High-frequency motor modelling: Parameter variation due to manufacturing

Karel Vanthuyne, Mehmet Gulec, Peter Sergeant

Abstract – **In this paper, high-frequency (HF) modelling of electric machines with random wound distributed windings is investigated to highlight the parameter variation due to the manufacturing. HF modelling of electric machines can be performed by impedance measurements of the stator windings. The random wound windings introduce variability in the motor model limiting parameter estimation accuracy. These parameters are the following: series resistance, main inductance, skin effect and capacitive coupling of individual turns in the windings and from the windings to the frame. By measuring the impedance of the 3-phase windings of seven consecutively produced induction motors the variability due to the random wound windings can be studied. These seven motors are then compared to one another and to an eighth motor that was produced at a different point in time. From this it is illustrated that the behavior varies even when motors were produced consecutively.**

Index Terms—**Distributed windings, High Frequency, Induction motor, Manufacturing variation, Electric-motor modelling, Permanent magnet motor, Stator windings, 10 MHz RLC-measurement**

I. Introduction

DUE to the increased use of inverter drives and fast switches in these drives, damage and behavioral studies are increasingly important to accurately represent electric motors [1]-[2]. Inverter driven electric motors are subjected to PWM signals containing steep flanked pulses, these pulses can cause winding insulation and bearing damage. Simple motor models include the main inductance and stator resistance, optionally skin effect can be modelled as well. The PWM switching frequency is even higher in the kHz range followed by the steep flanks of the PWM pulses themselves containing even higher frequency components. To include the higher frequency components, the low-frequency (LF) motor models need to be expanded to include HF components.

Many HF motor modelling strategies and equivalent schemes can be found in literature to describe the behavior of distributed windings. These models have been designed for varying bandwidth, starting from DC or a couple of kHz as the lowest frequency and 10MHz or even higher as the maximum frequency. These models focus on describing the behavior of one particular motor or motor type. In this paper, the focus is shifted from finding a suitable model to studying how the fitted parameters and behavior varies in between motors due to manufacturing tolerances or chosen construction. For example random wound distributed windings commonly used in induction motors and (permanent magnet) synchronous motors have varying parameters due to the random wound nature of the windings. The random wound windings will be studied in particular in this paper.

These HF models can be used to simulate surge response of a motor, design line filters to decrease peak voltage load and simulate operation when driven by power electronics more accurately. For this models and data fits can be found in literature as mentioned before, but according to the authors knowledge, no work has been done before to study the applicability of these results to other motors considered identical as they have been produced together and/or carry the same name tag and data. The aim of this paper is to demonstrate the variation due to manufacturing variability inherently coupled to the design choices.

The paper is structed as follow: In the first section, a short overview is explained for the major differences and possibilities related to the model choice. Next, HF models are explained. The 3rd section covers the measurement equipment. In the next section, motor parameters of random wound coil is explained, the HF measurement results are given and a datafit for all models is given.

II. HF Modelling

As described in the introduction, numerous HF electric motor winding models exist with varying complexity [3]-[18]. HF modeling and application approach is described in Fig. 1 for the major differences and possibilities related to the model choice. HF modeling approach consists of 5 phases: (1) motor, (2) measurement, (3) model, (4) comparison and (5) simulation. The 1st part covers the motor type to be modelled, in this case a motor with random wound distributed windings. This type of windings can be found in induction motors and (permanent magnet) synchronous motors From this the measurements can start (2nd phase), the measurement method depends on the available connections in the terminal box. If the motor can be reconfigured star-delta, each phase can be measured separately, preconfigured motors require post processing to identify the individual phases. Preconfigured motors with a fixed star or delta configuration reduce the amount of measurements that can be performed and thus the accuracy of the model, this can be seen as there are less connections available in the terminal box to measure at. In a 3rd phase the model is chosen to fit the motor winding impedance. This choice is based on the winding type e.g. (preconfigured) star-delta and the observed impedance

