Validation of a slot-based High-Frequency Model of a Hairpin Winding Stator in Time-Domain

Silvan Scheuermann, Martin Doppelbauer, Björn Hagemann, Antoine Jarosz, Benedikt Schmitz-Rode

***Abstract*—The winding insulation system of inverter-fed electrical machines is exposed to electrical stress due to unpredictable transient overvoltages. Based on previous works, the present study validates a slot-based HF-hairpin stator lumped parameter model in time domain by transient voltage excitation. Further, different winding schemes were investigated concerning the voltage distribution within the windings. Special interest is given to the behavior at very high frequencies above the resonance frequency. Additionally, an advantageous winding scheme concerning the voltage propagation was identified.**

***Index Terms*—AC machines, Circuit analysis, Electric machines, Impedance measurement, Insulation, Voltage measurement**

I. Introduction

As a consequence of the increasing demand for electric and hybrid-electric vehicles, the need for low-voltage electrical traction drives is undiminished. High volumes require a high degree of automation. Hairpin windings, which avoid complex winding processes are particularly suitable for this purpose. Special requirements are placed on the winding and the complete electric drive train. To increase the power density of the machine, the speed and torque must be increased in very limited installation spaces [1]. Inverters with high clock frequencies are used for the traction drives [2]. The use of fast switching insulated gate bipolar transistors (IGBTs) and metal oxide semiconductors (MOSFETs) in combination with silicon carbide (SiC) and gallium nitride (GaN) materials lead to high $\mathrm{d}u/\mathrm{d}t$ at the motor terminal. These steep voltage edges cause not only overvoltages, but also unevenly distributed voltages in the winding.

Usually, the highest voltages occur in the first or last turns, as shown in [3]. The applied DC link voltage of the converter can be far exceeded. This is caused by the superposition of numerous reflected voltage waves originating from the supply voltage. By reason of the impedance difference between the cable and the machine, the voltage propagation, especially in the first turns, is strongly influenced by the length of the cable [4].

Parasitic capacitances and inductances in electrical machines provide propagation paths for electromagnetic interference emissions [5] and can cause many damaging effects. Bearing currents, motor insulation stress, and other inference with the systems' environment are only a few examples that reduce the reliability of the motor. The voltage load in electrical machine windings or transformer systems [6] can cause partial discharges and therefore must be taken into account when designing the windings. Particularly advantageous winding schemes can help to protect the winding and increase the service life. Thus, it is important to simulate the transient voltage distribution and evaluate the voltage stress of the winding during inverter operation.

A model, already developed in previous work [7] is validated in this study by high frequent excitation of a motor and associated voltage measurements. Further, the available simulation model is applied to different winding schemes and the HF behavior is investigated by measurements and compared with the simulation. Finally, a particularly beneficial configuration can be proposed.

In Section 2 the slot-based HF-hairpin stator lumped parameter model is presented sparsely. The derived high-frequency model of the electrical machine and the determination of all circuit parameters have already been introduced in detail in [7]. The validity of the model was approved by impedance measurements. Section 3 covers the measurement setup and data processing. The main part of this study is presented in Section 4, in which the model is validated in the time domain by a transient voltage excitation and measurements. The following Section 5 applies the model and tests to different winding schemes and the comparison between those is given. Finally, a conclusion round up the study in Section 6.

II. Slot-based HF-hairpin stator lumped parameter simulation model

The proposed model was developed in a previous study [7] to simulate the HF behavior of a stator with hairpin windings. In doing so, it should be possible to analyze the transient voltage characteristics in the entire winding for any winding scheme. The lumped parameter model is implemented in the circuit simulation software LTSpice.

The single-slot level of the developed high-frequency model

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is shown in Fig. 1. To ensure comparability concerning the winding scheme, the simulation model is built on a slot-based domain. These single slots are then connected to represent the corresponding winding. This was done by an automated algorithm to avoid the error-prone and time-consuming process.

