

Chapter 4 – Performance Prediction

In this chapter the performance of the LS PMSM prototype is inspected. This is done using calculations and simulation. Some of the results will be used to validate the machine design documented in Chapter 3. The torque components used to predict the prototype's performance have already been calculated in Chapter 3 but have not yet been combined. This is done in this chapter.

The torque profile and the back-emf properties of the prototype will be inspected. The calculated and simulation results of the asynchronous and synchronous torque components will be compared. This is done to ensure that the method used to design the prototype is correct. The back-emf waveform and peak value will both be calculated and determined from the FEMM model. The peak back-emf value is a key component in calculating the braking torque of any LS PMSM. The wave form will also be used during validation of the machine.

4.1 Torque profile comparison

In Chapter 3 the different torque components of the LS PMSM prototype have been calculated and a plot was generated as a function of slip or load angle. Both the asynchronous and synchronous torque were inspected and compared.

4.1.1 Asynchronous torque profile.

Figure 4.1 contains the braking torque (T_m), asynchronous cage torque (T_{asy}) and the torque developed (T_d) by the machine

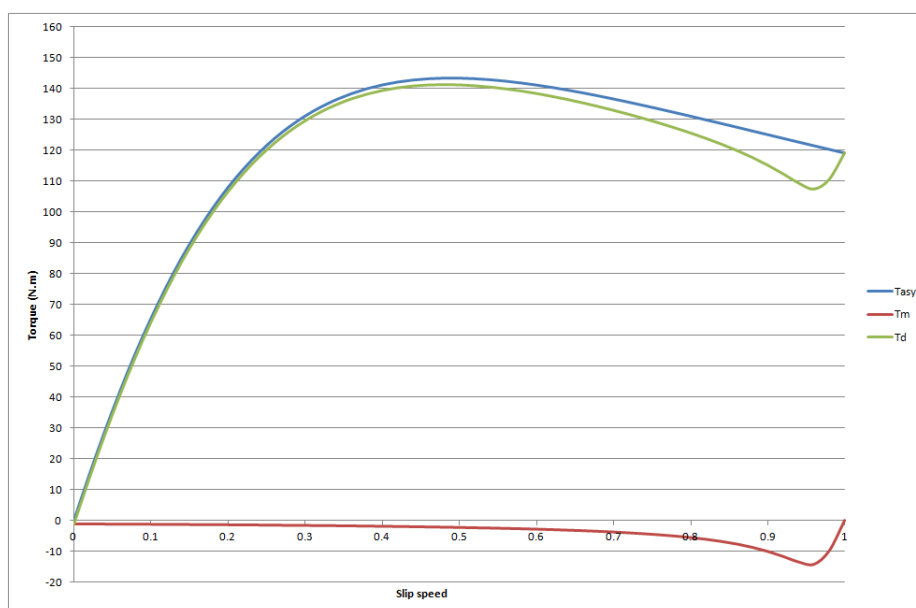


Figure 4.1: Torque vs. slip of different torque components

However for the T_{asy} torque component in Figure 4.1, the skin effect influence on the rotor parameters has not been taken into account. The skin effect parameter (ξ_{se}) is influenced by the rotor slot height, the conductivity of the material and stator frequency [3]

$$\xi_{se} = h_{rs} \sqrt{\frac{\omega \mu_0 \sigma_{Al}}{2}} \quad (4.1)$$

ξ_{se} is calculated as 0.68. Table 4.1 contains the information regarding the calculation of the rotor parameters.

Table 4.1: Adapted rotor parameters due to skin effect

Parameter	Value excluding skin effect (Ω)	Approximation Equation	Approximation value	New value (Ω)
R_2'	2.187	$R_{2start}' = \xi_{se} R_2'$	0.78	1.706
X_2'	1.615	$X_{2start}' = \left(\frac{3}{2\xi_{se}} \right) X_2'$	1.5	2.423

Depending on the slot shape the value can be adapted closer to 1. As a round bar is smaller in width at the bottom ξ_{se} is adapted to 0.78 to calculate the resistance. For the inductance, the calculated value of ξ_{se} is used in the brackets and calculated first, and then the bracket value is adapted from 2.2 to 1.5. Since mainly T_{asy} is changed by the skin effect, Figure 4.2 contains the two cage torque profiles and Figure 4.3 the new torque curve and components for the prototype as affected by skin effect.

