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Interior permanent magnet motors with non-overlapping concentrated windings or with integral slot windings for traction application

***Abstract**. These Interior permanent magnet machines using integral slot windings or non-overlapping concentrated windings are designed for traction applications. Four direct drive traction motors are analyzed: two 25 kW motors and two 100 kW motors at rated speed of 1000 min^{-1}. Analytical computations are verified by finite element analysis utilizing Cedrat's Flux2D. Concentrated tooth coil winding machines can be used also as traction motors and they can be designed to produce reluctance torque. The integral slot wound 25 kW motor has been built and measured.*

***Streszczenie.** W pracy przeanalizowano cztery typy silników elektrycznych dla napędów trakcyjnych: dwa - 25 kW i dwa – 100 kW z prędkością znamionową 1000 rpm. . Obliczenia analityczne zostały zweryfikowane poprzez symulację komputerową za pomocą pakietu Cedrat Flux 2D. Silnik o mocy 25 kW został wykonany i pomierzony. (**Silniki z wewnętrznym magnesem trwałym z nienachodzącymi na siebie uzwojeniami koncentrycznymi dla zastosowań trakcyjnych**)*

Keywords: non-overlapping concentrated winding, tooth coil, traction motor, reluctance torque.
Słowa kluczowe: nienachodzące na siebie uzwojenie, cewka zębowa, silnik trakcyjny, moment reluktancyjny.

Introduction

In this paper, interior permanent magnet machines using integral slot windings or non-overlapping concentrated tooth coil windings are designed and analyzed for traction applications. Nowadays, Permanent Magnet (PM) motors are often used in traction applications despite the slight difficulties to control the stator flux in the field weakening operation. A permanent magnet motor may be called also as synchronous reluctance motor because a PM motor can produce a significant amount of reluctance torque. This reluctance torque is produced due to the inductance difference between the direct and quadrature axes inductances and the stator current linkage. Power density is increased when adding interior permanent magnets to the reluctance machine. It was in the authors' interest to study if the reluctance torque can be beneficial also when using non-overlapping concentrated windings.

Two 25 kW motors were designed in the same frame as rated speed was fixed to 1000 min^{-1} for direct drive applications. Both motors should give at least 2 p.u. torques at low speed and approximately 0.6 p.u. at double speed. Analytical computations are verified by finite element analysis utilizing Cedrat's Flux2D. A non-overlapping concentrated winding machine can be designed to have a large field weakening range and to produce a significant amount of reluctance torque. The integral slot 25 kW, 240 Nm motor has been built and measured and, therefore, the theoretical computations are verified by real measurements. Another computation case was to build a traction motor for 100 kW. This traction motor has also the rated speed of 1000 min^{-1}, with the rated torque being appr. 1000 Nm. For this application also a concentrated wound and integral slot wound solution are presented and analyzed. In this paper the comparison and analysis of these four motors are discussed. [1-2].

Traction Motor Designs

Traction motor needs to produce a different amount of torque depending on the speed and, therefore, one should compute the loading through the speed area in which the field weakening occurs. A principal figure of the desired torque and power as a function of speed for a traction application is presented in Fig. 1 in per unit values. The supply voltage increases up to the rated voltage at speed of 1 p.u. and after that it will remain constant. The field weakening area can be found as the speed is higher than 1 p.u.

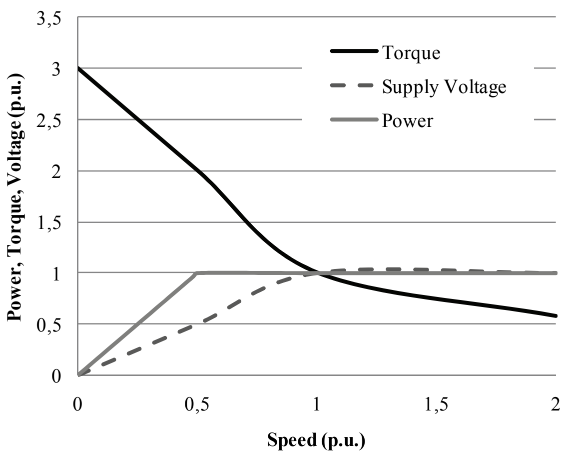


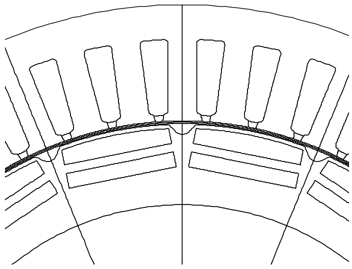
Fig. 1. Desired torque, available supply voltage and desired power as a function of speed.

