Field Oriented Control for a 60-Phase Intelligent Stator Cage Drive (ISCAD)

Andreas Greifelt
FEAAM GmbH
D-85577 Neubiberg, Germany
a.greifelt@feaam.de

Dieter Gerling
Chair of Electrical Drives and Actuators
University of Bundeswehr Munich
D-85577 Neubiberg, Germany
dieter.gerling@unibw.de

***Abstract*—This document shows a constructive solution in relation to the actual problems in modern transport by showing the advantages of the ISCAD drivetrain concept. The "Intelligent Stator Cage Drive" itself constitutes a 48V low voltage machine topology which forms the highly dynamic link between maximum mobile application safety and cost effectiveness without using environmentally harmful magnets. Within this paper the open loop and closed loop control are discussed besides the characteristics of the multiphase system.**

Keywords—intelligent stator cage drive (ISCAD), low costs, low voltage, high current, high power, high efficiency, Field Oriented Control (FOC), Automotive drive

I. Introduction

In future drive technologies for mobile applications, in particular for individual and public transport, there is still a higher attention to the reduction of greenhouse effect relevant emissions like CO2. The most promising technology for drivetrains is currently formed by the electric drive in various topologies combined with batteries or fuel-cell technologies. However, the development of commonplace high-voltage systems is at the moment accompanied by challenges in isolation, redundancy and material-related production costs. To solve these multiple problems which are primarily linked to the high voltage level it is necessary to reduce the voltage by keeping the power of the drivetrain at least constant. The reduction of voltage but maintaining power means a higher current in the coils of the machine. To avoid possible thermic side effects and maximize the filling factor for high currents, the fundamental new idea was to replace the coils and windings by statorbars (Fig. 1), which are not as sensitive as statorcoils to high currents [1]. The first advantage here is minimizing the resistance and maximizing the cooling relevant surface. In addition it is possible to choose the number of phases freely by choosing the number of statorbars which are connected with a ring at the back. The main advantage is that by connecting every bar with a dedicated half-bridge module it is possible to switch the pole pair number during operation which allows a fully new space of high dynamic adjustment of rotor speed and torque [2]. The use of MOSFETs instead of IGBT in combination with the extraordinarily smooth magnetomotive force (MMF) provided by the multiphase system causes a very high efficiency in full load but especially in the absolutely important partial load. Thus the technical features are superior to conventional topologies. The manufacturing of the machine is very cost-efficient because only aluminum and magnetic steel sheets are necessary for the production of machines. Environmentally harmful respectively monopoly resources such as neodymium or its secondary product neodymium iron boron are not used anymore. As a result the machine is far more environmentally friendly. The power electronics also come at a lower price because of the use of MOSFET technology instead of IGBTs. As rotor a standardized induction machine squirrel cage rotor can be used. This saves additional costs.

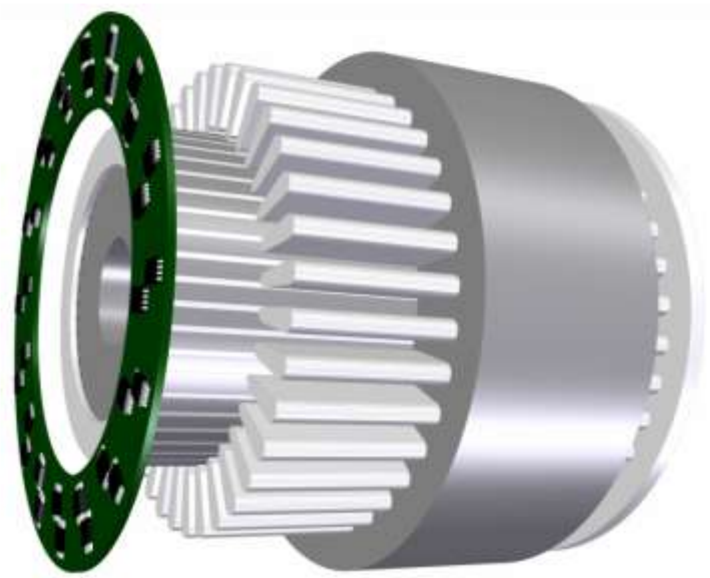

Fig. 1– Sketch of a highly integrated ISCAD drivetrain

The most advantageous applications for the 48V ISCAD topology are mobile applications like automobile, aircrafts and watercrafts. Especially the standards of the International Organization for Standardization (ISO) are fundamental for every vehicle subject to certification regulations. The current state of the art topologies are often fed by 360 V, which is linked to high isolation standards. According to these standards costs can be saved actively by saving engineering and material relating to isolation. Passively costs are saved, because an individual training of staff concerning high voltage inspection is not necessary any more. Especially for vehicle manufacturers and their establishments with affiliated workshops every member of the technical staff respective mechanic have to be trained and certified in working with high voltage drivetrains. With 48V drivetrains this is not a challenge any more. In the end even the customer is legally allowed to check the drivetrain without any form of danger. Tests with the first ISCAD functional model have shown that even during operation direct contact to the DC-bus is possible without risks.

II. Design and Modeling

A. *Premodeling of the Machine*

After the modeling of a few specific machine designs with finite element software the general analytical description of the characteristics of the topology was calculated [3]. After a few adaptions it was proven that the analytical calculation of parameters and the simulation results were almost concordant. With this information the next step was to build a software application to calculate the important values to quickly pre-design the machine. Not only the values were important for the hardware design of the machine but also for the design of the power electronics and further for the closed loop control. With this analytical description it is now possible to save time by quickly calculate the machine parameters and optimize or feed further tools. The current stand-alone proper working version of the pre-modeling software is based on Matlab and allows the calculation of all relevant parameters within seconds. If the software is executed as a script within Matlab, the values are directly written into the workspace to be used in the later described closed loop controls.

Further analysis of the calculated values has shown that the simulation and extraction of the electric parameters of several machines with the finite element method (FEM) is absolutely comparable with the analytic calculated values. Exemplary the stator main inductance of a 60-phase machine is shown in Fig. 2 as a function of the pole pair number, considering the slotting effect [4]. The discrepancy of the different calculating methods is lower than one percent, which supports the assumption that the analytical calculation is plausible.

