DESIGN AND ANALYSIS OF A YASA TYPE MOTOR

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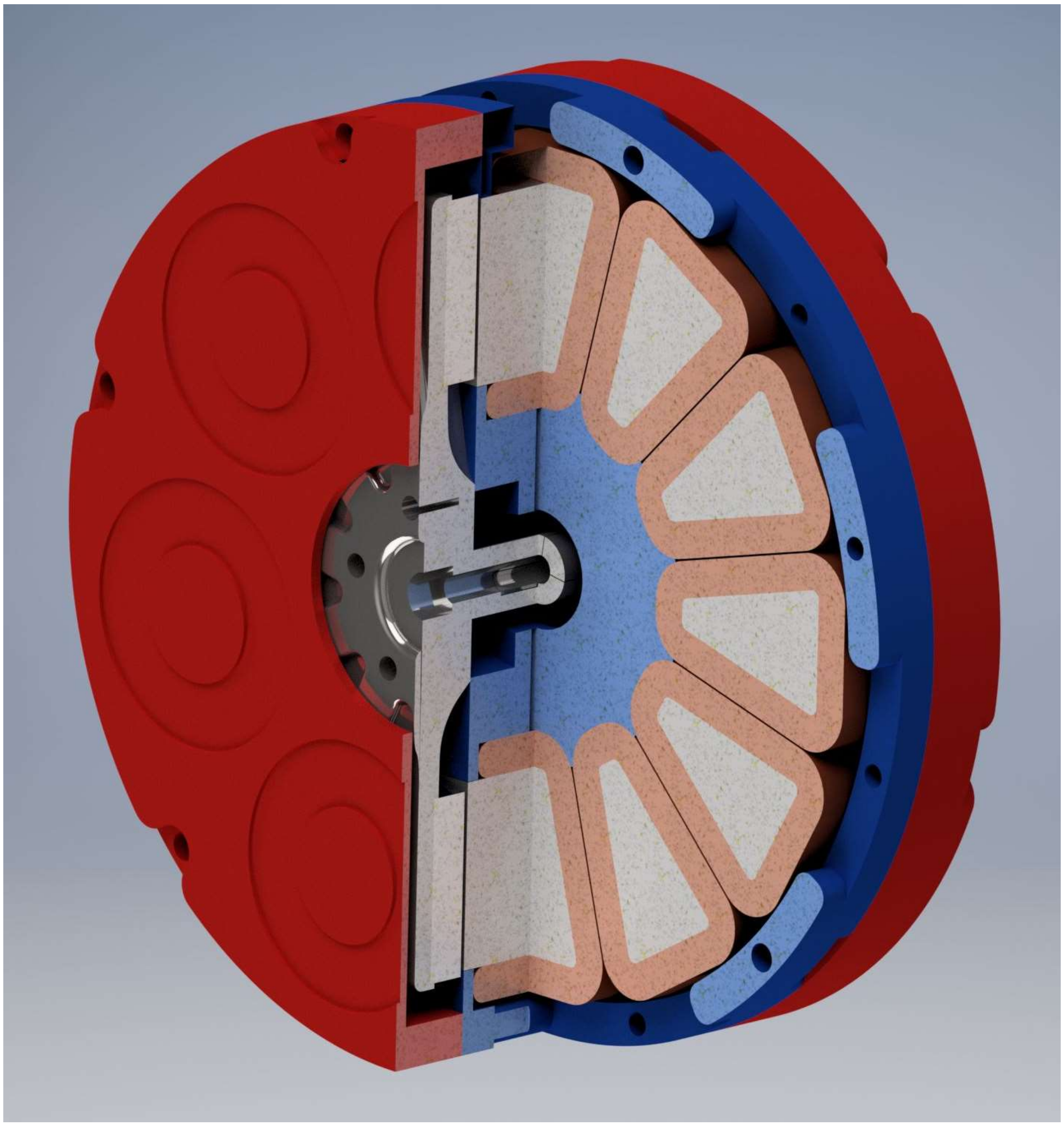

