Sensitivity Analysis on the Voltage Distribution within Windings of Electrical Machines fed by Wide Band Gap Converters

Marco Pastura, Stefano Nuzzo, Giovanni Franceschini, Giacomo Sala, Davide Barater

***Abstract* – In the last years, wide band gap devices are seeing a significant widespread in electric drives, due to their higher performance compared to conventional semiconductors. However, they also produce higher electric stress due to over-voltages and uneven voltage distributions among winding turns of electrical machines fed by them, which can lead to premature failures and/or reduced lifetimes.**

This paper presents a sensitivity analysis on the voltage distribution across stator winding turns of an electric motor intended for aerospace applications. The effects of the surge voltage characteristic parameters, such as dv/dt, voltage magnitude and parasitic impedances, are investigated. An equivalent circuit approach, based on the multi-transmission line theory, is developed and implemented in MatLab-Simulink environment, while the relevant circuital parameters are estimated through finite element analysis performed with MagNet® and ElecNet® software.

***Index Terms*—dv/dt, Voltage distribution, Insulation stress, Wide-Band-Gap devices, Sensitivity analysis, More Electric Aircraft, Electric drives**

I. Introduction

Variable speed drives (VSDs) have reached an enormous variety of applications, from household appliances to industrial, aerospace [1], automotive, renewable energy generation, etc. VSDs are often equipped with electrical machines fed by Pulse Width Modulation (PWM) converters. These are usually based on conventional switching Silicon devices, but in the last years the number of high switching frequency converters consisting of Wide Band Gap (WBG) semiconductors, such as Silicon Carbide (SiC) or Gallium Nitride (GaN), has grown. WBG devices can provide improved performance than traditional power switches [2]-[4]. The main advantages related to their use are:

- lower switching losses due to their shorter rise and fall times;
- the possibility of operating at higher switching frequencies, so that lower current harmonic content can be achieved;
- they can bear with higher voltages and temperatures;
- they feature a higher power density.

However, there also some drawbacks. High overvoltage caused by reflected wave phenomena, already well known for IGBT based drives [5], can occur even with cables of few meters due to their short rise times. According to (1), the machine terminal voltage V_l can reach up to twice the value of the inverter bus voltage V_{bus}, since the theoretical limit of the reflection coefficient K is 1. However, even higher values can be reached in some cases, for example when double pulsing occurs [5].

$$V_l = V_{bus}(1 + K) \quad (1)$$

In addition, the short rise times or, rather, their high dv/dt can trigger also an uneven voltage distribution across winding turns of the electrical machine, causing a higher turn to turn voltage stress [7]-[10]. If no precautions are taken, premature insulation failure can occur, leading to an inevitable stop of the drive [11]. High dv/dt are also related to a high frequency content in the order of a few MHz or more. This can cause unacceptable electromagnetic emissions which have to be reduced [12].

Considering the above it is clear that, while operations at higher efficiencies and enhanced power density are ever more required especially in the automotive and aerospace fields, on the other hand an electric drive should also meet a certain reliability level [13]. Therefore, its design represents a difficult task and is always the result of a trade-off study aimed at maximizing the above requirements.

A. *Motivation*

Possible solutions to overcome the main drawbacks of employing WBG devices in electric drives consist in introducing small passive filters for dv/dt and overshoot reduction [14]-[16] or multi-level converters [17]. However, both solutions would increase the overall cost of the drive. In order to achieve a satisfying trade-off in terms of better performance, improved reliability and reduced overall costs, investigations on the impact of over-voltages and voltage distribution in the cabling and machine windings are needed and solutions to reduce the voltage stress must be identified.

The overvoltage phenomenon is well known and has already been largely investigated. A lot of research has focused on the development of models or approaches to predict it, such as in [18]. In addition, while the over-voltage occurring at the machine terminals can be easily measured, a

This project has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation programme under grant agreement No 785513.

M. Pastura, S. Nuzzo, G. Franceschini and D. Barater are with the MeltIng Lab Group, Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Modena, Italy (e-mail: marco.pastura@unimore.it).

S. Nuzzo is also with the Power Electronics, Machines and Control Group, University of Nottingham, Nottingham, UK (e-mail: stefano.nuzzo@unimore.it).

Giacomo Sala is with the Department of Electrical, Electronic and Information Engineering "Guglielmo Marconi", University of Bologna, Italy.

direct access to the turns is needed to check the voltage distribution in the winding.

Very fast front transients are known to be the main cause for the non-linear response of the voltage distribution within the winding turns of an electrical machine fed by PWM power converters. These fronts are particularly emphasized when such converters are based on SiC and GaN semiconductors. The uneven voltage distribution can represent a big issue in random-wound windings, where the positions of the turns in each slot are unknown, so that the first turns can result near the last ones, increasing the turn to turn insulation stress as opposed to a form-wound winding.

