Experimental Statistical Method Predicting AC Losses on Random Windings and PWM Effect Evaluation

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Experimental Statistical Method Predicting AC Losses on Random Windings and PWM Effect Evaluation

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***Abstract*-- Nowadays, one of the challenges in transport electrification is the reduction of the components' size and weight in order to improve the power density. This is often achieved by designing electrical machines with higher rotational speeds and excitation frequencies. In addition, the converter needs to control the machine over a wide speed range given by the mission profile. Therefore, copper losses can significantly increase due to the combination of high frequency excitation and the harmonics introduced by the converter .The winding arrangement design plays a key role in the minimization of the copper losses, thus towards a higher efficiency and/or an improved power density. Different winding topologies can be adopted for high speed electrical machines and amongst them random windings are still one of the most widespread types. This paper presents an in depth study on AC losses in random windings for high frequency motor applications. An analytical method is compared against 2-D Finite Element (FE) simulation results. These are then compared to experimental measurements taken on a custom motorette. Importantly, in order to take into account the random positions of each strand within the machine slots, an Experimental Statistic Method (ESM) is proposed. The ESM allows to define the probability distribution which is useful to evaluate the winding copper losses at the design stage. The contribution of the Pulse Width Modulation (PWM) effect is also considered and experimentally evaluated.**

***Index Terms*-- Random windings, AC losses evaluation, high frequency, PWM effects, Electrical Machines.**

I. Introduction

Nowadays, transport electrification is one of the most viable solutions to reduce CO_2 emissions and meet fuel economy requirements. Governments and automotive industries are pushing their research programs to realize hybrid and pure electric powertrains for both automotive and aerospace, and in general for all transport applications. Challenging targets of 81g of CO_2 emission per km, fuel consumption of around 4.8 and 4.1 L/km for petrol and diesel vehicles [1], will be compulsory by 2025 in the EU for all new cars. Adopting drivetrains with high performance electrical machines is the way to meet the aforementioned requirements and to develop concepts and products capable to meet the modern markets' standards.

Another important challenge in transportation industry is the maximization of the power density, in terms of power to volume (kW/L) or power to mass (kW/kg) ratios [2]. The US Department of Energy (DOE) has recently announced technical targets for light duty electric vehicles with a goal to reach a power density target of 33 kW/L for a 100 kW traction drive system by 2025 [3]. To put things into perspective, Toyota and Nissan in their xEV platforms have achieved 4.8 and 4.2 kW/L, respectively.

It is necessary to intensify the efforts of designing high-speed AC machines to increase power density. However, higher excitation frequencies can lead to increasing the machine losses, such as the iron and copper losses. In next generation automotive drives, a typical electric/hybrid-electric vehicle propulsion motor can operate with a fundamental frequency higher than 1 kHz. Therefore winding AC losses cannot be neglected. Some preliminary considerations are needed to design the stator winding and rotor structure to improve the electrical machines performance [4], [5], [6].

Among the distributed windings used in industrial applications there are different types of wires available in the market, including round random winding, hairpin and Litz wires. In very high frequency applications, Litz wires are normally used. However, they present some manufacturing disadvantages, such as complex shaping and impregnation, low achievable fill factor, and high manufacturing costs [7]. Compared with the conventional stranded wire, Litz wire normally presents the best AC/DC losses ratio. However, due to its high cost, it is not an optimum solution for mass production, where the cost minimization is one of the key drivers.

It is possible to realize the hairpin winding with a fully automated process, thus a very high productivity rate is achievable. The main barrier for automating the production lines is the initial capital investment. Random winding allow semi-automatic production and the purchasing costs are

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reasonably lower than hairpin winding. In addition, the random windings permit to realize a wide range of configurations, compared to the relatively fewer configurations that are possible with hairpin windings. For the aforesaid reasons random windings are still the most widely employed.

The winding AC loss behavior at high frequency is gaining more interest in both academic and industrial research. Due to the complexity of the phenomena, modelling the copper losses at high frequency is very challenging. In fact, in addition to the DC resistance, other three components need to be segregated; skin effects, proximity effects and circulating currents.

So far, numeric (Finite Element) and analytic approaches are commonly used to predict the losses, which are widely presented in literature, though only a few of them are also validated experimentally. Dowell [8] evaluated the variation with the frequency of the winding resistance and leakage inductance for single layer, multilayer and sectionalized windings. Ferreira [9] presented a model to calculate AC resistance taking into account skin and proximity effects in windings. Based on the Dowell's model, Wojda and Kazimierczuk [10] performed an optimization for solid-round-wire winding AC resistance.

Liwschitz-Garik [11] discussed the ratios of AC/DC resistance and inductance for other complex bar shapes. Reatti and Kazimierczuk [12] reviewed several analytical expressions for the high-frequency winding resistance of inductors and compared the theoretical predictions against experimental results. Based on the subdomain models, the eddy current losses in windings of electric machines were calculated [13], [14].In [15] proposes an analytical method for calculating the AC losses of arbitrarily arranged and connected conductors.

All previous models have been developed under the condition of perfect transposition of the wires across the axial length; hence, the circulating current phenomena are not evaluated. To the best knowledge of the authors, there are no methods capable to take into account all the individual contributions of the AC losses considering the real strands' positions.

In [16] A combination of finite element analysis(FEA) and experimental measurement has been employed to evaluate the components that contribute to the overall winding power loss. The work presented on [17] studies impact of the number of stator winding parallel strands on the additional AC losses distribution in the slot where this winding is located. In [18] a FEA was been done to evaluate the impact of the parallel wires' placement.

In [19] a strand level Finite Element (FE) model has been generated to take into account all the contributing elements of the AC losses. It is demonstrated that Finite Element Analysis (FEA) gives very accurate results compared with experimental results if the position of each strands is controlled. A former is manufactured using 3D printing to fix exactly the position of the individual strands in an identical fashion to the ones considered in the FE analysis.

