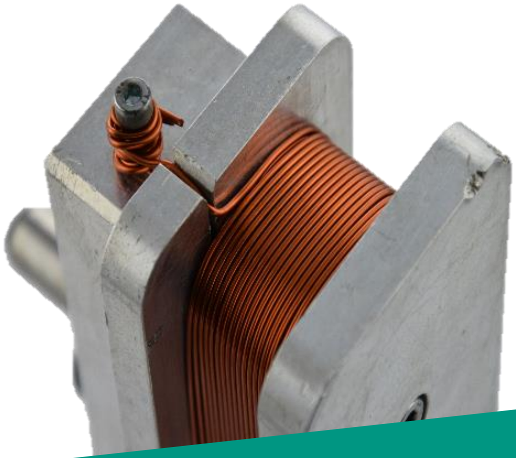

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Quo Vadis Winding Technology?

A study on the state of the art and research on future trends in automotive engineering

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1. Introduction and Backgrounds

Electromobility experienced an intensive and dynamic development not least because of the ambitious climate objectives of the German Federal Government and the most recent exhaust gas scandals of German OEMs and the associated strategic reorientation towards producing all-electric vehicles in large quantities. With the increasing number of electric vehicles to be produced, the supplier market as well as the producer market will change considerably in the next 10 years.

The core component of the conventional powertrain – the combustion engine – will be replaced or respectively complemented by one or more electric motors. Electric motors have been produced for over 100 years for the most different fields of industrial application and consumer products. However, the manufacturers of components for electric motors intended as traction drives for cars are facing novel challenges such as high standards in terms of winding and insulation quality and short cycle times as they are common for conventional drive units nowadays.

This study will, first of all, give a qualitative overview and a comparison of the drive concepts for vehicles and the motors they use. From this will be deduced and outlined the different rotor and stator designs associated with the various drive concepts. With this shall be shown, in an exemplary manner, which car concepts exist and what variety of electric motors is prevailing in current electric powertrains.

Building on this, the second part of the study takes a closer look at the production of the coil or winding being a core component of the energy producing stator. This way, the key competencies for realizing windings as well as the standards for the coils are demonstrated in order to derive the challenges involved and the approaches for producing them.

2. Electric Vehicle Concepts and their Drives

Basically, according to (Bauer et al. 2015) all electrified drives are understood as e-mobility drive concepts for bikes, motorbikes, classical cars and load carrying vehicles.

2.1. Overview of Alternative Drive Concepts

The study focuses on electric drives for passenger cars which of course present different challenges depending on the structure of the electric vehicle (hybrid or full electric). The vehicle structure of the different car concepts can be seen in Figure 1.

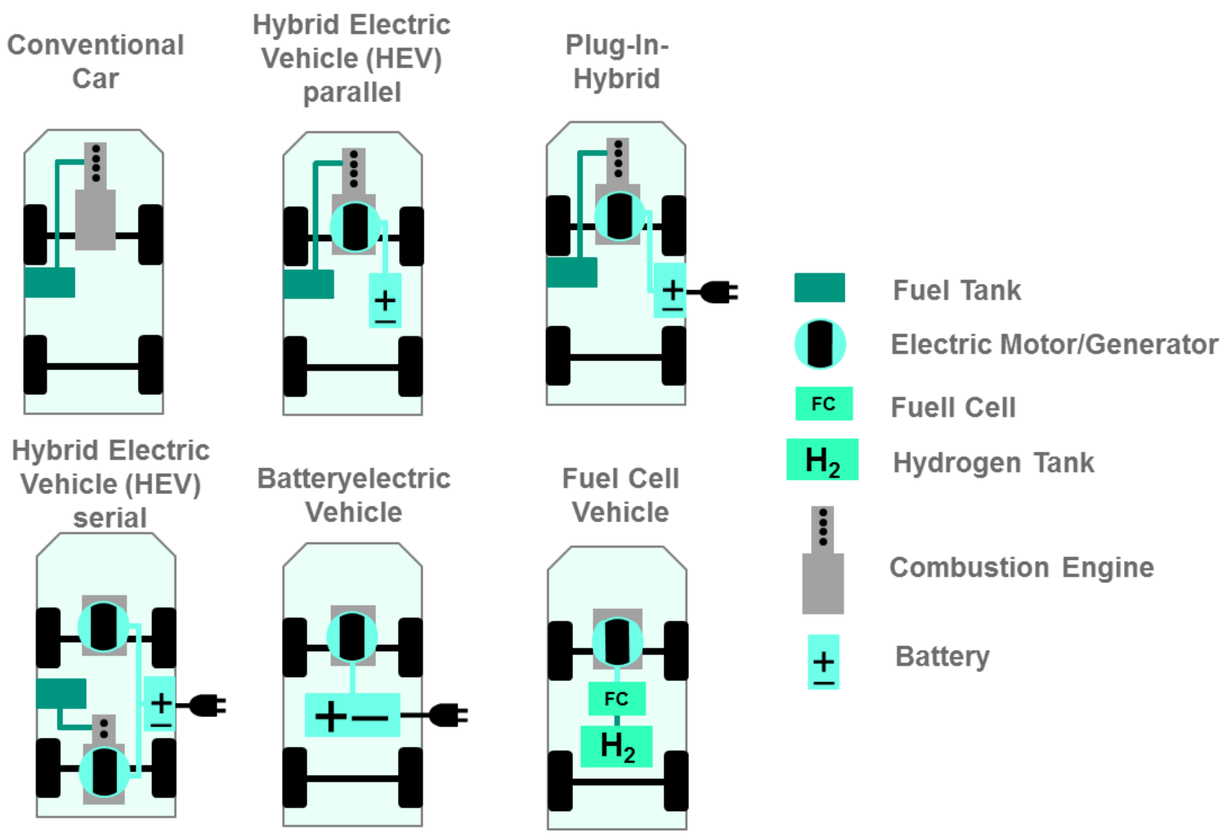

Figure 1: Overview of existing electric vehicle concepts (internally developed figure according to (Bauer et al. 2015))

Furthermore, the following car concepts and standards/requirements for their electric motors are shown:

- Hybrid Electric Vehicles (HEV)
    - Mild-HEV
    - Full-HEV

- Plug-In-HEV
- Battery Electric Vehicles (BEV)

The classification of these car concepts is made according to (Kampker 2014) based on the drive performance expressed in kW or rather the performance per kg vehicle mass in W/kg as well as the on-board network voltage in V. The transitions between the different hybrid car concepts are fluid (see Figure 2).