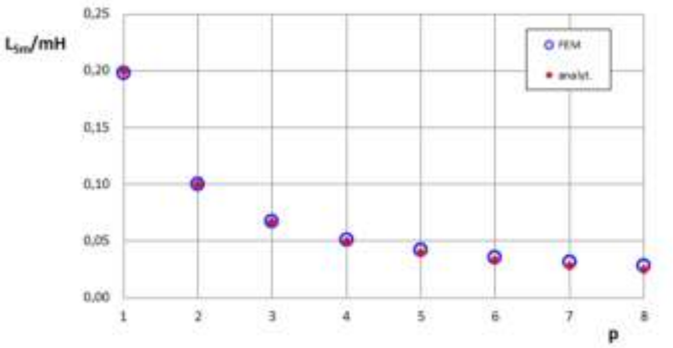

Fig. 2 – Comparison of analytical and FEM calculation of the stator main inductance L_{Sm}

B. *System Modelling in Matlab® Simulink®*

After calculating the model parameters it is possible to feed machine models with them to study the static and dynamic behavior of the specific machine. These results provide a basis for further optimizations of the behavior. For the analysis it is possible to resort to the usual asynchronous machine model which is adapted to the number of phases of the research object. Tests have shown that with an adaption of the Clarke-Transformation for multiphase purposes it is possible to get reasonable results of the static and dynamic behavior. The transformation of a n-phase system to a stator-oriented alpha-beta system (2.02) needs a transformation matrix T (2.03). For a better overview the abbreviation of the partial angle between two phase currents ε is introduced (2.01). The reverse calculation of the n-phase currents from the stator oriented currents results from the pseudo-inverse matrix T_I of (2.03) which is described in (2.05) and used with the calculation rule of (2.04).

$$\varepsilon = \frac{2\pi}{n} = \frac{360°}{n} \tag{2.01}$$

$$\begin{bmatrix} z_\alpha \\ z_\beta \end{bmatrix} = \underline{T} \cdot \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ \ldots \\ z_{n-1} \\ z_n \end{bmatrix} \tag{2.02}$$

$$\underline{T} = \frac{2}{n} \begin{bmatrix} 1 & \cos(1\cdot\varepsilon) & \cos(2\cdot\varepsilon) & \ldots & \cos((n-1)\cdot\varepsilon) \\ 0 & \sin(1\cdot\varepsilon) & \sin(2\cdot\varepsilon) & \ldots & \sin((n-1)\cdot\varepsilon) \end{bmatrix} \tag{2.03}$$

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ \ldots \\ z_n \end{bmatrix} = T_I \cdot \begin{bmatrix} z_\alpha \\ z_\beta \end{bmatrix} \tag{2.04}$$

$$T_I = \left[\underline{T} \cdot \left[\underline{T}\right]^T\right]^{-1} \cdot \left[\underline{T}\right]^T = \begin{bmatrix} 1 & 0 \\ \cos(1\cdot\varepsilon) & \sin(1\cdot\varepsilon) \\ \cos(2\cdot\varepsilon) & \sin(2\cdot\varepsilon) \\ \ldots & \ldots \\ \cos((n-1)\cdot\varepsilon) & \sin((n-1)\cdot\varepsilon) \end{bmatrix} \tag{2.05}$$

The ISCAD machine model itself can be built on the basis of standardized induction machine equations. The mathematically ideal model of the topology is equal to that of a normal topology of an induction machine except of some parameters e.g. in the skin effect behavior. For further analysis of the influence of these effects supplementary models are currently still under progress.

Currently a 60 phase model with an ISCAD topology was created with Matlab Simulink and is embedded analogously to Fig. 3 in a test bench. The input side is primary a voltage source with 60 phases and secondary a load which gives the reference torque to the model. The voltage level is 48 V DC multiplied with the maximum sine pulse modulated (SPWM) modulation index of (2.06) [5]. In addition the product is modulated with an adequate phase control factor.

$$m = \frac{\hat{U}_U}{U_d} \cdot \frac{1}{\sqrt{2}} = \frac{0.5}{\sqrt{2}} = 0.35 \qquad (2.06)$$

The voltage and the load can be static and dynamic. In the further analysis within the paper the voltage is static and load is analog to the bottom of Fig. 5 dynamic between plus-minus 300 Nm. The visualized outputs of the model are the flux, stator-current, rotor-speed and the torque.

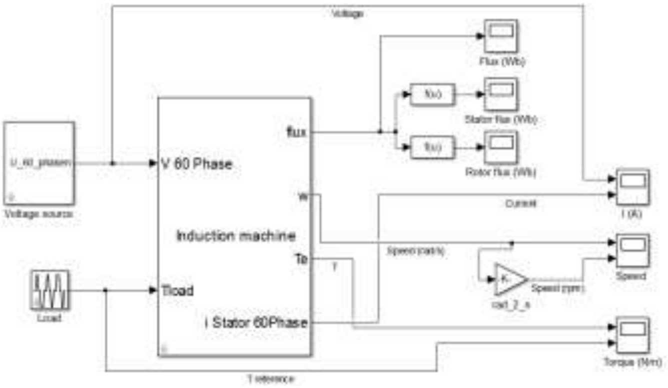

Fig. 3 – Matlab Simulink ISCAD model test bench overview for a 60 Phase model

The machine model (Fig. 4) contains loops for the calculation of the flux, the electromagnetic torque, the stator currents and the rotor speed using the fundamentals of standard induction machines. The inputs and outputs of the model are marked in blue and green. The necessary transformations of this 60-phase system are marked in yellow.

