q1}(i_1 = i_m,\ i_2 = -i_m/2,\ i_3 = -i_m/2) - \\ -\psi_{q1}(i_1 = 0,\ i_2 = 0,\ i_3 = 0)\Big) \tag{6}$$

where: $\Psi_{q1}$ – flux linked with 1[st] belt for nominal current in this belt and quadrature 0 axis rotor position, calculated according to (4), $i_m$ – maximal value of nominal current.

Because in the quadrature rotor position magnet flux, linked with 1[st] belt is equal to zero so dependence (6) could be simplified:

$$L_q = \frac{1}{i_m}\psi_1(i_1 = i_m,\ i_2 = -i_m/2,\ i_3 = -i_m/2) \tag{7}$$

For direct-axis synchronous inductance there is necessary to solve field task in which current distribution is the same as on the figure 4, and rotor keeps direct-axis position (as on figure 3). In the direct-axis rotor position flux produced by stator currents can add to or substrate from magnet flux, depending on sign, that means direction of current in the belt. Field distribution necessary for direct-axis inductance calculations for fluxes co-operations is presented on figure 5.

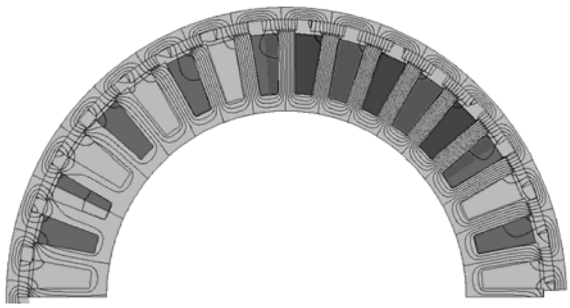

Fig.5. Magnetic field distribution for for direct-axis synchronous inductance calculation for conforming stator and rotor fluxes

Direct-axis synchronous inductance in both cases is calculated form dependence:

$$L_d = \frac{\psi_{d1}(i_1 = \pm i_m,\ i_2 = \mp i_m/2,\ i_3 = \mp i_m/2) - \psi_{d1m}}{\pm\, i_m} \tag{8}$$

where: $\Psi_{d1}$ – flux linked with 1[st] belt for nominal current and direct-axis rotor position, calculated using formula (4) $\pm i_m$ – maximal positive or negative value of nominal current, $\Psi_{d1m}$ – flux produced by magnets, linked with 1[st] belt (calculated in the section 1).

For positive current value, flux $\Psi_{d1}$ is greater than $\Psi_{d1m}$ but absolute value of fluxes difference due to magnetic circuit saturation is less than for negative current values. So direct-axis synchronous inductance for fluxes counteraction is greater than inductance for fluxes co-operation. This is advantageous while machine rotational speed increasing over the nominal value by decreasing of flux linked with stator winding belt.

**4. Magnet span for which the torque ripples became minimal**

In the aim to make angular magnet span on rotor pole pitch independent from pole number in the project calculations the coefficient of filling or cover pole pitch with magnets is introduced. This coefficient marked as $\alpha_e$ is defined as relation of angular magnet span to angular pole pitch.

With increasing of magnet span mass of the magnet which is most expensive material in the motor increase. In the same time, mean value of electromagnetic torque monotonously increase, although torque increment decreases (Fig. 7). For this reason magnet span is not an independent variable in the optimization task because for material cost criterion, optimal value of magnet span would be equal to minimal admissible value. It turns out that the magnet span influences also quantity of instantaneous electromagnetic torque ripple value. In the process of machine design one strives for minimizing of torque ripples for they are cause of vibrations and noise. The rule that magnet span will be determined in such a way that torque ripples are minimal is accepted.