At the lowest speed the torque needed is very high and the machine can benefit of its capability of producing reluctance torque. At the high speed range, to achieve a large field weakening, large enough p.u. inductances are needed to be capable of diminishing the stator flux linkage. [3-4]. Analytical calculation was based on the machine d-q axis model and the vector presentation. The results are verified by finite element analysis utilizing Cedrat's Flux2D and also practical measurements of the prototype. The machine parameters are given in table I.

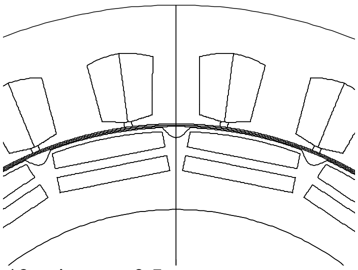
Table 1. Traction Machine Parameters

Slots per pole and phase, q	1	0.5	1	0.5
Stator slots, Q_s	48	24	42	24
Poles, $2p$	16	16	14	16
Power, P [kW]	25	25	100	100
Frequency at 1000 min^{-1}, f_s [Hz]	133	133	117	133
Length of the stator stack, l_s [mm]	65	65	150	150
Stator outer diameter, $D_{s,out}$ [mm]	380	380	430	430
Stator inner diameter, $D_{s,in}$ [mm]	287	287	330	330
q-axis inductance, L_q [p.u.]	0.4	0.33	0.3	0.47
d-axis inductance, L_d [p.u.]	0.3	0.28	0.24	0.4
Inductance ratio L_q/L_d	1.3	1.2	1.3	1.2

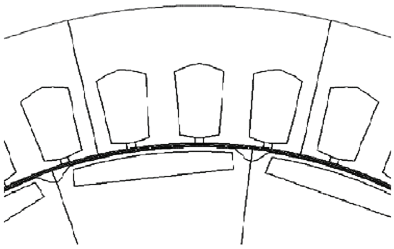
The mechanical structures are shown in Fig. 2: a) the integral slot motor and b) the non-overlapping concentrated winding motor. The inductance parameters, shown in Table I, are computed with finite element analysis at the rated speed and at the rated current of 100 A and 160 A. The structure with two magnets was selected because of the strict mass limit of the machine. The big amount of poles and the double straight permanent magnet placement instead of a V-positioning result in some reluctance torque and as small stator and rotor yokes as possible. In case of 100 kW motor designs, only one magnet per pole is utilized in order to save manufacturing costs. Large dimensions result in large amount of materials and, therefore, saving must be done. The permanent magnet material has remanent flux density of 1.2 T, permeability of 1.05 and coercive force of 980 kA/m. The isotropic resistivity of permanent magnet is set to 1.5×10^{-6} Ωm. The steel material used is M270-35A.



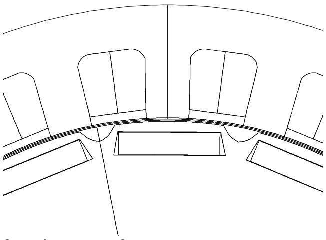
a) 48 slots and 16 poles, q = 1



b) 24 slots and 16 poles, q = 0.5



c) 42 slots and 14 poles, q = 1



d) 24 slots and 16 poles, q = 0.5

Fig. 2. a) Integral slot 25 kW motor with 48 slots and 16 poles, b) 25 kW tooth winding motor with 24 slots and 16 poles, c) 100 kW integral slot motor with 42 slots and 14 poles, and d) 100 kW tooth winding motor with 24 slots, 16 poles and open slots.

The open slot in Fig. 2 d) for the non-overlapping concentrated winding yields to easier manufacturing and gives possibility to use pre-fabricated tooth coils and thereby aims to economical series production. When the non-overlapping concentrated wound motor is designed to have open slots, there will be a large dip in the flux density distribution as it can be seen in Fig. 3. The desired flux density and torque are sufficient regardless of this dip. It has been earlier noticed that high peak torque can be obtained also with open slots and embedded magnets [4-6].

