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Selected aspects of designing motor for direct vehicle wheel drive

Streszczenie. *Szerokie zainteresowanie elektromobilnością wzmaga wśród konstruktorów oraz producentów rozwój elektrycznych układów napędowych, w tym elektrycznych silników trakcyjnych. Poszukiwane są rozwiązania pozwalające na zwiększenie gęstości mocy silnika, zwiększenie jego efektywności energetycznej oraz ograniczenie kosztów produkcji. Duże znaczenie w tym zakresie odgrywa równieżdostępność materiałów, takich jak magnesy trwałe, niskostratne blachy elektrotechniczne czy żywice epoksydowe. Jednym zrozwiązańjest koncepcja zabudowy silników napędowych w piastach kół pojazdu, pozwalająca na bezpośredni (bez dodatkowych urządzeń pośredniczących) napęd kół. Rozwiązanie to choć znane od lat, w ostatnim czasie cieszy się coraz większym zainteresowaniem w praktyce. W niniejszym artykule przedstawiono kilka wybranych aspektów oraz problemów analizowanych w czasie projektowania tego rodzaju silnika z przeznaczeniem do pojazdu osobowego. Omówiono sposób doboru najważniejszych parametrów eksploatacyjnych silnika, wybrane problemy podczas projektowania obwodu elektromagnetycznego oraz możliwości poprawy niezwykle istotnego dla tego typu rozwiązania współczynnika gęstości mocy.* ***Wybrane aspekty projektowania silników do bezpośredniego napędu***

Abstract. *Widespread interest in electromobility results in intensified development (design and manufacture) of electrical drives, including electrical traction motors. Currently the attention is focused on searching for motor designs with increased power density, increased power effectiveness and limited manufacturing costs. The accessibility of materials such as permanent magnets, lamination sheets with low lossiness or epoxy resins is also significant. One possible solution is to build drive motor into a wheel hub. This allows for a direct drive, without additional intermediate devices. This type of design has been known for years, but lately it started to evoke more and more practical interest. Several selected aspects and issues arising in design of motor dedicated to passenger vehicle are presented in this paper. The method of selecting motor's most important operational parameters is discussed as well as some problems with design of electromagnetic circuit and possibilities of improving power density coefficient, which is a major issue with motors of this particular type.*

Słowa kluczowe: silnik w piaście koła, silnik z magnesami, napęd elektryczny.
Keywords: wheel hub motor, permanent magnet motor, electric drive.

Introduction

Widespread interest in electromobility results in intensified development (design and manufacture) of electrical traction motors. Currently the attention is focused on elaborating designs of high-efficiency drive units. "High-efficiency" corresponds to designs with high values of power density coefficients, high efficiency coefficients and with limited manufacturing costs taken into account. Accessibility of materials is most important (permanent neodymium magnets, low-lossiness electrical sheets, epoxy resins).

Lots of projects related to electric traction drives have been undertaken in Institute of Electrical Drives and Machines KOMEL [1]. Current project is focused on design of motor built into the wheel hub and dedicated to direct drive of electrical vehicle. This project is financed by Narodowe Centrum Badań i Rozwoju (National Centre for Research and Development) within the framework of LIDER VII programme. This type of design has been known for some years, but lately it has aroused much interest. During the project numerous numerical analyses were run in order to develop electromagnetic circuit, cooling system and mechanical design of the motor [2,3,4]. Two prototype motors (shown in Fig.1) were designed, built and lab tested on the basis of these analyses.

Several selected aspects and issues analysed during design of investigated motor dedicated to passenger vehicle are presented in current paper. Method of selecting most important operational parameters of the motor is discussed as well as selected problems of electromagnetic circuit design and possibilities of improving power density coefficient (power per unit mass), which is most significant in case of such design. When wheels are directly driven (and proper operational parameters are maintained at the same time), reduction of motor weight is a priority, since this mass is classified as unsprung mass [4,5,6].

