Integrating the Magnetics of an LCL Filter into a High Speed Machine with Pre-Compressed Coils

Mohamed Awad S Mohamed[1], Simon M. Lambert[2], Barrie C. Mecrow[3], Xu Deng[4], Sana Ullah[5], Alexander C. Smith[6]
1; School of EEE, Newcastle University, Newcastle Upon Tyne, UK, mohamed.mohamed@ncl.ac.uk
2; School of EEE, Newcastle University, Newcastle Upon Tyne, UK, simon.lambert@ncl.ac.uk
3; School of EEE, Newcastle University, Newcastle Upon Tyne, UK, barrie.mecrow@ncl.ac.uk
4; School of EEE, Newcastle University, Newcastle Upon Tyne, UK, xu.deng@ncl.ac.uk
5; School of EEE, Newcastle University, Newcastle Upon Tyne, UK, s.ullah@ncl.ac.uk
6; School of EECE, Manchester University, Manchester, UK, Sandy.smith@manchester.ac.uk

***Abstract*— This paper presents a high speed electric machine with integrated magnetics of the grid side LCL filter. The integrated drive has been designed to take full advantages of sharing the machine stator structure for volume reduction. The main outcome of this paper is firstly, the ability to integrate all six LCL filter inductors into the proposed machine by sharing the original machine's magnetic circuit without magnetic cross-coupling neither between the integrated filter inductor windings nor with the main machine magnetic circuit. Secondly, both the main machine coils and the filter inductor coils are pre-compressed directly to the double slot stator teeth to form a solid component with fill factors for the main machine and filter windings of 60% and 50% respectively. The use of a segmented stator enabled rapid and repeatable construction of the proposed geometry. There are number of important design features which are not possible with conventional preformed Litz windings for the main machine coils. For example, the main machine coils were formed with safety margin from the machine slot opening along with the restriction of slot area through use of a sliding jig which holds the coil in the required form during the annealing process. As such this paper presents a number of novel electromagnetic design and manufacturing processes which enhance the performance and functionality of the integrated drive concept.**

Keywords—Integrated ac inductors; integrated high speed machine; passive components; pre-compressed coils.

I. INTRODUCTION

High power density drives are an important target for a wide range of applications such as aerospace, automotive and traction motors. As machine volume approximates proportionality with machine torque high-speed machines are required for achieving very high power densities. When the drive is grid connected, an LCL input power filter will be required acting as an interface between the utility grid and drive side. The overarching role of input filter is to reduce harmonics resulting from the non-linear behavior of the power electronic rectifier being injected into the utility grid and to make the drive more robust against unbalanced supply voltages. In literature considerable effort has been taken to reduce the size of passive components [1-11]. However, for high power, very high speed drives the size of passive filter components (inductors and capacitors) become significant (or even dominant) compared to the machine. The envelope of the filter components are rarely congruent with that of the machine leading a poor utilization of the available volume in which to install the drive, thus it becomes desirable to more effectively integrate the various components of the drive in a more compact manner. Integrated motor drives offer potential benefits such as direct replacement of inefficient direct on line motors, higher power density and lower time and cost of installation compared to separate drive and motor systems [12] and [13].

The research presented in this paper particularly focuses on the mechanical and electromagnetic integration of the magnetic passive LCL filter components (i.e. grid and drive side inductors) into a high speed electrical machine architecture.

Unlike a traditional electric drive as depicted in Fig. 1, in this work the six inductors which form part of the LCL filter are physically integrated into the machine structure.

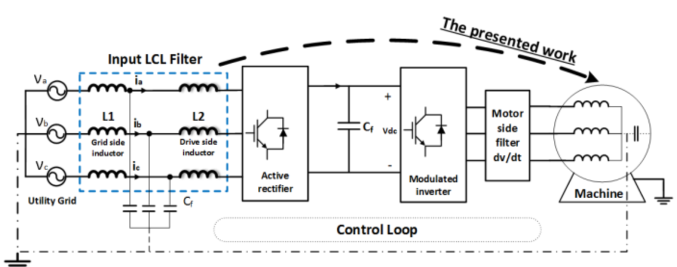

Fig. 1. A general schematic of an electric drive included input power LCL filter

Further improvement on coil fill factors as well as ease of assembly have been achieved by introducing a method of pre-compressing coils directly to the modular stator. By integrating passive filter components (i.e. 3-phase grid and drive side inductors) into the machine along with pre-compressed stator windings, a functional single unit motor drive system with high power density has been obtained. In the demonstrator described in this paper the other components of the integrated drive (power electronics, capacitors, control electronics etc.) have also been fully integrated into the machine structure however the integration of these devices is beyond the scope of this paper.

