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Winding Connection Solutions for an Integrated Synchronous Motor Drive

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Abstract—With increased demand in electric drives applications for higher power density, higher efficiency and higher temperature operation, integrated motor drives are gaining greater interest in automotive, aerospace and other specialist applications. Integrated drives not only physically integrate the various components of the drive (power electronic devices, filter components etc.) they must also integrate the various connections between these components. Although fewer articles report this integration it is nevertheless of equal importance to the integration of the active and passive parts. This paper presents three winding connection solutions including two PCB (Printed Circuit Board) based solutions and a busbar solution for an integrated permanent magnet synchronous motor drive with fully integrated filter magnetics. Firstly, the design process and parameter selection considerations for two PCB solutions are presented demonstrating the requirement for extremely thick copper layers and extra connection wires. Afterwards, a busbar solution considering skin effect and litz wire connections is proposed. The total thickness, manufacture difficulty and requirement of extra connection wires of different winding configurations are compared. Finally, the busbar solution is shown to be the optimum winding connection solution.

Keywords—busbar, integrated motor drive, synchronous machine, winding connection

I. INTRODUCTION

The traditional physically separated motor and drive systems, consisting of discrete subsystems, have shifted to more compactly integrated, higher power dense, motor-drive combinations in the past two decades [1] and this concept has been defined as Integrated Motor Drive (IMD) [2, 3]. The IMD concepts have recently received greater attention in literature due to lots of advantages they provided, and are increasingly seen as the standard for future automotive applications [4-6]. In general the most significant advantages include the ability to directly replace direct on line machines with variable speed drives, lower EMI [7], less loss and higher power density.

However, the compact structure of IMDs also leads to many other challenges. A common problem is the localised high temperatures generated from concentrated converter losses. This raises a challenge for converter cooling design and thermal management especially when converter is close to other heat sources such as stator windings [8, 9]. Mechanical vibration and mechanical stability also cause reliability problems in IMDs. Machines operating in harsh environments such as aviation and

traction applications are exposed to extreme vibration. Since converters in IMDs are mounted in or on machine housings, this exposes the converter to significant vibration problems [10, 11]. Besides, reliability of connection methods such as thermal-joint components and screws may be seriously affected by high vibration. All these issues are ongoing topics of IMDs design.

In [12] an electrical machine with integrated grid LCL filter components has been proposed based upon previous efforts that have been undertaken to integrate and reduce the size of passive components in integrated AC drives [13, 14]. The design procedure for these three-phase LCL filters has been introduced, demonstrating a total envelope and volume advantage in integrating the filter inductors into the machine stator through use of auxiliary slots to house the inductors. Fig. 1 presents a 3D representation of the auxiliary slot mounted inductors, this outer slot design is chosen to reduce winding coupling between filter inductors and main coils.

However, as the LCL filter inductors are integrated with the stator and in order to enhance electromagnetic compatibility and reduce copper losses, all inductors need to be connected in the limited space inside of the machine housing. Therefore, this integrated LCL filter design gives rise to a new challenge of winding connection requiring a total of 72 individual coil terminations and routings within a very small volume which has limits dictated by the machine dimensions.

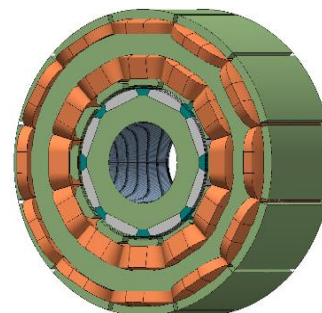


Fig. 1. 3D representation of auxiliary slot mounted inductors

In this paper, three different winding connection solutions are proposed including two Printed Circuit Board (PCB) based design solutions and a busbar design solution. Firstly, the design process and parameter selection considerations for two PCB solutions are presented in Section II. However, extremely thick copper layers and extra connection wires are need in two the PCB solutions. Afterward, a busbar solution considering skin effect and litz wire connections is proposed in Section III. The total thickness, manufacturability and requirement of extra

connection wires of different winding connection solutions are compared.

