

Chapter 6 – Testing and Evaluation

In this chapter the results obtained during the testing of the LS PMSM prototype are provided. The test results are compared with Weg's LS PMSM machine, WQuattro. The results are used to validate the machine design. All the relevant testing was done at Marthinusen & Coutts. The test results are discussed at the end of the chapter.

During the manufacturing process some deviations to the original design were made, the biggest of which was the change in the stator wiring configuration. The effect of the change in stator wiring will be discussed and addressed under each relevant machine test.

6.1 Test procedure

The test procedure for the prototype is divided into two parts. For the first part the standard ISO IM test is done on the machine. As there is no testing standard available against which an LS PMSM machine can be tested to, it was decided to test it as an IM. The following tests will be performed on the prototype:

- Stator DC and Inductance test
- No load test
- Locked rotor test
- Load capability test

As with the IM, the listed tests can be used to determine the machine parameters and performance. From the test results a conclusion can be constructed to whether these tests and the methods used are applicable to LS PMSM machines.

For the second part of the tests the back-emf waveform will be measured. This waveform provides valuable information regarding the PM in the rotor, the stator winding configuration and air gap dimension. The comparison between the actual, simulated and calculated back-emf waveform will be part of the validation process.

6.2 Stator DC and inductance test

The goal of this test is to determine the stator coil resistance (R_l) and inductance (X_l). The first step is to recalculate the stator parameters for a delta connection since the winding configuration changes during manufacturing. This is done by using the Excel sheet developed during the design period of the prototype. Table 6.1 contains the new calculated values for both star and delta connection. The transposed star connection is done so it is possible to compare the performance of the machine using the single line equivalent method.

Table 6.1: Star and Delta connection stator parameters

Parameter	Delta connection (Ω)	Transposed star connection (Ω)
R_l	2.296	1.53
X_l	7.464	4.976

To measure the coil resistance a DC test was performed on each coil individually with the aid of a Megger that calculated each coil's resistance. The results are listed as in Table 6.2.

Table 6.2: DC test results

Coil	Value (Ω)
<i>Coil 1</i>	2.268
<i>Coil 2</i>	2.265
<i>Coil 3</i>	2.261

As the coil resistance was calculated as 2.296 Ω and the average value of the coils in Table 6.2 is 2.265 Ω . The 1.35 % deviation between actual and calculated results is acceptable.

To measure the impedance of the stator a Megger was connected to the stator. During the test it became clear that to measure the impedance of the stator, the rotor must be removed as the flux due to the PMs interfered with the measuring equipment. Table 6.3 contains the test results

Table 6.3: Stator inductance test results

Connection	Voltage (V)	Current (A)
<i>Star</i>	129	10.6
<i>Delta</i>	32.7	2.72

With the data in Table 6.3 the coil impedance is calculated as 7.68 Ω , the calculated coil inductance is 7.464 Ω which provides a difference of 2.89 %. The difference is well within the acceptable 10% range. As the calculated parameters and the actual values differ by less than 3% the stator calculation method is assumed to be validated.

6.3 No-Load test

The no-load test is performed by connecting the machine to rated voltage and operating the machine freely without a load. For an LS PMSM the rotor operates at rated speed and there is no slip between the rotor and stator thus the rotor impedance is infinite. For an IM the slip is so close to zero the assumption is made that the slip is zero and the rotor impedance is thus infinite, however in practice this is not totally true due to the IM operation relying on the slip speed.

From the no-load test the stator core resistance (R_{iron}), iron loss (P_{iron}), magnetizing inductance (X_m) and no-load power factor can be determined. Table 6.4 contains the no-load test results

Table 6.4: No-load test results

V_{line}	525 V
I_{line}	3.67 A
P_{in}	190 W
Power factor	0.07
speed	1500 r/min

During the no-load test the line-starting capability of the machine without a load was also investigated. The prototype was line-started several times and synchronized each time; this was confirmed by the rotor speed measurement. The machine also has very low vibration levels once running at rated speed.