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II. DESIGN OF THE ORIGINAL MOTOR

The prototype high speed high power permanent magnet synchronous motor (PMSM) has been designed for suitability of integrated motor drive. The motor being feed by an active converter, which has eight poles, twelve teeth, surface mounted neodymium-boron permanent magnet rotor separated by a wedge of non-magnetic material, and windings wound with fully pitched coils. The stator material was chosen as JNEX-core where a core losses in high frequency ranges is extremely low. A 3D presentation of the PMSM and assembled rotor is shown in Fig. 2 and 3. The losses of magnets rotor are reduced up to 83% by segmenting magnets circumferentially.

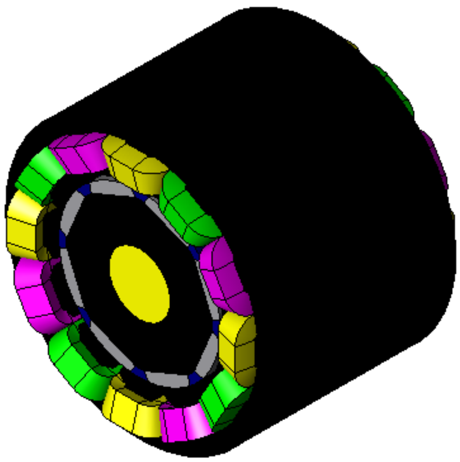


Fig. 2. 3D presentation of the high speed PMSM

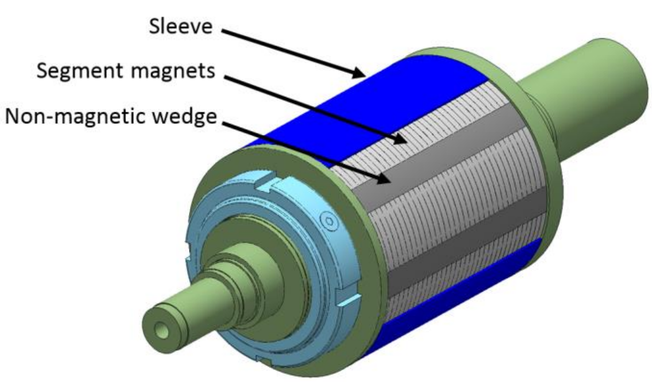


Fig. 3. Rotor assembly, showing segmented magnets

Particular attention was paid in the proposed machine design with regards to achieve high power density along with simple structure segmented stator design and hence the functionality of integrated motor drive concept was applicable.

III. DESIGN OF INTEGRATED HIGH SPEED MACHINE

Different integration methods for magnetic filter elements have been carried out in [8] and the selective method is called integrated double slot machine (IDSM). The integration of solely drive side inductors (L_2) achieves lower volume and losses compared to a traditional discrete 3-phase drive side inductors by 86% and 22% respectively. For the selective method, the stator lamination of the original PM machine was modified to double as 3-phase LCL filter inductors integrated into the machine structure [13]. The advantage of proposed stator geometry with integrated inductors is to limit the interaction between the magnetic fields of filter inductors and that in the core back due to the PM machine. Since the integration of 3- phase drive side inductors (L_2) was achieved as presented in [13], further work has been carried out to integrate the grid side inductors (L_1) of input LCL filter. The specifications of drive and LCL filter are given in Table 1.