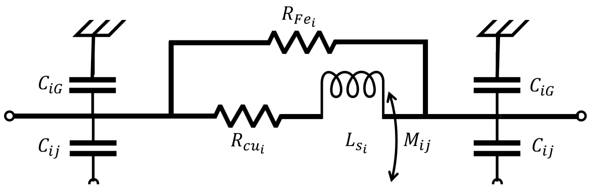


Fig. 1: Single slot level based high-frequency model of [7]

The development of this lumped parameter model to simulate the CM- and DM-impedances is demonstrated in [7]. The single-slot level based high-frequency model contains for each coil-side of the following ideal components:

- Resistance $R_{\mathbf{cu,i}}$
- Inductance $L_{\mathbf{s,i}}$
- Mutual inductance $M_{\mathbf{ij}}$ between coil-sides in one slot
- Two capacitances $C_{\mathbf{iG}}$ respectively $C_{\mathbf{ij}}$ for the stack length.

All elements used in the simulation model are assumed to be ideal without frequency dependency. The overall validity of this assumption has been shown in [7]. The parameters were calculated analytically or derived by measurement. The detailed methodology is also presented in [7]. The measurement setup of the RLC-measurements with a Keysight E4990A Impedance Analyzer [8] is shown in Fig. 2.

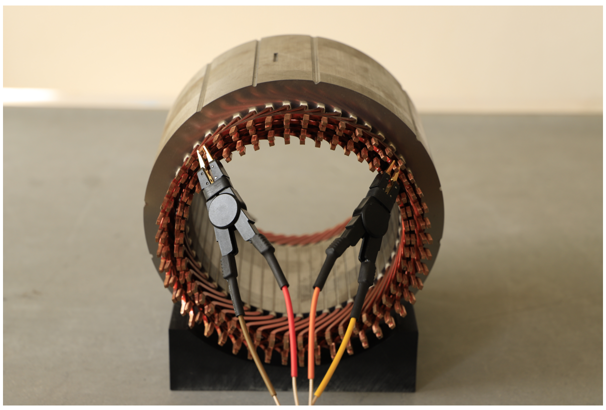
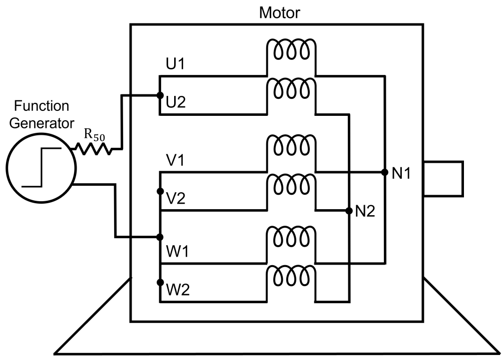


Fig. 2: RLC-measurement setup

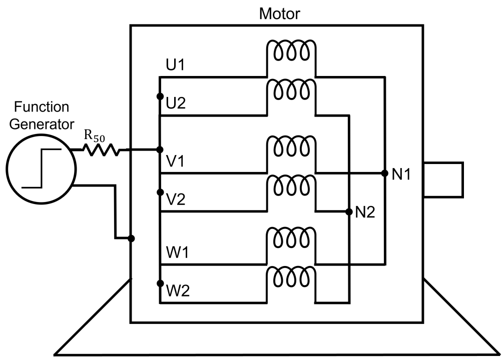
III. Validation of the Model by Transient Voltage Excitation

A. Measurement setup

For the purpose of the validation of the simulation model and to investigate the transient voltage distribution in the motors' windings, a Toellner TOE 7761 Arbitrary Function Generator [9] was used. This voltage source represents the switch-on behavior of an inverter. Consequently, the electrical circuit was excited with an adjustable input voltage in the form of a voltage pulse or a sinusoidal voltage form with variable frequencies. In inverter operations, e.g. automotive applications, different switching states can produce differential mode (DM) and common mode (CM) signals. These two are ensured by different wiring connections of the instruments.
In DM connection, shown in Fig. 3(a), the input voltage is applied between the terminal of phase U and the short-circuited phases V and W. In contrast, Fig. 3(b) represents the CM configuration. The input voltage is applied to all three phases U, V, and W, which are short-circuited; the ground potential is connected to the stator lamination stack.