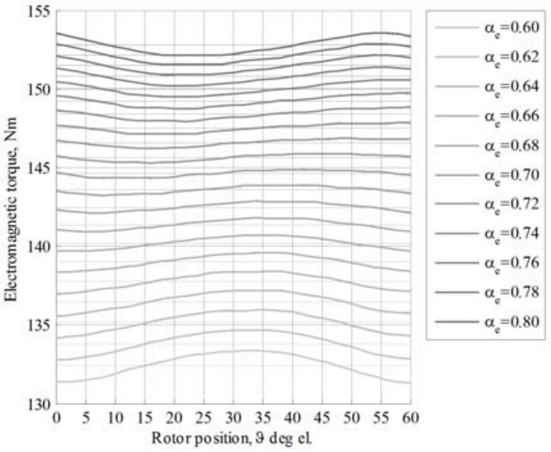


Fig.6. Instantaneous and mean values of electromagnetic torque in respect to rotor position for nominal current and quadrature-axis rotor position for different magnet span

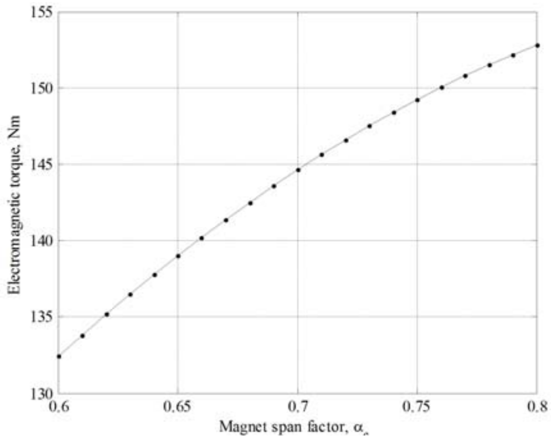


Fig.7. Dependence of mean electromagnetic torque value on magnet span for nominal current and quadrature-axis rotor position

For determining such a magnet span there is necessary to solve series of field tasks. For given magnet span, as a result of series of field tasks solutions the dependence of instantaneous electromagnetic torque on rotor position is calculated within the 60 electrical degree range. Simultaneously with rotor position change the belt currents are changed in such a way that constant quadrature-axis rotor position in respect to stator mmf is kept. The sinusoidal, mono-harmonic current waveform of nominal value is adopted. Calculations are repeated for few magnet spans.

On figure 6 the results of series of calculation in which the magnet span was changed within the range 0,6 to 0,8 with step 0,01. Apart of instantaneous value of torque using narrow line the mean torque value within the considered range of rotor position is marked. On figure 7 the dependence of mean torque value on magnet span is presented. Picture reveals that together with increase of magnet span magnet effectiveness represented by the quantity of produced torque decreases. For span increase from 0,6 to 0,8 that means 33% increase in respect to the initial value, torque increased from 132,5 to 152,5 Nm that means 15,1% increase.

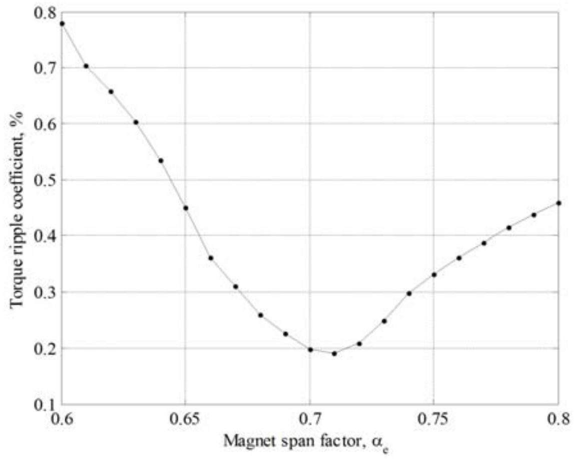


Fig.8. Dependence of torque ripples coefficient on magnet span for nominal current and quadrature-axis rotor position

For evaluation of torque ripples the torque ripples coefficient is introduced, defined as relation of difference of maximal and minimal value to the doubled mean value and expressed in per cent units:

$$k_{pT} = \frac{T_{e\max}(\vartheta) - T_{e\min}(\vartheta)}{2T_{em}} 100\% \tag{9}$$

where: $T_{e\max}$, $T_{e\min}$ – respectively maximal and minimal torque value for rotor position change $\vartheta$ in the range of 60 electrical degree, $T_{em}$ – torque mean value within this range.