The analytical approaches for AC loss calculation are much faster when compared to FEA. On the other hand, they are accurate only under certain hypothesis, which are usually very far from the reality. In addition, the analytical approaches usually consider some geometry simplifications which are not always representative of a real case. For example, in the 1D models, the strand is assumed to be regularly positioned along layers through the tangential direction, whilst in the 2D models the strand is assumed to be regularly positioned along layers in the radial and tangential directions. FEA is very accurate in predicting AC losses when considering a specific model that represents exactly the real wires' distribution.

In mass production usually the number of winding manufactured is very high. For random winding only a semiautomatic solution is possible; this means that all configurations present strand positions which are unique for each machine manufactured. The estimation of the losses in a winding, based on FEA, which takes into account only a specific wire distribution, could be affected by other errors, especially for high frequency application where the AC losses are significantly dependant on the frequency.

Thus, this design approach could lead to an overestimation or underestimation of the losses, considering that the even an automated (or semi-automated) manufacturing process cannot guarantee the same positioning of the wires for all the batches of machines produced. Furthermore, variations in AC losses will also affect the performance of the cooling systems, and a resultant hotspot is likely to lead to insulation failures.

FEA and analytical methods highlight an important drawback on the importance of predicting the strands' position which can significantly impact the accuracy of the result.

Furthermore in variable speed drives the mission profile that the electrical machine needs to deliver is possible only through the power electronic control. The latter introduces additional harmonics which can significantly increase the AC losses.

From the foregoing discussions, since it is impossible to predict the strands position in the slot, which are randomly displaced, and since their position can significantly affect the AC losses - especially at higher frequencies - the conventional (FEA and analytical) methods are not robust enough.

Therefore, to overcome the aforementioned issue, this work proposes an Experimental Statistic Method (ESM) which evaluates the probability to have a certain amount of losses. The ESM provides the parameters required to describe the probability density of the AC losses for a certain geometry and a certain winding configuration, which becomes useful in designing the winding especially for series production where the process is semiautomatic and the strands position changes every time.

This paper is organized as follows: in section II, the analytical and FE methods are described and discussed. In section III, the proposed ESM is introduced. In section IV details about the case study investigated are given. In section V, two experimental setups are described, the first one is related to the ESM and the second one is related to the PWM effect evaluation. Finally, the conclusions from this research are drawn in section VI.

II. Conventional Methods

In this section both analytical and FE methods, which are commonly used to predict the AC losses for high frequency applications, are reported.

The hypothesis of all the analytical methods presented in literature, is that the slot height is higher than the slot width (by over 3 times), and hence it can be assumed that the radial component of the magnetic field is negligible compared to the tangential one. This assumption is as much verified as much farer the conductor is from the slot opening and the bottom of the slot, where both contributes of the field are significant. In the Fig.1 it is shown how it changes the field path with the slot geometry. Under such assumptions a 1-D analytical model is considered as a good compromise between accuracy and implementation effort. A strand level FE model is built in this section and the results obtained with both methods are compared and discussed.

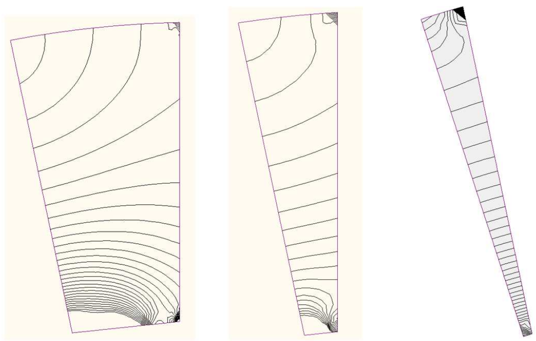

Fig. 1. Magnetic field path: a) ratio high/width equal to 1.8, b) ratio high/width equal to 3.8,c) ratio high/width equal to 7.2

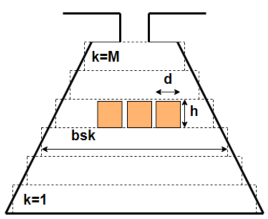

Fig. 2. Sketch of one slot: discretized domain.

A. Analytical Method.

The total AC winding losses as a function of the frequency *f* are given by the contribution of four terms:

$$P_{AC}(f) = P_{DC} + P_{skin}(f) + P_{prox}(f) + P_{circ}(f) \quad (1)$$

Where P_{DC} represent the DC losses, $P_{skin}(f)$ describe the skin effect, $P_{prox}(f)$ take into account the proximity losses and $P_{circ}(f)$ take into account the circulating current losses.
It is possible to analytically calculate the DC losses accurately by knowledge of the winding DC resistance:

$$R_{DC} = \frac{n_{turns}\,\rho_{cu}\,l_{stk}}{Area_{cu}} \quad (2)$$

Where n_{turns} is number of turns, ρ_{cu} is the copper resistivity, l_{stk} is the stack length, while $Area_{cu}$ is the copper cross section.
The DC losses can be reduced by increasing the slot fill factor. Without significant loss in accuracy, P_{skin} and P_{prox} can be neglected in the end winding [20]. It is possible to express the other elements of (1) with a dimensionless AC loss factor K_{AC}

$$P_{AC} = K_{AC}(f) * P_{DC} \quad (3)$$

K_{AC} is a function of η which define the ratio between the conductor diameter *D* and the skin depth.

$$\eta = \frac{D}{\delta}\,;\, \delta = \sqrt{\frac{1}{\Pi * \sigma * f * \mu_0}} \quad (4)$$