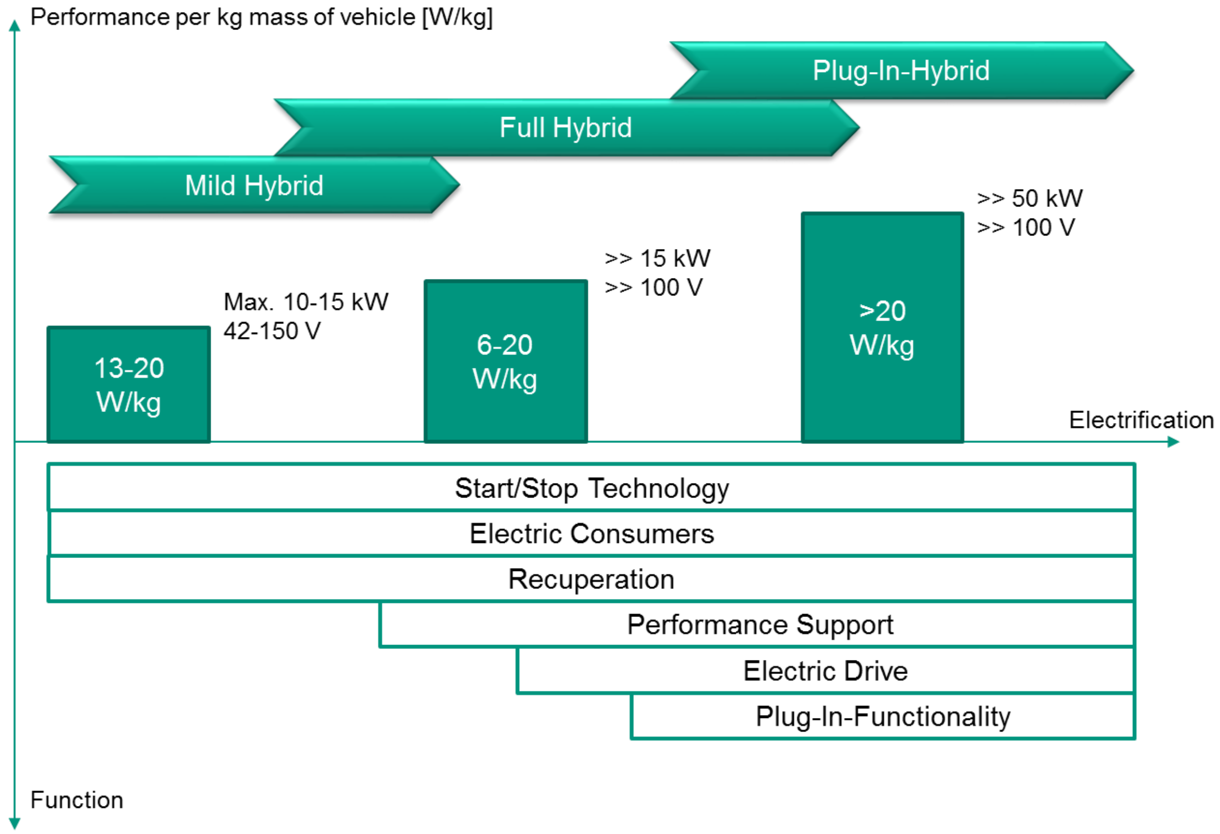

Figure 2: Comparison of the different hybrid concepts (internally developed figure based on (Kampker 2014, S.119))

2.1.1. Mild-Hybrid Electric Vehicle

After the so-called Micro Hybrid, where according to (Bauer et al. 2015) a start/stop technology as well as a regenerative braking system (recuperation of brake energy) is installed but the combustion engine is not electrically assisted, the Mild Hybrid presents the first hybridization category. According to (Lienkamp 2016) it is not possible with a Mild Hybrid to drive purely electric. The electric machine recovers only kinetic energy when braking (recuperation) and supports the combustion engine during acceleration (boosting). This way, an electric machine with about 10 kW (corresponds to approx. 14 HP) is installed in a mild hybrid system according to (Lienkamp 2012). One example for a mild hybrid is the Mercedes S-Class. However, according to (Lienkamp 2012) the mild hybrid belongs to a medium sized vehicle class in order to be profitable because in smaller cars the costs as well as their additional weight would be too high on a proportional basis.

2.1.2. Full-Hybrid Electric Vehicle

With the hybridization of a vehicle, it is possible to reduce the emissions according to (Lienkamp 2014) compared to classical cars with combustion engines of up to 50 g CO2/km. An electric motor assists according to (Bauer et al. 2015) the engine of classical propulsion. According to (Bauer et al. 2015) an all-electric propulsion is partly possible for a limited range. However, the hybrid car is only profitable according to (Lienkamp 2014) for driving cycles with high acceleration phases since at higher speeds or during highway travel an even higher energy consumption can be observed sometimes due to the higher weight and a powertrain partly only optimized for urban traffic. In a fully hybrid car such as the pioneer Toyota Prius, a much higher electric capacity is installed according to (Lienkamp 2012) in the range of 50 kW (about 68 HP).

2.1.3. Plug-In Hybrid Electric Vehicle

Plug-in hybrid vehicles reach an electric range of about 25-50 km, according to (Lienkamp 2014). The plug-in hybrid cars currently available on the market are sold at a very high price according to (Lienkamp 2014) since two drive trains are installed. The additional weight causes poorer driving dynamics compared to the conventional or all-electric cars. In contrast to the full hybrid, the battery of the plug-in hybrid is rechargeable via the network according to (Bauer et al. 2015). Currently sold and designed plug-in hybrid models, as stated by (Bauer et al. 2015) are the Toyota Prius Plug-In for instance or the Porsche Panamera S E-Hybrid, the Mercedes Benz S 500 PLUG-IN HYBRID and the BMW i8. The following models are currently in the planning phase or already sold as serial plug-in hybrids with range extender: the Chevrolet Volt, Opel Ampera, Cadillac ELR and BMW i3, as reported by (Bauer et al. 2015).

2.1.4. Battery Electric Vehicle

As stated by (Bauer et al. 2015), a battery electric vehicle is characterized by a powerful electric motor and a battery that can be recharged via the grid. In contrast to hybrid cars these purely electric cars have no combustion engine and therefor no fuel tank and no exhaust system. For charging the battery, only the grid and the recuperation are used, see (Bauer et al. 2015). The purely electric cars offer an impressive driving experience according to (Lienkamp 2014), an evenly high acceleration from 0 to 100 and no jolts due to gear changing. In addition, the electric drive of the vehicle ensures a quiet ride close to noiseless at standstill as well as an emission-free driving. As stated by (Lienkamp 2014) a disadvantage beside the high acquisition cost is the limited range at present and thus the fear of the consumers to conk out with the car somewhere in the middle of nowhere. The currently sold and planned models according to (Bauer et al. 2015) are for example, the Mitsubishi i-MiEV, the Nissan Leaf, the Smart ForTwo Electric Drive, the Tesla Model S or the Mercedes-Benz B-class with electric drive, the Mercedes EQ, the VW ID, the BMW iNext, the Tesla Model 3, the VW e-UP and, finally, the Opel e-Ampera.

2.2. Electric Motors for Traction Drives

The electric motor as a drive component within the electric drive train is a particular challenge for the production technology. As said by (acatech – Deutsche Akademie der Technikwissenschaften 2009) "A challenge that can be named in this context is the production of high quantities at a high quality with a weight and installation space of the electric motor that are the decisive criteria, eventually." At present, mainly asynchronous motors (ASM), permanently excited synchronous motors (PSM) and separately or DC-excited synchronous motors are used for electric cars, see (Bauer et al. 2015). The technology behind these motors is well known from industrial motors but needs to be adapted now to the challenges of customer requirements such as driving comfort, acceleration behavior, no wear, high battery efficiency requirements etc. and the limited installation space within the powertrain of a car and requirements from the automotive branch like cost pressure, resistance regarding changing environments, just-in-time delivery, no rejects and no mistakes in the vehicle delivery, must be considered. It is therefore necessary to describe the features and characteristics of these motors and the cars in which they are built in more closely below. Furthermore, other highly promising drive concepts for traction applications will be presented.

2.2.1. Asynchronous Motor (ASM)

According to (Hofmann 2010), the asynchronous machine is mainly characterized by its low cost and its robustness. As stated by (Kampker 2014), the rotor as well as the stator consist of stratified iron sheets insulated from one another to avoid the development of eddy currents. For the rotor, however, there are two different configurations in which the rotor, according to (Kampker 2014), is equipped either with aluminum or copper bars (cage rotor) or with a winding drawn into the rotor grooves (slip ring rotor). The low cost of the ASM results from the fact that this kind of machine configuration can do completely without expensive magnetic materials. Since there is no need for magnets, the machine is very cost-effective, according to (Lienkamp 2014),but it is heavier compared to a PSM with the same continuous rated power. A serious disadvantage of the ASM is the rotor wear due to the slip ring contacts causing a replacement of this component after a certain number of driven kilometers. Tesla, for example, uses an ASM in its electric drive train, see (Lienkamp 2016).

