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OPTIMIZATION OF THE OPERATION BEHAVIOUR OF A PERMANENT MAGNET EXCITED TRANSVERSE FLUX MOTOR FOR DIRECT SERVO-DRIVE APPLICATIONS

Uwe Werner
University of Applied Science Bremerhaven, Laboratory for Electrical Machines
and Devices, An der Karlstadt 8, 27568 Bremerhaven, Germany
e-mail: uwerner@hs-bremerhaven.de

Abstract: This paper presents a control based upon optimised current waveforms with switching on current harmonics to achieve an accurate position and speed control with reduced ripples in torque shape for a transverse flux motor. The approaches are verified by measured results at a two phase prototype of a magnet exicited transverse flux motor.

Keywords: adjustable speed drive, servo-drive, permanent magnet motor, transverse flux motor.

1. INTRODUCTION

For some years, there has been a strong trend towards drive solutions with direct drives. Direct drives are often realised with high torque motors which, as a rule, represent the slowly running machines. They reach very high torques at low speed. Consequently, the gear can be saved; it increases the complete degree of efficiency and the dynamic properties of the drive system. The aim of this technology is to increase the torque density ($\mathrm{Nm/m^2}$) or also the weight bounded torque density (Nm/kg) depending on the load (power, speed). To drive a direct coupled motor-load-system the speed and the position of the direct motor have to be controlled accurately. To realise this accurate control a constant torque of the motor over the whole operation range is needed. This paper presents how the cogging torque of the transverse flux motor (TFM) can be minimized by an optimal current control with switching on current harmonics to reach the required speed and position control.

The fulfilment of the requirements of direct drives in terms of small volume and weight of motors with high torque densities at low speeds plays an important role using the transverse flux technology. This means that a transverse flux machine with the same power rating is reduced in size and weight compared to conventional machines. An additional advantage of transverse flux machines is their higher efficiency. At present, the force densities of normal asynchronous motors can achieve up to 20–30 kN/m². Water-cooled and force density optimized high-performance machines can reach 65 kN/m² and for a short time even up to 80 kN/m². The norm for the synchronous machines complies with 40–60 kN/m². Transverse flux reluctance machines can achieve up to 60 kN/m² and the water-cooled permanent magnet transverse flux machine yields more than 200 kN/m².

Besides the described advantages there are a few disadvantages of transverse flux machines. These are the ripples in the torque shape, the normal force fluctuation, the low power factor and the complex core design. The torque ripples and normal force fluctuation produce noise and vibrations. There are some kinds of solutions to reduce the torque ripples and the normal force fluctuation. One of them is modifying the geometry for the magnetic path or to use learning control methods to reduce the torque ripples.

Furthermore, an appropriate current waveform based on model calculated algorithms can be applied to the machine. In this paper innovative methods are introduced in which a constant torque can be produced by optimised current waveforms in a two-phase permanent magnet excited transverse flux machine (prototype data in Table 1).

2. THE TRANSVERSE FLUX MOTOR

Transverse flux motors represent one of the topologies of the electrical machines with high force densities. The form of this electrical machine represents an essential innovation in the use of direct drives. The fulfilment of the requirements in terms of small volume and weight of motors with high torque densities at low speeds plays an important role.

The concept of transverse flux machines was developed at the beginning of the 20th century. But due to a lack of appropriate electronic devices and converters the practical use of these types of machines started only many decades later.

In the 80ies Prof. Weh from the Technical University of Brunswick, as one of the pioneers in this field, has developed new types of machines based on the transverse flux principle. These machines were used as uncontrolled traction force drives. The availability of intelligent power converters today allows extending the use of transverse flux machines for applications where the control of speed and energy fluctuation is required.

A typical feature of transverse flux machines is the magnetic flux path which has sections where the flux is transverse to the rotation plane and the ring-shaped winding in the stator in which the direction of the current corresponds with the movement direction of the rotor. Fig. 1 shows a classical structure of one phase of a TFM with magnets situated in the rotor.