((a)) Differential Mode (DM) configuration



((b)) Common Mode (CM) configuration

Fig. 3: Measurement setup

In [7], the CM- and DM-impedance measurement results with an impedance analyzer of the investigated stator are shown. The first resonance frequency has been found at around 900 kHz. To investigate the high frequent voltage distribution of the winding, sinusoidal voltage excitations at frequencies above the resonance were set.
For all investigated winding schemes, identical stator lamination stacks with 48 slots and four layers per slot have been used. One stator with hairpin windings has already been available, the other winding configurations have been self-wound with a round wire of 2.24 mm diameter. To check, if the transferability of the results using round wire instead

of hairpins is given, the same windings scheme was wound first. It is referred to as 'WS0' in the following.
Winding scheme 'WS1', which was also wound with round wires, has been identified as best regarding the insulation stress with help of the simulation tool. Both are full-pitched windings using the properties of Table I.

TABLE I: Properties of the winding

Number of slots	N	48
Number of phases	m	3
Number of pole pairs	p	4
Number of layers	n_{L}	4
Number of parallel paths	n_{pp}	2

The peculiarity of the demonstrated winding scheme 'WS1' in this study is the beginning layer of the first strand. While 'WS0' has its terminal connections on the first respectively fourth layer, the terminal connections of both parallel paths of 'WS1' are within the same layer but on different faces of the stator.
In this study, the measurement setup inspired by [10] was used. Consistent with the respective wiring of Fig. 3, the stator windings were connected to the function generator, and at each slot opening, voltage measurements were made. For higher comparability, all measurement data was normalized with its reference input signal, measured at the terminal wire. The setup for the measurements with passive probes is shown in Fig. 4.

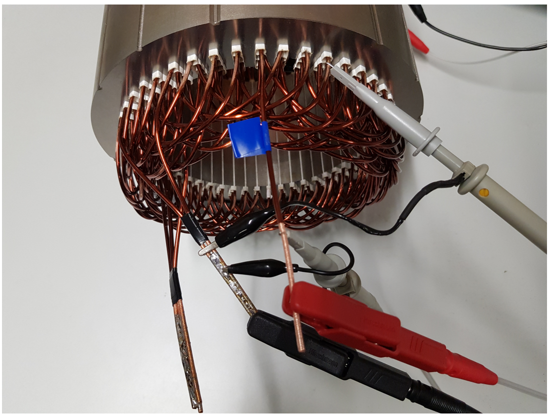


Fig. 4: Measurement setup for 'WS1' in DM connection

B. Processing of the measurement data

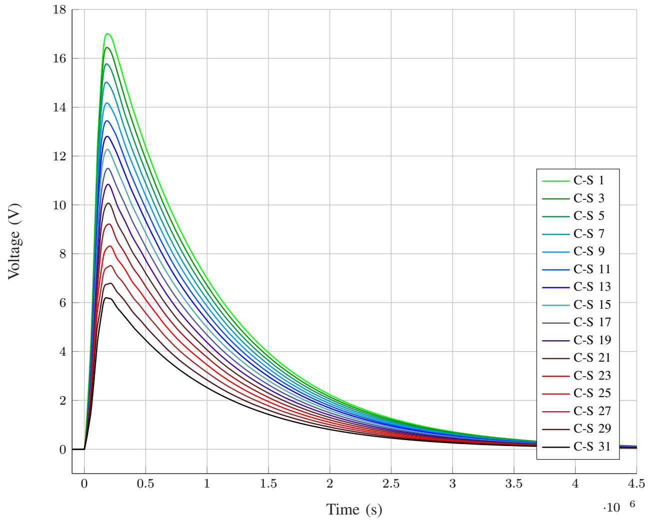
To obtain more valid measurement results with less measurement or quantization noise, especially for step excitation, the measurements were performed with a periodic switching frequency, and further, averaging mode over eight periods on the oscilloscope was set. In addition, the measurement results were preprocessed with a Gaussian filter before evaluation. Eq. (1) was implemented in MATLAB in discrete time with adjustable width and variance of the filter.