2.2.2. Permanent Magnet Synchronous Motor (PSM)

The most frequently applied type of synchronous machines is the permanently excited synchronous machine (PSM). According to (Hofmann 2010) this machine type is very often used in modern electric cars (hybrid as well as full electric). Permanent magnets mostly made of neodymium-iron-boron (NdFeB) materials are used here for developing the exciter field. The magnets are normally introduced into punched out pockets (embedded magnets) of the rotor stack. The advantages of the permanently excited synchronous machine are their very high efficiency of up to 94 %, as reported by (Lienkamp 2014), and the simple and low-maintenance design without sliding contacts or brushes and their very high power density of 1,5 W/kg. Disadvantageous are the decreasing efficiency at high speeds as well as in the partial load range and the reliance on rare earths such as neodymium. The PSM is used by BMW and VW as stated by (Lienkamp 2014, 2016).

2.2.3. DC-Excited Synchronous Motor (DCSM)

The design of the stator of a DC-excited synchronous machine (DCSM) is the same as in a PSM or ASM. According to (Hofmann 2010) the DCSM is magnetized by direct current excited revolving fields and the rotor presents salient poles with windings. The DC-exited SM does not use magnets and is therefore load-free in case of voltage drop according to (Lienkamp 2014). However, there has to be applied a slip ring transmitter - similar to the one used in an ASM - in order to build up the field inside the rotor, which needs to be replaced after about 100.000 km. So, the DC-excited SM represents a compromise between the ASM and the PSM, see (Lienkamp 2016). The DC-excited SM is used by Renault according to (Lienkamp 2014).

2.2.4. Additional Types of Motors

The reluctance motor (RM) and the transverse flux motor (TFM) present additional motor concepts, which however are according to (Spath et al. 2010) currently still in the state of research and thus not ready for series production of electrical drive trains in personal vehicles. However, according to the current state of the art, these engines are not yet installed in series-production vehicles. Neither can their implementation presently be predicted. Consequently, they shall not be further considered in this study.

Another example is the direct-current motor (DCM), which has already been developed very widely according to (Spath und Bauer 2012) and has already been used in the Honda Insight see (Spath et al. 2010). But this kind of motor has a very high cooling effort, poor efficiency and a very high noise level with a high production effort.

A comparison of all types of engines can be found in Table 1. Since the reluctance motor, the transverse flux machine and the direct current motor are no longer used or are not yet used in vehicles due to the above mentioned properties, they are not considered further in this study.

Table 1: Comparing different types of electric machines – own compilation based on (Spath und Bauer 2012; Spath et al. 2010; Kampker 2014); Legend: ○ very poor, ● excellent

	ASM	PSM	DCSM	RM	TFM	DCM
Power density	◕	●	◑	◕	●	◕
Max. speed	●	●	◕	●	○	○
Efficiency	◕	●	◕	◕	●	○
Cost	●	◕	◔	●	◔	◕
Development status	◕	◑	○	◑	◔	●
Reliability	●	◕	◕	●	◕	◕
Controllability	◑	◕	◕	●	●	●
Noise level	◕	◕	◕	◕	◕	◔
Manufacturing costs	●	◕	◕	●	◑	◔
Volume	◕	●	●	◕	◕	◔
Weight	◕	●	◕	◔	◕	◔

Since the battery cells as energy supplier in the first generations of BEVs will be purchased from the Asian market in the years to come, western OEMs are currently aiming for an inhouse production of electric motors and thus face the technological challenges related to. For the purpose of maintaining the added value and the possibility to differentiate from competitors and jobs in Germany (acatech – Deutsche Akademie der Technikwissenschaften 2009) seems necessary for the OEMs to identify and master the required know-how as well as the core manufacturing skills. As a consequence, the supplying industry from the classical powertrain, is re-adjusting their core business from the decreasing diesel engine market (i.e. Bosch, Continental, ZF) to these new technologies. These challenges shall therefore be presented in this study. For this objective, drive concepts of selected OEMs shall be depicted first by researching the current state of the art.

2.3. Quality Criteria for Windings of Traction Motors

To evaluate the motor winding, comparable criteria must be identified that allow comparing different winding processes. For this purpose, the National Platform of Electromobility (NPE) has defined electric drive systems which can be directly transferred to the winding of an electric engine (Nationale Plattform Elektromobilität 2010, S. 4).

Thus, the NPE demands that the overall system cost of the electric drive train must be reduced by 2/3. Repercussions on production technology manifest in the setting up of particularly flexible and highly automated series production facilities for manufacturing electric motors. Another demand constitutes in the duplication of the vehicle's power density and power-weight ratio. The winding of the motor can contribute to meeting these demands by keeping the winding heads as low as possible and thus minimizing the use of copper. The engine's copper fill factor must be maximized for the purpose of increasing efficiency. In a final demand, the NPE calls for improving reliability and quality of the electric motor which in turn can be met by avoiding manufacturing errors. As a consequence, to avoid a reject production errors during the motors' manufacturing (e.g. during wire up) have to be eliminated. In particular, high stresses for the wires during the process should be avoided. Even though, according to (Beckmöller 2013; Jovanoski 2015) the wires are becoming much more resistant, they however have to bear substantial stress factors during the production of windings and thus constitute a product of constant change.

2.4. Product Research of selected OEMs

2.4.1. BMW

With its i-series, BMW has been the first German OEM to launch electric vehicles on the market which are mass produced and sold. According to (Lienkamp 2016) the range of the i3 has increased to 300 km under the NEDC due to the new cell generation. The i8 technologically represents an outstanding PHEV, according to (Lienkamp 2016) however, because of its classification as a sports car and the currently demanded sales price, it is only suitable for small quantities. The BMW media portal (BMW 2014) reveals that BMW produces engines with distributed windings using the insert technique, but in a low volume manufactory production.

2.4.2. VW

Among other things, it is especially due to the current diesel scandal that Volkswagen and its subsidiaries are facing the challenge of revising their corporate strategy. Electromobility shall function as one of its key components. According to (Lienkamp 2016) the company will offer 48V mild HEVs for gasoline and diesel engines because of financial reasons. It was for two platforms, namely its all-electric vehicles: the e-up! and the e-Golf that VW has developed a modular electric toolkit (MEB) for BEV (Lienkamp 2014). With the current battery technology, these Volkswagen vehicles reach a range of 100 km in real operation, according to (Lienkamp 2014). The VW media portal (VW Group 2015) reveals that Volkswagen has produced an engine for the e-up! with distributed windings using the flyer and insert processes.

2.4.3. Tesla

According to (Lienkamp 2014), Tesla is the market leader in the BEV sector. (Lienkamp 2016) regards the Model S to be the only vehicle able to offer a range of up to 500 km in customer operation and thus able to cover in most cases the cruising range offer of hybrid vehicles. Tesla only uses conventional components for its car bodies (aluminum structures in comparison to CFRP structures) and drive trains (asynchronous machines). Also, the Tesla media portal (Tesla 2015) shows that the Model S's engine is classically produced with the insert technology. With its Model 3, Tesla will launch a novel electric vehicle onto the market in 2017.

2.4.4. Daimler

It was already in 2009, that Daimler acquired corporate shares of Tesla Motors and has thus had early access to expertise knowledge of the electric mobility company in the areas of drive and battery technology. Even after selling the share in 2014, the cooperation is still upheld. This is for example reflected in the fact, that the drive concept of the BEV B-Class consists of Tesla components (Lienkamp 2016). Daimler has announced the market launch of the e-smart for 2017.

