Fault Analysis of Linear Winding Processes for Noncircular Orthocyclic Coils

Investigation of winding scheme dependencies within the winding process development

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***Abstract* - This paper comprises an overview of different aspects for the development of an orthocyclic winding scheme design. Based on an analysis of the process dependencies, winding faults will be characterized and counter measures will be introduced. It is the overall goal to investigate the use of different process parameters for fault correction and to investigate the parameter dependencies regarding winding speed on the winding scheme. For a detailed process investigation, the application of a multi-body-dynamic simulation will be introduced.**

Keywords – Coil Winding Processes, Orthocyclic Winding Scheme, Noncircular Coil Design

I. INTRODUCTION

The coil winding process is determining the winding properties of electric drives and thus can influence the performance of an electric drive system. From a manufacturing point of view two different types, the distributed windings (fig.1a) and concentrated windings (fig.1.b/c), need to be separated due to their different design and resulting manufacturing processes. But only the concentrated winding is suitable for an orthocyclic winding scheme. This particular scheme enables a high fill factor which is needed for higher power densities, which is why it will be focused in this paper.

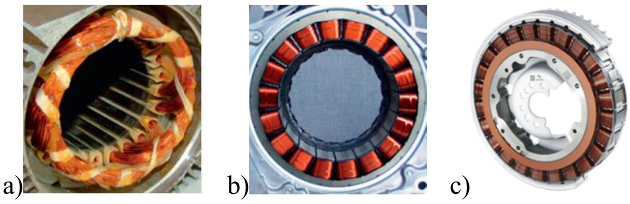

Fig. 1. Display of stator designs with distributed windings (a) and concentrated windings (b,c); Source: a, b - [2], c - ZF AG

A. Area of application for concentrated windings

Although the distributed winding is commonly used for most motors in industry and electric mobility applications, the concentrated windings offer the possibility for different manufacturing processes like direct winding methods which can provide better winding properties, like higher fill factors and improved thermal behavior. Due to this fact and the possibility of an easily scalable winding process they are used in permanent synchronous machines for hybrid electric mobility applications [1, p.35]. The negative electromagnetic properties with higher harmonics in the air gap limit the area of application to small power machines and slow speed operations. The reason is that the magnetic pole width of the machine can't vary much from the coil width. Since a concentrated winding has always a coil span of one, the pole distance is one as well. As a result the number of magnetic poles of the electric machine rises with the diameter of the electric machine. In order to achieve high power densities which are needed for electric traction systems, high speeds are used rather than high torques. The reason is that increased torques need higher overall machinery sizes and thus cause higher costs. Higher speeds however, would cause several fundamental wave frequencies due to the high pole number of the concentrated winding which leads to higher losses and a decreased power density. Due to these reasons concentrated windings are used in gear integrated hybrid electric vehicles which have rather small power densities and a lower operation speed due to the gear. Currently they are used in hybrid electric drives from the companies Audi, Bosch, Daimler, Honda, Porsche, Volkswagen and ZF. The relevant parameters for coils used in hybrid electric stator applications are summarized in table I. Otherwise, concentrated windings are used in machine for automation purposes like stepper motors.

TABLE I; SUMMARY OF RELEVANT STATOR TOOTH PARAMETERS [3]

Parameter	**Value range**	**Tolerance range**
Wire diameter	0.5 mm … 1.5 mm	±0,005 mm … ±0,015 mm
Number of turns per layer	10 … 30	-
Number of layers	3 … 20	-
Electric Resistance	10 mΩ … 1000 mΩ	10 mΩ … 50 mΩ
Inductance	2 mH … 80 mH	-
Aspect Ratio (Width : Length)	1:3 … 1:8	-
Length of bobbin	60 mm … 200 mm	±0,03 mm
Width of bobbin	15 mm … 45 mm	±0,03 mm

B. Resulting challenges for coil winding manufacturing

A benefit of the concentrated winding is the fact of stator segmentation which leads to higher number of equal pieces for every stator and a cost efficiency in production. As a result, productivity of concentrated winding machines must increase significantly in order to fulfill the forecasted automotive quantity demands while ensuring the high automotive quality standards. In addition, the transition from industrial small wire gauge applications, such as ignition coils in combustion engines or motor coils used in pumps, to larger wire gauge applications as traction motors, increases the process complexity. This is caused by a rising influence of the noncircular coil shape and the wire material properties which challenges the winding machine manufacturer. Wire tension control efforts rise, caused by higher coil body geometry aspect ratios and an increased impact of wire deformation effects. Lower productivity and higher efforts are the result. In order to adapt the process to commissioning these new challenges, to ensure the automotive coil tolerance spectrum and provide a sufficient machine output the winding process has to be examined again under the given criterions of wire material properties and the corresponding process parameters. [3]

C. Introduction of the Linear Winding Process

In contrast to the indirect winding processes, like the insert technique, where the wire is spooled onto a carrier and then pulled into the grooves of the stator, direct winding processes comprise the benefit of direct wire handling. As a result of indirect winding processes, the groove space is neither filled completely nor with a scheme. The wires form a winding head outside the groove, which does not contribute to the motor performance but causes additional copper losses and weight. Aside from the described groove fill factor and shorter winding heads, concentrated windings provide a flush winding with better thermal properties. The induced wire stresses during the direct winding process are smaller as well [4]. This is important for the wire diameter, since an elastoplastic deformation of the wire diameter will lead to an increased electric resistance and thus increased copper losses of the motor [3].