$$f(t) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp^{-\frac{t^2}{2\sigma^2}} \tag{1}$$

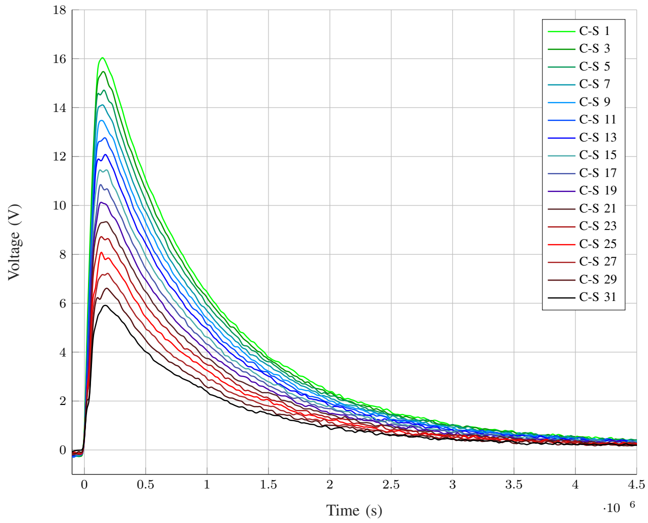
In order not to change the signal energy, the filter is normalized to 1. No padding or clamping is done at the edges, but areas outside the range of values are omitted and the normalization is adjusted accordingly. A Gaussian filter with $\sigma = 6.25$ and 21 grid points was used here. Thereby the curves are not smoothed too strong and the characteristic course and amplitude are preserved.

C. Model validation by step excitation in Differential Mode configuration

For each of the measurements, the corresponding simulations were performed with identical parameters. Fig. 5 presents the simulated and measured results.



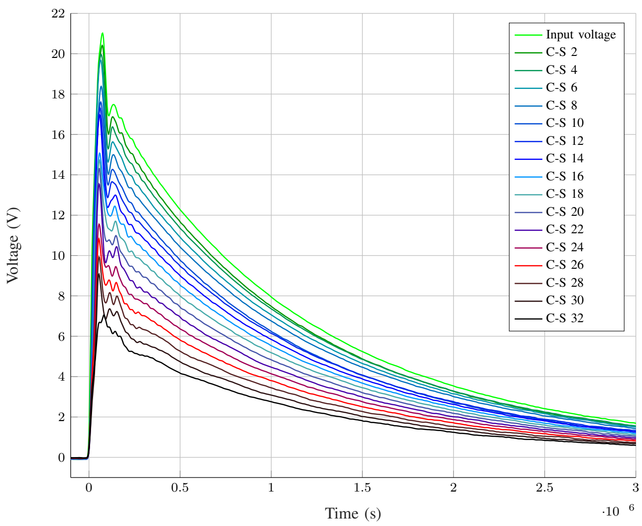
((a)) Hairpin stator 'WS0' simulation - DM-Step-Excitation



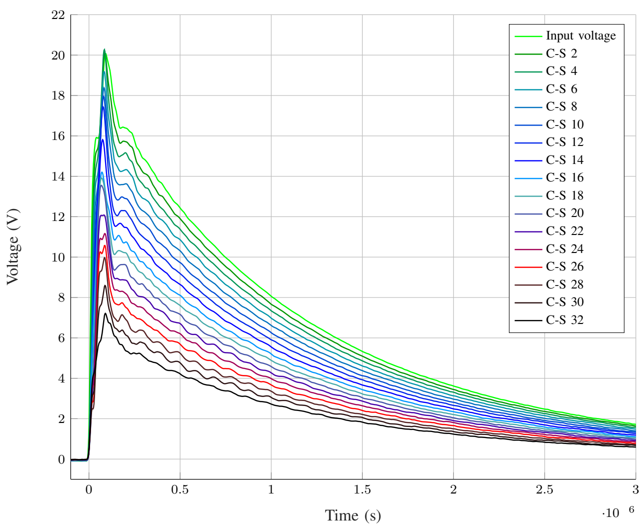
((b)) Hairpin stator 'WS0' measurement - DM-Step-Excitation

Fig. 5: Simulated and measured voltages at different coil-sides (C-S)

The winding was excited by a voltage step with U_{in} =20 V_{pp} and a rise time t_{rise} =10 ns. It is shown, that in both cases, the voltage initially increases steeply and decreases exponentially. Due to the negligible resistance of the winding, compared to the internal resistance of the function generator of 50 Ω, the voltage drops to a negligible steady-state final value. Thus, the curves are mainly determined by the inductance.
Further, Fig. 5 indicates an overall agreement of the simulation model, not only in the frequency domain as shown in [7], but also in the time domain it is adequate to predict transient effects.



