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Energy Systems 344 Assignment 2

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Nomenclature

Variables and functions

D^2L	Calculated parameter representing a value.
η	Efficiency of the system.
pf	Power factor.
P_{Mech}	Mechanical power.
n_s	Synchronous speed.
k_w	Constant value.
B_{Airgap}	Air gap flux density.
$\bar{J}$	Electric loading.
L	Stator core length.
D	Air gap diameter.
L_{Airgap}	Air-gap length.
π	Mathematical constant pi.
ϕ_m	Flux per pole.
T_{ph}	Turns per phase.
S_s	Number of stator slots.
Z_{ss}	Number of conductors per stator slot.
I_{ph}	Stator current per phase.
A_c	Cross-sectional area of each stator conductor.
τ	Pole pitch.
L_{MLT}	Mean length of a single turn winding.
R_{Stator}	Stator resistance per phase.
R_{Rotor}	Stator resistance per phase.
A_{slot}	Slot area.
W_{st}	Width of the stator teeth.
W_{ss}	Stator slot width.
d_{cs}	Depth of stator yoke.
d_{ss}	Depth of stator slot.
D_o	Outer diameter of the stator.
S_r	Number of rotor slots.
N_{eff}	Turns ratio.
J_r	Rotor current density.

$B_{\text{Rotor Yoke}}$	Rotor yoke flux density.
$B_{\text{Rotor Teeth}}$	Rotor teeth flux density.
T_R	Rotor turns per phase.
Z_{rs}	Number of rotor conductors per slot.
I_r	Rotor current per phase.
A_r	Cross-sectional area of each rotor conductor.
A_{rslot}	Slot area for the rotor.
W_{rt}	Width of the rotor teeth.
W_{rs}	Rotor slot width.
d_{cr}	Depth of rotor yoke.
d_{rs}	Depth of rotor slot.
D_{shaft}	Shaft diameter of the IM.

Chapter 1

Assignment 2:

1.1. Analytical Calculation & Design

1.1.1. Design Choices:

This assignment focus on creating and simulating a three-phase wound rotor induction motor. This motor is specifically designed for the application of a variable-speed pump. The motor is designed by following design procedures set out in the assignment, [1]. The wound rotor induction motor, should be designed for the given parameter in table 1.1 below. The stack length should be below 120 mm and the maximum current (rms) should be 5.5 A rms. Thus, it means when designing the stator and rotor for the motor, the desired currents should be less than 5.5 A rms. The outer diameter of the stator should also be designed for a value of less than 140 mm. Thus, the desired D_O should be less than 140 mm for the stator.

1.1.2. Analysis of an efficient induction motor:

The efficiency of the induction motor design is considered successful when we achieve the desired outer diameters for both the stator and rotor. Additionally, if we can maintain an RMS current for both the stator and rotor that is less than 5.5 A but still close to the maximum design current, the design is deemed sufficient. To further assess the design, we can employ software analysis tools such as ANSYS. These tools allow us to analyze various parameters like Stator Current, Rotor Current, Induced Voltage, Torque, Core Losses, L_{dq}, etc. The results are presented as transient rectangular plots, which serve as a confirmation that our induction motor functions as intended based on analytical design specifications. Table 1.1 and Table 1.2 below illustrates the given parameters and the chosen design values for the induction motor.

Table 1.1: Given Parameters

Variable	Value
k_w	0.955
pf	0.76
Frequency	50 Hz
P_{Mech}	2.2 - 0.05 = 2.15 kW
n_s	$\frac{1500}{60} = 25$ rad/s
π	3.141592
V_{ph}	$\frac{380}{\sqrt{3}} = 219.39V$
ρ_{Copper}	$1.91 \times 10^{-8}\,\Omega\,\mathrm{m}$
SF	0.95
poles	4 poles

Table 1.2: Chosen Values

Variable	Value
η	0.8499
q	3
J	$6.499\,\mathrm{A\,mm^{-2}}$
B_{Airgap}	0.5 T
$\bar{J}$	$29\,500\,\mathrm{A\,mm^{-1}}$
K_{FF}	0.4
$B_{StatorTeeth}$	1.699 T
$B_{StatorYoke}$	1.4499 T

1.1.3. Stator Design of motor

The design of the stator and the equations used is specified within, [1] and the design process was followed as specified.
Firstly D^2L can be calculated:

$$D^2L = \frac{P_{\text{Mech}}}{(\eta)\,(\text{pf})\,(n_s)\,(1.11)\,(\pi^2)\,(k_w)\,(B_{\text{Airgap}})\left(\bar{J}\right)(10^{-3})} = 7.2018 \times 10^{-4} m^3$$

Next, I choose a stator core length of **L = 0.118 m**. With the chosen stator core length, the air gap diameter can be calculated:

$$D = \left(\frac{D^2 L}{L}\right)^{\frac{1}{2}} = 0.0781\,\mathrm{m}$$

Next, Air-gap length was calculated:

$$L_{Airgap} = 0.2 + 2\sqrt{D \cdot L} = 0.3920\,\mathrm{mm}$$

Next, flux per pole is calculated as:

$$\phi_m = \frac{B_{\mathrm{airgap}} \cdot \pi \cdot D \cdot L}{\mathrm{poles}} = 0.0043\,\mathrm{Wb}$$