Some research on the winding voltage distribution has been carried out over the past years [7]-[10], focusing on rather complex modeling approaches which often rely upon finite element analysis (FEA). However, a detailed sensitivity analysis on the main parameters affecting such a phenomenon is missing, thus the aim of this paper is to provide an investigation on the effects of rise time, dv/dt, duty cycle, supply frequency, etc., typical of WBG-based electric drives.

II. MODEL DESCRIPTION

Before focusing on the sensitivity study, a detailed modeling approach is developed and implemented. Its description is dealt with in this section.

A. Equivalent circuit

During steady state, the voltage distribution across winding turns is uniform. However, this assumption is not valid when fast transients occur. This behavior in the machine windings is related to the high frequency (HF) impedances of the turns, where skin effect, proximity and parasitic couplings through stray capacitances play an important role. Once the HF impedances are estimated, an equivalent circuit of the series connected turns can be built. The equivalent circuit is envisioned following the theory of multi-conductor transmission line model [19]. For the sake of the sensitivity study, only one phase coil is considered. In general, the coil consists of a certain number of turns connected in series. The circuital elements characterizing each turn are its resistance R_i, its self-inductance L_i, its capacitive coupling with the other coil turns C_{ij} and towards the ground reference C_{ig} (i.e. the iron parts), as reported in Fig. 1. Each turn can be seen as a small RLC filter, gradually reducing the slope of the voltage waveform. This fact, combined with the different values of R, L and C of the whole coil, determine a non-uniform voltage distribution depending on their different position in the slot.

In Fig. *1* v_{fed} is the PWM voltage coming from the converter, defined by certain characteristic parameters, including magnitude, dv/dt, PWM frequency, duty cycle. These are the main parameters used for the sensitivity analysis. As an example, the case when 1) the magnitude is 500 V, 2) the PWM frequency is 50 kHz, 3) the dv/dt is 20 kV/µs and 4) the duty cycle is 0.5, is reported in Fig. 2.

Applying the first and second Kirchhoff's laws (2) and (3) to the equivalent circuit of the coil comprising *n* turns (thus *n* nodes), it is possible to determine both the node voltages v_i and the currents i_i entering each node. Equations (2) and (3) are simultaneously solved for each node of the equivalent circuit. The resulting set of equations can be implemented in any dynamic system solver to find the voltage stress between different turns. MatLab-Simulink is selected to do so in this work.

$$i_i - i_{i+1} - C_{ig}\frac{dv_i}{dt} - \sum_{\substack{j=1 \\ j\neq i}}^{n} C_{i,j}\frac{d(v_i - v_j)}{dt} = 0 \qquad (2)$$

$$v_{i-1} - v_i - R_{i,i}i_i - L_{i,i}\frac{di_i}{dt} - \sum_{\substack{j=1 \\ j\neq i}}^{n} L_{i,j}\frac{di_j}{dt} = 0 \qquad (3)$$

