Design of a Printed Circuit Board Motor with Integrated Driver

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***Abstract*—This document presents an integrated printed circuit board (PCB) motor design that is specifically optimized for compactness and power dense applications. Featuring Gallium Nitride switches and high switching frequency to overcome the current ripple.**

***Index Terms*—GaN, High-Frequency, PCB Motor, Integrated Drive, Field Oriented Control**

I. Introduction

PCB motors have been becoming more and more popular every day due to their convenience in production; manufacturing with available infrastructure is a substantial advantage over building custom technology to produce one motor and then leave it futile. [1]-[5] When it comes to the type of motor, axial-flux machines are known to be labor-intensive to manufacture. Laying the windings using a sub-micrometer accurate, cheap, and fast PCB building process is more advantageous in axial-flux motor structure because of their planar stator geometry. Axial Flux Permanent Magnet Synchronous (AFPMSM) motors have a wide range of use in the industry, from avionics to servo drive systems.[6]

The main challenges in designing a PCB motor are their low turn numbers and low phase inductances due to their relatively large effective air gaps.

Low inductance motors have better dynamic response due to having an electrical time constant that is low.[7].However, low inductance motors require a high-performance inverter design. Low inductance motor current waveforms suffer from high ripple current; sometimes, even elaborate control methods fall behind in reaching switching frequencies higher than 200khz [7].

The most general solution in the driver industry is to add line inductors to the motor, which inherently contradicts axial motors' power and torque density features, increases complexity, and adds an extra cost. Adding an inductor in series with windings further decreases the effective voltage seen by the motor and increases the power loss, which is extra important in the space industry.

The more preferred method is increasing the switching frequency, which can lower the motor current ripple to controllable levels. High switching frequencies have been a goal that is hard to achieve using conventional semiconductor technology. Wide bandgap devices have been emerging for the last decade; gallium nitride (GaN) and silicon carbide (SiC) switches are examples that have started to be used widely in the industry.

Related problems of low inductance motors and their effect on drives are further discussed in this paper. A PCB motor with an integrated GaN driver is designed. The mechanical structure is comprehensively discussed, a schematic diagram of the drive circuit, as well as its PCB layout, are analyzed. At the same time, the microcontroller and the control algorithm is detailed to precisely to work with very low inductance PCB motors. The design and the production are explored in this proposed, all-inclusive printed circuit board with an integrated driver Fig 1.

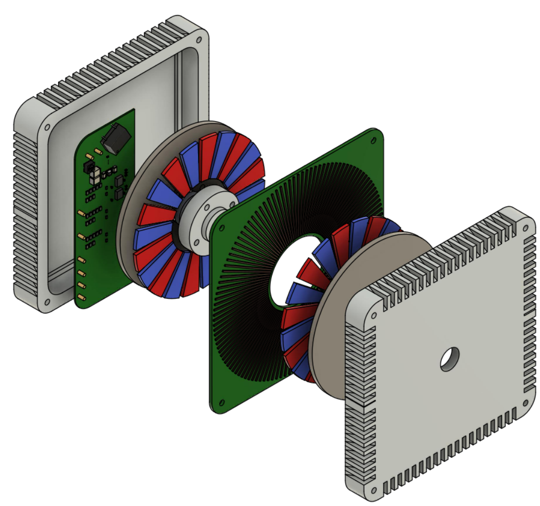

Fig. 1. Exploded view of the proposed motor.

II. Preliminary Design

A. Early Motor Design

A variety of motor structures have been examined to find the most appropriate one to use in a power-dense PCB motor with just sufficient space to fit the required power stage and control stage as well as sensors and connectors in the right place.

Early on, we focused on two topologies; single-sided rotor, double-sided rotor. Fundamental analytical examination

This project is conducted by PowerLab, which is a research group in Department of Electrical and Electronics Engineering in METU, Ankara

showed that Eddie losses produced in the windings' static back core negatively affect the motor's efficiency and the maximum power while making the thermal management harder to control. We strayed away from the single-sided rotor idea and moved on with the double-sided. This strategy comes with increased torque, which is another step towards a dense torque motor Fig 2.