((a)) Round wire stator 'WS0' measurement - DM-Step-Excitation



((b)) Round wire stator 'WS1' measurement - DM-Step-Excitation

Fig. 6: Simulated and measured voltages at different coil-sides (C-S)

Only a difference by approx. 1 V in the amplitude of the voltage can be observed.

To validate also the agreement of the substitution of the hairpin coils by round wire, Figs. 6(a) and 6(b) are presented.

IV. Simulation and Experimental Result

A. *Step excitation in Differential Mode configuration*

Comparing Figs. 5(b) and 6(a), it can be noticed that the round wire winding has higher voltage overshoots than the original hairpin stator. This is explainable with help of impedance measurements. It can be noticed that these windings have smaller winding-stator capacitances C_{WS}, which results in a higher resonance frequency. The direct comparison of the voltage curves of both round wire winding schemes in Figs. 6(a) and 6(b), 'WS1' exhibits lower voltage peaks than 'WS0'.

B. *Step excitation in Common Mode configuration*

Without referencing, it can be concluded, that there is also great consistency between the simulation and measurement results in Common Mode configuration. The voltage rises to a steady-state final value with a certain time constant. This progression is mainly influenced by the winding-stator capacitance C_{WS}.
In the Appendix (Section VII), the measurements of the different stators in CM configuration are given (Figs. 10 to 12). The individual curves intersect after a half-wave at approx. 0.25 µs. This corresponds to a frequency of 2 MHz. The superimposed waves are caused by the resonance frequency in CM configuration, determined by impedance measurements. In the voltage over time measurement curves, directly at the beginning at approx. 0.05 µs a voltage peak is present. It can be assumed that the high resonance frequency of the windings' terminals or the differential probes is its cause.
The measurement results of the round wire windings indicate the significant influence of the smaller winding-stator capacitance C_{WS} in comparison to the original hairpin winding. A higher resonance frequency causes a superposition of high-frequency oscillations in the voltage rise.
It is presumed, that primarily these high-frequency voltage oscillations are implicated as harmful and responsible for the insulation damage caused by voltage stress. To investigate these interesting phenomena, the windings were excited with high-frequency sinusoidal voltages.

C. *Sinusoidal excitation*

To investigate the very high-frequency behavior of the stators' windings directly, they were fed with sinusoidal voltages of different frequencies. For higher comparability, the results must be normalized to the input voltage. Fig. 7 represents the under-resonant voltage excitation in DM configuration and f_{in} =500 kHz.

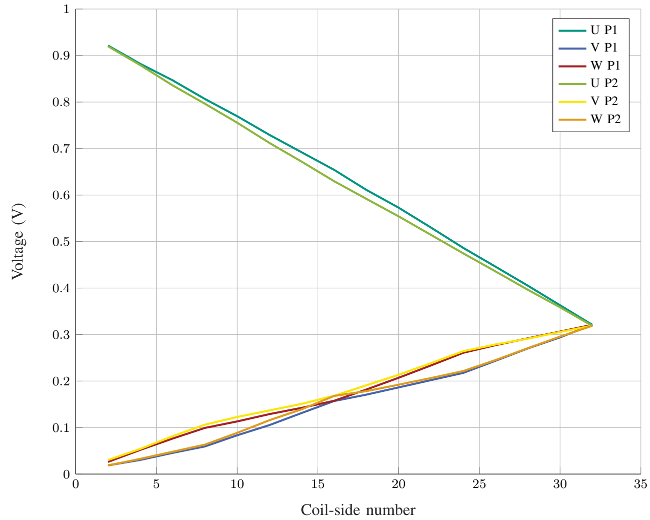


Fig. 7: Hairpin stator 'WS0': normalized DM-measurement result (f_{in} =500 kHz)

Below the resonance frequency of approx. $f_{\text{res}} \approx 900$ kHz (proved in [7]), at all different frequency levels, a uniform linear voltage drop across the windings or rather the inductors was measured. However, if the frequency is increased above the resonance frequency, the voltage distribution changes significantly.