Prototype motor No.2 is an "evolutionary" version of prototype motor No.1. It has been designed taking into account conclusions drawn from analysis of previous version's tests. The basic parameters of both motors are presented in Table 1. It must be stressed that design of version 2 is not ultimate, since research is still under way.

a) b)

Fig.1. a) Prototype motor No.1, b) Prototype motor No.1

Table 1. Basic parameters of prototype motors dedicated to wheel hub assembly

Parameter			Motor nr 1	Motor nr 2
Rated power	P_n	[kW]	49.5	60
Rated torque	T_n	[Nm]	450	420
Rated rot. speed	n_n	[rpm]	1050	1360
Rated voltage DC	U_{DC}	[V]	350	350
Rated current	I_n	[A]	175	195
Efficiency	η	%	91.1	93.5
Number of poles	2p	-	32	56
Max. torque	$T_{max.}$	[Nm]	750	730
Max.rotational speed	$n_{max.}$	[rpm]	1360	1360
Mass	M	[kg]	36	28

Determination of basic operational parameters of the motor

At the start of design procedure for electromagnetic circuit of motor dedicated to direct wheel drive in passenger car we must first of all take into account size limitations arising from wheel rim and brake dimensions. In case of discussed prototype motors, we have assumed that wheel rim is size 17'' and that car will be driven by motors built into each wheel of rear axle. The following size limitations for electromagnetic circuit of the motor have then been determined:

- Rotor's outer diameter– max.375 mm
- Stator's inner diameter – min. 280 mm
- Length of active iron laminations– max. 60 mm

It must be noted that size limitations are present for outer (maximum) dimensions and inner (minimum) dimension both. In order to determine the required motor parameters, we must first of all use the traction curve of the vehicle to which we dedicate the new motor. For instance, traction curves for 3 selected vehicles are shown in Fig.2. To calculate these curves, it has been assumed that vehicle travels along a planar surface (inclination is 0%).

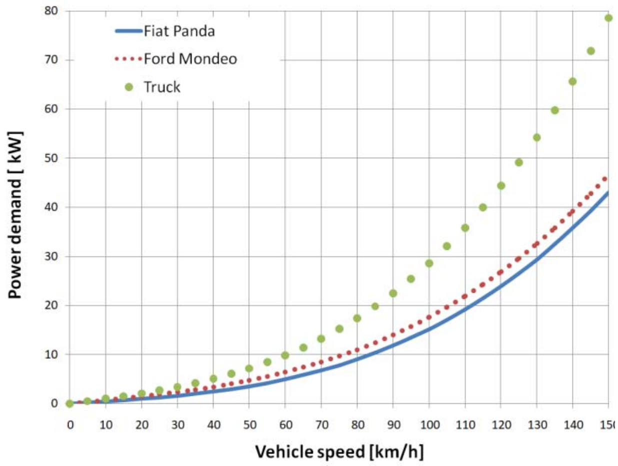


Fig.2. Theoretical traction curves of selected vehicles vs. speed

The basic motor parameters which should be determined and which adequately characterise possibilities of the drive are [7]:

- maximum rotational speed,
- rated rotational speed,
- motor's rated power,
- rated torque,
- maximum torque,
- maximum speed obtainable for maximum torque.

Maximum motor's speed (with wheel dimension taken into consideration) will determine maximum possible vehicle speed. In case of discussed prototype motors this speed is 1360 rpm. This parameter has been selected in such a way that it might be possible to attain maximum speed of *c.* 150 km/h. It may be observed that maximum power demand (without taking into account transient/instantaneous states) corresponds to maximum speed. Moreover, if we consider that the user might want to drive at maximum speed over extended periods of time, motor should be characterized by possibility of operating at power corresponding to maximum speed (*cf.* traction curve) for a long time. Therefore, we must initially assume that this is the required rated power and speed. During subsequent design stages these values may be modified on account of other reasons; still, the values determined in the described way are minimum values required of the motor. Therefore, in the discussed case it has been determined that rated power should be equal to at least 25 kW at 1360 rpm (one axle carries two motors). The supply voltage has been calculated for this rated power and it is equal to 350 V DC.