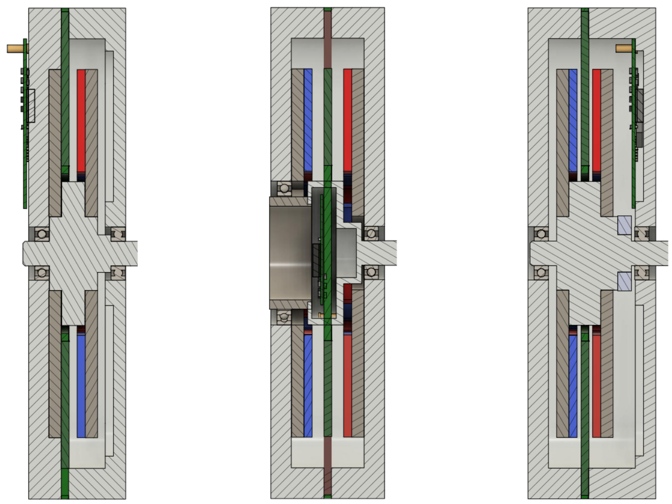

Fig. 2. Previous motor topologies

B. Early Driver Design

At the preliminary design stage of the electronics hardware, we decided on using a monolithic GaN FET and driver chip. There were a few of them; Texas Instruments and EPC (Efficient Power Conversion Inc.). We started with EPC2152. It was the one that has the smallest dimensions. Later, as it is understood that the part was inaccessible, we moved on with Texas Instruments LMG5200. Fortunately, the datasheet of the LMG5200 was very detailed.

The power stage had to be isolated electrically from the controller stage. The targeted switching frequency forced this isolation of the stages. High di/dt and dv/dt on the power stage might affect the controller. The primary approach on the power stage was to be as compact and modular as possible.

To Achieving compactness, the first thoughts were placing the drive circuit in the middle of the windings. Early on, windings were placed more outwards to increase the motor's torque, Clearing the center for any component to put on. But problems arise with sensitive components placed near to the fast-moving magnets. To further increase the power density, the design had another revision to go. An increase in motor speed meant that power output also increases. Utilizing the middle section for windings with the increased speed approach enabled the motor to be more compact. It also signifies that a new placement for the electronics needed to be found.

Another design change had to be made on the encoder of the motor. Compact shaft-end rotary sensors were forcing the

TABLE I
MOTOR SPECIFICATIONS

Parameter	Value	Parameter	Value
Power	250 W	Torque	400 mN.m
Speed	6000 rpm	Frequency	1000 Hz
V_{phase}	17.3 V	I_{phase}	5 A
Pole	20	Air Gap	1 mm
Magnet Thickness	2 mm	Core Thickness	3 mm
R_{outer}	45 mm	R_{inner}	20 mm
PCB thickness	0.6x3 ± 1 mm	Trace Width	0.8 mm
Trace Clearance	0.2 mm	Copper Thickness	2 oz/ft^2
Number of layers	2	$Mass_{rotor}$	370 gr

motor to be longer in the axial direction, so we moved on with an off-axis hall-effect position sensor.

III. MAGNETIC DESIGN

A. Analytical Calculation

Analytic modeling is the first step towards designing a motor. Having the mathematical representation of the motor enables researchers to differentiate on viable options. This analytical step cuts on time of individually analyzing motors using finite element analysis (FEA), which is known that it is time and computation consuming process.[7].

The winding topology is selected as unequal width parallel winding (UEW). It is a similar topology to the parallel winding, but the trace width increases radially. As the electrical resistance is lower than parallel winding, its copper losses are reduced, and having a greater copper area also reduces the thermal resistance to the air. This topology is proposed in a recent paper from one of our colleagues [6], and it is shown that this design out-performs the others, primarily on the torque/loss parameter.

Analytic representation starts with the derivation of air gap magnetic flux density; then, the flux linkage can be calculated. Induced phase voltages are computed as the second step using other factors such as layer number and winding factor. Finally, considering phase currents and nominal speed, the output torque is produced.

