MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRONICS AND ELECTRICAL ENGINEERING

Selected Topics on Electrical Machines (EE 568)
Final Project Report

July 2022

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GitHub link

I. Machine specifications

- Direct drive surface mounted radial flux
- 1MW generator
- speed of 18 rpm
- Line voltage 3.3 kV
- Natural air cooling

Main objectives: a light machine and low-cost machine (beware of PM cost)

II. Literature review

To perform the research several questions should be answered from literature review as much as possible. The most important ones are:

- Suitable slot/pole combinations for direct drive wind generator?
- Suitable winding arrangement for direct drive wind generator?
    - Distributed or concentrated winding
- Inner rotor structure or outer rotor structure?
    - Advantages and disadvantages of each one
- Initial sizing of the machine
- Current density value for an air cooled 1MW generator

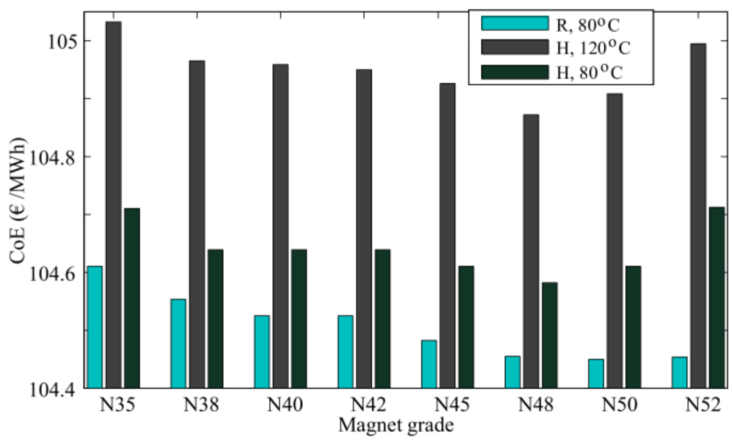
To perform the literature review, among many papers, fifteen papers were selected based on sufficient similarity with the topic and thereby read carefully. Here summary of these papers and important points concluded in the papers are presented.

[1] proposes a comparison with outer rotor PM generator (ORPMG) and switch reluctance generator for direct drive with power of 3 MW. Outer diameter of ORPMG stator is 5 m and stack length is 1.2 m with 80 poles and 480 slots.

[2] conducts research on the thermal design of water-cooled direct drive permanent magnet synchronous generator. Power rating is 8 MW in this paper. It is mentioned in the paper that magnet temperature must be between 120-150 °C. Plus, due to short circuits that might happen, the magnet temperature should be limited to 100 °C which means current density of the machine is highly limited and thereby especially for an air-cooled machine will yield a large machine. This is the reason the authors in [2] paper suggest a water-cooling system and considered J (current density) is 7 A/mm^2. This is an inner rotor PM generator (IRPMG) with stator outer diameter of 7.6 m and stack length of 1.7 m with 120 poles and 144 slots. Moreover, since the speed is very low in large direct drive wind generators 10-20 rpm. Therefore, core losses are small and most of losses come from the stator copper. For instance, in [2], the stator copper losses were considered 450 kW while total core and magnet loss is less than 40 kW.

[3,4] investigates different slot/pole combinations for the direct drive wind generators including both concentrated windings (CWs) and distributed windings (DWs) in outer rotor structure. The investigated slot/pole combinations are included in Table I. Considered machine is 1.6 MW with speed of 7 rpm and forces air cooling.

[5] considers the magnet grade and temperature in design of an IRPMG with rated speed of 11 rpm, with three power level of 6, 8 and 10 MW. In this paper, effect of magnet types by considering different magnet such as, N35, N38, N40, N42, N45, N48, N50 and N52 at different temperatures is investigated. Authors also implemented a cost model considering the all the machines' parts such as magnet types. What I understand from this paper is that with N48 magnet type overall cost of the energy productions is minimized but the magnet temperature should be kept in a certain range (Fig. 1).



Effect of different magnet grade on cost of energy [5]