Next turns per phase is calculated as:

$$T_{\mathrm{ph}} = \frac{ke \cdot V_{ph}}{4.44 \cdot k_w \cdot \mathrm{freq} \cdot \phi_m} = 215$$

Next number of stator slots is calculated as:

$$S_s = 3 \cdot \mathrm{poles} \cdot q = 36$$

Next, the number of conductors per slot is calculated as:

$$Z_{ss} = \frac{3 \cdot 2 \cdot T_{ph}}{S_s} = 36$$

Next, stator current per phase is calculated as:

$$I_{\mathrm{ph}} = \frac{P_{\mathrm{Mech}} \cdot 10^3}{3 \cdot \eta \cdot \mathrm{pf} \cdot V_{\mathrm{ph}}} = 5.0572\,\mathrm{A}$$

I_{ph} is the designed current for the stator. Thus the calculated value of 5.0572 A, are less than the maximum allowable current of 5.5 A. This confirms that the design process worked as intended.

Next, cross-section area of each conductor is calculated as:

$$A_c = \frac{I_{ph}}{J} \cdot 10^{-6} = 7.7816 \times 10^{-7}\,\mathrm{m}^2$$

Next, pole pitch is calculated as:

$$\tau = \frac{\pi \cdot D}{\mathrm{poles}} = 0.0614\,\mathrm{m}$$

Next, mean length of a single turn winding is calculated as:

$$L_{\mathrm{MLT}} = 2 \cdot L + 2.3 \cdot \tau = 0.3771\,\mathrm{m}$$

Next, stator resistance per phase is calculated as:

$$R_{Stator} = \frac{\rho_{copper} \cdot L_{\mathrm{MLT}} \cdot T_{ph}}{A_c} = 1.9878\,\Omega$$

Next, slot area is calculated as:

$$A_{\mathrm{slot}} = \frac{A_c \cdot Z_{ss}}{K_{\mathrm{FF}}} = 6.9628 \times 10^{-5}\,\mathrm{m}^2$$

Next, the width of the stator teeth is calculated as:

$$W_{\mathrm{st}} = \frac{\phi_m \cdot \mathrm{poles}}{S_s \cdot L \cdot B_{StatorTeeth}} = 0.0024\,\mathrm{m}$$

Next, stator slot width is calculated as:

$$W_{\mathrm{ss}} = \frac{\pi \cdot D - S_s \cdot W_{\mathrm{st}}}{S_s} = 0.0044\,\mathrm{m}$$

Next, depth of stator yoke is calculated as:

$$d_{\mathrm{cs}} = \frac{\phi_m/2}{B_{StatorYoke} \cdot L \cdot SF} = 0.0133\,\mathrm{m}$$

Next, the depth of stator slot is calculated as:

$$d_{\mathrm{ss}} = \frac{A_{\mathrm{slot}}}{W_{\mathrm{ss}}} = 0.0158\,\mathrm{m}$$

The wire diameter for the stator can also be calculated as:

$$Diameter_{Stator} = 2 \cdot \sqrt{\frac{A_c}{\pi}} = 1mm$$

Finally, the outer diameter of the stator is calculated as:

$$D_o = D + 2 \cdot L_{AirGap} \cdot 10^{-3} + 2 \cdot d_{\mathrm{ss}} + 2 \cdot d_{\mathrm{cs}} = 0.1371\,\mathrm{m}$$

The calculated value for D_O is calculated as 137.1 mm, which works in the design of an induced motor. This calculated value is below the maximum 140 mm for the outer diameter of the stator.

1.1.4. Rotor Design of motor

The design of the rotor and the equations used is specified within, [1] and the design process specified there was followed to calculate the following values:
Rotor turns per phase (T_R) is:

$$T_R = \mathrm{round}\left(\frac{T_{ph}}{N_{\mathrm{eff}}}\right) = 165$$

Table 1.3: Rotor Design Parameters Chosen and Calculated

Variable	Value
S_r	$3 \cdot \text{poles} \cdot \left(\frac{2}{3}\right) \cdot q = 24$
N_{eff}	1.3
J_r	$6.499\,\text{A}\,\text{mm}^{-2}$
$B_{\text{Rotor Yoke}}$	1.2 T
$B_{\text{Rotor Teeth}}$	1.7 T

The number of rotor conductors per slot (Z_{rs}) is:

$$Z_{rs} = \text{round}\left(\frac{3 \cdot 2 \cdot T_R}{S_r}\right) = 41$$

Rotor current per phase (I_r) is:

$$I_r = k_w \cdot I_{ph} \cdot N_{\text{eff}} \cdot 0.85 = 5.3368\,\text{A}$$

I_R is the designed current for the rotor. Thus the calculated value of 5.3368 A, are less than the maximum allowable current of 5.5 A. This confirms that the design process worked as intended.