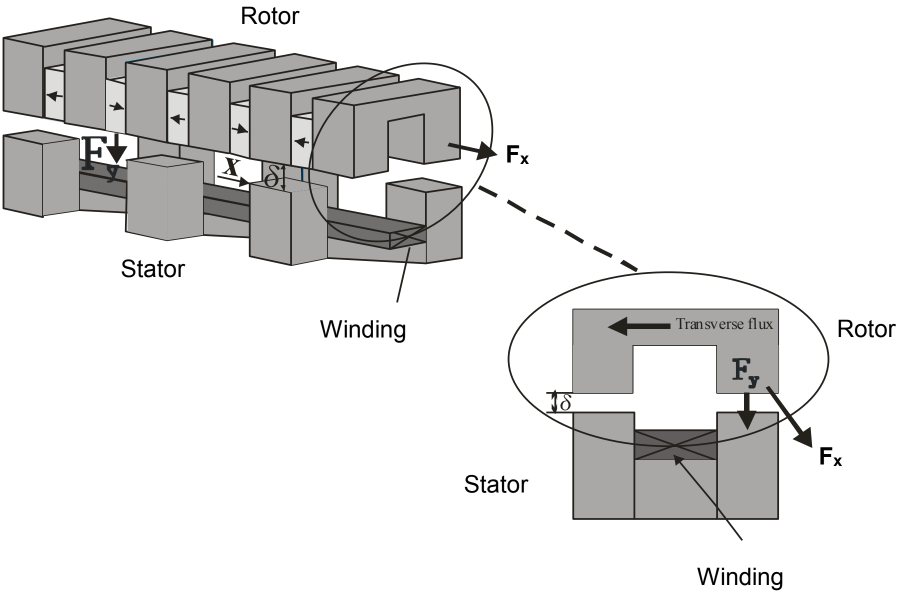

Fig. 1. Structure of a permanent magnet excited TFM with flux concentrating configuration

The stator is composed of several C-shape cores which are connected together and incorporate the stator winding. Permanent magnets are mounted in the moving part of the machine. The permanent magnet arrangement is in a so called flux concentrating design where the direction of the magnetization corresponds to the direction of the movement. The number of the machine poles is equal to the number of the permanent magnets. One pole pitch τ is the distance between two permanent magnets with opposite polarity.

The transverse flux design has two main advantages:

- independently design of the magnetic and the electrical circuit which leads to realisation of higher torque values by increasing the number of the pole pairs without affecting the electrical circuit parameters;
- absence of end-turns in the stator windings which results in reduced losses.

The innovative design of the flux path combined with the use of new magnet materials lead to very high-performance machines with three to five times higher power densities compared to conventional DC, synchronous and induction machines. This means that a transverse flux machine with the same power rating is reduced in size and weight compared to conventional machines. An additional advantage of transverse flux machines is their higher efficiency. There are two main reasons for this: the reduced copper losses, due to the absence of end-turns in stator winding, and the fact that the magnetic circuit and the electrical circuit do not share the same space.

In general there are three structural concepts for these machines: active rotor machines with permanent magnets on the rotor, passive rotor reluctance transversal machines without any permanent magnets and passive rotor transversal flux machines with permanent magnets on the stator. The rotor can be designed as an internal or an external one. There are single- and multi- phase machines, depending on the number of independent stator windings which are mounted axially on the machine shaft. The structure can also be modified by using up to four tracks which are related to the number of active air gaps [Viorel et al. 2003; Weh 1988; Weh and May 1986; Werner, Schüttler and Orlik 2005].

3. THE PROTOTYPE MOTOR

The prototype machine is a 10 kW two phase permanent magnet excited TFM in flux concentrating configuration with an outer rotor. Fig. 2 shows the prototype during the assembly process. The 74 magnets with an alternating magnetisation orientation have been mounted with the rotor. The maximum torque of the machine is round about 1000 Nm. The nominal speed is in the range of 100 rpm. Parameters of the prototype are listed in the following Table 1. The permanent magnet arrangement has a flux collecting design. The windings in each phase of the machine have 66 turns. The developed air cooled transverse flux motor reach a force density of 117 kN/m^2 or a weight (the whole machine weight) bounded force density of round about 35 N/kg.