II. PCB SOLUTIONS

Fig. 2 shows the winding arrangement of the integrated motor drive. For the three-phase 12/8 permanent magnet synchronous machine, there are twelve main phase windings, and each phase has four concentrated windings connected in parallel. Three phase LCL filters are designed, and each grid/drive side inductor consists of four concentrated coils. Therefore, there are 36 distributed coils in total, which means a total of 72 winding terminals which need to be connected and routed. The coil specifications are given in Table I.

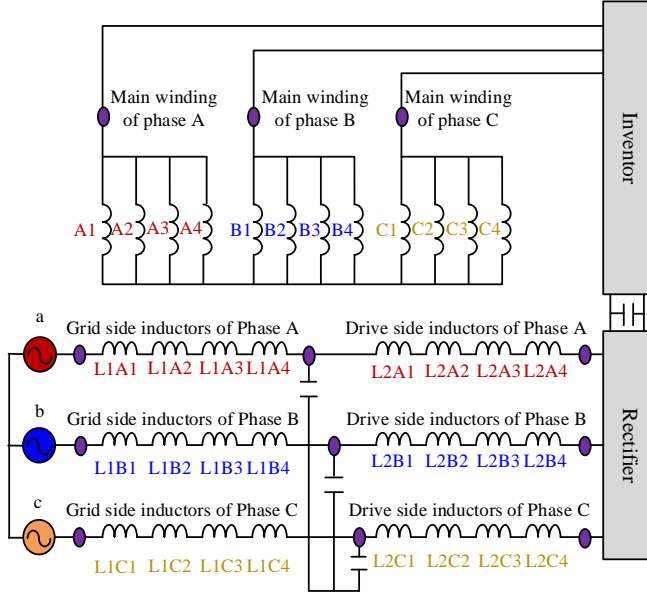


Fig. 2. Winding connection of the integrated synchronous motor drive

TABLE I. WINDING CONFIGURATIONS FOR MACHINE COILS

| 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 |
| Winding Type | Concentrated | Concentrated | Concentrated |
| Coil Connection | Parallel | Series | Series |
| Number of Turns/Phase | 36 per coil, 4 coils in parallel per phase (144) | 1 per coil, 4 coils in series per phase (4) | 7 per coil, 4 coils in series per phase (28) |
| Conductor diameter | 20 strands \times 30 AWG | 6 Strands \times 18 AWG | 6 Strands \times 18 AWG |
| Number of poles in the stator | 8 | 16 | 10 |

However, as the stator diameter of the prototype is only 138mm, radial extension is undesirable (due to increasing

volume by a square factor) and axial extension should be kept to a minimum to maintain high power density the space is too limited to connect all the windings inside of the machine housing using the wire or flying leads. Therefore, the winding interconnects need to be connected on a planar power board.

A. PCB Solution 1 (with one board)

The first option to connect all inductor windings is to design a PCB according to the design parameters as shown in Table II. The PCB outer diameter is selected as same as the stator minus a clearance of 1mm.

TABLE II. PCB DESIGN PARAMETERS

| | |
|--|-----|
| PCB outer diameter(mm) | 136 |
| PCB inner diameter(mm) | 30 |
| Current rating of inductors(A RMS) | 53 |
| Current rating of main windings(A RMS) | 48 |
| Current rating of the neutral point(A RMS) | 83 |

Ignoring the machine windings, there are 24 inductor windings and 48 winding connection pads on board as shown in Fig. 3. The grid side inductors are arranged along the tangential direction, whilst the converter side inductor are along the radial direction. The main reason for this arrangement is to increase the utilization factor of top and bottom layers on the PCB, as the middle layer of the PCB faces more serious heat dissipation problems.

