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ORIGINAL PAPER

Design and analysis of radiaxial induction motor

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Abstract

In this study, design and analysis studies of an asynchronous motor with a tapered geometry for a two-person electric vehicle were carried out. The goal of this study is to analyze change in the taper angle for this asynchronous motor in terms of the power factor, efficiency, starting torque, breakdown torque, and rated torque. First, the vehicle dynamics and the asynchronous motor structure were analyzed. Then, axial, radial, and hybrid (radiaxial) flux electric motor models and the purpose of these models were investigated. Literature studies have shown that there is no work related to angle optimization for a radiaxial flux with a conical geometry hybrid structure for an asynchronous motor. The required motor characteristics for a two-person electric vehicle have been calculated. Then, the package volume for the in-wheel motor was analyzed, and the maximum diameter and length of the asynchronous motor were determined. The minimum diameter of this engine package was also specified considering magnetic limit conditions such as saturation factor for rotor and stator of the asynchronous motor. Nine asynchronous motor models were designed and analyzed considering the maximum and minimum motor diameters to investigate the optimal taper angle of this asynchronous motor. And the results were discussed and evaluated.

Keywords Electric vehicles · Finite element analysis · Induction motor · Magnetic flux · Traction motors

1 Introduction

Recently, the global warming has been discussed as the most important concern for main problems by scientists and governments. The research shows that fossil fuel consumption leads to increased global warming [1]. The global warming and energy crisis have revealed that the development of electric vehicle technologies is needed immediately [2]. Using the high-efficiency electric motor is accepted as improving the global warming by reducing CO_2 emission [3]. The traction systems with electric motor provide wide torque–speed range, high power density, and high power efficiency [4]. There is no doubt that electric vehicle will be part of transportation solution of the future. However, the electric vehicle must ensure a big effort to replace the vehicle (fossil fuel consumption) in the market [5]. The demand of environmentally friendly products and fuel efficiency contribute to increasing interest in clean energy and energy saving. In this scope, the hybrid electric vehicle is an applicable solution for the traction systems with electric motor due to increasing their popularity in the automotive market [6–9]. The energy management for the electric vehicle with limited power supply such as battery is a critical issue. The energy losses can be minimized by designing and producing appropriate motor and using appropriate driving methods [10, 11].

The electric vehicle is the best application to reduce emission and fuel consumption and to improve the air quality. Basically, the electric vehicle technology can be divided into three main groups: EV (electric vehicle), HEV (hybrid electric vehicle), and PHEV (plug-in hybrid electric vehicle). The structure of flow chain for EV technology is shown in Fig. 1 [12–14].

Since the ground vehicles are designed to go in one direction, only the lateral dynamics in one dimension are considered. The lateral force is composed of five force components: inertia force, vehicle drag force, air friction, wheel friction resistance, and gravity force. Figure 2 shows the lateral force components on a sloping path for a moving vehicle. Air friction (F_{aero}), rolling resistance (F_{roll}), and traction force (F_x) are represented by the following equation [15, 16]:

$$F_x = m_v \cdot \frac{d}{dt} \cdot V_x + F_{aero} + F_{roll} + m_v \cdot g \cdot \sin\alpha, \quad (1)$$

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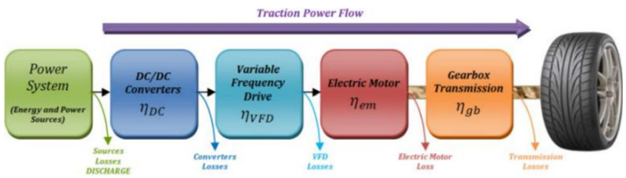

Fig. 1 The structure of flow chain for electric vehicle

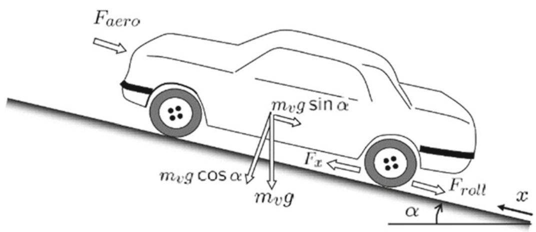

Fig. 2 Lateral forces on vehicle body

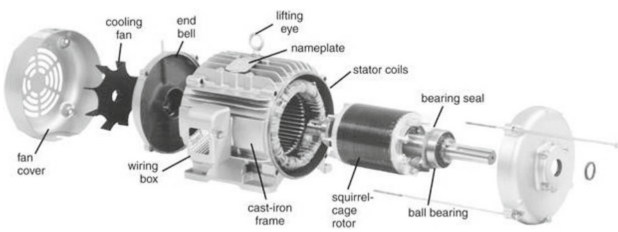

Fig. 3 Asynchronous motor structure

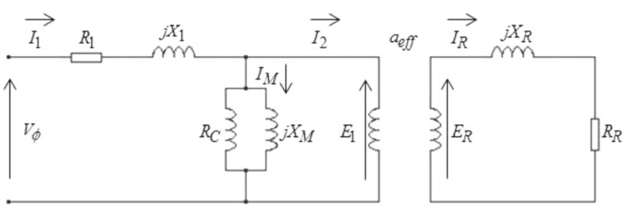

Fig. 4 The equivalent circuit model of asynchronous motor [17]

where m_v is the total mass of vehicle including passenger, V_x is the vehicle speed, α is the road gradient, and g is the gravity. In this direction, the traction force of a vehicle can be calculated by Eq. (1) [15, 16].

In this study, the asynchronous motor technology was used for power traction of electric vehicle. There are two types of asynchronous motor: squirrel cage and wound rotor. In the squirrel cage, the stator windings are directly connected to the source, the rotor windings are placed outside the rotor with longitudinal bars, and rotor bars are short-circuited with short-circuit bar. The wound rotor is similar to the squirrel cage except for the rotor bars. In wound rotor, rotor winding is made by isolating the rotor winding. This study regards to the type of squirrel cage asynchronous motor, which is shown in Fig. 3 [17].

The equivalent circuit model of an asynchronous motor is modeled such as a transformer. This transformer model of an asynchronous motor must be created as three independent circuits for three-phase systems. Figure 4 shows the transformer model for an asynchronous motor, where a_{eff} is the transformer ratio, X_{M} is the magnetization reactance, R_C is the iron loss, R_1 is the stator resistance, R_{R} is the rotor resistance, X_1 is the leakage inductance, X_{R} is the leakage inductance, E_1 is the applied voltage, and E_R is the produced voltage [17].

In general, there are two types of magnetic flux directions of an electric motor: radial flux motor and axial flux motor. Figure 5 shows historical development chart of radial, axial, and radial–axial types of magnetic flux and bearing of the electric motor.

Flogvall worked on the permanent magnet motor with conical geometry. Here, it is claimed that stator and rotor with conical geometry produce higher output torque because the torque of motor depends on the length of motor [18].

Mohamed and Emad conducted research on magnetic bearing. Adjustable conical bearing was created so as to observe air-gap flux and motor speed [19].