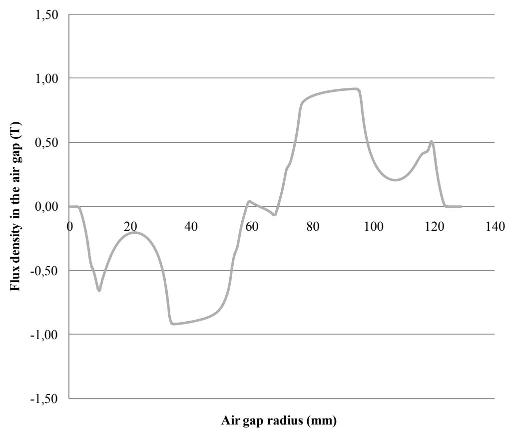


Fig. 3. Flux density in the air gap for concentrated wound motor having 24 slots and 16 poles (motor d in Fig 2).

Computation results

A set of finite element analyses was performed to evaluate the characters of the motors. Finite element method has been used to get accurate computed values in the field weakening area in where the nonlinear effects may happen. The currents, inductances, losses and torques should be calculated as accurately as possible over the wide speed range. The torques are computed as a function of load angle at a low speed of 500 min^{-1}, at the rated speed 1000 min^{-1} and at a high speed 2000 min^{-1}. The finite element computations are based on Cedrat's Flux2D program package using transient analysis and magneto static computations.

Table 2. Computation results: 25 kW loss values at rated speed 1000 min^{-1} and at rated torque 240 Nm. 100 kW loss values at rated speed 1000 min^{-1} and at rated torque 960 Nm.

Slots per pole and phase, q	1	0.5	1	0.5
The amount of Copper, [kg]	10	6.5	24	20
The amount of Permanent Magnets, [kg]	4.7	4.7	7.4	8.2
Max. Flux density in teeth, [T]	1.65	1.9	1.9	1.65
Max. Flux density in yoke, [T]	1.5	1.3	1.3	1.15
Power, [kW]	25	25	100	100
Peak Torque, [p.u.]	2.0	1.9	2.1	2.0
3 I^2R losses, [kW]	0.7	0.6	2.2	1.8
Iron losses, [kW]	0.24	0.25	1.1	0.6
PM losses, [kW]	0.05	0.4	0.2	0.3
Additional losses, [kW]	0.4	0.4	0.8	0.8
Efficiency (at rated point)	0.945	0.935	0.96	0.964
Tangential stress, [kPa]	30	30	40	40

The 25 kW motors achieve 2.5 p.u. and the 100 kW motors 2 p.u. peak torques at 300 A current. The difference is because the 100 kW motors are designed to higher tangential stresses of 40 kPa and the 25 kW ones to 30 kPa. The material amount of the q = 1 motors is slightly higher than with q = 0.5 motors. Small savings of material can be made by suitable designing. The manufacturing cost of the 100 kW q = 0.5 motor makes it more interesting as it can utilize pre-fabricated tooth coils. [7].

The iron losses were about the same range with the integral slot windings and with the concentrated windings. The 3 I^2R losses show some benefit for the concentrated windings having very short end windings. The 3 I^2R losses are dominating at the low speed range.

Permanent magnet losses: Losses in permanent magnets are caused by the eddy currents flowing though them. Eddy currents are caused both by permeance and stator harmonics. Therefore, at no load situation the magnet losses computed the with finite element method are significantly smaller than the PM losses calculated under load, especially, when dealing with non-overlapping concentrated windings that produce large stator harmonics. In non-overlapping concentrated wound PM machines the magnets suffer from the eddy current losses due to the large amount of stator winding created harmonics. This is often solved neatly by using segmented magnets. [8-9]. The 25 kW integral slot wound motor has 50 W losses in the permanent magnets as the 25 kW concentrated wound motor has 400 W with similar bulky magnets. In the 100 kW machine with tooth windings the magnets are constructed of 10 segments – thereby the PM losses are about at the same level as when using integral slot windings and semi closed slots.