Cross-section area of each rotor conductor (A_r):

$$A_r = \frac{I_r}{J_r} \cdot 10^{-6} = 8.2117 \times 10^{-7}\,\text{m}^2$$

Slot area for rotor (A_{rslot}) is:

$$A_{rslot} = \frac{A_r \cdot Z_{rs}}{K_{FF}} = 8.4170 \times 10^{-5}\,\text{m}^2$$

The width of the rotor teeth (w_{rt}) is:

$$W_{rt} = \frac{\phi_m}{\frac{S_r}{\text{poles}} \cdot L \cdot B_{RotorTeeth}} = 0.0036\,\text{m}$$

Rotor slot width (w_{rs}) is:

$$W_{rs} = \frac{\pi \cdot D - S_r \cdot W_{rt}}{S_r} = 0.0066\,\text{m}$$

The depth of rotor yoke (d_{cr}) is:

$$d_{cr} = \frac{\frac{\phi_m}{2}}{B_{RotorYoke} \cdot L \cdot SF} = 0.0161\,\text{m}$$

The depth of rotor yoke (d_{rs}) is:

$$d_{rs} = \frac{A_{rslot}}{W_{rs}} = 0.0127\,\text{m}$$

The resistance of the rotor is the following:

$$R_{\text{rotor}} = \rho_{\text{Copper}} \cdot \frac{L_{\text{MLT}} \cdot T_{\text{R}}}{A_r} = 1.4473\,\Omega$$

The wire diameter for the rotor can also be calculated as:

$$Diameter_{Rotor} = 2 \cdot \sqrt{\frac{A_r}{\pi}} = 0.9953mm$$

Finally, the shaft diameter of the IM (D_{Shaft}) is:

$$D_{\text{shaft}} = D - 2 \cdot d_{cr} - 2 \cdot d_{rs} = 0.0205\,\text{m}$$

1.2. Performance and efficiency calculations

The maximum stator outer diameter (mm) is specified as 140 mm within [1]. The calculated D_O of the stator was calculated as 137.1 mm. This diameter falls within the specified 140 mm, thus meaning the design of the stator will work when simulating on ANSYS. The resistance per phase (R_{Stator}) was calculated as $1.9878\,\Omega$.The stator current was calculated as $I_{ph} =$ 5.0572 A, which is am accurate amount of current for the design of each phase of the stator.

1.2.1. Calculation of rated induced Torque:

The slip of the rotor is calculated as:

$$slip = \frac{1500 - 1400}{1400} = 0.0714$$

The rated induced torque is calculated as:

$$T_{Rated} = \frac{P_{Mech} \cdot 10^3}{1400 \cdot \frac{\pi}{30}} = 14.6650\,\text{Nm}$$

The rated induced torque calculated above is the theoretical value of the torque, which is equal to 14.6650 Nm.

1.2.2. Efficiency Calculation Using ANSYS:

The theoretical rated induced torque is calculated as 14.6650 Nm, but the measured induced torque is measured as 12.1237 Nm on ANSYS. It is a bit lower than the theoretical calculation, but it's still quite accurate. The ANSYS torque is less than theoretical, because the theoretical assumes ideal conditions. The core losses and eddy currents within the induced motor would also affect the torque and decrease it. The load also affects the torque and causes it to decreases lower than the theoretical calculation.

Using the $T_{Simulated}$ = 12.1237 Nm, the efficiency for the designed induced motor can be calculated. The following formulas were used to achieve this.

The P_Output power is calculated as:

$$P_{Output} = T_{Simulated} \cdot n_m \cdot \frac{\cdot 2\pi}{60} = 1777.4\,\mathrm{W}$$

Using $P_{Input} = P_{Mech}$ = 2200 W, the efficiency of the induced motor can be calculated as:

$$\eta = \frac{P_{\text{Output}}}{P_{\text{Input}}} \cdot 100\% = 80.790\%$$

Thus, the efficiency calculated is 80.790 % for the induced motor, which is relatively close to the chosen efficiency of 85%. This means that the design of the induced motor is effective and the chosen design values works.

1.3. Results from ANSYS Maxwell

1.3.1. Maxwell Screenshots:

Figure 1.1 below illustrates the flux density of the motor in the different regions of the motor.

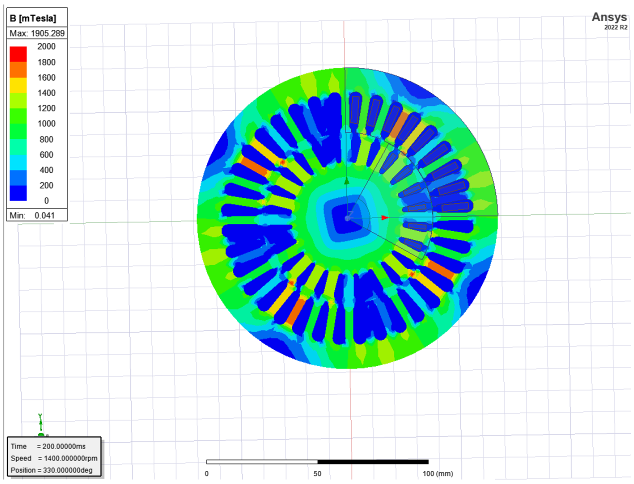

Figure 1.1: Flux Density Region Diagram of the motor

The flux density within the stator and rotor is illustrated on figure 1.2 as a plot.