TABLE I. SPECIFICATIONS OF DRIVE AND LCL FILTER MAGNETIC COMPONENTS

Drive input power (kW)		38
Grid input current (A RMS)		53
Machine Pole number		8
Machine speed (RPM)		25000
Switching frequency (kHz)		40
Magnetic inductances of LCL filter (μH) per phase	***L_1(Grid side)***	5
	L_2(Grid side)	160

A. *Integrated Magnetics of LCL Power Filter*

The geometry of ac filter inductors is dictated by the electric machine design and the desired inductance determined by power rating application. The design process for the IDSM begins with the geometry of the high speed electric machine which in this case has 12 teeth. The additional filter slots are essentially extensions of the 12-slot geometry as shown in Fig. 2. The integrated inductor design is driven by the required storage energy and hence the optimal length of inductor airgap and number of turns as given in 1-4 [6] and [13].

$$Energy\ stored\ = \frac{1}{2}\, L\, i^2 \tag{1}$$

$$NI = \emptyset\, \mathcal{R}_{eq} \tag{2}$$

$$\mathcal{R}_{eq} = \mathcal{R}_{gap} + \mathcal{R}_{steel} = \frac{1}{\mu_\circ\, A_{min}}\left(L_g + \frac{L_m}{\mu_r}\right) \tag{3}$$

The inductance of the inductor windings is defined as

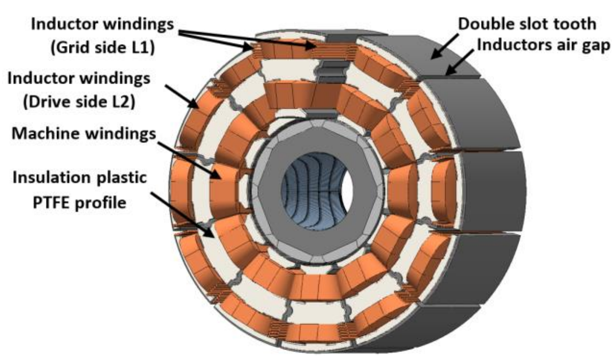
$$L = \frac{\psi}{I} = \frac{N^2}{\mathcal{R}_{eq}} \tag{4}$$

where NI is the magneto-motive force (amp-turn), $\emptyset$ the magnetic flux resultant from the inductor winding, $\mathcal{R}_{eq}$ the equivalent reluctance of the inductor magnetic circuit, L_m the magnetic flux path length, L_g the air gap length, A_{min} is the minimum cross-section area of steel in the magnetic path and ψ is the flux linkage of the inductor winding.

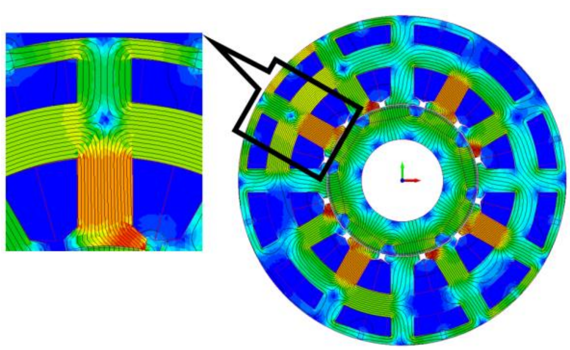
Since the magnetic flux induced by the integrated inductors has independent paths, the interaction with machine magnetic circuit is avoided. The winding arrangements are carefully selected so that the pole number of each of the main winding, grid side and drive side inductors all have different pole numbers to avoid cross-coupling and are selected in such a way as to avoid unbalanced magnetic poles.

The filter inductors share the same slot and since the drive side inductor dominates (L1= 5μH per phase, L2=160μH per phase) the integrated inductor geometry is initially designed considering solely the largest 3-phase filter drive side inductors. The small grid side filter inductors are incorporated into the same slots requiring an increased fill factor.

The stator of IDSM is segmented for ease of assembly of the machine and ac inductors windings. The proposed geometry of IDSM is illustrated diagrammatically with a flux contour plot in Fig. 4 demonstrating the separate flux paths for the main machine flux and the filter inductor flux.



