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EE568

Final Project:

Design of a Salient-Pole Synchronous Hydro-Generator

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Introduction

A recent urge towards the use of renewable energy as a source for electricity production has formed due to a growing concern for fossil fuel consumption and depletion which in turn eventuates to release of greenhouse gases to the atmosphere and destruction of natural resources [1-2].

Hydropower being one of the major sources amongst the various sources of renewable energy, holds about 17 percent of the global power generation [2-4]. Hydroelectric systems consist of various components such as generator, turbine, control system, etc. [5]. Considering the generator component of the system, although AC machines have shown a proper performance in tackling the renewable energy sources, there is continuing research on utilizing other machines for this purpose. Due to their mature technology and high power ratings, synchronous generators have been the most common type of the machines used in large hydropower stations. Synchronous generators have the disadvantage of large amounts of field loss and requiring refurbishment of slip rings and brushes. On the other hand, induction generators and permanent magnet synchronous generators are more desirable for small hydropower systems because of the high fluctuations in water flow [6].

Renovation of hydroelectric generators is of high concern [6]. Partial discharge (PD) is one of the factors giving rise to this issue. PD is an electrical discharge, which does not link the electrodes between an insulation system completely under high electric field stress [7]. This phenomenon results in the aging of the insulation system. Partial discharge shows itself where the semi-conductive and stress-grading coatings of high voltage bars overlap. Reapplying the coatings can be useful for the repairment. However, the effect of this method will vanish after a short while, and it calls for regular repairs [8].

Another important topic regarding the hydro generators is copper loss reduction. For this matter, acquiring an acceptable coil design can lead to better thermal characteristics and enhanced heat dissipation [9]. Moreover, design of loads connected to hydro generators requires to be employed with sinusoidal EMF. Geometrical improvements can be applied to the rotor pole shape of the salient pole synchronous generator to achieve a better sinusoidal approximation for the rotor MMF. In addition, relative positioning of the damper winding and the slots in the stator side has a significant role in diminishing the slot ripple and producing a smoother MMF waveform [10].

In this study, a salient pole synchronous hydroelectric generator will be designed to meet some pre-defined specifications. In the first step, an analytical calculation and sizing will be carried out. Next, an FEA analysis using ANSYS MAXWELL software will be performed by implementing the same dimensions resulting from the first step and defining suitable boundaries and well-defined meshing. Finally, there will be a comparison between the analytical and FEA results to discuss the possible inconsistencies.

Analytical Calculation & Sizing

Design will be carried out with the help of the values given in Table 1.

Table 1. Input Data

Input Data	
Rated apparent power (MVA)	44
Power factor (lagging)	0.9
Rated speed (rpm)	187.5
Rated voltage (line-line) (KV)	13.8
Machine type	Salient-pole synchrnous generator
Cooling method	Air-forced

The larger the value of machine constant, the smaller is the volume (D2L) of the machine, and this will be effective in reducing the cost. Machine constant is larger if machine is designed for higher specific magnetic and electrical loadings. Due to the limitations in the ranges that these two values can be chosen from, there should be a compromise.

Designing with higher magnetic loading, will give a rise to the possibility of saturation, hence core losses will increase, and as a result the efficiency will decrease, and the temperature will rise more which will demand better insulation and cooling. In addition, with higher magnetic loading, more magneto-motive force is required to pass the flux through the airgap, which increases the magnetizing current resulting in lower power factor. But in the case of a synchronous alternator, magnetizing current is not much of an issue since it is provided with dc excitation.

If designed with high electrical loading, there will be large amount of copper loss in the windings. This will cause issues related to heat dissipation in the slots and thermal expansion. High value of electrical loading should also be taken into consideration when selecting the insulation material and thickness.

In the recent years, the insulation production has gotten more advanced. Therefore, in this design a rather high electrical loading has been chosen to compensate for the low magnetic loading.

Magnetic loading (avg): 0.75 T

Electrical loading (rms): 55000 A/m

$$C = \frac{\pi^2}{2} k_{w1} \hat{A} \hat{B}$$

For the calculation of the machine constant, k_{w1} is required and it depends on the winding design. Here, machine constant can be calculated for $k_{w1} = 1$, and after the winding diagram is decided, it can be recalculated with the actual value of k_{w1}.

$$C = \frac{\pi^2}{2} \times 1 \times \left(\frac{55000}{1000} \times \sqrt{2}\right) \times \left(0.75 \times \frac{\pi}{2}\right)$$

$$C = 452.1979378 \text{ kVAs/m3}$$

$$S_i = CD_i^2 L' n_{syn}$$

$n_{syn}: mechanincal\ frequency\ (Hz)$

Apparent power: $S_i = 44000\ kVA$

$$n_{syn} = \frac{f}{p}$$

$p: pole\ pairs$

Calculating number of poles:

$$n = \frac{120 \times f}{poles}$$

$f = 50\ Hz$

$n = 187.5\ rpm$

$$poles = \frac{120 \times 50}{187.5} = 32$$

$$p = \frac{32}{2} = 16$$

$$n_{syn} = \frac{50}{16} = 3.125\ Hz$$

$$D_i^2 L' = \frac{44000}{452.1979378 \times 3.125} = 31.13680719 \text{ m3}$$

Notice that, this value is for $k_{w1} = 1$, and it should be reevaluated later.

Aspect ratio (X):

$$X = \frac{L'}{D_i}$$

Typical aspect ratio for synchronous machines is derived using the following equation:

$$X \approx \frac{\pi}{4p}\sqrt{p} = 0.196349541$$

$$D_i = 5.412709624\ m$$

$$L' = 1.062783049 \text{ m}$$

Winding design:

Selecting number of slots (Q) considering the tooth thickness limitations:

$$Tooth\ thickness = \frac{1}{2} \times \frac{\pi \times D_i}{Q}$$

If $Q = 240$:

$$Tooth\ thickness = \frac{1}{2} \times \frac{\pi \times 5.412709624 \times 1000}{240} = 35.42\ mm$$

If $Q = 252$:

$$Tooth\ thickness = \frac{1}{2} \times \frac{\pi \times 5.412709624 \times 1000}{240} = 33.73\ mm$$

If $Q = 264$:

$$Tooth\ thickness = \frac{1}{2} \times \frac{\pi \times 5.412709624 \times 1000}{240} = 32.20\ mm$$

If $Q = 276$:

$$Tooth\ thickness = \frac{1}{2} \times \frac{\pi \times 5.412709624 \times 1000}{240} = 30.80\ mm$$

All these values could be possible to design, but since there is no need for a very large tooth thickness, the rest of the design will be carried out choosing $Q = 252$.