2.4.5. Toyota

With the Prius Hybrid, Toyota has its great strength in the HEVs and the biggest lead in large-series production of hybrid vehicles, according to (Lienkamp 2016). An all-electric vehicle is currently not sold by Toyota. The Toyota media portal (Toyota USA 2016) reveals that, for the first time, plug-in coils (so-called hairpins) will be used in the new Toyota Prius Prime as stator coils. This represents an innovation compared to the Toyota Prius equipped with concentrated single-tooth windings.

3. Production Technologies for Electric Motors

The production process chain for electric motors has long been known due to the experiences made when manufacturing e-motors for industrial applications and will most likely not change substantially. However, according to (Roland Berger Strategy Consultants 2011) the applied production technologies will have to be altered and further developed in the individual production steps in order to meet the demanded production costs.

The classic process chain for manufacturing rotors and stators is depicted in Figure 3.

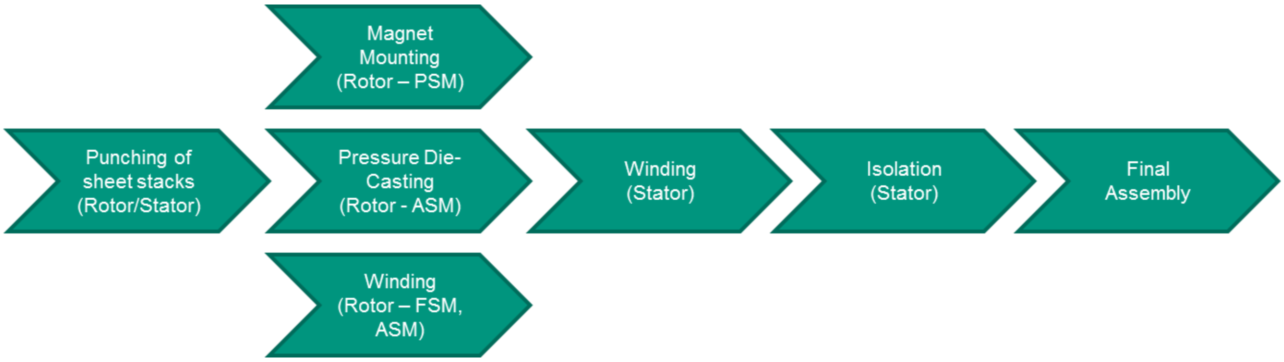

Figure 3: Simplified manufacturing process chain of electric motors (ASM, PSM) according to (Roland Berger Strategy Consultants 2011))

The most important process step constitutes in generating the stator winding, according to (Roland Berger Strategy Consultants 2011). Thus this step will be focused within the next chapters of this study.

3.1. Overview of Winding Technologies Existing on the Market

First, an overview of the winding technologies existing on the market shall be presented. In addition to the classic winding processes with enameled copper wire, preformed coils and flat wire wave windings produced by forming are considered as well. Manual trickle winding shall not be further considered since it does not represent an automated process suitable for those high volumes demanded in the automobile industry. But it is applied in the manufactory production if high performance motors like for the Formel-e series.

3.1.1. Linear Winding Process

According to (Hagedorn et al. 2016) the linear winding technique covers a wide range of application when manufacturing electric winding material with complex winding tasks. The term linear winding technique originates from the type of wire placement. Here, the movement of the wire guide and the rotational movement of the winding spindle occur synchronously and at a constant speed (see Figure 4) according to (Feldmann et al. 2013). The linear winding process is mainly used in electrical engineering for the purpose of winding rotation-symmetric components.

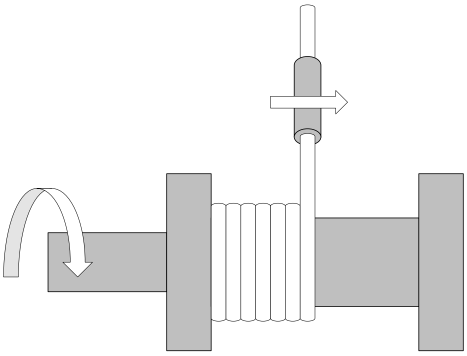

Figure 4: Schematic depiction of the linear winding process (own figure based on (Feldmann et al. 2013))

When dealing with traction drives, linear winding is applied for manufacturing concentrated single-tooth windings. According to (Hagedorn et al. 2016), coils may be produced at optimum productivity for serial application using a multi-spindle machine. However, the rectangle design of the coil body also handicaps the manufacturing process which is why the winding speed cannot be compared with the process times for round coils.

(Hagedorn 2015) holds the position that due to the orthocyclic winding of the linear winding process excellent fill factors can be achieved and that profile wires can be processed. Winding phase pole chains is also possible and wires can automatically be positioned at the contact points of the single-teeth.

3.1.2. Flyer Winding Process

According to (Hagedorn et al. 2016), the term flyer winding technique stems from its movement, a movement which causes the winding machine to quickly rotate the tool for the purpose of winding the component. The coil body is fixedly grasped and the wire leads the rotation movement through a flyer arm around itself (see Figure 5: Schematic depiction of the flyer winding process (own figure based on). This key characteristic constitutes a substantial difference in comparison to the linear winding technique. (Feldmann et al. 2013) state that the flyer winding process is mainly applied for winding coil forms such as rotors or coil bodies of high weight as for example transformers.

According to (Hagedorn 2015), flyer winding is a well-established process for concentrated and distributed windings of externally grooved stators and rotors as well as single teeth.

Winding can be performed directly for manufacturing concentrated windings or via a delineator. For direct winding, small winding heads are a characteristic feature and the stator can be connected automatically to the nozzle flyer. (Hagedorn 2015) states that the ideal application is achieved when wires of small diameters are used. Flyer winding constitutes a cost-efficient process for high winding numbers. A multi-spindle arrangement is feasible and the orthocyclic winding allows for the generation of high fill factors. Usually, the flyer winding is a common solution for the production of air coils on so called template flyer for the insert technique.

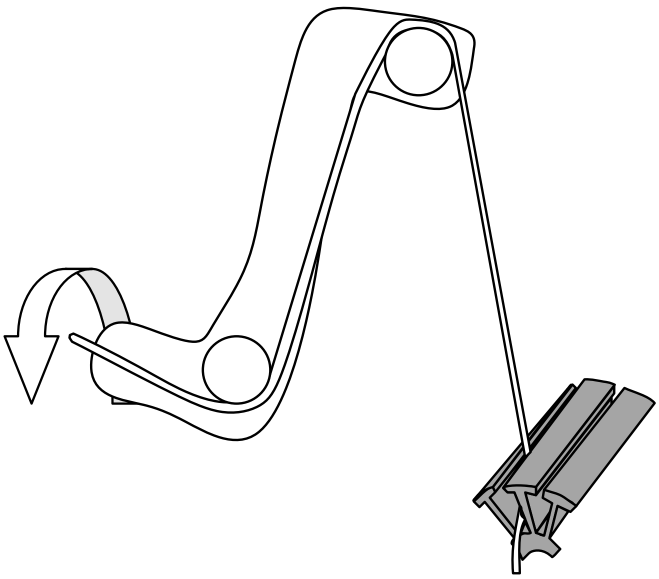

Figure 5: Schematic depiction of the flyer winding process (own figure based on (Feldmann et al. 2013))

3.1.3. Needle Winding Process

In contrast to linear and flyer winding, the term needle winding stems from the geometric structure of the wire guide or respectively the nozzle, according to (Hagedorn et al. 2016). The wire guide in the form of a needle runs the entire pathway located directly at the coil body and thus demonstrates the main difference compared to the previously described winding processes. The performed movement combines a raising and lowering of the needle carrier with the needle and a swiveling of the stator. According to (Tzscheutschler et al. 1990) the slightly dated term hoisting and swiveling process derives from this movement.