Lin and Gau investigated the control of conical magnetic bearing by the linearization of output feedback [20].

Luo et al. proposed an improvement in axial flux motor. The method presents radial flux rather than axial flux for axial flux motor. The performance parameters such as flux distribution, inductance, and torque were investigated by finite element method. It was observed that the method provided a wide torque rather than conventional asynchronous motor and permanent magnet brushless motor [21].

Tenhunen et al. dealt with electromagnetic forces on induction motor with cylindrical rotor and conical rotor. Cylindrical movement and conical movement were defined eccentric movement on the rigid rotor. Also they used active magnetic bearing so as to measure electromagnetic forces and produce eccentric rotor movement [22].

Parviainen et al. investigated the comparison of axial and radial flux low-speed motors [23].

Kascak et al. worked on permanent magnet motor/generator without bearing. Conical geometry that provides radial and axial bearing without requiring any bearing components was investigated [24].

Zhao et al. investigated the axial and radial flux motor. Magnetic coupling between axial and radial flux was observed. It was claimed that axial part provides reducing torque ripple and radial part reduces cogging torque [25].

Pillai et al. conducted the shaft breaks of brushless generator used in railway. It is found that the failures are caused by mechanical problem and rotor eccentricity due to the unbalanced magnetic load [26].

Kascak et al. presented laboratory and simulation studies for new bearing type with magnetic levitation. Permanent magnet produces flux on rotor. So this flux leads to unbalanced force on rotor. Conical geometry for motor allows to

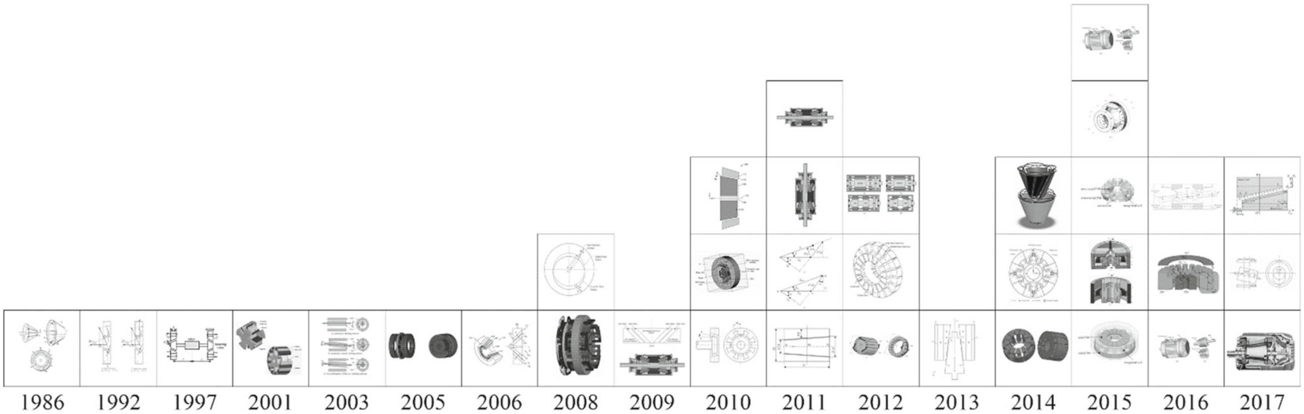

Fig. 5 Radial, axial and radial–axial magnetic flux studies in the literature [18–52]

create radial direction force and axial direction force. In this way, this axial and radial force suppresses unbalanced force on rotor [27].

Song et al. proposed a dynamic absorber to control unbalanced vibration of motor. They used conical absorber. This study is based on control of dynamic absorber [28].

Li et al. investigated the effect of working at high temperature for permanent magnet motor with axial and radial flux by using finite element method [29].

Alfermann et al. conducted the increasing output torque of permanent magnet motor. It is claimed that output torque can be optimized and back EMF (electromotive force) can be reduced by using conical geometry [30].

Ghıta and Trifu proposed a control method for wind turbine with variable speed. Here, the rotor of generator has conical geometry with permanent magnet. Conical rotor geometry has some advantages such as motor breaking electrically because high wind speed leads to some problems due to the mechanical limitations for generator [31]. Besides, linearization for generator characteristics is dealt with so as to improve nonlinear motor characteristics [32].

Kascak et al. proposed a method to improve bearing characteristic for high-performance application rather than conventional mechanic bearing (permanent magnet). Two conical motors opposite each other were investigated to provide rotation of rotor with five-axis levitation [33]. Further, the proposed model was redesigned for high-speed flywheel [34].

Nasiri-Gheidari and Lesani investigated the radial and axial flux motors. Particularly, axial flux asynchronous motors were investigated the comparison of conventional asynchronous motors [35].

Nair et al. conducted the research on permanent magnet axial and radial flux motor. It was observed that permanent magnet axial and radial flux motor structure increases motor torque [36].

Munteanu et al. proposed a new type motor with bearingless permanent magnet. This motor contains in two half-conical air gaps on shaft. It is claimed that the structure provides active magnetic bearing (six degrees of freedom) without using any bearing component [37].

Shepard and Picard conducted the research on rotor assembly for permanent magnet motor with conical geometry [38].

Wei et al. worked on axial and radial flux permanent magnet motor. This motor has two rotors. It was investigated in terms of radial and axial [39].

Xu and Sun investigated the both radial magnetic bearing and radial–axial magnetic bearing. They proposed a new magnetic bearing for small structure [40].

Abrahamsson et al. claimed that a motor with brushless DC coreless double rotor provides low loss. Also, they designed self-bearing suspension by assembling stator winding on conical surface [41].

Li et al. investigated the active and passive suspension characteristics of axial and radial hybrid bearing system [42].

Seo et al. designed an axial and radial flux motor permanent magnet motor for a bicycle. It was analyzed by finite element method. Besides, they compared it with conventional radial flux motor [43]. On the other hand, Ro et al. conducted a research on high power density for this hybrid motor. It was observed that air-gap flux density and power density increased [44].

Yang (2015) conducted an improvement in output torque for radial and axial flux permanent magnet motor compared with conventional motor [45].

Guo et al. analyzed an asynchronous motor with conical rotor in terms of the thermal characteristic [46, 47].

Nasiri-Zarandi et al. designed and analyzed a new hybrid hysteresis motor with axial and radial flux so as to increase output torque for conventional hysteresis. It is claimed that new method provides increasing output torque [48].

Fig. 6 Two-passenger electric vehicle view [53]

Table 1 The parameters of vehicle dynamics for two-passenger electric vehicle [53]

Parameters	Value	Unit
Aerodynamics drag coefficient	0.3	–
Air mass density	1.2	kg/m^3
Rolling resistance	0.001	–
Curb weight	375	kg
Acceleration (0–45 km/s)	6	sn
Wheel width	0.20	m
Wheel tire diameter	0.56	m
Wheel rim diameter	0.33	m
Front track	1094	mm
Unladen height	1454	mm

Messager and Binder conducted the research on bearing and eccentricity for a permanent magnet synchronous motor with two conical rotors [49].