To calculate X_m both the method discussed in [3] and [4] are used. In [4] an approximated single phase model is used to calculate the parameters whereas [3] uses the 3-phase test data. Table 6.5 contains the parameters as calculated with [4] and Table 6.6 the parameters using [3]

Table 6.5: No-load parameters using [4]

	Equation	Value
P_{phase}	$P_{phase} = \frac{P_{in}}{3}$	63.33 W
R_{iron}	$R_{iron} = \frac{V_{phase}^2}{P_{phase}}$	4350.97 Ω
Power Factor	$pf = \frac{P_{phase}}{V_{phase} I_{phase}}$	0.057
I_m	$I_m = I_{phase} \sqrt{1 - pf^2}$	2.115 A
X_m	$X_m = \frac{V_{phase}}{I_m}$	248.176 Ω

The two different methods provided similar values for X_m and the no-load pf. However the core resistance value differs for the two methods. The difference can be accredited to the differences in the approach used to calculate the core resistance. The correct value will be known once the no-load parameters are hand-calculated with the aid of the simulation model and the equations provided in [3].

Table 6.6: No-load parameters using [3]

	Equation	Value
P_{iron}	$P_{iron} = P_{in} - 3R_1 I_{phase}^2$	144 W
R_{iron}	$R_{iron} = \frac{P_{iron}}{3I_{phase}^2}$	16.06 Ω
Power Factor	$pf = \frac{P_{in}}{3V_{phase} I_{phase}}$	0.057
X_m	$X_m = \frac{V_{phase} \sqrt{1 - pf^2}}{I_{phase}} - X_1$	247.371 Ω

In [3], a method is provided to calculate X_m , $I_{no-load}$, P_{iron} and R_{iron} using machine design equations. Table 6.7 contains the calculated values of each parameter.

Table 6.7: Calculated no-load parameters

Parameter	Value
X_m	244.21 Ω
P_{iron}	124.383 W
$I_{no-load}$	3.651 A
R_{iron}	9.33 Ω

By comparing the calculated parameters in Table 6.7 with the actual machine parameters determined from the test the following conclusion can be made: the calculated no-load current and the actual no-load current differs by less than 1%. The calculated no-load current is a function of the stator resistance and inductance and magnetising inductance as indicated by Equation 6.1.

$$I_{no-load} \approx \frac{V_{phase}}{\sqrt{R_1^2 + (X_1 + X_m)^2}} \quad (6.1)$$

Since all three calculated parameters are within 10% of the actual values the same method used to calculate an IM no-load current can be used to calculate the LS PMSM current. This is also true for the magnetising inductance since the actual value and the calculated value differs with less than 10 %. However the stator iron loss and core resistance differ from the measured values. This can be due to the fact the calculated values are influenced by the designer's input regarding the hysteresis loss value for the lamination material that is a function of the flux density. Although these two values differ slightly more than 10% of the actual values the no-load test method for an IM can be used on an LS PMSM

6.4 Locked rotor rest

The locked rotor test is done by constraining the rotor to determine the starting rotor resistance and inductance parameters of the prototype. The starting torque of the prototype can also be calculated from the locked rotor test data.

A variable three-phase supply is used to increase the voltage in increments up to rated current. The line voltage and current is measured along with the input power. Table 6.8 contains the test data

Table 6.8: Locked rotor test data

Line Current (A)	Line Voltage (V)	Input Power (W)
1	30	20
2	72	82
3	110	200
4	141	352
5	180	625
6	220	1050
7	273	1853
8	312	2231
9	351	2793
10	405	3450

To calculate the rotor parameters the method in [3] is used. Only the one method is used as the one listed in [4] is similar. By plotting the voltage over current data a linear correlation is obtained and an exponential plot is obtained when the input power over current is plotted. Both the plot forms correlate to the correct form. Table 6.9 contains the calculated parameters using the data at rated current (10 A).