B. Generative Optimization

The generative algorithm is used to select the adequate parameters for our motor. The algorithm needs parameters to choose from. Parameters to be optimized are selected as outer diameter, inner diameter, pole count, and turn number. Some of the values are set constant as our needs, such as rotation per minute (RPM), copper thickness, nominal speed, etc. Boundaries are set to get results in logical limits, for example, maximum outer radius for the magnets. Also, some outputs, such as core thickness and induced voltages, are calculated in this process. The primary purpose of the process is to get the objective function optimized, which is to maximize the torque

TABLE II
OPTIMIZED RESULTS

R_{inner}	R_{outer}	Pole	P_{eddy}	P_{copper}	Efficiency	l_{core}	Torque	$V_{induced}$	B_{peak}	M_{total}	obj
22.00	46.00	18.00	5.78	8.93	0.94	2.16	0.402	16.84	0.630	388.03	0.319
19.00	46.50	18.00	5.55	8.72	0.95	2.06	0.403	16.87	0.627	405.26	0.320
19.00	46.00	18.00	5.43	8.57	0.95	2.04	0.390	16.32	0.626	393.70	0.323
22.00	45.50	18.00	5.65	8.75	0.94	2.14	0.387	16.22	0.629	376.46	0.323
19.50	46.50	18.00	5.51	8.64	0.95	2.08	0.399	16.72	0.627	404.67	0.324
22.50	46.00	18.00	5.74	8.83	0.94	2.19	0.397	16.62	0.630	386.64	0.324
19.00	45.50	18.00	5.31	8.41	0.95	2.02	0.377	15.79	0.625	382.33	0.325
25.00	47.00	20.00	6.79	8.69	0.94	2.04	0.403	16.88	0.626	368.69	0.325
19.50	46.00	18.00	5.40	8.48	0.95	2.06	0.386	16.18	0.627	393.07	0.327

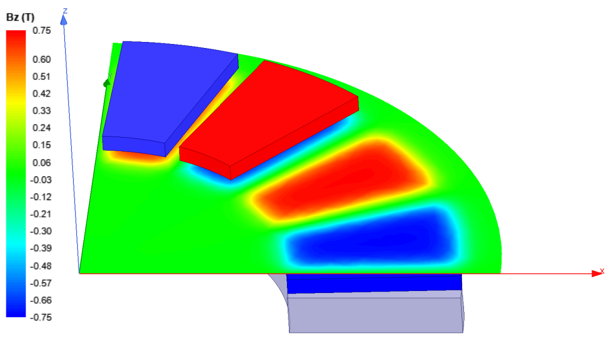

Fig. 3. ANSYS verification.

density stated as torque/liters. After running the optimization study, converged results are listed as Table II. Final motor parameters are listed in Table I

C. Simulation Verification

In order to check our analysis results and verify the optimized parameters, a finite element analysis study had to be done. The finite element model of the machine is constructed on ANSYS maxwell 3D solver. Magnetic field density distribution can be seen in Fig 3. It coincides with the analytical results found previously.

IV. ELECTRICAL DESIGN

A. Specifications

Driving motors with low inductance, as our proposed PCB motor, is a challenging task. Our approach is increasing the switching frequency substantially to keep the current in control. Using GaN transistors, this challenging task became easier.

The proposed integrated driver has strict rules to obey; it has to have a small form factor, and it should be as efficient as possible to keep the thermals in control in a closed environment. This 3 phase inverter is designed to work with 28 V DC, but its range is up to 80 V, and it can supply 7 amperes continuous per phase with a peak current rating of 10 amperes. Absolute encoder input and temperature sensors connect to this board. The main control algorithm is field-oriented control (FOC). The communication interface is selected as USB with optional CAN integration. It has position, speed, and torque control protocols to be able to control. It consists of two subparts, namely the power stage and the control stage.

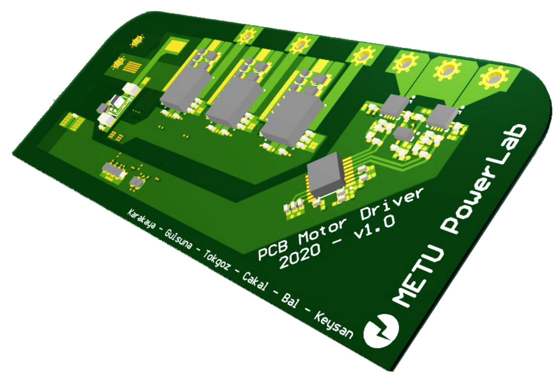

Fig. 4. Power Stage PCB.

