EVS28
KINTEX, Korea, May 3-6, 2015

Intelligent Stator Cage Winding for Automotive Traction Electric Machines

Gurakuq Dajaku[1)], Florian Bachheibl[2)], Adrian Patzak[2)], and Dieter Gerling[2)]

[1)]FEAAM GmbH, [2)]Universitaet der Bundeswehr Muenchen
D-85577 Neubiberg, Germany, Tel: +49 89 6004 4120, Fax: +49 89 6004 3718
E-mail: gurakuq.dajaku@unibw.de

Abstract

This paper present two different asynchronous and synchronous reluctance traction machines designed using the new stator cage winding. The both machines with the new winding concept show high torque density and efficiency, low costs and simple manufacturing, and thermally robust. For the asynchronous machine, different control strategies, such as pole-switching or multi pole-pair operation are implemented to increase the efficiency at the entire torque-speed region. On the other side, the synchronous reluctance machine show high efficiency, and additionally, as results of negligible rotor losses it is available to operate also with a simple passive air cooling.

Keywords: intelligent stator cage drive (ISCAD), electric machine, low costs, high efficiency, battery electric vehicle, hybrid electric vehicle

1 Introduction

For the past several years permanent magnet (PM) synchronous machines have found wide applications in electric vehicles and hybrid electric vehicles (EV/HEVs) [1 to 4]. Interior PM (IPM) machines equipped with distributed windings (DW) in stator have been shown to be a good candidate for high-speed and high power density traction application. Compared with fractional-slot concentrated windings (FSCW), the use of DW solves the problems with high rotor losses, rotor heating, as well noise and vibrations [5, 6]. The main merit of DW is the high quality of the magneto motive force (MMF) distribution. DW with sinusoidal MMF distribution show high performances concerning the torque ripple, rotor losses, and other above mentioned problems, and are applicable also for other machine types such as asynchronous machines, synchronous reluctance machines, and wound-field synchronous machine. Recently, Tesla model-S is using an asynchronous machine with DW as traction machine [7]. Continental also has developed a wound-field synchronous traction motor with the same winding type [8]. Of course, also many other companies show increased activities to develop non-rare earth PM traction motors with this winding type [3]. Otherwise, the DW are related also with several drawbacks and problems such as manufacturing complexity and high production costs, overlapping coils with large end-winding length, low slot filling factor, high Ohmic losses in the stator winding, and so on [9]. To overcome the drawbacks and problems with the DW, however, simultaneously at the same time to use the merits of this winding type concerning the high MMF waveform quality, reference [10-12] presents a new traction drive system that is based on a novel stator cage winding for electric machines. The complete system is called as the Intelligent Stator Cage Drive (ISCAD), while the new winding as the ISCAD winding. The new winding type offers several advantages such as, simple and cheaper construction and manufacturing, extremely short end winding length, high quality MMF waveform, variety control strategies for the MMF function, as well, high thermal capability, simple cooling, greater fault tolerance, and so on.

In this paper different asynchronous and also synchronous reluctance traction machines based on the ISCAD concept are designed and analysed. The studied machines are designed considering the Tesla model-S ASM traction motor as benchmark. Several electromagnetic and thermal simulations are performed to determine and evaluate the performances of the ISCAD motors. A special consideration is taken during optimization of the machine efficiency using pole changing and also the multi-pole-pairs operation control strategies. Further, cooling capability and cooling efficiency are investigated for the new and also the reference machine. Last but not least, the both ISCAD synchronous reluctance and ASM machines are compared concerning the power density, machine losses, efficiency and thermal behaviours.