Roggia et al. worked on axial position control for an induction motor with conical rotor [50].

Basheer and Bindui conducted the research on preventing unbalanced magnetic forces in an induction motor with conical geometry by developing a feed-forward control method [51].

Chai et al. worked on permanent magnet synchronous motor with conical rotor. It is claimed that the proposed method can be increased maximum speed and maximum output torque [52].

In this paper, the effect of the taper angle on asynchronous motor performance parameters is investigated because literature studies have shown that there is no work related to angle optimization for a radiaxial flux with a conical geometry hybrid structure for an asynchronous motor which is designed by considering an asynchronous motor with a tapered geometry for a two-person electric vehicle.

2 Materials and methods

In the literature, bearing performances, thermal analysis, position control and use of hybrid geometries have been mentioned for the radial and axial flux motors. In this study, the required electric motor for two-passenger electric vehicle was designed. This electric motor was designed as a conical structure so as to use radial and axial fluxes. Furthermore, it was analyzed in terms of taper angle and motor performance parameters. Figure 6 shows the typical two-passenger electric vehicle model. Also, the parameters of vehicle dynamics in Fig. 6 are given in Table 1.

When using the data in Table 1, it is necessary to have a minimum torque of 120 Nm to climb a road with 10° of inclination. Besides, the electric motor with the 13-inch wheel rim diameter must produce 20 Nm of torque at 1300 RPM to reach 80 km/h. At the same time, it is estimated that this electric motor should have a motor power of 12.8 KW to reach 0–45 km/h in 6 s. These calculation requirements for electric vehicle motor are given in Table 2.

This study proposed in-wheel traction system to reduce transmission loss. Therefore, the electric motor was designed for rear wheels. Thus, the requirements for electric motor are divided into two types: torque and power requirements. Accordingly, the results obtained when the requirements are recalculated are given in Table 3.

Wheel dimensions are fundamental parameters of in-wheel motor. So, boundary dimensions must be defined first. In this study, 13-inch wheel rim for the electric vehicle was used. Dimensions for 13-inch wheel rim are equal to 0.33 m for motor diameter and 0.20 m for motor length. Considering the motor construction and fittings components, a diameter of 0.28 m and a length of 0.15 m are set as the maximum dimensions for which an in-wheel motor can be designed. The material used for rotor and stator is M19_24G which has some restrictions for magnetic flux density such as saturation in stator and rotor yoke and teeth. Therefore, not to exceed permissible value (Tesla), minimum outer diameter should not be lower than 190 mm. In this context, to analyze taper angle of motor nine different motors are designed from 190 to 280 mm in terms of the outer diameter in Ansys Maxwell 3D. These asynchronous motors are shown in Fig. 7.

3 Results

In this study, finite element method was used to analyze the motor model in Fig. 7. The asynchronous motors modeled in Ansys Maxwell 3D are analyzed in the transient solver in terms of taper angle and the motor performance parameters that are power factor, efficiency, starting torque, breakdown torque, reaching time of breakdown torque, breakdown RPM,

Table 2 The required motor for two-passenger electric vehicle

Starting torque @ 10° grade	Rated torque @ 1300 RPM	Breakdown power
120 Nm	20 Nm	12.8 kW

Table 3 The required motor of 4 × 2 traction system for two-passenger electric vehicle

Starting torque @ 10° grade	Rated torque @ 1300 RPM	Breakdown power
60 Nm	10 Nm	6.4 kW

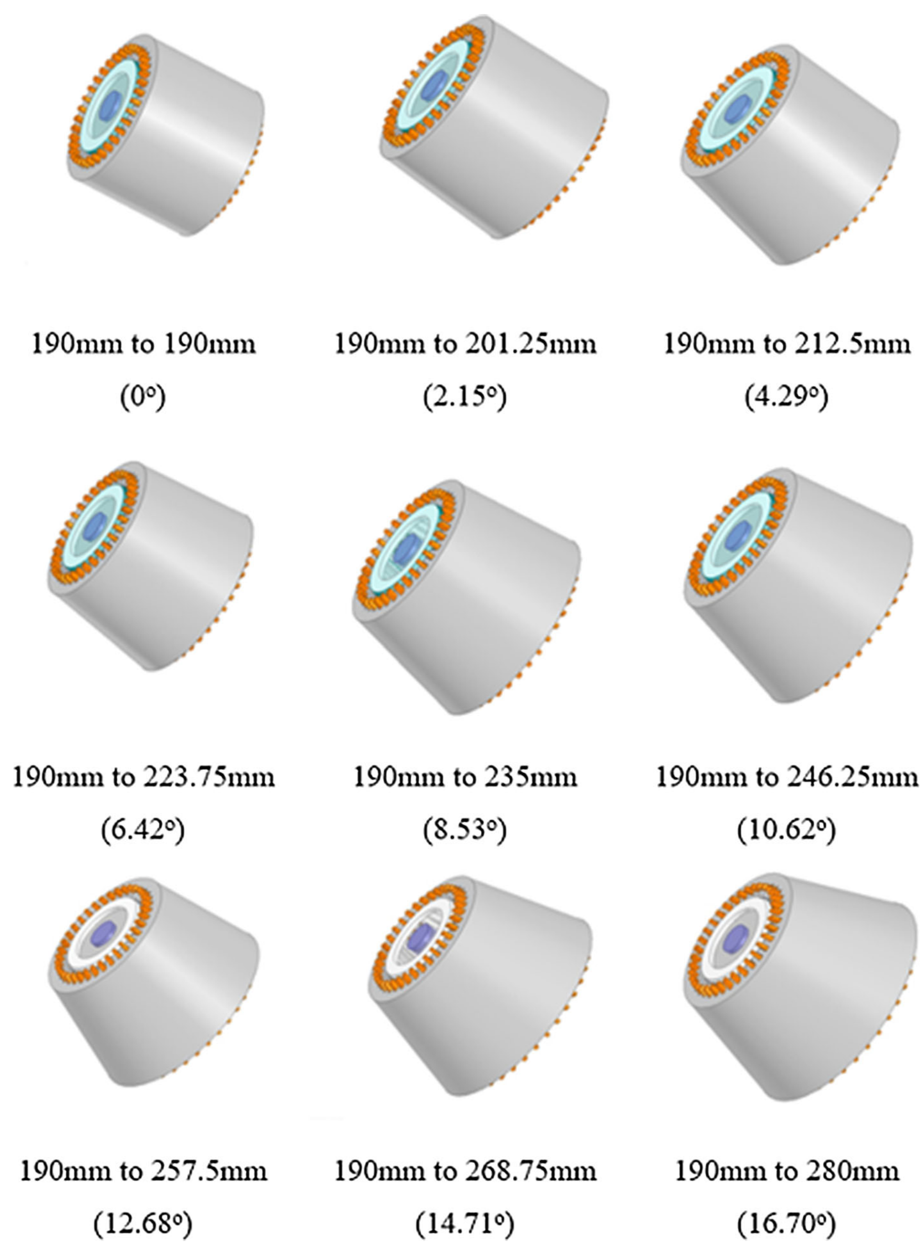

Fig. 7 Asynchronous motor models in Ansys Maxwell 3D environment from 190–190 mm to 190–280 mm for outer diameter

rated torque, reaching time of rated torque, and rated RPM, which are given in Table 4. All asynchronous motor models shown in Fig. 7 have same properties such as pole number (four poles) and operating conditions such as input voltage (380 V) and frequency (50 Hz). The simulation results from getting analysis can be used for defining taper angle to provide the optimum performance from radiaxial flux in-wheel asynchronous motor.