From the results in Table 6.9 it is clear that the parameters calculated are not even close to the parameter values determined with the technique as in Chapter 3 and Chapter 4 ($R_{2start}' = 5.46 \Omega$ and $X_{2start}' = 7.65 \Omega$). The starting torque is also very low compared to the calculated starting torque in Chapter 4. The difference in the torque along with other differences identified during the testing will be discussed in the conclusion of the chapter.

Table 6.9: Rotor parameter calculations from locked rotor data

	Equation	Value
R_{2_start}	$R_{2_start} = \frac{P_{in}}{3I_{phase}^2} - R_1$	32.25 Ω
Power Factor	$pf = \frac{P_{phase}}{V_{phase} I_{phase}}$	0.126
X_{2_start}	$X_{2_start} = \frac{V_{phase} \sqrt{1 - pf^2}}{I_{phase}} - X_1$	82.54 Ω
T_{start}	$T_{start} = \frac{3pR_{2_start} \left(I_{phase} \frac{V_{rated}}{V_{phase}} \right)^2}{\omega}$	17.229 N.m

6.5 Load capability

To test the machine's load capability, two tests are done. For the first test the machine is operated at no-load and the load is increased up to the point that the machine is pulled out of synchronism. For the second test the load is already applied at start up and the machine is line-started. The machine must synchronize with the load applied. The load is increased from 0 N.m up to the maximum load with which that the machine can synchronize.

6.5.1 Pull out torque

This test is done to determine the maximum pull out torque that is required to desynchronize the machine. The machine is connected to a braking dynamo and operated at no-load. The load is gradually increased to the point where the rotor desynchronized with the stator.

The maximum pull-out torque load is 20.37 N.m and the line current is measured at 11.56A. During the test it was found that once the load reaches this value the rotor was forced out of synchronism and the rotor came close to stand still.

6.5.2 Maximum fixed starting torque

This test is done to determine the maximum starting load with which the machine can synchronize. The start-up is seen as a success only once the rotor is synchronized with the stator.

The maximum fixed load that the prototype is able to line-start with is 8.56 N.m. The line current was measured at 10.74 A

6.5.3 Conclusion

In both test the machine underperformed severely. The maximum pull out torque for an LS PMSM according to calculations in Chapter 6 must be higher than the rated torque. The prototype could not reach 50 % of the rated torque value and with the measured maximum start-up the possibility of starting the machine connected to a fan load is also questionable as the start-up torque developed by the prototype might not be enough to overcome the breakaway load as stated in Chapter 2.

6.6 Back-emf waveform.

To measure the back-emf waveform of the prototype the machine, it was connected to a second machine capable of rotating at the rated speed of the prototype. Each coil is connected to a digital oscilloscope and the data points are imported into Excel. Figure 6.1 contains the prototype's back-emf waveforms of each coil.