2 ISCAD Machine

According to [10], the new ISCAD winding is constructed analogous with the ASM cage rotor. The stator consists of a stack of iron lamination and massive conductors (bars) in each slot, being short-circuited at one axial end of the machine using an end-connection ring, Fig.1. In the

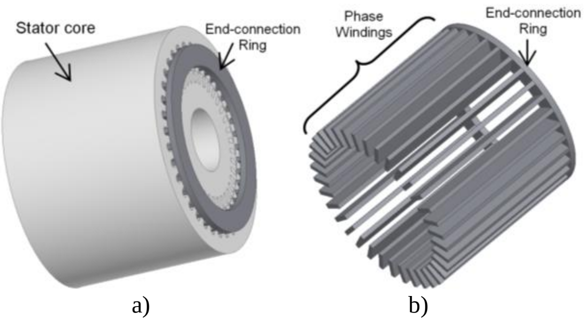


Figure 1: a). New stator core with the winding, b). Stator cage winding

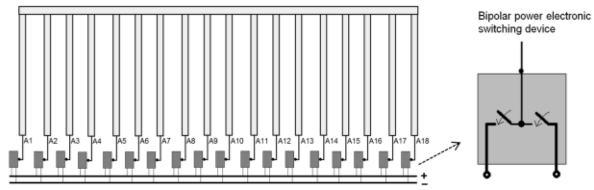


Figure 2: The m-phase stator winding supplied with multiphase inverter

opposite stator side the conductor terminals are connected directly to the supply source devices. Each conductor (stator slot) is a phase winding itself and is supplied with its own supply device as is illustrated in Fig. 2.

The production of the ISCAD winding is very cheap and simple compared with the conventional winding. The cage winding with the all massive conductors connected to one end-ring can be manufactured separately, and then it can be shifted in the stator slots as is illustrated in Fig.1. Or, another possible solution is to use the die casting method for producing the stator cage winding, analogous with the ASM rotor. For the both winding manufacturing cases a high slot fill factor up to 100% can be realized that is about 2.5 times higher than for the conventional distributed windings. This results to low resistance and low Ohmic losses. Thus, as results of the high slot fill factor, it is possible to use *Aluminium* material instead of *Copper*.

Concerning the cooling capability, the ISCAD winding construction offers a possibility to make a direct cooling of the stator winding conductors by cooling the end-ring component with an integrated cooling channel inside the end-ring section, or mounting it on the end-ring lateral and/or radial faces. Fig. 3 illustrates the new cooling technique with a cooling channel mounted directly on the end-ring lateral side. For the proposed technique, the Ohmic losses generated on the end-ring region can be cooled directly, while the Ohmic losses generated on the winding bars inside the machine can be cooled very efficiency [10]. Further, concerning the stator iron losses, the new stator design represent a low thermal resistance between the stator core region and the winding bar conductors, since no slot insulation sheet and also air-gap exists between the winding bars and stator teeth/yoke regions. Therefore, the direct end-ring cooling method is efficient also for this part of losses.

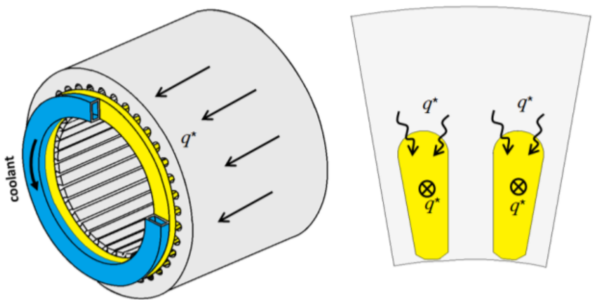


Figure 3: New cooling method with cooling channel mounted on the end-ring lateral side

3 Control Strategies

As with the new stator cage machine there is the possibility to energize each conductor (slot) separately, this feature gives a great variety of possible modes of operations:

- Changing the number of pole-pairs (even during operation) for the asynchronous machines,
- Multi pole-pairs operation,
- Controlling the amplitude and frequency of corresponding pole-pairs separately,
- Changing the number of active phases (even during operation),
- Active phases being distributed symmetrically or non-symmetrically along the machine circumference,
- Changing the mode of operation to ensure an optimum efficiency (depending on the operation point),
- Changing the mode of operation to ensure an optimum system life-time.