An analysis has been done to choose the proper value for coil throw of the winding design, and the results are as follows:

Table 2. Fundamental winding factor for different slot/pitch combinations

winding factor of the fundamental component				
Q\coilpitch	6	7	8	9
252	0.894840962	0.946687259	0.960992649	0.937189852
258	0.884450547	0.940481375	0.960926436	0.945012134
264	0.873905142	0.93364254	0.959635664	0.950945055
270	0.863263052	0.926279073	0.957284088	0.955206602
276	0.852573167	0.918484369	0.954015233	0.957990521
282	0.841876404	0.910338971	0.94995495	0.959468999
288	0.831206922	0.901912355	0.945213637	0.959795081

Table 3. 3rd harmonic winding factor for different slot/pitch combinations

winding factor of the 3rd harmonic				
Q\coilpitch	6	7	8	9
252	-0.293419418	-0.585660736	-0.674371799	-0.528723521
258	-0.24090412	-0.548454388	-0.673915406	-0.575633568
264	-0.189494021	-0.508319051	-0.665756373	-0.611820751
270	-0.139500791	-0.466089194	-0.651031316	-0.638122542
276	-0.091154303	-0.422470421	-0.630779549	-0.655430151
282	-0.044617691	-0.378054452	-0.605939604	-0.664648333
288	0	-0.333333333	-0.577350269	-0.666666667

Table 4. 5th harmonic winding factor for different slot/pitch combinations

winding factor of the 5th harmonic				
Q\coilpitch	6	7	8	9
252	-0.066835845	0.14575233	0.224990609	0.098383299
258	-0.095463036	0.11481653	0.224489705	0.137456892
264	-0.120674236	0.082957264	0.216914104	0.168687786
270	-0.142463594	0.05111232	0.203507916	0.191940681
276	-0.160913773	0.020021828	0.185471216	0.207464832
282	-0.176169962	-0.009747993	0.163917628	0.215777446
288	-0.188419312	-0.037780266	0.139849939	0.217567882

There should be a compromise between going for the best fundamental winding factor and going for the lower winding factor of the harmonics. Here, it has been preferred to have a better fundamental winding factor and this is feasible by choosing $coil\ pitch\ (coil\ throw) = 8$.

Since the pole pitch in terms of slot number is $\frac{252}{32} = 7.875$, the chosen winding design is over-pitched ($8 > 7.875$).

Now actual winding factor can be calculated:

Slot/pole/phase (q):

$$q = \frac{Q}{2mp} = \frac{252}{2 \times 3 \times 16} = 2.625$$

q is not an integer, so this results in a fractional slot winding design.

Distribution Factor:

$$k_{dn} = \frac{\sin(\frac{qn\alpha_u}{2})}{q\, sin(\frac{n\alpha_u}{2})}$$

Pitch Factor:

$$k_{pn} = sin(\frac{n\lambda}{2})$$

Winding Factor:

$$k_{wn} = k_{dn} \times k_{pn}$$

λ: $coil\ pitch\ (electrical\ degree)$

α_u: $slot\ angle\ (electrical\ degree)$

n: $harmonic\ number$

Calculating fundamental winding factor ($n = 1$):

$$\alpha_u = \frac{360° \times 16}{252} = 22.85714286°$$

$$\lambda = \frac{360°}{252} \times \frac{8}{7.875} \times 16 = 182.8571429°$$

$$k_{d1} = \frac{\sin(\frac{2.625 \times 1 \times 22.85714286°}{2})}{2.625 \times sin(\frac{1 \times 22.85714286°}{2})}$$

$$k_{d1} = 0.961291436$$

$$k_{p1} = sin(\frac{1 \times 182.8571429°}{2})$$

$$k_{p1} = 0.999689182$$

$$k_{w1} = 0.961291436 \times 0.999689182$$

$$k_{w1} = 0.960992649$$

According to MOTORCAD, this design has a winding factor lower than what we calculated analytically. This discrepancy is due to the unusual winding design which makes it incorrect to use the pitch factor equation in this case. Therefore, $k_{w1} = 0.954732$ will be used for the next derivations.

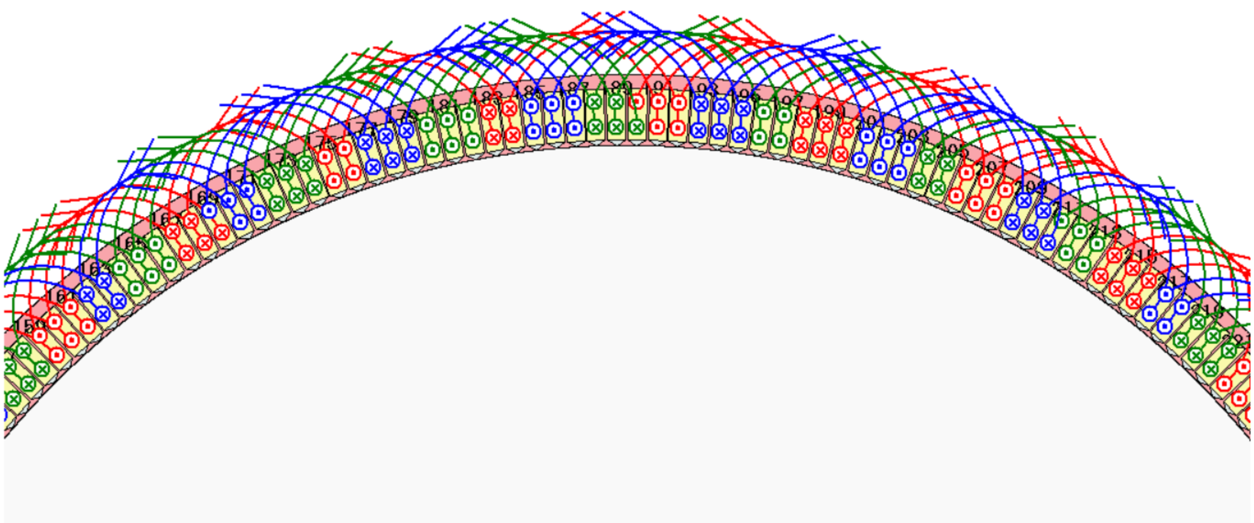

Figure 1. Winding design in MotorCAD for coil throw=8 and Q=252

Now, the actual machine constant, inner stator diameter and axial length can be recalculated:

$$C = 452.1979378 \times 0.954732$$

$$C = 431.7278416 \text{ kVAs/m3}$$

$$D_i^2 L' = \frac{44000}{431.7278416 \times 3.125} = 32.61313875 \text{ m3}$$

$$D_i = 5.496938812\ m$$

$$L' = 1.079321412 \text{ m}$$

Airgap length calculation:

According to the Design of Rotating Electrical Machines book by Juha Pyrhonen, the following equation can be an acceptable approximation for determining the airgap of a salient pole synchronous machine:

$$\delta = \gamma \tau_p \frac{A}{\hat{B}_\delta}$$

$\hat{B}_\delta$: $peak\ airgap\ flux\ density\ (T)$

A: $electrical\ loading\ (\frac{A}{m})$

τ_p: $pole\ pitch\ (m)$

For salient-pole synchronous machine γ coefficient is 4×10^{-7}.