The relationship between taper angle and power factor is directly proportional. But, the relationship between taper

Table 4 The simulation results from getting Ansys Maxwell transient solver for in-wheel asynchronous motor of electric vehicle

Parameters	From radial flux motor to radiaxial flux motor (motor length 150 mm for all models)								
Motor diameters	190–190 mm	190–201.25 mm	190–212.5 mm	190–223.75 mm	190–235 mm	190–246.25 mm	190–257.5 mm	190–268.27 mm	190–280 mm
Taper angle (°)	0	2.15	4.29	6.42	8.53	10.62	12.68	14.71	16.70
Power Factor	0.783	0.805	0.827	0.832	0.839	0.860	0.865	0.877	0.876
Efficiency (%)	68.87%	66.84%	69.68%	72.24%	69.33%	68.58%	66.33%	64.07%	57.40%
Starting torque (Nm)	61.47	67.60	65.25	67.40	64.30	64.40	59.01	59.03	55.60
Breakdown torque (Nm)	82.1	79.86	77.65	80.13	77.99	84.94	74.74	84.10	75.29
Breakdown time (ms)	51	129	205	236	353	376	552	642	689
Breakdown RPM	850	1002	978	932	977	908	908	920	814
Rated torque (Nm)	55.56	54.41	58.34	56.96	56.01	54.32	52.62	55.83	50.64
Rated time (ms)	106	230	382	469	675	809	1828	2018	4012
Rated RPM	1300	1300	1300	1300	1300	1300	1300	1300	1300

angle and efficiency is not directly proportional. In here, there is a nonlinear relationship. This relationship is similar for rated torque, breakdown torque and starting torque. Therefore, considering maximum efficiency, optimum power factor, and required motor performance parameters, the radiaxial flux motor model, the outer diameter of which is 190–223.75 mm, provides the optimum results for motor performance. The radiaxial flux asynchronous motor model mesh views are shown in Fig. 8. Also, Fig. 9 shows the magnetic flux density in which values are within permissible limit values.

Figure 10 shows that torque–speed–position versus time curve from getting analysis results for optimum radiaxial flux asynchronous motor. Figure 11 shows the torque versus speed curve. Power factor, efficiency, starting torque, breakdown torque, reaching time of breakdown torque, breakdown RPM, rated torque, reaching time of rated torque, and rated RPM in Table 4 are obtained from Figs. 10 and 11 for radiaxial flux motor which has outer diameter from 190 to 223.75 mm and motor length 150 mm. Similarly, obtained results for the other motor models are getting from related motor curves such as torque–speed–position versus time and torque versus speed. Besides, the detailed information about Fig. 11 is given in “Appendix.” The equivalent circuit parameters of the optimum radiaxial motor (outer diameter from 190 to 223.75 mm and motor length 150 mm) are stator resistance ($R_1 = 1.96$ O), rotor resistance ($R_R = 1.04$ O), stator leakage reactance ($X_1 = 1.5$ O), rotor leakage reactance ($X_R = 2.15$ O), and magnetization reactance ($X_M = 36.31$ O).

4 Discussion

Analysis of radial flux induction motor and radiaxial flux induction motor shows the relationship between motor performance parameters and motor dimensions such as motor diameter and taper angle.

Table 4 shows the change in parameters with increasing taper angle of radiaxial motor. The findings from Table 5 are summarized and compared in Table 5, which shows the change in parameter for radial and radiaxial flux induction motors.

The power factor of radial flux motor and radiaxial flux motor shows similar results. When the diameter of the motor or taper angle increases, the power factor has increased. Increasing the taper angle of radiaxial flux motor gives various results for the efficiency. Considering the physical dimension of the motor and moment of inertia for the rotor, taper angle of radiaxial flux motor has an optimal value for the efficiency. Radial flux motor and radiaxial flux motor have similar results for starting torque, which shows negative trend when the taper angle increases. Breakdown torque shows the various results by changing the taper angle of radiaxial flux

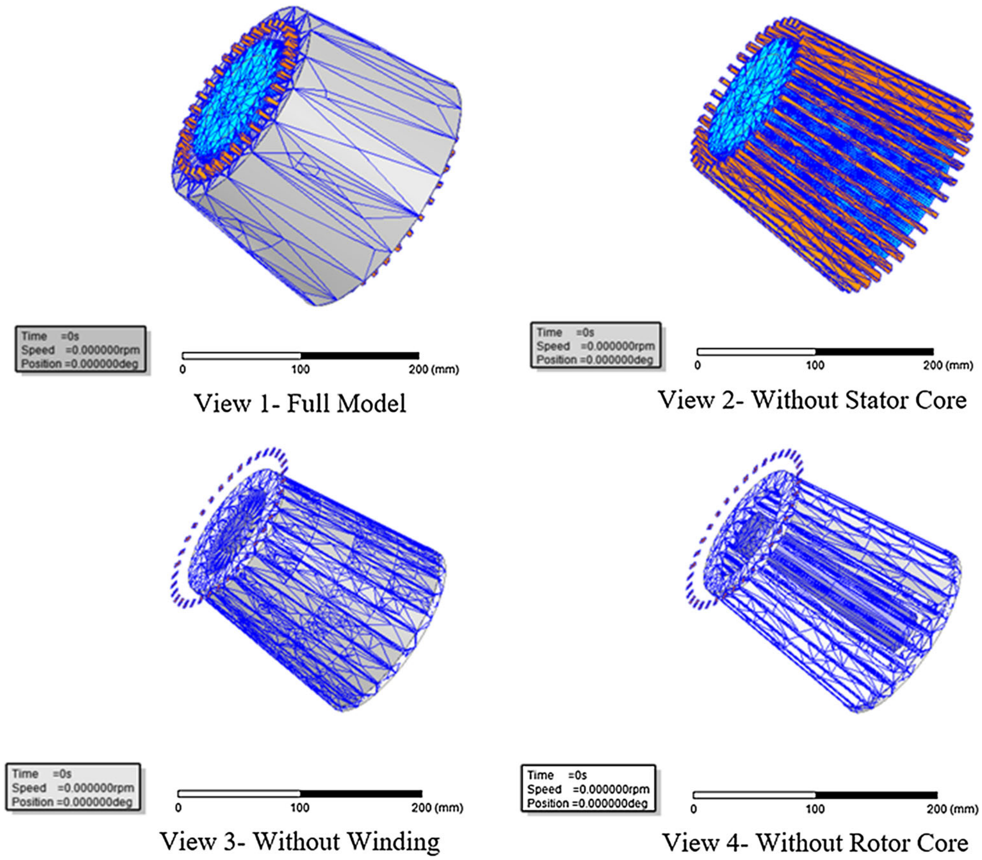

Fig. 8 The mesh views of radiaxial flux asynchronous motor model (motor outer diameter from 190 to 223.75 mm and motor length 150 mm) in Ansys Maxwell 3D Environment