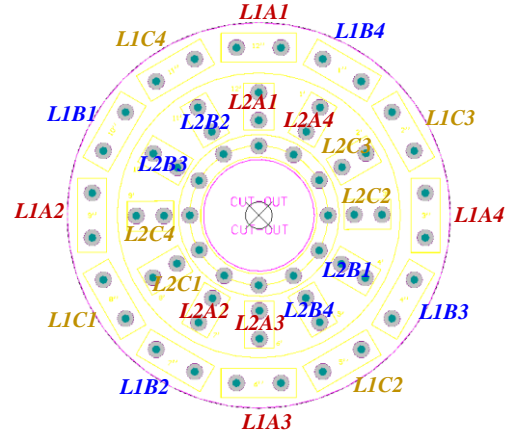


Fig. 3. Winding connection pads arrangement on PCB

The cross-sectional area of tracks and clearances between tracks are calculated according to (1) to (3) from the IPC-2221 generic standard on printed board design.

$$I = 0.024 \times \Delta T^{0.44} \times A^{0.725} \quad (1)$$

$$I = 0.048 \times \Delta T^{0.44} \times A^{0.725} \quad (2)$$

$$L_{clear} = 0.5842 + 0.00508 \times V \quad (3)$$

Where I is the maximum current in Amps, ΔT is temperature rise above ambient in $^{\circ}\text{C}$, A is cross-sectional area in mils^2 , V is the peak voltage between two tracks and L_{clear} is track clearance in mm.

According to the design parameters in Table II, the winding connection PCB Solution 1 is designed as shown in Fig. 4, track width and clearance are shown in Table III. There are three layers employed on board. The majority of tracks are arranged in the top layer and bottom layers. However, due to clearance limitation, the thickness of external layers are 1.4mm (35oz/ft²), which is obviously not a practical parameter for PCB manufacture.

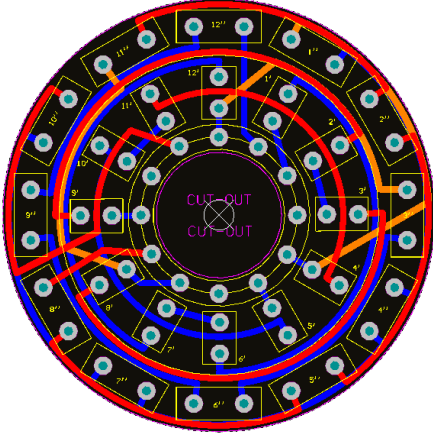


Fig. 4. Winding connection solution with one PCB

TABLE III. TRACK WIDTH AND CLEARANCE IN PCB SOLUTION 1

| | Copper thickness(oz/ft ²) | Track width(mm) | Track Clearance(mm) |
|--------------|---------------------------------------|-----------------|---------------------|
| Top layer | 32 | 2.3 | 6.2 |
| Middle layer | 3 | 2.4 | 3.6 |
| Bottom layer | 32 | 2.3 | 6.2 |

B. PCB Solution 2 (with two boards)

The main reason giving rise to the unpractically thick tracks in PCB Solution 1 is space limitation. A simple way to achieve more available space on board is splitting previous PCB to two boards. Therefore, the following PCB Solution 2 is proposed.

In this solution, the PCB designed in previous section is split into two boards which are drive side winding connection PCB 1 and grid side winding connection PCB 2 as shown in Fig. 5. The grid side inductor connection PCB is arranged on one side of the machine which will be connected with an external capacitor PCB, while drive side winding connection PCB is on the other side. Two PCBs of this winding connection solution are represented in Fig. 6 and Fig. 7.

The thickness of copper on board is reduced to 0.28mm (8oz/ft²), which is significantly reduced compared with the previous PCB solution and is reasonable for PCB manufacture. The track widths on the board are shown in Table IV.