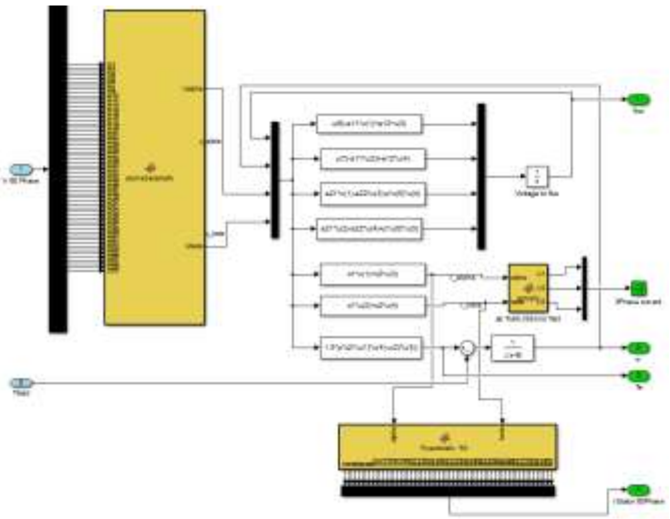

Fig. 4 – Matlab Simulink ISCAD model Overview

Simulation of the torque (Fig. 5) shows a plausible characteristic. The 4-polepair machine starts after a short transient effect to rotate with the 5 Hz-sine-voltage based no-load speed of 74.9 rpm (Fig. 8). The reference torque load is zero, so that the machine just has to compensate the friction effects. After raising the load torque up to 300 Nm the machine holds the torque. The current rises in relation to the higher torque (Fig. 7). Reducing or reversing the torque load influences the current and speed characteristics as expected. The correlation between the input voltage and the stator current (Fig. 6) seems also to be plausible. The high current has not to be classified as implausible because the phase control factor of the sine wave is not optimal, so that the machine gets much more current than it needs e.g. to hold the no-load operation point.

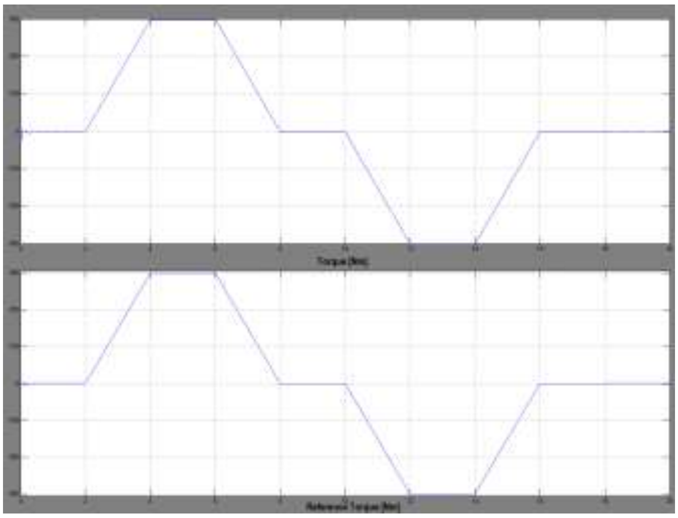

Fig. 5 – ISCAD model simulation result of the machine toque (top) in comparison to the reference torque load (bottom)

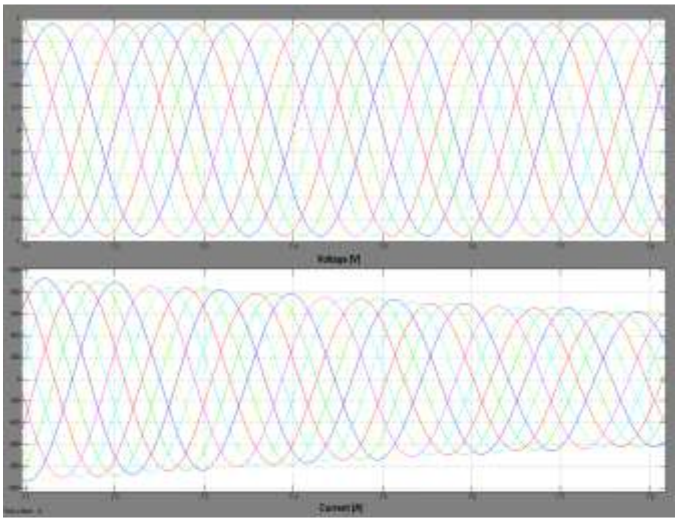

Fig. 6 – ISCAD model simulation result of the stator voltage (top) with phase control factor of five percent in comparison to the resulting stator current (bottom).

Tests at the University of Bundeswehr Munich with an 18-phase functional model of the machine topology have shown an assimilable relation between voltage, stator current and rotor speed. Fig. 9 shows a measured static no-load operation current of 100 A with a frequency of 3 Hz. The rotor speed is about 180 rpm with a pole pair number of one. A switching of the pole pair number from one to two respective four while operating the machine halves respectively quarters the rotor speed.

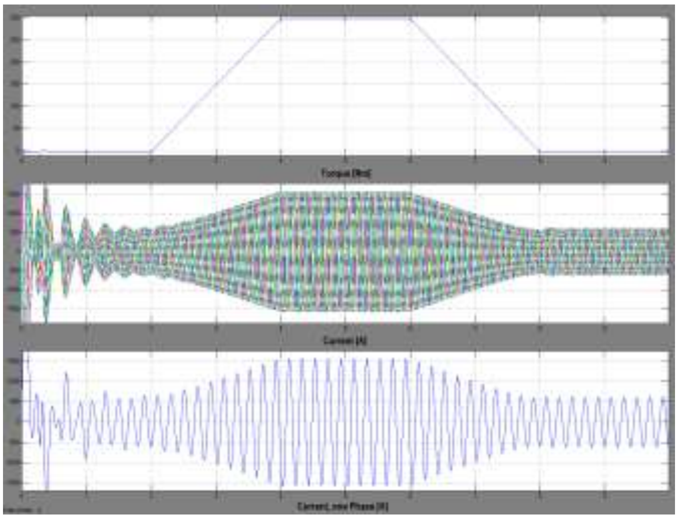

Fig. 7 – ISCAD model simulation result of torque (top) in comparison to stator current of ten (mid) and one phase (bottom)