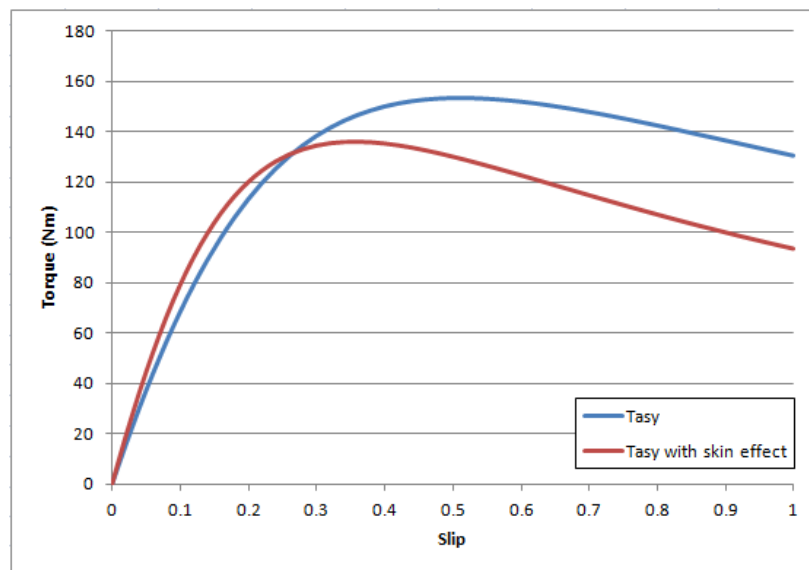


Figure 4.2: Cage torque with and without skin effect

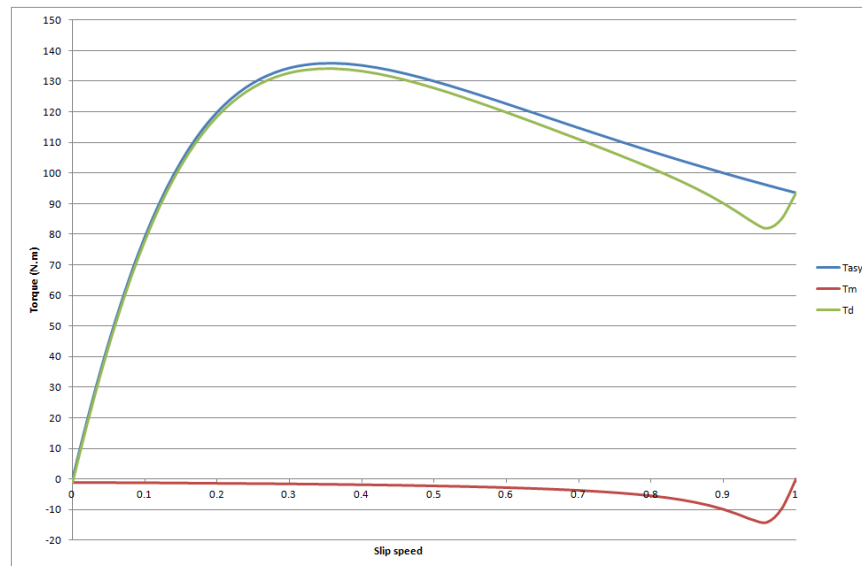


Figure 4.3: Torque vs. slip of different torque components (including skin effect)

The change in rotor parameters also change the starting and breakdown values as calculated in Table 3.30. The new values is indicated in Table 4.2