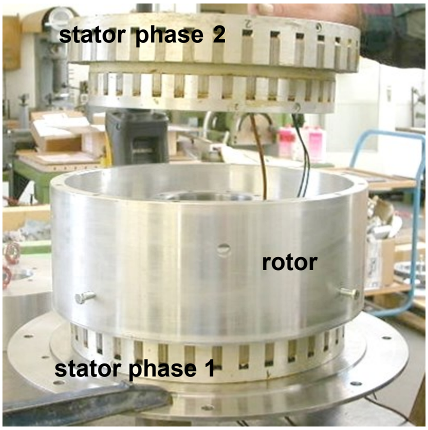

Fig. 2. The two phase TFPM prototype

Table 1. Parameters of the prototype

no. of the rotor poles	74	
no. of phases	2	
no. of windings/phase	66	
pole pitch	13,75	mm
stator teeth width	1,53	mm
air gap	0,9	mm
output power	10	kW
nominal speed	100	rpm
nominal current eff.	26	A
nominal voltage	220	V
maximum torque	1000	Nm
efficiency	92	%
outer diameter	338	mm
stator length	230	mm
total weight	165	kg

4. THE TEST STAND

The prototype has been integrated into a test stand. A block diagram of the test stands component parts is shown in Fig. 3. Basic components of the test stand are the prototype TPFM, the loading drive which is a combination of a DC machine and a gear box, the power converter as well as current, speed and torque measurement devices. The gear has to adjust the load site speed and torque value to the low speed and high torque of the TFPM motor side.

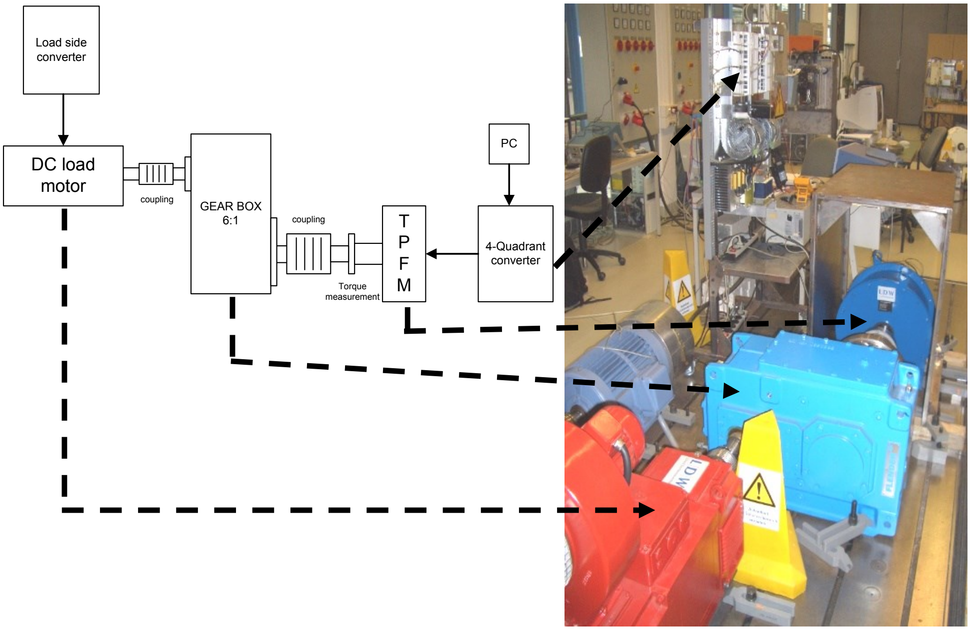

Fig. 3. Overview of the test stand of transverse flux motor

5. THE OPTIMISED CURRENT WAVEFORMS

Based on its principle, the transverse flux motor has forced points of no torque. The distance of these zero points is one pole pitch. Therefore a minimum of two phases has to be used in a permanent magnet excited transverse flux motor to compensate these points of no torque. The torques of those both phases is added together at the shaft of the motor. To get a cogging free torque both phases have to be coupled with a 90 degree shifted current and a special current waveform is needed, too.

How to get those waveforms is described in the following. A very simple and intuitive method [Vinogradski et al. 2004] of minimizing the cogging torque of a TFM with two phases is the trapezoid method. The essential principle of this method is based on generating a trapezoid torque waveform which has a cycle of one pole pitch and which is smaller than the maximal possible torque (Fig. 4).

There is no need to choose a curve with maximum value (as shown in the example). It is possible to use smaller values. By using an analytical model (described in Werner, Vinogradski and Orlik 2004), it is possible to calculate the corresponding current in this phase on each position of the rotor in order to achieve the required torque waveform. The total torque of both phases forms a cogging free curve at the maximum value of the trapezoids.