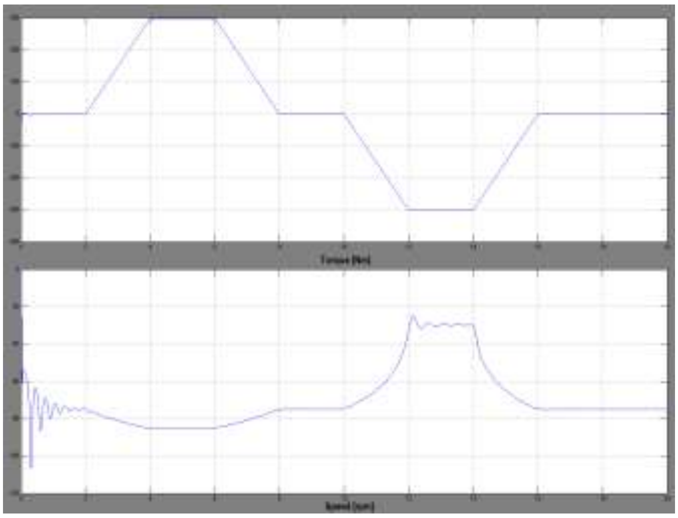

Fig. 8 – ISCAD model simulation result of the torque (top) and rotor speed (bottom) in rounds per minute

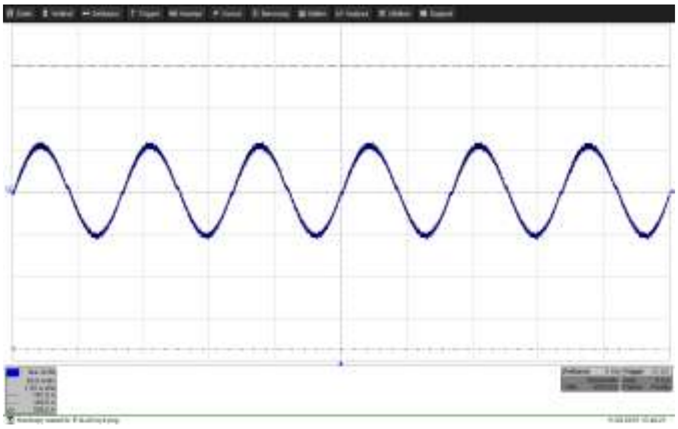

Fig. 9 – Current measurement of the ISCAD prototype with pole pair number of one and 3 Hz sine frequency switched with 50kHz

C. Hardware Periphery

To examine or to use the machine topology e.g. at a real hardware test-bench some further hardware is needed. This subchapter shall show which main parts are necessary for the open loop or closed loop controlled machine in reality.

The first part after the machine within the drivetrain is the connector towards the power electronics. The requirements of this connector are on the one hand an extremely low material resistance and on the other hand an extremely low contact resistance. Low resistances are very important, because the use of e.g. a 60-phase topology automatically implicates 60 resistances which can massively decrease the efficiency. The losses are rising with the square of the current per statorbar which is critical due to the high current supply of the statorbars (2.07).

$$P_{Loss,Connector} = R_{Connector} \cdot i_{Bar}^{2} \quad (2.07)$$

In addition to the resistance the active conductor cross-section has to be adapted in relation to the maximum current. The actual state of research is shown in Fig. 10. The shown CAD model is a pierced, welded and pressed metal sheet. The statorbar is inserted in negative z-direction. After the insertion the connector is screwed four times onto the pre-drilled bar. It is recommendable to use oversized screws that the oxide layer at the bar is partly removed. An alternative to screwing would be electro-welding or soldering. In large-scale production lines this connection would be done fully automatized by machines to save resources.

The second part of the connector is mounted to the power electronic. This is done by screwing or electro-welding. A so called press-fit connection is also possible but still in a development status for high current applications.

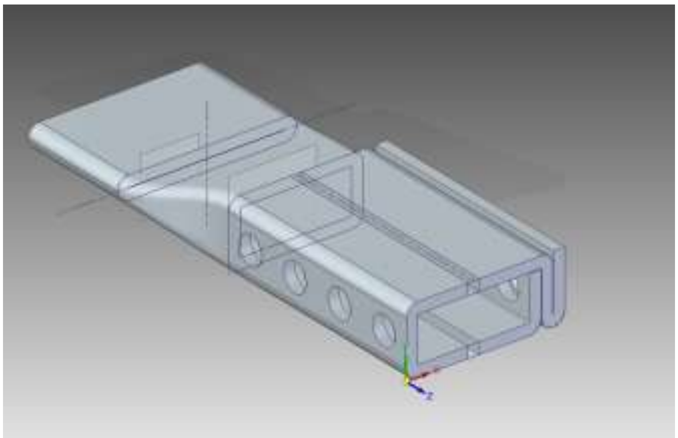

Fig. 10 – High current connector between a ISCAD statorbar and a half bridge power electronic module

The following part within drivetrain is the power electronics. As already mentioned one half-bridge module (Fig. 11) is used per statorbar to maximize the degrees of freedom. Each module contains at least one low-side and one high-side MOSFET to switch the currents. The MOSFETS are connected to drivers, which amplify the PWM signals coming from a microcontroller or a field programmable gate array

(FPGA) board. A challenge is here to cool down the semiconductors after a peak power. A potent cooling has to be installed to minimize the temperature regeneration time constant so that a derating of the power electronics can be avoided.

Fig. 11 – ISCAD half bridge module prototype

The microcontroller is the last part of the drivetrain. It creates the PWM signals on the basis of the user defined target voltage, frequency, rotor speed or torque. In addition, the measured current and torque respectively speed values are used for the control in here. Thus the controller has to contain an open or closed loop control method. Possible methods are described in the following chapter.

III. Control Methods

Respective to the final utilization of the ISCAD machine it is necessary to create a control method. For (further) research or working on a testbench it is mostly fully sufficient to use a voltage and frequency depended open loop control. For utilization as a traction drive or something comparable it is necessary to use a closed loop control like the field oriented control (FOC) or a space vector control. The main difference is the necessity of measured values within the closed loop control. In this case the advantage of multiple phases becomes a small disadvantage, because without a reliable flux-observer it is necessary to measure all phases to control the machine correctly or recognize a possible failure. Nevertheless, in contrast to three phase machines, a failure of one phase has significant fewer consequences to the total current, because the percentage of phase malfunctions will always be lower. In a 60 phase machine an improbably total of 20 phases have to be damaged until a comparable failure percentage is reached. Even in this case the ISCAD machine would still be able to spin. The mentioned measurement is therefore more useful for a correct control than for failure measurement.