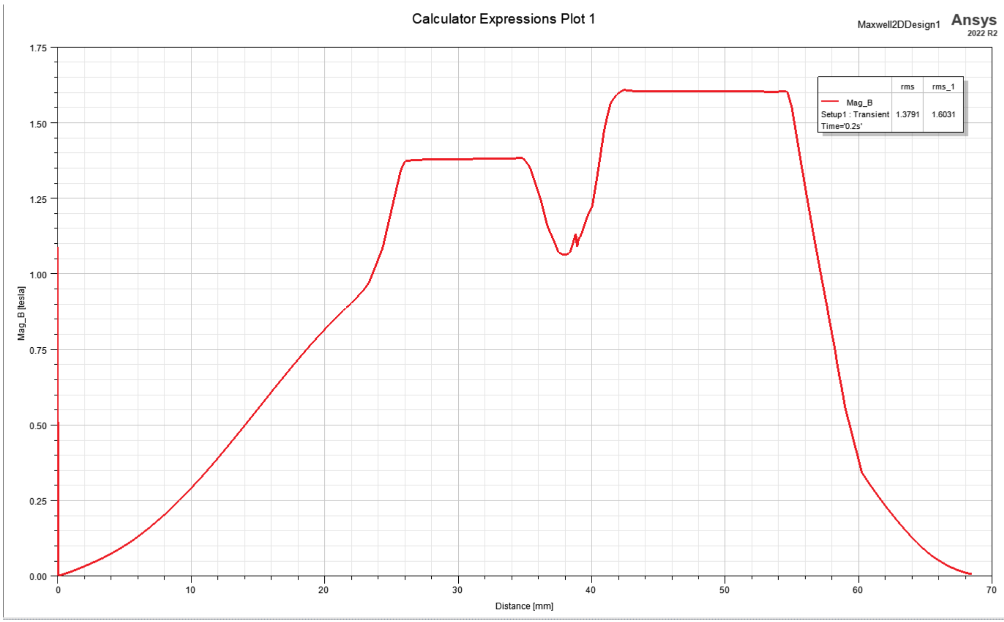

Figure 1.2: Flux Density Plot of Stator and Rotor

Figure 1.3 below illustrates the phase currents for the stator. The rms current value of each phase is close to the calculated value of 5.0572 A. The measured values in ANSYS is 4.55 A per phase. This measured stator current is very close to the calculated value. The difference between calculations and simulated results is 0.50722 A. The lower stator current still works, because the current per phase for the stator is below the maximum stator current of 5.5 A.

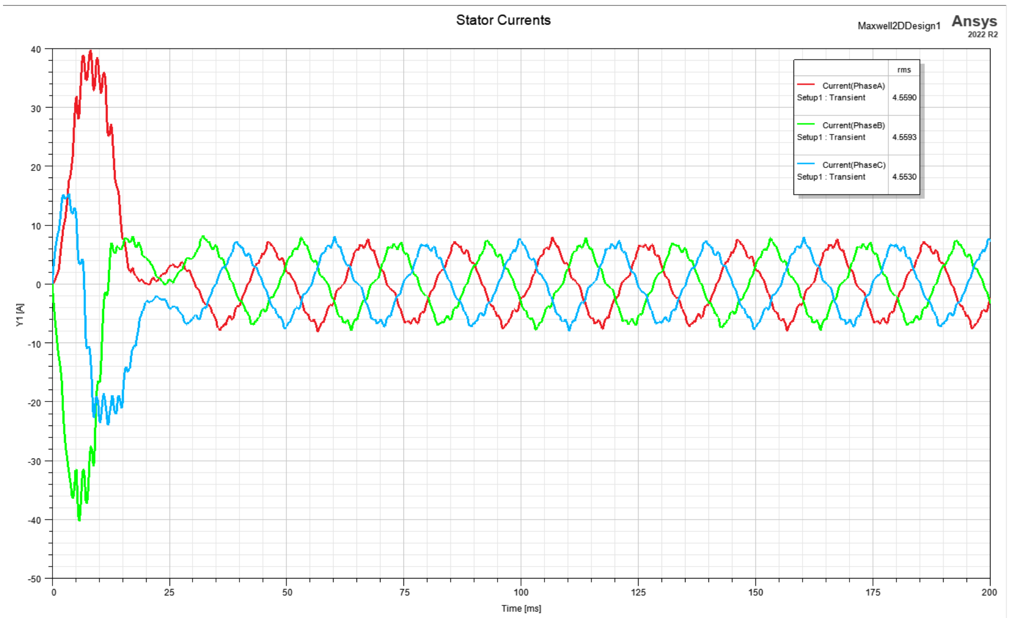

Figure 1.3: The Stator Phase Currents from ANSYS

The steady transient plot of the stator current is illustrated in figure 1.4 below.