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obtained in phase (2). These models can vary in complexity as will be described in III. Once the motor winding characteristic has been measured and modelled as described in phases (2) and (3), different motors can be compared (4^{th} phase). For this the raw data obtained in phase (2) is preferred as the datafit performed during phase (3) introduces additional variability. Once sufficient motors with identical nameplates have been measured, statistics can be applied. Based on the data of many motors, and average motor characteristic can be determined combined with a deviation or alternatively 5^{th} percentile parameters can be determined. 5^{th} percentile parameters lie towards the extremes of the observed behavior, in phase (5) this data can be used for lifetime estimations. The 5^{th} percentile data, least favorable for lifetime, can be used to estimate the lifetime of that particular motor. This way, 95% of motors will have a better lifetime as they have more favorable parameters. What are considered favorable parameters is out of scope for this paper and depends on the lifetime aspect considered, e.g. inter turn discharges, turn to frame discharges, bearing currents, …

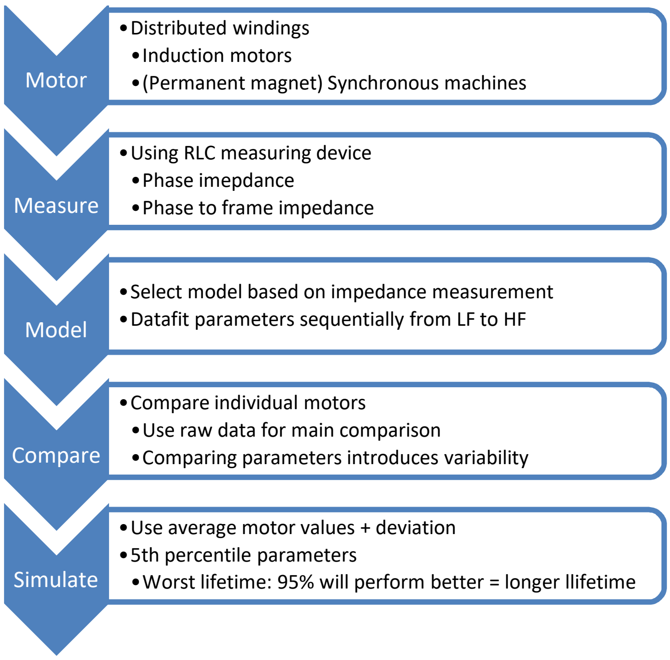


Fig. 1. HF modeling approach.

III. HF MODELS

HF models can vary in complexity and frequency range, focusing only on the high frequency range or including the low frequency components as well. The complexity can be varied by modelling the stator coil as one single piece coil on the low complexity end, modelling the individual coils present in the motor in a series-parallel configuration gives a medium level complexity while modelling each individual turn of the windings gives the highest possible complexity.

1) Frequency range

HF modelling can include low-frequency components as well, namely the main inductance and DC resistance of the stator windings. If the focus lies on HF behavior, these components can be omitted to reduce complexity and thus simulation time.

The highest required frequency depends on motor power as illustrated in [3], the resonance peak is determined by the winding inductance and the capacitive coupling to the stator which scale with motor power. As a result, it can be deduced from [3] that the impedance resonance peak occurs at higher frequencies with increasing motor power.

2) Low complexity models

Various low complexity models can be found in [3]-[13]. RLC components are used to represent at least 2 or 3 main components based on physics. First, the main inductance and DC-resistance are modelled by an *RL* component, this can be omitted if only the HF behavior is modelled and thus RLC-measurements are performed using a higher starting frequency. The modelling of the HF components can be done by the investigation of the skin effect as a parallel *RL* component if the main inductance is modelled as well, the capacitive coupling is either modelled as two capacitors to ground to form a Pi-scheme or an equivalent parallel capacitor. Depending on the motor winding topology, components can be added to increase the accuracy of the fit, further refining the model of the previously mentioned components.

3) Data fit low complexity models

RLC-measurements provide impedance and phase angle or real and complex components of the impedance as a function of frequency. Performing a data fit can be done stepwise in frequency bands, starting with a DC measurement the DC-resistance can be determined. The main inductance of the stator windings can be found in the DC till 50-60 Hz band, these low frequency components can be kept fixed at high frequencies. As mentioned earlier, the impedance resonance peak shifts with the motor power and therefore no predefined frequency can be given to fit the skin effect and capacitive coupling components. As these occur at increasing frequencies and in clear frequency bands, data can be used when their behavior is dominant to perform data fits.