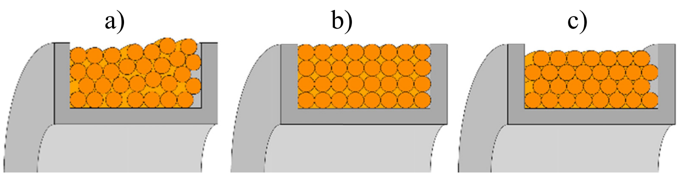

Fig. 2. a) wild winding, b) layer winding c) orthocyclic winding

In order to achieve the desired product parameters with a mechanical fill factor of about 0.65, the orthocyclic winding schematics has to be applied. In comparison to other winding schematics (Fig. 2a,b) it places the upper number of turns in between the spaces from the layer below, which creates a compact winding as displayed in Fig. 2c.

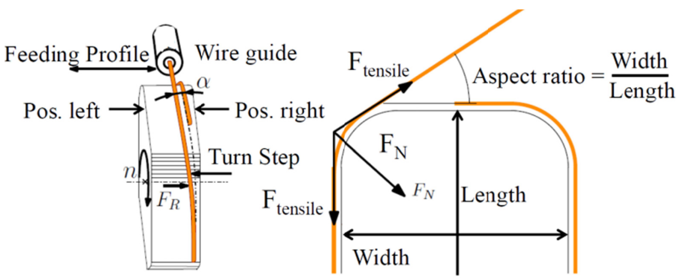

Fig. 3. Schematics of the linear winding process

The linear winding process is displayed in Fig. 3. After fixing the wire at the coil bobbin, a rotation of the bobbin leads to a tensile force, which places the wire around the bobbin. The location of placement is determined through a feeding axis [5]. Aside from the accurate placement of the wire within the winding process high-speed handling is important to assure a considerable machine output. On one hand, speed and accuracy can be assured if the wire is placed on the bobbin using a certain wire tension. On the other hand, the disturbance, caused by the aspect ratio and the winding method, leading to high peaks in the wire tension, as displayed in Fig. 3 on the right, can cause an elastoplastic deformation of the wire. The wire brake has to smooth these tension fluctuations and assure a proper winding quality. In conclusion, a proper wire placement and a steady wire tensile stress are essential for a sufficient winding process.

Since these parameters are dependent on various different influences, current efforts to optimize process and machining technology have reached their limits. Due to the fact that most determining wire parameters cannot be measured within the process, the impact of critical influences in the process, which can differ due to production variations, is thus unknown. Critical parameters can be categorized into machine, process and semi-finished goods like:

- Wire: Diameter, Stiffness, Damping, Friction Behavior
- Coil Bobbin: Stiffness, Surface Texture, Radius of Curvature
- Process: Tensile Force, Castor Angle, Feeding Motion, Winding Speed

II. METHODOLOGY

In order to meet the coil property demands, the fundamental requirement of a concentrated winding is the faultless design of the winding scheme. The orthocyclic winding scheme provides the highest fill factor but challenges the winding manufacturer due to the need of an accurate wire placement on the coil bobbin. The wire placement itself depends on various parameters whose influence on the winding result is mostly unknown. Previous research has determined the importance of the following example parameters and dependencies:

- Wire gauge tolerances and coil body design [6]
- Anti-friction coating [7] and the castor angle α which has been first investigated for circular coils by [9] with a maximum angle $\alpha_{\boldsymbol{max}}$ per wire gauge d_D and coil body diameter d_{Cb}:

$$\alpha_{max} = 51.52 \cdot d_{Cb}^{-0.41} + 11.31 \cdot d_{\boldsymbol{Cb}}^{-0.33} \ln(d_D) \qquad (1)$$

- Wire tension ripples [8]

A holistic approach however hasn't been applied yet, in particular for noncircular coils, which is why this paper will investigate the dependencies of the winding scheme design using the following steps:

1. Definition of winding faults by geometry
2. Categorization of winding fault dependencies into parameters of the process, wire and coil bobbin
3. Characterization of cross-dependencies

4. Evaluation of most influencing parameter dependencies
5. Winding experiment series
6. Analysis of experimental results

III. THEREOTICAL WINDING FAULT ANALYSIS

The presented results for the theoretical analysis of the winding faults are based on a workshop, which has been organized and executed with the winding company Aumann. The results are displayed with a house of quality in table II. At first, possible winding faults were categorized into faults of the electric properties, wire properties, winding scheme properties and the dimensions of the coil, as listed in the first row.