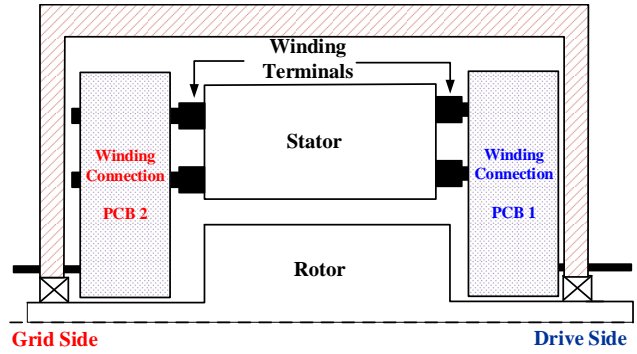


Fig. 5. Assembly diagram of the PCB Solution 2

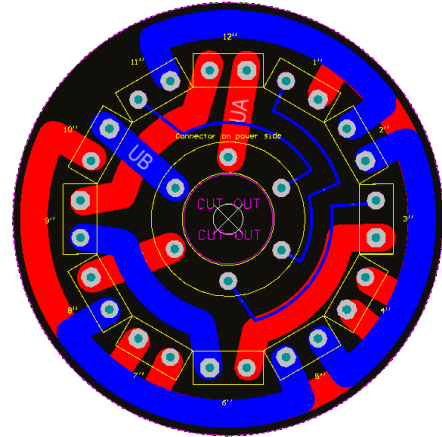


Fig. 6. Grid side PCB of winding connection solution with two PCBs

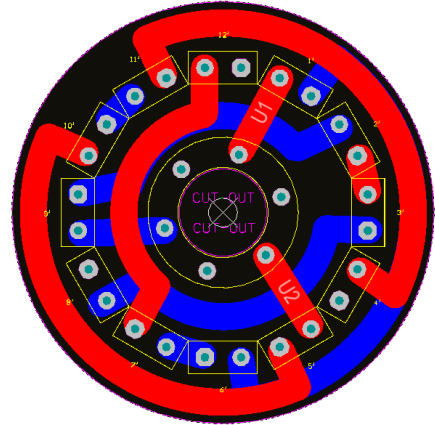


Fig. 7. Drive side PCB of winding connection solution with two PCBs

However, the two capacitor connection points for each phase are split between the two individual boards which means the capacitor terminals need to straddle the machine axially. Three extra cables are needed to “bridge” the two boards at either end of the machine and three extra capacitor connection points are required. Besides this drawback, in this winding connection solution, extra external connection terminals are required, which leads to an obvious drawback that the axial length cannot be used properly.

TABLE IV. TRACK WIDTH AND CLEARANCE IN PCB SOLUTION 2

| | Copper thickness(oz/ft ²) | Track width(mm) | Track Clearance(mm) |
|--------------------------------|---------------------------------------|-----------------|---------------------|
| Top layer of grid side PCB | 8 | 9.0 | 3.5 |
| Bottom layer of grid side PCB | 8 | 1.0-9.0 | 3.5 |
| Top layer of drive side PCB | 8 | 9.0 | 5.7 |
| Bottom layer of drive side PCB | 8 | 9.0 | 5.7 |

III. BUSBAR SOLUTION

Due to all the manufacture and axial length limitation of the PCB solutions 1 and 2, a copper busbar design is proposed as shown in Fig. 8. This is a four-layer busbar design including all filter inductor connections, three-phase power connections and three-phase main winding connections.

The three copper pins on the top of the design are input connectors for three-phase power. All the other busbars are embedded into grooves in 4mm thick PTFE (Poly Tetra Fluoro Ethylene) boards for isolation and mechanical fixing. The dielectric strength of the PTFE is 80MV/m[15]. As a guide to manufacturing limitations, the minimum width of the barrier between two busbars in one layer is 1.0mm, and the minimum thickness between two busbars on two adjacent layers is also 1.0mm giving an insulation breakdown voltage well in excess of the working voltages of the drive.