4) Medium complexity models

Increasing the complexity can be done by using multiple models similar to the low complexity models in a series parallel configuration representing the physical coil packs present in the motor [9], [11]-[13]. The added complexity allows for modelling of the coil-to-coil resonance inside the stator windings and gives a better representation of the voltage distribution inside the stator windings during transients. Using these models based on RLC-measurements is not as straightforward as with the low-complexity models.

The same RLC-measurement data is available for medium and low complexity model data fits, medium complexity models also require knowledge of the coil configuration inside the motor and possibly additional information of the individual coils if not identical.

Once the stator coil layout is known, the medium complexity model can be created. It is clear that this type of model will have a multiple of the low-level model parameters that need to be fitted. For this, assumptions need to be made lacking measurement points. If all coils are intended equal by the design, this can be assumed the case for modelling as well. In this modelling approach, the interaction between coils is neglected as in practice these are coupled magnetically and capacitively if they share a slot or lie close together at the stator ends.

5) High complexity and hybrid models

Complexity can be increased even further by modelling each individual turn present in the stator as mentioned in [9], [14]. For medium complexity models, this requires additional measurements or valid assumptions to fit the increasing number of parameters due to model refinement and interaction of the individual turns that should be modelled to obtain representable results. [15]-[18] opted for a hybrid approach by modelling the turns of interest individually and lumping the remainder of the stator windings in a low or medium complexity model. In these publications, the model parameters for the individual turns were obtained by using finite element models and form wound coils or careful measurement of the actual wire position in the slot. Without additional measurement points, it is deemed infeasible to use these models based on RLC-measurements of the entire winding at once.

Hybrid models are a good way to limit the model complexity while still providing sufficient insight in for example the first turns of the windings during surge loads or PWM pulses in case of an inverter fed motor.

IV. RLC Measurement Device

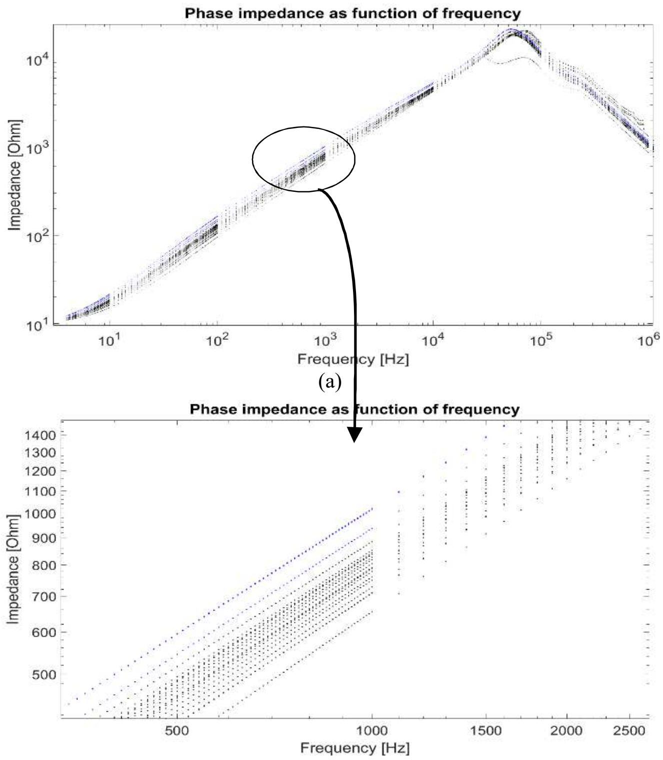
The measurements performed are performed using a Hioki IM3536-01 RLC measurement device to characterize the motor windings. This device is capable of measuring impedance at a DC level and in a 4Hz to 10MHz frequency band. The optional L2000 probes are used in order to get close to the terminal box of the motor. The L2000 has been validated for using up to 10MHz by Hioki. The measurement setup using RLC meter is given in Fig. 2. On the left side of the figure, a 750W induction motor is situated. The IM3536 has an overall accuracy of ±0.05% on the impedance and ±0.03° on the phase angle over the entire frequency band according to Hioki.

Fig. 2. Measurement setup using Hioki IM3536 and L2000 probes.