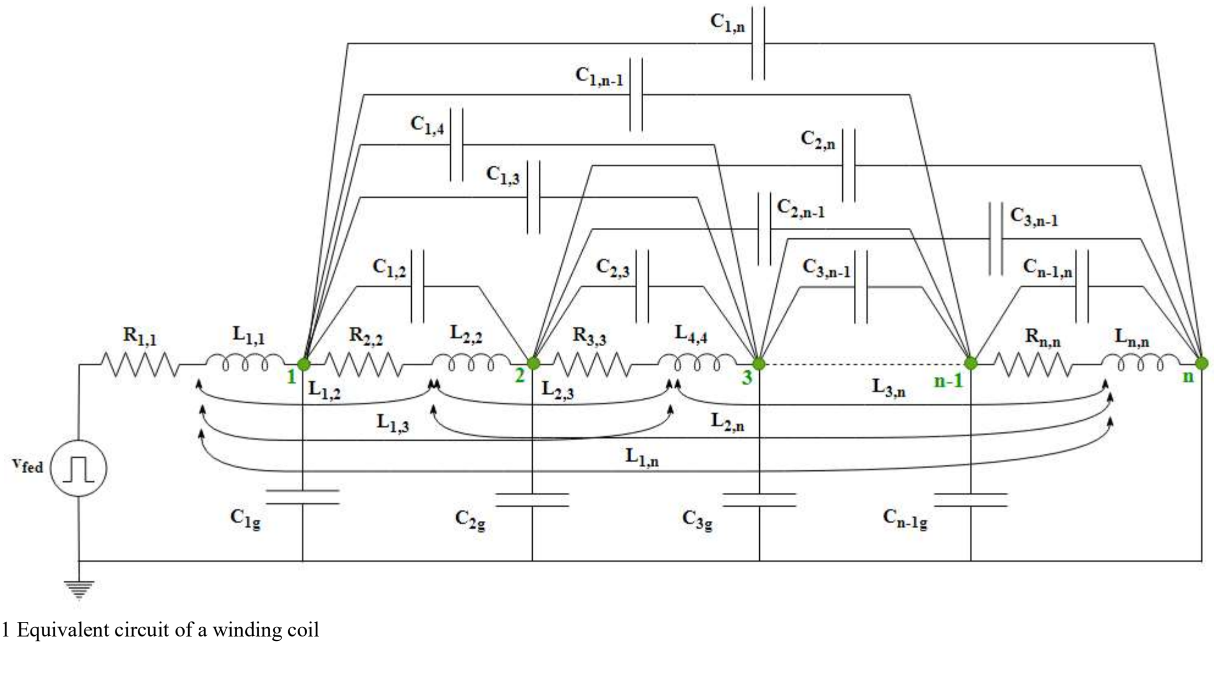

Fig. 1 Equivalent circuit of a winding coil

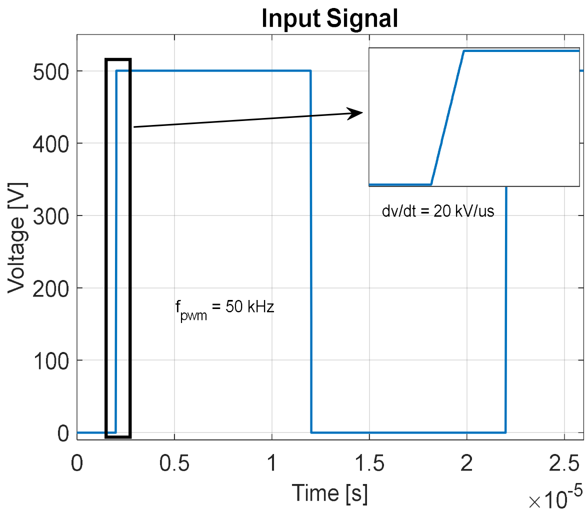

Fig. 2 Example of input voltage waveform from the converter output

B. FEA Model

As underlined in the previous section, the HF equivalent parameters need to be found. Their estimation has been done via FEA. The capacitive couplings have been calculated through time harmonic simulations using the electrostatic field software ElecNet®, while inductances and resistances have been found using the time harmonic simulations of the magnetic field software MagNet®. Their values are associated to a specific frequency, which, for this case study, is in the order of MHz and is a function of the voltage input rise time t_r. Assuming that the frequency response of the system can be approximated as a response of a 1st order system to a step input, the bandwidth of the signal f_r is as in (4). Then, the frequency f_r is used for the FEA evaluations.

$$f_r \approx \frac{0.35}{t_r} \quad (4)$$

The model for the FEA evaluations is in 2D. This allows to minimize the computation times (as opposed to a 3D analysis) for the drawing of the geometry and for the equivalent circuit parameters' calculation, which have been done through MatLab scripting interfacing with the two FEA software. The geometry is based on a single slot of an existing double layer permanent magnet machine for aerospace applications. Fig. 3 shows a field map of the 2D FEA slot model developed, comprising 24 conductors divided in 2 layers. The study is focused on the upper layer only, thus 12 conductors are considered for the sensitivity study on the voltage distribution. More observations and assumptions related to the model are summarized as follows:

- Since the model is in 2D, border effects and end windings are neglected in the analysis, thus only the coil active sides are taken into account.
- The capacitances' calculation is performed with the electrostatic analysis, so it is independent from frequency. This assumption can be considered true with a good approximation. In fact, the influence of frequency on the capacitances is negligible compared to its influence on resistances and inductances.
- Inductive and capacitive couplings between turns placed in different slots can be neglected. At the considered operating frequencies, the ferromagnetic parts act as an electromagnetic shield as it can be seen by the flux lines in Fig. 3.
- Each turn is modelled as an equivalent conductor as in [10], meaning that the eventual parallel strands comprising the conductor are not considered.
- Inductive and capacitive couplings between the 2 coils belonging to the upper and lower slot layers envisioned in Fig. 3 have negligible effects.

All these assumptions enable important computation time saving and simplification of the model.

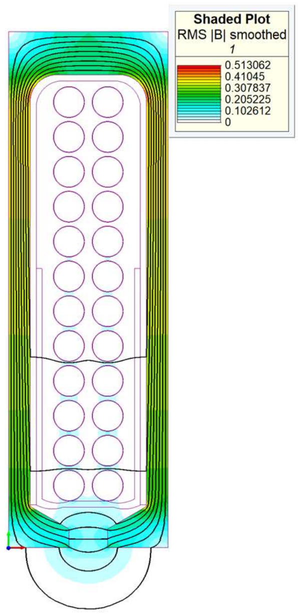

Fig. 3 2D FE model of the slot: flux lines are mainly confined in the ferromagnetic part outside the slot.