Based on customer needs the faults have been weighted and specified in detailed. The next step includes a categorization of possible influencing parameters display on the left column, which can be divided into parameters of the machine and the geometry as well as the mechanical properties of the wire and coil bobbin. Given the experimental experience of Aumann, the parameters were analyzed regarding their deviation range and assigned a corresponding value between zero and five. The result of the theoretical analysis can be reviewed in the bottom row and the right column. The bottom row is a value in how far the winding fault interferes with the chosen parameters, which is displayed in figure 4

TABLE II; ANALYSIS OF WINDING FAULTS AND INFLUENCING PARAMETERS

				Electric proteries			Wire prop.		Winding scheme			Dimension		
		Winding Fault	Deviation Range (0-5)	Faulty electric resistance	Short circuit	Defective hv-resistance	Wire damage	Wire fracture	Winding scheme (wild)	Loose winding	Concision of winding	Defective outer diameter	Defective inner Diamater	Weighted cross interaction of parameter and winding fault
		Parameter / Weight(1-6)		6	5	6	5	5	5	6	5	6	5	
Process	Machine	Winding speed ramp up	0	1	1	1	1	1	2	3	0	2	0	0
		Machine damping	4	1	1	1	1	1	2	2	0	2	0	244
		Machine intertia	4	1	1	1	1	1	2	2	0	2	0	244
		Castor angle	2	1	1	1	1	1	3	3	1	3	0	166
		Wire feeding speed	2	1	2	2	1	1	3	1	1	3	0	164
		Wire feed turning point	3	1	2	2	1	1	3	3	1	3	0	282
		Exit angle	0	3	3	3	3	3	3	3	3	3	3	0
		Winding speed	1	3	3	3	3	3	3	3	3	3	3	162
	Wire	Wire tension (global)	4	3	3	3	3	3	3	3	3	3	3	648
		Wire tension (local)	5	3	3	3	3	3	3	3	3	3	3	810
		Cross osscilation	3	1	2	2	2	2	2	2	1	2	3	306
		Longitudinal oscc.	3	1	2	2	2	2	2	2	3	2	3	336
		Transversal oscc.	4	1	2	2	2	2	2	2	3	2	2	428
		Free wire length	1	2	3	3	3	3	3	3	3	3	3	156
		Anti frction coating	2	3	3	3	3	3	3	1	1	3	3	280
Wire	Geometry	Outer wire gauge	2	3	1	1	1	1	3	3	1	3	2	210
		Inner wire gauge	2	3	1	1	1	1	3	3	1	3	2	210
		Plastic deformation	4	3	3	3	3	3	3	1	3	3	3	600
		Linear expansion	4	3	3	3	1	1	2	3	3	2	3	524
		Lateral contraction	4	1	3	3	1	1	2	1	1	2	2	368
		Defect of ovality	1	2	1	1	1	1	3	1	0	3	0	72
		Degree of insulation	1	1	3	3	3	3	1	1	0	1	0	86
	Mechanical properties	Wire hardness	1	3	3	3	3	3	3	3	3	3	3	162
		Poisson ratio	1	1	1	1	1	1	1	1	1	1	0	49
		Youngs-Modul	1	0	1	1	1	1	3	1	2	3	3	85
		Failure strain	1	3	3	3	3	3	3	3	3	3	3	162
		0,2% Yield Point	1	3	1	1	1	1	1	3	2	1	2	88
		Tensile strength	1	3	3	3	3	3	3	3	3	3	3	162
		Srping back behavior	2	3	3	3	3	3	3	3	3	3	1	304
		Dynamic bending behavior	2	3	3	3	3	3	3	3	3	3	3	324
		Static bending behavior	2	3	3	3	3	3	3	3	3	3	2	314
Coil bobbin	Geometry	Winding ground	3	0	3	3	3	3	3	1	0	3	0	306
		Length	4	0	1	1	1	1	1	1	2	1	3	252
		Width	2	3	3	3	3	3	3	2	2	3	3	302
		Aspect ratio	3	3	3	3	3	3	3	1	2	3	3	435
		Winding width	3	0	1	1	3	3	3	3	1	3	3	336
		Radius of curvature	3	3	3	3	3	3	3	2	3	3	3	468
	Mech. Prop.	Youngs-Modul	3	0	0	0	1	1	1	1	0	1	3	126
		Mech. stability	4	1	2	2	1	1	3	1	2	3	3	408
		Friction	1	0	1	1	1	1	1	3	2	1	3	75
Cross interaction of a winding fault with parameters				990	1010	1212	930	930	1170	1158	850	1404	1000	

