

Chapter 7 – Conclusion and Recommendations

The chapter contains the conclusion regarding the design and performance of the prototype, recommendations and areas that need further investigation and unresolved issues. Possible future work is also discussed.

7.1 Conclusions

The goal of this project was to design and manufacture an LS PMSM prototype to gain a better understanding in the operation and implementation of this machine type and to provide a foundation for future research. This section provides a conclusion with regards to the design, manufacturing and machine performance.

7.1.1 Machine design

The first step in the design was to determine the active machine length and rotor diameter. This was done by combining the minimum and maximum tangential stress boundaries for an IM and PMSM found in the literature. As the LS PMSM mainly operated as a PMSM once synchronised, a shorter and smaller rotor was selected than an IM of similar specifications.

Once the main machine dimensions were determined the stator was designed. The stator design consists of the winding configuration, slot shape design and verification of the design. It was decided to skew the stator instead of the rotor to eliminate slot harmonics, reduce cogging torque and machine vibrations. In Section 6.6.1 the difference in a skewed machine vs. un-skewed machine's back-emf waveform is provided. From the figures in this section there is a noticeable difference in the voltage ripple of the induced voltage waveform. As skewing influence the torque ripple of a machine the effects and advantages of incorporating it in an LS PMSM machine still need to be further investigated. The back-emf waveform however provides additional insight into the effects of skewing.

As part of the winding configuration a short pitched double layer design was selected. This reduces the amount of copper used in the stator winding as the end windings become shorter thus also reducing conductive losses. The double layer configuration that was selected in the design differs from the manufactured stator. The manufactured stator placed two full coil sets ($2N_s$) in a single slot which is short pitched by one slot. The design however uses a single coil (N_s) that is divided into two half coil sets. The half coil set is then short pitched and as a result the number of turns per slot stays the same but there may be two different phases in a slot. The differences in the required slot size of the manufactured stator and designed stator is that the designed stator slot can be smaller thus lowering the flux density in the stator. Although the stator winding layout differs from the design, the shape of measured back-emf waveform correlates with that of the predicted waveform in Chapter 4 when normalized. This proves that only the

amount of turns differs and not the layout of the windings. The true effects of the designed winding layout can only be investigated once the stator is correctly wound.

The rotor design can be divided into two separate designs that were combined to form the LS PMSM. The two designs were completed individually but designed with the other in mind. The PMSM rotor was designed first as PM influenced the LS PMSM rotor negatively by developing a braking torque which is the highest at low rotational speed. The IM cage must be designed to overcome the braking torque. The braking torque of an LS PMSM is influenced by the induced back-emf, direct and quadrature inductances. All three of these components are greatly dependent on the PMSM rotor topology. The possible topologies for an LS PMSM are only limited by the incorporation of the IM cage in the rotor. For the prototype it was decided to only investigate the four most commonly used configurations and as a result the ICFM was selected. It provided the highest amount of air gap flux density with the lowest possible PM volume. The ICFM topology has significant leakage flux inside the rotor which was reduced by manufacturing the rotor shaft from stainless steel as it is a non-magnetic metal. The PMSM rotor is a salient pole machine due to the magnets inside the rotor which added a reluctance torque component to the magnetic torque. The selected topology forced the maximum torque to be produced at a torque angle greater than 90° whereas other salient pole topologies usually produce maximum torque below 90° .

The IM cage was designed to produce the breakdown torque between $s = 0$ and $s = 0.25$ of the transient period and that the starting torque is adequate to start a fan load. The slot shape possibilities for the rotor were limited by the cage manufacturing processes. The bars for the cage to be slid into the rotor slots, either a round or rectangular slot is the best option from a manufacturing point of view. The rotor slot was designed to have a very low leakage flux component thus increasing the torque production of the machine. A higher rotor bar current density was selected since the current is only induced during the transient period of the machine. This resulted in a lower required slot area. It was decided to use round bars as they are easier to manufacture.

The final step in the rotor design was to combine the IM and PMSM designs to form the LS PMSM rotor. Next the machine's performance was evaluated. The torque profile was compiled incorporating the influence that the skin effect has on the rotor parameters. One area of the machine's performance that requires investigation is the transient modelling to acquire the behaviour of different components like the current, actual torque production setting time and load synchronization capabilities. To do this a transient mathematical machine model is needed.

Since the stator of the prototype differs from the design further investigation into the design process is needed.

7.1.2 Manufacturing

The LSPMSM stator was manufactured using the same techniques used as for IMs and even though it was skewed by one slot the assembly of the lamination stack posed no added complication. The stator was also wound in the same manner as an IM and had no added complication. The only difference between a skewed and un-skewed stator with respect to manufacturing is that a skewed stator must be welded on the outside instead of using cleats to keep the stack together.