(a)

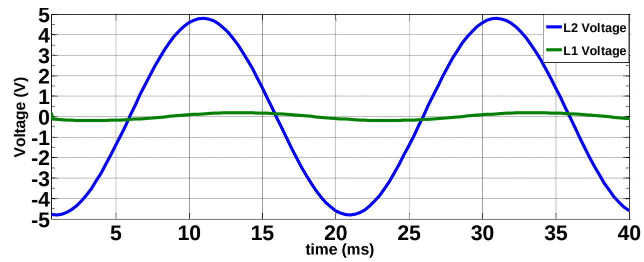


(b)

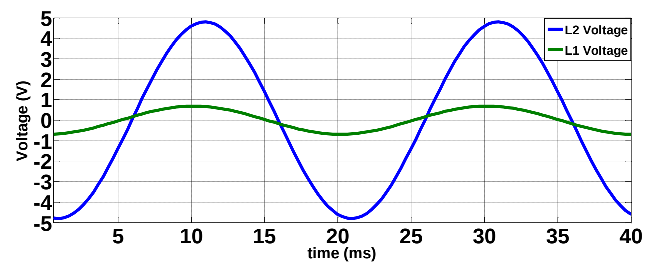
Fig. 4. a) Contour plot for the IDSM, b) 3D presentation of the general schematic of IDSM

B. *Winding configuration of integrated LCL filter inductors*

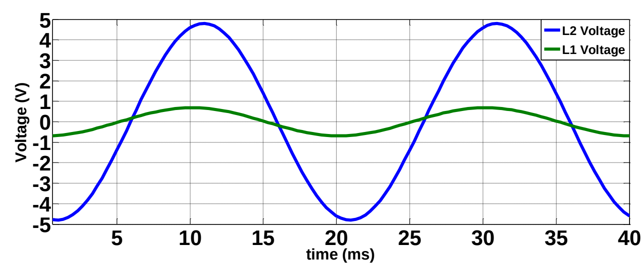
The integrated geometry of filter inductors is intended to minimize the volume of filter and combine it with the machine structure in a single envelope. As coils of both inductors L1 and L2 of the LCL filter share the same outer slots - and hence magnetic paths -different pole combinations for L1 and L2 have been simulated using FE analysis to investigate the degree of undesired mutual coupling between L1 and L2. The following figure is illustrated a single phase voltage of grid and drive side inductors as shown in Fig. 5.



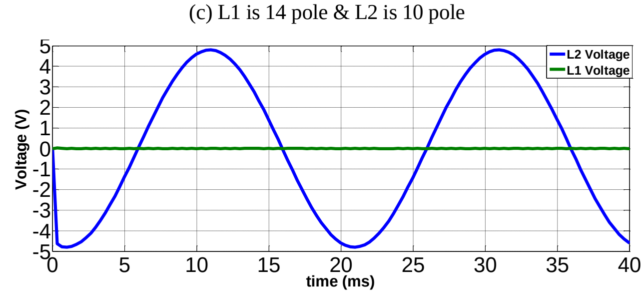
(a) L1 is 2 pole & L2 is 10 pole



(b) L1 is 10 pole & L2 is 10 pole



(c) L1 is 14 pole & L2 is 10 pole



(d) L1 is 16 pole & L2 is 10 pole

Fig. 5. Cross-coupling investigation between integrated filter inductors at different number of poles in the stator

The number of poles of the larger inductor, L2, was fixed at 10 poles while the number of poles of L1 was varied. Rated current was applied to L2 and the induced voltage on L1 is observed (with L1 open circuit). The induced voltages on L1 for a single phase LCL filter inductors are presented in Fig. 5. Normalizing for the turns ratio the four pole combinations studied; 2:10, 10:10, 14:10 and 16:10, have coupling factors of

22%, 100%, 100% and 0% respectively (10:10 and 14:10 are essentially the same pole combinations).

Further investigation has been carried out in relation to discovering the possibility of mutual coupling between integrated filter inductors and the original high speed machine circuit. Finite element analysis was used to observe the open line armature voltage (i.e. Back-emf, Line voltage) of the base machine before and after integrating ac filter inductors into the machine as shown in Fig. 6.