Where σ is the copper conductivity and μ_0 is the void permeability. The model below, presented in [21], is very accurate under its hypothesis, and is used to predict losses for a real case study, where some hypotheses are not fully respected. The authors in [21] considered the following assumptions: 1) Permeability of iron core is infinite; 2) End effects are neglected; 3) Magnetic field lines are horizontal across the slots; 4) Sinusoidal current is applied to conductors; 5) Conductors are positioned in floors with height equal to the diameter of conductors D as shown in Fig.2.
From the Maxwell equations (5) and (6) below:

$$\nabla x B = \mu J \quad (5)$$

where B= μH;

$$\nabla x E = -\frac{\delta B}{\delta t} \quad (6)$$

where $J = \sigma E$; the active power relative to the n_k conductors in the k-th floor can be expressed as:

$$P_{0k} = \frac{\lambda l}{2\sigma b_{ck}}\left[i_0^2 n_k \frac{\sinh(2\varepsilon)+\sin(2\varepsilon)}{\cosh(2\varepsilon)-\cos(2\varepsilon)} + \frac{2I_{0k}(I_{0k}+i_0 n_k)}{n_k}\frac{\sinh(\varepsilon)-\sin(\varepsilon)}{\cosh(\varepsilon)+\cos(\varepsilon)}\right] \quad (7)$$

where:

$$\varepsilon = \lambda h = h\sqrt{\frac{b_{ck}\,\omega\sigma\mu_0}{b_{sk}\,2}}\;;\, b_{ck} = d n_k\;;\, I_{0k} = \sum_0^{k-1} i_0 n_k \quad (8)$$

Where b_{ck} is the effective copper width, while b_{sk} is the corresponding slot width. ω is the electrical pulsation and I_{0k} is the floor current.

B. Finite Element Model

To evaluate the AC losses, the machine is analyzed by means of 2D FE, using commercially available FE software package MagNet from Mentor Graphics. A strand level model is realized to be able to estimate the AC Losses. A mesh sensitivity analysis was performed. Time harmonic simulations are used with the electrical circuit fed by a sinusoidal current.
The stator core is made using silicon iron (SiFe) laminations of grade M270-35A. The coil's material is copper with a conductivity of 5.77×10^7[S/m].Two different stators featuring trapezoidal slots and with 2 and 4 slots per pole per phase (q) respectively, are considered in this work.
Fig. 3 shows in detail the FE models where each bundle is highlighted with a different color. In Fig. 3 (a) and (b), where the slot per pole per phase number is 'q' = 2 (q2), the turns are distributed vertically (VT) in (a) and horizontally (HZ) in (b), respectively. The turns are numbered from 1 to 16. On the

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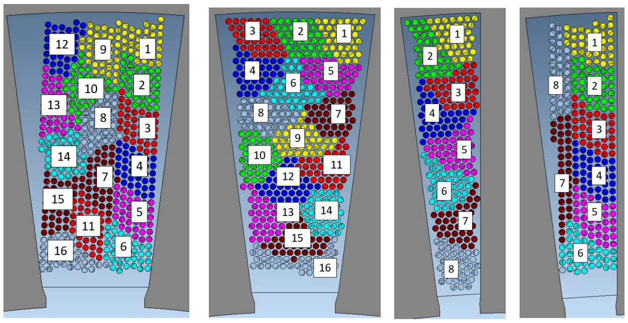

a) (b) (c) (d)

Fig. 3. Finite Element Models: a) q2_VT, b) q2_HZ, c) q4_VT, d) q4_HZ.

other hand, in Fig. 3 (c) and (d), for q = 4, the turns are numbered from 1 to 8, with (c) and (d) corresponding again to vertical (VT) and horizontal (HZ) distributions, respectively.
Since the AC losses mainly depend on the leakage flux in the slot [20], only one slot is modeled at the strand level in order to reduce the computational time. The AC losses are then given by the modeled slot multiplied by the number of slots per phase. To reduce the computational time and in order to have an accurate estimation, two different circuits are realized as shown in Fig.4 (c) and (d). The first circuit, which is more time consuming, considers all the strands in the slot and each conductor is defined as "solid" in order to consider the uneven distribution of the current. The second circuit considers that the rest of the slots are defined as "stranded", where the current distribution is considered even. This methodology presents the advantage of a lower computational time, while it estimates the copper losses and reproduces the field in the slot accurately.
The winding is modeled in two different ways for both stators in order to consider two different winding configurations with different strand positions.

C. Results

The results obtained with the described analytical and FE models are compared. In the FEA, the circuit, shown in Fig.4, is energized with a sinusoidal current with RMS values of 7 A and 14 A. For each current value, the frequency is varied from 0Hz to 1000 Hz, in steps of 100Hz. The results confirm that K_{AC} is independent from the current magnitude.
In Fig. 5 the current distribution and the flux density map are shown. The two slots in both Fig. 5 a) and b) show that one slot is representing all individual strands, while the adjacent slot is without strands. In fact, for the latter the current is considered uniformly distributed (like in the case supplied by direct current).
In Fig. 6, K_{AC} as obtained from FE and analytical methods is shown as a function of the frequency. It is clear that there is a mismatch between the analytical results and the FE ones, especially for frequencies above 200 Hz. This difference is because the analytical model considers a 1D field and it is not able to capture the circulating current contribution. The FEA considers a 2D field and thus it is able to capture also the circulating current effect as shown in Fig.5. For ease of comparative reference, in Fig. 7, the error between FE and analytical prediction is shown. In addition, as the frequency increases, the FE analysis shows that the influence of the positions on the AC losses increases as well.

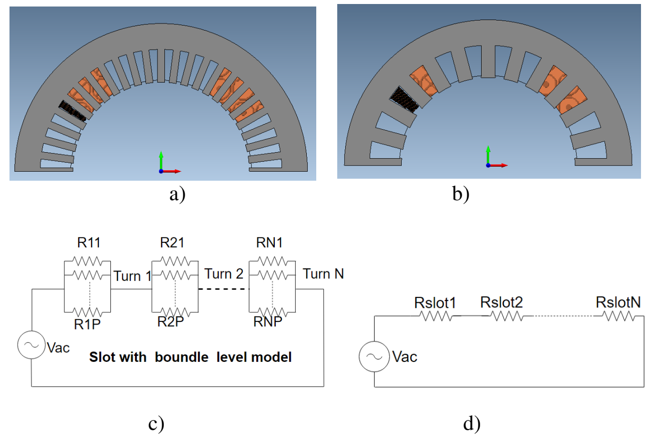

Fig. 4. Finite Element Models: a) motorette_q4, b) motorette_q2, c) circuit of detailed slot, d) circuit of non detailed slots.