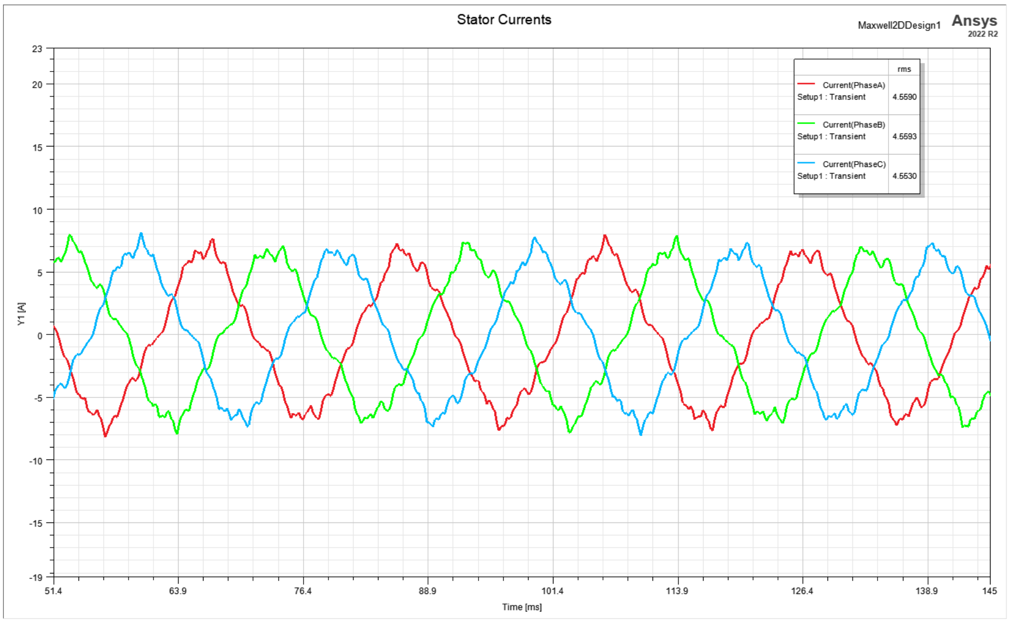

Figure 1.4: The Stator Phase Currents from ANSYS showing Only Stable Transient

Figure 1.5 below illustrates the phase currents for the rotor. The rms current value of each phase is close to the calculated value of 5.3361 A. The measured values in ANSYS is 5.15 A per phase. This measured stator current is very close to the calculated value. The difference between calculations and simulated results is 0.1836 A. The lower rotor current still works, because the current per phase for the rotor is below the maximum stator current of 5.5 A.

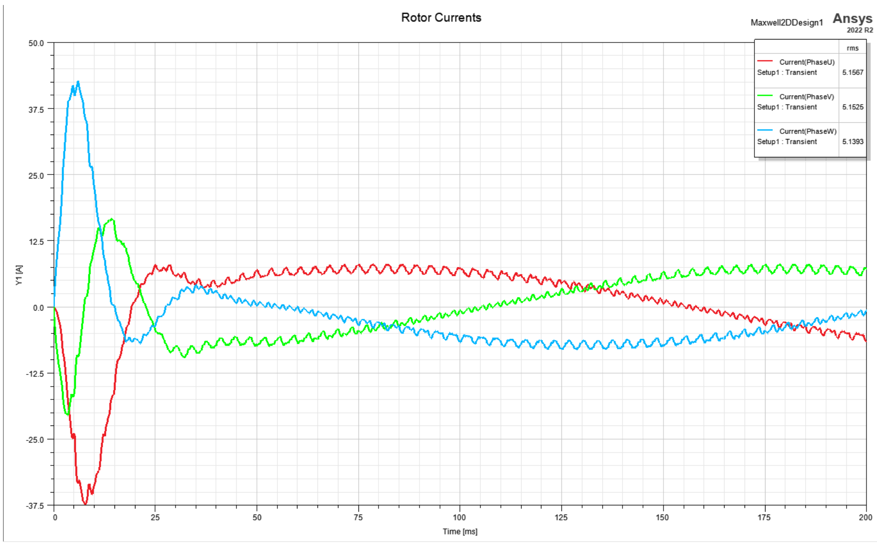

Figure 1.5: The Rotor Phase Currents from ANSYS

The steady transient plot of the rotor current is illustrated in figure 1.6 below.

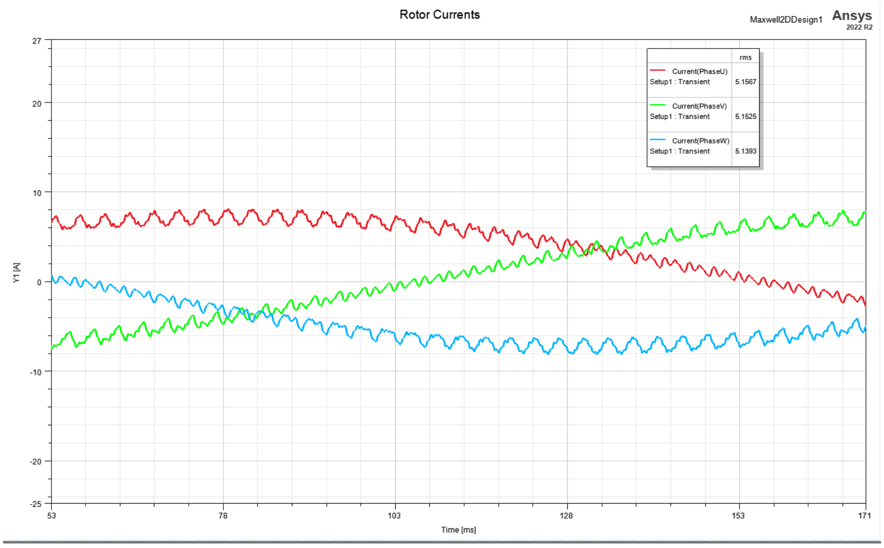

Figure 1.6: The Rotor Phase Currents from ANSYS showing Only Stable Transient

Figure 1.8 below illustrates the torque for the motor. The plot illustrates the rms and ripple value of the torque of the motor.