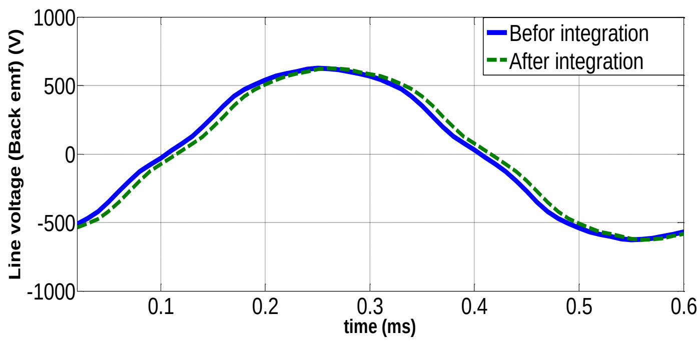


Fig. 6. The original machine back emf line voltage before and after integration

As shown in Fig. 6, the machine circuit is magnetically isolated where the original machine performance as 98% was not affected by integrating LCL filter inductors, however the common stator core back is not heavily loaded (i.e. Magnetic field saturation should be avoided within the proposed double slot machine geometry).

Based on the pole slot combination as given in Fig. 5-d for the filter inductors, the IDSM windings configuration is chosen as 16, 10 and 8 poles for L1, L2 and the main machine windings respectively. Table 2 explained the windings configuration for IDSM. Due to different operating frequencies 50 Hz and 1.66 KHz for LCL filter inductors and the original machine, different copper wires have been used and hence the AC losses have reduced for the original high speed permanent magnet synchronous machine.

TABLE II. WINDINGS CONFIGURATION FOR LITZ AND SOLID WIRES

Integrated Motor Parameters	Base machine windings	LCL Filter inductor windings	
		L_1 *(Grid side)*	L_2 *(Drive side)*
Type of Copper Wire	Litz wire	Stranded solid wire	Stranded solid wire
Number of Turns	36 per coil (equiv. 144 per phase)	1 per coil (equiv. 4 per phase)	7 per coil (equiv. 28 per phase)
Conductor diameter	20 strands × 30 AWG	6 Strands × 18 AWG	6 Strands × 18 AWG
Fill Factor	60%	50% (Same Slot-Concentrated windings)	
Phase Resistance	0.029 Ohms	0.0025 Ohms	0.022 Ohms
Phase Inductance	0.21 mH	5μH	160μH
Number of poles in the stator	8	16	10

As the magnetics LCL filter elements integrated into the high speed machine geometry, the functionality of enhancing power density is carried out with the perspective of pre-compressed coils. This achievement is discussed in the next section.

IV. DIRECT ON-TOOTH COMPRESSED COILS

All of the stator coils of the IDSM are concentrated windings which allows the stator to be designed as segmented for ease of assembly. The main machine windings are located in the inner slot with the two filter coils located in the second, outer slot as shown in Fig. 7.

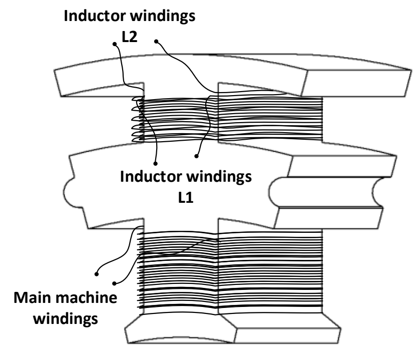


Fig. 7. Single tooth stator segment

An advantage of being able to precisely form the coils in a repeatable and controlled manner is that the coil shaping can be designed to minimize leakage and losses resulting from effects such as fringing at the slot opening. Slot fringing in the IDSM is shown in Fig. 8.

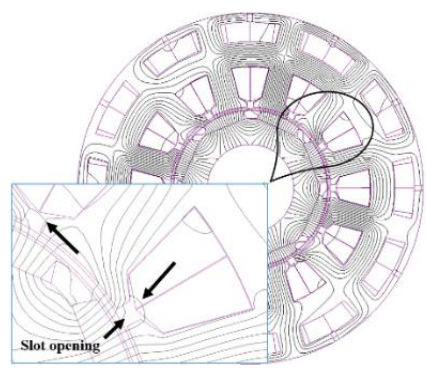
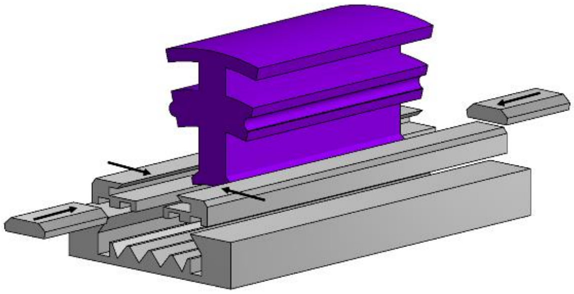
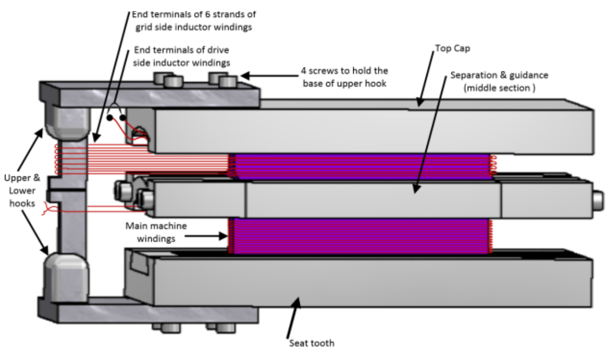