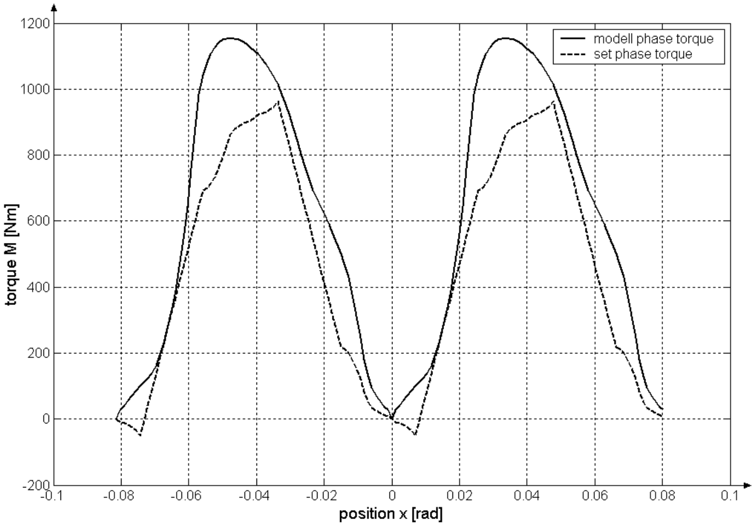

Fig. 4. Trapezoid curve less than maximum torque

The results of Fig. 5 and Fig. 6 can be achieved by application of the modified simple method to the maximal possible torque. It is possible to achieve a cogging-free torque of high level with the modified trapezoid method. The used calculation is very simple and makes it possible to apply this in online operation, e.g. in an error-case shutdown scenario. It does rely on the set of characteristic curves and the correct injection of the winding current.

The corresponding current wave has been computed using the developed analytical model and is shown in Fig. 5. Applying this current wave to a two phase TFM leads to production of a torque shape which is almost free of ripples.

In Fig. 6 the proposed torque wave forms for two phases of the machine and the resulting torque are depicted. Generating the optimal trapezoid torque in the machine requires a supply of the machine with an appropriate current. Depending on the position of the rotor the corresponding current values will be applied to each machine phase.