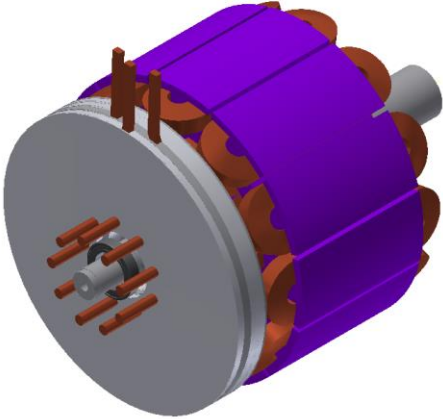


Fig. 8. 3D representation of busbars assembled with machine

Considering the skin effect of conductors, the skin depth of all busbars are calculated according to (4),

$$\delta = \sqrt{\frac{\rho}{\pi\mu_0 f}} \quad (4)$$

Where ρ is resistivity of conductor material in Ω/m , μ_0 is permeability of free space and equals to $4\pi \times 10^{-7} H/m$ [16], f is frequency in Hz and δ is skin depth in m. The current frequency in filter inductor busbars are 50Hz. The current frequency in main winding busbars and neutral point busbar at base speed (25000r/min) is calculated by (5),

$$f = \frac{N_s \times P}{60} = \frac{25000 \times 4}{60} = 1666 \quad (5)$$

Where N_s is the synchronous speed, P is the pole pair number. Hence, for copper at 20°C ($\rho=17n\Omega/m$),

$$\delta_{50Hz} = \sqrt{\frac{\rho}{\pi\mu_0 f}} = \sqrt{\frac{17 \times 10^{-9}}{\pi \times 4\pi \times 10^{-7} \times 50}} = 9.28 \times 10^{-3} \quad (6)$$

$$\delta_{1666Hz} = \sqrt{\frac{\rho}{\pi\mu_0 f}} = \sqrt{\frac{17 \times 10^{-9}}{\pi \times 4\pi \times 10^{-7} \times 1666}} = 1.61 \times 10^{-3} \quad (7)$$

The dimension of busbars employed in this solution are shown in Table V. Considering the calculated skin depth, 3mm thick 4mm wide copper busbars are designed for filter inductors and main windings. Since neutral point needs to carry higher current, a 6mm thick 4 mm wide copper busbar is designed for neutral point. The connections between internal busbars and external converters are designed with 3/16 inch (4.8mm) diameter copper rods.

TABLE V. BUSBAR DESIGN PARAMETERS

| | Thickness (mm) | Width (mm) | Diameter (mm) | Current Density J(A/mm ²) |
|--------------------------------|----------------|------------|---------------|---------------------------------------|
| Filter inductors | 3.0 | 4.0 | | 4.4 |
| Main windings | 3.0 | 4.0 | | 4.0 |
| Neutral | 6.0 | 4.0 | | 3.5 |
| Copper rods | | | 4.8 | 2.7- 2.9 |
| Holes on inductor busbars | | | 3.3 | |
| Holes on neutral busbar | | | 1.8 | |
| Holes on main windings busbars | | | 1.8-4.8 | |

Four layer busbars are illustrated layer by layer in Fig. 9 to Fig. 12. As shown in Fig. 9, grid side inductors, three-phase windings and half of the neutral point busbars are arranged in this layer. Four connection holes are designed on three-phase winding busbars to connect each of the four litz wires in one phase individually. There are 3mm thick grooves integrated on the 4 mm PTFE board, and 1mm thick PTFE is reserved on bottom for isolation between busbar layer 1 and the machine.

As shown in Fig. 10, drive side inductors and half of the neutral point busbars are arranged in layer 2. Since neutral point needs to carry higher current, the thickness of it is double that of the normal busbar, in order to fit it, there are two grooves designed for the neutral busbar individually: one is the 3mm thick groove on the front side of layer 1, the other one is the 3mm thick groove on the back side of layer 2, therefore the neutral busbar is stuck in the middle. Twelve 1.8mm holes are designed on neutral busbar to fit twelve neutral points from phase coils as illustrated in Fig. 2.