Fig. 8. Fringing in the slot opening

As discussed in the previous section high fill factors are required to attain the power density required for this demonstrator. In previous literature high fill factors have been achieved by pre-pressing coils into a solid form then inserting the coils over the tooth structure [14] and [15]. The double slot geometry of the IDSM does not allow for a simple stator design which can utilize this manufacturing process. Moreover, thermal resistance between the coil and the stator, which is the main thermal path for copper losses, significantly increases as the gap between the coil bunch and the stator material grows larger. Thus, a direct on-tooth coil compression has been utilized whereby the coils are directly wound onto a tooth segment then compressed in a pressing tool onto the stator tooth creating a precise coil formation for each of the three coils. The pressing operation achieves a significantly higher fill factor and enhanced thermal conductivity between the copper windings and machine stator. The on-tooth pressing method is outlined in Fig. 9.

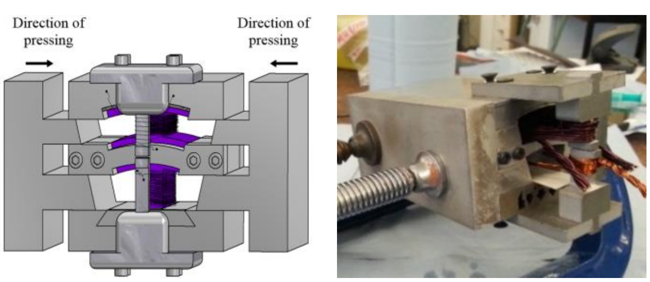


1. The stator tooth segment is loaded into the winding jig seat



2. The winding jig is fitted to the tooth segment and the coils wound. Locating hooks hold the wire in place once wound

3. Coils are impregnated with thermally activated bonding agent, Ultimag 2002L.



4. The pressing punch is applied and coils are forced into a regular shape. The assembly is placed in an oven at 165̊C and the bonding agent is allowed anneal.

Fig. 9. On-tooth pressing method and tooling

The pressing tool has been designed to force the coil away from the slot opening thus reducing the loss created from the slot opening fringing effect (Fig. 10). The final geometry of compressed coils for the double slot tooth segment is shown in Fig. 10 and 11.

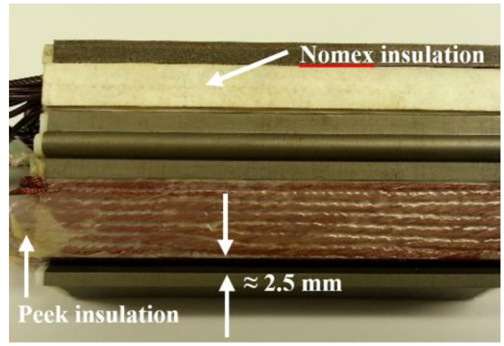


Fig. 10. On-tooth pressed coils

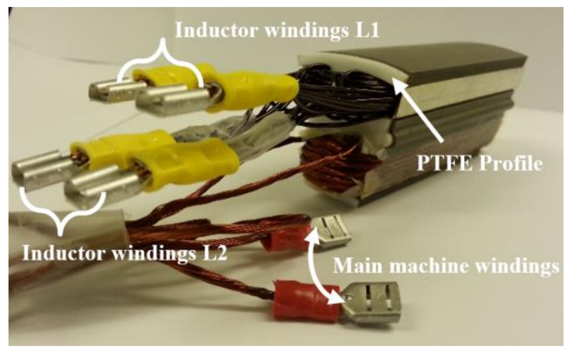


Fig. 11. 3D presentation of double slot tooth with end windings terminals

V. Experimental Results

A one-quarter machine motorette (Fig. 12 and 13) has been constructed to assess the effectiveness of the integrated inductors. Various magnitudes of 50 Hz current was applied to the filter inductors to compare the measured inductances with the FEA simulation results.