V. Random Wound Coil: Motor Parameters and Measurement on 8 Induction Motors

As illustrated in [15]-[17], the position of the individual conductors in the stator slot determines the capacitive coupling of the turn to the stator iron. Combined with the relative position of the individual conductors which affects the turn-to-turn capacitive coupling. The HF behavior of the windings is affected by the position of at least the first and last couple of turns of the windings. Especially at higher frequencies when the capacitive behavior dominates the equivalent impedance, this determines the equivalent capacitance.

Due to the random nature of random wound windings, this results in varying HF and LF behavior of motors that can be observed in the impedance measurement of the number of 8 750W induction machines (one is shown in Fig. 2). The 3 phases of each machines were measured individually and plotted separately. The variation of the impedance by frequency for induction machines are given in Fig. 3. The Fig. 3-(a) shows the results in full frequency range of 4 Hz to 1 MHz while Fig. 3-(b) shows the results around 1 kHz to better demonstration of the difference of the phases. Seven motors have consecutive serial numbers, while number eight was produced in a different batch and is thus plotted in blue.



(b)

Fig. 3. (a) Variation of impedance by (a) full frequency range for 750W induction machines and (b) focusing around 1kHz frequency. Motor number eight shown in blue is of a different batch.

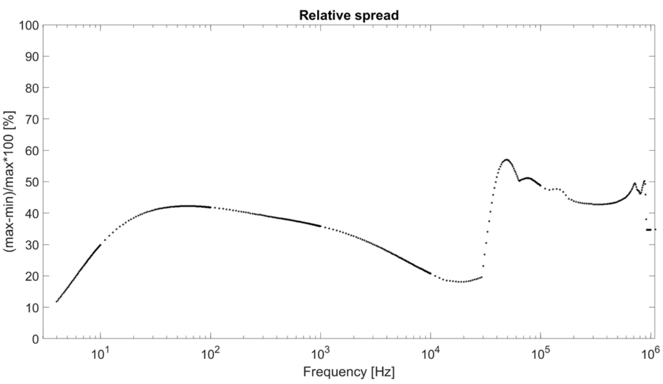
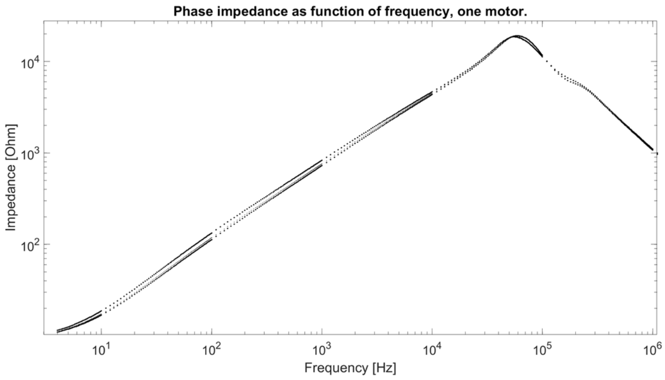
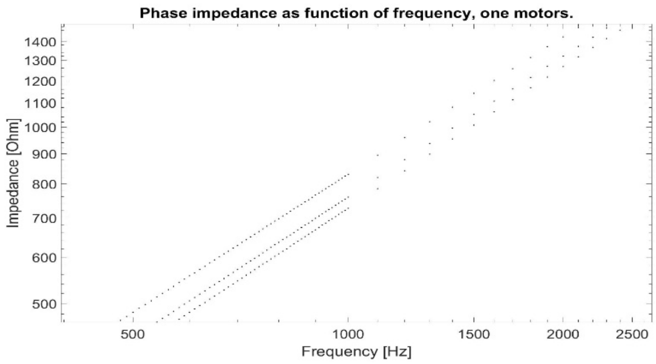


Fig. 4. Data spread of the individual motors plotted in Fig. 3, for each frequency the difference between highest and lowest value is compared to the highest one.

Comparing the lowest impedance value to the highest, the relative spread can be compared to the accuracy of the measuring device and is shown in Fig. 4. In this case, the measuring device has an accuracy of 0.05% as mentioned in section IV. and the relative spread is at least 10%. The differences observed in Fig. 3 is thus far from the measurement accuracy and related to the motor construction. This means that the different motors can be distinguished from one to another based on their HF behavior. This does not only hold for separate motors but for individual windings in one motor as well as shown in Fig. 5. The 3-phase resonance frequency does drift more in between motors than individual phases of one motor. But there is still a difference in between phases that can clearly be observed.



