A Comparative Study of Additively Manufactured Low-Power-Loss Windings for PM Machines

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Keywords: ELECTRICAL WINDING, ADDITIVE MANUFACTURING, POWER LOSS, PM MACHINE

Abstract

This theoretical study explores concepts of electrical windings in application to low-voltage permanent magnet (PM) machines. The research focus has been placed on low-power-loss winding designs, with the use of modern additive manufacturing (AM) techniques in mind. A case study PM machine with concentrated winding topology has been used to demonstrate how the AM enabled winding concepts compare with the more conventional constructions. To make the comparison more relevant, the theoretical body of work has been supported with the existing know-how in electrical machines construction and latest developments in AM. The research findings suggest that the AM winding concepts offer similar power losses with simpler winding fabrication and assembly, subject to further advancement in AM.

1 Introduction

The design process of the low-voltage electrical windings is governed by a number of principles, one of which stipulates the low-power-loss winding operation. The low-power-loss requirement is typically achieved by assuring a ‘good’ stator-slot utilisation, which corresponds to a ‘high’ conductor fill factor (low dc winding power loss) [1]-[3]. It is important to note that the power loss analysis is usually accompanied with an appropriate thermal design-study to ensure effective heat (power loss) removal from the winding body [4]-[6].

As the modern applications of PM machines often require operation at high speeds/frequencies, the winding construction with ‘high’ conductor fill factor is no longer sufficient [4]-[6]. This is due to the high-frequency winding effects including skin, proximity and rotational, which need to be carefully balanced to provide the low-power-loss winding design. It is important to note here, that the rotational effect refers to the winding ac power loss induced by variation of the magnetic flux leakage due to rotation of PM rotor. The rotational winding ac power loss is present event at open-circuit operation, i.e. no excitation/terminal current present. There are several techniques for reducing the ac winding power losses with the use of appropriate conductor size, profile and lay among others [1]-[6].

In the context of high-volume applications, e.g. automotive industry, the design solutions assuring low-cost and repeatable manufacturing are preferred. But, the existing low-power-loss winding designs are limited by the commonly used materials and fabrication methods. If these constraints of manufacturing windings were to be removed, new avenues of windings design could be considered/explored. The additive manufacturing (AM) has shown a great potential across multitude of application and might be the new technology enabling future low-power-loss winding designs [7]-[10], [15].

The use of AM has been explored by several authors in the context of construction of electrical machines. All vital machine subassemblies have been trailed including the

electrical windings. It has been demonstrated that the existing AM allows for fabrication of both aluminium (AlSi10Mg) and copper (CuCr1Zr) alloys based concentrated windings [10]. The material alloying required for AM has some detrimental effects on the winding thermal and electrical conductivity [7], [9]. In particular, the electrical conductivity of AM copper components has been shown to be between 75% and 90% of that given by the International Annealed Copper Standard (IACS).

Clearly, the use of less electrically conductive winding material will have an adverse impact on the power loss of the AM windings. In this theoretical study, the authors attempts to answer the following question: could the use of current AM techniques produce electrical windings with similar power loss and level of manufacturing/assembly complexity as for the more conventional design solutions? The theoretical findings discussed in this paper suggest that some of the analysed AM winding concepts generate power losses comparable to the more conventional winding builds. Also, the AM of windings offers potentially simpler fabrication and assembly processes, both of which are to be explored in more detail as the AM of windings matures.

2. Case Study

As a baseline for this study, a machine design with 16 poles and 24 slots and double-layer concentrated winding has been assumed (rated power, 80kW and rated rotational speed 8,000rpm). The magnetic loading, B_1 , is equal to 1.0T (with sinusoidal variation of the air-gap magnetic flux density) and electric loading, Q_{rms} , is in range from 60,000A/m to 80,000A/m (approximate rated conductor current density, $10A_{rms}/mm^2$). The fundamental operating frequency is approximately 1kHz and consequently the ac winding effects are expected to be non-negligible, here. Fig. 1a) – WVA presents a model representation of the stator-winding assembly. It is assumed here that the stator is segmented,

a) – winding variant A (WVA)

b) – winding variant B (WVB)

c) – winding variant C (WVC)

d) – winding variant D (WVD)

