Vehicle Integration of ISCAD – 110 kW, 48 V Traction Drive

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ISCAD is a high power low voltage traction system. With a power of up to 200 kW or more and a battery voltage of 48 V, ISCAD is a game changing traction drive system. Counter-intuitively, it is able to improve efficiency by up to 25 % compared to conventional electric drives due to outstanding partial load efficiency. After presenting a test bench prototype in 2016, an integrated compact ISCAD drive has been developed and implemented in a vehicle. This paper presents the first high power 48 V battery electric vehicle. The parameters of an integrated ISCAD system are presented and the car integration is described in detail. A vehicle simulation investigates the driving range of the demonstrator car for several driving cycles in addition.

Keywords—ISCAD; 48 V; traction drive; BEV; car integration; high efficiency.

I. Revolution in Individual Mobility

Electric vehicles are still considered to be niche products, but tendencies in global relevant markets clearly show that the breakthrough is already here. Heavily decreasing battery costs by almost 80 % since 2010 are one of the reasons for exponentially growing annual sales [1]. A significant share in total global passenger car sales can be reached before 2025 and there is a potential to mix up the list of popular manufacturers. Almost all parts of the Chevrolet Bolt drive are developed and produced by LG [2], which means that a big amount of added value is shifted from a traditional OEM to a rather recent supplier. The EV market attracts a big number of new players with new technical concepts for a tough competition. As the offer of electric passenger cars increases there are exploding sales especially in the biggest market – China. In January 2018 around 30,000 new energy vehicles were sold in China, over four times more than in January 2017 [3]. Significant market shares are scheduled for the next years. This has a great impact on car manufacturers all over the world. Popular brands already announced the end of a purely ICE-based product portfolio and a rapid increase in electrified cars.

At the moment, the driving range of electric cars is considered insufficient and the cost is still high. The problems, however do not only originate in the battery. Although the focus of the research community seems to have been moving towards batteries, electric motors can also contribute much to an alleviation of the cost. Currently, however, they often contain large amounts of problematic rare earth materials, which are almost exclusively supplied by China and their price has already skyrocketed once in recent years. Furthermore, the copper coils inside the stator are complicated and expensive in production and even the material copper is bound to run short with a mid-term prospect of 80 million electric vehicles a year.

The electrical system inside all state-of-the-art electric vehicles is based upon a battery usually with high operating voltages between 300 V and 800 V. In fact, this involves potential risk of electrical shocks in case of failures. High effort is taken in order to implement safety measures inside the car. Furthermore, maintenance or modifications can only be executed by trained high voltage experts. This must be considered a real handicap since a comprehensive, global high voltage infrastructure for EV operation is costly both in a financial and technical point of view. The risk inherent in poorly serviced, old vehicles and the cost of decommissioning a malfunctioning vehicle with a potential insulation failure cannot even be quantified. It is therefore considered desirable by the authors to develop a drive system that can generate traction power at a safe-to-touch voltage. This is why ISCAD has been conceived. But there is more to it than a safe operating voltage.

Due to the technology “ISCAD" – acronym for “Intelligent Stator Cage Drive” – the driving range of electric vehicles can be increased by up to 25 % in the WLTP without increasing battery capacity [4]. The energy cost for customers is reduced and the maintenance effort decreases due to the safe-to-touch, extra-low voltage system. Furthermore, the motor is ideal for highest volume production due to its simple construction and the substitution of problematic materials by cheap and highly available elements.

II. Introduction Of ISCAD

In contrast to the trend of many car OEMs to further increase the battery voltage of electric vehicles, ISCAD represents an extra-low voltage high power traction system [5]. ISCAD is capable of delivering 200 kW or even more with a safe, extra-low battery voltage such as 48 V. This unique selling proposition is made possible due to a highly parallelized structure from battery to electric motor. Regarding the motor, copper windings of conventional stators are replaced by a cage of solid aluminum bars. Due to the excellent slot filling factor above 90 %, copper is not essentially needed and hence, cost and weight can be reduced. All bars are connected to a massive aluminum ring on one axial end of the stator iron stack and electrically shorted. At the opposite side, one dedicated MOSFET half-bridge is attached to each bar in order to individually supply phase currents. The principle of ISCAD is shown in Fig. 1.