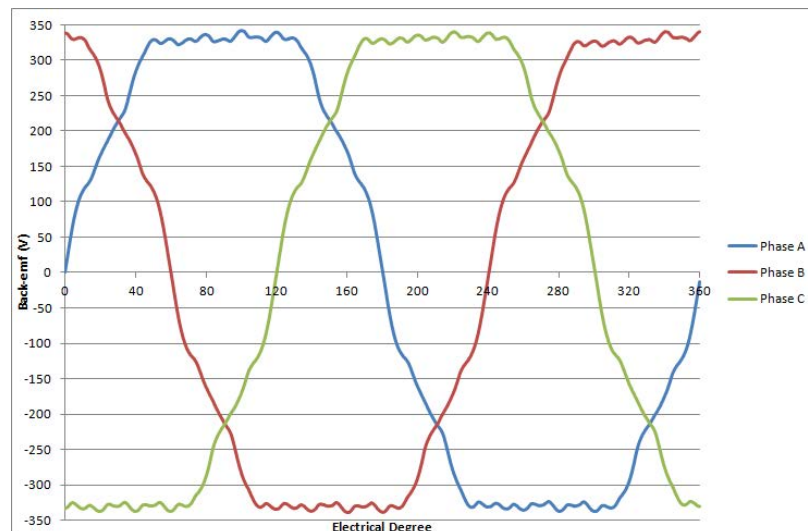


Figure 6.1: Measured 3-phase back-emf waveform

The three phases are 120° out of phase with respect to each other with the peak voltage value at 341.98 V. Figure 6.2 compares the measured back-emf waveform against the ANSYS Maxwell[®] simulation waveform. From the figure it is clear that the actual and simulated waveform is similar in terms of shape and period. However the peak measured value is $\pm 18\%$ less than the simulated value of 419.91 V. The difference between the rated voltage and the actual back-emf value is 64% whereas the simulated is only 80%. The ratio between the rated and back-emf voltage is critical for torque production at synchronous speed. The closer to 100% the ratio is the higher the synchronous torque will be. The simulated value is at the lower ends of the acceptable value and the actual value is far below the required ratio value. The difference in peak back-emf value will be discussed at the end of Chapter 6 as well as the effect it has on the machine's operation.

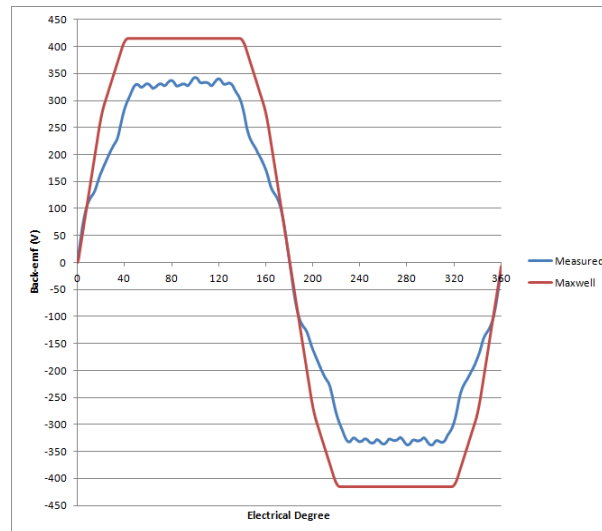


Figure 6.2: Measured back-emf waveform vs. simulated waveform

6.6.1 Investigation of skewing on the Back-emf waveform

During the back-emf wave measurement it was decided to investigate the effects of incorporating skewing in the machine design. The WQuattro LS PMSM range of Weg uses a un-skewed IM stator. As it is difficult to skew the rotor bars and PMs the WQuattro does not incorporate skewing in the design.

Figure 6.3 shows the back-emf waveform of the prototype machine along with the WQuattro's back-emf waveform. The WQuattro's back-emf was extracted in the same way as the prototype. The WQuattro used is a 2.2 kW 380/200 V machine. The 7.5kW 525 V WQuattro machine could not be used due to physical test setup limitations. The focus of the comparison is the effect of incorporating skewing in the machine design and not the actual waveform. Figure 6.3 contains the back-emf waveforms and Figure 6.4 the normalized waveform.