Dependence of torque ripples coefficient on magnet span is presented on figure 8. Dependence reveals that minimal torque ripples occurs for magnet span defined by coefficient value $\alpha_e$=0,71.

**Results of project calculations**

Project calculations were performed according to described algorithm for three machine variants with different number of stator groves: 30, 36 and 42. Even number of groves was chosen to eliminate unbalanced magnetic pull. Unbalanced magnetic pull causes increase of vibrations and noise and quicker bearing wear. Such a pull exists if pole number differs from groves number by 1, e.g. 33 groves and 32 poles. For each number of groves few numbers of poles were considered. Finally those pole numbers were accepted for which winding factor is possibly biggest and period of cogging torque is possibly smallest. Exemplary values of cogging torque period and winding factor for 36 groves and few poles number are put together in Table1.

Table 1. Cogging torque periods and winding factors for 36 stator groves and different rotor pole numbers

| Rotor pole number | 24 | 26 | 28 | 30 | 32 | 34 |
|---|---|---|---|---|---|---|
| Cogging torque period, deg | 5,0 | 0,7692 | 1,4286 | 2,0 | 1,25 | 0,5882 |
| Winding factor | 0,866 | 0,8666 | 0,9019 | 0,933 | 0,9452 | 0,9525 |

Table 1 reveals that in case of 36 groves winding factor is biggest and cogging torque period is smallest for pole number equal to 34. In the same manner the most advantageous pole numbers in rest variants were chosen. In all cases pole numbers were less by 2 than groves number.

For each variant the project calculations were performed. In each case the same efficiency equal to 91%, external machine diameter limited by internal wheel diameter was accepted. Results of performed calculations reveal that 1st variant characterizes lowest mass and cost. Mass and cost increase for 2nd variant is hardly noticeable and amount respectively 2,3% and 1,5%. Third variant characterizes substantially higher mass and cost.

Table 2. Optimal values of independent variables

| Variable | Value |
|---|---|
| $d_{si}$ – internal stator diameter [mm] | 215 |
| $d_{sy}$ – stator yoke diameter [mm] | 235 |
| $d$ – external stator diameter [mm] | 307 |
| $d_{ri}$ – internal rotor core diameter [mm] | 321 |
| $d_{re}$ – external rotor core diameter [mm] | 335 |
| $l$ – stator stack length [mm] | 63 |
| $b_d$ – stator tooth width [mm] | 10 |

In the 2nd machine variant coils thickness is by 17% lower in respect to 1st variant. Due to this the heat emission from winding to the core and liquid cooled frame is better. Moreover in the second variant belt coil number linked in series is even and equal to 6. Such a coil group can be divided in to equal parts and obtain multiphase unsymmetrical winding. After division of coil group in to two parts with 3 coils in each the 6-belt winding is obtained that consists of two three-phase windings shifted one against other by 30 degree. Ability of dividing winding in to two separately supplied parts leads to higher reliability of drive. From this reason for prototyping the 2nd variant of machine with 36 groves and 34 poles is selected. Optimal values in mm of independent variables for selected variant are put together in Table 2.

**Summary**

In the paper the substantiation of choice of machine for direct electric car drive is presented. This is synchronous radial field machine with permanent magnets and external rotor. Considering low rotational velocity the multi-pole machine with concentrated fractional slot winding is applied. Due to high torque overload machine is cooled with liquid.

Construction of machine integrated with hub and encoder required for control circuit is described. Machine stator is mounted to car suspension system. Car wheel is screwed to the motor rotor.

The method of machine design, realized in the iterative way in two subsequent and severally repeated stages is presented. In the 1st stage the circuit model and optimization method is used, in the 2nd stage field model WES-2D is used.

Presented design method was used for calculations of three machine variants with the same efficiency but different groves and pole numbers. Substantiation of machine variant with 36 groves and 34 poles choice for prototyping is presented.

Regarding limited paper volume prototyping and tests results are presented in separate paper that is the second part of presented elaboration.

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