Losses: Fig 4. shows the torque and current values as function of speed for the non-overlapping concentrated wound 100 kW motor. Fig. 4 b) shows the iron losses, 3 I^2R losses and losses in the permanent magnets. These values are computed utilizing Flux 2D. Fig. 5 shows the torque and current values as function of speed for the 100 kW integral slot winding motor with 42 slots and 14 poles.

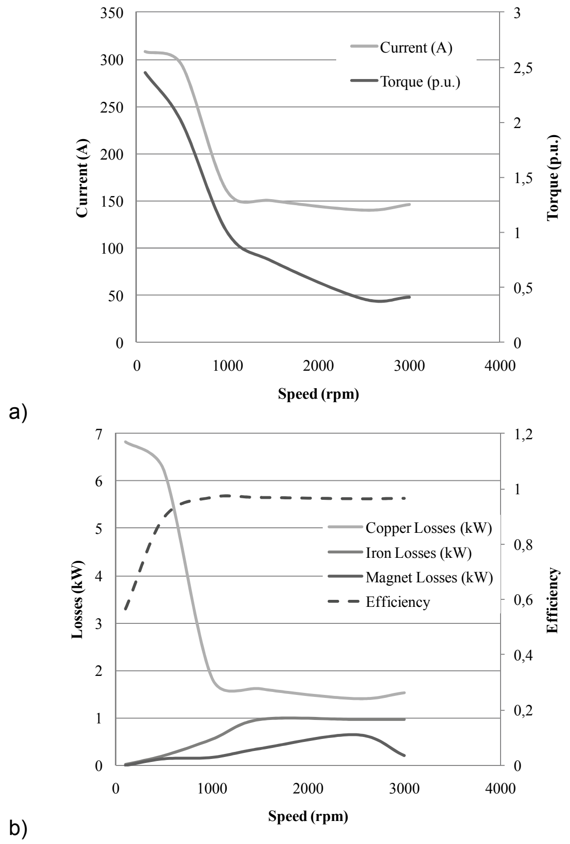


Fig. 4. a) Torque and current versus speed. b) Efficiency and loss distribution of the 100 kW tooth winding motor with 24 slots and 16 poles.

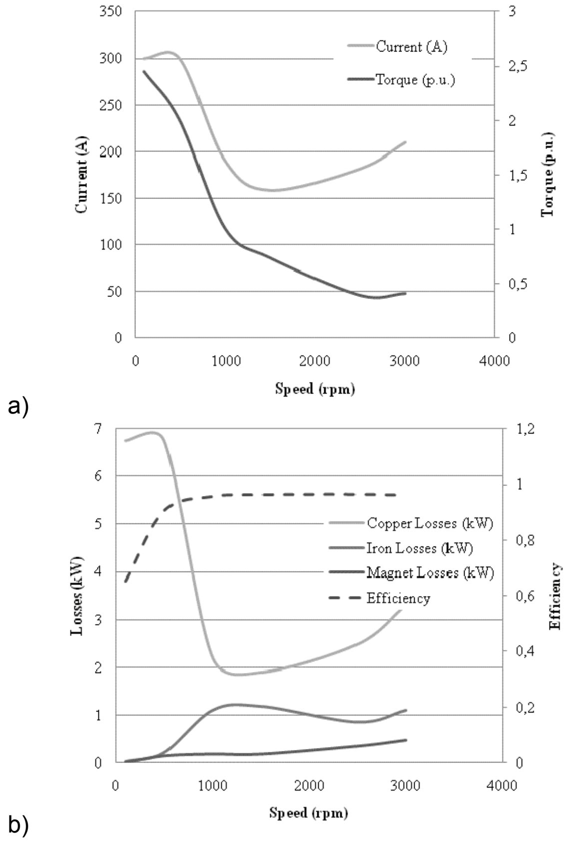


Fig. 5. a) Torque and current versus speed b) Efficiency and loss distribution of the 100 kW integral slot winding motor with 42 slots and 14 poles.

The integral slot winding 25 kW traction motor was built and tested. Fig. 6 illustrates the test set up of the machine.

