

ISCAD - Electric High Performance Drive for Individual Mobility at Extra-Low Voltages

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ABSTRACT

State-of-the-art electrical drives for electric vehicles (EV) run on a battery voltage above 60 V (HV). This paper presents an alternative approach for use in future EVs: The Intelligent Stator Cage Drive (ISCAD) - an extra-low voltage drive for highest performance at battery voltages below 60 V (LV). First of all, the novel drive components are introduced with references to previously published papers on more concept details. A highly parallel set-up is chosen for maximum current capability and extremely low resistances. The novel 60-phase induction machine is made of solid aluminum bars instead of copper windings in the stator and a common squirrel cage rotor. The MOSFET-based inverter individually supplies every single stator bar in order to shape an extraordinarily smooth air gap magnetic field. New degrees of freedom in inverter control are used to continuously adapt the induction machine's number of pole pairs to ideally match vehicle demand on torque and speed, thus implementing an electrical gearbox. Simulations of the driving cycle efficiency promise great advantages of ISCAD over a HV reference system in electrical machine, inverter and battery. Focus is set on a first low-budget proof-of-principle, which comprises a 3D-printed aluminum stator cage and an 18-phase inverter. Set-up of a test bench and first practical experiences, which confirm the principle of operation, are shown.

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INTRODUCTION

During the past decades people's demand for safety, comfort and individuality as a fundament of quality of life became increasingly meaningful. Independent and flexible mobility thereof is a very important factor and automotive manufacturers understand to satisfy customers by continuously improving their cars and implementing novel features into those already complex and highly sophisticated systems.

This rising number of electrical components increases the power demand, which is satisfied by the on-board electric supply. The generator is driven by the internal combustion engine, which also guarantees the high dynamics of modern cars. Even very efficient state-of-the-art engines still spend a considerable amount of limited fossil fuels.

Strong focus is currently set on technologies to significantly decrease fuel consumption, since governments all over the world released regulations in order to limit emission of carbon dioxide. These regulations define targets for new passenger car fleet averages:

- China: 120 g CO₂/km in 2020 [1]
- Europe: 95 g CO₂/km in 2021 [2], [3]

- India: based on weight: 113 g CO₂/km in 2021-22 for 1150 kg average weight and petrol fueled fleet [4]
- USA: 89 g CO₂/km in 2025 [5]

Manufacturers face painful penalties in case of exceedance and thus, measures for reduction of CO₂ emissions attain more and more importance. Focus is set on efficiency optimization of combustion engines. Mainly, down-sizing and down-speeding promise potential in reduction of fuel consumption, but optimizations on combustion engine and transmission increasingly suffer from a bad cost-value ratio. There are features which reduce emissions in official test procedures but do not show effect in real customer driving cycles. Recent headlines concerning manipulated diesel tests indicate growing difficulties in achieving the upcoming limits. A study carried out by The International Council on Clean Transportation (ICCT) reveals real-world exhaust (both CO₂ and NO_x) from modern diesel cars to be significantly higher than identified in official EU or US measurement procedures [6], [7]. The threat of official measurements on vehicles on road under real test conditions further raises pressure on OEMs.

Electrification of drives is an effective way to keep dynamic driving feasible while significantly decreasing emissions. Portfolios from micro hybrids to plug-in hybrids (PHEV) are continuously extended by more

high complexity multiple drive systems forces designers to sensitively adjust subsystems to each other. The high number of additional components accompanies more effort in maintenance, though.

Currently, battery electric vehicles (BEV) become a serious option even to newcomers in automotive manufacturing because of the simple construction of an electrical drive. Advances in science and engineering concerning battery technology and packaging promise enhanced driving ranges and reduced expenses. There are already cars below \$40,000 announced to be released in 2017 and to exceed a range of 300 km without any combustion technologies inside. Big investments in battery production capacities can be assumed to further accelerate market penetration of BEVs. Electrification of drives is progressively considered the right path and global sales volume of both PHEVs and BEVs is continuously growing.

Traction drives of BEVs are commonly supplied by HV battery voltages between 250 V and 400 V (see Table 1) and different manufacturers tend to even raise the battery voltage to around 800 V (e.g. AVL Coup-e 800 [8], Porsche Mission E). Obviously, currents can be kept quite small at high system voltages and conductor material between battery and inverter is reduced. There is a lot of effort, however, in order to keep the HV system safe. Galvanic decoupling, insulation monitoring etc. significantly raise the cost of the electric power train.