Fig. 1. Alternative winding designs, a) conventional (baseline) winding with round profile conductor (48 turns, 1.7mm diameter, $k_p = 56\%$) - WVA, b) conventional with rectangular edge wound conductor (12 turns, 1.7mm $\times$ 6mm, $k_p = 64\%$) - WVB, c) AM with horizontally laminated conductors (12 turns, 1.7mm $\times$ 6mm, $k_p = 64\%$) - WVC, d) AM with 'variable' profile laminated conductors (12 turns, 'variable profile' conductor, $k_p = 79\%$) - WVD, where k_p is the conductor fill factor (maximum theoretical value for a given winding construction)

which allows for the winding to be precision wound directly on the tooth body, with a single round profile conductor per turn (approximate conductor diameter, 1.7mm). Such stator-winding construction is rather common across the automotive industry, in particular when hybrid vehicles are considered. In this analysis, relatively large number of conductors per tooth

is considered, 48, which encourages parallel connection of individual coils per phase, for a given dc link voltage limit. The high number of turns per tooth leads to reduced diameter of an individual conductor per turn, and consequently results in reduced ac winding power loss. A drawback of such design is lesser stator-slot utilisation as compared with alternative designs, e.g. edge wound winding with rectangular profile conductor, WVB – Fig. 1b). Here, however the rotational ac power loss is particularly challenging due to open-slot stator topology required to accommodate for the preformed winding. To mitigate the rotational ac effect, the conductor's size close to the slot opening needs to be appropriately reduced. This might be difficult to achieve when using conventional winding methods, as the use of multi-stranded bundle of conductors would have a detrimental effect on the overall winding power loss or cost, e.g. if a 'random' or Litz wire was to be considered.

Fig. 1c) – WVC presents an AM winding concept where, the winding turns close to slot opening are 'laminated' along the conductor's length, e.g. active length. Such a construction forms local parallel paths of smaller conductors resulting in reduced rotational ac winding effects. As the 'lamination' process involves leaving gaps between parallel paths during AM process, the overall conductor size would need to be adjusted to provide identical dc resistance per turn for the solid and 'laminated' conductors. Fig. 1d) – WVD shows another winding concept enabled by AM. Here, the individual conductor dimensions per turn are adjusted to fully utilise the stator slot to compensate for lower electrical conductivity of copper alloy used in AM. The drawback of such design is that the conductor characteristic dimension (conductor thickness) is larger towards the slot opening. This is expected to have a detrimental effect on the excitation induced ac winding power loss. Note that the overall conductor cross-section area is identical for each of the winding turns.

3 Analysis

The theoretical investigation presented in this paper is based on two- (2D) and three-dimensional (3D) time-stepping finite element analyses (FEAs) of selected winding variants, some of which were discussed in the previous section. In all analysed cases, the winding input Ampere turns product (rated, 1,200A_{rms} turn) is the same, accounting for the specific winding/coils electrical connections per a single phase. The excitation current has an ideal-sinusoidal time variation. Also, for the initial study, the winding temperature is fixed to 20°C. Both the excitation (maximum torque per Ampere (MTPA)) and rotational (open-circuit) ac winding power loss components are analysed in detail. It is important to mention that in this analysis the end-winding model representation does not account for any conductor cross-over or displacement, which are required for practical-hardware implementation of the analysed winding variants, Fig. 1. However, as the end-winding region exhibits significantly lower ac power loss, the exact conductor lay in FEAs is usually of lesser importance. The initial results from 3D FEAs have confirmed that the end-winding ac effects are insignificant and consequently 2D FEAs have been used for majority of the analysed windings. Note that both stator and rotor assemblies are included in the FEAs.

Fig. 2. Distribution of current density (absolute value at a single time step) in the top turn of the edge-wound winding at 8,000rpm, a) conventional edge-wound winding construction - WVB, b) AM enabled winding concepts with parallel path (9 parallel paths per conductor width) – WVC

In the FEAs, the individual conductors are represented as solid conductors, which are linked with an appropriate external circuit emulating electrical connections between individual conductors/coils/phases, where appropriate. Also, electrical conductivity of the conductors is assumed to be 100% IACS for the baseline winding and 75%-90% IACS for the AM winding concepts, when analysing power losses for MPTA operation.