Table 4.2: New starting and breakdown values

Parameter	Symbol	Without skin effect	With skin effect	% Change
Starting torque	T_{start}	55.93 A	52.37 A	6.4 %
Starting torque	T_{start}	130.67 N.m	93.604 N.m	28.4 %
Breakdown torque	T_{bd}	153.59 N.m	136.01 N.m	11.45 %
T_{bd} slip speed	s_{bd}	0.511	0.356	30.3 %

From Table 4.2 it is clear that the skin effect has a big influence on the starting torque and the speed at which the maximum torque is generated. The change in breakdown slip speed is now closer to synchronous speed. This increases the synchronization capabilities of the machine. Although the starting torque has been reduced it is still high enough to start with a fan load.

In Figure 4.4, the calculated torque plot is compared against the simulation results. The simulated results are within acceptable range of the calculated values. The only notable difference is the starting torque.

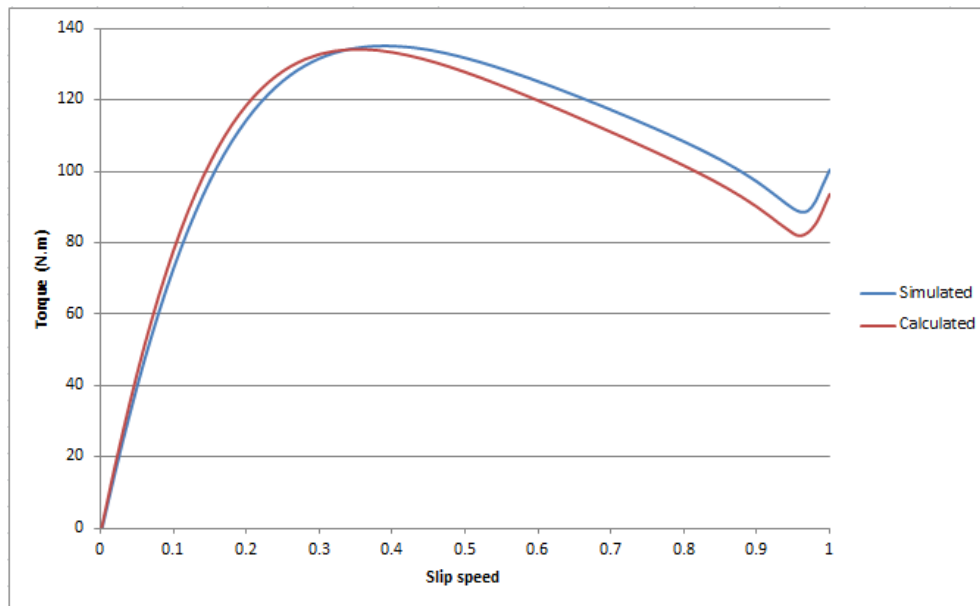


Figure 4.4: Simulated torque curve vs. calculated torque curve

Table 4.3 contains the breakdown and starting values for both the simulated and calculated machine.

Table 4.3: Simulation vs. calculated starting and breakdown results.

Parameter	Symbol	Calculated	Simulated	% Difference
Starting torque	T_{start}	93.604 N.m	100.94 N.m	7.2 %
Breakdown torque	T_{bd}	136.01 N.m	135.20 N.m	0.5 %
T_{bd} slip speed	s_{bd}	0.356	0.4	11 %

4.1.2 Synchronous torque profile

The last comparison between the FEMM model and the calculated model is the torque vs. load angle plot as indicated in Figure 4.5. This plot indicates the maximum torque provide once the machine is synchronized. Both torque values are calculated from the air gap power. The maximum calculated torque is 48.9 N.m at $\delta = 120^\circ$. The simulated maximum torque is 48.39 N.m at $\delta = 119^\circ$. However the rated torque for a 7.5 kW 4 pole machine is 47.74 N.m. For the calculated torque plot this occurs at $\delta = 112^\circ$ and for the simulated model at $\delta = 113^\circ$. Thus the angle at which both the rated torque and maximum torque occur are within range of each other. This is the same for the maximum torque.