UPGRADING FROM 6 TO 8 MW AND 10 MW: COST AND ENERGY

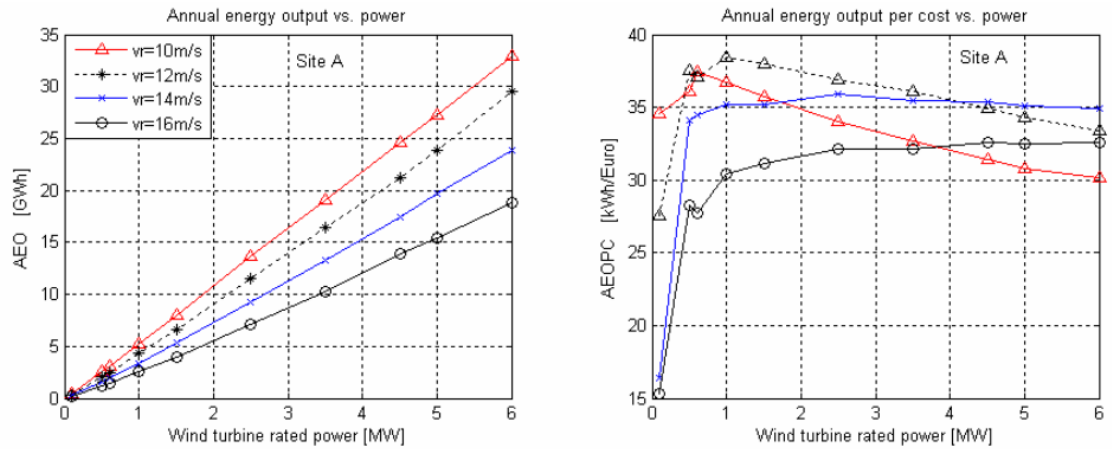
	8 MW	10 MW
Active materials cost	8.6% increased	12.2% increased
Structural material cost	24.2% increased	26.6% increased
Tower cost	2.2% decreased	3.2% decreased
Substructure and foundation cost	2.1% increased	9.5% increased
Wind firm rest of the turbine capital cost	5.4% decreased	8.2% decreased
Annual energy production	1.8% decreased	2.2% decreased

cost increase from 8 MW to 10 MW machine

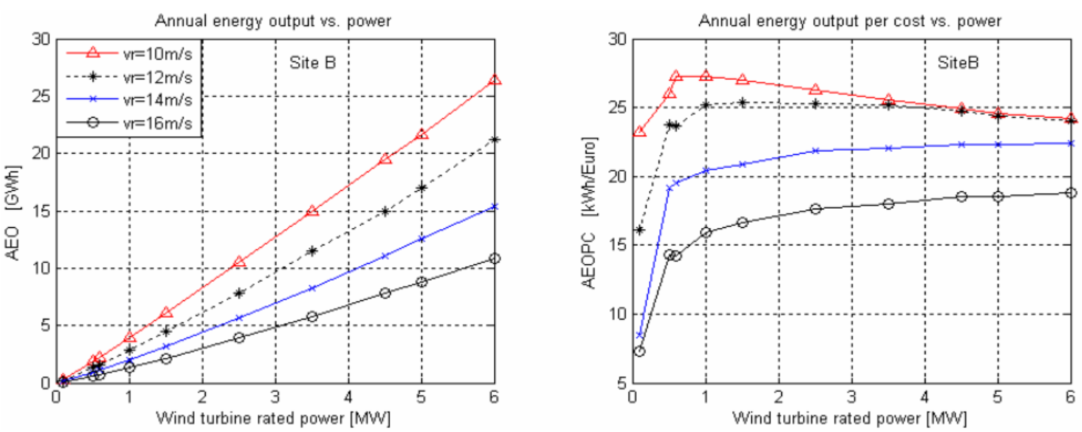
Fig. 1, [5]

[6] proposes a method to optimize the 6 MW IRPMG with Ferrite, Y40 and N40H magnets. Four objective functions were introduced to optimize the machines and compare them. Considering the torque density (Nm/kg) N40H can produce 8.5 times more torque density. However, the overall cost of these two machines is close. Paper was published in 2016.

[7] is a nice paper, investigates designing IRPMGs from 500kW to 6 MW and comparing annual energy output (AEO) and AEO per generator system cost (AEOPC) at three different sites (A, B and C). The main difference between these sites is wind average speed.



Site A



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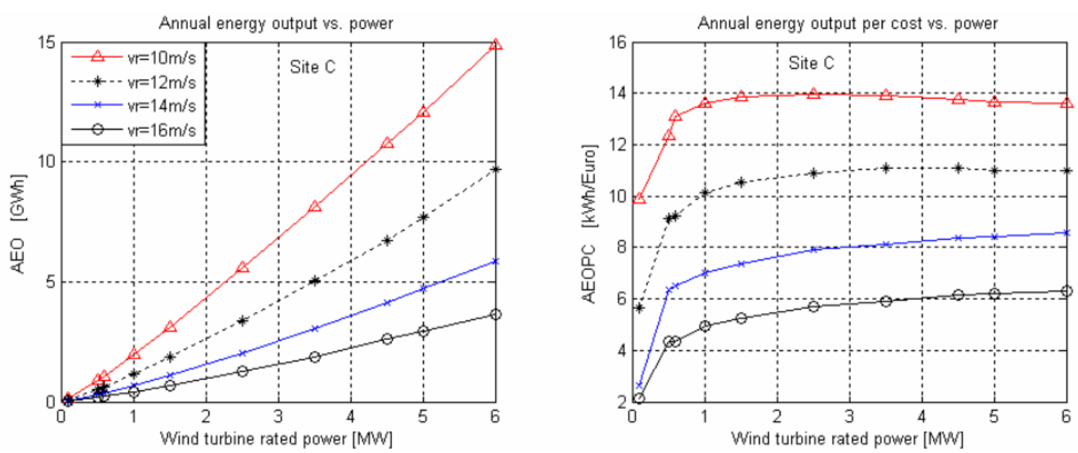


Site C

Fig. 2, [7]

[8] is about the noise and vibration in IRPMGs. Technically the most important choice regarding noise and vibration is slot/pole combination. In this paper, harmonic current injection is employed to reduce noise and vibration.