In order to determine remaining operational parameters of the motor, several chosen operational states of the vehicle have been analysed. These are:

- Case 1 – uphill drive, inclination 20%, constant speed 50 km/h, route length 1 km
- Case2 – uphill drive, inclination 15%, route length 5 km
- Case 3 – acceleration up to 100 km/h over 15 s
- Case 4 – acceleration up to 100 km/h over 10 s.

It must be noted that all above operational states may be classified as instantaneous states. Going uphill at 50 km/h over 1 km route will take e*c.* 1min, while with speed equal to 70 km/h and route length 5 km it will take *c.* 4.5 min. Therefore, the calculated power and torque parameters should be treated as instantaneous values as well.

Table 2. Characteristic operational states of the vehicle with calculated motor parameters for Fiat Panda and 2 motors at axle

	Motor parameters		
Case 1 Car speed 50 km/h – Inclination 20%, route length 1 km	P	kW	23.5
	T	Nm	500
	n	rpm	450
Case 2 Car speed70 km/h – Inclination 15%, route length 5 km	P	kW	26.3
	T	Nm	400
	n	rpm	630
Case 3 Car acceleration: 0-100 km/h in 15s	P	kW	49
	T	Nm	520
	n	rpm	900
Case 4 Car acceleration: 0-100 km/h in 10s	P	kW	70
	T	Nm	740
	n	rpm	900

Looking at results shown in Fig.2 and Table 2, the following regularities may be discerned:

1. Only driving at constant speed may be classified as a continuous duty operation. Maximum speed for traction curve determines minimum required long-lasting power (for a given speed),
2. Car's maximum torque is governed by vehicle dynamics. As the time required for attaining a given speed is reduced, the maximum torque must be increased. In some cases, maximum torque may be additionally determined by e.g. driving over a curb,
3. Apart from maximum value of the torque, speed value corresponding to average maximum torque should be considered (this results from case 3 and case 4). If this speed is lower, then time required for attaining the assumed speed (e.g. 100 km/h) will be longer, since torque will have to be reduced (constant power zone operation),
4. Maximum speed of the motor is imposed by assumed maximum speed of the vehicle.

Table 3. Parameter values for prototype motors - required and obtained during lab tests; maximum speed has been assumed to be equal to rated speed.

Parameter		Required value	Motor No. 1	Motor No. 2
Rated rot. speed	[rpm]	1360	1360	1360
Max. rotational speed	[rpm]	1360	1360	1360
Rated power	[kW]	25	45	60
Rated torque	[Nm]	175	315	420
Max. torque	[Nm]	750	730	710
Max. rotationalspeed for max. torque	[rpm]	900	900	900
Mass	[kg]	30	36	28

Basing on the above analysis, the minimum required parameters of direct wheel drive motor for Fiat Panda car have been assumed:

- maximum/rated rotational speed – 1360 rpm
- Motor's rated power– min. 25 kW

- rated torque –min. 175 Nm
- maximum torque– 750 Nm
- maximum speed attainable for average maximum torque – *c.* 900 rpm.

Taking the above requirements into account together with the size limitations, a multi-variant analysis of different designs of electromagnetic circuits for prototype motors has been carried out. Finally, the designed prototype motors were manufactured. Their parameters calculated from laboratory tests as well as required parameter values are set in Table 3. It must be noted that determined rated values relate to rated/maximum speed.

Analysing the data set out in Table 3, we may observe that for prototype motors continuous power and torque values are almost twice as high asrequired values. These values are due inter alia to a distinct motor design (dimensions); while the assumed requirements as to maximum power and torque are met, the continuous power value is very high. Motor weight was the superior criterion used in modification of motor design (prototype No.1). It has been limited to less than 30 kg thanks to increased number of magnetic pole pairs and decreased height of stator core; at the same time, area of surface giving up the heat in the cooling system has been increased. Additionally, lots of work in this project have focused on elaboration of highly effective cooling system – see Fig.3.