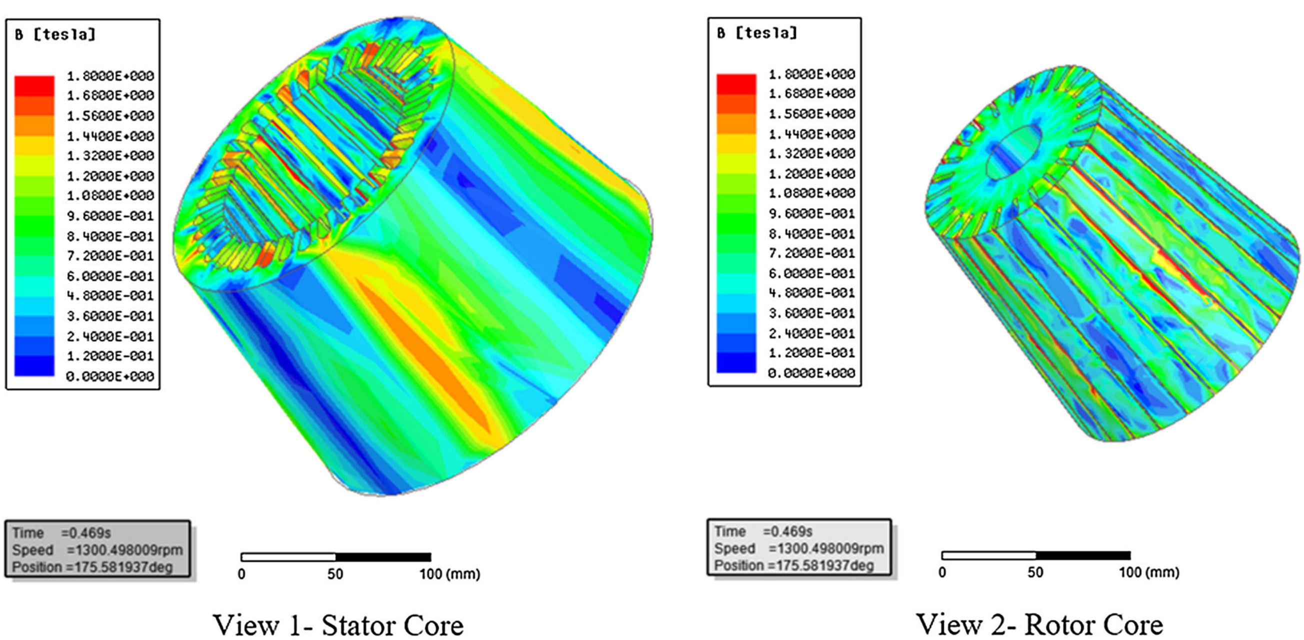

Fig. 9 The magnetic flux density views of radiaxial flux asynchronous motor model (motor outer diameter from 190 to 223.75 mm and motor length 150 mm) in Ansys Maxwell 3D Environment

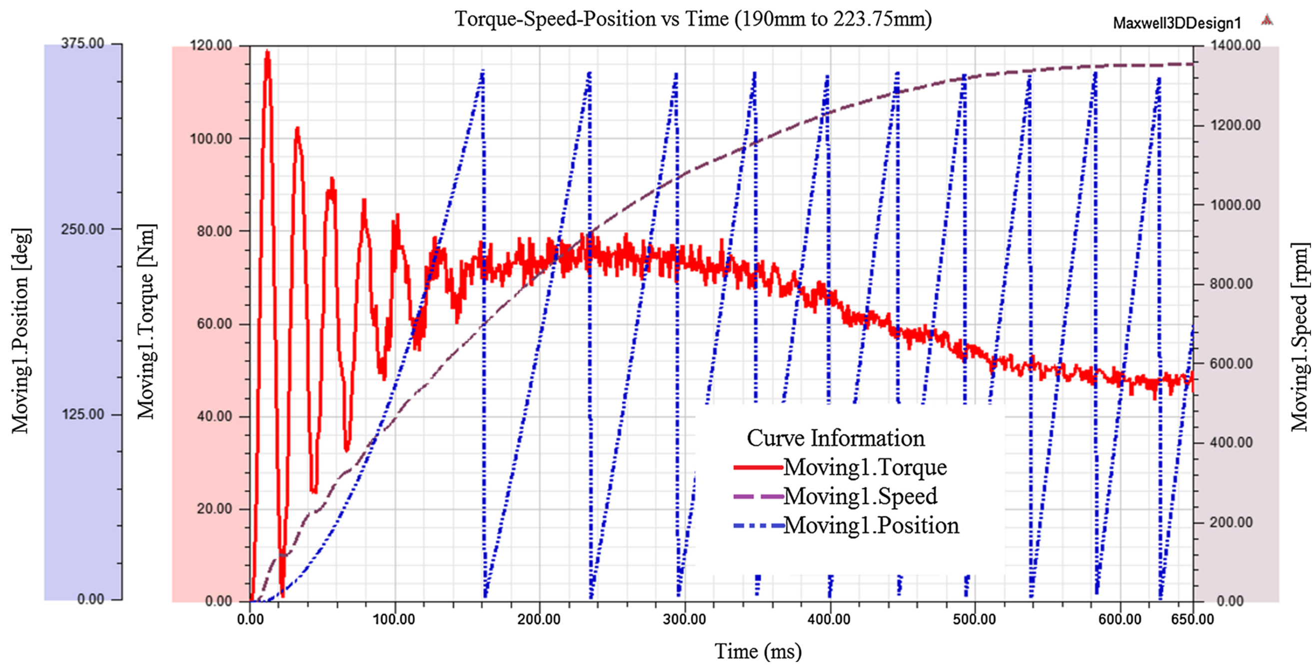

Fig. 10 Torque–speed–position versus time curve of radiaxial flux asynchronous motor model (motor outer diameter from 190 to 223.75 mm and motor length 150 mm) in Ansys Maxwell 3D environment