Since this machine is a huge generator, there can be significant vibrations and movements. Hence, we will consider a coefficient with the value of 1.5 for dealing with a heavy-duty machine:

$$\delta = 1.5 \times 4 \times 10^{-7} \times 539.6607059 \times \frac{55000}{1.178097245}$$

$$\delta = 15.116582 \text{ mm}$$

Rotor outer diameter ($\boldsymbol{d_o}$):

$$d_o = D_i - 2 \times \delta$$

$$d_o = 5466.705648\ mm$$

Stator outer diameter ($\boldsymbol{D_o}$):

Taking the $\frac{D_i}{D_o}$ ratio to be 0.9 for 32 number of poles,

$$D_o = 6107.709791\ mm$$

Number of turns per phase ($\boldsymbol{N_{ph}}$):

Assuming $induced\ voltage = terminal\ voltage$, N_{ph} can be derived from the equation below:

$$V_{ph-rms} = 4.44 f_i k_w N_{ph} \emptyset_p$$

$\emptyset_p$: flux per pole

$$\emptyset_p = B_g \times A_p$$

B_g and A_p are the magnetic loading and pole area respectively.

$$\emptyset_p = 0.75 \times \frac{\pi \times 5.484975692 \times 1.076972459}{32}$$

$$\emptyset_p = 0.434951129\ Wb$$

$$V_{ph-rms} = \frac{V_{L-L}}{\sqrt{3}}$$

$$V_{L-L} = 13800\ volts$$

$$N_{ph} = \frac{V_{ph-rms}}{4.44 f_i k_w \emptyset_p}$$

$$N_{ph} = \frac{13800/\sqrt{3}}{4.44 \times 50 \times 0.954732 \times 0.434951129}$$

$$N_{ph} = 85.86278219$$

Since number of turns per phase should be an integer, $N_{ph} = 84$ is chosen for this design.

To keep the terminal voltage in the rated value, decreasing the number of turns will lead to higher flux per pole, which can be reevaluated as follows:

$$\emptyset_p = 0.434951129\ \times \frac{85.86278219}{84}$$

$$\emptyset_p = 0.444596596\ Wb$$

New magnetic loading will be:

$$B_g = 0.766631984\ T$$

Total number of turns:

$$N_{tot} = 84 \times 3 = 252$$

$$N_{tot} = 252$$

Total number of conductors:

$$cond_{tot} = 252 \times 2 = 504$$

Conductor per slot:

$$cond_{per\ slot} = \frac{504}{252}$$

$$cond_{per\ slot} = 2$$

To find the area of the conductors, a current density should be assigned for the armature winding.

Due to the relatively high value of electrical loading, to stay in the safe zone, the current density in the stator windings is set to be $3.5\ A/mm^2$.

$$J_a = 3.5\ A/mm^2$$

Phase current (rms):

$$I_{ph} = \frac{S}{\sqrt{3} \times V_{L-L}}$$

$$I_{ph} = \frac{44000000}{\sqrt{3} \times 13800}$$

$$I_{ph} = 1840.826945\ A$$

$$J_a = \frac{I_{ph}}{A_{cond}}$$

$$A_{cond} = \frac{1840.826945}{3.5}$$

$$A_{cond} = 525.9505558\ mm^2$$

Total area of conductors in a slot:

$$A_{cond-slot} = 525.9505558 \times 2 = 1051.901112\ mm^2$$

$$A_{cond-slot} = 1051.901112\ mm^2$$

Before getting slot/tooth dimensions, proper flux densities should be assigned to different parts of the stator and rotor core.
The following values are taken from Table 6.1 in chapter 6 of Design of Rotating Electrical Machines book by Juha Pyrhonen, and are as follows:

Table 5. Chosen flux densities for different parts of the machine

flux densities	
tooth flux density (peak)	1.8
tooth flux density (avg)	1.1459156
stator back-core flux density (peak)	1.6
stator back-core flux density (avg)	1.0185916
rotor back-core flux density (peak)	1.2
rotor back-core flux density (avg)	0.7639437
pole core flux density (peak)	1.8
pole core flux density (avg)	1.1459156

Tooth width:

$$Teeth\ per\ pole\ = \frac{252}{32} = 7.875$$

If the flux only goes through the teeth:

$$tL' = \frac{\emptyset_p/Teeth\ per\ pole}{B_t}$$

$$B_t: flux\ density\ in\ tooth$$

$$t: tooth\ width$$

$$t = \frac{0.444596596/7.875}{1.14591559 \times 1.076972459}$$

$$t = 45.74654979\ mm$$

Slot pitch (τ_p):

$$\tau_p = \frac{\pi D_i}{Q}$$

$$\tau_p = \frac{\pi \times 5484.975692}{252}$$

$$\tau_p = 68.37920373\ mm$$

Slot width (s):

$$s = \tau_p - t$$

$$s = 68.37920373 - 45.74654979$$

$$s = 22.632654\ mm$$

Stator back core thickness (h_{bs}):

$$h_{bs}L' = \frac{\emptyset_p/2}{B_{bs}}$$

$$h_{bs} = \frac{0.444596596/2}{1.018591636 \times 1.076972459}$$

$$h_{bs} = 202.6429198\ mm$$

Slot height (h_s):

$$h_s = \frac{D_o - D_i}{2} - h_{bs}$$

$$h_s = \frac{6094.417435 - 5484.975692}{2} - 202.6429198$$

$$h_s = 102.077952\ mm$$

Slot area (A_{slot}):

$$A_{slot} = h_s \times s$$

$$A_{slot} = 102.077952 \times 22.632654$$

$$A_{slot} = 2310.294962\ mm^2$$

Rotor back core thickness ($\boldsymbol{h_{br}}$):

$$h_{br}L' = \frac{\emptyset_p/2}{B_{br}}$$

$$h_{br} = \frac{0.444596596/2}{0.763943727 \times 1.076972459}$$

$$h_{br} = 270.1905597\ mm$$

Pole width ($\boldsymbol{w_p}$):

$$w_pL' = \frac{\emptyset_p}{B_p}$$

$$w_p = \frac{0.444596596}{1.14591559 \times 1.076972459}$$

$$w_p = 360.2540796\ mm$$

Checking the fill factor in the stator slots:

$$fill\ factor = \frac{A_{cond-slot}}{A_{slot}}$$

$$fill\ factor = \frac{1051.901112}{2310.294962}$$

$$fill\ factor = 0.455310308$$

Since, this machine has a high voltage value, there should be enough insulation to avoid the risks faults. Hence, the value of fill factor is acceptable.