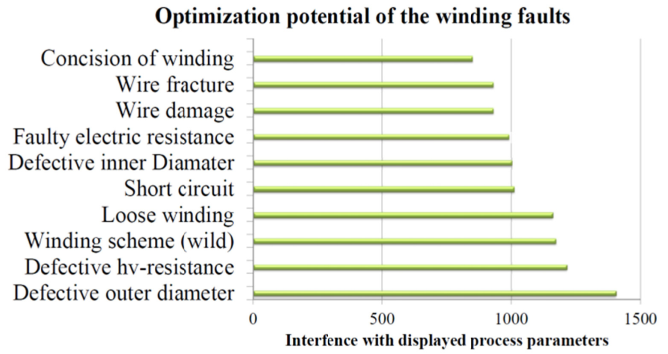

Fig. 4 Intereference of the winding faults

Since the concision of the winding and the wire facture as well as wire damage have the lowest values it could be determined that the wire stresses and a flush winding are the most difficult occurring faults, due to the lack of influencing parameters. But in comparison to the other fault influence values, none of the faults seems to have a significant advantage or disadvantage regarding the process development. The influence of different winding parameters, as displayed in figure 5 shows a more diverse behavior regarding their influence.

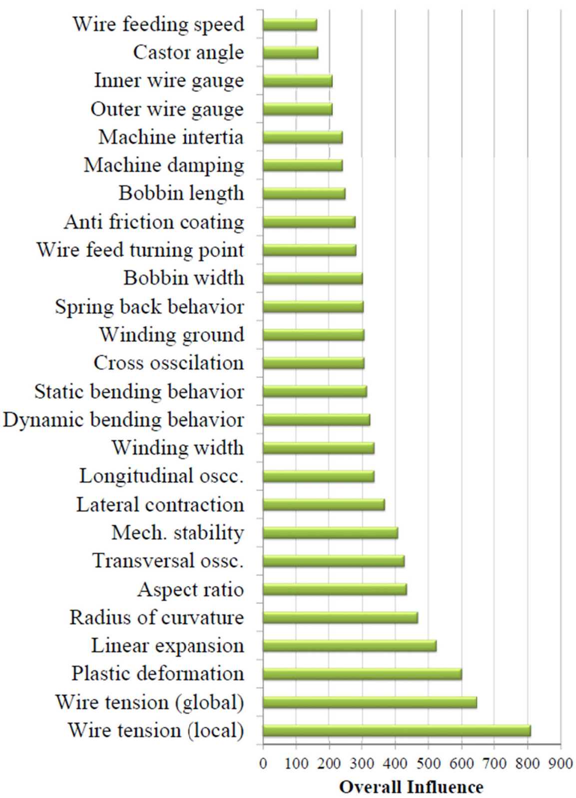

Fig. 5. Influence of the winding parameters on the faults

In comparison to the other parameter, the wire tension seems to have a significant influence on several winding faults. The local wire tension describes a local influence on the wire stresses which can lead to a higher tension than the one that is measured at the wire brake. In particular for noncircular coil bobbins a tension peak is induced by positioning the wire around the coil body edges. The importance of wire tension leads to an importance of the wire deformation behavior which is displayed by the next ranked parameters: plastic deformation behavior, linear expansion, the radius of curvature and the aspect ratio.

IV. Experimental Winding Fault Analysis

A. *Experimental setup*

The experiments were performed using a TW-2 machine from the company Aumann. This linear winding machine is suitable to winding speeds up to 3000 rpm using a maximum wire gauge of 5 mm. For the experiments a coil body dummy was designed according to the values of table III.

Table III; Summary of Test Coil Parameters

Parameter	Value range
Wire diameter	1.18 mm
Number of turns per layer	10
Number of layers	15
Aspect Ratio	1:5
Length of bobbin	120 mm
Width of bobbin	24 mm

Machine settings were defined by the winding area, feeding motion of the wire guide, winding speed and the desired wire tension as a set point for the wire brake. Due to the scope of the investigation a further modification for the experimental set-up was not necessary. In total 228 winding experiments were performed for the 1.18 mm wire gauge in order to achieve an orthocyclic winding scheme for 15 layers at a speed of 300 rpm.

B. *Fault Characterization*

For the experimental fault characterization a geometry based fault description has been used in order to describe the result of each winding experiment. This is based on the assumption that a correct winding scheme will always fulfill the desired values for shape and inductance. The different types of faults are displayed in figure 6.

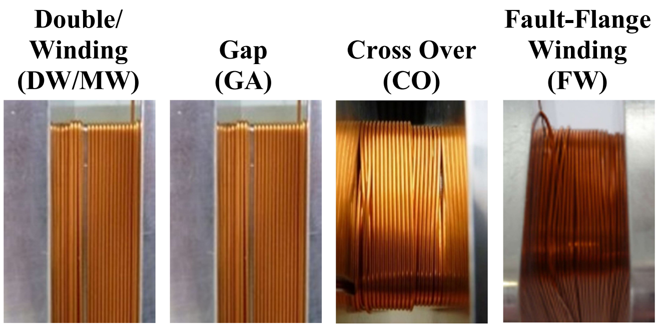

Fig. 6. Display of typical winding faults during the initial set-up phase

A double or multiple winding describes a shift of one or more wires into the layer above. The gap displays the opposite. A cross over describes a change in the wire feeding direction, placing the wire onto the wrong side of the previous turn and thus cross it. The missing flange winding summarizes either a missing or defective first winding in a new layer.