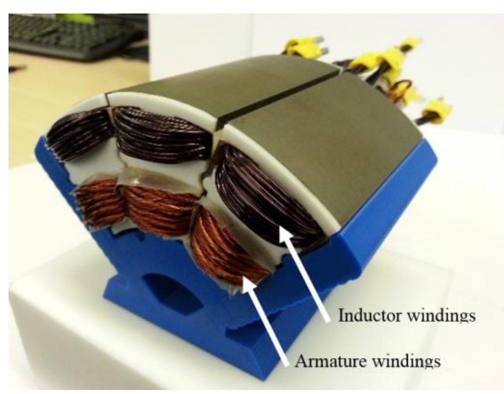


Fig. 12. 3-tooth fully assembled IDSM motorette

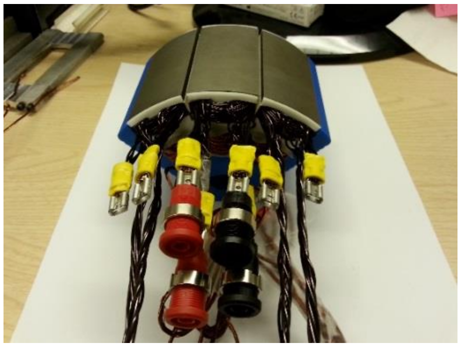


Fig. 13. Three tooth motorette with test leads

The inductances for both filter inductors L1 and L2 were measured for the middle tooth and compared with obtained results from FEA simulation as shown in Table 2.

TABLE III. SIMULATED AND MEASURED INDUCTANCES FOR THE IDSM FILTER WINDINGS

Grid input current (A RMS)	**FEA results Inductances of LCL filter (μH)**		**Measured results Inductances of LCL filter (μH)**	
	L_1	L_2	L_1	L_2
1.5	1.03	42	0.99	34
2.5	1.03	42	0.99	35
3.5	1.03	42	0.99	36
4.5	1.03	42	0.99	36

The full double slot stator has been assembled as shown in Fig. 14. A rapid plastic motor housing was used to verify the ease of assembly of integrated double slot stator teeth.

Fig. 14. The demonstrator of stator of integrated double slot machine

The achievement of volume reduction including 3-phase inductors of LCL filter (i.e. grid and drive side inductors) is 87.6% compared to the total volume (L1+L2) of conventional discrete LCL filter inductors. However, the integrated filter inductors added additional heat to the base machine and so a sufficient jacket water cooling system has been designed. The cooling system is shared by base machine with filter inductors and power electronic devices of the active converter.

The presented demonstrator in Fig. 14 is a part of full packaged integrated motor drive geometry where the other drive components (power electronics, capacitors, control electronics etc.) have been fully integrated into this demonstrator. However, the integration of these devices is beyond the scope of this paper.

VI. CONCLUSION

The three phase LCL filter inductors have been successfully integrated into the high speed machine without affecting the performance of the original motor. The intent of this work is to reduce the overall volume of the combination of the machine and grid filter magnetics through better utilization of the available volume and envelope. A significant reduction volume has been achieved by integrating the 3-phase filter inductors into the proposed machine as 87.6 % compared to that discrete filter inductors. The challenges of magnetic interaction between the three different fields resulting from the main machine winding and the two filter windings have been discussed as well as the mitigation thereof.

On-tooth pressed windings have been introduced and demonstrated in the IDSM showing higher than usually achievable fill factors for both Litz and plain strand wire. A unique manufacturing method for multi-slot direct on-tooth pressing has been shown to give reliable and repeatable coils formed in such a way as to mitigate poor thermal contact as well as leakage losses due to poor conductor placement.

The described manufacturing method allows simple assembly of the stator and has shown to yield measured inductances which correlate with the expected values from FEA simulation.

ACKNOWLEDGMENT

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