A. Voltage Frequency Open Loop Control (UFC)

For a voltage frequency control (Fig. 12) a sinewave function and a counter is needed within the microcontroller. An additional pole pair reference is possible. The sinewave function has to be variable in amplitude and frequency. After generating the digital sine signal it has to be compared to a counter. The counter itself counts to a maximum and jumps back to zero (saw tooth) respective counts down to zero (triangle). The maximum of the counter is chosen by the micro controller and the wished sampling frequency of the PWM signal which correlates to the maximum MOSFET switching frequency (3.01). The MOSFET border frequency must be taken from the datasheet.

$$f_{\max,MOSFET} = \frac{f_{work,\mu c}}{N_{\max,counter}} \tag{3.01}$$

It is important to adjust the boundary points of the sine so that it is comparable to the counter. If e.g. the maximum of the counter is defined by 10 Bit than the sine needs to be modified that the maximum of the sine is also 1024 and the minimum is zero.

The half-bridge output port for the high-side MOSFET needs to see a logical high if the amplitude of the sine is lower than the counter and a logical zero if the sine is higher than the counter. The low side signal is contrary except a dead-time is needed. The procedure needs to be made for every phase of the machine with a matching phase offset ε (2.01). With this method the variable digital sine wave is restored as a potent current by the half bridges. To switch the pole pair number the sine signals are fitted to the number of favored phases. For a 60-phase machine Table 1 gives information about the necessary phase shift between two neighboring stator bar currents. While operating with pole pair number one every current is 6 degrees shifted, so that one electrical sine wave develops over the geometrical stator circle. While operating with pole pair number two every current is 12 degrees shifted, so that the first 30 phases and the second 30 phases build two electrical sine waves over the geometrical 360 degrees. As a consequence two pole pairs develop. The phase shift φ dependent on the number of available phases m and favored pole pair number p is calculated with (3.02).

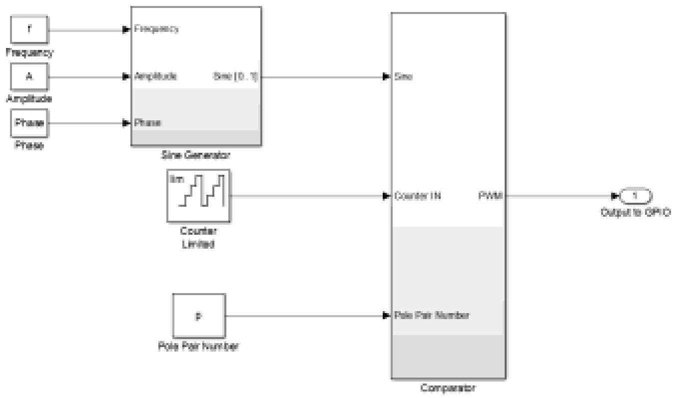

Fig. 12 - Example for one phase of a Matlab Simulink based Voltage Frequency Open Loop Control

Table 1 – Phase shift between to neighboring stator bar currents in correlation to the number of pole pairs for a 60 phase machine

Number of pole pairs	Phase shift between to neighboring stator bar currents
1	6°
2	12°
3	18°
4	24°

$$\varphi = \frac{360^\circ}{m} \cdot p \qquad (3.02)$$

Applicatory analysis of the stator currents proved that this kind of open loop control works properly. Fig. 13 shows the stator current while reducing the sine frequency from 3 Hz to 2 Hz. In several tests with switching the pole pair number also no critical peaks were recognized, so that in conclusion pole pair switching while operating is feasible. A suitable simultaneous changing of the sine frequency is advisable so that the mechanical rotor speed stays constant.

Fig. 13 – Measured stator current while reducing the sine frequency from 3 Hz to 2 Hz

B. *Field Oriented Control (FOC)*

For automotive application a machine needs to be (torque-) controlled. One of the most common methods for a closed loop control for induction machines is the Field Oriented Control (Fig. 14) [6]. The main aspect here is a pre-generated efficiency respective flux map depending on torque and mechanical rotation speed of the machine to guarantee anytime a maximum efficiency in the whole operating range. The map is integrated into the inner control loop besides a flux controller and the d-axis current controller. This constellation is reasonable because the d-axis current is a result of the machine's magnetizing flux. The outer control loop includes the torque generating q-axis current controller and the torque controller itself as input requirement. A speed controller can also be implemented into the cascade but is not necessary for a torque demanding application. Some inputs have to be calculated for the compensation of the controllers. This task is done by the IM Model in the upper section of Fig. 14. The model calculates the currents of d- and q-axis, the rotor flux angular velocity and the rotor flux angle. An additional torque or a speed observer can also be implemented in here if one of the parameters cannot be measured. The last point is the decoupling network. It is able to decouple the d- and q- axis currents. This is necessary because they are directly linked and would not be individually controllable without a decoupling method. The transformations from the n-phase system into a 2-axis system within the FOC have already been mentioned in chapter 2b. The FOC can be built with MATLAB Simulink and integrated in a microcontroller or a FPGA Board. A FPGA is here advantageous because of its ability for high-grade time indifferent parallel multi task operating.