Eq. (1) describes the current in *k*-th stator slot in general form, where the amplitude C_ξ, frequency ω_ξ, and the number of pole-pairs p_ξ are denoted as variable parameters. Thus, depending on the operation modes, or the machine type, these parameters can be controlled separately. This can be useful for different machine types and also for different operation modes, such as,

- Self-exciting synchronous machine according to [13], where the working wave is used for torque production and a harmonic wave is used to transfer energy to the rotor. For this machine type, the working wave and the rotor excitation wave can be controlled independently.
- Multi pole-pairs ASM; the ASM can operate with several pole-pairs simultaneously if the rotation speed of the all excited poles is the same. This condition can be fulfilled with the new winding by varying the supply frequencies of corresponding poles.
- Hybrid machines; another applications can be found also on the hybrid rotor machines such as, a combined asynchronous and PM rotor, asynchronous and reluctance rotor, PM and reluctance rotor, multi-pole pairs PM or reluctance rotor, and so on.

$$i_{S,k} = \hat{I} \cdot \sum_{\xi=1}^{\xi_{max}} C_\xi \cdot \cos\left(\omega_\xi t - p_\xi \cdot (k-1)\frac{2\pi}{Q_S}\right) \qquad (1)$$

4 ISCAD Traction Machines

Two different traction machines are designed and investigated considering the Tesla model-S asynchronous traction motor as reference machine (volume and power). The first machine design is an asynchronous motor with 60-slots stator cage and 73-slots rotor cage configuration, while the second machine type is a four poles synchronous reluctance motor. The both machines are investigated under the same geometrical and electromagnetic constraints that are resumed in Table-1. Several simulation results for different operation points are presented in following to show the performances and capabilities of the proposed ISCAD machines.

4.1 ISCAD-ASM

As well shown from Table-1, for the ISCAD asynchronous machine (ASM), the aluminium material is selected for the both stator and rotor cage windings. Further, the number of pole-pairs is taken as variable parameter, thus for the ASM rotor the number of poles is varied depending on the operation points. For the base speed and for the maximal required torque (maximal power) this parameter is selected to be equal two. However, for other load conditions (as will be shown later) the number of pole-pairs is switched to one, or also a combination of a one and two can be selected. Thus, for a four poles ASM condition and also for the maximal power, Table-2 and Fig. 4 compares the results for the proposed ISCAD-ASM with the reference machine used in Tesla model-S. It has to be pointed out, that the benchmark calculation for

Table 1: Main specification data

Specification	ISCAD-ASM	ISCAD-SRM
Outer diameter	253 mm	253 mm
Total axial length	270 mm	270 mm
Active length	250 mm	250 mm
Air-gap length	0,5 mm	0,5 mm
Number of poles	variable	4
Number of stator slots	60	60
Number of rotor slots	73	--
Material, stator winding	Aluminium	Aluminium
Material, rotor winding	Aluminium	--
UDC	24 V	24 V
Maximal torque	600 Nm	600 Nm
Maximal speed	14000 rpm	14000 rpm

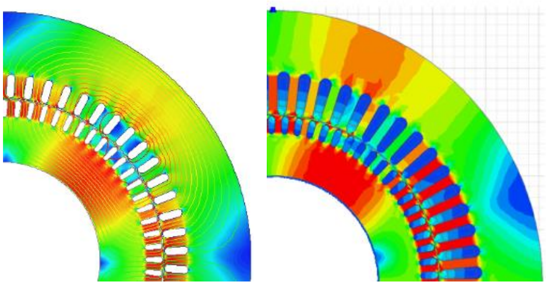
the reference ASM is done using a self-developed FEM model based on published or estimated machine data. Considering the Ohmic losses which represent the dominant losses for the both machines, it can be seen here that with the new ISCAD-ASM design these losses are reduced for about 50% even Alumminium material is used for the stator and rotor cage. Another advantage on the ISCAD machine is also the very smooth torque response, Fig. 5. Thus, for this machine type none stator or rotor skewing is required.