The rotor topology along with the cage design eliminated the option of inserting the magnets after the end rings were welded into place. This is because the end ring covered part of the magnets slot. The magnet slot size selected was too small making it nearly impossible to slide the magnets into the assembled stack. When the end rings were welded into place the PMs were exposed to heat generated by the welding.

After the testing initial testing was done the machine was disassembled and both the rotor and stator were inspected for any damages due to operation. No faults were found and the machine was reassembled. After several demonstrations the machine was reopened and there were clear indications of damages on the rotor. Several welding fractures were visible on the end rings where the rotor bar meets the outer surface of the ring. This can be due to the high temperature generated by the induced currents in conjunction with weld that were weakened when the rotor was machined down as the excess material on the end rings was also machined away. This is a clear indication that the other manufacturing techniques and rotor cage material need investigation.

As the simulation results for the design correlated to the WQuattro's performance one can assume that the PM performance was affected by the heat during the manufacturing. However further investigation into this is needed. Other manufacturing techniques should be investigated.

7.1.3 Machine performance

The prototype machine performed well under no-load conditions when connected in delta. It synchronized well with the stator field and the calculated no-load parameters are within 10 % of the measured parameters. The no-load performance of the prototype is also similar to the WQuattro machine. However the transient performance of the machine with regards to settling time and line current profile still needs to be investigated. Furthermore the machine could only be connected in delta due to the manufacturing error with the winding configuration thus no conclusion can be made regarding the no-load performance in star connection.

The back-emf waveform of the prototype provided valuable information regarding the PMs in the rotor and the air gap length. Since the normalized waveforms of both the simulated and measured machine are similar it is possible that the PMs were partly demagnetised due to the high temperature when the end

rings were welded into place. The difference in the back-emf can also be due to differences in the designed and manufactured air gap. The rotor lamination's outer diameter was manufactured to size and once the stack rotor was assembled the rotor did not fit freely inside the stator. The rotor was machined down to fit which increased the air gap. To determine the exact cause of the decrease in induced voltage further investigation is needed. The possibility also exists that the inside diameter of the stator stack is not consistent.

As a result of the lower back-emf, the torque production is also affected. Similar to a PMSM, an LS PMSM is depended on the back-emf for torque production. The literature states that the back-emf should be between 0.8 and 1.1 p.u to the rated voltage for the machine to develop adequate torque. The measured back-emf is only 0.64 p.u. and as a result a lower maximum torque production is expected at synchronous speed. This was also confirmed by the pull out load test.

As the actual and simulated back-emf differs too much it is difficult to provide an accurate conclusion regarding the PM sizing technique used and whether the PM volume that was added to accommodate for the leakage flux in the rotor was enough. The possibility also exists that the magnet was undersized and as a result also reduced the back-emf. However both FEM packages used provided similar results regarding the back-emf (which was within the range of 0.8 to 1.1). The comparison between the normalized back-emf waveforms from Maxwell and the actual waveform is very similar thus even if the magnets was undersized this cannot be seen as the main cause of the lower back-emf but it can still be include in one of the causes.

To determine the rotor parameters the locked rotor test was performed on the prototype. From the results it became clear that this test can't be used to determine the rotor parameters. The cause of this still needs further investigation as well as other test techniques.

7.2 Recommendations

In this section the recommendation regarding certain aspects of the project is made with respect to future work on the prototype and related research. The aspects that require further investigation on the prototype are also discussed and possible solutions are formulated.

7.2.1 Stator winding

One of the main problems of the prototype was the incorrect wiring of the stator. This made the validation of the prototype design difficult. The winding configuration also limited the connection type to delta whereas with the designed stator the machine would have been able to operate in both delta and star connection. Thus it is recommended that before any attempt is made to solve the machine's performance limitation the stator must be rewound according to the design specifications as provided in Chapters 3 and

5. The machine must then be retested and the results compared to the predicted results as well as the current test data.

Once the correct machine has been tested and the predicted results are not within the acceptable margin the next step would be to measure the dimensions of the machine to determine whether the suggested causes in Chapter 6 are the actual cause.

7.2.2 Rotor manufacturing technique

Although the design and design process could not be properly validated the verified machine simulations suggested that the machine would have performed as predicted with the manufactured stator. From the back-emf measurements it became clear that either the magnets were damaged during manufacturing due to heat exposure and/or the air gap was larger than the specified value due to the machining of the rotor. Manufacturing is to blame in both cases.

To determine if the air gap is larger than it should be the rotor and stator dimensions must be measured in several axial and radial positions. This will also determine if the air gap is consistent over the length of the machine. If it is found that the air gap is larger, one solution would be to replace the PM in the rotor with a higher B_r value. This would be difficult to do as the end rings cover part of the magnet slot.

For future designs the outer diameter of the rotor laminations must be increased by at least two to three times the air gap length. This will provide enough added material to ensure that the rotor can be machined down to the designed air gap.