Since the full-load field MMF per pole (F_R) gives the $N_f I_f$, the following steps will be taken to find this value:

Phasor diagram for the lagging case has been presented in the figure below:

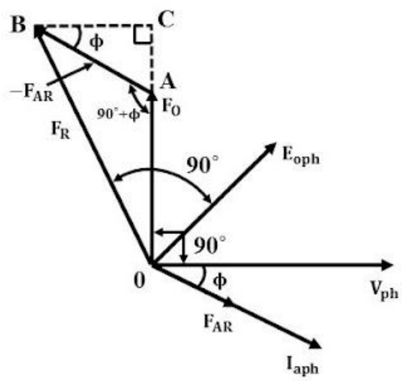

Figure 2. Phasor diagram for MMF vectorial summation

where, F_o is the no-load field MMF per pole, F_{AR} is the armature MMF per pole and $\cos(\emptyset)$ is the power factor (PF).

For a 3-phase system, F_{AR} is calculated using the following equation:

$$F_{AR} = \frac{2.7 \times N_{ph} I_{ph} k_{w1}}{poles}$$

$$F_{AR} = 12537.93749\ A.Turns$$

Next, F_o will be determined with the knowledge that:

$$SCR = \frac{F_o}{F_{AR}}$$

SCR is the defined as the Short Circuit Ratio.

According to *A Course in Electrical Machine Design by A.K.Sawney,* Typical values of SCR for Hydro alternators may be in the range of 1 to 1.5.

Assuming $SCR = 1.3$ for this design, it is established that:

$$F_o = 1.3 \times 12537.93749$$

$$F_o = 16299.31874\ A.Turns$$

Now, the value for the full-load field MMF per pole (F_R), can be found as follows:

$${F_R}^2 = (F_o + F_{AR} \sin \emptyset)^2 + (F_{AR} \cos \emptyset)^2$$

$$\cos \emptyset = 0.9$$

$$\sin \emptyset = 0.435889894$$

$$F_R = 24515.79991\ A.Turns$$

This is also the value of $N_f I_f$:

$$F_R = N_f I_f = 24515.79991\ A.Turns$$

Assuming the following values for the field winding:

$$J_f = 4\ A/mm^2$$

$$fill\ factor = 0.4$$

Total area for field winding in the space between two poles can be calculated as follows:

$$A_{f-tot} = N_f \times \frac{I_f}{J_f} \times 2$$

$$A_{f-tot} = \frac{24515.79991}{4} \times 2$$

$$A_{f-tot} = 12257.89996\ mm^2$$

Area of empty space between poles is equal to: $\frac{A_{f-tot}}{fill\ factor} = 30644.74989\ mm^2$

Now, determining the pole height can be proceeded by assuming a value for shaft diameter and finding the width of empty part next to a pole:

Shaft Diameter: $\boldsymbol{D_{sh} = 4000\ mm}$

Width of empty part next to a pole (w_{emp}):

$$w_{emp} = \frac{\pi(D_{sh} + 2 \times h_{br}) - poles \times w_p}{poles}$$

$$w_{emp} = 85.49679443\ mm$$

Total pole height ($\boldsymbol{h_{p-tot}}$)**:**

$$h_{p-tot} = \frac{d_o}{2} - \frac{D_{sh}}{2} - h_{br}$$

$$h_{p-tot} = 457.2136031\ mm$$

Pole body height (h_{p-body}):

$$h_{p-body} = \frac{A_{f-tot}}{fill\ factor \times w_{emp}}$$

$$h_{p-body} = 358.4315657\ mm$$

Pole shoe height (h_{shoe}):

$$h_{shoe} = h_{p-tot} - h_{p-body}$$

$$h_{shoe} = 98.78203737\ mm$$

Assuming cross-section of field winding to be:

$$A_f = 85\ mm^2$$

Total **number of turns for field winding** will be:

$$N_f = \frac{A_{f-tot}}{A_f}$$

$$N_f = 72.10529386$$

Now, using the value of N_f and $N_f I_f$ which has been calculated before, **field current** is determined as:

$$I_f = 340.497221\ A$$

Material selection:

According to [11], segmented laminations made from silicone steel with 0.35- or 0.50-mm thickness are the common material used in hydro generator cores due to their low loss.

This design has been carried out with the material choice of **Cogent Power M270-50A**, and it has been selected from the library of ANSYS MAXWELL.

And for the windings, aluminum and copper are two popular choices which both have their merits and drawbacks. Although aluminum outrivals copper when it comes to weight and cost, in this huge generator, thermal issues and cooling are of greater concern. Therefore, **copper** is a better choice here due to its high thermal conductivity.

Electrical circuit parameter estimation:

Flux per pole:

$$\emptyset_p = B_g \times A_p$$

$$\emptyset_p = 0.444596596\ Wb$$

Induced voltage ($\boldsymbol{E_a}$):

$$E_a = 4.44 f_i k_w N_{ph} \emptyset_p$$

$$E_a = 7794.581249\ volts$$

Armature phase resistance ($\boldsymbol{R_a}$):

$$R_a = \frac{\rho \times M.L.T \times N_{ph}}{A_{cond}}$$

$M.L.T: mean\ length\ per\ turn$

$\rho: resistivity\ of\ copper\ (1.68e^{-8})$

$$M.L.T = \frac{2\pi \frac{coil\ pitch}{pole\ pitch} D_i}{poles} + 2L'$$

$$M.L.T = 3410.412786\ mm$$

$$R_a = 0.009150622\ ohms$$

Field resistance ($\boldsymbol{R_f}$):

$$M.L.T = 3449.343692\ mm$$

$$R_f = 1.570758072\ ohms$$

FEA Modelling

FEA results have been carried out using ANSYS MAXWELL and are presented in this section. Consistencies and any discrepancies will be discussed in the next section.