(a)



(b)

Fig. 5. Impedance of the 3 phases of an induction motor plotted together, a difference can be observed albeit smaller than in Fig. 3: (a) full frequency range and (b) focusing around 1 kHz frequency.

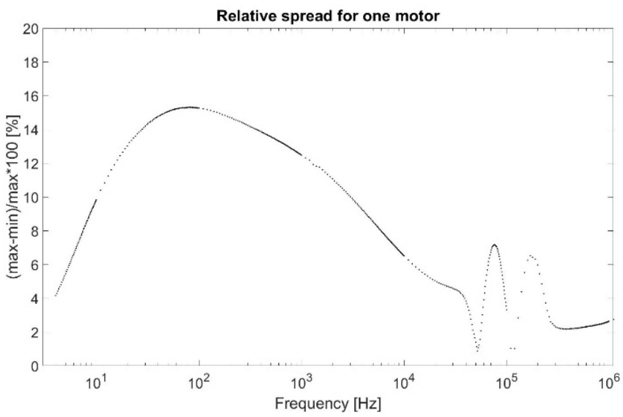


Fig. 6. Impedance of 3 phases of one motor plotted together, a difference can be observed albeit smaller than in Fig. 2.

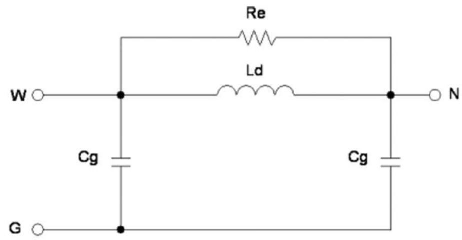
Fig. 6 shows the relative spread of the impedance shown in Fig. 5, this spread is smaller than the one for the individual motors, but still significant compared to the measurement error. The worst in motor phase to phase spread observed peaked near 30% and varied strongly in between motors. Random wound motors thus not only show variation in between motors but asymmetry inside each motor as well.

The HF model parameter study performed by [3] based on motor power rating shows similar inter motor deviations albeit using different motor types of identical power rating or only two motors to compare. This paper did not focus on product variation due to manufacturing, but data provided shows similar differences in between motors with equal power rating as observed here. Similar motors showed 10% or higher deviation in the fitted parameters when comparing two induction motors of same power rating.

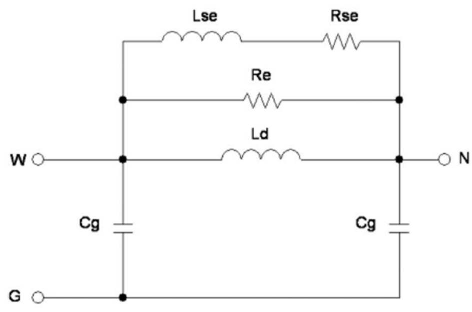
This supports the previous statements that product variation also affects model parameters and consequently simulation results.

VI. DATAFIT

Using the acquired data from the previous section, a datafit can be done to determine the equivalent motor model parameters. For this, the model presented by [3] is used (shown in Fig. 7 below), with the addition of the DC resistance in series. All previous measurements shown were taken in between points marked as "W" and "N".



(a)



(b)

Fig. 7. HF motor winding model as presented by [3], (a) without skin-effect and (b) with skin-effect modelled.

Using this model, the obtained parameters are shown in Table *1*. It can be observed that the DC resistance RDC does not vary much with the different motors, overall the parameters only vary 4,86% or less. The DC resistance is correlated to the amount of copper used in the motor and thus easily controlled during manufacturing with coil size. The main inductance also varies little per motor (less than 5%) in between the individual phases, but overall on a motor to motor basis a larger variation of up to 41% was observed. This variation was also observed in Fig. 4 around 40 to 60Hz. The motor to motor variation in inductance could be related to differences in the magnetic material used.

Table 1 Low frequency parameter datafit per motor and phase, DC resistance RDC and main inductance Ld.