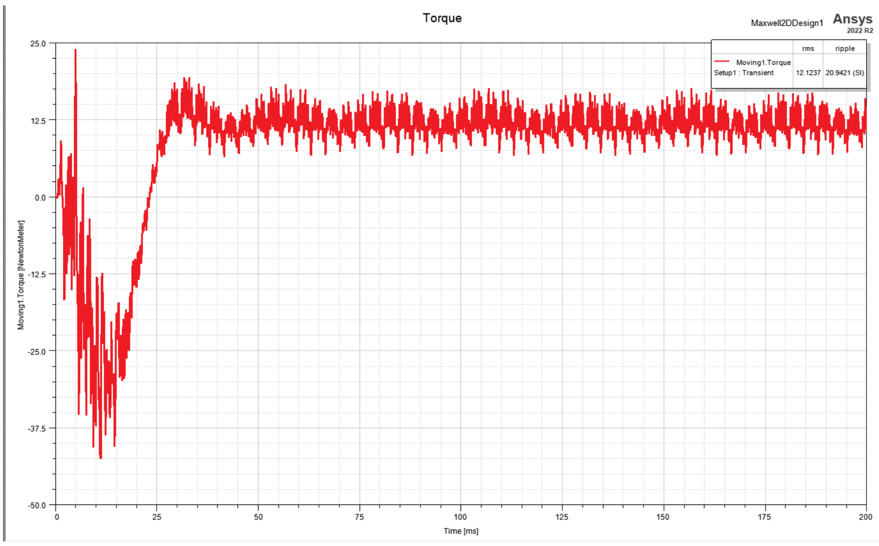

Figure 1.7: Torque Plots from ANSYS

Figure 1.8 below illustrates the stable transient torque for the motor.

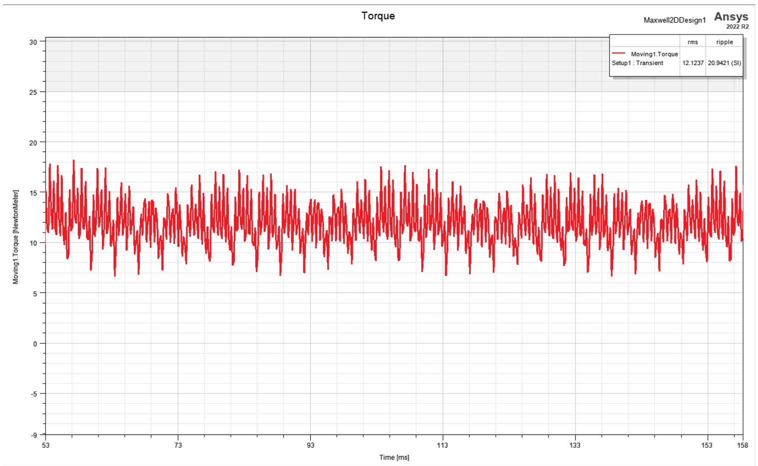

Figure 1.8: Stable Transient Torque plots from ANSYS

Figure 1.9 below illustrates inductance of L_q and L_d both on the same plot. The plot illustrates the inductance's in rms (mH).

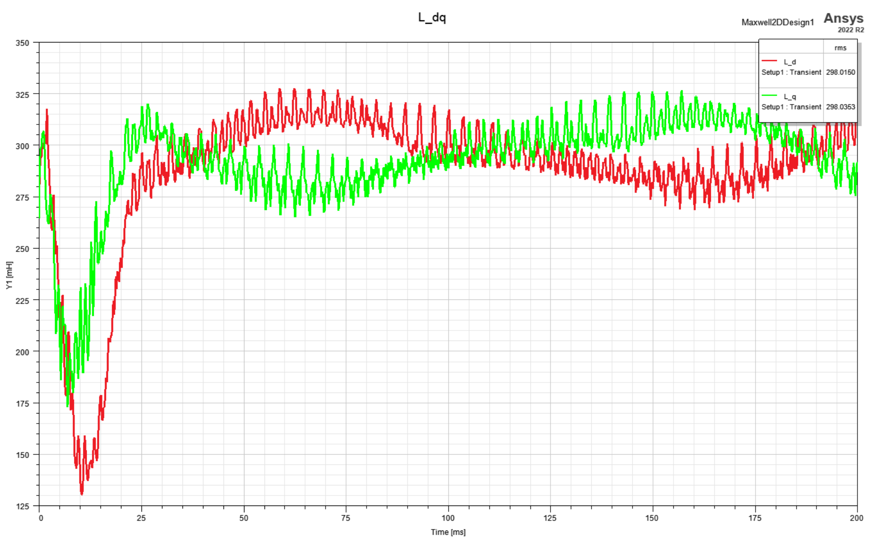

Figure 1.9: L_{dq} Plot from ANSYS

Figure 1.10 illustrates the L_{dq} at a stable transient for each phase.