According to (Hagedorn 2015), the needle winding process represents a well-established method for performing concentrated windings with small winding heads. The stator is completely processed which also includes the automatic cladding of the stator. Furthermore, (Hagedorn 2015) is of the opinion that the needle winding process' characteristic features constitute in low tool costs and a minor setup effort which in turn allows a multi-spindle setup and is thus suitable for large series production. Best fill factors can be achieved for internally grooved stators of small engines using the needle winding technique without having to perform a segmentation of the stacked sheets. New winding machines with more than two axes even facilitate the production of distributed windings with the needle winding process (Stenzel et al. 2014a; Sell-Le Blanc und Hagedorn 2016).

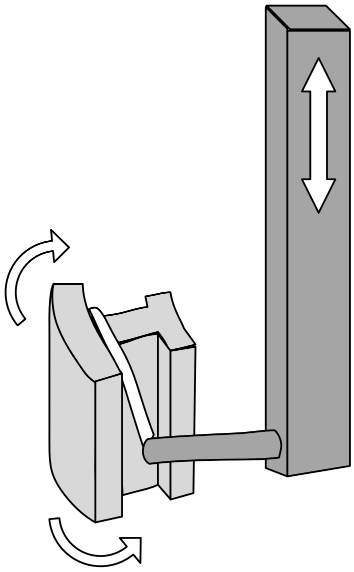

Figure 6: Schematic depiction of the needle winding process (own figure based on (Feldmann et al. 2013))

3.1.4. Insert Process

According to (Hagedorn et al. 2016) the winding to be mounted must first be processed in the form of an air coil with a feeder flyer winding station directly onto an insert tool or with a linear winding machine onto a mask for the purpose of conducting the insert process (see Figure 7 left).

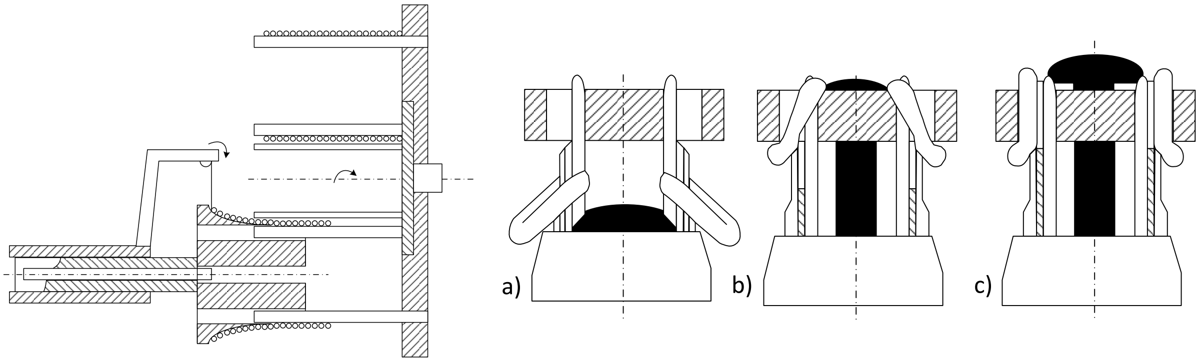

Figure 7: Schematic depiction of the feeder flyer process (left) and the insert process (right) (own figure based on (Tzscheutschler et al. 1990))

The insert process itself takes place in three stages, according to (Tzscheutschler et al. 1990) (see Figure 7: Schematic depiction of the feeder flyer process (left) and the insert process (right) (own figure based on right). In the first phase (see Figure 7: Schematic depiction of the feeder flyer process (left) and the insert process (right) (own figure based on right, a)), the tool penetrates the stator. In the second phase (see Figure 7: Schematic depiction of the feeder flyer process (left) and the insert process (right) (own figure based on right, b)), the insert gear cluster is extended. This way, the insertion of the coil into the slot commences. Once the wires have entered the slot, a slot liner is introduced, according to (Hagedorn et al. 2016), which shall prevent the wires from squeezing out of the slot after removing the insert tool. In phase three (see Figure 7: Schematic depiction of the feeder flyer process (left) and the insert process (right) (own figure based on right, c)), the coil is completely drawn in.

(Hagedorn et al. 2016) are of the conviction that the insert process represents the most widely used application for manufacturing distributed windings in closed stators. The reason for this lies in the short cycle times and the broad application range in terms of stator and winding geometry. It is due to the secondary assembly that the wires cannot be placed into the slot in a targeted manner which is why this process is referred to as indirect winding.

3.1.5. Producing preformed Coils

Numerous coil groups are basically summed up under the term preformed coil. Therefore, various names describing preformed coils of different shapes and designs emerge in literature. Among others, (Braymer 1920) and (Richter 1952) for example, describe single and dual diamond coils, bent and straight concentric coils and so-called plug-in coils. Furthermore, they describe coils which have not been produced with massive conductive material but with rods (like the Roebel-Rod). Plug-in coils or hairpin coils are often used for traction drives since they can easily be handled and produced. The coils are easy to manufacture and to handle, but come along with a high contacting effort, which is why it is linked to higher reject rates in the next production steps (Mechler 2010).

The mechanical forming of the winding elements is performed, according to (Sequenz 1973), with special equipment such as winding forms or spreading devices. (Bălă et al. 1969) state that the respective technology is selected based upon the number of items to be produced. In case a massive conductor or an already finished plastic rod shall serve as the base material, it must first be brought to the respective length once it has been leveled. The material will be cut then with an automatic stretching and cutting machine after it has been pulled off by a coiler.

According to (Sequenz 1973), the coils are subsequently placed onto the winding masks in the respectively desired basic form. In line with (Heiles 1936; Much 1983), this endeavor is carried out with a special device which prevents the rod from escaping from the plane and which bends the material to the form of a horseshoe or hairpin with parallel legs. Figure 8 illustrates the respective forms of the plug-in coils between the individual working steps. The main challenge when manufacturing preformed coil windings constitutes in the assembly and contacting of the multitude of individual elements. In case of omitting the complex contacting this process would be ideal for a motor manufacturing application (Mechler 2010).

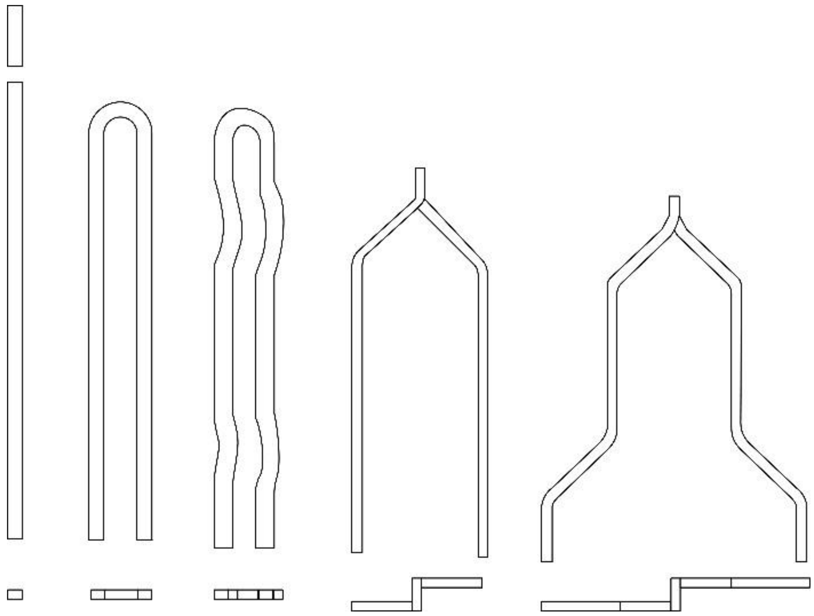

Figure 8: Schematic depiction of the bending process for plug-in coils (own figure based on (Bălă et al. 1969))

3.1.6. Continuous Hairpin Winding

According to (Sadiku und Witt 2009), this manufacturing technique represents a winding alternative which consists of a continuous rectangular o square profile wire.