A. *Variable pole-pairs operation*

As well mentioned earlier, with the new ISCAD-ASM we have the opportunity to change the number of pole-pairs of the machine even during operation, and with this to utilize the best efficiency in the torque-speed map. In the following Fig. 6, there are illustrated the regions with maximal efficiency that can be obtained using the pole switching control strategy. Thus, for low torque region (low saturation condition), the new machine can be operate with low number of pole-pairs at the entire speed range, e.g. p=1. For this condition, the iron losses, and also the skin and proximity effect on the stator and rotor bars can be reduced significantly, and with this a high efficiency in the machine can be achieved. Further, with increased load torque the number of pole pairs can be switched from one to two, and so one. For high torque or overloaded case, a high number of poles can be chosen. Therefore, using this control method, the new ISCAD-ASM is available to deliver a high efficiency over a wide torque-speed area. To validate the efficiency of the new pole-switching control strategy, the machine performances at two different rotor speeds are investigated. Table-3 compares the obtained results for the case where the number of pole-pairs is switched from one to two. To make the comparison in proper way, the simulations are performed under the same rotor slip condition for the both operation modes. From the results, it can

Table 2: Comparison of results for the maximal power

Results	**Tesla ASM**	**ISCAD ASM**
speed [rpm]	5300	5300
Torque [Nm]	600	600
Stator Ohmic Losses [kW]	21,4	8,6
Rotor Ohmic Losses [kW]	14,9	9
Iron Losses [kW]	1,2	1,14
efficiency [%]	89,8	94,7



a) b)

Figure 4: Flux density distribution und the maximal load; a). ISCAD-ASM, b). Tesla model-S ASM

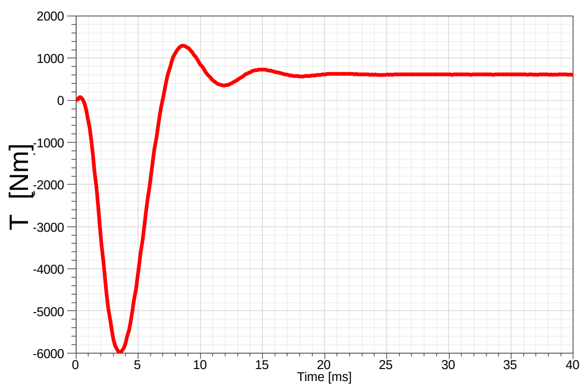


Fig. 5: Torque response for the maximal load for the ISCAD-ASM

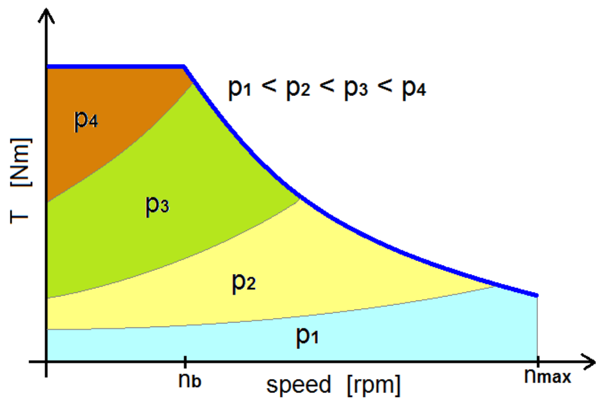


Figure 6: Regions with maximal machine efficiency

Table 3: ISCAD-ASM with pole-switching operation

Results		**p = 1**	**p = 2**
Torque [Nm]	10000 rpm	106	100
Ohmic Losses [kW]		2,3	4,65
Iron Losses [kW]		0,42	0,64
efficiency [%]		97,4	95,3
Torque [Nm]	14000 rpm	198	200
Ohmic Losses [kW]		9	18,8
Iron Losses [kW]		0,96	1,23
efficiency [%]		96,6	93,8

concluded that, with the pole-switching control strategy the machine efficiency can be improved significantly. For the considered load conditions the machine losses, especially the Joule losses in the stator&rotor cage windings are reduced for about 50% when the number of pole-pairs is switched from two to one.