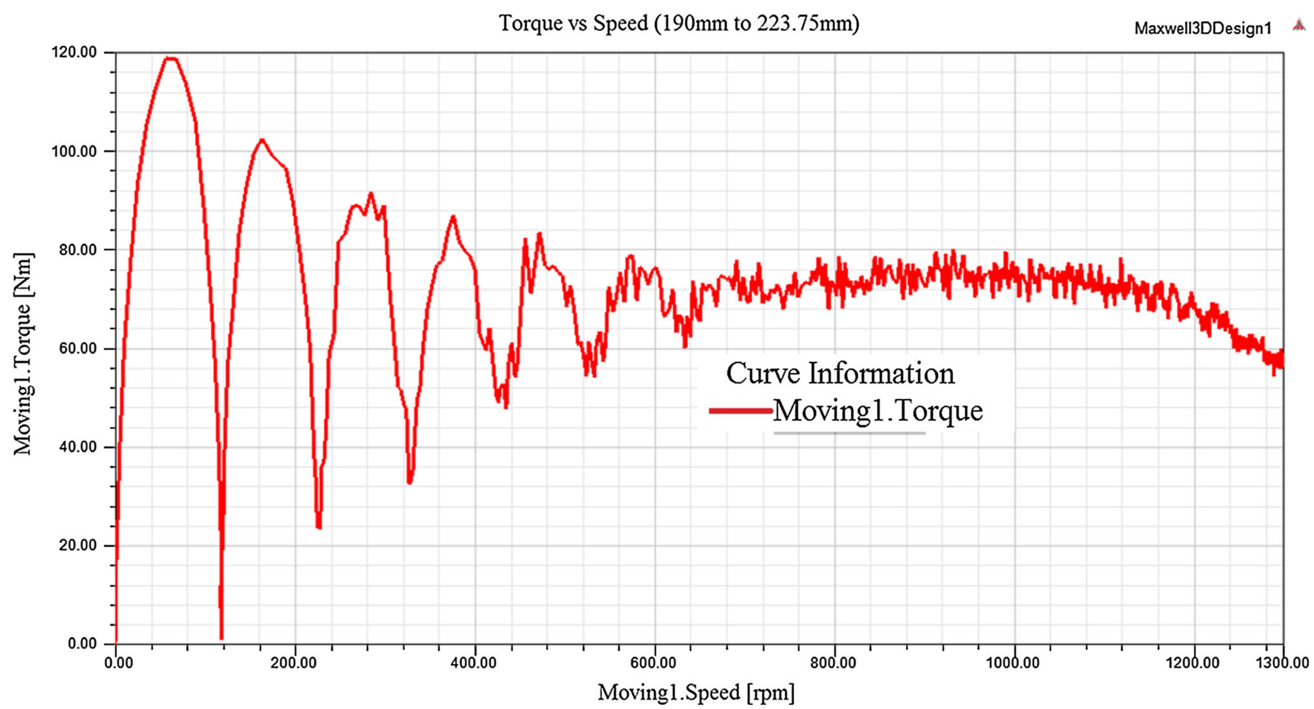

Fig. 11 Torque versus speed curve of radiaxial flux asynchronous motor model (motor outer diameter from 190 to 223.75 mm and motor length 150 mm) in Ansys Maxwell 3D environment

motor. But these various results are not linear or exponential form. The reaching time for the breakdown torque is similar for radial and radiaxial flux motor. Increasing the taper angle leads to long reaching time for the breakdown torque. Breakdown RPM shows decreasing trend when the taper angle for the radiaxial flux motor increases. On the other hand, this situation for breakdown RPM is proportional directly to radial flux motor. With the change in the taper angle for the radiaxial flux motor, the rated torque changes. The obtained results point out an optimum value at a certain taper angle due to

Table 5 The parameter investigation of radial and radiaxial flux asynchronous motor

	With increasing diameter for radial flux motor	With increasing taper angle for radiaxial flux motor
Power factor	↑	↑
Efficiency (%)	⌒	⌒
Starting torque (Nm)	↓	↓
Breakdown torque (Nm)	↓	⌒
Breakdown time (ms)	↑	↑
Breakdown (RPM)	↑	↑
Rated torque (Nm)	⌒	⌒
Rated time (ms)	↑	↑
Rated (RPM)	–	–

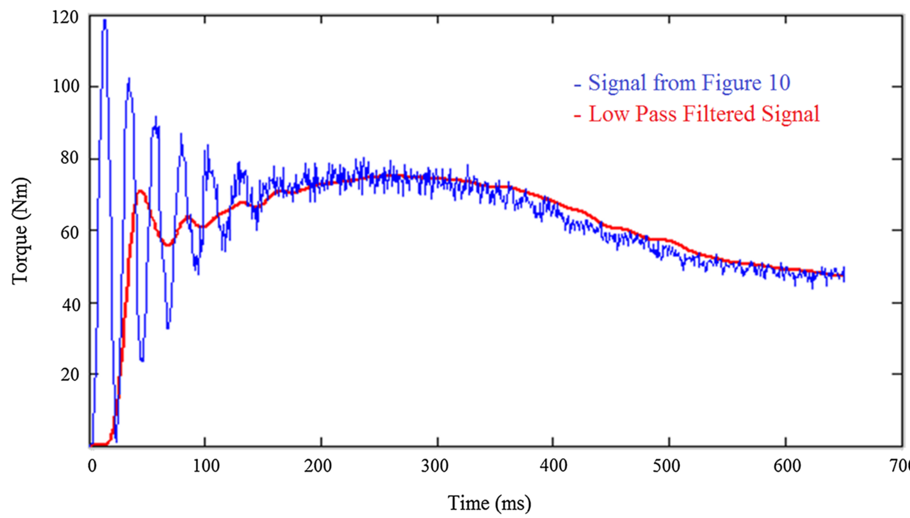

Fig. 12 Torque versus time curve of radiaxial flux asynchronous motor model (motor outer diameter from 190 to 223.75 mm and motor length 150 mm) and low-pass filter response curve of radiaxial flux asynchronous motor model for 25 Hz

the moment of inertia. The reaching time for the rated torque shows the same behavior for radial motor and radiaxial flux motor. By increasing taper angle, the reaching time for the rated torque takes long time.

5 Conclusion

In this paper, nine asynchronous motor models shown in Fig. 7 were designed and analyzed considering the maximum and minimum motor diameters to investigate the optimal taper angle of this asynchronous motor in terms of the power factor, efficiency, starting torque, breakdown torque, and rated torque. The results from getting the analysis show that 6.42° is the optimal taper angle in Table 4. Therefore, 190–223.75 mm in Table 5 is optimal geometry for radiaxial flux motor. Furthermore, the radiaxial flux motor improves the power factor, starting torque, and breakdown torque in comparison with radial flux motor. The rated torque of the motor is similar for radial flux motor and radiaxial flux motor.

On the other hand, the reasons for the difficulty in production and the labor costs forces to selection of the radial motor, the radiaxial flux motor which allows vehicle weight reductions and reduced raw material usage.

The radiaxial flux motor reduces severely the iron losses relatively to radial flux motor; therefore, radiaxial flux motor provides increasing the air-gap power and thus enables increasing the efficiency.