If the stator is combined with a simple squirrel cage rotor, used materials are aluminum, silicon and iron exclusively – cheap materials with almost unlimited resources on earth. The working principle of such an ISCAD motor is comparably to an induction machine, but due to the high number of stator bars and individual phase control, there is almost unlimited freedom to configure the air gap magnetic field. The quality of the magnetic field can be improved thereby, which results in a higher torque density and lower losses due to a reduced spatial harmonic content. Furthermore, different numbers of poles can be generated and a smooth fading from one configuration into another is possible due to transient superposition of two rotating fields. Fig. 2 shows an exemplary set-up with 12 stator bars/phases and different pole configurations due to variation of current supply.

The dynamic adaptation of the shape of the magnetic field to the required load profile has great advantages: firstly, different drive efficiencies are reached with different configurations. While a conventionally wound motor has its ideal efficiency in a rather narrow operating area, ISCAD combines several motors in a single housing. Different pole configurations generate the area of maximum efficiency at different speed and torque and thus, the total area of maximum efficiency is spread extremely. This sort of "virtual gearbox" is absolutely unique and makes an ISCAD motor fundamentally advantageous over other motor types. The partial load efficiency, which is very important for load cycles especially in passenger vehicles, is significantly increased.

Secondly, the widths of the yokes in both stator and rotor can be reduced. Operating points with high torque demand are driven in a higher pole configuration. This makes the total flux per loop, i.e. pole smaller (cp. Fig. 2) and consequently, the area of magnetic active material can be reduced while maintaining

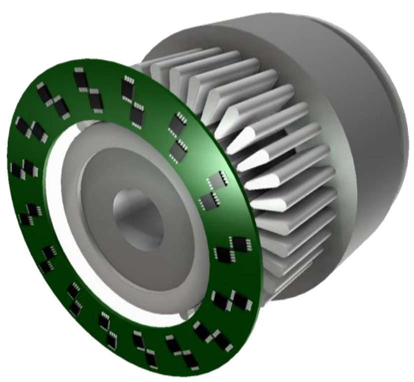

Fig. 1. Set-up of ISCAD: the aluminium bars inside the stator core are connected to a short ciruit ring on the backside. A dedicated power electronics unit is connected to each aluminium bar.

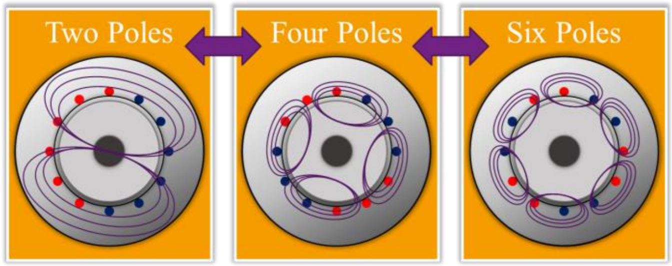

Fig. 2. Different pole configurations can be generated by individual control of the currents in every single stator bar/slot. The efficiency can be optimized by adaption of these.

the total torque. Partial load operating points with reduced torque and hence, flux especially at higher speeds can be driven in lower pole configurations in order to reduce frequencies and AC losses. This pole chance mechanism enables higher efficiencies whilst maintaining a light-weight structure.

Every single bar of the stator cage is fed by a dedicated power electronics unit (cp. Fig. 1). The motor induces extra-low voltages due to the low number of turns per "coil" which makes it possible for ISCAD to use low cost MOSFETs instead of expensive HV IGBTs and hence, losses in partial load operation are drastically reduced [6]. Due to the diode characteristic of IGBTs in conducting condition, there is a constant forward voltage offset and a current-depending share. In comparison, MOSFETs have an electron channel which behaves like a resistance and a linear relationship between forward current and voltage drop therefore. If the MOSFET inverter is designed to reach a similar efficiency at maximum load as the IGBT reference, there will be less conduction losses in partial load conditions, because the product of voltage drop and forward current is lower (cp. Fig. 3). The loss behavior in partial load is crucial for passenger car driving scenarios, where the requested drive power is below 20 kW most of the time.