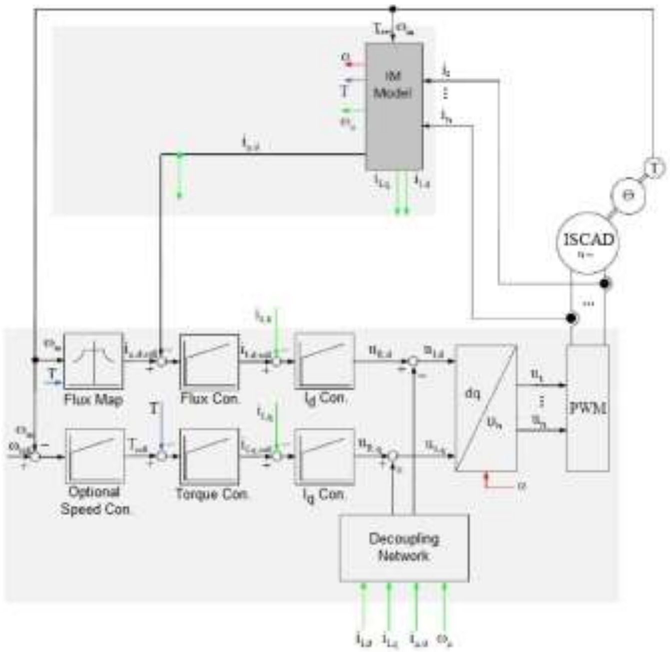

Fig. 14 – Diagram of a multiphase Field Oriented Control for ISCAD machines

The basic thought of the creation of the FOC for a multiphase ISCAD machine is to keep the fundamentals of the FOC for three phase machines. This simplification is possible, because the chapter two has shown that the fundamentals of standard induction machines are also valid for the special ISCAD topology.

Further research at the Chair of Electrical Drives and Actuators at the University of Bundeswehr Munich have shown several positive test results in case of induction machines with concentrated windings [7]. Fig. 15 shows the enhancement of a FOC for a three phase machine. The inputs like set torque, rotor speed and load torque are colored in yellow. The basic simulation structure for the stator current in d- and q-axis are colored in blue. The reference model of the 60-phase ISCAD machine is colored in green. The red boxes are the transformation blocks analog to the mentioned chapter 2b. The control itself is inked in grey. It contains analog to Fig. 14 five controllers and an efficiency map. The user is free to choose between rotor speed or torque control by manual switches. The parametrization of the FOC controllers is done with the Ziegler and Nichols method by analyzing the unit step response of the corresponding servo loop. The analysis is showing if the loop is fundamentally stable and which kind of controller respective regulator parameters is necessary to compensate the behavior [8]. Modern tools like the Matlab Simulink Control Design PID Tuning Tool are useful to support and accelerate the controller design. This tool has been used for the flux controller within the discussed FOC. The results are shown in Fig. 16. The control loop has a PT2 behavior with a small overshoot and a discrepancy in the final value. To compensate it is necessary to increase the values for the integrator and the gain, so that the step function response is equal to one. The tool accomplishes the task within seconds with a small failure rate, as long as the loop can be linearized. As always the user has to be aware of program or linearization failures. Tests have shown that because of the complexity of the control the fixed simulation time step size has to be smaller than one microsecond to avoid numerical failures. Alternatively it is possible to multiply the calculated values of the 60-phase machine with three orders of magnitude to increase the totals and decrease the likelihood of numerical errors.

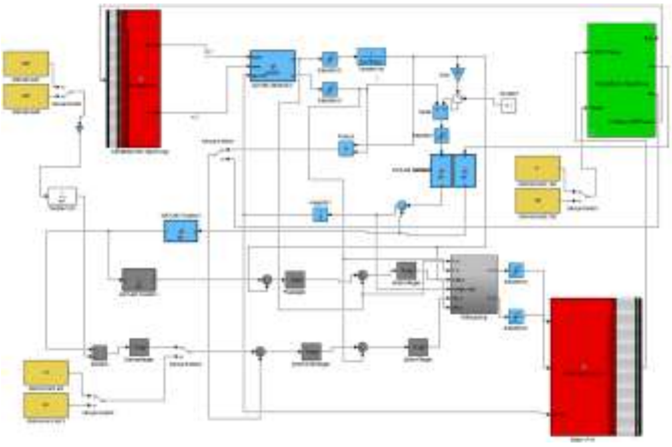

Fig. 15 – FOC model for a 60 phase ISCAD machine model in Matlab Simulink

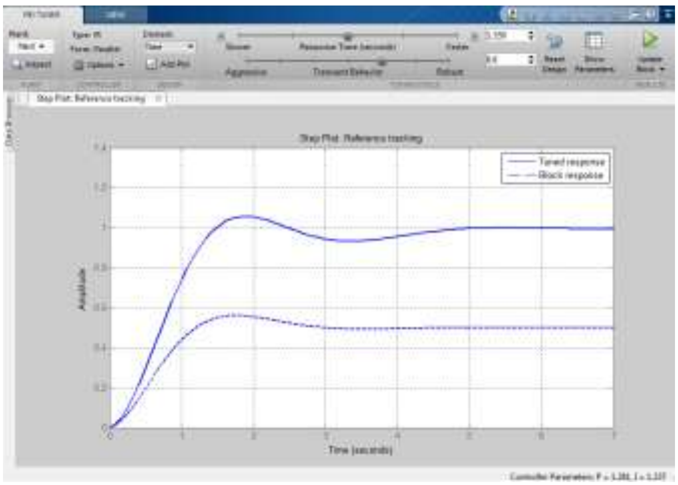

Fig. 16 – Function course of the Matlab Simulink Control Design PID Tuning Tool for the used flux controller

The results of the control model are convincing. Fig. 17 shows the course of the current, rotor speed and torque with usual machine parameters. The current frequency and amplitude correlate to the speed of the rotor, which on the other hand correlates to the given desired value of 100 rpm from the beginning. The load torque was changed after 3.2 seconds abruptly from 10 Nm to 50 Nm. The control was able to balance the load change after 4.5 seconds. The transient behavior, especially for the torque, is also plausible. Fig. 18 shows the closed loop control behavior of a change in desired rotor speed. After 5.5 seconds the reference was increased from 100 rpm to 200 rpm. The change finishes after 1.5 seconds accompanied by a torque ripple. The current course is still convincing. The results were totally reproducible in several simulation runs.