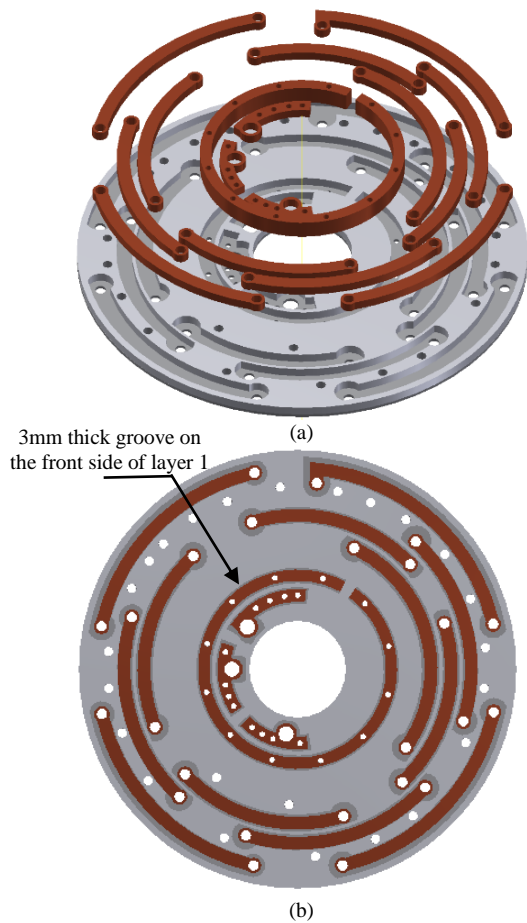


Fig. 9. Layer 1 of the busbar design: (a)3D (2) 2D front side

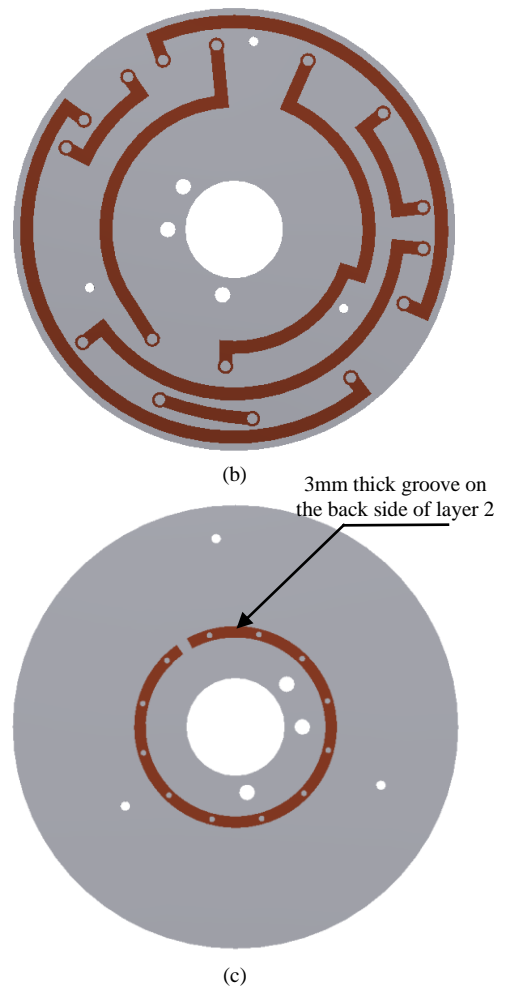
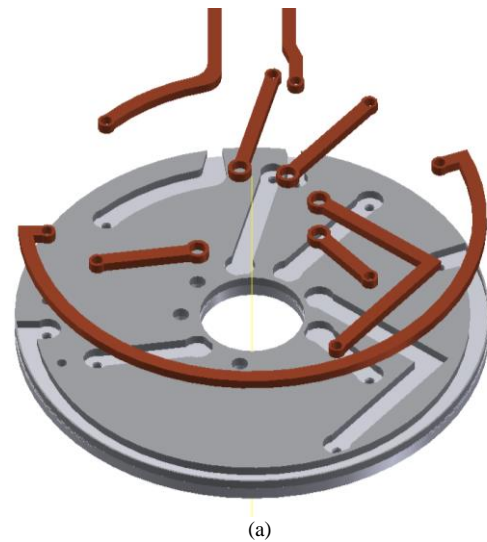
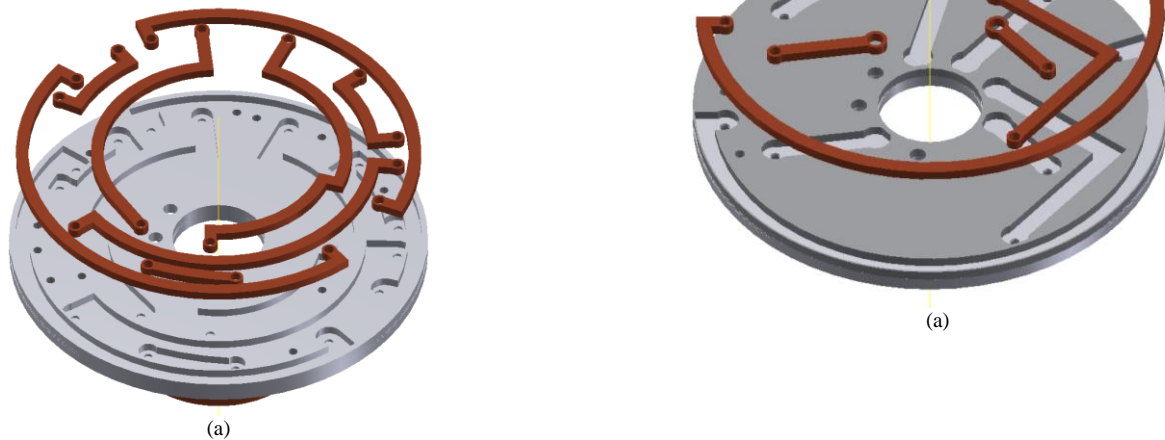