Considering the advantages both concerning the reconfigurable motor and the efficient semi-conductors, ISCAD promises an excellent efficiency across the total torque and speed envelope. Comprehensive simulations have been carried out in order to evaluate the total energy demand of electric drives in different driving cycles such as the NEDC, the WLTC and the

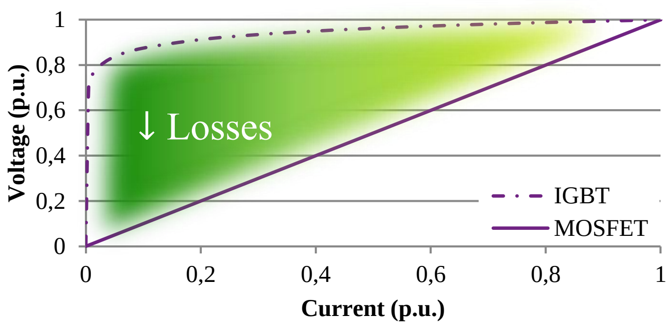

Fig. 3. Conduction losses in partial load operating points are heavily reduced by usage of MOSFETs instead of IGBTs due to the lower voltage drop at low currents.

CADC. ISCAD reaches an efficiency improvement of around 25 % in comparison to conventional both induction machine and permanent magnet drives in electric vehicles [4]. Since ISCAD has an increased average efficiency, less energy is wasted and thus, a vehicle's driving range is enhanced without increasing battery capacity.

Additionally, MOSFETs have reduced switching losses which allows for higher switching frequencies. Therefore, it is possible to eliminate audible inverter noise because switching frequencies above 20 kHz are used. In comparison, state-of-the-art IGBT inverters have a switching frequency between 8 kHz and 16 kHz which generates substantial noise. Due to the high number of phases, smart shifting of switching patterns is used to further multiply the effective DC link capacitor current frequency [7]. The size of the DC link capacitor and hence, cost can be reduced to a small share.

ISCAD represents an extra-low voltage high-current solution for mobility applications [8]. In general, there is an increased DC-conductor cross section needed in case of ISCAD. However, there is a reduction of complexity in the electrical DC system, since HV safety measures such as galvanic isolation are not necessary. The international standard ISO 6469 treats “Electrically propelled road vehicles – Safety specifications” and consists of four parts. The scope of these standards is on DC voltages higher than 60 V and RMS AC voltages above 30 V. There are several guidelines derived all over the world which define rules for electric vehicles using HV batteries [9-11]. ISCAD makes high performance drives possible at a nominal 48 V DC system without a lot of effort on protection against electrical shock.

If costs for power transmission system are plotted versus the distance involved, there is an intersection between LV and HV. There is a bigger demand on conductor material on the one hand, but smaller cost for electrical safety on the other hand. Obviously, it does not make sense to transport energy from wind power plants along hundreds of kilometers using low voltages, but in very compact electric transportation systems for individual mobility, it has to be questioned, whether HV solutions are the right choice.

A low voltage high current setup has advantages even for the high energy content battery [12]. An increase of capacity and energy for a parallel configuration in comparison to a serial configuration can be achieved versus several charge and discharge cycles. In addition, the influence of single cells with lower capacity is reduced in a parallel configuration. Thus, there is a clearly reduced effort for balancing of battery cells.

ISCAD provides efficient and simple components and is an enabler for high power applications without a costly and hazardous HV infrastructure – from development to product end of life – being necessary.

III. Integrated ISCAD System

In 2016, the first ISCAD prototype was developed and the advantages of ISCAD have been proven on a test bench setup. For a highly integrated traction drive, many steps in development are necessary. Thus, the first prototype consisted of a motor with separated inverter. Cables were used to connect the aluminum bars to the power electronic half bridges. Indeed, a very high efficiency was reached with this setup, but the system dimensions exceeded available space in vehicles.

Based on the experience with this system, an improved prototype was designed for car integration. Fig. 4. presents the integrated ISCAD system which combines electrical machine and power electronics in a highly compact design. A summary of the integrated ISCAD system parameters is shown in Table I. The drive system is designed for a peak power of 110 kW and a continuous power of 55 kW. The electrical machine (right part of the drive) includes 42 aluminum bars and a water glycol cooling system which is considered in the presented parameters. Regarding the active parts of the machine, a power density of more than 2 kW/kg is achieved. This is a presentable value for induction machines and there is still much potential for reducing weight and space.

The power electronics (left part in Fig. 4) include 42 half bridge modules based on LV MOSFETs whose phase taps are directly connected to the aluminum bars of the machine. On the DC side, all half bridges are connected to the 48 V DC-bus of the drive system. The cooling systems of inverter and machine are integrated. The inverter outlet feeds coolant directly into the cooler end of the cooling circuit of the electrical machine. Every half bridge module includes a phase current sensor as well as a temperature sensor.