Introduction

This paper goes through the basis of analysis behind an Axial flux YASA type motor. The YASA type motor concept or Yokeless And Segmented Armature motor is currently in development by multiple companies because of its low speed, high torque and low mass characteristics. The idea behind the YASA motor is that each stator segment can be built separately and contains a non-shared ferrite core. The use of a non-shared ferrite core between coils in an axial flux motor allows the use of grain-oriented electrical steels in the stator teeth causing the total saturation currents to get higher and stator losses to decrease. The yokeless design is characterised by its shorter flux path, hence the flux goes through the stator into the rotor and directly back into the adjacent stators. [1]

In this study a small axial flux motor is designed for a concept in wheel hub motor. Design constraints for this motor included:

- Motor must have a maximum overall diameter of 4.5 inches.
- Have a maximum torque output of 20Nm.
- Have a operating range from 0-20000 RPM.
- Have the ability to be stacked for higher torque capabilities.
- To minimize the cogging torque.

Motor specifications are chosen as ideal values for a small electric vehicle that could have a scalable power output based on the number of motors placed in parallel with each other. For a hub motor a small size is required to minimize the unsprung mass in the wheel and with the scalability the vehicle can be optimized for multiple scenarios. A small motor like this can typically/commonly be used in vehicle starter motors as well in small generation applications. The small radius of the rotor also reduces the rotational inertia of the motor allowing quick changes in response.

With the constraints above being defined, first it is ideal to determine the coil arrangement of the motor. As seen below 12 stator cores with 10 magnets/rotor was chosen. The 10 magnets are arranged to minimize motor cogging torque while still providing enough strength in the stator for the pull between the rotor and stator poles. The table displayed below is used as a reference for poles vs stator bars and was verified in EMS for the coil arrangement.

teeth Poles	3	6	9	12	15	18	reduction
2	ABC	ABCabc	AacBBaCCb	AAccBBaaCCbb	AAACCbbbaaCCCbb	AAAcccBBBaaaCCCbbb	1
4	ABC	ABCABC	ABaCAcBCb	AcBaCbAcBaCb	AAcBaCCbAcBBaCb	AAcBBaCCbAAcBBaCCb	2
6			ABCABCABC			AcBaCbAcBaCbAcBaCb	3
8	ABC	ABCABC	AaABbBCcC	ABCABCABCABC	AcaCABabABCbcBc	ABaCAcBCbABaCacBCb	4
10	ABC	AbCaBc	AaABbBCcC	AabBCcaABbcC A-b-C-a-B-c	ABCABCABCABCABC	AcabABCbcaCABabcBC	5
12			ABCABCABC			ABCABCABCABCABC AaBbCcAaBbCcAaBbCc A-B-C-A-B-C-A-B-C	6
14	ABC	AcBaCb	ACaBAbCBc	AacCBbaACcbB A-b-C-a-B-c	AaAaABbBbBCcCcC	AabcCABbcaABCcabBC	7
16	ABC	ABCABC	AAbCCaBBc	ABCABCABCABC	AaAaACcCcCBbBbB	AaABbBCcCAaABbBCcC	8
20						AaABbBCcCAaABbBCcC	10

Figure 1: Winding Diagram for Electric Motor's [3]

After the coil arrangement, the stator teeth shape was determined using the magnets as a reference it proves to provide using the same angular displacement $\theta = 360°/teeth$ =30° between stators was found to provide the best magnetic coupling with the rotor. The thickness of the magnets is then found iteratively to minimize cogging torque and the total reluctance torque at full stator current. A thickness of .1875” demonstrated the best performance.

Winding Calculation

When designing an electric motor, a balance between losses and power output is a must, the initial simulations reveal that a coil current of 4000At will saturate the stator bars. In such case, it was crucial to determine the most appropriate wire size for the heat loss at 4000 At. This concept is represented in table 1 below: The wire area in mm^2 is used to find the appropriate wire size. The small size of this motor heavily relies on a high coil winding factor and so ideally, a rectangular cross section magnet wire would be used.