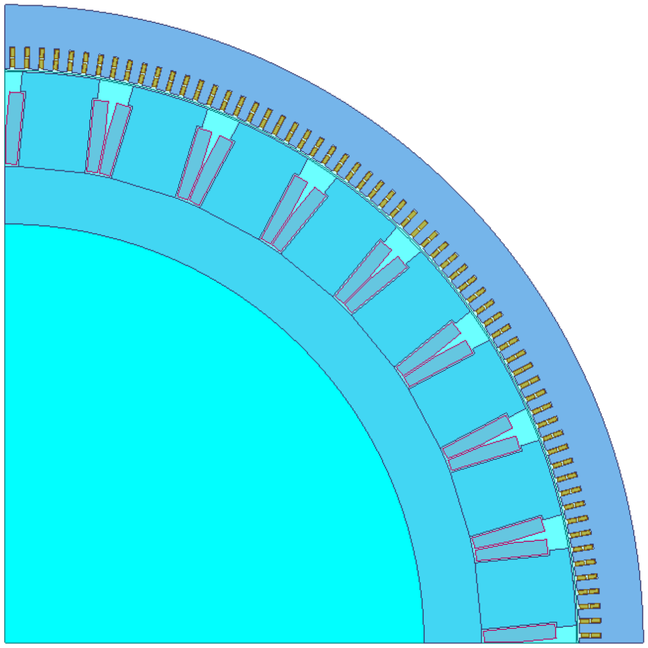

Figure 3. 2D Model in ANSYS MAXWELL

Resulting waveforms:

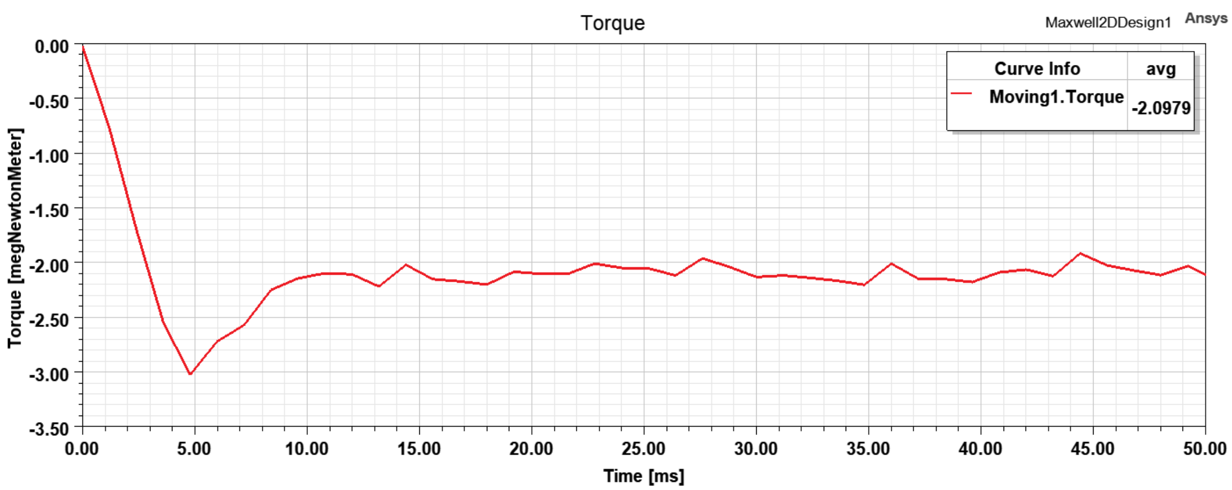

Figure 4. Torque vs. Time

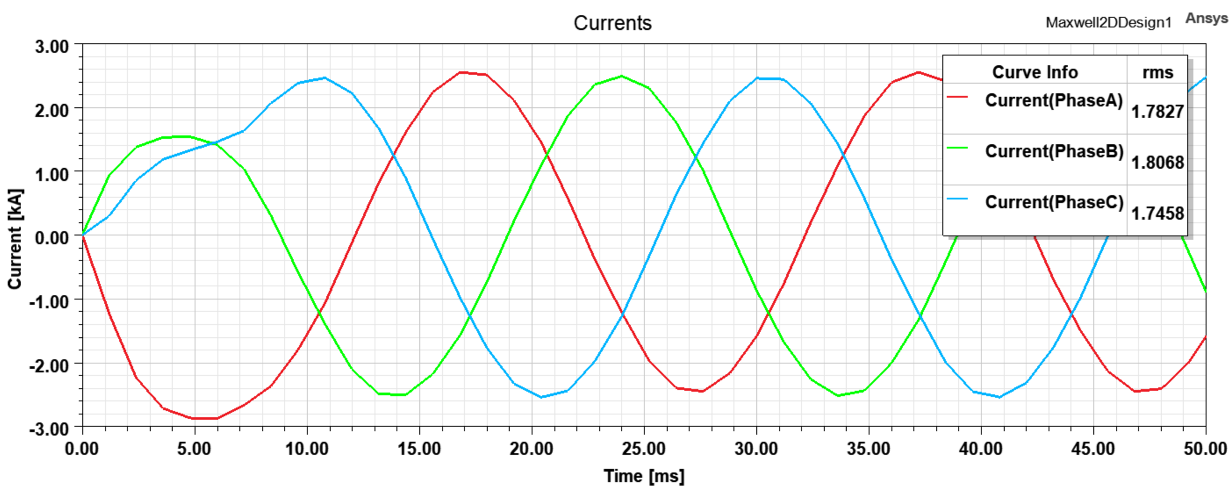

Figure 5. Current vs. Time

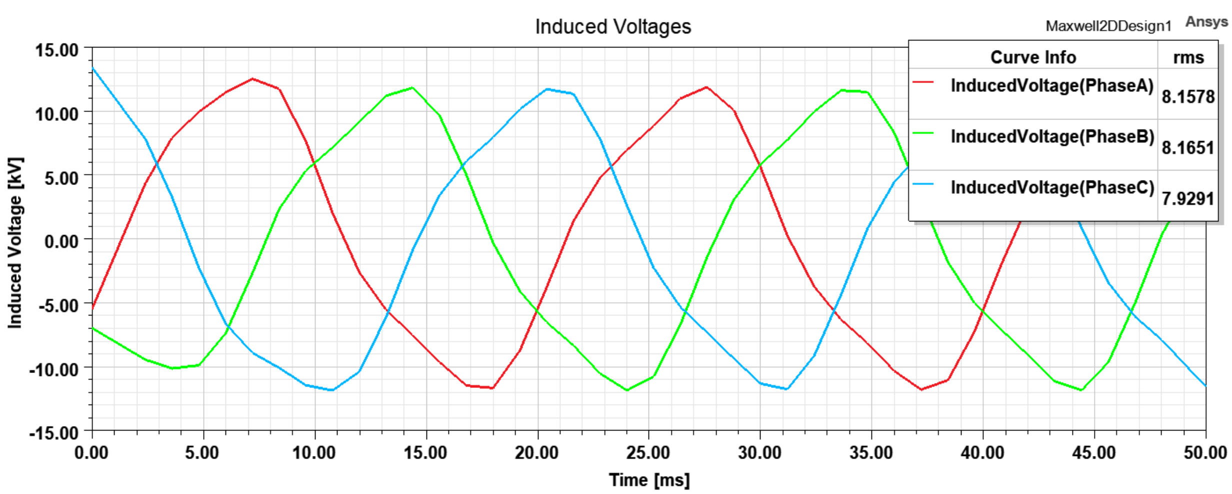

Figure 6. Induced Voltage vs. Time

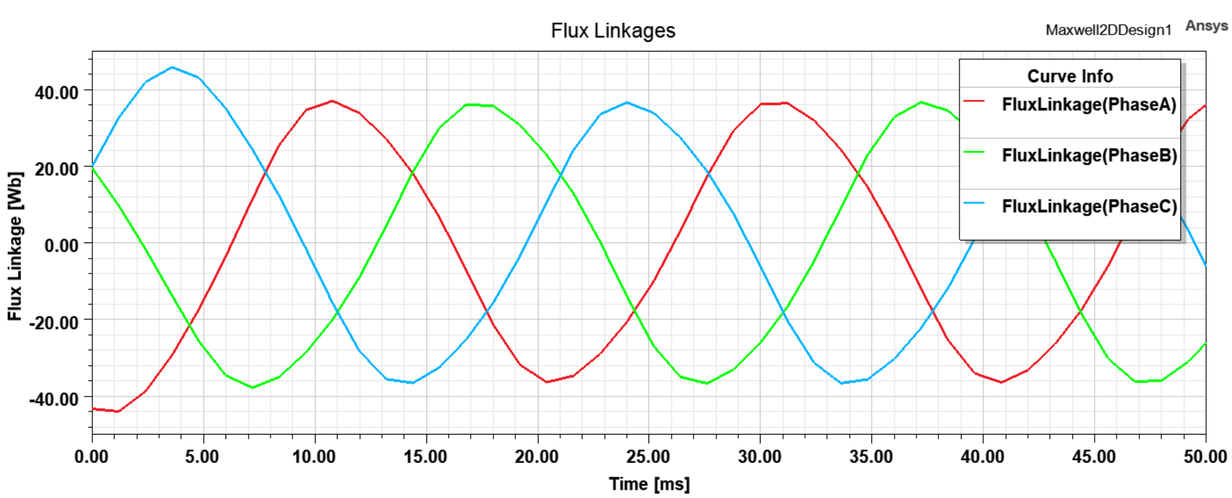

Figure 7. Flux Linkage vs. Time

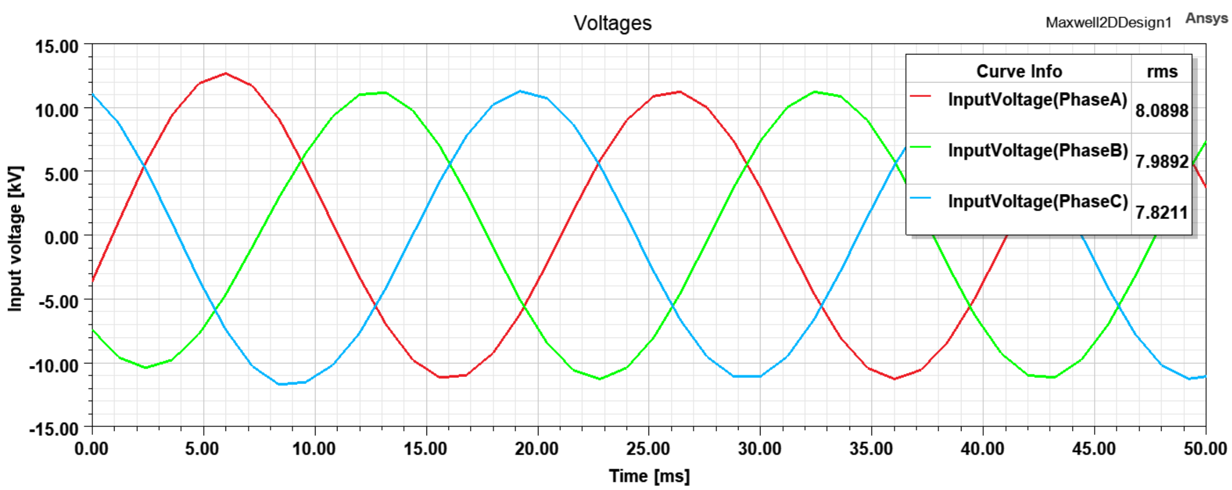

Figure 8. Input Voltage vs. Time

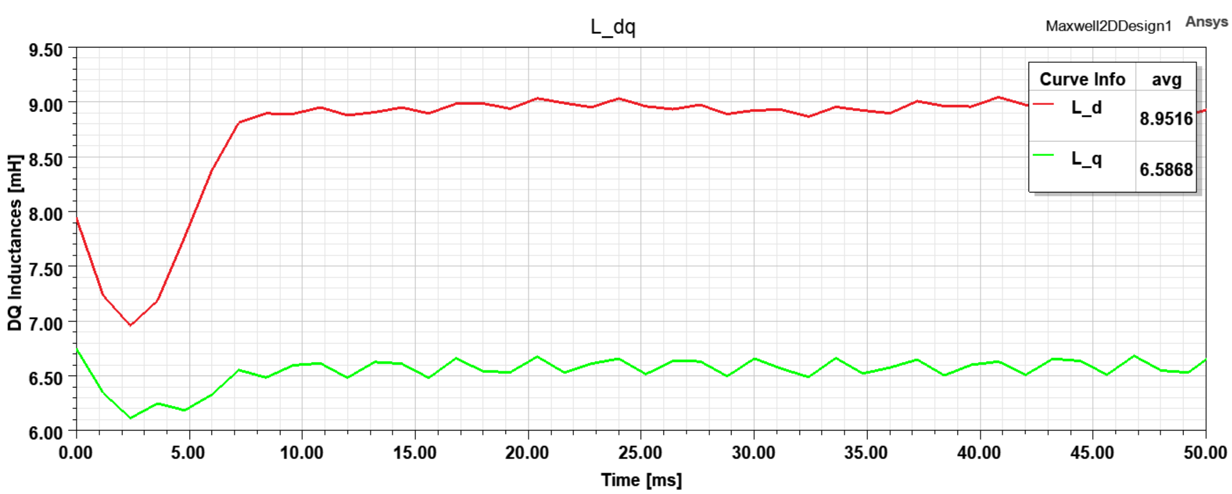

Figure 9. DQ Inductance vs. Time

The significant difference between direct-axis and quadrature-axis inductances in Figure 9, stems from the saliency in the machine which adds a reluctance element to the torque.