Between electrical machine and power electronics, a control board is inserted. This control unit is connected to all sensors and generates the PWM signals to control the power electronic half bridges. Communication to an external control device is also included. The drive system is taken into operation including a current and torque control loop. All low-level functions, control functions and safety functions are implemented on a low-cost FPGA.

Fig. 4. ISCAD system developed for vehicle integration: power electronics (purple) and electrical machine (right part) are merged to one drive component.

TABLE I : PARAMETERS OF INTEGRATED ISCAD SYSTEM.

Parameter	Value
Motor type	ISCAD induction machine
Peak power	110 kW
Continuous power	55 kW
Max. torque	240 Nm
Max. speed	11500 rpm
Voltage	48 V
Number of phases	42
Dimensions	35 cm diameter, 46,5 cm length
Mass	70 kg
Cooling system	Water / glycol

IV. ISCAD PROTOTYPE CAR

Simulated efficiency values and real driving experience are two different pairs of shoes. As the integrated ISCAD drive is sufficiently compact, it is not only possible but even more necessary to build up a prototype car in order to showcase the power and overall performance of ISCAD in a passenger vehicle. ISCAD provides the very best conditions for a mass market product: low costs, high efficiency and redundancy without use of limited materials such as rare earths or copper. Therefore, it is ideally suited for the mass market and therefore, the mass market family car VW Touran is chosen as demonstrator car for the ISCAD system. Fig. 5 presents the demonstrator car with converted electrical drivetrain.

The selected car initially included a two liters TDI diesel engine with a power of 103 kW. With the conversion to an electric car with integrated ISCAD drive, the total drivetrain power is slightly increased. As first step, all components of the combustion engine system were removed. This includes engine,

Fig. 5. VW Touran with integrated ISCAD system as demonstrator car.

exhaust system, fuel tank and gearbox. The maximum speed of the electrical machine allows a coverage of the total speed range of the car using a constant ratio. The weight of all removed components amounts to around 270 kg.

The ISCAD system includes the integrated drive, a 48 V traction battery, a 48 V power net and an ISCAD control device. The integrated drive is placed in the motor compartment of the car. The mechanical integration of electrical machine is shown in Fig. 6. The volume of electrical machine and power electronics is much smaller in comparison to the combustion system. Therefore, the motor compartment provides additional space for a part of the traction battery.

The traction battery is designed for a capacity of 40 kWh and is separated into two parts in order to fit into the available space. Half of it is located where the fuel tank has been and the other half is placed instead of the diesel engine. Each half of the battery provides a maximum peak current of 1200 A and a continuous current of 600 A. A BMS including a current sensor and disconnection switch is attached to both battery parts. The battery represents a total weight of 220 kg. The first part is placed in the motor compartment on top of the electrical drive as shown in Fig. 7. This allows for a short cable length between battery and motor. The second part fits in the now-available space of the former fuel tank. Consequently, a higher diameter of connection cable is necessary in order to ensure a symmetrical load for both battery parts. The battery separation constitutes a drawback for the power net design at the expense of a combustion vehicle retrofit. Most BEVs available on the market include a battery pack in the underfloor of the vehicle. The distance between battery and axle including the electrical drive is very short. This allows a more advantageous design of ISCAD power net as outlined in chapter II.

Fig. 6. Gearbox with constant ratio (left) and electrical machine (right) in the lower motor compartment.

Fig. 7. First part of the battery pack behind the radiator grill and on board charger in the upper part of the motor compartment.

Considering the rated power of integrated ISCAD system a diameter of less than 500 mm² of a copper conductor is sufficient to reduce losses in the DC cables. In this first prototype vehicle the DC bus is realized with several copper cables which are placed in a coaxial configuration in order to reduce the magnetic field. For future ISCAD systems, the use of aluminum coaxial cables is planned. This promises a lighter and much more cost-effective solution.

An ISCAD control device is used to handle the interface between vehicle, ISCAD system and driver. Sensors for driving direction and accelerator pedal are connected to the control device. The BMS communicates via CAN bus with this control device. It is the interface to the vehicle and fulfills high-level-functions such as derating of the drive. To do so, it predefines a desired value for the torque control. Several parameters are considered for a potential derating of the system, for example high temperature of one component (motor, inverter, battery) or in case of DC-current limitations due to an empty battery.