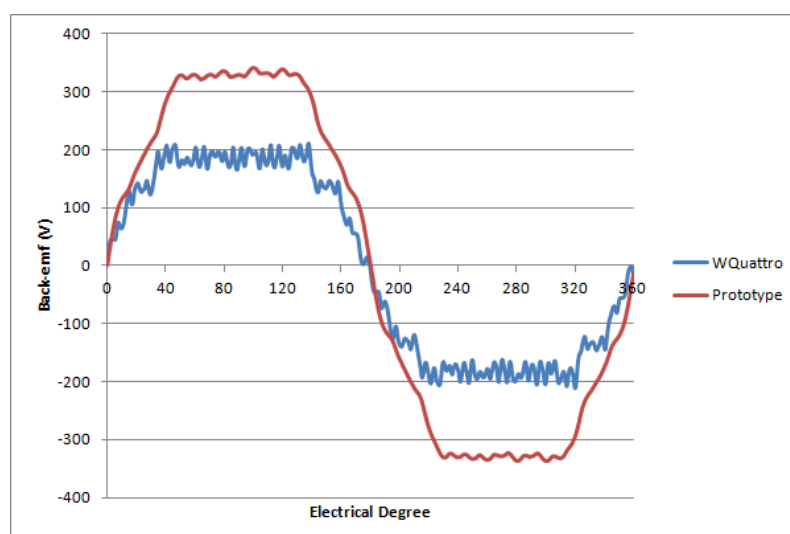


Figure 6.3: Back-emf waveform with and without skewing

In Figure 6.4 it is clear that the prototype machine with its skewed stator provided a much smoother wave with a lot less noise ripple on the induced voltage waveform. The constant change in voltage on the WQuattro wave can be accredited to the PM that wants to align with the stator teeth that introduces a higher reluctance component. This can also be seen if the rotor is spun by and released to come to standstill. The free rotation has a lot of cogging and has dedicated positions at which it wants to be in rest. This is not the case with the prototype machine. The free hand rotation is very smooth and has no preference rest position.

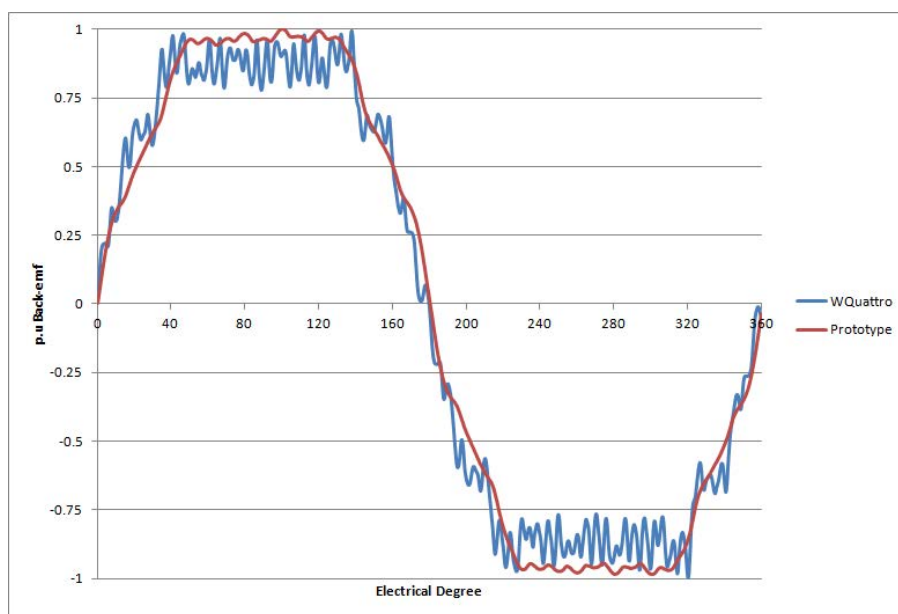


Figure 6.4: Normalized back-emf waveforms of Figure 6.3

During no-load operation and back-emf extraction the vibration level of the WQuattro machine was noticeably higher than the prototype machine. This could also be due to the un-skewed machine. It must be noted that no formal vibration test was done on either machines and this is only an observation made during the tests.

6.7 Comparison of the prototype vs. WQuattro

As part of the testing phase of the project a 7.5kW 525V WQuattro machine was also subjected to the no-load and full load test to compare the prototype's performance against a commercially available machine. Although the prototype machine did not perform as expected under load the no-load comparison can still be done. Table 6.10 contains the no-load test data and parameters that have been calculated using the method in [3].

The prototype compared well with the WQuattro in terms of the line current, core resistance and magnetising inductance. All three of these values are within 10 % of the WQuattro's values. Both the

input power and the iron core losses are lower for the prototype. The lower core losses can be due to the lower stator lamination volume of the prototype.