The difficulty when manufacturing such a stator consists, according to (Sadiku und Witt 2009), in the fact that the strong rectangular wire cannot be bent easily using the conventional winding and insert process. Consequently, two individual rectangular strings are first manufactured on a special bending machine as depicted in Figure 9a. Subsequently, they are put together to form a complete winding, as illustrated in Figure 9b. Then, this entire winding is introduced into the insulated stator package by a magazine via an intermediate step of a tool action, according to (Plikat und Mertens 2011).

In contrast to the preformed coil process, a continuous winding is generated which must be mounted afterwards. Analog to the preformed coil technique, the greatest challenge of this approach lies in mounting the winding without causing any damage.

This technology combines the benefits of classical round wire winding technology and the hairpin technology.

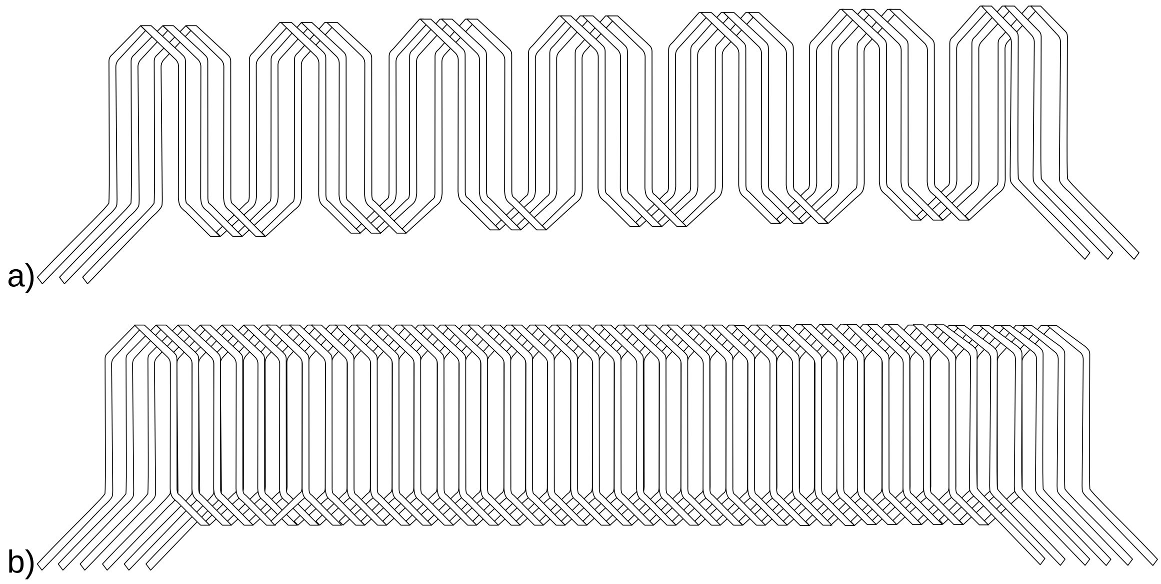

Figure 9: Schematic depiction of a Continuous Hairpin Winding (own figure based on (Sadiku und Witt 2009))

4. Overview of Classical Winding Methods for Traction Drives

As already described, asynchronous machines, permanent magnet synchronous machines or DC-excited synchronous machines are primarily used in traction drives. The stator winding of the machines can be distributed or concentrated windings as shown in Figure 10. However, significant additional expenses can be observed in power electronics mainly for the asynchronous machines when using concentrated windings instead of distributed windings to ensure a comparable machine performance. (Gerling et al. 2012)

According to the current state of the art, distributed windings are typically produced by using the insert technique. Even the hairpin windings or preformed coils are typically manufactured in a distributed way. The methods, however, are no classical winding processes but secondary assembly processes based on forming. That is why they are not included in the category of winding with wire according to (DIN 8580) or (DIN 8593-5).

Manufacturing distributed windings with the needle winding process is a new trend. But this requires auxiliary wire feeding tools inside the winding head such as the ones presented in (Stenzel et al. 2014a). The continuous hairpin technology is suitable for the production of distributed stator windings as well.

Distributed rotor windings are typically produced using the flyer winding method.

Concentrated windings are manufactured using the needle winding process onto internally grooved lamination stators. In case of internally grooved stators consisting of chains of poles which are then put together to form the stator, the needle winding as well as the flyer winding process can be applied. For winding single teeth, linear winding is commonly used but also the flyer winding technique.

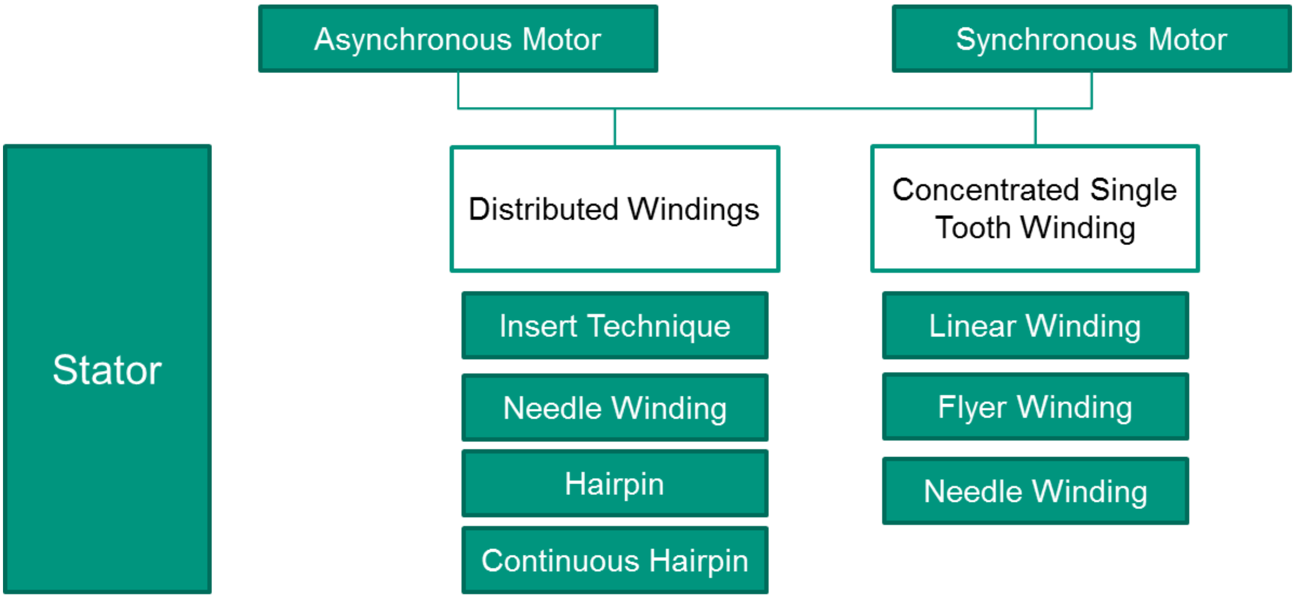

Figure 10: Overview of winding processes relevant for the electromobility - internally developed figure based on (Bauer et al. 2015)

4.1. Advantages and Disadvantages of different Winding Processes

In order to be able to compare these winding methods, a distinction needs to be made between round wire winding and the coils made by forming and the flat wire wave winding. Since the production of these different types of coils is very diverse, this chapter only discusses the classic round wire winding method. A closer look at the forming methods is taken later when talking of new approaches in winding technology.

In case of the round wire winding processes, there are basically two different winding types. According to (Hagedorn et al. 2016), linear winding, flyer winding and needle winding belong to the direct winding methods and the insert process belongs to the indirect winding methods. The difference lies in the way of applying the wire onto the coil body or stator tooth. As the word "direct" already indicates, the wire is wrapped directly onto the coil body (bobbin) or stator tooth during direct winding whereas in the insert process the already (directly) pre-wound coils are introduced into the stator and therefore onto the stator teeth in a second step.