III. Voltage Distribution Sensitivity Analysis

A. Preliminary considerations

Once a certain slot geometry and the materials have been chosen, the voltage distribution among winding turns depends only on the input voltage. As mentioned above and as shown in Fig. 1, the input voltage's main parameters are switching frequency, duty cycle, amplitude and dv/dt. Once the above parameters have been set, the node voltages of the circuit can be computed. The instantaneous voltage drop V_{di} for the i_{th} turn is then calculated as $V_{di} = v_{i-1} - v_i$. If the voltage distribution was uniform, the peak value of the instantaneous voltage drop across each turn would be close to the steady-state value.

As underlined before, the most stressed turns are the first ones, while the voltage drop waveform tends to become more similar in the subsequent turns. In particular, the first turn will feature the higher value of instantaneous voltage drop. Hence this value can be taken as a reference to estimate how much the voltage distribution is uneven. Lower values would then correspond to a more uniform distribution.

B. *Preliminary simulations – duty cycle and switching frequency*

Some parameters have an important impact on the distribution across the turns, while others have been proved to have a negligible contribution. Short rise times or high dv/dt are the main causes for the uneven distribution. Also, a higher amplitude of the input voltage would certainly increase the voltage drop across each turn. Therefore, a sensitivity analysis with a variation of these two parameters is worth to be done.

On the other hand, switching frequency and duty cycle of the converter voltage waveform have no impact since they do not affect the HF content of the waveform which determines the voltage distribution. The HF content is in fact mainly related to the rise time of the converter waveform. An example proof is provided in Fig. 4 and Fig. 5, which show the results of two simulations where only the duty cycle has been changed. An uneven voltage distribution appears, since there is great difference from the peak to the steady-state values and even between the two turns (a uniform distribution would result in similar amplitudes in every time instant). The voltage drop is calculated according to (5) for the first turn (indicated as 'Turn 1' in the figures), while (6) is used for the second turn (indicated as 'Turn 2' in the figures). For both the figures, the input voltage has an amplitude of 500 V, the dv/dt is 10 kV/µs and the switching frequency is 50 kHz. The duty cycle is 10% for Fig. 4 and 90% for Fig. 5. Nevertheless, the number of voltage transients in a fixed time depends on the switching frequency, so a higher switching frequency can still negatively affect the insulation lifetime even if it has no influence on the voltage distribution or peak value.

$$V_{d1} = v_{fed} - v_1 \tag{5}$$

$$V_{d2} = v_1 - v_2 \tag{6}$$

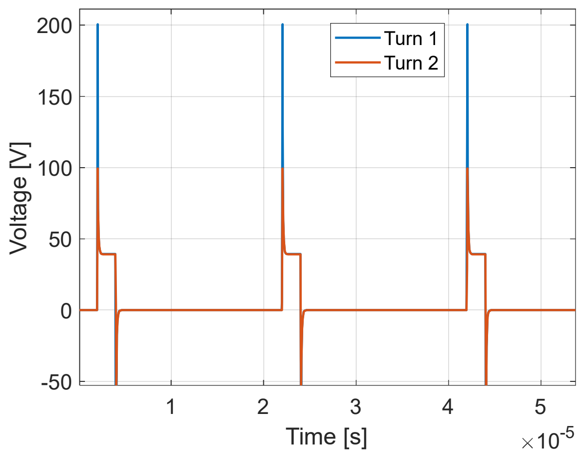

Fig. 4 Instantaneous voltage drop across the first two turns (Turn 1 and Turn 2). Duty cycle 10%.

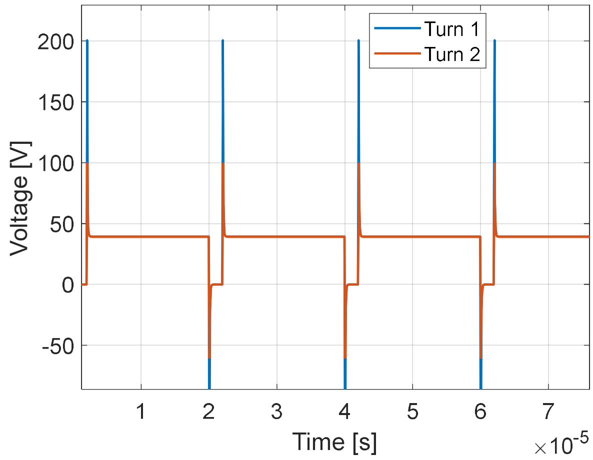

Fig. 5 Instantaneous voltage drop across the first two turns (Turn 1 and Turn 2). Duty cycle 90%.