Fig. 10. Layer 2 of the busbar design: (a) 3D (2) 2D front side (3) 2D back side

Fig. 11 and Fig. 12 show layers 3 and 4 of the busbar solution. The main purpose of these two layers is to connect internal inductors and main windings with external three-phase power, filter capacitors, the rectifier and the inverter according to twelve purple connection points in Fig. 2. Three-phase power busbars are extended from outer edge of these two layer to external power. Drive side inductor busbars, three-phase winding busbars and three-phase filter capacitor busbars are extended to nine holes distributed evenly along the inner edge which protrude through the endplate of the machine which is where the drive PCBs are mounted.



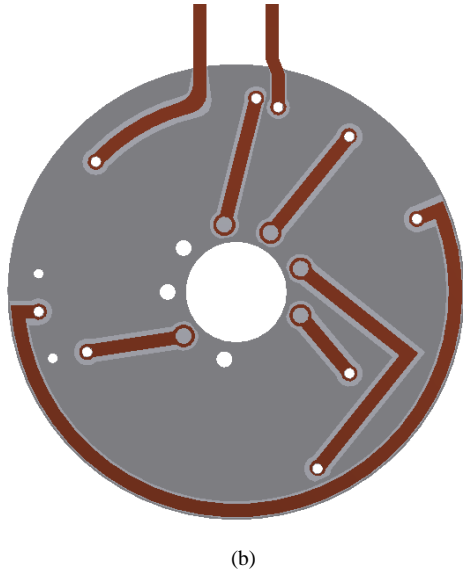


Fig. 11. Layer 3 of the busbar design: (a)3D (2) 2D front side

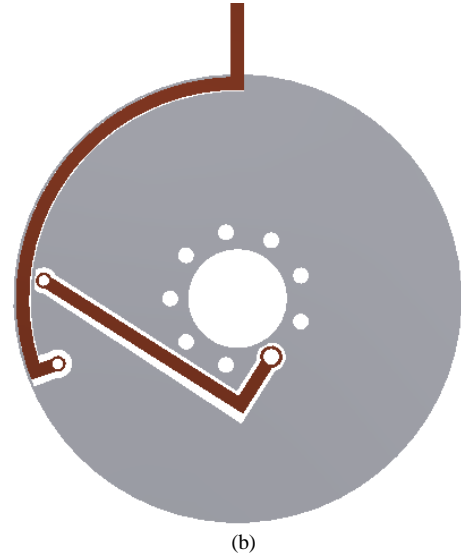


Fig. 12. Layer 4 of the busbar design: (a)3D (2) 2D front side

Comparisons of three proposed winding connection solutions are shown in Table VI. The total thickness of PCBs are calculated, which includes the thickness of copper layer, solder layer and dielectric layer. The PCB solution 1 has the smallest total thickness, but it cannot be manufactured easily due to its unreasonable copper thickness. It is obvious that the PCB solution 2 has the smallest total thickness of PCBs due to more spare space on two boards. However, it needs three extra connection wires (carrying 53A RMS current) bridging the axial length of the machine which is difficult to implement. Although busbar solution has the largest thickness of all three solutions, it is far easier to manufacture and do not need any extra wire connections. Moreover, all Litz wires of the main machine are also connected in the busbar solution which is not the case with either PCB solution. Consequently, the proposed busbar solution is selected to be the optimum winding connection solution for the integrated permanent magnet synchronous motor drive.

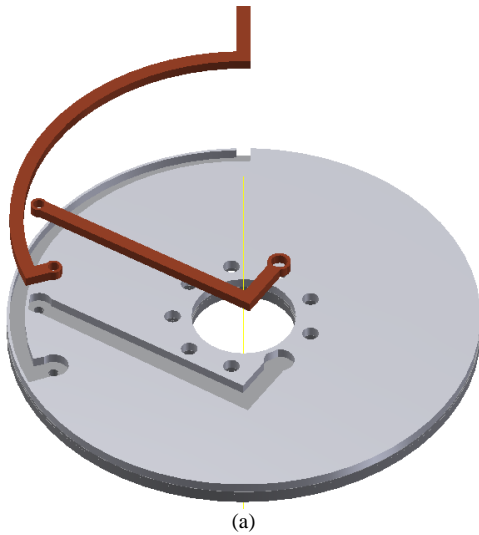


TABLE VI. COMPARISONS OF THREE PROPOSED WINDING CONNECTION SOLUTIONS

| | Thickness of PCB/ busbar (mm) | End winding + Lock nut thickness (mm) | Total thickness (mm) | Manufacture possibility (Yes/No) | Extra wire connection (Yes/No) | Phase winding included (Yes/No) |