In order to be able to assess the different winding methods, first, the typical process features according to (Hagedorn et al. 2016) of the named methods are compared with one another in Table 2.

Table 2: Comparing round wire winding methods according to (Hagedorn et al. 2016)

	Linear winding	Needle winding	Flyer winding	Insert technique
Max. speed in windings/min	30,000	2,500	12,000	12,000 (Flyer)
Producible winding scheme	Orthocyclic	Orthocyclic	Orthocyclic	Wild winding
Theoretically producible mech. filling factor	90.1%	90.1%	90.1%	60%
In reality producible mech. filling factor	85%	85%	85%	55%
Winding types	Concentrated winding	Concentrated & distributed winding	Concentrated & distributed winding	Distributed winding
Load on wire	Low	High	Medium	High
Investment cost	Low	Medium	Medium	High
Automation level	High	High	High	Medium

As the product research of some OEMs already showed in section 2.4, the insert technique with a flyer winding center installed upstream are preferred by most of the OEMs in the machines they currently use for series production, since such equipment can already reach the currently needed output with the same cycle times as known from the production and assembly of conventional motors. As reported by (Halder 2013), the insert technique is universally applicable and has a high market and technology potential.

However, the insert method also entails disadvantages compared to the direct winding methods. The first disadvantage of the insert process is that it cannot be fully automated. As stated by (Kühl 2014), the contacting can only be performed manually. According to (Kampker 2014), the reason for it lies in the limpness of the winding ends because they are not fixed when pulled into the stator. This makes the process step according to (Tzscheutschler et al. 1990) not only time-consuming but, as stated by (Kampker 2014), also expensive and error-prone.

Furthermore, the wire is subjected to very high loads due to the indirect winding process step of pulling it into the stator, see (Kampker 2014). These high loads can lead to wire elongation caused by transversal contraction according to (Stenzel et al. 2015b), which may in turn result in poorer resistance and inductance values. In addition, wire crossings occur during the insert of the winding which according to (König 2001) lead to cavities between the windings and layers and thus to reduced performance density or smaller wire diameters. According to (Würfel und Raggan 2014), the wire crossing can blockade up to 20% of the winding space depending on the motor. The mechanical stress to which the winding in operation is subjected, if wire crossings exist, leads also to a reduced life of the electric motor by manufacturing experience (Gröning 2016). For manufacturing of high performance motors, the high requirements in combination with the high wire stresses during the winding and the small process times lead to high rejects rates caused by wire tears due to high process forces.

Additionally, the insert tool has to be adapted to the stator to be wound. Since these tools are very complex single pieces of the highest quality, they come at a very high cost and, the flexibility of such a tool is very poor because it is almost impossible to use these tools for other stator diameters.

Electric motors created by the insert technique implicate very high winding heads according to (Kampker 2014), by which copper is introduced into the motor unnecessarily.

For a direct comparison of direct and indirect winding methods, the studies of (Gerling 2011) and (Inoue et al. 2011) can be used for example. So, according to (Gerling 2011), the losses of a directly wound motor with a concentrated winding of the same weight were 20% lower when compared to a pulled-in concentrated winding in the FTP72 cycle. Hence, it also leads to 10% lower motor costs (due to reduced number of grooves) and to cheaper power electronics (10%). This results in a greater range of the operated vehicle or cost savings in production, according to (Gerling 2012), due to the higher efficiency of a directly wound drive motor of the same weight.

Furthermore, as said by (Hagedorn 2011), up to 50% less copper and up to 30% less stator sheet metal are required for a directly wound small motor to have the same performance. However, this effect decreases with increasing motor dimensions, but it still exists in a relevant size in a traction drive.

With a direct winding much smaller winding heads result, according to (Kampker 2014), so that 20% less installation space is necessary to provide the same performance, as reported by (Hagedorn 2013). Moreover, a directly wound motor generates less heat as per (Stenzel et al. 2014b) due to the smaller winding head and the missing wire crossings inside the grooves while its performance and size remains unchanged.

A last essential advantage of direct winding according to (Hagedorn et al. 2016) is that motors or coils for motors can be wound fully automated with these technologies. Therefore, no subsequent manual work is necessary anymore and man-made errors can be avoided in the wiring.

4.2. Key Know-How for the Various Winding Methods

From a product related technical point of view, a comparison between the direct and indirect winding methods has already been made and, the pros and cons of each method and their effects onto the product have been examined more closely. Also, an introduction to the different winding methods has already been given.

The major challenge in production engineering is aside from the complex equipment cinematics mostly the secure processing of the semi-manufactured good wire. The decisive factor is a comprehension of the wire deformation behavior during winding on the coil bobbin and the existing cross-interactions if the wire with the machine components. This knowledge is currently concentrated with a few employees that deal with wires and winding machines on daily basis. For a deep comprehension of the wire properties it is necessary from a scientific point of view to understand the wire as key semi-manufactured good and its deformation characteristics (Bönig et al. 2015; Bönig et al. 2014; Sell-Le Blanc et al. 2014; Sell-Le Blanc et al. 2013). In order to improve the wire processing based on the deformation knowledge, the challenge of wire tension force control for high speed applications needs to be met with novel actuator and sensor solutions.

But in order to be able to master the production-related challenges for stator and coil winding from an equipment manufacturer's point of view, it is necessary to know all the essential equipment components for the different processes as well as their operation and use. Therefore, the system components for existing winding techniques are described below with the example of a needle winding machine and an insert center with a flyer winding station installed upstream.

4.3. Equipment components for existing winding techniques

According to (Hagedorn et al. 2016), in a classical 2-axes needle winding machine for winding internally grooved stators beside the same or similar machine elements such as machine frame, protective housing, controlling and wire feeding, also system components specifically tailored for that winding task are installed in every machine. That way, different types and combinations of wire brakes and balancing systems can be chosen for the wire drawing control system. There are mechanical and electrical wire brakes and, if necessary, they are combined with a primary or secondary balancing system (Hagedorn et al. 2016). The wire itself is led from the supply spool over guides and pulley onto the wire brake, see (Feldmann et al. 2013), and from there via a possibly existing balancing system through the wire guide (a needle in case of needle winding) onto the stator to be wound.

The insert center with the upstream installed flyer winding station, however, differs in many respects from a needle winding machine. The basic components of a flyer winding station are the same as in a needle winding machine. But the flyer is a so-called template flyer according to (Hagedorn et al. 2016) that has guiding/sliding blocks in the rotation center of the flyer in the form of a template. An inner segment of the tool that is moved close to the stator completes these important tool sets. The guide jaws are adapted to each stator as product-specific tools. The transfer of the individual spools occurs without feed, as stated by (Hagedorn et al. 2016). The last windings of each coil need to be pushed out via a device into the winding tool. The structure of the winding tool is represented schematically in Figure 11: Depiction of the winding tool - own graphic based on where the stator (1) is fixed above the tool. Then the coil (2) is guided through the mushroom-shaped insert tool (3) and drawn via the outer (4) and inner needles (5) into the stator. The insert device itself is mostly controlled by a hydraulic feed axis.

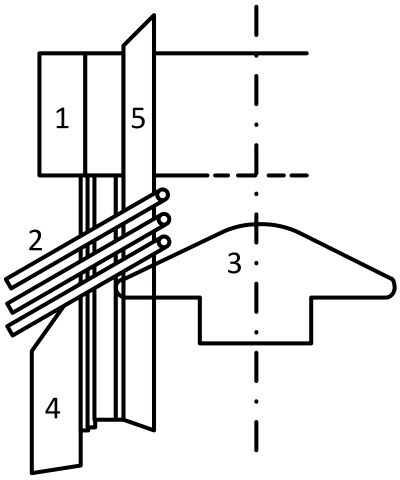

Figure 11: Depiction of the winding tool - own graphic based on (Tzscheutschler et al. 1990)

5. New Approaches in the Winding Technology

Despite its many disadvantages, the insert process is prevalent in producing distributed windings. However, in the last years, there is a trend towards the direct winding of distributed windings with the needle winding technique or with rectangular flat wires for high performance motors.