In the over-resonant case, the voltage distribution is strongly non-uniform. Capacitive couplings between the coil-sides C_{ij} and between winding and stator lamination stack C_{WS} occur, which gives the CM configuration a higher weight of interest. Fig. 8 represents the voltage distribution after over-resonant excitation in CM configuration.

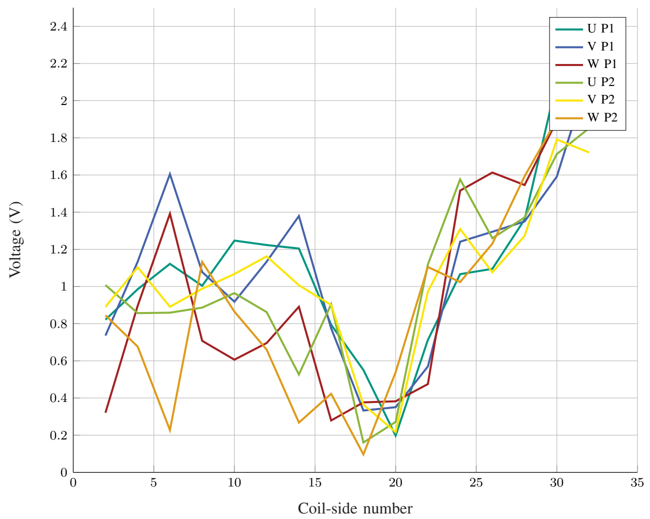
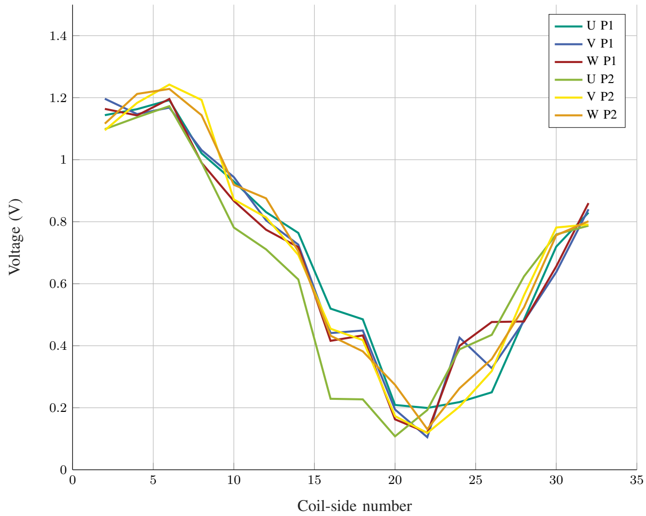


Fig. 8: Hairpin stator 'WS0': normalized CM-measurement result (f_{in} =10 MHz)

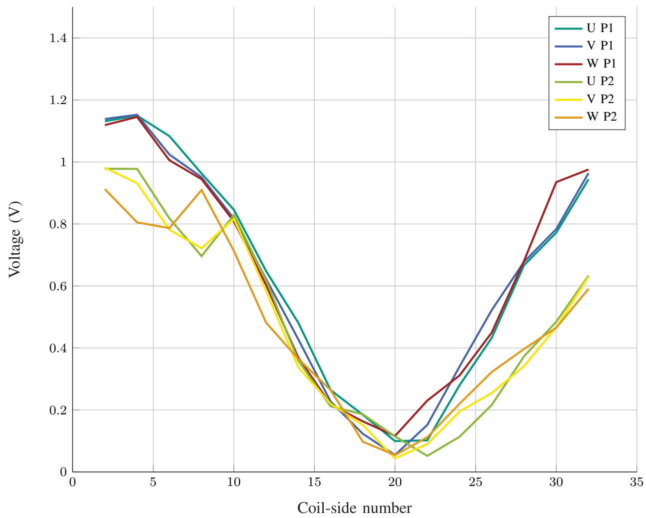
Besides a non-uniform voltage distribution, the measurement, as well as the simulation model reveal low voltages in the midpoint of the winding at coil-side number 16. At this position, jumpers of the 4-layer winding are located. The winding changes its turns from layers 1-2 to layers 3-4 or rather inversely for the second parallel path.