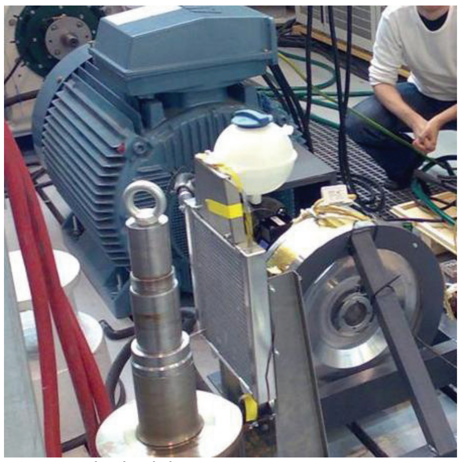


Fig. 6. Test set up in the laboratory.

According to the measurements the 25 kW motor fulfills the requirements set for it. The efficiency at the rated torque of 240 Nm and speed 1000 min^{-1} was 94 % as the computed value is 94.5%. At start the peak torque of 700 Nm was achieved for some seconds. Otherwise, the computational results and the measurement results match very well.

Conclusion

Interior PM machine producing also reluctance torque using integral slot winding was compared to interior PM motor with concentrated tooth winding. According to the finite element analyses there was an inductance difference between the direct and quadrature axes inductances also in the case of concentrated windings, which means that there can be reluctance torque when using concentrated winding, too. It can be concluded that both machines can be driven in the field weakening utilizing their large enough inductances. A 25 kW integral slot machine has been manufactured and measured, and it fulfills the requirements at different speeds. In future, also the 100 kW concentrated tooth winding traction motor will be also built and the results will be verified also by measurements.

REFERENCES

[1] H. Seok-Hee, W. L. Soong, T. M. Jahns, M. K. Guven, M. S. Illindala, Reducing Harmonic Eddy-Current Losses in the Stator Teeth of Interior Permanent Magnet Synchronous Machines During Flux Weakening, *IEEE Transactions on Energy Conversion*, Vol. 25, Iss. 2, pp. 441-449, June 2010

[2] A. Vagati, G. Pellegrino, P. Guglielmi, Comparison between SPM and IPM motor drives for EV application. *The XIX International Conference on Electrical Machines - ICEM 2010*, Rome, Italia.

[3] S. Chaithongsuk, B. Nahid-Mobarakeh, N. Takorabet, J. P. Caron, F. Meibody-Tabar, Optimal design of PM motors to achieve efficient flux weakening strategy in variable speed control applications, *The XIX International Conference on Electrical Machines - ICEM 2010*, Rome, Italia.

[4] J. J. Germishuizen, M. J. Kamper, Maarten J., IPM Traction Machine With Single Layer Non-Overlapping Concentrated Windings, *IEEE Transactions on Industry Applications*, Vol 45 no 4 july/august 2009. 1387-1394.

[5] L. Chong, R. Dutta, M. F. Rahman, Field Weakening Performance of a Concentrated Wound PM Machine with Rotor and Magnet Geometry Variation, *Power and Energy Society General Meeting, 2010 IEEE*, 25-29 July 2010, On pages 1 – 4, Minneapolis, MN, E-ISBN: 978-1-4244-8357-0

[6] P. Lindh, H. Jussila, M. Niemelä, A. Parviainen, J. Pyrhönen, Comparison of Concentrated Winding Permanent Magnet Motors With Embedded and Surface-Mounted Rotor Magnets, *IEEE Transactions on Magnetics*, 2009, vol. 45, nro. 5, p. 2085-2089, ISSN 0018-9464.

[7] P. Salminen, H. Jussila, M. Niemelä, J. Pyrhönen, Concentrated wound permanent magnet motors with different pole pair numbers, 2007, p. CD julkaisu, *ISEF, International Symposium on Electromagnetic Fields in Mechanotronics, Electrical and Electronic Engineering*, 13. - 15. 9. 2007, Prague, Tsechk, ISBN 978-80-01-03784-3.

[8] H. Jussila, Ph.D. dissertation, Concentrated winding multiphase permanent magnet machine design and electromagnetic properties - Case axial flux machine, Acta Universitatis Lappeenrantaensis, ISBN 978-952-214-882-7.

[9] H. Polinder, and M. J. Hoeijmakers, Eddy-current losses in the segmented surface magnets of a PM machine, *IET Electric Power Applications*. Vol. 146, Issue 3, pp. 261-266. 1999.

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