B. *Multi pole-pairs operation*

With the pole-switching control strategy presented above we have seen the possibility to increase machine efficiency at specific torque-speed regions. However, in the boundaries between regions there still to exists a discrete transition on the efficiency values. Thus, to have an uniform machine efficiency over the entire map, it is required to implement additionally a second switching method that performs a continual switching from one pole-pair to the second pole-pair. Since, the new ISCAD-ASM is available to operate also with "*multi-pole-pairs*" simultaneously, this control method can provide a smooth transition between different pole operation. Fig. 7 illustrates the continuous pole-switching using the new control method, where the *multi-pole-pairs* control strategy is applied during pole-switching. It is important to note here that, with this method, in one side the pole changing can be performed very softly without influencing the torque or speed response, however, other sides the machine efficiency on the transient regions further can be improved, and with this it is possible to realize a very homogenous high efficiency area in the entire torque-speed map of the machine.

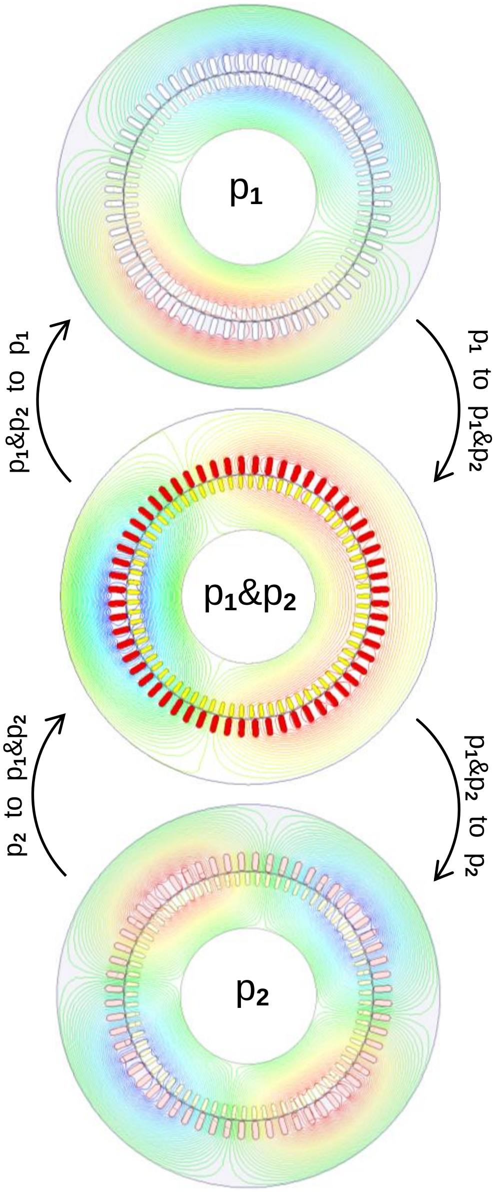


Figure 7: Multi-pole-pair ISCAD ASM operation

4.2 ISCAD-SRM

The second machine type considered in this paper is the synchronous reluctance machine designed using the same ISCAD concept (ISCAD-SRM). Analogous with the first ASM, the new ISCAD-SRM is designed under the same available volume. In fact, to make a proper comparison, the same stator is considered for the both machines. Fig. 8 shows the geometry and the field distribution for the studied four poles SRM.

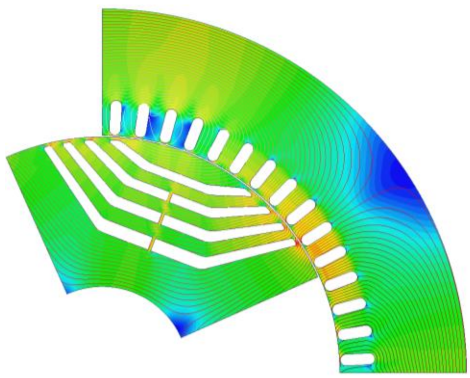


Figure 8: Four poles ISCAD SRM

Table 5: Comparison of results for the maximal power

Results	**ISCAD-SRM**	**ISCAD-ASM**
speed [rpm]	5300	5300
Torque [Nm]	520	600
Stator Ohmic Losses [kW]	8,75	8,6
Rotor Ohmic Losses [kW]	--	9
Iron Losses [kW]	1,6	1,14
efficiency [%]	96,6	94,7

Further, Table-5 compares the both ISCAD machines under the same excited load current (620Arms). The derived results show that, concerning the torque capability the ISCAD-SRM produce about 13% less torque, however, as result of reluctance rotor (none winding in the rotor) this machine type has very low rotor losses that results to a high efficiency machine, and as will be seen below, to a thermally robust design.