C. *Analysis on dv/dt and amplitude*

The analysis on the impact of different dv/dt and voltage amplitudes is performed, and the results are shown both in absolute values and in p.u. The voltage amplitude is varied from 300 V to 800 V with a step of 100 V, while the dv/dt ranges from 2 kV/µs to 20 kV/µs with a step of 2 kV/µs, so that a wide spectrum of voltages, dv/dt and consequently rise times is available. The results in p.u have been found using the input voltage amplitude as a reference value, so that a proper comparison could be done also regarding the proportions of voltage distribution with different amplitudes. The reference for the evaluation of the uneven voltage distribution is the peak value of the voltage drop on the first turn. For a certain voltage input amplitude, higher voltage drops across the first turn are associated to a more uneven distribution. Two 3D maps are plotted in Fig. 6 and Fig. 7 These show the trends of the maximum voltage drops against dv/dt and magnitude, respectively considering absolute values and p.u. ones. In Fig. 6, it can be clearly observed that with increasing dv/dt values the voltage drop increases for all the considered amplitudes. Also, the maximum voltage drop across the first turn increases for higher input voltage amplitudes, as this corresponds to higher rise times. On the contrary, Fig. 7 shows that lower values of the feeding voltage magnitude determine a higher voltage drop in p.u, which means that the distribution is less uniform. Hence when two waveforms of different amplitudes, but same dv/dt, are applied to the winding, the voltage distribution would result more uneven for the lower voltage value, while in terms of absolute voltage drop the maximum value is associated to the higher amplitude input. Indeed, this result is not unexpected: an input voltage of 400 V and dv/dt of 20 kV/µs has a lower rise time (16 ns) than an input voltage of 800 V and 20 kV/µs (32 ns). This also means that, according to (4), the 400 V waveform has a bandwidth which is about twice than that at 800 V, thus the voltage distribution is less uniform. Therefore, Fig. 7 confirms the direct correlation of rise time and voltage distribution, while the dv/dt needs one more variable, which is the voltage amplitude. Hence, the general conclusions can be summarized as reported in (7) and (8), being V_a the amplitude of v_{fed}.

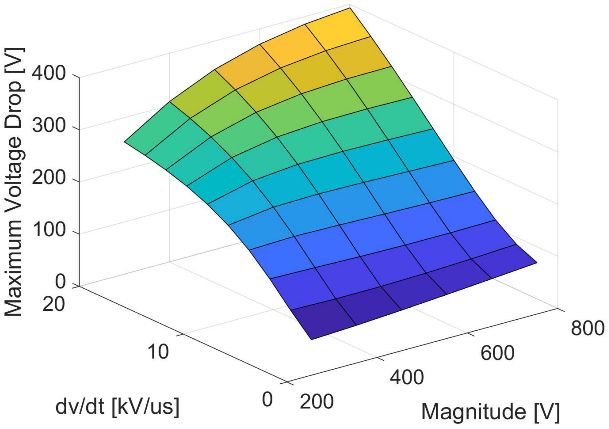

Fig. 6. 3D map of the instantaneous maximum voltage drop across the first turn.

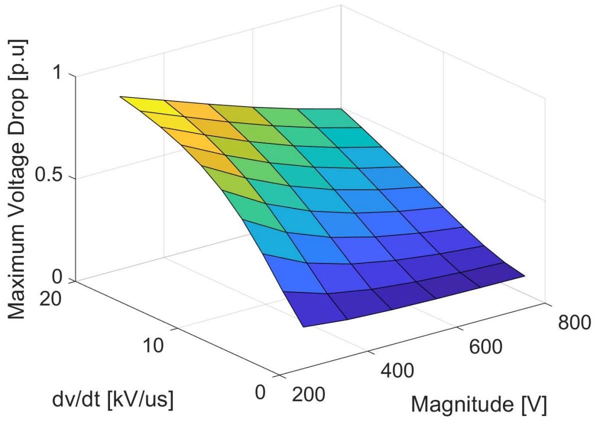

Fig. 7 3D map of the instantaneous maximum voltage drop across the first turn in p.u.

$$Voltage\ distribution = f(t_r) \quad (7)$$

$$Voltage\ distribution = f(V_a, {}^{dv}/_{dt}) \quad (8)$$

D. Further Analysis

The voltage distribution depends on the input voltage for a fixed geometry of the winding, however wire location and geometry (e.g. different cross-section areas or shapes) can determine a different impact. Inductances and resistances values are frequency dependent, whereas the capacitances are mainly determined by the location of each turn with respect to the slot wall (i.e. the tooth) and to the rest of the slot conductors. For example, considering fixed slot and wire geometries, different scenarios could be found in a random-wound winding as simplistically illustrated in Fig. 8. This figure shows 4 possible configurations which would result in 4 different capacitance matrices, both in terms of turn to ground and turn to turn values. For these reasons, further analyses can be done varying the main turn circuital parameters, i.e. inductances, capacitances and resistances. This analysis has been performed with a fixed voltage of 500 V and a dv/dt of 10 kV/μs. The impact of the impedance parameters has been estimated again with the evaluation of the peak voltage drop across the first turn of the coil. In particular, the analysis has been carried out by multiplying the resistance, capacitance and inductance matrices by different coefficients ranging from 0.1 to 1.