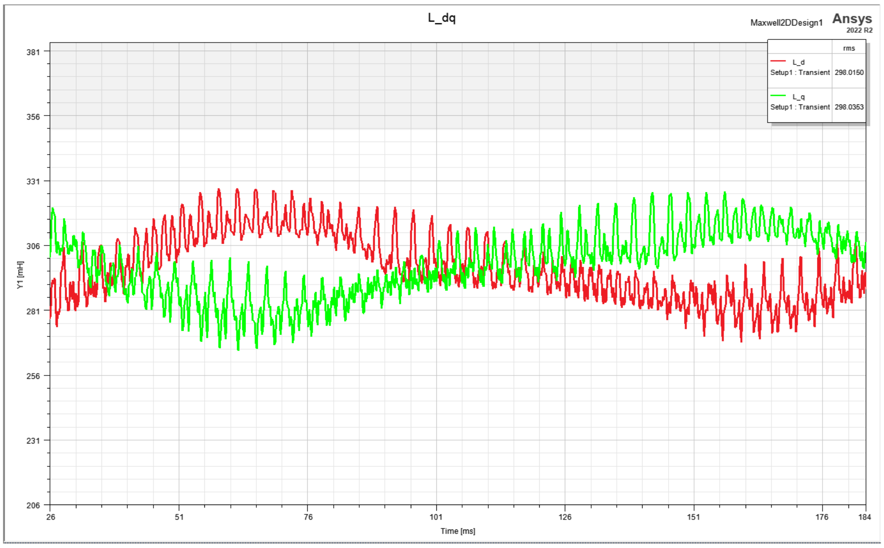

Figure 1.10: L_{dq} Plot from ANSYS

Figure 1.11 below illustrates flux (WB) of $Flux_q$ and $Flux_d$ both on the same plot.

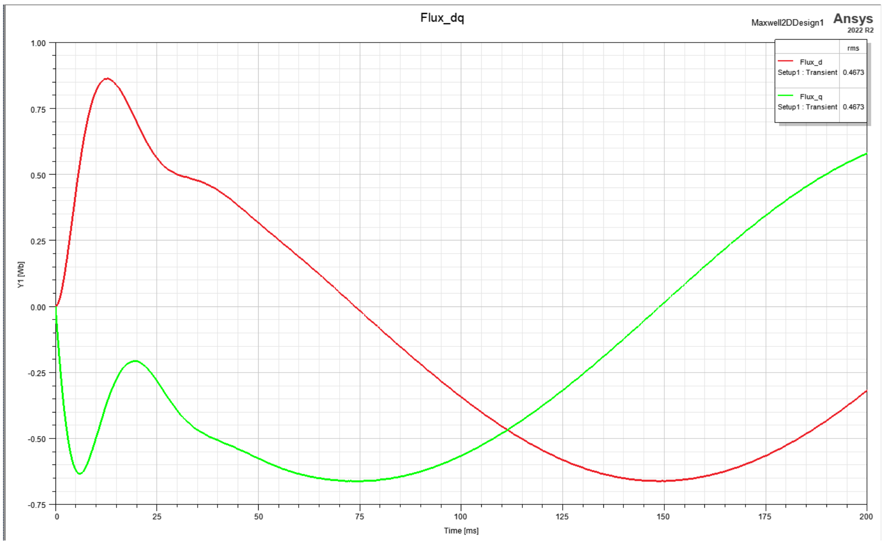

Figure 1.11: $Flux_{dq}$ Plot from ANSYS

The stable transient of the $Flux_{dq}$ is illustrates in figure 1.12

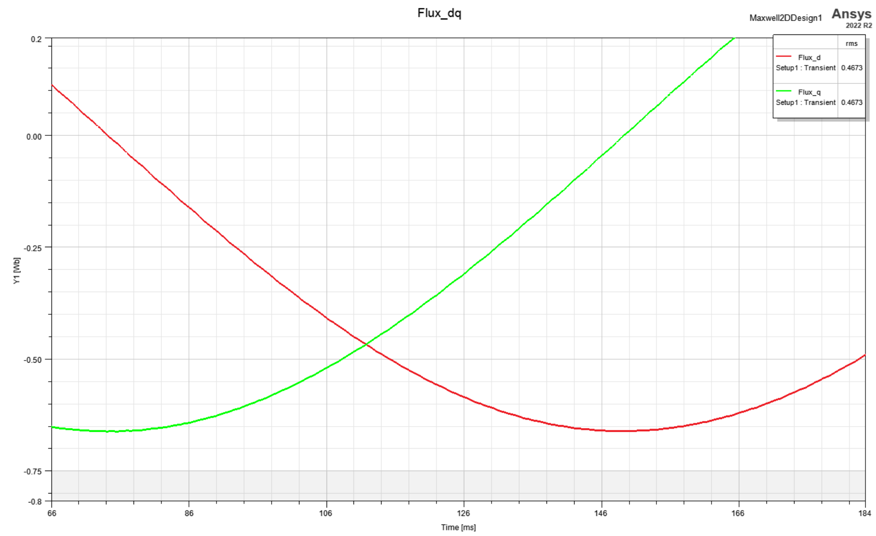

Figure 1.12: Stable Transient of $Flux_{dq}$ Plot from ANSYS

Figure 1.14 below illustrates induced voltage of the rotor. The plot illustrates the induced voltage in rms voltage.