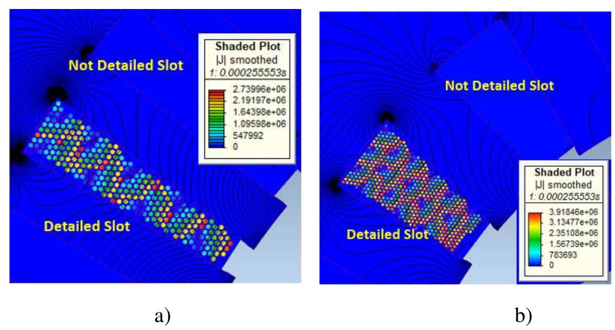

Fig. 5. Current density distribution: a) Motorette_q4, b) Motorette_q2.

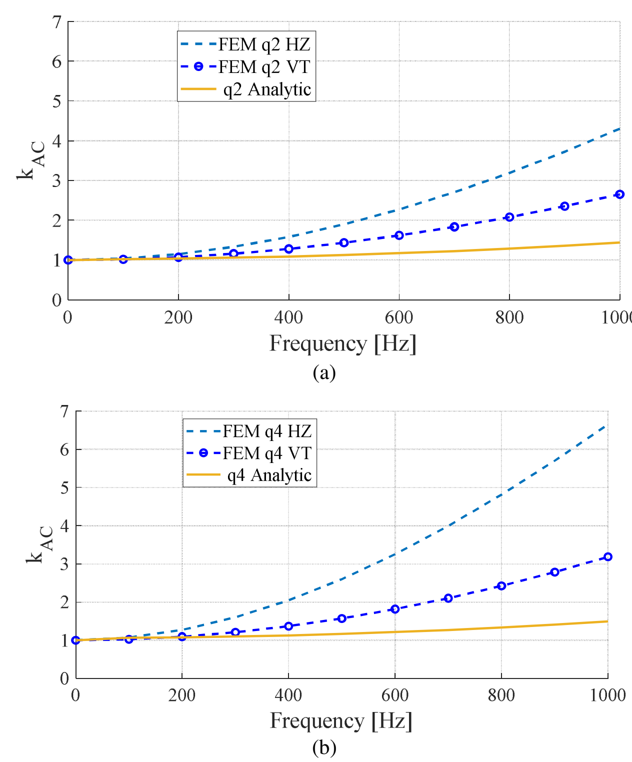

Fig. 6. Analytical Vs FEA results: a) Stator with q=2, b) Stator with q=4.

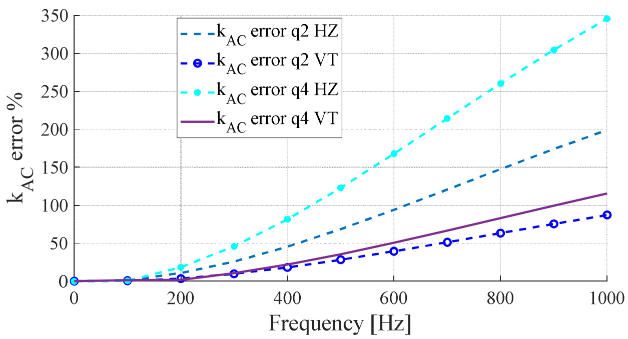

Fig. 7. K_{AC} error between analytical method and FE models.

III. Experimental Statistical Method (ESM)

A. Basics of Statistics

As demonstrated in the previous section, the AC losses are dependent on the strands' position. It is impossible to predict without any error the strands' position. The error in predicting the strands' position can be considered as a random variable, and in such case a statistical approach is needed.

Each error obtained in predicting the AC losses during a measurement can be called an observation. A large set of 'N' observations represent the population, while a small set of 'n'-observations represent a sample. The probability distribution describes the probability to have the event x_i of the population. Different types of probability distribution are present.

The central limit theorem says that, under conditions almost always satisfied in the real world of experimentation, the distribution of a linear function of errors will tend to a normal distribution as the number of its components becomes large. In [22], it is stated that at least thirty events are required in order to have an approximation to a normal distribution.

The function of the normal distribution Eq.(9) is fully described by two parameters : mean μ described in Eq.(10), called also the mathematical expectation of x_i and the standard deviation in Eq.(11) which define the spread of the distribution. These two parameters are important to provide information also for the other kind of probability distribution present in literature. Fig. 8 shows the normal distribution for different values of standard deviations.

$$f(x) = \frac{1}{\sigma\sqrt{2\,\pi}}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{9}$$

where

$$\mu = \frac{1}{N}\sum_i^N x_i \tag{10}$$

$$\sigma = \sqrt{\sigma^2} = \sqrt{\frac{\sum_i^N (x_i-\mu)^2}{N}} \tag{11}$$

The range $\mu \pm \sigma$ has the 68% of the probability to include an event x_i, while for the range $\mu \pm 2\sigma$ the corresponding probability is 95%. The greater the range the higher is the probability that it includes an event x_i .The normally distributed quantity 'x' is often best expressed in terms of a standardized normal deviation as per eq (12). Using the values reported in [22] it is possible to obtain the probability of the event x_1.

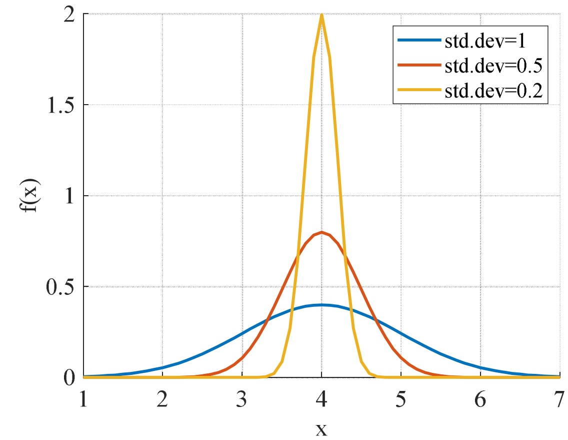

Fig. 8. Normal Distribution Example with $\mu = 4$ and $\sigma = 1, 0.5, 0.2$.

$$z_i = \frac{(x_1-\mu)}{\sigma} \tag{12}$$

B. Description of the ESM

Since it is impossible to predict the position of each strand in a random winding, an ESM is proposed to address this issue. AC losses are highly dependent on the strands' positions, which can have a number of different combinations. This method aims to identify the parameters needed to define the Probability distribution of AC losses for a certain winding configuration. Using the same amount of copper in the winding in order to maintain the same length, material properties and DC electrical resistance, the motorettes which are a section of the stator as shown in Fig.8 are physically wound for thirty times in order to have thirty events of x_i.