[9] is about life cycle assessment of 15 MW High-Temperature Superconductor and Permanent-Magnet Direct-Drive Synchronous Generators for Offshore windfarms. Design specifications are presented in Table II.

Table II the design specifications if super conductor and PM direct drive generators.

Parameter	Description	Value		Unit
		PMDDSG	HTSDDSG	
L	Total active length	2.4		m
N_{ph}	Number of phases	9	3	
D_g	Air gap diameter	13.2	5.5	m
D_{so}	Outer armature diameter	13.9	6.6	m
D_{ri}	Inner rotor diameter	12.3	4.8	m
g	Gap thickness	13	5	mm
Stator				
N_s	Number of armature slots	234	234	
N_{cs}	Number of coils per slot	2	2	
W_{si}	Stator coil width at R_{si}	40	67	mm
d_s	Stator coil height	91	40	mm
Y_{sth}	Stator yoke thickness	70	270	mm
Rotor				
N_p	Number of rotor poles	200	26	
W_{ri}	Rotor slot / magnet width at R_{so}	170	435	mm
d_r	Rotor slot height	65	70	mm
Y_{rth}	Rotor yoke thickness	70	270	mm

[10] investigates the effect of the number of slots per pole on performance of permanent magnet generator direct driven by wind turbine. The rate power is 2 MW. Table III and Fig. 3 shows related slot/pole combinations and results from [10].

Table III, the considered slot/pole combinations in [10]

	1	2	3	4	5
Number of poles	60	60	60	80	120
Number of slots	144	216	288	288	288
Slot number per pole	12/5	18/5	24/5	18/5	12/5
Teeth flux density / T	1.5-1.7	1.5-1.7	1.5-1.7	1.5-1.7	1.5-1.7
pole embrace	0.64-0.92	0.64-0.92	0.64-0.92	0.64-0.92	0.64-0.92

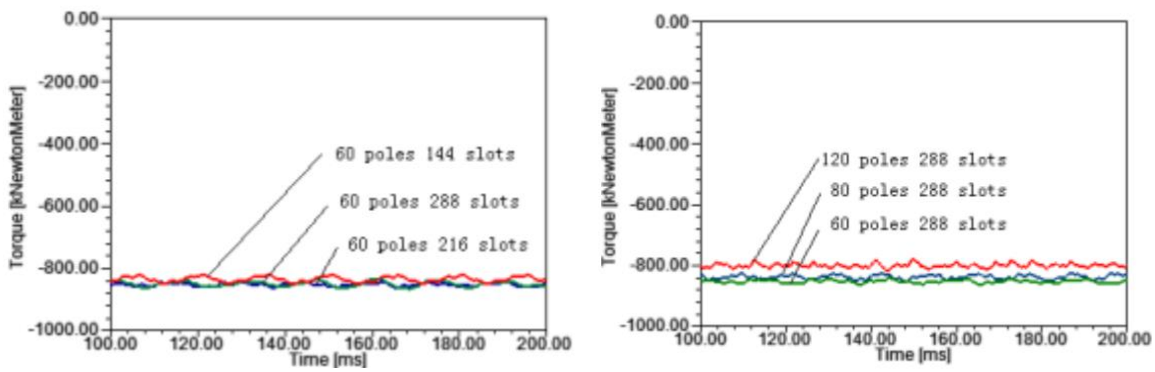


Fig. 3, Torque values from [10]

[11] proposed a design methodology for IRPMG and provided results for the machine from 750 kW to 10 MW. Results includes cost comparison too ([11] published in 2007). As show in Table IV.

Table IV, machine parameters and related results from [11]

Rated Power [MW]	0.75	1.5	3.0	5.0	10.0
rotor diameter D [m]	50	70	90	116	170
Rated wind speed v_N [m/s]	11.2	11.3	12	12	11.7
Rated rotor speed n_r [rpm]	28.6	20.5	16	14.8	10
Generator system dimensions					
Air gap diameter D_{i1} [m]	2.6	3.8	5.2	6.5	10.3
Stator length l_s [m]	0.7	0.8	1.18	1.48	1.8
Number of pole pairs Np	67	80	84	100	157
Magnet height h_m [mm]	12.7	17.1	15.8	15.3	20.5
Magnet width b_m [mm]	61	74.6	97.2	102	103
System weight [Ton]					
Generator active material	3.65	8.91	19.3	29.1	56.5
Nacelle cover	0.63	0.89	1.36	1.87	3.44
Support structure (inc. shaft)	5.18	5.98	7.67	9.89	16.1
Total	**9.46**	**15.8**	**28.3**	**40.9**	**76.1**
Weight per kilowatt [kg/kW]	**12.6**	**10.5**	**9.43**	**8.18**	**7.61**