V. Investigation of an Alternative Winding Scheme

The previously presented methodology has been applied to different winding schemes. The validation of the substitution of the hairpin coils by round wire is already presented in Figs. 6(a) and 6(b). The input voltage has been modeled with a sinusoidal excitation of different frequencies. The simulation and measurements of the voltage stress have been performed in both, CM and DM configurations. In Figs. 9(a) and 9(b) the voltage distribution after over-resonant excitation, f_{in} =10 MHz, in CM configuration is shown.



((a)) Round wire stator 'WS0'



((b)) Round wire stator 'WS1'

Fig. 9: Normalized CM-measurement result for both winding schemes (f_{in} =10 MHz)

The relevant magnitude to investigate the voltage stress of the insulation system is the voltage difference between the coil-side of two layers but also the maximum absolute voltage caused by voltage overshoots. The evaluation was executed in tabular form.
To summarize the analysis, the critical insulation stress was identified, if the sequence number difference between coil-sides of two layers in one slot is high.
In the under-resonant case, the location was identified as near the terminals. By reason of the winding symmetry of this special winding scheme ('WS0'), the first and last coil of the two parallel paths lie next to each other, hence the sequence number difference is at maximum.
The over-resonant excitation determines the location of the jumpers as critical, where the winding jumps from layers 1-2 to layers 3-4 for the next revolution.
The improvements applied to the optimized winding schemes (e.g. WS1') are mainly the jumper lengths and the terminals' position and further the sequence number of the windings itself.
By simulations, it was observed that 'WS1' has the lowest insulation stress between adjacent coil-sides in both, CM and DM configuration as well as a particularly uniform voltage distribution. Regarding short-pitched windings, it was seen that high voltage differences between two adjacent coil-sides of two different phases can appear.
An increase to four parallel paths shows particular optimization potential, expected from other variants with the number of parallel paths as another degree of freedom in the windings' design.

VI. Conclusion

A high-frequency model for a hairpin winding stator on a slot-based approach has already been introduced in [7]. The validation of this model in the time domain has been shown in this study. The correlation between the simulated and measured voltage distribution shows high accuracy. Hence, the model can be directly applied to evaluate the voltage stress of the insulation system within a stator lamination stack. Further, it is useful to identify critical stress locations and can be used to optimize the winding scheme itself.
For the objective to investigate the influence of the winding schemes on the transient voltage distribution, two stators were wound by hand with round wire. One with the same winding scheme as the available series hairpin stator, another was identified as beneficial in simulations. For every winding scheme, measurements data were collected and compared with the simulations. It has been demonstrated, that the transient excitation of the windings and the resulting voltage distribution show great similarity for both coil shapes. It can be concluded, that for voltage surge studies, the replacement of hairpin coil shapes by round wire due to easier prototype manufacturing and handling is valid. Another result is the identification of a beneficial winding scheme by application of the developed methodology.
Based on this study and previous works, the next improvement of the model must conclude the calculation of the lumped parameters on basis of geometric data, e.g. with the help of numeric or analytical approaches. The identification of high-frequency effects and insulation stress in motors also regarding partial discharge machining in insulation systems in early motor design stages is considered as a key objective.