|------------------------|-------------------------------|---------------------------------------|----------------------|----------------------------------|--------------------------------|---------------------------------|
| PCB Solution 1 | 5.4 | 10.0 | 15.4 | No | No | No |
| PCB Solution 2 | 3.7 | 18.0 | 21.7 | Yes | Yes | No |
| Busbar Solution | 16.5 | 10.0 | 26.5 | Yes | No | Yes |

IV. CONCLUSION

In this paper, three winding connection solutions for an integrated permanent magnet synchronous motor drive are proposed, which are PCB solution 1, PCB solution 2 and a busbar solution.

PCB solution 1 integrates all the connection tracks onto a three-layer PCB. The main problem of this design is that the copper layer is especially thick (32oz/ft²), which is difficult to manufacture. In order to solve this problem PCB solution 2 is proposed. Two PCB boards are employed in this solution, hence double the space on board is available compared with the PCB solution 1. The copper thickness of the PCB solution 2 is reduced to 8oz/ft². However, as the capacitor (of the LCL filter) connection points are split between the two PCBs assembled on either axial side of the machine individually, three extra connection wires, bridging the machine axially and carrying full line current are required which is difficult to implement.

In order to avoid all the problems of the PCB solutions, a four-layer busbar solution is proposed. Considering skin effect, 3mm thick and 6mm thick copper busbars are designed and implanted in grooves integrated in four 4mm thick PTFE boards.

The total axial length of the busbar solution is 26.5mm. Although this busbar solution has larger thickness compared with PCB solutions, it does not need extra cables and is possible to manufacture. Moreover, the busbar solution is the only one which considers the phase winding (litz wire) connections of all of the three solutions. Consequently, the proposed busbar solution is selected to be the optimum winding connection solution for the integrated permanent magnet synchronous motor drive.

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