Table 1: Cable Winding Size

AT	TURNS	height	width	DIV	wire h	wire w	Wire A (in^2)	Wire A (mm^2)	Length (in)	Length (m)	Resistance	Amps	Power
4000	30	0.625	0.200	5	0.125	0.040	0.005	3.226	87.000	2.210	0.012	133.333	204.598
4000	32	0.625	0.200	5	0.125	0.040	0.005	3.226	92.800	2.357	0.012	125.000	191.811
4000	34	0.625	0.200	5	0.125	0.040	0.005	3.226	98.600	2.504	0.013	117.647	180.528
4000	36	0.625	0.200	6	0.104	0.033	0.003	2.240	104.400	2.652	0.020	111.111	245.518
4000	38	0.625	0.200	6	0.104	0.033	0.003	2.240	110.200	2.799	0.021	105.263	232.596
4000	40	0.625	0.200	6	0.104	0.033	0.003	2.240	116.000	2.946	0.022	100.000	220.966
4000	42	0.625	0.200	6	0.089	0.033	0.003	1.920	121.800	3.094	0.027	95.238	245.518
4000	44	0.625	0.200	6	0.104	0.033	0.003	2.240	127.600	3.241	0.024	90.909	200.878
4000	46	0.625	0.200	6	0.104	0.033	0.003	2.240	133.400	3.388	0.025	86.957	192.145
4000	48	0.625	0.200	6	0.104	0.033	0.003	2.240	139.200	3.536	0.027	83.333	184.139
4000	50	0.625	0.200	7	0.089	0.029	0.003	1.646	145.000	3.683	0.038	80.000	240.608
4000	52	0.625	0.200	7	0.089	0.029	0.003	1.646	150.800	3.830	0.039	76.923	231.354
4000	54	0.625	0.200	7	0.089	0.029	0.003	1.646	156.600	3.978	0.041	74.074	222.785
4000	56	0.625	0.200	7	0.089	0.029	0.003	1.646	162.400	4.125	0.042	71.429	214.828
4000	58	0.625	0.200	7	0.089	0.029	0.003	1.646	168.200	4.272	0.044	68.966	207.420
4000	60	0.625	0.200	7	0.089	0.029	0.003	1.646	174.000	4.420	0.045	66.667	200.506
4000	62	0.625	0.200	7	0.089	0.029	0.003	1.646	179.800	4.567	0.047	64.516	194.039
4000	64	0.625	0.200	8	0.078	0.025	0.002	1.260	185.600	4.714	0.063	62.500	245.518
4000	66	0.625	0.200	8	0.078	0.025	0.002	1.260	191.400	4.862	0.065	60.606	238.078
4000	68	0.625	0.200	8	0.078	0.025	0.002	1.260	197.200	5.009	0.067	58.824	231.076
4000	70	0.625	0.200	8	0.078	0.025	0.002	1.260	203.000	5.156	0.069	57.143	224.474
4000	72	0.625	0.200	8	0.078	0.025	0.002	1.260	208.800	5.304	0.071	55.556	218.238
4000	74	0.625	0.200	8	0.078	0.025	0.002	1.260	214.600	5.451	0.073	54.054	212.340
4000	76	0.625	0.200	8	0.078	0.025	0.002	1.260	220.400	5.598	0.075	52.632	206.752
4000	78	0.625	0.200	8	0.078	0.025	0.002	1.260	226.200	5.745	0.077	51.282	201.451
4000	80	0.625	0.200	8	0.078	0.025	0.002	1.260	232.000	5.893	0.079	50.000	196.414