Table 6.10: No-load comparison of prototype vs. WQuattro

	Prototype	WQuattro
V_{line}	525 V	525 V
I_{line}	3.67 A	3.55 A
P_{in}	190 W	230 W
Power factor	0.07	0.08
Speed	1500 r/min	1500 r/min
P_{iron}	144 W	187.6 W
R_{iron}	16.06 Ω	14.88 Ω
Calculated Power Factor	0.057	0.071
X_m	247.371 Ω	255.49 Ω

The full load test data of the WQuattro connected in delta is listed in Table 6.11.

Table 6.11: WQuattro full load test data

	WQuattro
V_{line}	525 V
I_{line}	10.7 A
Active input power	8.7 kW
Reactive output power	7.5 kW
Power Factor	0.87
Torque	50.4 N.m

6.8 Machine performance conclusion

From the test results it is clear that there are several differences in the calculated and actual performance values. However focus is placed on the test results that correlate with the calculated values.

Although the stator winding configuration is not the same as the design, the design method proved to provide accurate stator resistance and impedance values thus validating the stator design method. The no-load test results also correlated well to the calculated values and as a result can be used to determine the magnetising inductance, no-load pf. However more investigation is needed to determine if the core resistance and loss determined from the test is an accurate representation of these values. Alternative methods in calculating these parameters during the machine phase must also be investigated and the effects that the PMs have on the results. The synchronization capability of the rotor during no-load test was also successfully verified using both the line-start and variable voltage starting techniques.

From the load test it is clear that the prototype did not perform as predicted in Chapter 5. This can be contributed mainly to two factors: one of which is demagnetisation of the PMs in the rotor due to the high temperature it was exposed to during manufacturing; the other is an increased or inconsistent air gap. The possibility of the two claims became relevant once the back-emf was measured. As stated in Section 6.6, the measured back-emf waveform is an accurate representation of the simulated waveform in both shape and period. The difference in peak value suggests that the flux produced by the PM is lower than expected and/or the air gap is larger than the designed value (0.5 mm).

The synchronous torque production of an LS PMSM is dependent on RMS back-emf, X_d and X_q value. Since the peak value is lower the RMS value will also be lower. If the synchronous torque equation, Equation 2.11, is inspected it can be seen that the torque are directly proportional to the back-emf and indirectly proportional to the inductance. Both X_d and X_q is indirectly proportional to the air gap length. Thus an increase in air gap length, decrease the inductance and the back-emf.

$$T_{syn} = \frac{m}{\omega} \left[\frac{V_{ph} E_0}{X_d} \sin \delta + \frac{V_{ph}^2}{2} \left(\frac{1}{X_q} - \frac{1}{X_d} \right) \sin(2\delta) \right] \quad (2.11)$$

The 33H grade PMs used in the rotor has a maximum operation temperature of 120 °C. If this temperature is exceeded, the magnet is demagnetised. The demagnetization effects are dependent on the temperature and the time it was exposed to it. If temperature rises above ±350 °C the effects are permanent. The damage due to the high temperature exposure is reduced flux production of the magnet. Partial demagnetisation is also possible as the entire magnet may not be exposed to the same temperature.

When the end rings were welded into place, the rotor laminations were exposed to very high temperatures caused by the welder. As the PM is situated inside the lamination stack they too were exposed to this temperature. The stack was left to cool naturally thus increasing the heat exposure of the magnets. The actual temperature the stack was exposed to is uncertain and the negative affect it had on the magnets needs further investigation.

In conclusion, although attempts were made to test the machine by changing the machine connection from delta to star to test the prototype, this cannot be seen as viable solution and no formal conclusion can be made regarding the machine's performance as a whole and the design methodology followed. It was however possible to formulate conclusions on individual components such as the stator design method and the verification and validation thereof.

In this chapter the prototype was subjected to a number of tests to determine the performance as well as the machine parameters. The prototype performed well at no-load and synchronized with the stator when

line-started. However the machine's load capabilities were very limited and further investigation into the reason why the developed torque was so low was also done. It was found that the locked rotor test done on IM usually could not provided accurate rotor parameter data thus other methods must be investigated. The back-emf waveform shape and phase compared well to the simulated waveform however, the maximum value was lower than the simulation results and requires further investigation.