C. *Fault Analysis*

According to the introduced gemeotry faults the winding experiment results were documented, with a statement for each layer. The overall amount of faults and the type distribution over all layers are displayed in figure 7. The most common faults according to this study are the missing flange winding and a double winding. These results match the literature in which it is stated, that the layer step displays the most challenging design aspect for noncircular coil winding schemes in regards to the flange winding. The double winding represents the influence of wire gauge tolerance and other process uncertainties which disturb a correct wire placement.

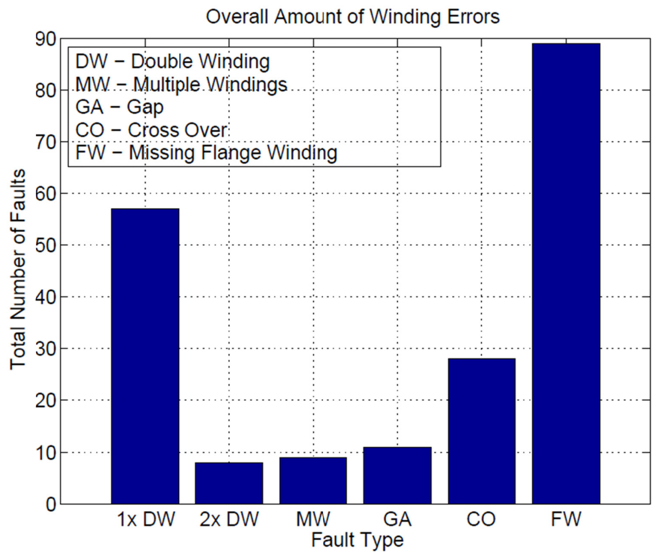

Fig. 7 Fault occurance during winding scheme design process

A layer based fault analysis, as displayed in figure 8, shows that the most difficult layer designs are the first layers due to the strong influence of the radius of curvature of the coil bobbin and the dependencies within the scheme.

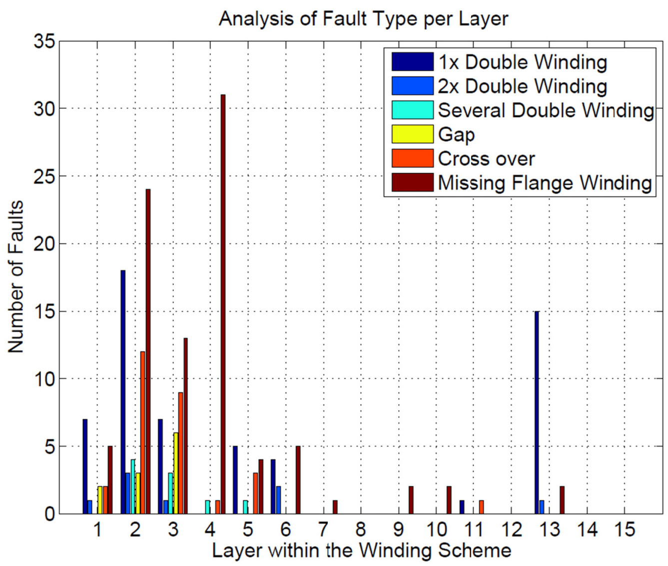

Fig. 8. Layer specific fault occurrence

This explains the high number of double or multiple turns within the first layers. A missing flange winding however, can also occur in higher layers due to the difficulties with the layer step design. A graphic display of the winding surface change with a rising amount of layers is given in figure 9. This results in the fact that for the first layer a separate winding routine with different parameters is used in comparison to the following layers until the final number of turns has been reached.

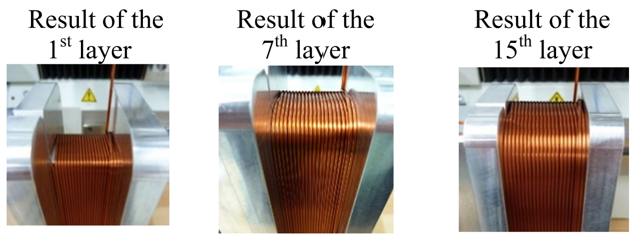

Fig. 9. Change in the winding surface geometry with number of turns

The overall number of faults exceeds the number of experiments due to the fact that faults occur together and can cause each other. Caused by this reason an analysis of possible fault linkages has been performed which is displayed in Fig. 10. Only the combination of two faults occurring in layer together has been investigated. The amount of three fault types occurring in one layer at once was observed to be insignificant. The diagonal row from fault type A and fault type B display the amount of faults by itself. Several statements can be derived from the analysis:

- A missing flange winding will most likely cause another fault due to the missing wire self-guidance
- A cross over is very likely to cause a double winding
- A gap is either cause by a double winding or a missing flange winding
- Multiple windings seem to occur only by themselves