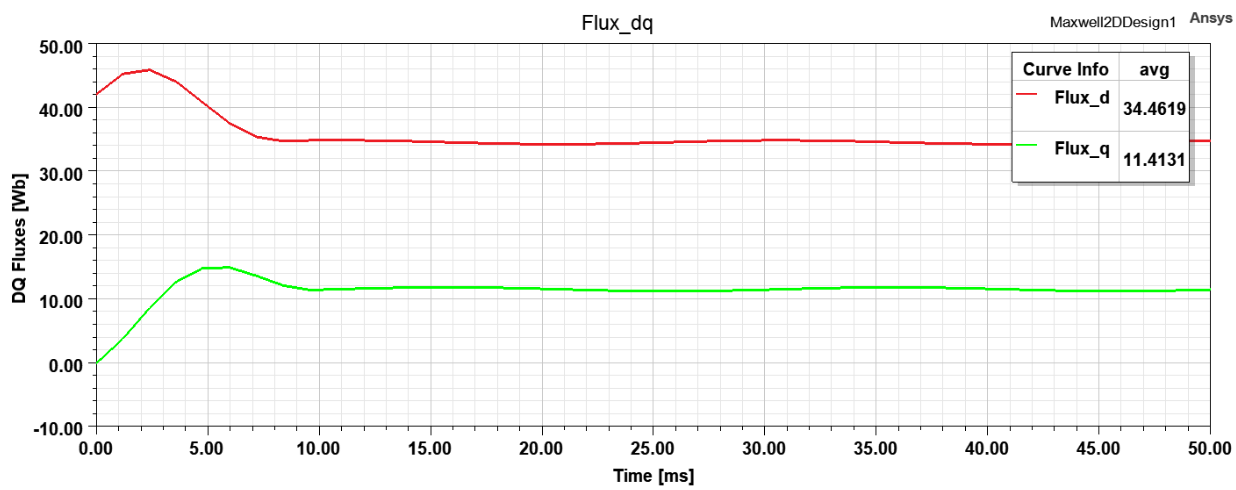

Figure 9. DQ Flux vs. Time

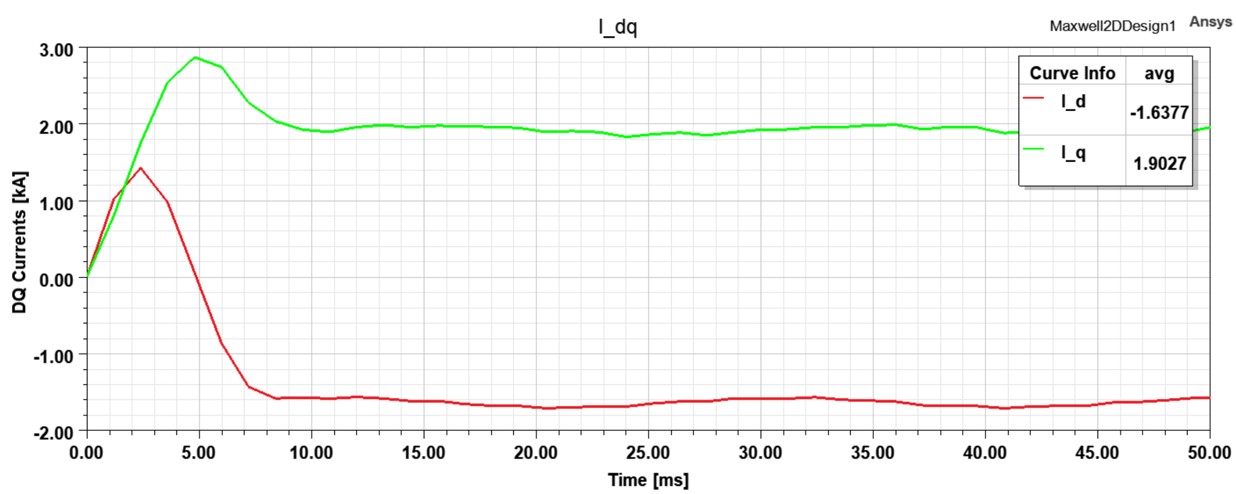

Figure 11. DQ Current vs. Time

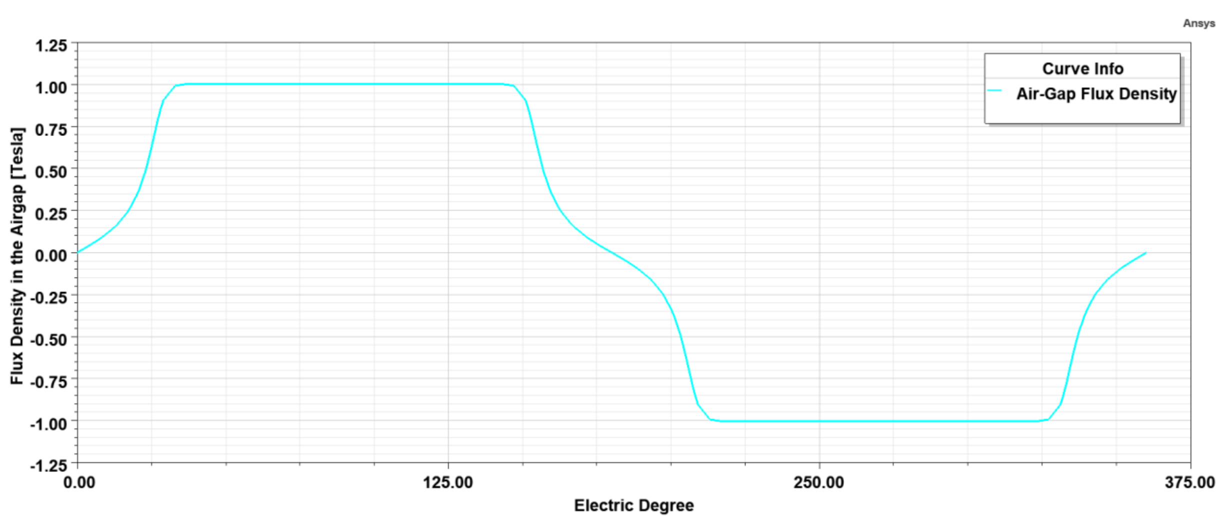

Figure 10. Airgap Flux Density vs. Time (No-Load)