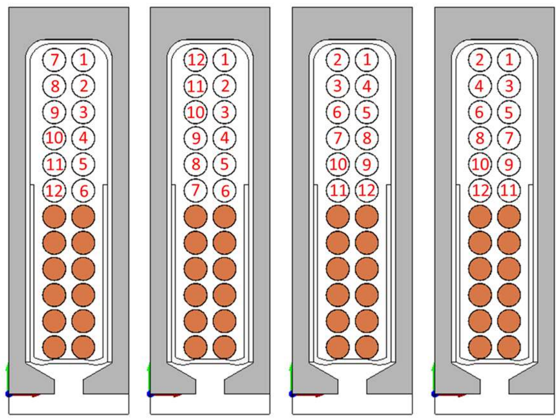

Fig. 8 Example of 4 configurations with different conductors' location.

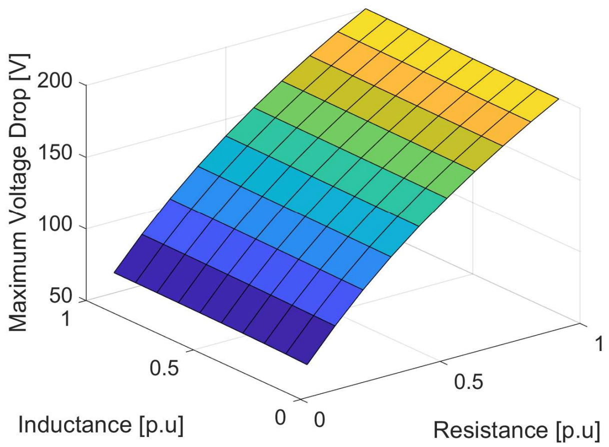

Fig. 9 3D map of the instantaneous maximum voltage drop across the first turn as function of inductance and resistance coefficients.

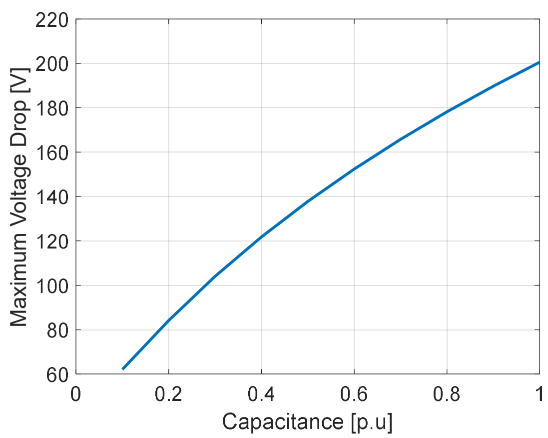

Fig. 10 Maximum voltage drop across the first turn as function of capacitance coefficient.

The results are shown in Fig. 9 and Fig. 10. It can be seen that both the capacitances and the resistances have a significant impact, while the impact of the inductances is very low. For the capacitances and resistances, the trend is the same. Bigger values correspond to a worse voltage distribution. Hence, with a reduction of the parasitic capacitances or of the conductors' resistances, a more uniform voltage distribution can be achieved. The FEA evaluation showed that resistance values are mainly affected by proximity effects rather than the skin effect. Fig. *11* shows the instantaneous voltage drop for the first three turns of the coil when the resistance matrix coefficient is 0.1 (i.e. the resistances are 0.1 p.u. of the values evaluated with FEA for the reference system). The peak values of the voltage drops are not very different. In addition, they are not very distant from the steady-state values, which means that the distribution is only slightly uneven. Considering all the above, it can be concluded that the parameters mostly affecting the voltage distribution within windings of electrical machines fed by fast switching converters are the turns' series resistances and the capacitances, besides obviously the input voltage amplitudes and gradients (dv/dt). Table I provides an example of the impact on the voltage distribution given by the three principal factors when they are modified by a factor equal to 2. The voltage reference value is 500 V.

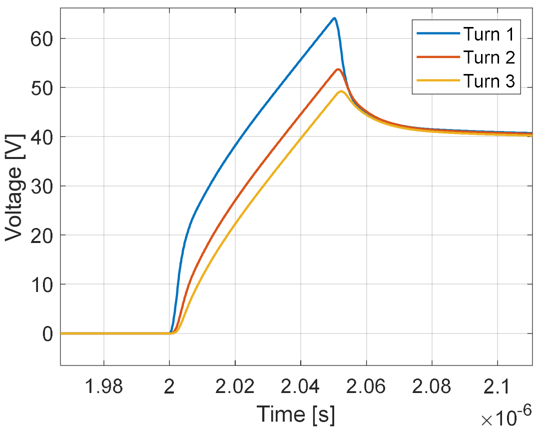

Fig. 11 Voltage drop across 1st, 2nd and 3rd turns.