Components cost [kEuro]					
Generator active material	33.8	82.8	160	254	529
Generator construction	23.5	66.4	170	325	1155
Nacelle cover	6.5	10.5	17.8	36.1	55.7
Converter	30	60	120	200	400
Electrical subsystem	28.4	56.8	113	189	378
Generator system cost	**122**	**277**	**581**	**1004**	**2518**
Cost per kilowatt [Euro/kW]	**163**	**185**	**194**	**201**	**252**
Annual energy					
Copper loss [MWh]	119	140	225	415	849
Iron loss [MWh]	23.9	63.4	89	121	237
Converter loss [MWh]	75.1	151	265	478	1006
Total loss [MWh]	218	354	579	1014	2092
AEP [GWh]	**2.12**	**4.28**	**8.05**	**13.3**	**27.6**

[12] is a good paper because the machine rating is 1.5 MW (@17.4 rpm) and it is a practical design which was manufactured in a Chinese company. Therefore, [12] is one of my main references in this project. Two slot/pole combinations (120p/432s and 78p/324s) are investigated. The 78p/324s is found to have a better performance and lower torque ripple. Several results are presented such as effect of pole arc and magnet thickness on the output power.

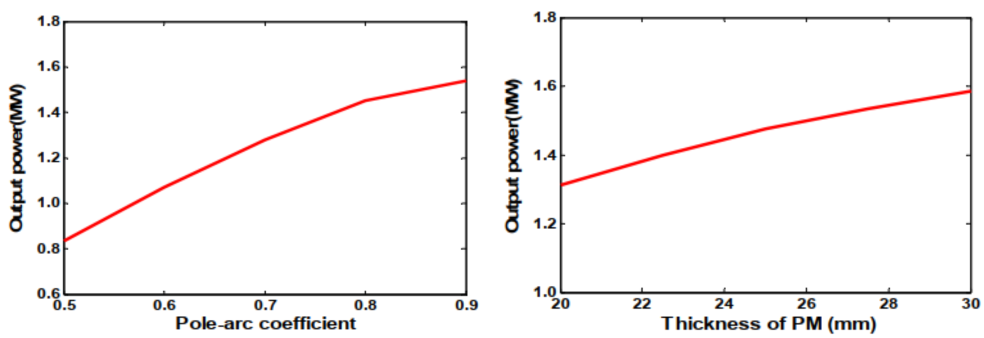


Fig. 4 results from [12]

[13] investigates the design method and comparison between superconductor synchronous generator (SCSG) and IRPMG for 10 MW power. Comparison also includes cost of SCSG and IRPMG (paper published in 2016). Parameters of the designed machine are shown in Table V. Several results are shown in Fig. 5.

Table IV, Machine parameters from [13]

		SCSG		PMSG-O	
	Air gap diameter D_s (m)	6	10	6	10
	Generator active length l_s (m)	2.51	1.15	2.87	1.53
x_1	Pole pair number p	22	38	40	94
x_2	Inner pole span angle α (electrical degree)	68	66	76	72
x_3	Outer pole span angle β (electrical degree)	72	72	n/a	n/a
x_4	Field coil height h_f or magnet length l_m (mm)	14	10	46	28
x_5	Armature slot height h_s (mm)	108	114	104	118
x_6	Ratio of armature tooth width to slot pitch b_t/τ_s	0.62	0.65	0.60	0.65
x_7	Armature yoke height h_{sy} (mm)	110	114	72	60
x_8	Field yoke height h_{ry} (mm)	112	108	74	38

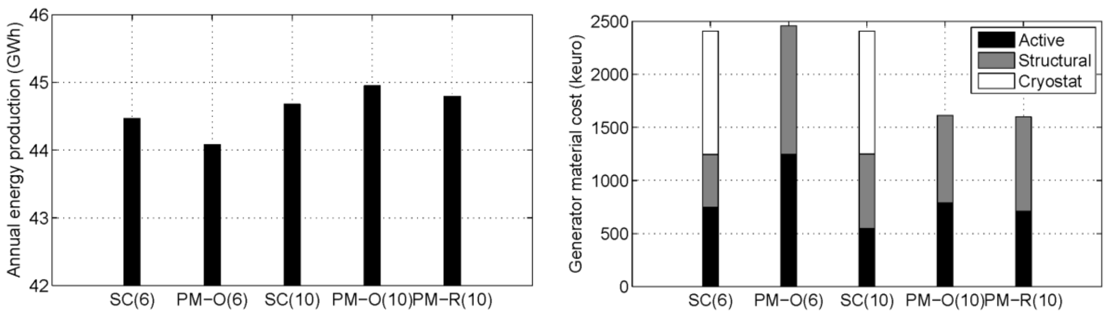


Fig. 5, comparison of generator cost and annual energy production from [13], PM-O is the optimized design and PM-R is the reference design in [13]

[14] investigates and compares surface mount IRPMG and interior IRPMG with concentrated windings. Therefore, two machines are investigated with different rotors.

Table VI, Machine parameters from [14]

Parameters	Unit	SPM	IPM
Size parameters			
Pole Number		220	160
Slot Number		264	192
Stator Outer Diameter	mm	8,000	8,000
Rotor Outer Diameter	mm	7,686	7,664
Magent Thickness	mm	32	34
Magent Length	mm	91	126
Stack Length	mm	1,023	980
Slot Depth	mm	119.4	120.4
Tooth Width	mm	45.5	62.5
Volume	m^3	51.4	49.3

At the conclusion it was mentioned that surface mounted PMSG has less total weight and cost, lower torque ripple, and better demagnetization performances compared to that of the IPM generator, while the large-scale IPM generator has higher torque per volume and less magnet loss than that of the SPM generator.