A comparison of car properties before and after drivetrain conversion shows that all components of the ISCAD system fit into the gained space of the removed combustion system. There is no need to reduce available space in passenger compartment or trunk. The weight of all ISCAD components is slightly higher in comparison to the former drivetrain. This is mainly ascribed to the weight of the battery and typical for BEVs. The increase of weight is below 50 kg and thus almost negligible, especially for a technical approval process to obtain a street legalization. The demonstrator car is taken into operation at this moment. In order to ensure safety, it is necessary to provide a couple of safety functions which need extensive test procedures. This is realized on a roller dynamometer and subsequently, on a vehicle test track.

V. Driving Range Simulation

Before setting up the vehicle, a feasibility analysis has been performed. Since the VW Touran is a relatively large vehicle with a high air drag, it had to be determined whether the drive's power is sufficient to drive the vehicle in relevant operating cycles. Obtaining the expected range and energy use was also a goal of the simulation. Table II shows the relevant parameters that are required to simulate acceleration capability and energy use.

Performing the type of analysis required for the estimation of energy use and acceleration capacity requires a model considering aerodynamic drag, rolling resistance loss, gearbox and differential losses, battery and cabling loss and finally, the motor and inverter loss. For a more detailed analysis, auxiliary consumers such as vacuum and power steering pump and fans are also taken into consideration while comfort consumers such as air conditioner and media units are not considered. Fig. 8 gives an overview over the interdependencies.

Due to the interdependencies, setting up a such model is quite challenging. There are however some sophisticated simulation tools on the market which provide a convenient library of predefined model components that can be integrated

Table II : Vehicle parameters relevant for the simulation.

Parameter	Value
Drag coefficient	0.31
A	2.52 m²
m	1675 kg
Tire type	195/65/r15
Tire circumference, unloaded	1.93 m
Tire rolling friction coefficient	0.01
Gear ratio, shaft to wheel	7.2
Gearbox and differential efficiency	95 %
Battery capacity	40 kWh
Battery DoD	80 %
Auxiliary consumers	300 W

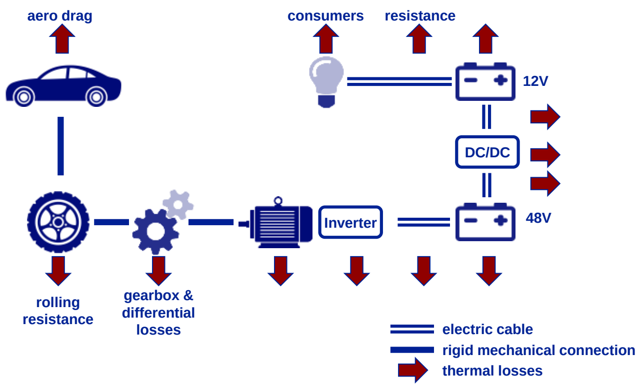

Fig. 8. Relevant model components for analysis of energy consumption and acceleration potential (credit: TESIS DYNAware GmbH).

into ones own simulation. For this simulation, DYNA4 of TESIS DYNAware has been chosen. It is based on MATLAB/Simulink and provides a comprehensive model repository where every component is represented in different levels of fidelity, see Fig. 9. Own components can also be integrated into the simulation. Therefore, the tool can be used both for high level energy analyses and on the other hand for in-depth controller development and even HIL/SIL-applications or analyses of the thermal architecture.

In the case of this study, motor and inverter were represented by a tabled model. The data required was generated using FEM for the machine and analytical calculations, respectively circuit simulations, for the inverter. The detailed process is described in [4]. Depending on the mesh resolution in the torque-speed-plane, the accuracy of the model can be adapted and the parameterizing effort scales correspondingly. The vehicle's behavior was simulated for the driving cycles NEDC, WLTC and Artemis Urban Cycle (CADC). These three cycles can be considered as low acceleration, realistic driving behavior and aggressive urban driving, respectively. The analysis conducted in [4] showed that the ISCAD drive performs outstandingly in all three scenarios.