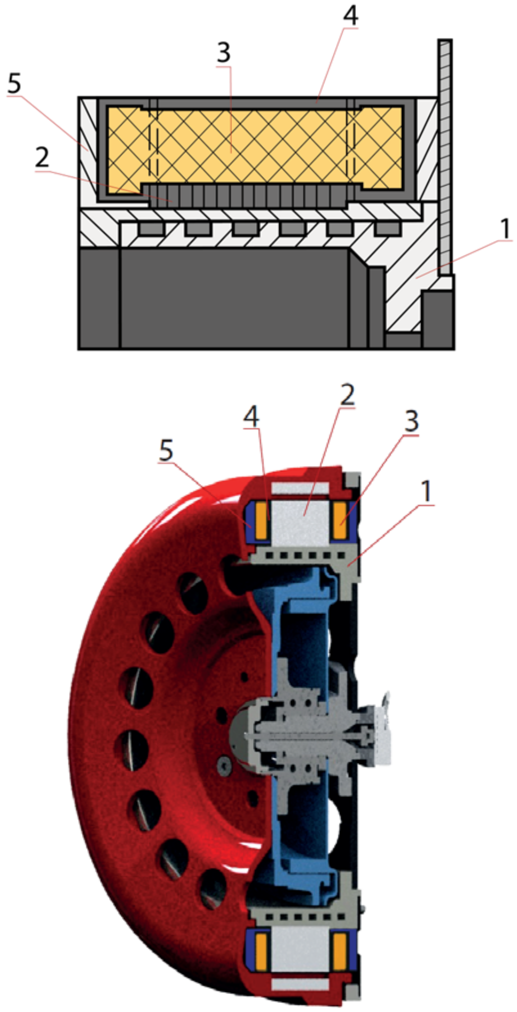


Fig.3. Cross-section of prototype motor No.1 and scheme of cooling circuit: 1 – structural element of the stator with water jacket, 2 – stator core, 3 – winding, 4- thermally conducting epoxy, 5 – aluminium radiator

Power density coefficient and motor weight

In case of motors built into wheels, motor weight is of primary importance. This is so-called unsprung mass which influences suspension performance and drive comfort. Additional wheel weight increases magnitude of suspension vibrations and lengthens their attenuation [4,5,6].Therefore, we should aim at smallest possible weight of motors built into wheels. In the current project it has been assumed that a single motor should weigh *c.* 30 kg. Managing the required values (see Table 3) of the different parameters simultaneously with the imposed weight limitation is difficult. Moreover, it should be noted that when weight/volume of active materials in electromagnetic circuit is decreased, motor's efficiency usually falls down as well. That is why in case of the discussed design particular attention has been paid to the selection of proper materials as well as increasing the effectiveness of the cooling system. These issues have been investigated and presented e.g. in [3].

After analysing different variants of cooling system, a system of special aluminium radiators has been applied in prototype motor No.2; these allow for better flow of heat from coil outhangs to the housing. The space between winding and housing has been packed with dedicated thermally conducting epoxy (Fig.3).

On account of high operating frequency (*c.*600 Hz), stator/rotor cores use low-lossiness sheets of Hi-Lite type, 0.27 mm thick. Use of a greater number of magnetic poles has made it possible to decrease rotor core height; hence stator/rotor core weight has been limited and the outreach of coil outhangs has been decreased as well.

Application of these solutions brought about the attainment of required values of maximum motor torque and speed (prototype motor No.2), while motor weight was lessened by *c.* 8 kg. Moreover, for the maximum rotational speed, continuous power of 60 kW has been obtained. This operating point has been adopted as rated point in accordance with the methodology described earlier and taking into account the fact that it is maximum continuous power. Finally, power density coefficient for rated power is equal to 2.14 kW/kg.