[15] investigates the magnet shape manipulation and skew effect to reduce torque ripple based on analytical approaches.

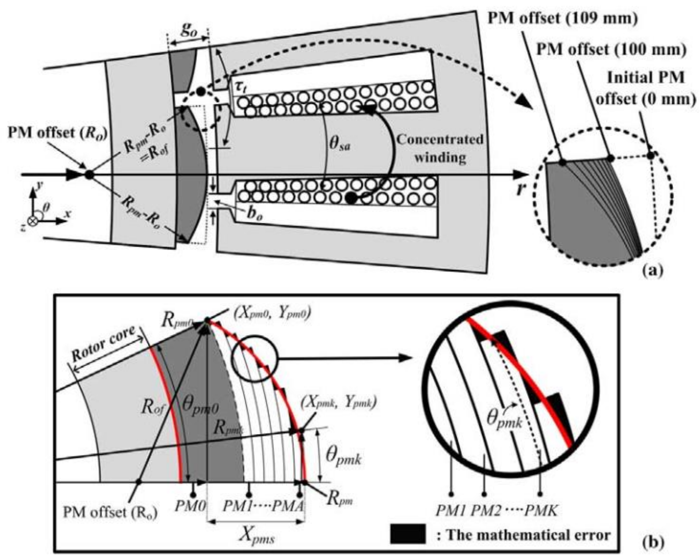


Fig. 6, The magnet shape and skew effect in [15]

III. Summary of conducted research in this project

The most important choice is slot/pole combination in this project. Slot/pole combination will identify the type of windings (CW or DW). CWs has the advantage of simpler structure and lower end winding while DWs can suppress harmonics in the airgap and hence, reduce torque ripple. Therefore, to design an acceptable machine, various slot/pole combinations should be considered. Table VII displays the slot/pole combinations that is considered to obtain a good result in this project.

Conducted research is as follows. Firstly, an analysis performed to find the best slot/pole combinations considering the winding factor. In this regard, all the winding factors up to 31th harmonic for various poles (40-100) and slots (60-400) are calculated using a code in MATLAB, related results were exported in an excel file (the slot/pole combinations that has fundamental harmonic > 0.8) and available in the GitHub. There are several software and websites that provide such results. However, they normally provide the fundamental winding factor but in this excel file there are also winding factor up to 31th harmonic. Furthermore, there are two cost functions, these cost functions can be taken as a measure to compare amount of torque ripple in the machine (lower cost function lower torque ripple).

So, by doing the literature review several slot pole combinations were identified. Plus, by utilizing the exported excel file, the one is able to have a deeper look into winding factor and decide which slot/pole combinations has a better potential.

Slot/pole combinations with CWs are the ones that firstly considered for simulation. Because technically without the proper designed model in FEA, for the application it is impossible to decide which slot/pole combinations can be a good candidate.

By using the MotorCAD, ten models designed, and related results are presented in Table VII. It should be noted that from literature review/sizing the outer diameter of machine for 1 MW identified to be around 3 meters. Moreover, inner and outer rotor designs are considered and compared in the simulations. The reason to consider outer rotor structure is that, since it is an air-cooled machine, hence, current density is highly limited and by putting magnet in the outer rotor more magnets can be placed, and more power can be generated. So, it is worth doing the design in FEA.

Additionally, from literature review it was identified that current density for an air-cooled generator at this size should be around 2 A/mm^2. Obviously, by putting heat exchangers and ducts in the axial length of the machine, the total heat transfer can be improved and as a result the axial length of the machine can be decreased, or current density increased in either case total cost of the machine is affected. Technically, in this project my main goal is to design a decent machine with power around 1MW. Hence, current density in all the machines is considered to be 2 A/mm^2 and airgap length is 5 mm. Plus, the axial length set to a fixed value of 700 mm but the outer diameter of the machine is adapted to generate 1 MW power. As a result, the inner rotor machine has larger size and total mass.

An important thing to consider in such huge machines with magnets is the cogging torque which is also included in Table VII.