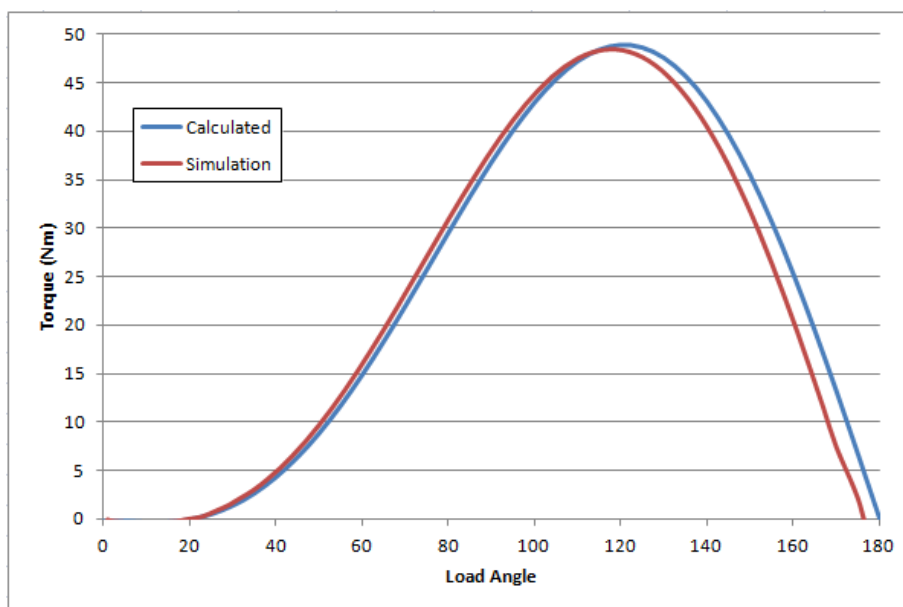


Figure 4.5: Load angle of simulated torque vs. calculated torque

From the torque comparison between the calculated values and simulation results it is clear that both methods provide similar results. The starting torque and breakdown torque differ slightly. This can be due to a difference in rotor or stator parameters (resistance and inductance) or the calculation method used by the simulation package.

Table 4.4 contains the simulated and calculated parameters. The skin effect is included in the calculated parameters as the FEM simulation also incorporates the skin effect, thus providing an accurate resistance and inductance comparison.

Table 4.4: Parameter comparison

Parameter	Simulated (Ω)	Calculation (Ω)	% Difference
R_1	1.423	1.428	< 1 %
R_2'	1.679	1.787	6 %
X_1	3.02	2.387	26 %
X_2'	1.802	1.6473	9.3 %

By using the simulated parameters values in Table 4.4 and calculating the starting current using Equation 3.37, the starting current is 52.84 A giving a difference of less than 1% from the calculated parameter starting current. By using the simulation parameters in equation listed in Table 3.27 the starting torque is calculated as 89.53 N.m. This is 10.843 N.m less what the simulated result. R_2' is calculated from the simulation starting torque as 1.882 Ω .

As all the parameters except the stator inductance are within 10%, the effect of changing this value so that it is within 10% of the calculated value is investigated. By reducing the stator inductance the starting

torque and current increases. Thus the conclusion can be that the simulation package uses a different method to calculate the starting and breakdown values since a higher starting torque is obtained in the simulation package using a higher stator inductance.

4.2 Back-emf waveform of LS PMSM prototype

The PM induced back-emf in an LS PMSM is one of the unique aspects of these machines as it is not dependant on a connected electrical source as with an IM. The back-emf of an LS PMSM is a function of the PM flux linkage (λ_{pm}) with the stator coil phases with respect to the rotational speed of the rotor. Depending on the rotor position during rotation, each phases experience the PM linkage flux differently.