In terms of the output power per kg unit (for motor weight), radiaxial flux motor has advantages such as weight reduction up to 50% in comparison with radial flux motor.

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Appendix

There are harmonic torques in Figs. 10 and 11. These harmonic torques are called by crawling torque which consists of third, fifth, and seventh harmonics that may rotate in forward or backward direction at Ns/3, Ns/5, and Ns/7 speeds, respectively (Ns: synchronous speed). Therefore, these harmonic toques are produced in addition with essential torque. Ns is equal to 1500 RPM for four poles and 50 Hz system. Also, Ns is equal to 25 RPS or 25 Hz. When 25 Hz is used for corner frequency of low-pass filter, Fig. 12 is obtained. Figure 12 shows the essential torque curve from getting simulation results and low-pass filter response.

References

1. Ahmad MZ, Sulaiman E, Kosaka T (2015) Optimization of outer-rotor hybrid excitation FSM for in-wheel direct drive electric vehicle. In: 2015 IEEE international conference on mechatronics (ICM), pp 091–090, 6-8 March 2015. [Online]. https://doi.org/10.1109/ICMECH.2015.7084061
2. Sant A, Khadkikar V, Xiao W, Zeineldin H (2015) Four-axis vector-controlled dual-rotor PMSM for plug-in electric vehicles. IEEE Trans Ind Electron 62(5):3202–3212. https://doi.org/10.1109/TIE.2014.2387094
3. Chiba A, Kiyota K, Hoshi N, Takemoto M, Ogasawara S (2015) Development of a rare-earth-free SR motor with high torque density for hybrid vehicles. IEEE Trans Energy Convers 30(1):175–182. https://doi.org/10.1109/TEC.2014.2343962
4. Chen L, Hopkinson D, Wang J, Cockburn A, Sparkes M, O'Neill W (2015) Reduced dysprosium permanent magnets and their applications in electric vehicle traction motors. IEEE Trans Magn. https://doi.org/10.1109/TMAG.2015.2437373
5. Biltutanu A, Florea ML (2015) Modeling and testing of electric vehicle propulsion systems. UPB Sci Bull Ser C Electr Eng 77(3):201–212
6. Al-Aawar N, Arkadan ARA (2015) Optimal control strategy for hybrid electric vehicle powertrain. IEEE J Emerg Sel Top Power Electron 3(2):362–370. https://doi.org/10.1109/JESTPE.2014.2323019
7. Hua W, Zhang G, Cheng M (2015) Investigation and design of a high-power flux-switching permanent magnet machine for hybrid electric vehicles. Magn IEEE Trans 51(3):1–5. https://doi.org/10.1109/TMAG.2014.2345732
8. Chun YD, Park BG, Kim DJ, Choi JH, Han PW (2016) Development and performance investigation on 60 kW induction motor for EV propulsion. J Electr Eng Technol 11(3):639–643. https://doi.org/10.5370/JEET.2016.11.1.1921
9. Ruuskanen V, Nerg J, Pyrhönen J, Ruotsalainen S, Kennel R (2015) Drive cycle analysis of a permanent-magnet traction motor based on magnetostatic finite-element analysis. IEEE Trans Vech Technol 64(3):1249–1254. https://doi.org/10.1109/TVT.2014.2329014
10. Yang Y-P, Wang J-P, Wu S-W, Luh Y-P (2004) Design and control of axial-flux brushless DC wheel motors for electric vehicles-part II: optimal current waveforms and performance test. IEEE Trans Magn 40(4):1883–1891. https://doi.org/10.1109/TMAG.2004.828165
11. Rahman KM, Jurkovic S, Stancu C, Morgante J, Savagian PJ (2015) Design and performance of electrical propulsion system of extended range electric vehicle (EREV) chevrolet volt. IEEE Trans Ind Appl. https://doi.org/10.1109/TIA.2014.2363015
12. Shafiei A, Carli G, Williamson SS (2014) Electric and plug-in hybrid electric vehicles", power electronics for renewable energy systems, transportation and industrial applications. Wiley-IEEE press, Hoboken, pp 387–421
13. Hewu W, Jiuyu D, Minggao O (2013) Vehicle powertrain technology, sustainable automotive energy system in China. Springer, Berlin, pp 59–107
14. Beloiu R, Iorgulescu M, Savulescu C (2014) Dynamic response of electric machines for electric vehicles/hybrid electric vehicles (EV/HEV). In: Autonomous vehicles: intelligent transport systems and smart technologies. Nova Science Publisher, New York, pp 353–377
15. Nam KH (2010) AC motor control and electrical vehicle applications. CRC Press, Florida, p 351
16. Mökükcü MS (2014) Electrical vehicle design and implementation, M.Sc. Thesis, Istanbul Technical University, Istanbul
17. Chapman SJ (2003) Electric machinery fundamentals, 4th edn. McGraw-Hill Science, New York, p 773
18. Flogvall AG (1986) Motor arrangement comprising at least three co-planar conical motors. US Philips Corp, US4628220 (A)
19. Mohamed AM, Emad FP (1992) Conical magnetic bearings with radial and thrust control. IEEE Trans Autom Control 37(12):1859–1868. https://doi.org/10.1109/9.182473
20. Lin L-C, Gau T-B (1997) Feedback linearization and fuzzy control for conical magnetic bearings. IEEE Trans Control Syst Technol 5(4):417–426. https://doi.org/10.1109/87.595923
21. Luo J, Huang S, Chen S, Lipo TA (2001) Design and experiments of a novel axial flux circumferential current permanent magnet (AFCC) machine with radial airgap. IEEE-IAS Conf Rec 2:2001. https://doi.org/10.1109/IAS.2001.955901
22. Tenhunen A, Benedetti T, Holopainen TP, Arkkio A (2003) Electromagnetic forces of the cage rotor in conical whirling motion. IEE Proc Electr Power Appl. https://doi.org/10.1049/ip-epa:20030365
23. Parviainen A, Niemelä M, Pyrhönen J, Mantere LJ (2005) Performance comparison between low-speed axial-flux and radial-flux permanent magnet machines including mechanical constraints. IEEE Int Electr Mach Drives Conf. https://doi.org/10.1109/IEMDC.2005.195948
24. Kascak P, Jansen R, Dever T (2006) Conical bearingless motor/generator. University of Toledo, US2006238053 (A1)
25. Zhao H, Li L, Zheng P, Liu R, Zhao J (2008) Research on the axial–radial flux compound-structure permanent-magnet synchronous machine (CSPMSM) used for HEV. In: Proceedings international conference electrical machine system, pp 3250–3253
26. Pillai KPP, Nair S, Bindu GR (2008) Unbalanced magnetic pull in train-lighting brushless alternators with static eccentricity. IEEE Trans Vech Technol 57(1):120–126. https://doi.org/10.1109/TVT.2007.901966
27. Kascak P, Jansen R, Dever T, Nagorny A, Loparo K (2009) Bearingless five-axis rotor levitation with two pole pair separated conical motors. In: Conference record of IEEE industrial applications society annual meeting, October 2009. [Online]. https://doi.org/10.1109/IAS.2009.5324866
28. Song F, Liu H, Song B, Shao H, Feng H (2010) Analysis control characteristics of clearance control magnetic dynamic absorber. In: Proceedings of the 8th world congress on intelligent control and automation, IEEE. [Online]. https://doi.org/10.1109/WCICA.2010.5554572