5 Thermal analysis

Two different cooling concepts are investigated during the thermal analysis of the traction machines presented in this paper. Firstly the active fluid cooling is considered for the all machine designs, where for this case, the studied machines are assumed to be mounted inside a water cooled jacked with 80°C coolant temperature, and also with 2000 *W/*(*Km²*) coolant convection coefficient. As operation point, the maximal load condition (*Tmax* at *5300rpm*) is selected for investigation. Further, as results of high rotor losses for the ASMs, these machine types are investigated transiently, whereas the temperature for the ISCAD-SRM is determined for the steady state case. Fig. 9 gives the temperature distribution for the maximal required power after 240s simulation time. Also here, the new ISCAD-ASM show better thermal results compared with the reference machine that is mainly as results of low thermal resistance between the stator bars and core, and also the low loss density [10]. On the other side, the temperature results presented in Fig. 10 for the ISCAD-SRM show low temperature at steady-state even the machine is considered to operate under the maximal load. Considering here that, since usually the traction machines should be available to operate under the maximal load only for short time (few seconds), a passive simple air-cooling method could be possible for this machine type to hold the temperatures under the critical point. Therefore, to prove this assumption, an additional thermal analysis is carried out on the ISCAD-SRM under the passive air-cooling condition with 50 *W/*(*Km²*) coolant convection coefficient. The temperature results after 240s simulation time given in Fig. 11 validate the healthy operation of the machine also with passive cooling method. Thus, considering the low machine temperature under the maximal load condition, it can be concluded that, the new ISCAD-SRM doesn't require complex and also expensive cooling jacked as for the usually traction machines, and with this the total machine costs further can be decreased.

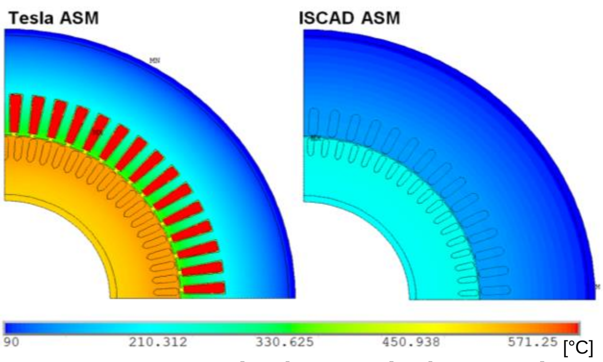


Figure 9: Temperature distribution under the maximal load at 250s

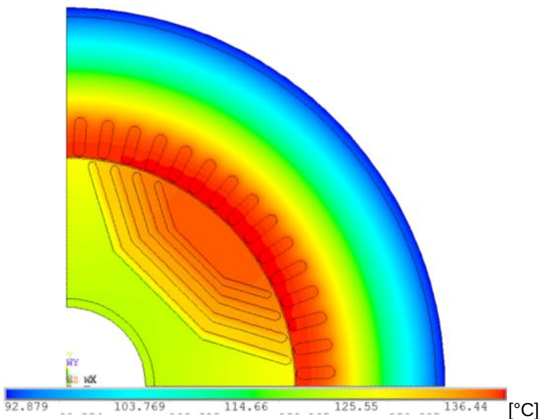


Figure 10: ISCAD-SRM with active fluid cooling; Temperature distribution at steady state under the maximal power