Table 1. Overview of nominal battery voltages of BEVs already on market

Vehicle	Nominal Voltage	Max. mech. power
BMW i3	355 V	125 kW
Nissan Leaf	360 V	80 kW
Tesla Model S P85	366 V	310 kW
VW e-up!	374 V	60 kW

If an electrical drive is implemented inside a very compact system, there might be a cheaper solution at extra-low voltages. Currently, an additional 48 V power supply is discussed for upper-class vehicles to reduce the fuel consumption by mild hybridization of the power train. The power of the electric motor/generator usually is far below 20 kW [9]–[11]. Recently, the company nanoFlowcell presented a prototypical 48 V based vehicle called QUANTiNO. It is driven by four separate motors with a peak power of 25 kW each. However, the seriousness of this car manufacturer is doubted in the engineering community. In 2002 a prototypical extra-low voltage traction motor based on a homopolar machine has been shown with a rated power of 100 kW. Unfortunately, it was very heavy and had a comparably poor efficiency [12]. Until now, there are no further extra-low voltage drives available for high power electric vehicles. A new approach is presented in the following sections.

COMPONENTS OF ISCAD

Conventional drives for electric vehicles convert electrical into mechanical power using three phases:

$$P_{mech} \sim 3U_{ph}I_{ph} \quad (1)$$

The basic idea about ISCAD is to keep phase currents in a similar order of magnitude while reducing phase voltages to a safe level. The requirements on mechanical power will still be fulfilled, if the number of phases is increased (see Figure 1).

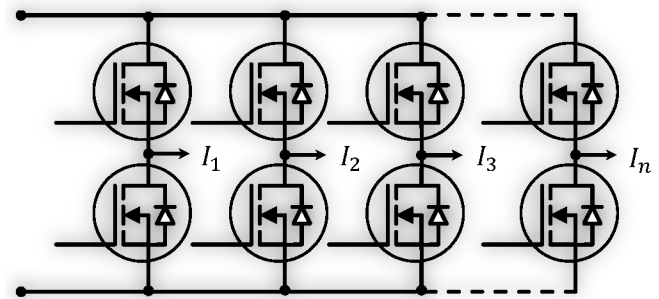


Figure 1. ISCAD introduces a novel electrical multi-phase drive based on extra-low voltages. Highest power can be delivered by an increased number of parallel phases.

The number of turns per phase winding of a conventional electrical machine is used to scale its operating voltage, which leads to the core of the proposed novel drive: there is only half a turn per phase.

The Electrical Machine

The slots of the stator lamination stack are filled with solid bars instead of wound coils. These bars are mounted to a short-circuit ring on one axial stator end and left open on the other. The electrically conducting part of the stator is very similar to an induction machine's squirrel cage rotor. Figure 2 shows the “stator cage” inside a short stack of iron core.

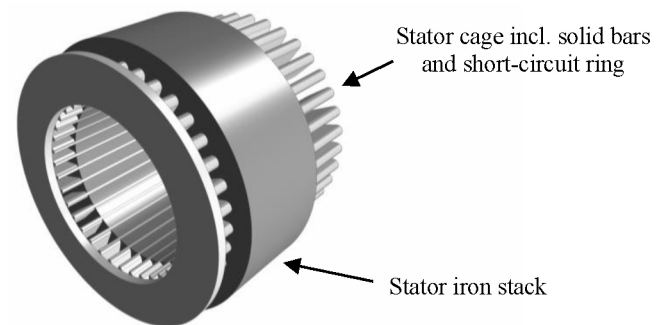


Figure 2. Instead of wound coils there are solid bars inside the stator iron core.

The bars can either be pre-fabricated and afterwards insert or directly cast in case of closed stator slots. There are increased ohmic losses at higher current frequencies due to the solid material instead of stranded wires. AC effects, e.g. eddy currents, additionally increase losses inside the conductor material, but an excellent filling factor close to 100 % can be reached. This enables utilization of cost-saving materials, e.g. aluminum, as replacement for expensive copper. Since the conductivity of aluminum is smaller, there are less eddy currents also and the disadvantage in electrical resistance (DC plus AC share) over copper decreases. Nevertheless, the number of pairs of poles must be kept small for high speed regions in order to reduce AC

losses. Research on cheap materials with anisotropic electrical conductivity is an important step to further improve machine efficiency in future.

There is a thin layer of electrically isolating material between iron core and stator bars necessary in order to avoid short-circuits between adjacent phases through the iron sheets. Upcoming investigations will show whether or not the naturally occurring oxide layer is sufficient. In either case, focus will be put on keeping thermal resistances small. Heat needs to overcome several layers of isolation to reach the coolant in case of conventionally wound coils, e.g.:

- Wire insulation
- Secondary isolation for improved thermal behavior inside slot, e.g. using resin
- Paper or plastic tooth isolation

Failure in isolation often causes short-circuits between single wires, which are critical especially on distributed windings and possibly induces subsequent errors in the whole drive. In case of solid bars, there is an improved thermal conduction and the continuous power rating of the electrical machine is significantly increased (see Figure 3). Furthermore, number of failure mechanisms is reduced because of the simple construction.