Figure 2: Cable winding size

Simulation Results

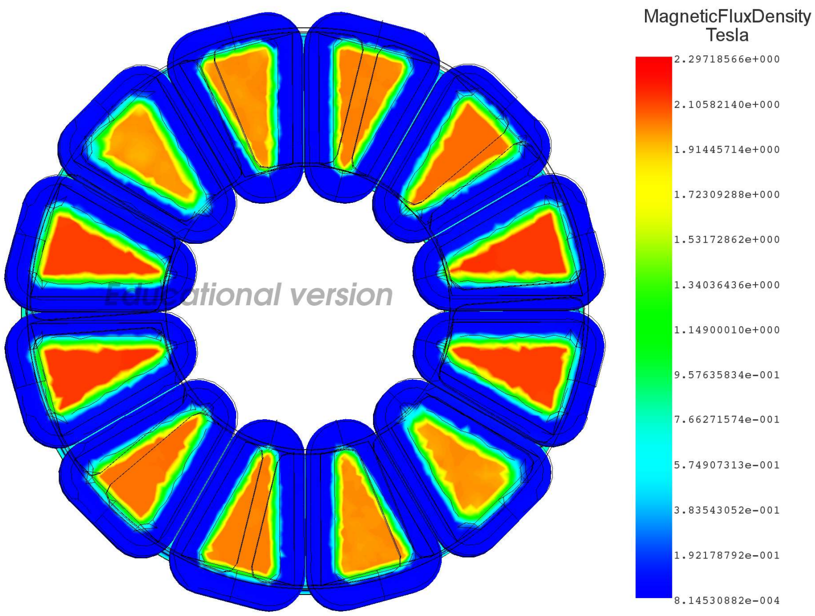

Figure 3: Full saturation B [T]

Figure 3 above displays the motor stator core saturation at full load (4000At). The magnitude of the flux density is almost 2.3T in the stator cores thanks to the use of grain-oriented electrical steels which are essential in a motor of this size.

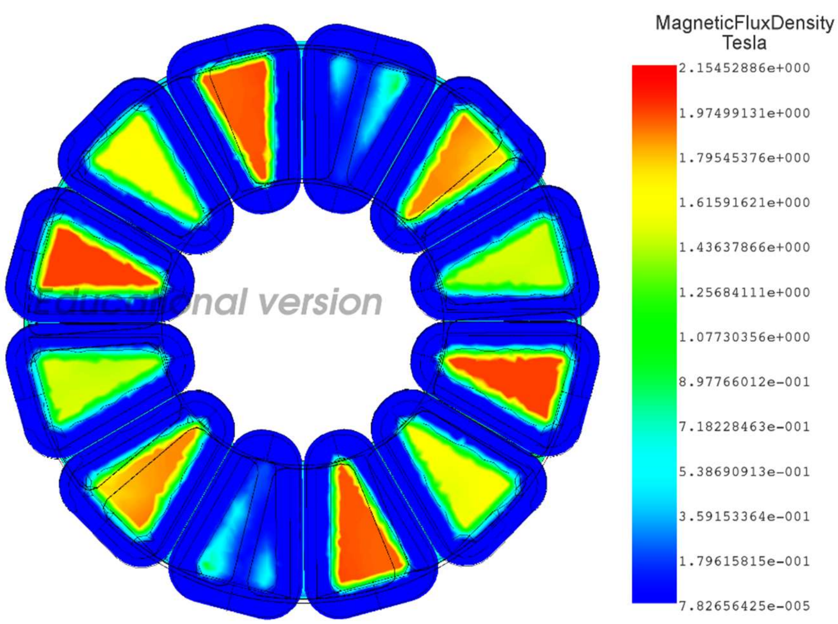

Figure 4: No current B [T]

At a free rotation load the above magnetic field saturation is obtained, figure 4 above manifests the flux coupling between both rotors and how strong the coupling is under no load.