To plot the back-emf of a machine the peak induced voltage must be calculated by

$$E_{peak} = \lambda_{pm-phase} \omega_r \quad (4.1)$$

with ω_r the rotational speed of the rotor E_{peak} the peak induced voltage and $\lambda_{pm-phase}$ the flux linkage value of the PM with a given phase. $\lambda_{pm-phase}$ can also be replaced with λ_{pm_a} , λ_{pm_b} and λ_{pm_c} .

The flux linkage of each phase is calculated in FEMM, by setting the phase current's value to zero. This simulates the rotor rotating at synchronous speed. To calculate the peak back-emf value one of the phases must be aligned with the rotor d-axis. Once the flux linkage value of each phase is extracted the RMS back-emf value is calculated as 186.167 V. This value correlates well with the RMS phase back-emf value calculated in ANSYS Maxwell® as 190.19 V. To plot the back-emf waveform as a function of rotor position (θ_r) the following equation is used:

$$E(\theta_r) = E_{peak} \sin(2\theta_r) \quad (4.2)$$

Another method of determining the back-emf waveform is to perform a time step analysis using FEMM. This is done by performing the same simulation as above to extract the different phase flux linkage values. The difference however is that the rotor is rotated by a certain mechanical angle after each simulation between 0° and 90°.

Figure 4.6 represents the PM flux linkage waveform of each coil phase. The various phases experience the maximum flux at the point that the phase is allied with the rotor d-axis and as a result at that point the flux linkage is at its highest. The pole pitch of the machine is 45° and this correlates with the flux linkage waveform.

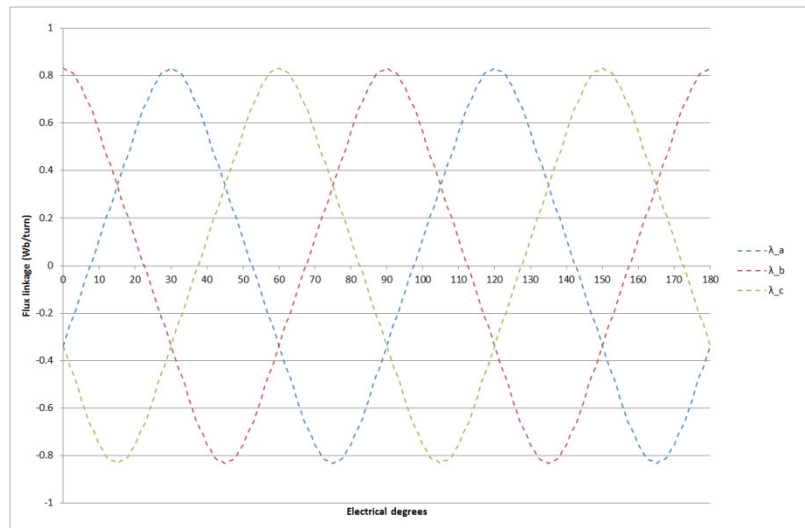


Figure 4.6: Flux linkage waveform with results from FEMM

Figure 4.7 shows the back-emf waveform of using Equation 4.2 and simulation method.