4 Results and Observations

The initial exploratory work has been carried out to gain better understanding of the winding ac effects for the analysed design concepts. Fig. 2 shows distribution of the current density as a result of eddy-currents induced at open-circuit operation, 8,000rpm, for the winding conductors at the slot opening. Here, two winding variants are considered, the more conventional edge-wound, WVB – Fig. 1b) and AM enabled with ‘laminated’ conductors, WVC – Fig. 1c). It is evident, that the ‘lamination’ allows to significantly reduce the rotational winding ac effect. Also, it is shown that the eddy-current loops are formed mainly along the active length of the winding. This allows to simplify some of the FEAs to 2D domain, but careful considerations need to be taken when analysing winding variants with localised ‘lamination’ of conductors. Fig. 3 presents averaged open-circuit winding power loss (due to rotational ac effect) per winding turn/layer. Note that the winding power loss is per a single coil, with winding layer in Fig. 3a) equivalent to conductor/turn lay for the edge-wound wining. As anticipated, the results confirm that the winding rotational ac power loss is prohibitively high for the edge-wound winding WVB. In contrast, the baseline design, WVA, exhibit relatively low open-circuit winding

Fig. 3. Open-circuit averaged winding power loss per coil turn/layer at 8,000rpm, a) conventional (baseline) winding design with round profile conductors - WVA, b) conventional edge-wound winding with rectangular profile conductors - WVB; (power loss per a single winding coil is considered with 100% IACS and 20°C)

power loss, which is attributed to the reduced conductor size, conductor lay and shielding effect of the stator tooth tip. Also, it is shown that 2D and 3D power loss predictions correlate relatively well allowing to significantly reduce the computational time when using 2D FEAs. Fig. 4 shows initial ‘lamination’ patterns for AM enabled winding, WVC – Fig. 1c). To illustrate complexity of the electromagnetic interactions within the winding, the preliminary analysis assumes ‘lamination’ of a single and then four consecutive winding conductors at the slot opening. Two optional ‘lamination’ patterns are considered here, 9 parallel paths and 18 parallel paths. Here, the first ‘lamination’ pattern with the individual parallel paths formed by subdividing the initial solid conductor width, seems less challenging to fabricate. Note that the conductor size of approximately 300μm with spacing of 100μm can be reliably manufactured using AM techniques. Fig. 5 compares rotational ac winding power loss. The results show that the ‘laminated’ conductors generate significantly lower power loss. Interestingly, the ‘laminated’ conductors become ‘transparent’ to the rotor magnetic flux leakage leading to deeper penetration of the magnetic field and

Fig. 4. Alternative ‘lamination’ patterns of the winding with rectangular profile conductors; where, Example1 – (Ex1)

Fig. 5. Open-circuit averaged winding power loss per coil turn/layer at 8,000rpm; (power loss per a single winding coil is considered with 100% IACS and 20°C)

Fig. 6. Winding power loss at MTPA ac operation versus frequency for rated excitation a) WVC laminated winding – Ex1, WVC laminated winding – Ex2, c) WVC laminated winding – Ex3, d) WVC laminated winding – Ex4; (power loss per a single winding coil is considered at 20°C)

increased power loss generated by conductors placed lower in the stator slot. The ‘shielding’ effect of the solid conductors is particularly prominent for the edge-wound winding, WVB.

It has been shown that the rotational ac winding power loss can be alleviated by an appropriate ‘lamination’ of selected winding conductors (introduction of smaller profile

Fig. 7. Normalised winding ac power loss at MTPA and 8,000rpm; (power loss per a single winding coil is considered at 20°C)

conductors with parallel paths). However, the problem of excitation induced power losses due to the skin and proximity effects still remains. Here, the conductor characteristic dimension (diameter or thickness) and conductor placement in the slot are particularly important. In all analysed cases the conductor characteristic dimension is the same. The main difference lays in the conductor arrangement/profile due to the specific stator core designs, i.e. quasi-closed- and open-slot. It is expected that open-slot winding design might be more prone to the excitation ac effects due to better utilisation of the stator slot. To provide some insight into the excitation induced ac power losses further 2D FEAs have been performed. Fig. 6 shows power loss predictions (per a single coil) versus excitation frequency, where the upper frequency limit corresponds with the rated rotational speed, 8,000rpm. Here, MTPA operation with rated excitation is considered. The results show that the rotational effects dominate the overall power loss for all winding variants with ‘laminated’ conductors, WVC, whereas the ac effects are moderate for the baseline winding design, WVA. Assuming the overall power loss at ac operation is a superposition of the dc and constituent ac loss components (1), the excitation induced power loss can be derived [3], [6],

$$P_{ac} = P_{dc} + (P_{ac})|_E + (P_{ac})|_R \quad (1)$$

where, P_{dc} is the dc winding power loss component, $(P_{ac})|_E$ is the ac winding component from excitation (skin, proximity and circulating currents effects at rated operation) and $(P_{ac})|_R$ is the ac winding component from mechanical rotation of PM rotor (rotational effect at open-circuit operation).