B. Power Stage

This stage is the inverter stage, where the DC/AC inversion is made. It consists of three half-bridges. Instead of configuring each half-bridge with individual drivers, transistors, and passives, we decided to continue with an integrated half-bridge module (LMG5200 Fig 4.). This part has two GaN transistors and required gate drivers with the bootstrap configuration for high side switch injected into a mold producing a single module. Its dimensions are only 6mm x 8 mm x 2mm. This compactness is also advantageous in getting the low drive circuit inductance and power loop inductance. Dealing with high frequencies, we decided on isolating the whole power stage, which added extra PWM isolators (ADUM140E1BRQZ), but it made the system more reliable. Another problem was to find an isolated converter low enough to fit in a pancake-like compact motor. The selected part is PDS2-S5-S3-M by CUI inc. This part is selected with considerations on the controller board, which will be supplied only using this. The power board is provided directly from DC input, and the voltage is stepped down using two non-isolated buck converters. These converters are selected from the Texas Instruments WEBENCH tool are Having an isolated converter on-board provides single

DC input to the system, which is convenient. The current measurement is vital in the FOC algorithm; thus, we selected ACS711 current sensors from Allegro, two of them precisely for two motor phases. 100 kHz Bandwidth of these sensors is ideal for our high fast-rotating motor. The output of the current sensor was analog. We utilized an isolated analog to digital converter named ISLISL26312FVZ-T7A to guarantee the signal integrity and isolation between cards.

C. Control Stage

The control stage consists of a microcontroller (MCU) and its peripherals in general. The selected MCU is TMS320F28375D from Texas Instruments. It is a 32bit MCU with dual-core and runs up to 100 MHz, which should be appropriate for increasing the control loop frequency. The primary communication protocol from and to the motor is selected as USB2.0. There are a variety of sensors placed around this board. One of them is a temperature sensor, and the other one is an encoder. Encoder for this project was the critical glue that puts everything together, but it is sticky. It has to be compact with high resolution. MAQ470 is an automotive-grade hall-effect rotary position sensor. The selling point of this sensor was its ability to sense the magnetic field in an off-axis application. In our case, this feature helps us to reduce the axial length by almost 20%. After all that, this board is still in its schematic building stage. Consecutive decisions are made on it.

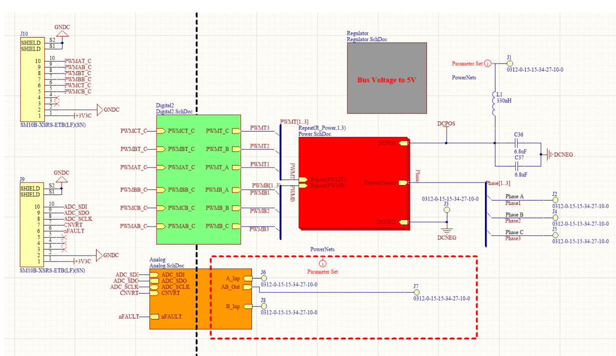

Fig. 5. Power board schematic.

V. Mechanical Design

Mechanical design of a block of steel and aluminum rotating at 6000 rounds per minute is nothing to be careless. The extra attention was given to the mechanical system. As with all rotating mechanical assemblies, our motor has bearings. Bearing selection is tedious work, but giving a general idea, it starts with the speed, of course. Slow rotating bearings have a lot of grease between their balls to reduce friction. As the speed increases, this grease becomes the part that the friction heat is generated. That is why our selected bearings come without grease, and their limits are around 15.000 rpm.

The main body of the motor, as we call casing, is machined from aluminum to achieve better power per kilogram ratio. The minimum wall thickness is selected as 3 mm. That is the common consensus around manufacturers, as thinner parts are harder to manufacture. All bolts are fixed to metric 3 for convenience.

The shaft holds the rotor steels, which the magnets are glued on. This structure is the whole rotor part; also, it is the most massive part of the motor. The shaft is single-piece aluminum explicitly designed to be manufactured using a lathe.

Mechanical pieces on PCBs are the connectors. Making a compact motor also requires compact connectors. We thought that a typical USB-C connector and a DC bus connector is all we need. The main challenge of the mechanics is the tight tolerances. A meticulous production process is needed for a motor at this compactness. A small imbalance in the rotor that would rotate around 6000 rpm causes unavoidable vibrations. A small error in the bearing holders can produce high stresses on parts, significantly reducing the motor's lifespan.