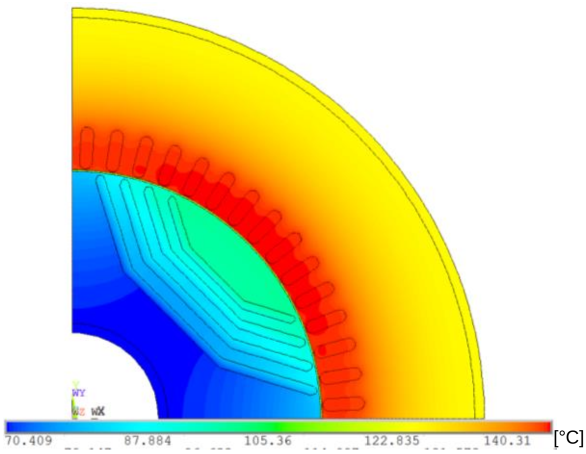


Figure 11: ISCAD-SRM with passive air cooling; Temperature distribution under the maximal load and at 250s simulation time

6 Conclusions

A new stator cage winding is presented and discussed, and its capability for applications in asynchronous and also synchronous reluctance machines is investigated. The new winding type is characterized with a simple construction and manufacturing, extremely short end winding length, high quality MMF waveform, high winding factor for the fundamental wave, and greater fault tolerance. Further, with the new stator cage machine there is the possibility to energize each conductor (slot) separately. This feature gives a great variety of possible modes of operations, such as: pole-switching, multi pole-pair operation, changing the number of active phases, and so on. Thus, based on the variety of control strategies and also the mode of operation the new machine type is called as intelligent stator cage drive (ISCAD).

Two different traction asynchronous and synchronous reluctance machines based on the ISCAD concept are investigated considering the Tesla model-S ASM traction motor as benchmark. Several electromagnetic and thermal simulations are performed to determine and evaluate the performances of the ISCAD motors. The obtained results show that,

ISCAD-ASM: provide high power density and high efficiency, the pole-switching and also the multi pole-pair operation increase the efficiency over the complete torque-speed region, thermally robust, low manufacturing cost, and aluminium material for the both stator and rotor cage windings.

ISCAD-SRM: provide high power density and high efficiency, the torque capability is for about 13% lower compared with ISCAD-ASM, otherwise the efficiency is higher, the rotor losses are negligible, thermally very robust, this machine type can operate also with passive cooling, the absence of rotor cage winding, and also the simple passive cooling reduce further the total costs for this machine type.

References

[1] P. Sekerak, V. Hrabovcova, et al., “Comparison of Synchronous Motors With Different Permanent Magnet and Winding Types,” IEEE Transactions on Magnetics, vol. 49, no. 3, pp. 1256–1263, Mar. 2013.

[2] L. Chen, J. Wang, et al., “ Optimizations of a Permanent Magnet Machine Targeting Different Driving Cycles for Electric Vehicles”, *International Electric Machines and Drives Conference* (IEMDC-2013), 12.-15. Mai 2013, Chicago, USA

[3] A. M. EL-Refaie, “Motors/Generators for Traction/Propulsion Application: A Review”, *IEEE Vehicular Technology Magazine*, vol. 8, No. 1, 2013, pp. 90-99.

[4] J. Merwerth, R. Dörfer, “The innovative Hybrid-Synchronous-Machine in the new BMW i3”, 3rd International Electric Drives Production Conference 2013 (EDPC-2013), 29.-30. October 2013, Nuremberg, Germany, pp. 224-227.

[5] J. Li, D. W. Choi, D. H. Son, Y. H. Cho, “Effects of MMF Harmonics on Rotor Eddy-Current Losses for Inner-Rotor Fractional Slot Axial Flux Permanent Magnet Synchronous Machines”, *IEEE Transactions on Magnetics*, Vol. 48, No. 2, pp. 839-842, February 2012.

[6] F. Magnussen, H. Lendenmann, “Parasitic Effects in PM Machines With Concentrated Windings”, *IEEE Transactions on Industry Applications*, Vol. 43, No. 5, pp. 1223-1232, September/Octomber 2007.

[7] http://www.teslamotors.com/de_DE/roadster/technology/motor

[8] [Online]. http://www.continental-corporation.com/www/pressportal_com_en/themes/press_releases/3_automotive_group/powertrain/press_releases/pr_2010_04_29_ elektromotoren_en.html.