Table VII, Comparison of studied machines*

Design	1	2	3	4	5	6	7	8	9	10
Slot	96	96	90	90	162	162	324	324	144	144
Pole	80	80	80	80	78	78	78	78	60	60
Inner or outer rotor	Outer rotor	inner rotor	Outer rotor	inner rotor	Outer rotor	inner rotor	Outer rotor	inner rotor	Outer rotor	inner rotor
Coil Pitch	1	1	1	1	2	2	4	4	2	2
Winding factor kw1	0.933	0.933	0.945	0.945	0.952	0.952	0.953	0.953	0.925	0.925
Output Power (MW)	1.059	1.04	1.01	1.04	1.09	1.09	1	1.05	1.01	1.04
Power factor	0.57	0.46	0.57	0.43	0.76	0.85	0.83	0.87	0.75	0.59
Torque ripple (%)	4.76	2.63	4.89	3.59	6.08	4.63	3.13	5.63	3.62	3.55
Copper loss (kW)	32.524	33.46	28.58	33.85	25.243	22.64	21.92	21.86	30.22	34.59
Core loss (kW)	22.08	10.96	22.83	22.79	20.17	13.85	18.89	11.19	13.42	8.02
Efficiency (%)	95.08	94.86	95.24	94.87	96.01	96.98	96.08	96.96	95.86	95.29
Outer diameter (mm)	3030	3300	3120	3300	3500	3800	3520	3800	3130	3250
Total Weight of active material (kg)	36270	44270	37940	44250	49700	58280	49820	58170	37970	43200
Total mass of magnets (kg)	1567	1084	1622	1017	1856	1784	1857	1784	1622	1066
Cogging torque peak to peak (kNm) *	27.91	41.16	70.44	51.87	19.33	38.84		9.95	26.93	15.89

*all the results are obtained from MotorCAD except for the cogging torque peak to peak which was obtained from Ansys Maxwell.

*Details of the conducted FEA is presented in FEA sections.

Details of the conducted FEA are

- Current density in all the machines is considered to be 2 A/mm^2
- Airgap length is 5 mm,
- Axial length in all machines is 700 mm
- Magnet grade is N35UH with Br of 1.21 at 20 ℃,
- Copper resistivity is 1.724e-8,
- Core Material is 400-50 at 20 ℃,

Further details are presented in FEA section.

IV. Analytical calculations and sizing

The analytical calculations in this project are as follows:

- Calculations of winding factor up to 31th harmonic for various slot/pole combinations (40-100 poles and 60-400 slots). The generated table is available in GitHub repository as an excel file.

Among available slot/pole combinations 10 were selected based on the machine sizing in which identified that machine outer diameter should be around 3 m. Maximum number of poles taken as 80 because higher than this number goes to 120 and 160 poles in which means magnet size is reduced to put in the same rotor circumference (magnet size become too small).

Also, regarding number of slots same issue could happen and machine end up with narrow teeth width. The 324 slots is high for this machine size (teeth width become too narrow). Hence, 162 slots is also added to slot/pole combinations to investigate. Based on the results in Table VII, the slot/pole combination of 144s/60p is selected to carry on the analytical implementation. It should be noted that the analytical approach explained in the book and lecture notes is for the inner rotor structure.

As shown in first section, an initial sizing of the machine based on the lecture notes will be presented. If the power factor of the machine is taken as 0.8, magnetic loading equal to 0.86 T, electrical loading 65 kA/m then the tangential stress is calculated from tangential stress rotor volume is calculated and by use of rotor volume and aspect ratio, the airgap diameter is calculated.