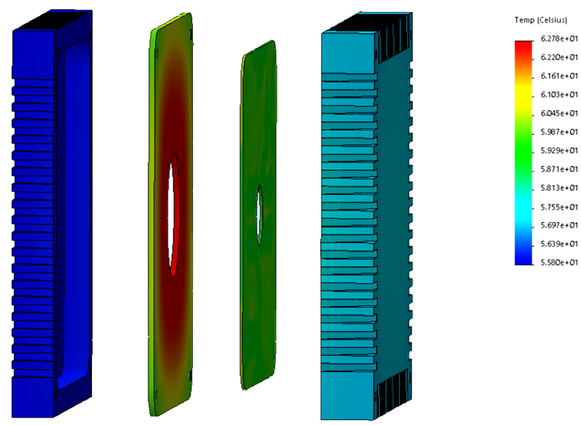

Fig. 6. Thermal Analysis.

VI. Thermal Insight

Nearly every component generates heat; it is unavoidable. Problems arise when one wants to enclose the heat source, isolating it from the surrounding. It is the exact thing we ought to do. Because of moving into in-runner motor topology, thermal management sought more attention. Mainly we have two heat sources from two boards;

Winding board

Driver board

Winding board produces heat due to two things; copper loss and eddy current loss. The analysis showed that we have 6.3 W of loss due to the windings' resistance and 3.6 W of loss due to generated eddy currents on the windings, and a total of 10 W is lost.

The Driver board also generates heat, especially when running at high speeds. We have four primary losses in our power board. Conduction loss, switching loss, drive circuit, and gate charge loss, and bootstrap diode loss. Here we have around a watt loss per half-bridge, so it adds up to 3 watts.

At first glance, one might think that 12 watts of loss is nothing compared to a 250-watt motor, but the problem is the high thermal resistances of these sources to the ambient. We decided on placing the heat sources to the case, effectively using it as a heat-sink. Countless FEA analyzes, and different placement of parts is proposed Fig 6. Finally, one seemed to work fine.

VII. Prototyping & Discussions

A multi-disciplinary project such as integrated motor and driver has numerous little details, and every piece of detail is important. This paper proposed a motor that is easy to produce using PCB manufacturing technology, suggested to drive it, on-board, with very high frequency using cutting-edge semiconductor technology. Detailed thoughts are expressed on lifespan, accessibility, ease of manufacturing, thermals, control algorithm, and many more areas on this complex design task. The phase we are in right now is the end of the design procedure. In the following months, the production process will begin, and intensive work on hardware needed to be made practically. Because of the projects' interdisciplinary aspect, our work could only come up to this point in around six months, but it is time to verify our work on the field.

References

[1] Y. Yang, J. Liang, and X. Xing, "Design and application of axial-flux permanent magnet wheel motors for an electric vehicle," in AFRICON 2009, Sep. 2009, pp. 1–5

[2] G. H. Jang and J. H. Chang, "Development of an axial-gap spindle motor for computer hard disk drives using PCB winding and dual air gaps," IEEE Transactions on Magnetics, vol. 38, no. 5 I, pp. 3297– 3299, 2002.

[3] S. Moury and M. T. Iqbal, "A permanent magnet generator with PCB stator for low speed marine current applications," Proceedings of 1st International Conference on the Developments in Renewable Energy Technology, ICDRET 2009, pp. 217–220, 2009.

[4] X. Wang, C. Hu, M. Zhao, L. Wu, and S. Zhou, "Design of multi-layer pcb coreless axial permanent magnet synchronous motor," in 2019 22nd International Conference on Electrical Machines and Systems (ICEMS), Aug 2019, pp. 1–4.

[5] J. Li, R. Qu, and Y. Cho, "Dynamic eccentricity in single-rotor single-stator axial flux permanent magnet synchronous machine with parallel path windings," in 2015 IEEE International Magnetics Conference (INTERMAG), May 2015, pp. 1–1.

[6] G. Cakal and O. Keysan. Design of double sided linear motor with easy to manufacture hairpin plate winding. In 2019 12th International Symposium on Linear Drives for Industry Applications (LDIA), pages 1–5, 2019.

[7] De, S., Rajne, M., Poosapati, S., Patel, C. and Gopakumar, K., 2012. Low-inductance axial flux BLDC motor drive for more electric aircraft. IET Power Electronics, 5(1), p.124.