Eddy-current losses in rotor/magnets

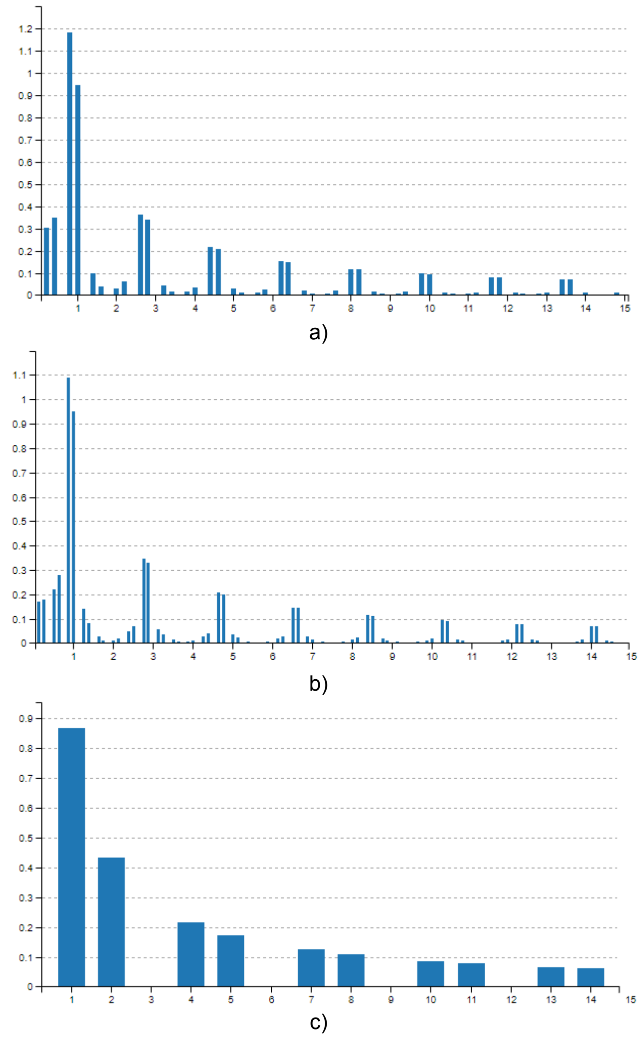
Obtaining suitably high number of magnetic pole pairs, while motor dimensions are limited by wheel size, is possible only if concentrated-type winding is used. Then, different combinations of number of magnetic poles $2p$ and number of stator slots Q_s may be applied. However, it must be remembered that apart from high winding factor obtained for each $Q_s/2p$configuration, another significant issue here is spatial distribution of magnetomotive force. MMF influences the extent of eddy-current losses in permanent magnets and in rotor (in case of solid rotor) [8,9,10]. This is even more important, if high operational frequency of the motor and high values of specific electric loading are considered.

Comparison of the MMF's spatial harmonics' spectra for three selected combinations of number of pole pairs $2p$and stator slot number $Q_s$is shown in Fig.4.These variants were analysed when electromagnetic circuit of prototype motor No.1 had been designed. Same cases are shown in Table 4, but values given are those calculated for eddy current losses and rotor core losses (assuming solid-type rotor).

The results shown in Table 4 prove a significant relationship between selected configuration of stator slot number/ number of magnetic poles and eddy-current losses in permanent magnets and rotor. In case of configuration $2p = 32$, $Q_s = 48$ the value of PM losses obtained was *c.* 10 times less than in remaining two cases. In order to limit eddy-current losses in permanent magnets, particular attention must be paid to magnitudes of spatial harmonics lower than fundamental harmonic (i.e. sub-harmonics). These in particular cause eddy-current loss generation in rotor elements [10].

Table 4. Calculated eddy-current losses in permanent magnets ΔP_{T_MAG} and in rotor ΔP_{T_RC} (assuming a solid rotor) for different configurations of numbers of pole pairs and stator slots at operating point *n* = 1000 rpm, *T* = 400 Nm.

$Q_s/2p$	ΔP_{T_RC}[W]	ΔP_{T_MAG}[W]
2p= 30, Q_s=27	3 588	3 803
2p= 32, Q_s=30	2 428	2 962
2p= 32, Q_s=48	110	340



a) b) c)

Fig.4. Distribution of winding space harmonics for magnetomotive force a) 2*p*=30, Q_s=27, b) 2*p*=32, Q_s=30, c) 2*p*=32, Q_s=48

Conclusion

Several aspects and problems arising during design of electromagnetic circuit of motor for direct wheel drive have been discussed in this paper. Method of selecting the most important motor parameters, possibilities of increasing power density have been described as well as the most significant issue in such drives, i.e. losses in permanent magnets and rotor. All issues demonstrated in the paper will be useful to designers and engineers trying to design such motors.

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