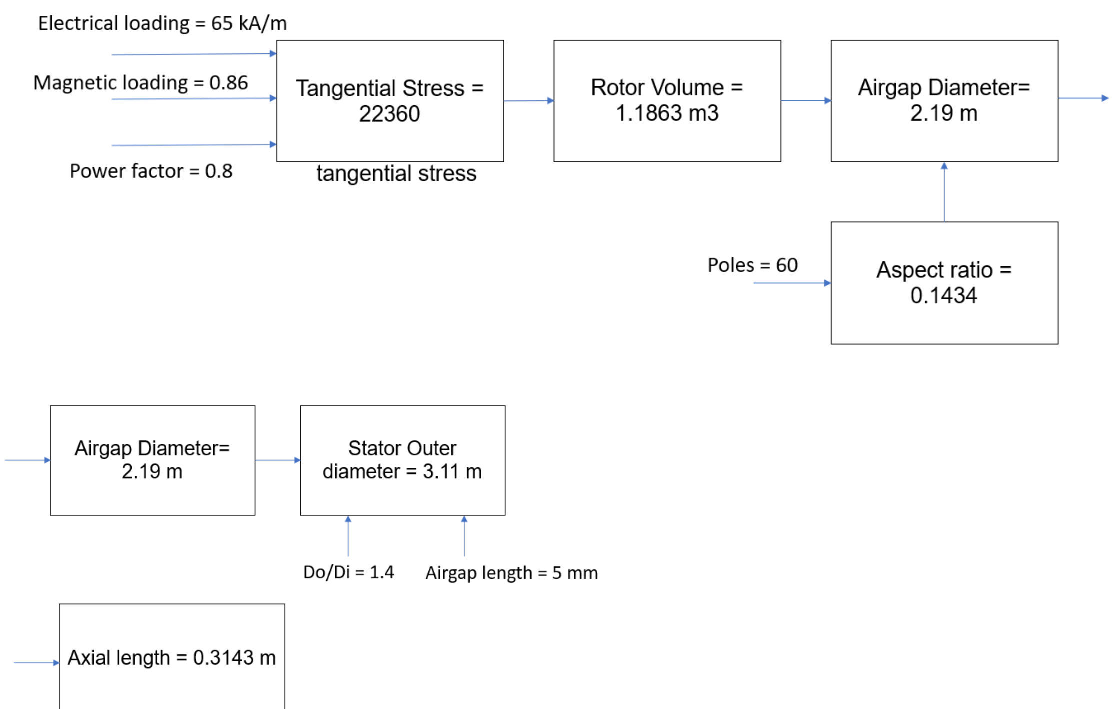


Fig. 7, analytical approach to do machine sizing

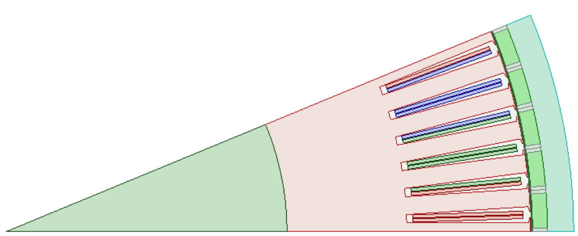
The equation in the book which gives the aspect ratio here yields a small value for axial length in which might not be valid for the machine. In the literature review this aspect ratio is always more than 0.2, this is the reason in the FEA models the axial length of all machines are taken to be 700 mm.

V. FEA Modelling

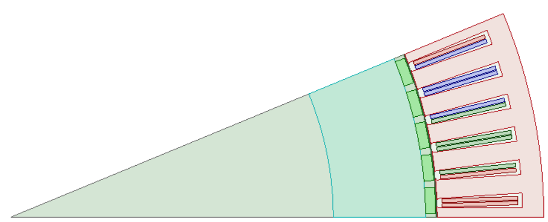
Ten models are implemented in MotorCAD. Initial outer diameter of 3 meter and axial length of 700 mm are selected and subsequently the outer diameters are adapted to generate 1 MW power while keeping the axial length of 700 mm fixed in all machines. Consequently, the machines that are designed are shown in Fig. 8.

Details of the conducted FEA are

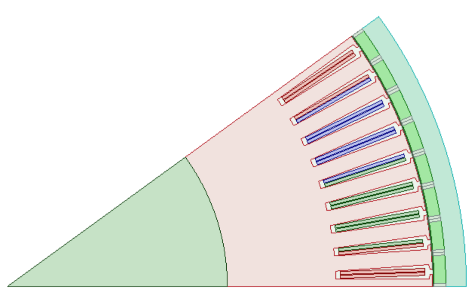
- Current density in all the machines is considered to be 2 A/mm2
- Airgap length is 5 mm,
- Axial length in all machines is 700 mm
- Magnet grade is N35UH with Br of 1.21 at 20 ℃
- Copper resistivity is 1.724e-8,
- Core Material is 400-50 at 20 ℃
- Slot fill factor 60 % (based on literature review)