For each configuration the AC losses are evaluated for two different RMS current values (7 A, 14 A) and in a frequency range from 100 Hz to 1000 Hz. Mean and standard deviations are calculated for each frequency.

IV. Case Study

The case study considered is a machine designed for automotive traction with power and maximum speed equal to 115 kW and 19000 rpm, respectively.

Being the scope of this work to validate the method proposed, only a portion of the total real phase present in the machine has been built for the motorette. It is needed to highlight that to estimate the real total losses in the machine it is necessary to consider all series coils of the total phase and in addition the circulating currents depend from the uneven distribution due to the total per strand and phase inductances of all the parallel strands of the complete phase. According to [19] it is sufficient to wind motorettes instead the full stator for a good approximation of the AC losses.

Two motorettes with trapezoidal slots are prototyped, with 2 and 4 slots per pole per phase as shown in Fig. 9 and Fig. 10 respectively. Their geometries are given in Table I.

The DC bus voltage in EVs is steadily increasing during the last few years, and nowadays this is in the range from 360 V to 700

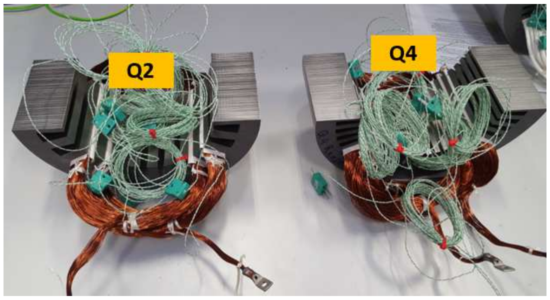

Fig. 9. Case study motorettes: with q=2 (left hand side) and q=4 (right hand side).

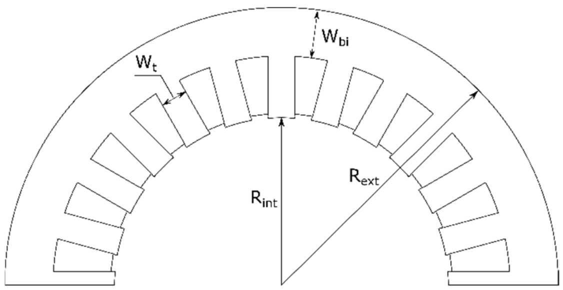

Fig. 10. Motorette parametric drawing.

TABLE I
MOTORETTE GEOMETRICAL PARAMETERS

Parameter	Description	Value(mm) Q2	Q4
R_{int}	Inner stator radius	65	65
R_{ext}	External stator radius	116.12	116.12
W_{bi}	Back-Iron height	20.4	20.4
W_t	Tooth width	10	5

TABLE II
WINDING DETAILS

Parameter	Value Q2	Q4
Strands in hand	32	32
Turns per phase	16	8
Copper diameter(mm)	0.56	0.56
Slot Filling Factor (%)	44	44

V for automotive applications [23]. In light of this, operations at high currents and high frequency require the windings to be designed with parallel paths [23]. In this work, the DC-link is set to 600 V. In Table II details about the winding are given.

V. EXPERIMENTAL CHARACTERIZATION

A. *Experimental Setup*

As mentioned in the introduction, two different experimental tests have been performed in this research. The first one aims to define the parameters (μ, σ) needed to have a description of the function distributions with the circuit energized with a pure sinusoidal current as shown in Fig. 11. The second one aims to estimate the losses when the motorettes are supplied by a PWM converter as shown in Fig. 12.

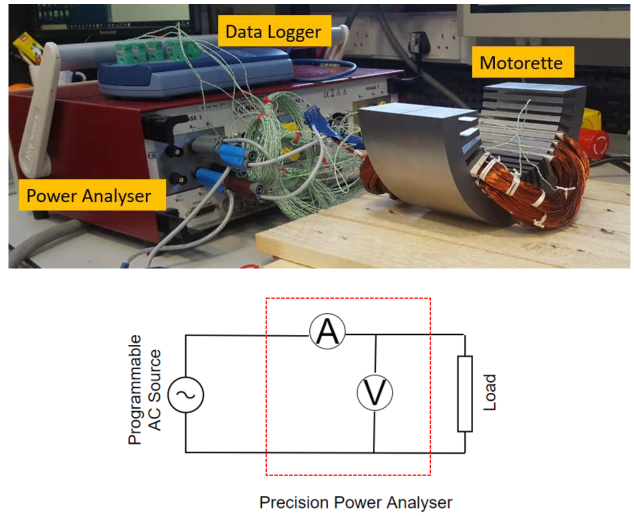

Fig. 11. Pure sine wave experimental set up and schematic layout.

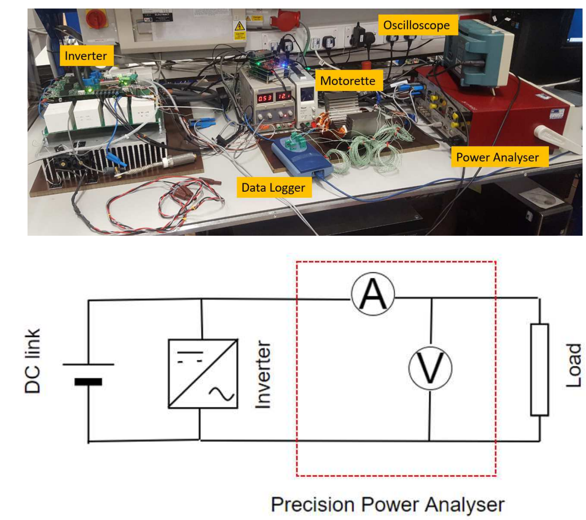

Fig. 12.PWM experimental setup and schematic layout.