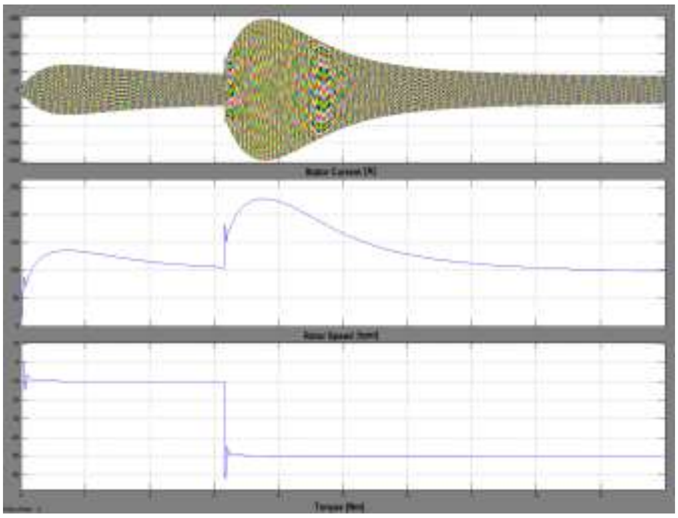

Fig. 17 – 60-phase ISCAD machine model simulation results of the stator current (top), rotor speed (mid) and torque (bottom) within a Field Oriented Control while torque switch from 10 Nm to 50 Nm

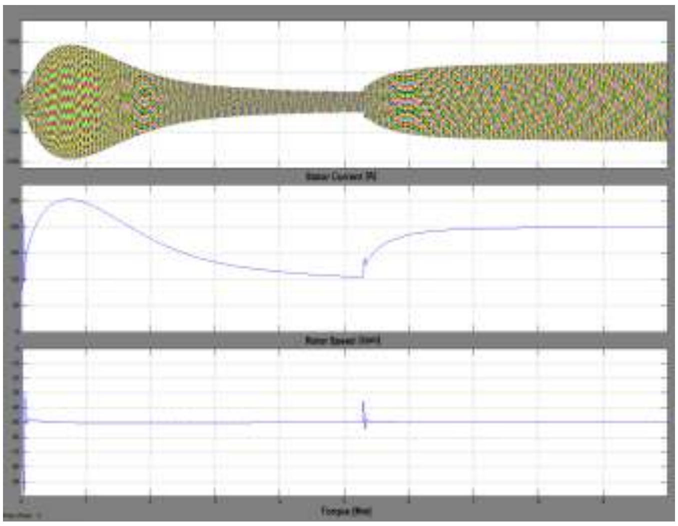

Fig. 18 – 60-phase ISCAD machine model simulation results of the stator current (top), rotor speed (mid) and torque (bottom) within a Field Oriented Control while speed switch from 100 rpm to 200 rpm

The next step was to confirm the concrete calculated ISCAD parameters of the 60-phase machine within the shown

FOC. Concerning the future application the torque-control was analyzed. The results of this simulation were convincing as well. Fig. 19 shows the course of the current, rotor speed and torque with the new calculated machine parameters. The current frequency and amplitude correlate to the speed of the rotor, which on the other hand correlates to the toque and its desired value of 100 Nm. The desired torque was changed after 5.2 seconds from 100 Nm to 150 Nm. The control was able to balance the load change within 0.3 seconds. The transient behavior, especially for the torque, is plausible. Fig. 20 shows the closed loop control behavior of a change with negative grade. After 5.8 seconds the reference was increased from 150 Nm to 50 Nm. The change finishes after 0.5 seconds without a torque ripple. The current course and its magnitude keeps still convincing. The results were totally reproducible in several simulation runs. The analysis shows, that with the calculated parameters of the 60-phase ISCAD machine the control time constants are smaller than before.

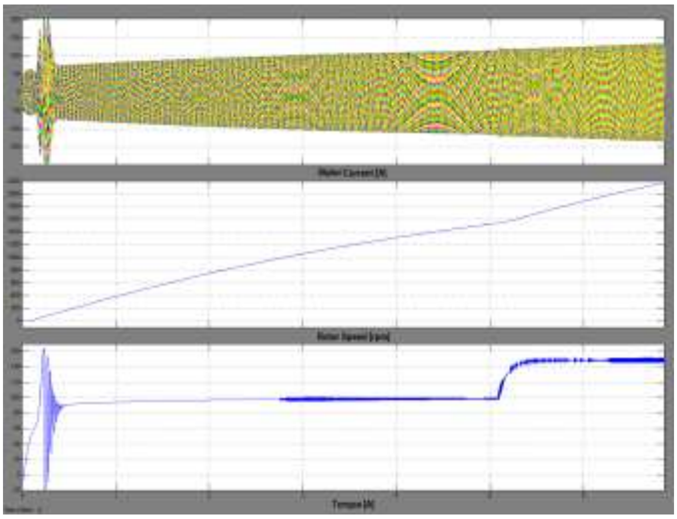

Fig. 19 – 60-phase ISCAD machine model simulation results of the stator current (top), rotor speed (mid) and torque (bottom) within a Field Oriented Control while torque switch from 100 Nm to 150 Nm

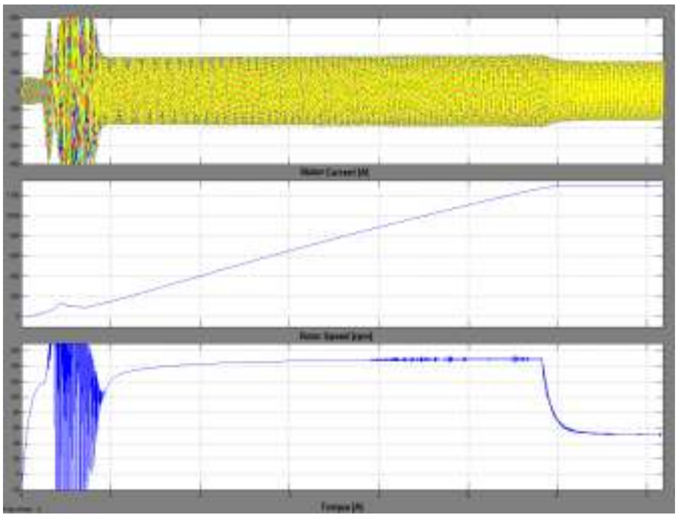

Fig. 20 – 60-phase ISCAD machine model simulation results of the stator current (top), rotor speed (mid) and torque (bottom) within a Field Oriented Control while torque switch from 150 Nm to 50 Nm

C. Direct Torque Control

The Direct Torque Control (DTC) is besides the FOC also predestined for automotive applications because of its reliable and stable torque control. To produce the best results in a closed loop control for the new topology a future consideration of the DTC is absolutely necessary.