That way, the needle winding technique offers the possibility of automated wiring the phase conductors and thus a full processing on a machine, according to (Hagedorn 2013). Even the reduction of contact points is obtained by this. In addition, the phase insulation can be regulated with stator end caps as reported by (Hagedorn 2013). One major benefit offered by the needle winding technique is the low stress on the wire during winding or rather the actively controllable wire load by regulated wire brakes. Additionally, a subsequent forming of the winding head is only needed to a very limited extent due to the high level of automation.

This trend is especially visible by the large number scientific publications and the number of patent applications for this method in recent years. From the area of small motor winding technology it is known, that an essential challenge for needle winding is the guiding in the winding head. For small motors this is done by endcaps or end disks. For larger motors this principle can be applied, but is in contrast to the requirement of an increase power density.

That is why (Stenzel et al. 2013; Stenzel und Richnow 2014) present a method that does not require endcaps and thus results in much smaller winding heads in comparison to winding heads that include endcaps. In addition, results of tests performed on prototypes have already been presented by (Stenzel et al. 2014b; Stenzel et al. 2015a) which also show that the patented ideas have been converted into real products.

On the industrial side (Lyschick et al. 2005) described the feasibility of direct winding using endcaps. The current application status is unknown for this patent. As well, a patent registration by (Battista 2015) provides the opportunity to produce internally grooved stators with distributed windings by using a needle winding machine with a pivoting needle. However, the presented process focusses on small stator applications using end caps. Further patent applications from the industry show a trend already back in 2004 for a direct winding application for larger stators. An approach patented by (Walter 2004) describes a process for distributed windings in inner grooved stators with the use of end caps. This approach, however, uses an auxiliary tool for the wire placement in the winding head. The patent was developed further by (Bolli et al. 2007), but the described process is incapable to place the wire directly into the tool on the winding head, cause by the chosen linear movement as degree of freedom. Further information regarding the industrial application is unavailable. Also (Hagedorn und Lüttge 2012) are presenting a possibility to produce distributed windings for internally grooved stators with a 5-axes needle winding machine and the respective winding tool. The presented approach uses a pivoting needle which is linked to the benefit of a direct wire placement in the end cap and already applied in industry according to (Grosse, T., Hameyer, K., Hagedorn, J. 2014).

However, all these patents and the systems resulting therefrom require specific tooling in order to be able to place the single phases inside the winding head, which may in turn lead to higher winding heads according to (Stenzel et al. 2014a).

Aside from research activities by Stenzel, in (Sell-Le Blanc und Hagedorn 2016; Sell-Le Blanc 2016) a winding method with a new kind of tooling that can be unmounted after the winding process and thus generates extremely small winding heads is presented. According to their own indication of source in (Sell-Le Blanc und Hagedorn 2016), also this new development resulted in a patent application and is already available for industrial application. The machine is in addition capable to process 15 parallel wires, which is setting a new standard in regards of productivity for needle winding equipment.

All the approaches described above are showing that the insert technique has lost its exclusive status in producing distributed round wire windings. Compared to the indirectly wound insert windings, the new approaches offer an immense potential because the wire crossings can be avoided that had been already viewed critically by (Kampker 2014, p. 153). Furthermore, a distributed and direct winding can be automated much better than an indirect one due to the controllability of the wire course, as stated by (Hagedorn et al. 2016, p. 212–213). Thus, the contacting processes can also be fully automated as presented by (Schneider et al. 2014).

Based on the mentioned advantages of direct winding methods, it can be said that the needle winding process for the direct winding of distributed windings is a serious competitor for the insert technique. According to (Sell-Le Blanc 2016), a coil section can already be produced in about five seconds providing with up to 15 parallel wires comparable values to the insert technique also in terms of productivity. In addition, with such a technology it would be possible to shorten the process times of stator manufacturing even further without the interruption caused by manual works and to get closer to the cycle times required by the automobile industry.

Another trend that can be observed is the manufacture of coils made of solid conductor material. As already described, the so-called hairpin coils are made of rectangular solid material. Another approach of producing preformed coils is presented in (Bickel et al.) where the coils consist of pressed round wires. In addition, (Stöck 2015a, 2015b) has pending patents on the usage of stranded wire for preformed coils. The manufacturing of continuous hairpin winding on the other hand faces different challenges regarding winding technology compared to round wire winding, in particular for the winding heads the given deformation based tasks cannot be compared to the classical coil winding. This is particularly outlined in the book contribution by (Sadiku und Witt 2009) and the registration of various patents for this technology, i.e. by (Shinichi et al. 2009), (Udea et al. 2004) and (Kaneiwa und Takasaki 2011), which have patented new approaches for the manufacturing of flat wire wave windings, but the status of industrialization respectively the manufacturing solution is currently not known. According to (MBB 2016) first industrial solutions for manufacturing of continuous hairpin windings in series production have been developed.

All these alternative winding methods have very high filling factors in common because the groove space can be perfectly utilized due to the rectangular form of the wire, so that the copper losses can be kept as low as possible.

According to (Ishigami et al. 2015), the continuous hairpin winding shows clear advantages over the conventional hairpin technique since only a few contact points arise. Beside a smaller winding head also the fact that the wiring effort is reduced to a minimum means a great benefit.

The large number of contact points when using the conventional hairpin technique or the pulled coil leads to a high amount of discards during the manufacturing process according to (Ishigami et al. 2014). As stated by (Ishigami et al. 2014), medium and large hairpin stators still need to be manufactured manually because of the still limited automation capacity of the currently available equipment. (Mechler 2010) also notes in his elaboration that the continuous hairpin method offers a higher automation capacity in contrast to the conventional hairpin technique.

So far, these methods have been listed in the specialist books (Tzscheutschler et al. 1990; Hagedorn et al. 2016) under manufacturing processes for coils but they do not belong to the classical winding methods since they are based on a forming process and thus cannot be assigned to the manufacturing process of joining with wire as per (DIN 8593-5). Only the pulled coil made of round wires is wound in a classical way in the first manufacturing step whereas the second step is based again on a forming process.

6. Summary and Outlook

In conclusion, this study has shown that the winding technology is currently a very fast growing industry that meets the challenges of the traction drives with a constant stream of new technologies.

As part of this study, the different electric drive concepts and the associated motors were shown and compared with one another at the beginning. Then, a research of the current products of some selected OEMs has been carried out.

Subsequently, the currently existing winding methods on the market were presented. Advantages and disadvantages of the round wire winding were pointed out and it became clear that the direct winding of electric motors is absolutely competitive compared to the indirect winding and that it offers distinct benefits in many areas. However, it needs to be clarified that each case of application always requires the correctly chosen winding method. Every type of winding has its reason for existence and has to be selected according to the application.

New approaches in the round wire winding technology have been analyzed and it could be demonstrated that the needle winding method with additional axes is a comparable method to the classical insert technique. Finally, also processes alternatives were considered, which cannot be classified as classical round wire winding methods according to (DIN 8593-5) but which due to the many advantages will penetrate more and more the market of winding technology. The combined benefits if hairpin technology with round wire winding technologies are combined in the continuous hairpin technology, which provides a whole new potential.

Summarized it can be stated, that the winding technology is an industrial sector that needs to intensify the cooperation between industry and science in order to meet the challenge of a strongly growing market with new developments that satisfy customer requirements.

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