Fig. 10 shows the simulation result for the WLTC. The violet line represents the locus of this cycle in the torque-speed-plane. Since the drive yields a maximum peak torque of 240 Nm, it becomes obvious that the drive has sufficient torque and power

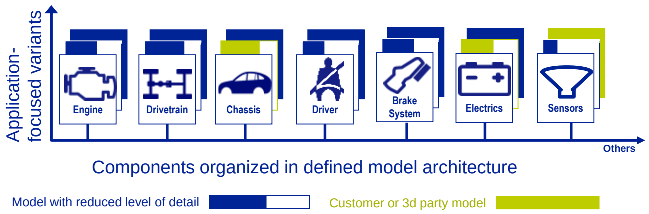

Fig. 9. Model repository with components of different level of fidelity in DYNA4 (credit: TESIS DYNAware GmbH).

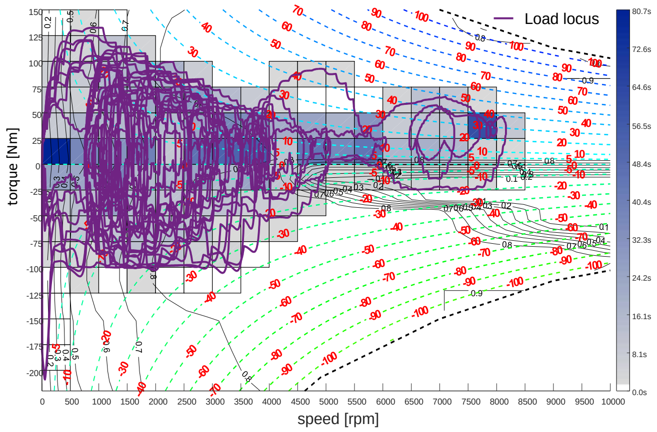

Fig. 10. Locus of load points, dwell time in speed-torque regions (colored rectangles) and iso-efficiency-lines for the WLTC.

to follow the WLTC cycle with the chosen vehicle. Furthermore, the colored rectangles in the figure display the accumulated dwell time for the overlain torque-speed-area. Since the drive has a continuous torque of 120 Nm and since it is capable of supplying peak torque for 10-15 seconds, it is clearly a perfect match for the VW Touran.

For the purpose of analyzing energy consumption and possible range, the same simulation has been conducted for the ARTEMIS Urban Cycle (CADC) and the NEDC. The results are summarized in Table III.

Obviously, the higher speed cycles lead to an increase in energy demand which is due to the poor aerodynamic performance of a drag coefficient of 0.31. The CADC urban cycle's maximum speed is 58 km/h, which means that rolling friction and internal drive losses are dominant by far. The maximum discharge of the battery has been fixed at 80 % (see Table III) for a conservative approach. Once the system is tested on the road and the reliability of the battery management has been evaluated, this value could also be increased to 90 %, resulting in a gain in driving range.

VI. Conclusion

This paper introduces ISCAD, a new high power extra-low voltage traction system. The highly parallel structure of the traction system from battery to motor achieves several advantages: increased efficiency and driving range of up to 25 %, a safe-to-touch operation voltage without the need of cost-intensive HV safety measures and a motor design without use of limited materials like copper or rare earths. ISCAD provides efficient and simple components and is an enabler for high power applications without a costly and hazardous HV infrastructure.

A first ISCAD prototype was developed in 2016 and the advantages has been proven on a test bench. Subsequent, an integrated compact ISCAD system was developed for car integration. The parameters of the ISCAD system with a power of 110 kW are presented in this paper.

In order to address mass market, a VW Touran including a combustion engine is chosen for conversion into an ISCAD demonstrator car. The combustion system including motor, gearbox, exhaust system and fuel tank are removed and replaced by integrated ISCAD system components. Latter fit in the now-available space and result in a negligible increase of total vehicle weight. The demonstrator car is taken into operation in beginning of 2018. In order to ensure safety, it is necessary to provide a couple of safety functions which need extensive test procedures. This is realized on a roller dynamometer and

Table III: Consumption data and range for different cycles.

Cycle	Energy [Wh]	Distance [km]	Consumption [kWh/100km]	Range [km]
WLTC	3904.2	23.27	16,78	191
NEDC	1628.6	11.02	14,78	217
CADC	908,2	4,88	18,61	172
RTS95	2696,8	7.82	20,86	153

subsequently, on a vehicle test track. As soon as full operation is achieved, measurement results of test bench, dynamometer and test track will be published.

A simulation model is used to estimate driving range of the ISCAD demonstrator car by now. Several driving cycles were considered. A consumption between 14,8 kWh/100km and 20,9 kWh/100km and a driving range between 153 km and 217 km were determined.

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