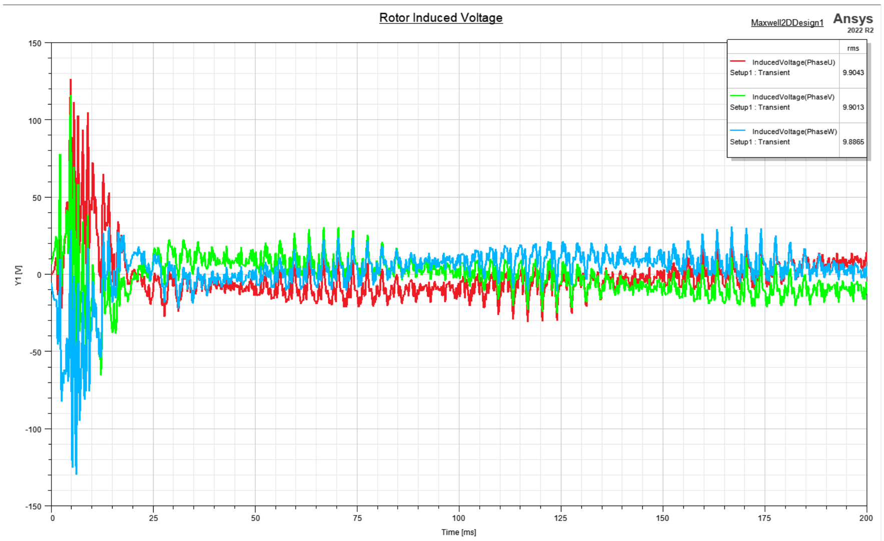

Figure 1.13: Rotor induced voltage plot from ANSYS

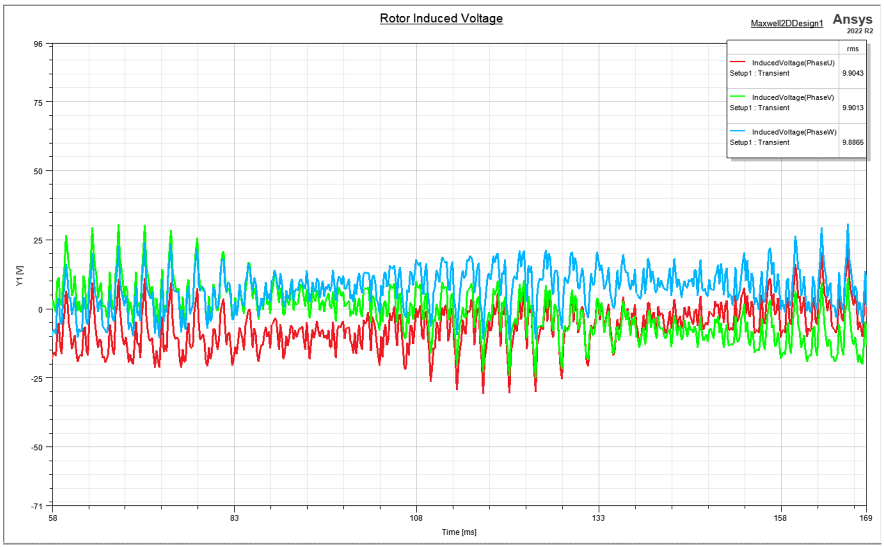

Figure 1.14: Stable transient of the rotor induced voltage plot from ANSYS

1.3.2. ANSYS Table Results

Table 1.4 below illustrates the measured values simulated within ANSYS of the flux density of the rotor and stator.

Rotor Flux Density (T)	Stator Flux Density (T)
1.3791 T	1.6031 T

Table 1.4: Flux Density of the Stator and Rotor table

Table 1.5 below illustrates the measured values simulated within ANSYS of each stator phase current. These values are close to the calculated value of $I_s tator = 5.056$ A.

Phase	Stator Current (rms) (A)
A	$4.5590A$
B	$4.5593A$
C	$4.5530A$

Table 1.5: Stator Current per phase table

Table 1.6 below illustrates the measured values simulated within ANSYS of each rotor phase current. These values are close to the calculated value of $I_s tator = 5.3361$ A.

Phase	Rotor Current (rms) (A)
U	$5.1567A$
V	$5.1525A$
W	$5.1393A$

Table 1.6: Rotor Current per phase table.

Table 1.7 below illustrates the measured values simulated within ANSYS of the torque of the motor. The torque is illustrated in the rms and ripple value.

Torque (rms) (Nm)	Torque (ripple) (SI)
12.1237 Nm	20.9421 SI

Table 1.7: Torque ripple and rms value table.

Table 1.8 below illustrates the measured core losses of the motor simulated within ANSYS. The table illustrates that there are 55.58 W losses.

Core losses (W)
55.5782 W

Table 1.8: Core losses value table

Bibliography

[1] [Online]. Available: https://learn.sun.ac.za/pluginfile.php/4539070/mod_folder/content/0/ES344%20Assignment%202.pdf?forcedownload=1