	RDC [Ohm]			Ld [mH]		
Motor	U	V	W	U	V	W
1	8,689	8,536	8,655	220	212	244
2	8,837	8,693	8,773	199	246	196
3	8,782	8,658	8,725	236	241	199
4	8,749	8,593	8,665	228	234	209
5	8,859	8,717	8,800	244	263	232
6	8,772	8,642	8,733	231	225	234
7	8,766	8,613	8,696	175	211	238
8	8,972	8,812	8,882	295	294	279

Next the capacitive coupling of the windings Cg and the equivalent resistance Re were modelled and are shown in Table *2*. This capacitance bundles the turn to turn capacitance, turn to frame capacitance, turn to rotor, rotor to frame and bearing capacitance values. More measurements are required to identify the individual values from this equivalent value.

Table 2 High frequency parameter datafit per motor and phase, capacitive coupling of the windings to the frame Cg and equivalent resistance Re.

	Cg [nF]			Re [kOhm]		
Motor	U	V	W	U	V	W
1	0,135	0,137	0,134	27,2	25,7	27,2
2	0,114	0,130	0,112	29,8	29,6	27,4
3	0,140	0,171	0,149	27,3	16,5	23,8
4	0,137	0,136	0,144	25,4	24,1	22,8
5	0,096	0,109	0,104	31,9	37,8	32,2
6	0,134	0,128	0,143	25,5	22,7	31,0
7	0,140	0,145	0,148	24,0	28,1	25,9
8	0,124	0,130	0,134	26,5	27,6	27,7

From Table *2* it can be observed that Cg has a maximum spread of 43,5% on a motor to motor basis, Fig. 4 shows a similar spread around 400 – 500kHz where the impedance plot shows capacitive behavior. This spread in Cg can be linked to the random placement of the first and last couple of turns in the stator slot per phase winding.

As mentioned in the previous sections, motor eight was produced in a different batch from the seven other motors. It is clear that this particular motor is a complete outlier to the other seven as seen in *Fig. 3*, from Table *1* it can also be observed in the somewhat higher DC resistance and main inductance. On the other hand, the motor cannot clearly be distinguished from the rest in Table *2* as the capacitance is linked to slot geometry, winding configuration and insulation. This shows that batch to batch changes also affect HF behavior of motors and should be taken into account. More data is required to draw further conclusions on which parameters vary and link design choices to parameter variation.

The datafit was so far based on Fig. 7 (a) , the model can be expanded with skin effect (b) but this requires further adjustment to give an accurate fit. The skin effect is thus omitted from this datafit. Based on the performed datafit it can be seen that the raw impedance plots give a good first indication of the parameter variation to be expected after datafit.

VII. Conclusion

HF Motor models are used in lifetime estimations and behavioral studies of inverter fed electrical machines. For this different modelling techniques exist each with their benefits and limitations. All of the considered modelling techniques build on RLC measurements and data fits. These measurements and data fits are for a particular motor and not a motor type. As a consequence, this paper focusses on the variability present in between motors and showcases the limited use of simulations using one particular motor. The random wound distributed windings were looked at in particular as the random nature of this design causes clear variability on an HF level. A measurement campaign on eight identical nameplate induction machines shows the variation due to design. Based on this data, simulations can be performed using 5th percentile parameters for lifetime, 95% of the motors that have more favorable parameters will thus show a longer lifetime. Using average and spread behavioral studies can be performed with trust regions and/or estimation of the applicability in practice. This paper thus aims at providing a basis for widespread application of HF models on series produces motors, lifetime estimations and behavioral studies rather than a case by case method used to this date. It was also observed that more data is required to draw further conclusions, link parameters to design choices and map variations. A first indication of the parameters was achieved and linked to raw measurement variation.

VIII. References

[1] Y. Wang, O. Lucia, Z. Zhang, S. Gao, Y. Guan and D. Xu, "A Review of High Frequency Power Converters and Related Technologies," in IEEE Open Journal of the Industrial Electronics Society, vol. 1, pp. 247-260, 2020, doi: 10.1109/OJIES.2020.3023691.

[2] T. Van Do, J. P. F. Trovão, K. Li and L. Boulon, "Wide-Bandgap Power Semiconductors for Electric Vehicle Systems: Challenges and Trends," in IEEE Vehicular Technology Magazine, vol. 16, no. 4, pp. 89-98, Dec. 2021, doi: 10.1109/MVT.2021.3112943.