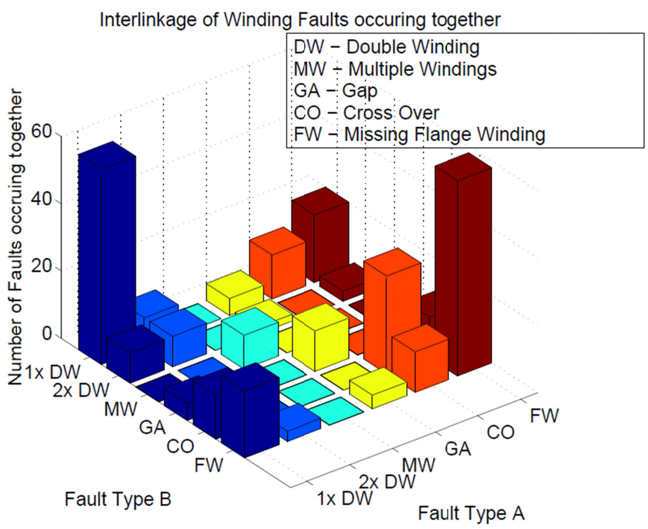

Fig. 10. Fault analysis for interlinkage

- Two double windings after each other will most likely occur with another single double winding in the following winding scheme

D. Fault Correction approches

The next step in the analysis is the investigation of possible counter measures for a fault correction. A change in design of the coil bobbin, the winding machine set up or the wire properties was not considered. Considered parameter changes were the machine settings: position of the winding area on the coil body surface, winding speed n, wire feed motion F and the wire tension applied through a tensile force. The analysis is carried out by a comparison of the fault types per layer and the necessary changes in the machine settings to achieve a faultless orthocyclic layer in the next experimental run. Figure 11 displays the distribution of parameter changes for a fault correction without the needed adjustment range.

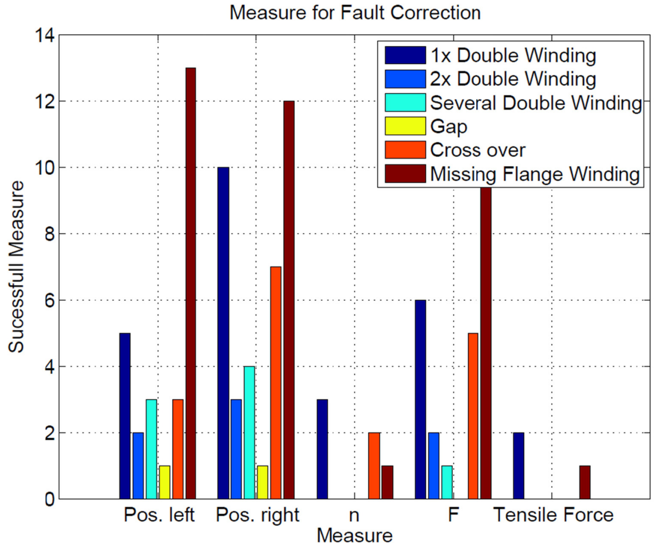

Fig. 11. Successful counter measure for fault correction

Due to the geometric definition of the faults the position of the winding area and feeding motion is essential for a fault correction. But also a change of the winding speed and tensile force can correct an occurred fault which displays a dynamic dependency of the process. The range for a successful correction of the faults is display in figure 12 for the winding position and feeding motion.

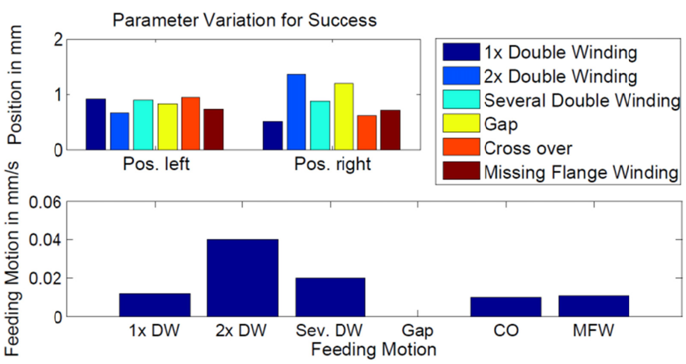

Fig. 12. Analysis of necessary parameter variation for feeding axis

The displayed values are the mean values over all successful fault corrections during the experimental series. Due to the needed change of the castor angle from synchronous, positive or negative position of the wire guide the values reach up to the wire gauge value. The necessary adjustment of the feeding motion is at a speed of 300 rpm only the tenth of a wire gauge and thus more precise and less fault susceptible. Figure 13 displays the adjustment range for the wire tension and winding speed.