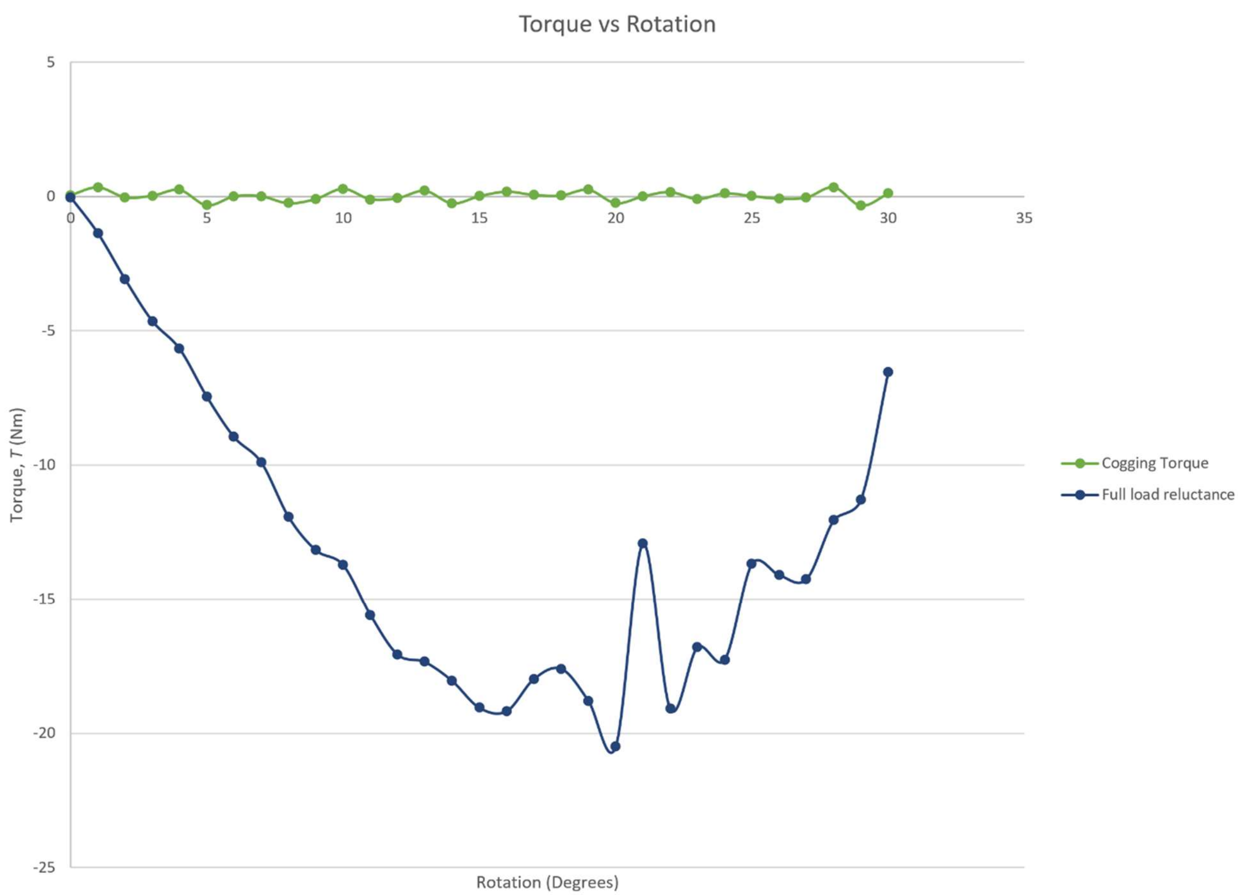

Figure 5: Torque vs Rotation

Figure 5 represents the reluctance torque required to rotate the motor in two conditions at a full load stator current condition at 4000At and while the motor is at a no-load stator current condition at 0At. The free rotation losses are smaller in comparison to the reluctance to rotation at full load, this is beneficial in EV's as free rotation losses affect range. [2]

Conclusions/Future Recommendations

This paper overviews the design of a small axial flux motor but does not contain any transient response results. The transient response parameters, more realistic losses, current distributions and functional response should be investigated in future studies. The objectives in a static scenario were met and exceeded, with a reluctance torque of 20.5Nm this would be the point when slip would occur under load and as such it can be assumed that the maximum torque output would be 20.5Nm which is above expectations.

In the future, a magneto-transient solver will be required to verify the full speed characteristics such as, rotational stability, efficiency vs load graph, thermal cooling requirements, full load torque vs speed, and voltage requirements for designing an inverter. Data obtained from the simulation studies run are placement of hall effect sensors for optimal torque coupling and phase inductance.

Thanks to EMWorks for supplying me with an educational copy of their EM Simulation software.

References

[1] T. Woolmer and M. Mcculloch, "Analysis of the Yokeless And Segmented Armature Machine," *2007 IEEE International Electric Machines & Drives Conference*, 2007.

[2] D. Moreels and P. Leijnen, "MAGNAX: HIGH EFFICIENCY AXIAL FLUX MACHINES." https://www.magnax.com/hubfs/WP-20High%20Efficiency%20Axial%20Flux%20Machines%20-%20whitepaper%20v1.5.pdf?hsCtaTracking=031f3fb5-bcfd-4f20-a35c-b2c399acb674%7C5f5531d7-81c2-4bb2-ab02-297a79a96279

[3] http://www.bavaria-direct.co.za/info/

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