29. Li W, Song C, Cao J, Li L (2010) Performance analysis of axial-radial flux type fully superconducting synchronous motor. In: 2010 international conference on power system technology (POWERCON), IEEE. [Online]. https://doi.org/10.1109/POWERCON.2010.5666101
30. Alfermann TJ, McGrew AL, El-Antably AM (2010) Permanent magnet machine with conical stator. GM Global Technology Operations LLC, US2010264768 (A1)
31. Ghıta C, Trifu I (2011) Aeolian synchronous generator with conical rotor. In: 7th International symposium on advanced topics in electrical engineering, the Faculty of Electrical Engineering, U.P.B., Bucharest
32. Ghıta C, Trifu I (2011) Linearization of aeolian synchronous generator with conical rotor. In: 7th international symposium on advanced topics in electrical engineering, The Faculty of Electrical Engineering, U.P.B., Bucharest
33. Kascak P, Jansen R, Dever T, Nagorny A, Loparo K (2011) Levitation performance of two opposed permanent magnet pole-pair separated conical bearingless motors. In: Conference record of the ieee energy conversion congress and exposition, Phoenix, AZ, September 2011. [Online]. https://doi.org/10.1109/ECCE.2011.6063980
34. Kascak P, Dever T, Jansen R, Nagorny A, Loparo K (2011) Motoring performance of a conical pole-pair separated bearingless electric machine. In: Conference record of IEEE energy tech, May 2011. [Online]. https://doi.org/10.1109/EnergyTech.2011.5948515
35. Nasiri-Gheidari Z, Lesani H (2012) A survey on axial flux induction motors. Przeglad Elektrotechniczny (Electrical Review), ISSN 0033-2097, R. 88 NR 2/2012
36. Nair SS, Shamsuddeen N, Dhinagar SJ (2012) A novel electromagnetic core structure for axial radial flux permanent magnet electric motor. In: 6th IET international conference on power electronics, machines and drives (PEMD 2012), IEEE 2012. [Online]. https://doi.org/10.1049/cp.2012.0163
37. Munteanu G, Binder A, Dewenter S (2012) Five-axis magnetic suspension with two conical air gap bearingless PM synchronous half-motors. In: Proceedings of the 2012 international symposium on power electronics electrical drives automation and motion (SPEEDAM), June 20–22, 2012. [Online], pp 1246–1251. https://doi.org/10.1109/SPEEDAM.2012.6264414
38. Shepard C, Picard JW (2013) Tapered rotor assembly. Hamilton Sundstrand Corp, US2013113324 (A1)
39. Wei X, Yang K, Pan Z, Xie H, Zhu C, Zhang Y (2014) Design of a novel axial-radial flux permanent magnet motor. In: 17th international conference on electrical machines and systems (ICEMS), IEEE 2014. [Online]. https://doi.org/10.1109/ICEMS.2014.7013441
40. Xu S, Sun J (2014) Decoupling structure for heteropolar permanent magnet biased radial magnetic bearing with subsidiary air-gap. IEEE Trans Magn 50(8):1–8. https://doi.org/10.1109/TMAG.2014.2312396
41. Abrahamsson J, Ogren J, Hedlund M (2014) A fully levitated cone-shaped Lorentz-type self-bearing machine with skewed windings. IEEE Trans Mag 50(9):1–9. https://doi.org/10.1109/TMAG.2014.2321104
42. Li S, Song L, Li S, Wang J, Lei X (2015) Decoupling active and passive hybrid axial and radial magnetic bearing. In: International conference on control, automation and information sciences (ICCAIS), IEEE 2015. [Online]. https://doi.org/10.1109/ICCAIS.2015.7338701
43. Seo JM, Rhyu SH, Jung IS, Jung HK (2015) A design of multi flux permanent magnet machine for electrical bicycles. IEEE Trans Magn. https://doi.org/10.1109/ICPE.2015.7167970
44. Ro J-S, Rhyu S-H, Jung I-S, Jung H-K, Seo JM (2015) Novel hybrid radial and axial flux permanent-magnet machine using integrated windings for high-power density. IEEE Trans Magn Magn. https://doi.org/10.1109/TMAG.2014.2344044
45. Yang G (2015) Method for improving motor torque density and radial and axial magnetic flux parallel-connected permanent magnet motor. Wuhan Huada New Motor Technology Co., Ltd., CN104716754A
46. Guo B, Huang Y, Guo Y, Zhu J (2015) Thermal analysis of the conical rotor motor using LPTN combined with fluid simulation. In: Proceedings of international conference on applied superconductivity and electromagnetic devices, IEEE 2015. [Online]. https://doi.org/10.1109/ASEMD.2015.7453499
47. Guo B, Huang Y, Guo Y, Zhu J (2016) Thermal analysis of the conical rotor motor using LPTN with accurate heat transfer coefficients. In: Transaction on applied superconductivity, IEEE 2016. [Online], vol 26(7). https://doi.org/10.1109/TASC.2016.2600584
48. Nasiri-Zarandi R, Mirsalim M, Tenconi A (2016) A novel hybrid hysteresis motor with combined radial and axial flux rotors. IEEE Trans Ind Electron 63:1684–1693. https://doi.org/10.1109/TIE.2015.2498142
49. Messager G, Binder A (2016) Observer-based pole placement control for a double conical high-speed bearingless permanent magnet synchronous motor. In: Power Electronics and Applications (EPE'16 ECCE Europe), IEEE 2016. https://doi.org/10.1109/EPE.2016.7695264
50. Roggia S, Cupertino F, Gerada C, Galea M (2017) Axial position estimation of conical shaped motors for aerospace traction application. In: Transaction on industrial applications, IEEE 2017. [Online]. https://doi.org/10.1109/TIA.2017.2717911
51. Basheer J, Bindu GR (2017) A novel technique to arrest unbalanced magnetic pull due to conical motion in three phase induction motor using feedforward control, In: International conference on nascent technologies in the engineering field (ICNTE-2017). [Online]. https://doi.org/10.1109/ICNTE.2017.7947908
52. Chai F, Zhao K, Li Z, Gan L (2017) Flux weakening performance of permanent magnet synchronous motor with a conical rotor. In: Transaction on magnetics, IEEE 2017. [Online]. https://doi.org/10.1109/TMAG.2017.2708139
53. Vehicle Dynamic Parameters (2018). Retrived from https://www.platinumrenault.co.uk/pdfs/new-cars/twizy.pdf