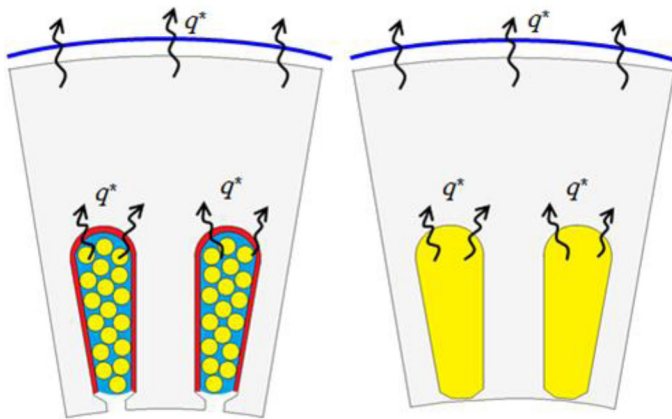


Figure 3. Different contacts and materials have to be considered for heat conduction to the water jacket in case of conventional wound coils (left) and ISCAD (right)

The main share of heat in electrical machines is usually generated in stator windings. The solid construction of stator bars and the short-circuit ring enables new methods with more efficient heat dissipation, e.g. cooling channels inside the ring (see Figure 4). Direction of heat transfer can thereby be reversed from iron sheets to bars to the stator ring.

There is a wye connection in case of ISCAD but no interconnection of multiple bars to form a phase winding. Hence, every single bar has to be individually supplied by an AC source. Since the current is adjustable in every stator slot, there is a large number of degrees of freedom in order to shape the air gap magnetomotive force (MMF). In comparison to a distributed winding there is a higher winding factor for the working harmonic but lower parasitic harmonic contents for an equal number of stator slots [13]. Furthermore, the MMF is not

determined by the kind of stator winding but by stator currents, which allows almost any shape of the air gap field. This can be used to switch between different numbers of magnetic poles (see Figure 5) or to even generate several pole pair numbers at the same time [14].

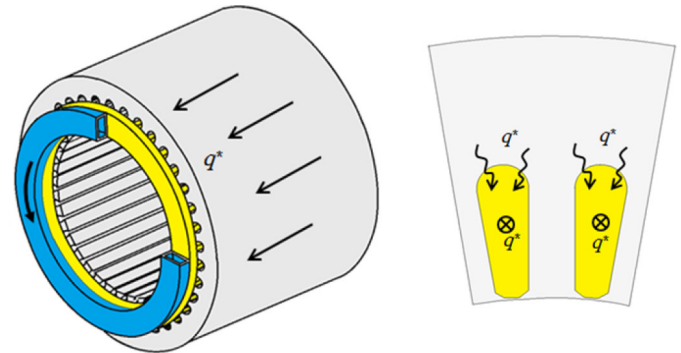


Figure 4. Cooling channels can be directly mounted to the short-circuit ring and hence, conductivity between heat source and sink minimized.

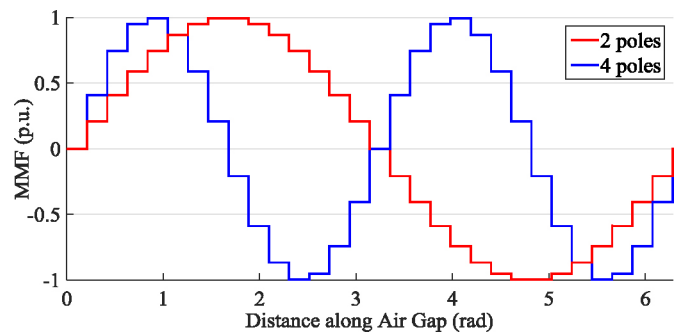


Figure 5. ISCAD introduces easy pole-changing by adaption of stator currents.

An induction machine's squirrel cage rotor is able to adopt the stator pole number and hence, several electrical machines can be created virtually. There are separate efficiency maps for every number of pole pairs and hence, losses can be reduced in the entire operating range by always selecting the ideal number of pairs of poles. First simulations show that this effect is ideally exploited in case of many magnetic poles for the high torque area and few poles for the high speed region. Advantages over conventionally wound machines are obtained especially in partial load conditions.

The Inverter

As already mentioned above, there is a dedicated AC source necessary for every single stator bar. A conventional half-bridge topology is considered due to its simple construction and well-established design (cp. Figure 1).

MOSFETs are considered the right choice and replace IGBTs in case of ISCAD since they are available in many voltage ratings below 600 V. The static on-resistance of a MOSFET electron channel can be reduced for lower breakdown voltages due to higher doping concentrations [15]. There are devices for 48 V applications which almost fall below a resistance of 1 mΩ [16]. For a constant forward current the power dissipation of MOSFETs is therefore reduced at smaller voltage ratings and costs for a given chip area also decrease. There are further advantages of MOSFETs over IGBTs.