VII. Appendix

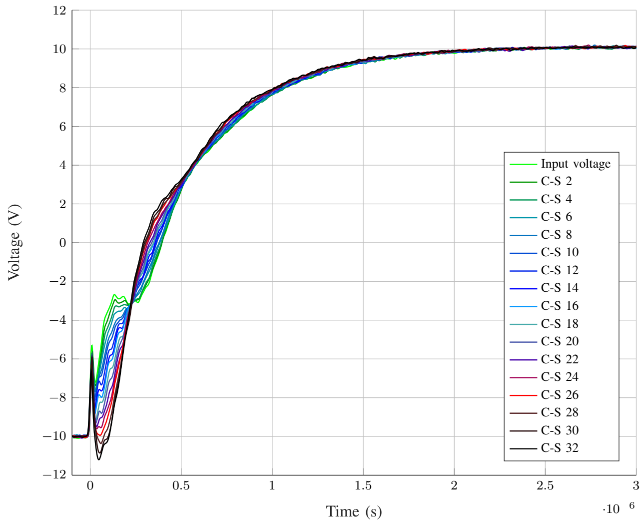


Fig. 10: Hairpin 'WS0' measurement - CM-Step-Excitation (U_{in} =20 Vpp)

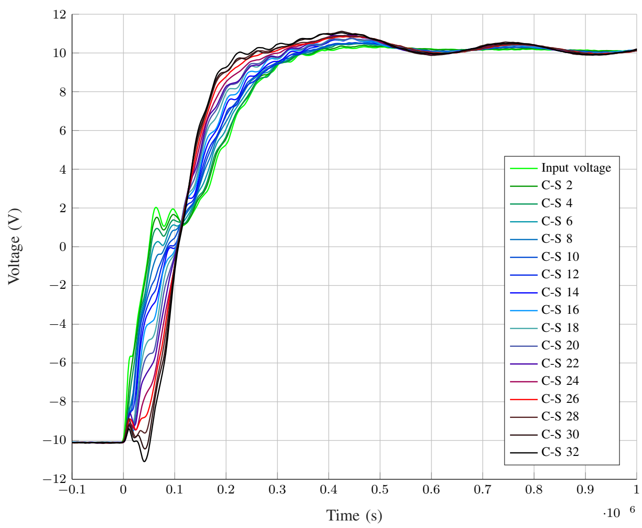


Fig. 11: Round wire stator 'WS0' measurement - CM-Step-Excitation (U_{in} =20 Vpp)

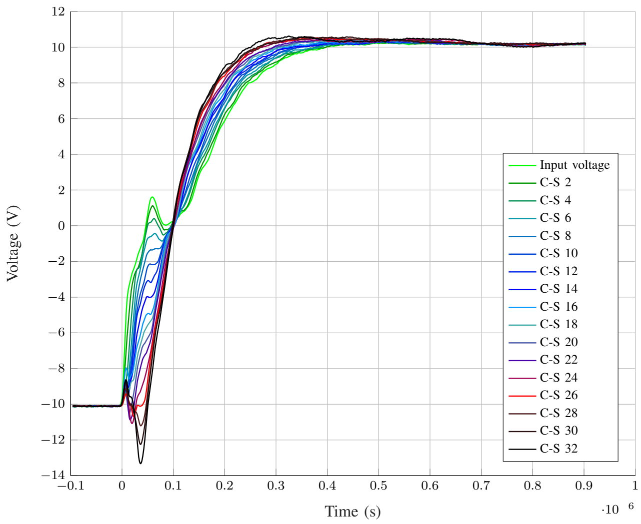


Fig. 12: Round wire stator 'WS1' measurement - CM-Step-Excitation ($U_{in} = 20$ Vpp)

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VIII. BIOGRAPHIES

Silvan Scheuermann was born in Pforzheim, Germany. He received a bachelor's degree in mechanical engineering and a master's degree in automotive engineering from the Technical University Munich (TUM) in 2015 and 2020, respectively. He is currently working as a research associate in electrical engineering and information technologies at the Karlsruhe Institute of Technology. His research interests include investigations, modeling, and beneficial design of electrical machines as well as measurement-based determination of parasitic effects.

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Benedikt Schmitz-Rode graduated at Karlsruhe Institute of Technology (KIT). He is currently working as a research associate in electrical engineering and information technologies. His research interests include modeling, control and monitoring electrical machines and inverters.