TABLE I
EXAMPLE OF THE IMPACT ON THE MAXIMUM VOLTAGE DROP ACROSS THE FIRST TURN FOR DIFFERENT PARAMETERS

	Initial Value	**Final Value**	**Peak Voltage Drop (1st Turn)**
Rise time	40 ns	20 ns	+74%
C	0.5 p.u	1 p.u	+45.50%
R	0.5 p.u	1 p.u	+45%

IV. CONCLUSIONS

With the spreading of WBG devices, higher performance drives can be designed, but increased challenges related to reliability aspects, such as early insulation failure, need also to be addressed. Among them, the uneven voltage distribution associated to fast rise times represents a serious source of electric stress. This paper has provided an analysis on the impact of the main parameters which might affect the voltage distribution among winding turns. The sensitivity study carried out in this paper highlighted that this phenomenon is mainly influenced by the applied waveform coming from the power converter and by the characteristic impedances of the turns. The most important waveform parameter is certainly the rise time, which can trigger a significantly non uniform voltage distribution across the machine coil turns. On the other hand, the dv/dt itself is not enough to determine with precision the voltage distribution. However, in the range of low voltage applications, dv/dt values in the order of a few kV/μs can be enough to determine a highly non uniform voltage distribution. The investigation also highlighted that the winding structure can influence this high frequency phenomenon. In particular, lowering the values of turn resistances and capacitances can mitigate the electric stress due to the winding voltage distribution, with potential benefits in terms of insulation lifetime. Contrarily, inductances seem to have a much lower impact. The future work will focus on the experimental validation of this paper's findings.

V. ACKNOWLEDGMENT

The project RAISE has received funding from the Clean Sky 2 Joint Undertaking under the European Union's Horizon 2020 research and innovation program under grant agreement No. 785513.

VI. REFERENCES

[1] Y. Wang, S. Nuzzo, H. Zhang, W. Zhao, C. Gerada and M. Galea, "Challenges and Opportunities for Wound Field Synchronous Generators in Future More Electric Aircraft," in *IEEE Transactions on Transportation Electrification*.

[2] F. Di Giovanni and S. Buonomo, "Latest developments in Silicon Carbide MOSFETs: Advantages and benefits vs. application," *AEIT Annual Conference 2013*, Mondello, 2013, pp. 1-6.

[3] S. Chen, W. Yu and D. Meyer, "Design and Implementation of Forced Air-cooled, 140kHz, 20kW SiC MOSFET based Vienna PFC," *2019 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Anaheim, CA, USA, 2019, pp. 1196-1203.

[4] D. Murthy-Bellur, E. Ayana, S. Kunin, B. Palmer and S. Varigonda, "WBG inverter for commercial power generation and vehicle electrification," *2015 IEEE International Workshop on Integrated Power Packaging (IWIPP)*, Chicago, IL, 2015, pp. 36-39.

[5] M. J. Melfi, "Low-Voltage PWM inverter-fed motor insulation issues", IEEE Transactions on Industry Applications, vol. 42, no. 1, pp. 128-133, 2006.

[6] G. Skibinski, D. Leggate and R. Kerkman, "Cable characteristics and their influence on motor over-voltages," *Proceedings of APEC 97 - Applied Power Electronics Conference*, Atlanta, GA, USA, 1997, pp. 114-121 vol.1.

[7] A. Krings, G. Paulsson, F. Sahlén and B. Holmgren, "Experimental investigation of the voltage distribution in form wound windings of large AC machines due to fast transients," 2016 XXII International

Conference on Electrical Machines (ICEM), Lausanne, 2016, pp. 1700-1706.

[8] Wan Jianru, Sun Yangjian and Xong Xianbin, "Research on nonuniform voltage distribution in winding turns of motor driven by high frequency pulse," *The 4th International Power Electronics and Motion Control Conference, 2004. IPEMC 2004.*, Xi'an, 2004, pp. 563-567 Vol.2.

[9] Y. Xie, J. Zhang, F. Leonardi, A. R. Munoz, M. W. Degner and F. Liang, "Voltage Stress Modeling and Measurement for Random-Wound Windings Driven by Inverters," 2019 IEEE International Electric Machines & Drives Conference (IEMDC), San Diego, CA, USA, 2019, pp. 1917-1924.

[10] Y. Xie, J. Zhang, F. Leonardi, A. R. Munoz, F. Liang and M. W. Degner, "Modeling and Verification of Electrical Stress in Inverter-Driven Electric Machine Windings," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 5742-5749.

[11] D. Barater, G. Buticchi, C. Gerada and J. Arellano-Padilla, "Diagnosis of incipient faults in PMSMs with coaxially insulated windings," *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, 2013, pp. 2756-2761.

[12] C. T. Morris, D. Han and B. Sarlioglu, "Comparison and evaluation of common mode EMI filter topologies for GaN-based motor drive systems," *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, Long Beach, CA, 2016, pp. 2950-2956.

[13] P. Giangrande, V. Madonna, S. Nuzzo and M. Galea, "Moving Toward a Reliability-Oriented Design Approach of Low-Voltage Electrical Machines by Including Insulation Thermal Aging Considerations," in IEEE Transactions on Transportation Electrification, vol. 6, no. 1, pp. 16-27, March 2020.