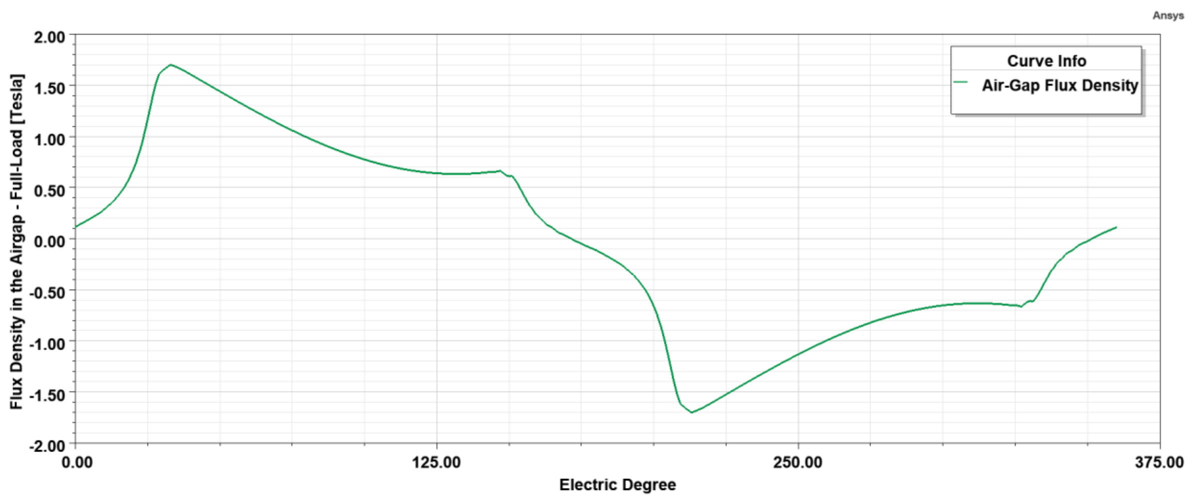

Figure 11. Airgap Flux Density vs. Time (Full-Load)

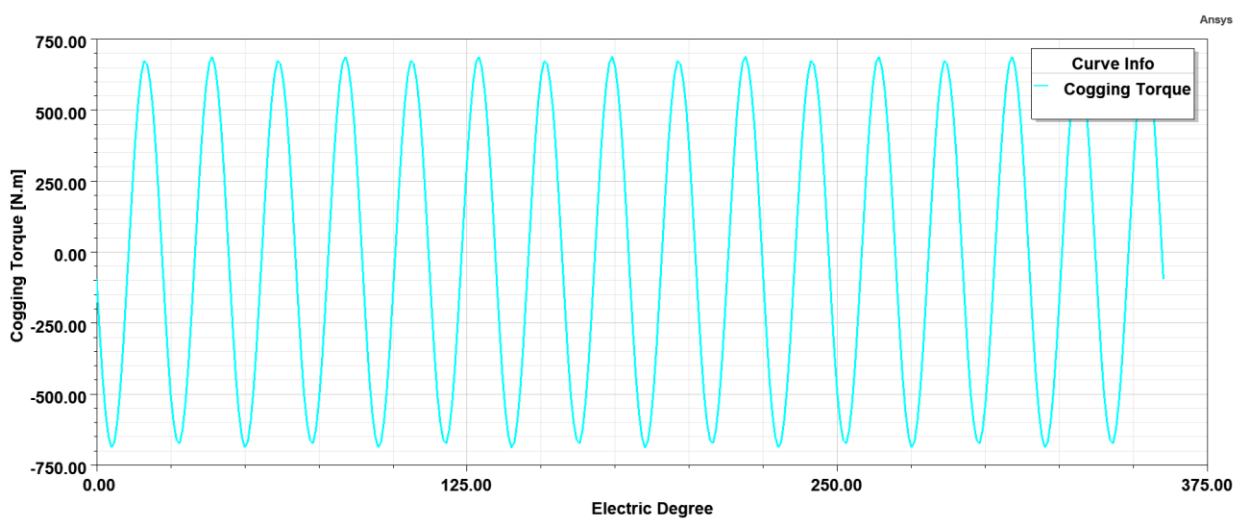

Figure 12. Cogging Torque vs. Time

As can be seen from Figure 13., this design shows a promising performance when it comes to cogging torque. This low value keeps the machine vibrations to in an acceptable level.

Comparison and Discussion

Several iterations and reevaluation of some parameters have been carried out in the analytical part of the design. The reasonings have been explained thoroughly in the same part.

The followings are the results taken from the RMxprt module of the ANSYS MAXWELL software:

Table 6. RMxprt results for rated values

Rated Values	
Input Power (kW)	40285.6
Output Power (kW)	39563.3
Efficiency (%)	98.2072
Shaft Torque (N.m)	2051730
Apparent Power (kVA)	44000
Power Factor	0.899167

Table 7. RMxprt results for Losses

Losses	
Iron-Core Loss (W)	148511
- Stator-Tooth Core Loss (W)	66375
- Stator-Yoke Core Loss (W)	76103.6
- Stator Surface Excess Loss (W)	0
- Rotor Surface Excess Loss (W)	6032.88
Mechanical Loss (W)	200
- Friction Loss (W)	100
- Windage Loss (W)	100
Additional Loss (W)	220000
Copper Loss (W)	353535
- Armature Copper Loss (W)	124924
- Field Copper Loss (W)	228611
- Exciter Loss (W)	0
Total Loss (W)	722247

Table 8. RMxprt and analytical results for armature resistance

Armature Resitance (ohms)	
FEA result	0.012289
Analytical result	0.009151

Table 9. RMxprt and analytical results for field resistance

Field Resitance (ohms)	
FEA result	1.74048
Analytical result	1.570758

Table 10. RMxprt results for flux densities

Max Flux Densities at No-Load (T)	
Stator Teeth	1.52714
Stator Yoke	1.07757
Pole Shoe	1.43281
Pole Body	1.65679
Rotor Yoke	0.94238
Air Gap	1.00209

According to Table 8 and Table 9, FEA results show an acceptable consistency with the analytical results. Moreover, flux densities are in a satisfactory range for each part of the machine as seen in Table 10.

Finally, some of the important parameters of the machine are presented in the tables below:

Table 11. RMxprt results for mass of different parts of the machine

Material Mass (Kg)	
Armature copper mass	4142.31
Field copper mass	5251.94
Armature core steel mass	39957.9
Rotor pole steel mass	45318.7
Rotor yoke steel mass	30194.9
Total net mass	124866

Table 12. Torque & power densities

Torque & Power Density	
Shaft torque (KNm)	2051.73
Rotor volume (m^3)	100.673104
Torque density (KNm/m^3)	20.38012059
Output power (KW)	39563.3
Power density (KW/m^3)	392.9877834

Table 13. Main dimension of the machine

Dimensions	
Outer diameter (mm)	6094.417435
Axial length (mm)	1076.972459
Aspect ratio	0.196349541

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