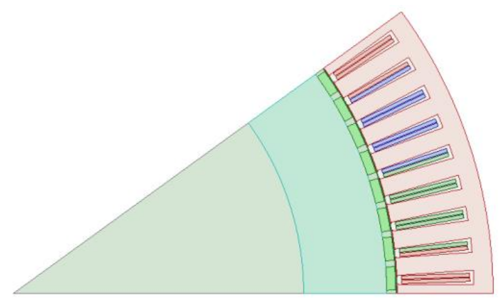
96s/80p outer rotor



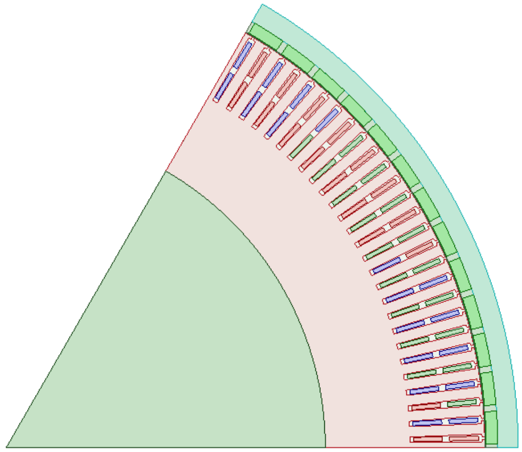
96s/80p inner rotor



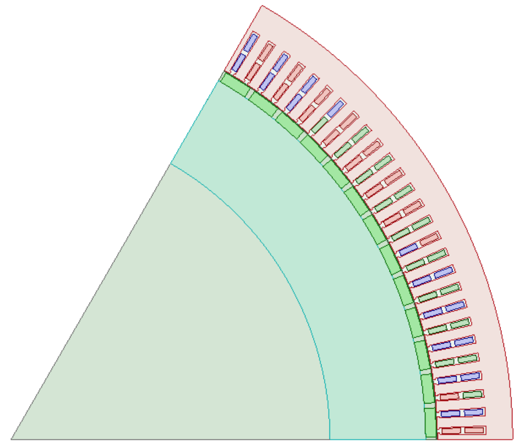
90s/80p outer rotor



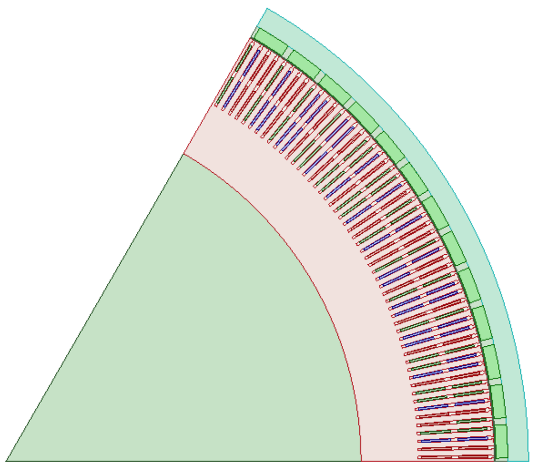
90s/80p inner rotor



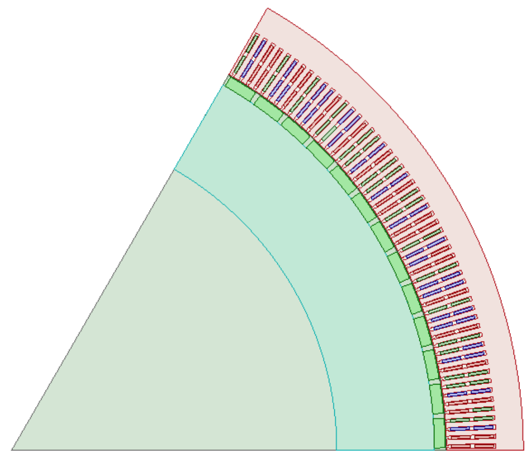
162s/78p outer rotor



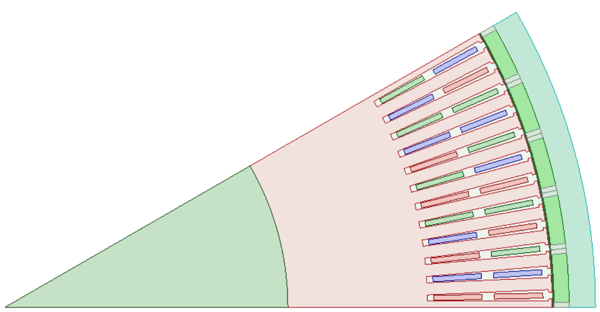
162s/78p inner rotor



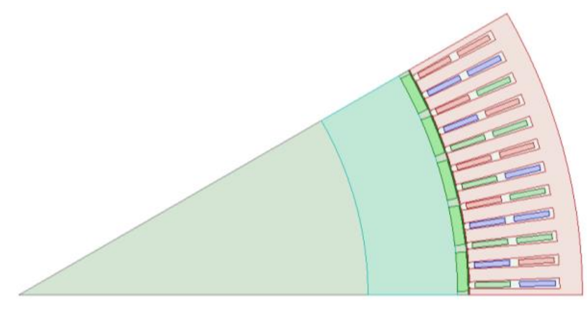
324s/78p outer rotor



324s/78p inner rotor



144s/60p outer rotor



144s/60p inner rotor

Fig. 8, the models implemented in MotorCAD and exported to Ansys Maxwell

Table VIII, results from of FEA models

Design number	1	2	3	4	5	6	7	8	9	10
Slot	96	96	90	90	162	162	324	324	144	144
Pole	80	80	80	80	78	78	78	78	60	60
Inner or outer rotor	Outer rotor	inner rotor	Outer rotor	inner rotor	Outer rotor	inner rotor	Outer rotor	inner rotor	Outer rotor	inner rotor
Coil Pitch	1	1	1	1	2	2	4	4	2	2
Winding factor kw1	0.933	0.933	0.945	0.945	0.952	0.952	0.953	0.953	0.925	0.925
Output Power (MW)	1.059	1.04	1.01	1.04	1.09	1.09	1	1.05	1.01	1.04
Power factor	0.57	0.46	0.57	0.43	0.76	0.85	0.83	0.87	0.75	0.59
Torque ripple (%)	4.76	2.63	4.89	3.59	6.08	4.63	3.13	5.63	3.62	3.55
Copper loss (kW)	32.524	33.46	28.58	33.85	25.243	22.64	21.92	21.86	30.22	34.59
Core loss (kW)	22.08	10.96	22.83	22.79	20.17	13.85	18.89	11.19	13.42	8.02
Efficiency (%)	95.08	94.86	95.24	94.87	96.01	96.98	96.08	96.96	95.86	95.29
Outer diameter (mm)	3030	3300	3120	3300	3500	3800	3520	3800	3130	3250
Total Weight of active material (kg)	36270	44270	37940	44250	49700	58280	49820	58170	37970	43200
Total mass of magnets (kg)	1567	1084	1622	1017	1856	1784	1857	1784	1622	1066
Cogging torque peak to peak (kNm) *	27.91	41.16	70.44	51.87	19.33	38.84		9.95	26.93	15.89

Results show that machines with CWs suffer from low power factor and for a machine at this size low power factor means bigger power electronics devices and higher cost. By looking at the results the design 9 (144s/60p outer rotor) has a low total mass and acceptable power factor of 0.75 while design 8 (324s/78p) has the maximum efficiency and power factor but at the expense of higher total volume of the machine. Furthermore, comparison of cogging torque design 8 has the lowest value which is another good property.

VI. References

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