[14] M. Pastura, S. Nuzzo, M. Kohler and D. Barater, "Dv/Dt Filtering Techniques for Electric Drives: Review and Challenges," IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 2019, pp. 7088-7093.

[15] H. Kim, B. Kim and S. Bhattacharya, "An Analytical Design Strategy and Implementation of a Dv/Dt Filter for WBG Devices Based High Speed Machine Drives," *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, Washington, DC, 2018, pp. 385-390.

[16] J. He *et al.*, "Multi-Domain Design Optimization of dv/dt Filter for SiC-Based Three-Phase Inverters in High-Frequency Motor-Drive Applications," in *IEEE Transactions on Industry Applications*, vol. 55, no. 5, pp. 5214-5222, Sept.-Oct. 2019.

[17] H. Pulakhandam, S. Bhattacharya and T. Byrd, "Hybrid Operation of a GaN-based Three-Level T-type Inverter for Pulse Load Applications," *2019 IEEE 7th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, Raleigh, NC, USA, 2019, pp. 378-383.

[18] G. Pietrini, D. Barater, C. Concari, M. Galea and C. Gerada, "Closed-form approach for predicting overvoltage transients in cable-fed PWM motor drives for MEA," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-7.

[19] M. T. Wright, S. J. Yang, and K. McLeay, “General theory of fast fronted interturn voltage distribution in electrical machine windings,” in Proc. Inst. Electr. Eng., 1983, pp. 257–264.

VII. BIOGRAPHIES

Marco Pastura received the M.Sc. degree in Electrical Engineering from the University of Pavia, Pavia, Italy in 2018. He is currently a Ph.D. student in “Automotive Engineering for Intelligent Mobility” at the Department of Engineering “Enzo Ferrari” at University of Modena and Reggio Emilia, Modena, Italy. His research interests are the electrical drives for automotive and aerospace applications with focus on high reliability electrical machines.

Stefano Nuzzo (S’17-M’18) received the B.Sc. and M.Sc. degrees in Electrical Engineering from the University of Pisa, Pisa, Italy, in 2011 and 2014, respectively. He received his Ph.D. degree in Electrical Engineering in 2018 from the University of Nottingham, Nottingham, U.K, where he is currently working as a Research Fellow within the Power Electronics, Machines and Control (PEMC) Group. Since January 2019, he is also a Research Fellow at the Department of Engineering "Enzo Ferrari" at University of Modena and Reggio, Modena, Italy. His research interests are the analysis, modelling and optimizations of electrical machines, with focus on salient-pole synchronous generators and brushless excitation systems for industrial power generation applications. He is also involved in a number of projects related to the more electric aircraft initiative and associated fields. Dr. Nuzzo is a Member of the IEEE Industrial Electronics Society (IES) and the IEEE Industry Applications Society (IAS). He constantly serves the scientific community as a reviewer for several journals and conferences.

Giovanni Franceschini received the M.Sc. degree in Electronic Engineering from the University of Bologna, Bologna, Italy. He is currently the Full Professor of Electric Drives with the Department of Engineering “Enzo Ferrari”, University of Modena and Reggio Emilia, Modena, Italy. He was the Coordinator of the European Project ALEA, to achieve complete and accurate lifetime models for electrical drives in aerospace applications. He is the author or co-author of more than 150 international papers. His research interests include power electronics for e-mobility and motor drives control and diagnostic.

Giacomo Sala received the B. Sc. in Power Engineering in 2012 the M. Sc. degree with honors in Electrical Engineering in 2014 and the Ph. D. in Electrical Machines and Drives in 2018 from the University of Bologna, Italy. He worked as a researcher until 2019 in the Power Electronics, Machines and Control Group, Department of Electrical and Electronic Engineering, The University of Nottingham. He is currently a researcher in the Department of Electrical, Electronic, and Information Engineering "Guglielmo Marconi" - DEI, University of Bologna, Italy. His research interests include design, modelling and control of multiphase electrical machines, fault tolerant controls and fault diagnosis of electrical drives.

Davide Barater (S’11-M’14) received the M.Sc. degree in Electronic Engineering in 2009 and the Ph.D. degree in Information Technology in 2014 from the University of Parma Italy. He was an honorary scholar at the University of Nottingham, U.K., during 2012, and a visiting researcher at the University of Kiel, DE in 2015. He is currently Assistant Professor at Department of Engineering “Enzo Ferrari”, University of Modena and Reggio Emilia, Italy. His research area is focused on power electronics for e-mobility and motor drives. He is the Coordinator of two European Project: RAISE, to evaluate the impact of the high voltage gradients, introduced by the fast commutations of new wide bandgap power devices (SiC, GaN), on the life time of electrical motor insulation systems; AUTO-MEA that aims to develop electrical motors and drives for next generation of electrical mobility. He is Associate Editor of IEEE Transactions on Industry Applications and author or co-author of more than 60 international papers.