Set-up for circuit fed with Pure Sinusoidal Current

A variable frequency power supply (CHROMA 61511, Programmable AC source up to 1kHz) is used to supply the motorettes. The total power loss is measured by a precision power analyzer (PPA 5530), shown in Fig.11. All the measurements are taken at the same winding temperature ($20°C$). The winding temperatures, during the tests, are monitored in real time with six K-type thermocouples placed in different positions inside the slot, in the end-windings and connected to a PICO TC-08 data logger. A high-velocity cooling fan is used to cool down the motorettes.

Set-up for circuit fed with Inverter

In this case, the motorettes are supplied by a full bridge converter. In order to quantify the harmonics contribution, an oscilloscope is used. The DC/AC inverter shown in Fig. 8 is controlled by a custom control platform built around the

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Microzed board based on the Zynq SoC (System on Chip) from Xilinx.

Sampling and switching frequencies are synchronized. The inverter is a custom DC/AC converter based on Silicon Carbide power modules (CAS120M12BM2) from Wolfspeed, a CREE company. The maximum switching frequency allowed by the custom gate drivers is 40kHz. Cooling system is air forced through the heatsink as shown in Fig. 12.

B. Iron loss separation

Since only the total loss measurements are available, it is impossible to separate the iron losses and the copper losses experimentally. Therefore, an iron loss estimation is needed.

TABLE III
MATERIAL COEFFICIENT FOR 0.35 MM SILICON IRON LAMINATION (20C)

Parameter	Value
α	1.207
β	1.771
K_h	0.009
K_e	3.244e-05

For sinusoidal excitation, the iron loss generated in the laminated core stack are calculated using the Steinmetz equation in each element of the meshed region and then averaged over the entire volume:

$$P = K_h f^{\alpha} B^{\beta} + K_e (sfB)^2 \quad (13)$$

Table III lists the material coefficients used for the iron loss predictions, which were derived from curve fitting of (13) from the material data provided by manufacturer.

C. Experimental Results

In this section, the results obtained with the two different setups are shown. The aim is to define the parameters useful to describe the distribution which are needed to predict the AC losses for this case study. In addition, the losses of the winding supplied with the PWM controlled inverter are experimentally evaluated for different switching frequencies.

Motorette fed with Pure Sinusoidal Current

Thanks to the equations (10) and (11) it is possible to calculate the mean (μ) and standard deviation (σ), where x_i is the K_{AC} of each measurement, while N is the total number of measurements, which in this case is equal to 30.The P_{DC} for both motorette is measured with a precision power meter for 7 amps and 14 amps. The motorette with q=2 has P_{DC} =2.55W and P_{DC} =10.21W respectively for 7amps and 14amps, instead the motorette with q=4 has P_{DC} =2.46W and P_{DC} =9.86W .In table IV there are these values obtained for the two motorette configurations at different frequencies. From the same table, the variance of K_{AC} increases with the frequency.

This confirms that the higher the frequency, the greater is the dependence of the losses on the position of the conductors. Fig. 13 and Fig.14 show the losses evaluated with the three methods at 1000 Hz, for 2 and 4 slots per pole per phase. With the red line is given an approximation of the distribution of to the histogram diagram which represent the experimental results with the K_{AC} value in the x-axis and in the y-axis there are the frequency of measures with K_{AC} in a defined range.

The analytical model shown a difference with respect to the experimental results, as expected, being unable to describe all the loss contributions. This method can lead to a wrong design of the cooling system.

In a production environment, with a considerable number of motors, the most reliable value to consider is the mean (μ). Around 68% of the windings manufactured have a value inside the range $\mu \pm \sigma$. The FEM method provides results that are true only for some particular cases, with a low probability to be verified. For example, considering the model FEM_q4_HZ at 1000Hz, thanks to the eq.12, where x_i is the K_{AC} value of the model (equal to 6.655), while μ and σ are in the table IV, it is possible to note that this event has the 0.0158% of probability to be verified.

The FEA can represent only a particular case that could be the worst one or the best one. Considering the models FEM_q4_HZ and FEM_q4_VT the first one has K_{AC} more than double compared to the second one. These values can underestimate or overestimate the losses and can lead to an inappropriate design of the cooling system.

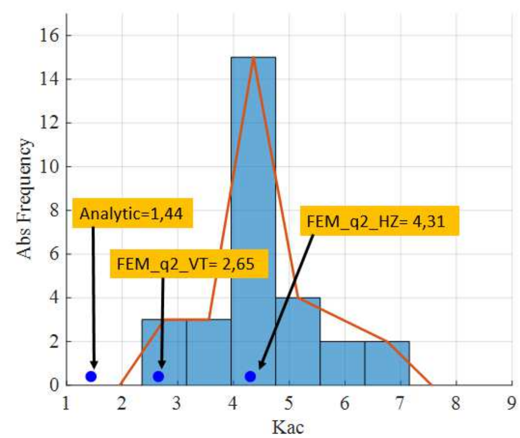

Fig. 13. Experimental Absolute Frequency of K_{AC} for motorette with q=2 at 1000Hz.

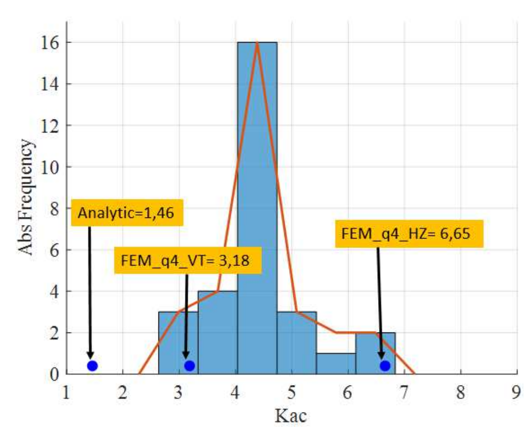

Fig. 14. Experimental Absolute Frequency of K_{AC} for motorette with q=4 at 1000Hz.