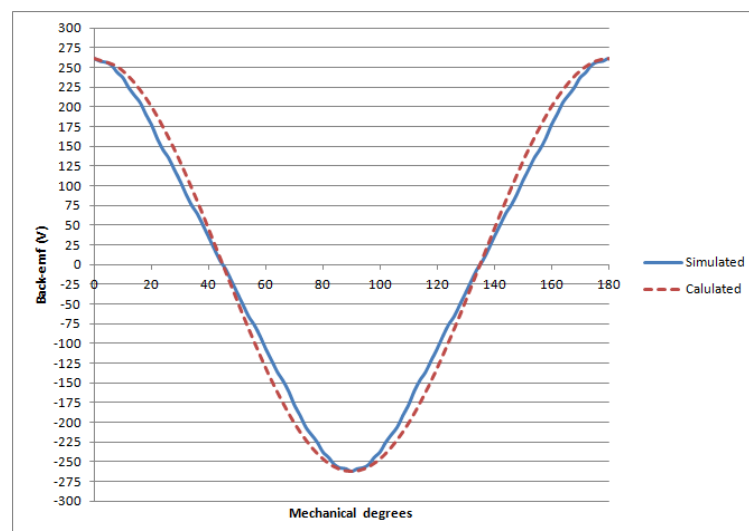


Figure 4.7: Calculated back-emf vs. simulate results back-emf

However both the methods above do not incorporate the effects of short pitching on the back-emf waveform but can still be used to calculate the peak value that is needed to calculate the braking torque of the machine. To incorporate the effects of short pitching some the extracted flux linkage values must be adapted.

As a coil does not span the entire pole pitch the flux linkage will be constant over a certain area as there is no change in flux. In [5], an adaptive constant is used to calculate the flux linkage for the constant flux area. Once the technique was employed on the flux linkage values Figure 4.8 was generated from the adapted simulation data. Figure 4.8 contains the induced voltage waveform of each phase

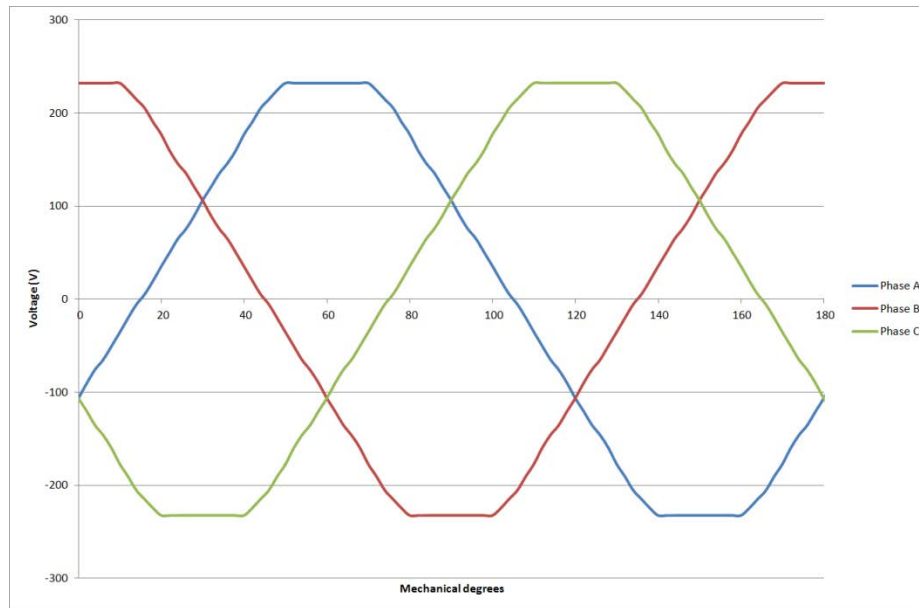


Figure 4.8: Back-emf waveform of each phase

From Figure 4.8 it is clear that by incorporating short pitching into the stator coil arrangement the peak value of the back-emf is reduced. This is due to the electromagnetic interaction between the PM and the shorter coil. As the coil is shorter there is a period at which there is no change in flux and the coil is exposed to the maximum PM flux. The ratio between pole and coil pitch is used to determine the reduction factor. However the peak value of the back-emf is induced in the coil for a longer period as a result of the longer exposure to the maximum flux. Although the peak voltage value is lower than with a full pitch winding, the RMS value is not greatly influenced thus the braking torque is very similar. However this can be design dependant.

In this chapter the torque performance curve and the back-emf waveform for the prototype was inspected and adapted accordingly. The torque curve was adapted by incorporating the influence that the skin effect has on the rotor inductance and resistance. The calculated back-emf wave form was compared to the back-emf waveform extracted from FEMM. Further investigation revealed that the FEMM waveform had to be adapted due to the short pitching of the stator coil. Both the torque curve and back-emf waveform showed a good fit.