The idea behind the direct torque control is comparable with the FOC, but with the difference not to control indirectly the torque in controlling the d- and q-axis current. Rather it is the thought to control the torque directly by changing the flux linkage and the torque for itself. The in Fig. 21 shown DTC overview shows similar to the FOC the measurement of the stator current and the rotor speed respective torque. An adaptive motor model calculates the non-measurable values. The calculated flux- and torque status is the input for a so called switching table. The switching table includes the switch settings for the half bridges, so that the current can be driven analog to the necessary flux for the favored rotation speed and torque. The switching can be done with a static or a dynamic frequency. The number of possible switching states can be calculated by the exponential function with base equal two and the exponent equal the number of half bridges, e.g. eight possible states for a 3-phase system. These eight states are used to represent a circular movement of the stator flux linkage shown in the left of Fig. 22 [9]. The real course is shown at the right side of Fig. 22. This course is not quite equal to a circle because the switching states are not enough to reproduce a true circle. Here a big advantage of the ISCAD topology comes in effect. The highly redundant multiphase composition of the stator contains e.g. for a 60-phase machine the same number of half bridges. So the possible amount of switching states is up to 1.2 trillion. So even after a condensation of switching states it is still possible to reproduce a circular flux linkage with an error value under one tenth of a per cent. This massive improvement reflects within the torque behavior concerning the dynamic response characteristics and the torque ripple, which are both very important for the mentioned application cases.

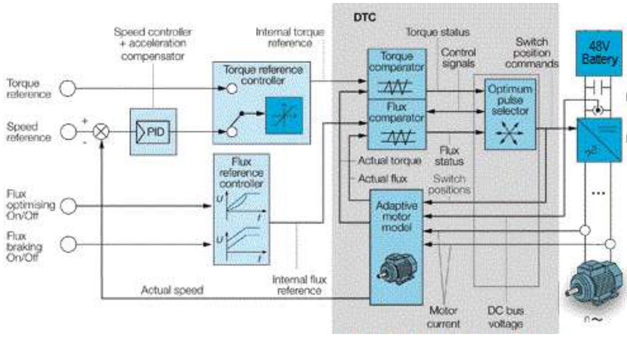

Fig. 21 – DTC System for an ISCAD drivetrain

Matlab Simulink provides an own block for the DTC, which can be adapted for several kinds of three-phase machines. A block for a multiphase control was up to the time of the publication of this paper not provided. A self-designed DTC is currently in progress.

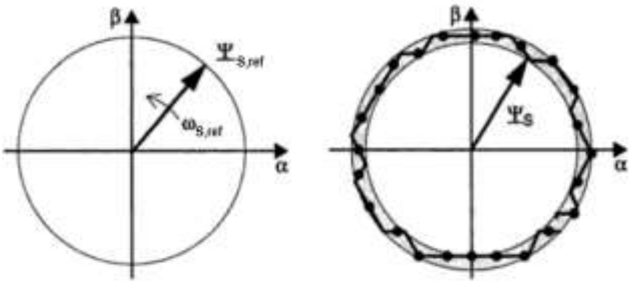

Fig. 22 – Movement direction and speed of the stator flux linkage (L: Reference, R: 3Phase System)

IV. CONCLUSION

Target of the paper was to show, that the Field Oriented Control for induction machines is still applicable in the case of an ISCAD multi-phase machine. After a short description of the fundamentals a 60-phase model was presented. This model delivered absolutely plausible simulation results. The necessary values were completely calculated analytically without any great expenditure of time. In a second step the structure of the drivetrain was described to analyze all necessary elements for an open loop or closed loop control. The favorited FOC was described theoretically and practically to show differences and commonalities. As a result the FOC worked properly with restriction in case of the reaction time. As far as possible this challenge is solved by an accurate adjustment of controller parameters, which was not completely possible due to time constraints. Furthermore a Direct Torque Control and its advantages in combination with the ISCAD topology were shortly introduced to give an outlook for further research and control optimization.

All in all the paper has shown that the ISCAD multi-phase induction machine topology is fully torque- and speed-controllable via a reliable Field Oriented Control.

ACKNOWLEDGEMENT

The author likes to thank Dr. rer. nat. José-Luis Marqués-López for the very helpful discussions concerning the mathematical multiphase transformations and M.Sc. Adrian Patzak and M.Sc. Florian Bachheibl concerning the cost-efficiency and ISO-permission aspects.

REFERENCES

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

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

[3] Gerling, D.; Dajaku, G.; Bachheibl, F.; Patzak, A.: *Analytical Calculation of the Novel Stator Cage Machine*, 18th International Conference on Electrical Machines and Systems (ICEMS-2015), 25.-28. Oktober 2015, Pattaya City, Thailand.

[4] Gerling, D.: *Analytical Inductance Calculation of the Stator Cage Machine* International Symposium on Industrial Electronics (ISIE-2016), 08.-10. June 2016, Santa Clara, CA, USA [Paper accepted]

[5] Specovius, J.: *Grundkurs Leistungselektronik – Bauelemente, Schaltungen, Systeme,* 7. edition, Springer Vieweg, Berlin, Germany, 2013

[6] Gerling, D.: *Electrical Machines - Mathematical Fundamentals of Machine Topologie,* 1. edition, Springer Vieweg, Heidelberg, Germany 2014

[7] Schwager, M.: Entwurf einer Regelung für einen integrierten Startergenerator auf Basis einer Asynchronmaschine mit konzentrierten Wicklungen – Masters Thesis #48 2015, chair of electrical drives and actuators, University of Bundeswehr Munich

[8] Ziegler, J. G.; Nichols, N. B.: *Optimum settings for automatic controllers*, Trans. ASME, 1942

[9] Jenni, F.; Wüest D.; *Steuerverfahren für selbstgeführe Stromrichter*, VDF Teubner, Stuttgart, 1995