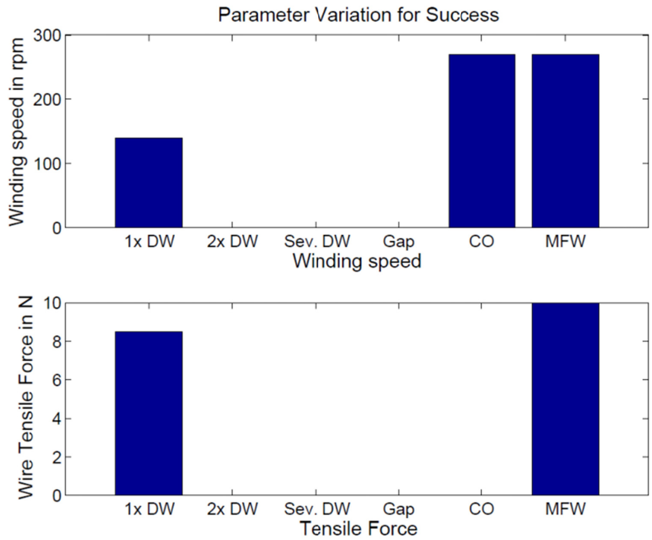

Fig. 13. Analysis of parameter variation for speed and wire tension

An adjustment of the speed has been proven effective if the flange winding is faulty. Otherwise it has been mostly used to determine the cause for certain faults but can also be used for a fault correction. The wire tension usually needs to be adjusted if the wire placement is done accurately by the feeding axis but the position of the wire changes due to lacking tension.

Due to the fact that the parameter change itself does not display the impact of the parameter on the process, a further analysis has been performed using a sensitivity function.

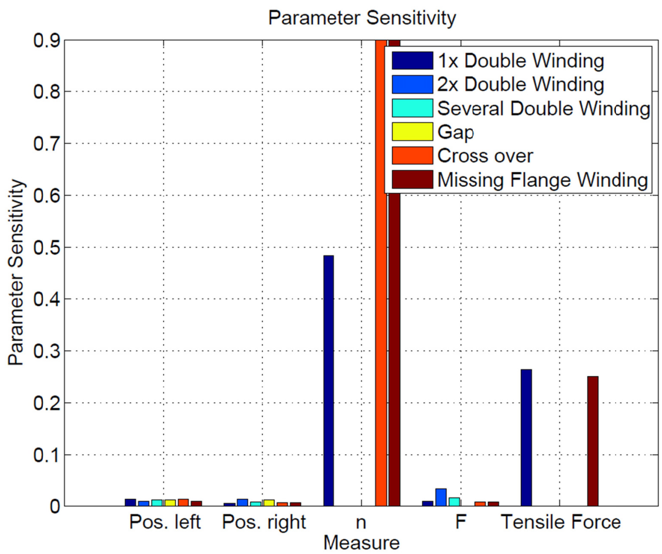

Fig. 14. Fault specific sensitivity analysis of parameter influences

$$S = \frac{\|P_{ok} - P_{old}\|}{P_{old}} \qquad (2)$$

The function is defined as the absolute value of the difference between the working parameter P_{ok} and the faulty parameter P_{old} normalized by the faulty parameter P_{old}. The sensitivity displays how a little change can affect the overall result. The result of the analysis is displayed in figure 14. In comparison to the absolute adjustment range the sensitivity changes the ranking of parameters. It is clear that small changes in the winding speed and tensile force result in large effects for the winding scheme. This result confirms the theoretical statement given in fig. 3 that the wire tension and winding speed are decisive for a fault occurrence and possible counter measures.

E. Speed dependencies of parameters

In the industrial environment higher winding speeds are desired for a higher productivity of the winding machine. Thus, it is the interest of the winding machine manufacturer to characterize the speed dependencies of the orthocyclic winding scheme design in order to achieve a faultless coil design at higher speeds. In order to serve this purpose a final analysis has been performed for a set of successful parameters for different winding speeds. The mean value and standard deviation of each parameter characterize in how far the parameters needed to be adjusted for a higher winding speed. The result is displayed in figure 15 for an experimental series from 30 to 300 rpm. The parameters Δv displays the ramp up of the winding spindle speed and the tilt angle describes the exit angle of the wire when leaving the wire guide. These parameters have been investigated for the previous analysis as well but didn't show any impact.

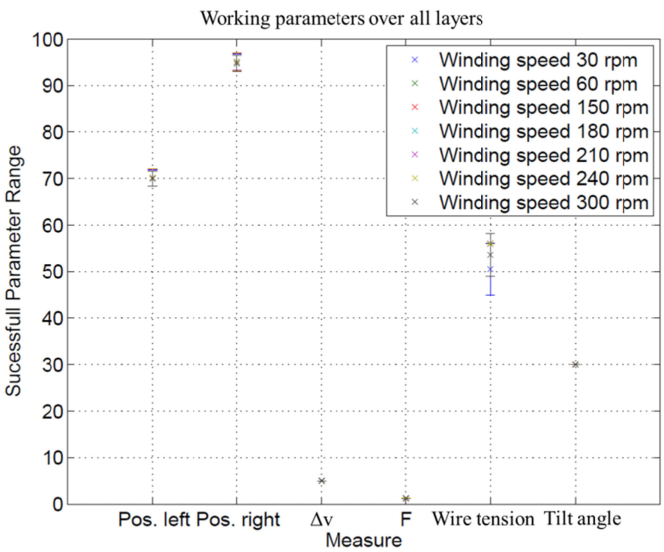

Fig. 15. Speed dependent working parameter ranges

It can be observed that the winding area on the coil and feeding motion seem to stay within their limits almost independent from the winding speed. The wire tension needs to be adjusted in order to achieve higher winding speeds. Generally it can be stated that for higher winding speeds a higher wire tension is necessary which leads to the problem of possible wire deformation and possibly faulty wire resistances.