[9] J. Li, D. W. Choi, D. H. Son, Y. H. Cho, “Effects of MMF Harmonics on Rotor Eddy-Current Losses for Inner-Rotor Fractional Slot Axial Flux Permanent Magnet Synchronous Machines”, *IEEE Transactions on Magnetics*, Vol. 48, No. 2, pp. 839-842, February 2012.

[10] G. Dajaku, D. Gerling, “Low Costs and High Efficiency Asynchronous Machine with Stator Cage Winding”, *IEEE International Electric Vehicle Conference 2014* (IEVC 2014), Florence, Italy, December 17-19, 2014,

[11] A. Patzak, D. Gerling, “Design of a Multi-Phase Inverter for Low Voltage High Power Electric Vehicles”, *IEEE International Electric Vehicle Conference 2014* (IEVC 2014), Florence, Italy, December 17-19, 2014.

[12] F. Bachheibl, D. Gerling, “High-Current, Low-Voltage Power Net”, *IEEE International Electric Vehicle Conference 2014* (IEVC 2014), Florence, Italy, December 17-19, 2014.

[13] G. Dajaku, D. Gerling, “New Self-Excited Synchronous Machine with Tooth Concentrated Winding”, 3rd International Electric Drives and Production Conference (EDPC-2013), 29.-30. Oktober 2013, Nürnberg, Germany, pp. 217-222.

Authors

Gurakuq Dajaku got his diploma degree in electrical engineering from the University of Prishtina, Kosova, in 1997 and the Ph.D. degree from the Universitaet der Bundeswehr Muenchen, Munich, Germany, in 2006. Since 2007 he has been a Senior Scientist with FEAAM GmbH, an engineering company in the field of electric drives. Since 2008 and 2010 he has been a Lecturer at the Universitaet der Bundeswehr Muenchen, Germany, and the University of Prishtina, Kosova, respectively. His research interest is in the field of electrical machines and drives. He has published numerous technical papers in different IEEE journals and conferences and has several international patents and patent pending applications. Dr. Dajaku received the Rheinmetall Foundation Award 2006 and the ITIS (Institute for Technical Intelligent Systems) Research Award 2006.

Prof. Dr.-Ing. Dieter Gerling
Institute for Electrical Drives, University of Federal Defense Munich, Werner-Heisenberg-Weg 39, 85579 Neubiberg, Germany. Tel: +49 89 6004 3708, Fax: +49 89 6004 3718
Email: dieter.gerling@unibw.de
URL: www.unibw.de/EAA
Born in 1961, Prof. Gerling got his diploma and Ph.D. degrees in Electrical Engineering from the Technical University of Aachen, Germany in 1986 and 1992, respectively. From 1986 to 1999 he was with Philips Research Laboratories in Aachen, Germany as Research Scientist and later as Senior Scientist. In 1999 Dr. Gerling joined Robert Bosch GmbH in Bühl, Germany as Director. Since 2001 he is Full Professor and Head of the Institute of Electrical Drives at the University of Federal Defense Munich, Germany.

Florian Bachheibl M.Sc. graduated from the Universitaet der Bundeswehr Muenchen in 2011 with a Master of Science in mechatronics engineering.
Since then, he has worked as a research assistant at the Institute of Electrical Drives and Actuators. His main research interests are the modelling of passive components, systems engineering and fields analysis.

Adrian Patzak M.Sc. is research member at the Institute of Electrical Drives at the University of Federal Defense Munich, Werner-Heisenberg-Weg 39, D-85577 Neubiberg, Germany (phone: +49 89 6004-3590; fax: -3718; email: Adrian.Patzak@unibw.de). Adrian Patzak was born in 1985 and received his Master degree in Electrical Engineering from the University of Applied Sciences Regensburg, Germany, in 2011. Afterwards he switched to the University of Federal Defense Munich, and since that he is working as a research assistant on Automotive Power Systems, Electric Machines and Control.