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TABLE IV
μ AND σ VALUE OF K_{ac} PROBABILITY DISTRIBUTION

Frequency (Hz)	μ Q2	μ Q4	σ Q2	σ Q4
100	1.30	1.20	0.14	0.10
200	1.81	1.36	0.41	0.16
300	2.23	1.64	0.54	0.31
400	2.61	1.96	0.61	0.39
500	2.93	2.26	0.71	0.48
600	3.30	2.59	0.85	0.56
700	3.71	2.95	0.90	0.64
800	4.00	3.38	1.06	0.86
900	4.29	3.78	1.21	0.96
1000	4.75	4.12	1.30	1.18

Motorette fed with Inverter

The harmonic contribution is related to the switching frequency of the PWM inverter. Three different values are chosen: 10kHz, 20kHz and 40kHz (maximum switching frequency of the converter). Fig. 15 shows the waveforms of the three different currents feeding the circuit.
Fig. 16 and Fig.17 shows the increment of AC losses, represented by the loss factor coefficient K_{AC}, due to the PWM effect. Compared to the pure sinusoidal current, the losses increase up to 35% when the fundamental is 1000 kHz as per Table V and Table VI.

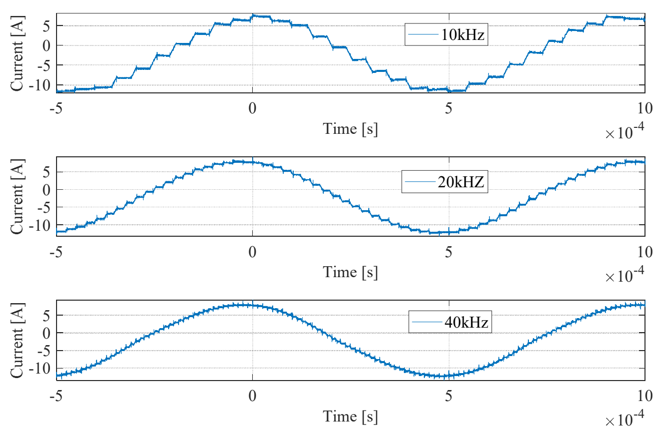

Fig. 15. Current waveforms for different switching frequencies: 10kHz, 20kHz, 40kHz.

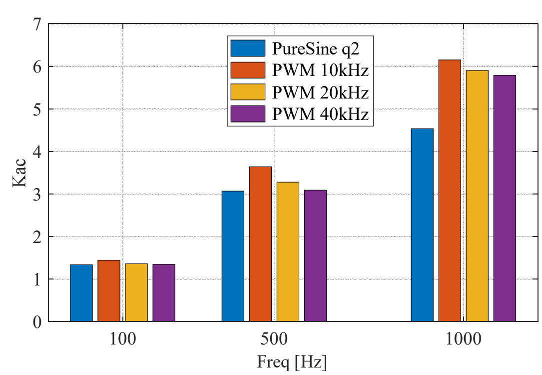

Fig. 16. Experimental K_{AC} obtained with pure sine and PWM for q=2.

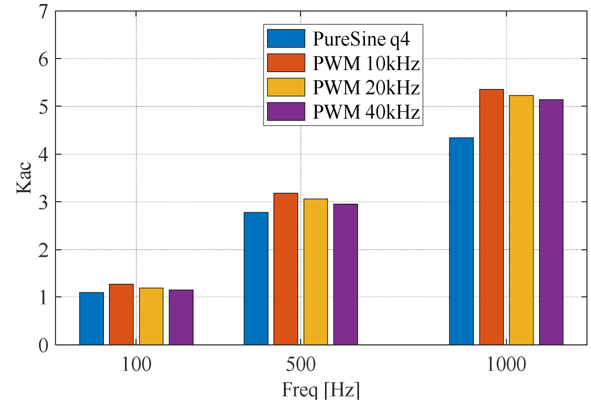

Fig. 17. Experimental K_{AC} obtained with pure sine and PWM for q=4.

TABLE VI
INCREASING OF LOSSES COMPARED WITH PURE SINE Q4

Frequency (Hz)	PWM_10	PWM_20	PWM_40
100	3.98%	2.18%	1.14%
500	9.35%	6.53%	4.15%
1000	23.31%	20.44%	18.47%

TABLE V
INCREASING OF LOSSES COMPARED WITH PURE SINE Q2

Frequency (Hz)	PWM_10	PWM_20	PWM_40
100	2.45%	0.53%	0.19%
500	12.57%	4.66%	0.4%
1000	35.72%	30.17%	27.71%

VI. Conclusion

In this work, AC losses in random windings have been evaluated. AC losses are highly dependent on the strands' position, especially at higher frequencies.
In production lines where the machine design is the same for all the batches, each winding manufactured presents some differences in the strands distribution, thus different winding losses arise.
The analytical and FE methods are not able to predict the random position of a real winding. For this reason, an Experimental Statistical Method, which is able to predict the AC losses in randomly distributed windings has been developed. The aim of the work is to determine the parameters needed to define the probability distribution, useful at system level while designing the motor winding as well as the associated cooling arrangement. In addition, the PWM effect on the total AC losses is evaluated and compared against the AC losses generated when supplying a sinusoidal current.
In this work, it is demonstrated that the estimation of the losses by analytical approach is not reliable and is not representing well the losses of machines manufactured in series. Parameters such as mean and standard deviations, providing information about the distribution, are determined for different frequencies on both motorettes analyzed.
This built the basis for future work where is planned to do a much higher number of experiments in order to have the

necessary data helpful to identify with precision the kind of distribution. Additionally also a more robust algorithm able to represent different slot layouts in FEM is planned to do with the aim to have more data also from simulations and to verify if the probability distributions from experimental tests and simulations are close each other.