V. Coil Winding Simulation

Using a design of experiment approach to investigate the mentioned dependencies leads to a high number of experiments and related costs for copper. Due to this fact an investigation method using multi-body-dynamic simulations was introduced in [4]. The wire is described as chain of single copper elements with joints in between them. By characterizing the joints with values for bending stiffness and other deformation related parameters they can describe the bending behavior of the wire during the winding process. A more detailed summary of the wire model was published in [3]. The model boundaries concerning which machine elements were modeled can be reviewed in figure 16.

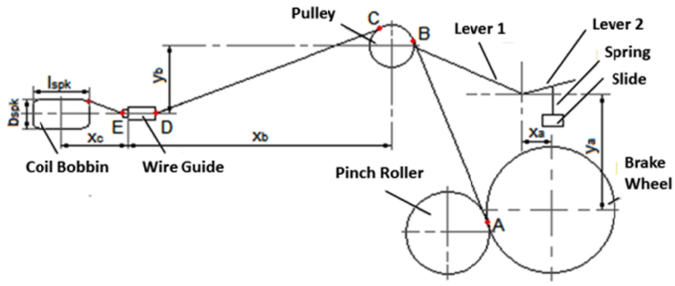

Fig. 16. Coil winding model setup [3]

In addition to the measurements, it is also possible to describe non measurable parameters and thus describe process limitations and dependencies more in detail. In [3] an investigation of the turn step behavior, as introduced in figure 3, was published. The result can be summarized with a Pareto diagram in figure 17. Displayed is the effect of a change in one parameter on the sliding movement of the wire prior the coil body edge.

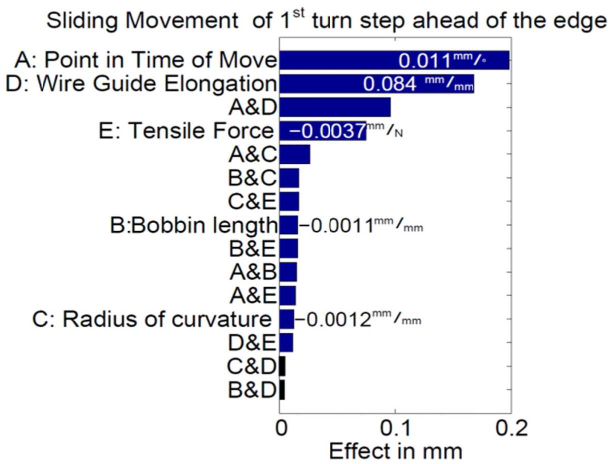

Fig. 17. Investigation of sliding motion for first turn [3]

The importance of the wire guide movement as well as the wire tension have been proved by simulation as well. In case of a digital wire guide movement the point in time for the movement also has its importance. But also the aspect ratio with the bobbin length and the radius of curvature of the coil body edges show some effect.

VI. Conclusion

In order to achieve a faultless production of orthocyclic winding schemes with noncircular coil bobbins different machine settings for different layers need to be applied. The wire tension and winding speed have a large influence on the winding scheme and thus need to be considered separately in the winding design process. A working parameter set for the flange winding is essential in order to use the self-guiding ability of the wire for the further layer development. For winding with higher speeds and thus a higher productivity, an effective wire brake system is necessary in order to apply an increased tension and to even out the tension disturbance peaks induced by the coil body edges. As a result of this paper the belonging parameters for occurring winding faults have been introduced which can help other winding manufacturers to put their machine into the first mode of operation for a new product.

VII. Outlook

The impact of the wire diameter and further parameters that were given in figure 3 need to be investigated and evaluated regarding their sensitivity and ability to improve the winding process. Due to the fact that not all parameters can measured within the process a simulation approach needs to be considered that can describe the parameter cross interaction for the whole winding process. One example for such an approach could be a Multi-Body-Dynamics Simulation that was first introduced by [4]. This approach has been successfully applied for study of the turn step motion which was published in [3].

VIII. Summary

Concentrated windings with an orthocyclic winding scheme are often used in gear integrated hybrid electric vehicles and industrial automation machines due to their high fill factor and excellent heat properties. The growing market for hybrid electric vehicles and the manufacturing friendly design of a stator segmentation increase the need for larger volume production. The linear winding offers a very productive process with low wire stresses and is thus suitable for a production of coils with smaller tolerances. But, the small automotive tolerances demand a further process knowledge in order to achieve the desired product parameters with a high machine output. In order to gain a deeper process knowledge winding faults need to be analyzed and possible process parameter dependencies investigated.

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