[3] A. Boglietti, A. Cavagnino, and M. Lazzari, “Experimental high frequency parameter identification of AC electrical motors,” in 2005 IEEE International Conference on Electric Machines and Drives, 2005, pp. 5–10. doi: 10.1109/iemdc.2005.195693.

[4] L. Wang, C. N. M. Ho, F. Canales, and J. Jatskevich, “High-frequency cable and motor modeling of long-cable-fed induction motor drive systems,” in 2010 IEEE Energy Conversion Congress and Exposition, ECCE 2010 - Proceedings, 2010, pp. 846–852. doi: 10.1109/ECCE.2010.5617906.

[5] A. Boglietti and E. Carpaneto, "Induction motor high frequency model," Conference Record of the 1999 IEEE Industry Applications Conference. Thirty-Forth IAS Annual Meeting (Cat. No.99CH36370), Phoenix, AZ, USA, 1999, pp. 1551-1558 vol.3, doi: 10.1109/IAS.1999.805947

[6] K. Gulez and A. A. Adam, “High-frequency common-mode modeling of permanent magnet synchronous motors,” IEEE Transactions on Electromagnetic Compatibility, vol. 50, no. 2, pp. 423–426, May 2008, doi: 10.1109/TEMC.2008.921032.

[7] X. Pan, R. Ehrhard, and R. Vick, “An Extended High Frequency Model of Permanent Magnet Synchronous Motors in Hybrid Vehicles,” 2011.

[8] N. Idir, Y. Weens, M. Moreau, and J. J. Franchaud, “High-frequency behavior models of AC motors,” in IEEE Transactions on Magnetics,

Jan. 2009, vol. 45, no. 1, pp. 133–1338. doi: 10.1109/TMAG.2008.2006006.
[9] P. Xie, G. Vakil, and C. Gerada, “Electric drive systems with long feeder cables,” IET Electric Power Applications, vol. 14, no. 1. Institution of Engineering and Technology, pp. 16–30, Jan. 01, 2020. doi: 10.1049/iet-epa.2018.5507.
[10] A. B. Vinayak, F. Alam, and A. K. Anand, Stator Inter Turn fault diagnosis by High-Frequency Modeling of Inverter Fed Induction Motor. 2020.
[11] G. Vidmar and D. Miljavec, “A Universal High-Frequency Three-Phase Electric-Motor Model Suitable for the Delta- and Star-Winding Connections,” IEEE Transactions on Power Electronics, vol. 30, no. 8, pp. 4365–4376, 2015, doi: 10.1109/TPEL.2014.2352452.
[12] Y. Hjshikawa and Haga, “A STLJDY OF VOLTAGE DISTRIBUTION IN MOTOR WINDINGS AGAINST STEEP-FRONTED SURGE.”
[13] M. Fujieda et al., “Analysis on Surge Voltage in Inverter-fed Motor Using Frequency Response Analysis,” 2019.
[14] O. A. Mohammed, S. Ganu, N. Abed, S. Liu, and Z. Liu, “High frequency PM synchronous motor model determined by FE analysis,” in IEEE Transactions on Magnetics, Apr. 2006, vol. 42, no. 4, pp. 1291–1294. doi: 10.1109/TMAG.2006.872412.
[15] H. A. Toliyat, G. Suresh, and A. Abur, “Simulation of Voltage Stress on the Inverter Fed Induction Motor Winding Supplied through Feeder Cable.”
[16] H. A. Toliyat, G. Suresh, and A. Abur, “Estimation of Voltage Distribution on the Inverter Fed Random Wound Induction Motor Windings Supplied through Feeder Cable,” 1999.
[17] D.-H. Hwang, K.-C. Lee, Y.-J. Kim, S.-W. Bae, D.-H. Kim, and C.-G. Ro, “Voltage Stresses on Stator Windings of Induction Motors Driven by IGBT PWM Inverters,” 2003.
[18] J. Zhang et al., “Analysis of inter-turn insulation of high voltage electrical machine by using multi-conductor transmission line model,” IEEE Transactions on Magnetics, vol. 49, no. 5, pp. 1905–1908, 2013, doi: 10.1109/TMAG.2013.2245873.

IX. BIOGRAPHIES

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