These parameters are dependent on the frequency but not on the current amplitude. AC losses values obtained by FEA are contained into function distributions defined with ESM, while the analytical method gave results out of this distribution. The FEA results might not be reliable for all the production batches. ESM demonstrates that the AC losses are heavily affected by the conductor position across the whole frequency range.

REFERENCES

[1] "The roadmap for transforming the EU into a competitive, low carbon economy by 2050," 2016. [Online]. Available: ec.europa.eu/ clima/sites/clima/.

[2] V. Madonna, A. Walker, P. Giangrande, G. Serra, C. Gerada, and M. Galea, "Improved Thermal Management and Analysis for Stator End-Windings of Electrical Machines," IEEE Transactions on Industrial Electronics, vol. 66, pp. 5057-5069, 2019.

[3] "Electrical and Electronics Technical Team Roadmap," [Online]. Available: https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Ro admap%2010-27-17.pdf, Accessed on: Dec. 12, 2018.

[4] Wrobel, D. Staton, R. Lock, J. Booker and D. Drury, "Winding Design for Minimum Power Loss and Low-Cost Manufacture in Application to Fixed-Speed PM Generator," in *IEEE Transactions on Industry Applications*, vol. 51, no. 5, pp. 3773-3782, Sept.-Oct. 2015.

[5] S. Nuzzo *et al.*, "A Methodology to Remove Stator Skew in Small–Medium Size Synchronous Generators via Innovative Damper Cage Designs," in *IEEE Transactions on Industrial Electronics*, vol. 66, no. 6, pp. 4296-4307, June 2019

[6] D. Fallows, S. Nuzzo, A. Costabeber and M. Galea, "Harmonic reduction methods for electrical generation: a review," in *IET Generation, Transmission & Distribution*, vol. 12, no. 13, pp. 3107-3113, 31 7 2018.

[7] P. Mellor, R. Wrobel and N. Simpson, "AC losses in high frequency electrical machine windings formed from large section conductors," *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Pittsburgh, PA, 2014, pp. 5563-5570.

[8] P. L. Dowell, "Effects of eddy currents in transformer windings," Proc.IEE, vol. 113, no. 8, pp. 1387–1394, Aug. 1966.

[9] J. A. Ferreira, "Improved analytical modeling of conductive losses in magnetic components," in *IEEE Transactions on Power Electronics*, vol. 9, no. 1, pp. 127-131, Jan. 1994.

[10] R. P. Wojda and M. K. Kazimierczuk, "Analytical optimization of s olidround-wire windings," IEEE Trans. Ind. Electron., vol. 60, no. 3, pp. 1033–1041, Mar. 2013

[11] M. M. Liwschitz-Garik, "Computation of skin effect in bars of squirrelcage rotors," Trans. Amer. Inst. Elect. Eng. Part III, Power App. Syst.,vol. 74, no. 3, pp. 768–771, Jan. 1955.

[12] A. Reatti and M. K. Kazimierczuk, "Comparison of various methods for calculating the AC resistance of inductors," IEEE Trans. Magn., vol. 38, no. 3, pp. 1512–1518, May 2002.

[13] T. Lubin, S. Mezani, and A. Rezzoug, "Analytical calculation of eddy currents in the slots of electrical machines: application to cage rotor induction motors," IEEE Trans. Magn., vol. 47, no. 11, pp. 4650–4659, Nov. 2011.

[14] L. J.Wu, Z. Q. Zhu, D. Staton, M. Popescu, and D. Hawkins, "Analytical model of eddy current loss in windings of permanent-magnet machines accounting for load," IEEE Trans. Magn., vol. 48, no. 7, pp. 2138–2151, Jul. 2012.

[15] C. Roth, F. Birnkammer and D. Gerling, "Analytical Model for AC Loss Calculation Applied to Parallel Conductors in Electrical Machines," *2018 XIII International Conference on Electrical Machines (ICEM)*, Alexandroupoli, 2018, pp. 1088-1094.

[16] P. Mellor, R. Wrobel, D. Salt and A. Griffo, "Experimental and analytical determination of proximity losses in a high-speed PM machine," *2013 IEEE Energy Conversion Congress and Exposition*, Denver, CO, 2013, pp. 3504-3511.

[17] I. Petrov, M. Polikarpova, P. Ponomarev, P. Lindh and J. Pyrhönen, "Investigation of additional AC losses in tooth-coil winding PMSM with high electrical frequency," *2016 XXII International Conference on Electrical Machines (ICEM)*, Lausanne, 2016, pp. 1841-1846.

[18] D. Bauer, P. Mamuschkin, H. Reuss and E. Nolle, "Influence of parallel wire placement on the AC copper losses in electrical machines," *2015 IEEE International Electric Machines & Drives Conference (IEMDC)*, Coeur d'Alene, ID, 2015, pp. 1247-1253.

[19] A. Bardalai *et al.*, "Reduction of Winding AC Losses by Accurate Conductor Placement in High Frequency Electrical Machines," in *IEEE Transactions on Industry Applications*, vol. 56, no. 1, pp. 183-193, Jan.-Feb. 2020.

[20] H. Hämäläinen, J. Pyrhönen and J. Nerg, "AC Resistance Factor in One-Layer Form-Wound Winding Used in Rotating Electrical Machines," in IEEE Transactions on Magnetics, vol. 49, no. 6, pp. 2967-2973, June 2013.

[21] S. Xu and H. Ren, "Analytical Computation for AC Resistance and Reactance of Electric Machine Windings in Ferromagnetic Slots," in *IEEE Transactions on Energy Conversion*, vol. 33, no. 4, pp. 1855-1864, Dec. 2018

[22] *George E. P. Box, J. Stuart Hunter, William G. Hunter - Statistics for Experimenters_ Design, Innovation, and Discovery, Second Edition (2005).*

[23] N. Bianchi and G. Berardi, "Analytical Approach to Design Hairpin Windings in High Performance Electric Vehicle Motors," *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, Portland, OR, 2018, pp. 4398-4405.

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