To ensure that the PM is not exposed to the heat during the welding process the magnets must be inserted after the end rings are welded into place. To ensure this is possible the magnet slot tolerance is selected to provide a sliding fit and that the end rings do not cover parts of the slot. If the end ring covers the slot opening the end ring must be designed so it is possible for the magnets to be slid into place. This however is machine design dependent and whether it is possible requires further investigation.

7.2.3 Testing method

During the project it became clear that there are still some areas with regards to testing of LS PMSM that need to be addressed and investigated. It is recommended that the testing method applicable to LS PMS machine is investigated as well as how results must be interpreted. Standards regarding settling time and the influence of load disturbances on the machine must also be investigated. Once all the relevant information is acquired a test document must be compiled to form as a machine performance guide.

7.2.4 Design techniques

The focus of the design for the project was mainly placed on the steady state behaviour. To gain a better understanding of an LS PMSM's behaviour and the interaction of the machine with the electrical network more focus must be placed on the transient behaviour of these machines. This can be done by compiling a transient model for an LS PMSM. However during the project it was found that the transient model is dependent on the machine's topology thus it is recommended that a method for compiling a model should be investigated.

The transient performance along with the steady state performance can be used to design a more efficient and stable machine. This information can also be used to investigate the effects of using LS PMSM's in an electric network as these machines are predominately used as IM replacements.

It was clear during the investigation of the predicted machine performance (Chapter 4) that the skin effect influence must be included during the design as it has a notable influence on parameters that influences the starting torque and transient operation of the machine. In Chapter 4 the skin effect influence was kept constant as the rotor speed increased however the skin effect is a function of the rotor frequency, thus as the rotor speeds up the rotor frequency decrease from 50 Hz to zero and this in turn reduces the influence of the skin effect. This can also be the reason why the simulation results differ from analytical determined torque curve that incorporates the influence of skin effect.

7.3 Possible future work

This section contains areas that were identified during the course of the project as possible future projects on LS PMSM technologies.

7.3.1 Design techniques for rotor skewing

During the tests done on the prototype and WQuattro machines it became clear that incorporating skewing in the machine design has advantages. The extend of the effect of incorporating skewing in the machine still needs further investigation but also the technique used to incorporate it. The impact of not incorporating skewing in an LS PMSM machine must also be investigated.

If a machine is designed from scratch as with this project, the solution is simple as the stator can be skewed. However if a completed machine stator is used and a retrofit design is done the solution is not that simple as stated in Chapter 5. Possible studies that can be done are:

- Is there a need to skew the rotor cage since it is only used for a short period during transient operation?

- Is it possible to skew PMs by incorporating a segmented step between the two rotor segments and what is needed to do it?
- Can the IM cage be replaced by an aluminium or copper sleeve for an LS PMSM?

7.3.2 Braking torque reduction techniques.

One of the biggest drawbacks of the LS PMSM machine is its limited load synchronisation capabilities. This is due to the braking torque that reduces the starting torque of the machine. This limits the application possibilities of the machine as the machine is more suited to drive higher loads at rated speed than it is capable of line starting. If a design technique or method is developed to overcome this, the installation of these machines can become more popular for applications other than pump or fan type loads.

Various research has been done on addressing the braking torque developed during starting by means of stator winding configuration or incorporating a mechanical device in the machine to hinder the development. However there is limited information regarding a rotor design method that can be used to provide better transient torque production or limiting the negative effects of braking torque.

7.3.3 Mathematic and dynamic model of LS PMSM

One of the biggest areas of interest and concerns shown by the industry is the availability of a machine model that can be used in electric network simulation packages. Depending on the application and the users need, one of two models is needed: a mathematical model or a dynamic behaviour model. Both these models can be used to simulate real-time effects that the machine can experience. The dynamic model is used to determine the behaviour of a machine over a period of time and is able to simulate certain occurrences to see how the machine would react. These models can also help the designer investigate and simulate the performance of the machine before it is manufactured. Currently the majority mathematical and FEM package only include a IM and PMSM machine model.

7.3.4 LS PMSM machine dimension sizing

During the early design phase of this project one of the biggest problems was to determine the main sizing dimensions (active length and rotor diameter) of the machine. It was not clear whether an LS PMSM could be sized as a PMSM or a synchronous machine with a damper cage. This was also not clear when the WQuattro was disassembled as this machine used the same stator as its W22 IM counterpart. This was confirmed by the winding layout document obtained from Weg. Thus the question still stands: how does the designer determine the main sizing dimensions of an LS PMSM if a retro fit design is not used?



In the chapter the conclusion regarding the performance, design methodology and manufacturing techniques on the prototype was made. Recommendations with regards to future work on the prototype were discussed along with other relevant research areas that need to be addressed.