In Fig. 6, the winding power loss predictions account for all excitation and rotational ac effects, P_{ac} . When manipulating the results by subtracting rotational power loss component from the overall winding power loss, the excitation induced power loss can be derived, $P_{dc} + (P_{ac})|_E$. It is evident that by mitigating the rotational ac winding power loss component the desired low-power-loss winding design can be achieved, i.e. excitation induced winding power losses are similar for WVA, WVB and WVC. However, the analysed ‘lamination’ concepts

Fig. 8. Stator winding variant with segmented teeth and ‘variable’ profile laminated conductors (12 turns, ‘variable profile’ conductor, $k_p = 75\%$) - WVE, where k_p is the conductor fill factor (maximum theoretical value for a given winding construction)

Fig. 9. Winding power loss at MTPA ac operation versus frequency for rated; (power loss per a single winding coil is considered at 20°C)

have been shown insufficient in reducing the rotational winding loss component to acceptable level, within the manufacturing constraints imposed by AM. Fig. 7 compares normalised winding ac power loss at MTPA and 8,000rpm, with WVC-Ex4 being the best among the analysed AM winding concepts. Note that WVC-Ex4 generate power loss approximately 3 times larger than for the baseline winding, WVA.

Clearly, employing similar conductor ‘lamination’ approach to WVD would not assure the target low-power-loss winding design. The combination of relatively high magnetic loading and open-slot stator topology makes the task of designing low-power-loss AM winding particularly challenging. In this analysis, the authors decided to explore other alternatives to the open-slot stator construction, e.g. stator with magnetic wedges or segmented tooth [11]-[14]. The later stator construction allows for core pack profile to be identical to the baseline winding design, WVA. Here the individual teeth with coils are slotted axially to the stator back iron core pack [13], [14]. Note that the prefabricated coils are inserted on the individual teeth from the stator back iron end rather than from the stator bore side, prior to the complete stator-winding assembly. Fig. 8 presents the proposed stator-winding construction with ‘variable’ profile conductors and conductor lamination pattern as for the Ex4, WVE. The calculated power loss data for WVE is shown in Fig. 9. Although, WVE is not

an exact like-for-like alternative to the baseline winding, WVA, it provides similar power loss. Note that WVE provides approximately 40% reduction and increase of generated power loss at the low and high speed operating extremities, respectively. When analysing the results in more detail, the characteristic crossover points for the windings with alternative AM copper alloys can be identified, 75% IACS and 90% IACS. This is caused by the change in dominant power loss component with increase of the excitation frequency. Initially, the dc power loss is the dominant one and consequently winding variant with 90% IACS is better suited to keep the overall winding power loss low. At higher frequencies beyond the cross over point, winding material with poorer electrical conductivity, 75% IACS provides low-power-loss solution by reducing the dominant, here ac winding power loss components.

6 Conclusions

The theoretical findings have shown that the problem of replacing the more conventional winding constructions, with like-for-like AM alternatives, is non-trivial. Although it has been demonstrated that the AM low-power-loss winding can be designed, the overall complexity of the stator-winding arrangement seems to be increased. A practical implementation of such winding build would need to be trailed before making any more definitive comments on the manufacture and assembly matters. As, the subject of AM windings is relatively new, more work is required to further explore and mature the technology.

When reviewing the existing literature devoted to AM in electrical machines, it is evident that physical properties of active materials used in construction of machines are frequently poorer than these for the conventionally fabricated parts. Consequently, replacing individual electrical subassemblies with AM alternatives might not meet the expectations in all cases. It seems that a more comprehensive approach, where the complete machine is AM might provide better performance gains.

At the moment, the metal AM is relatively expensive when considering prototyping a one of part. However, there are numerous examples of AM being used for in-volume fabrication, usually for high-end aerospace and automotive applications. There has been a considerable interest in employing AM in power electronics, electrical machines and drives (PEMD). It is the authors' opinion that commercial deployment of AM in fabrication of PEMD is just a matter of time.

5 Acknowledgements

The authors wish to thank the Advanced Propulsion Centre (APC) UK for supporting this work.

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