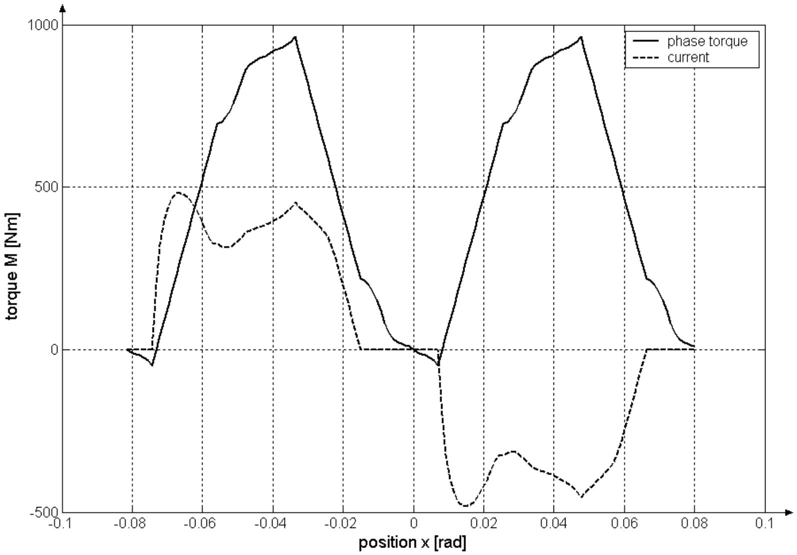

Fig. 5. The proposed modified trapezoid torque and the corresponding current

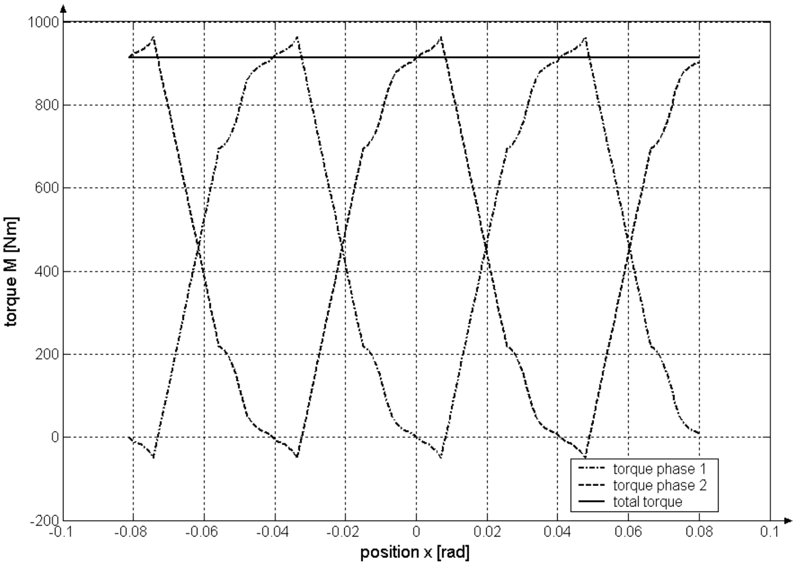

Fig. 6. Resulting minimized cogging torque

6. THE CONTROL STRUCTURE

Direct drive applications require a constant torque and a constant speed over a wide range of operation. For this purpose a closed loop speed and current control structure has been developed. An overview of the control structure has been shown in Fig. 7. With the described offline calculated optimised current waveforms an open loop torque control is realised to generate a minimal cogging torque. The current waveforms are stored into look-up tables in the microcontroller.

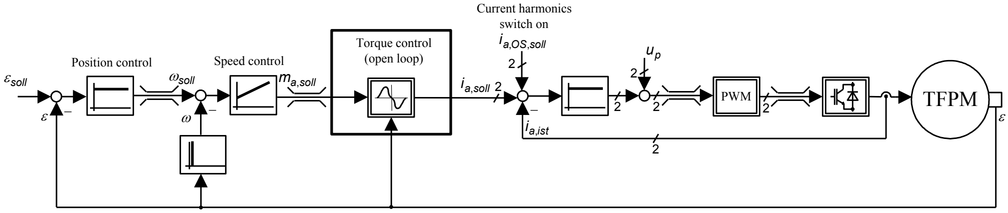

Fig. 7. Overview of the control structure

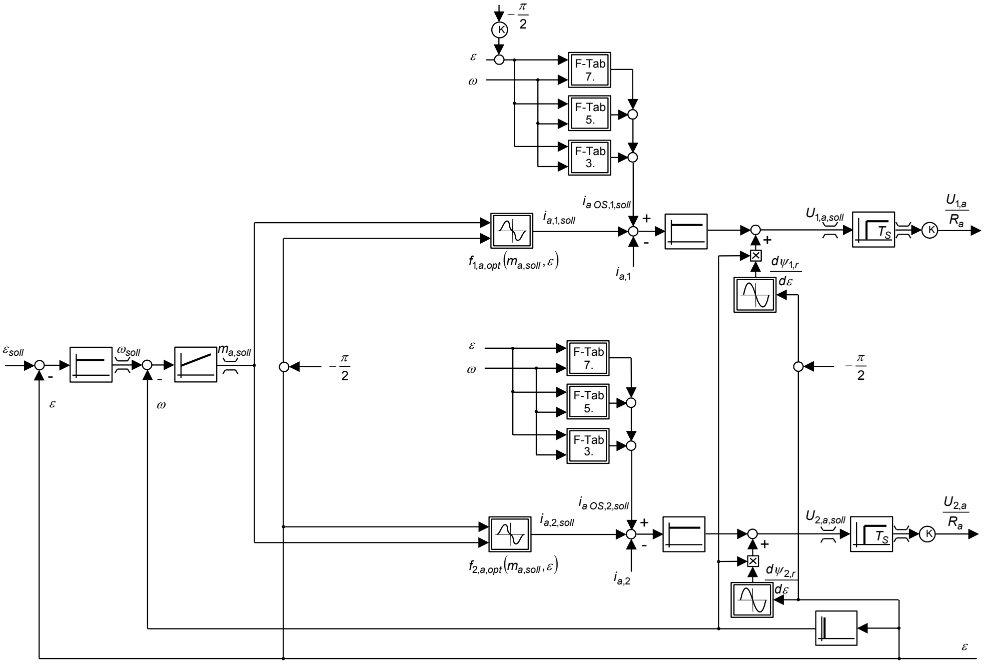

Fig. 8. Detailed control structure with current harmonics switch on

The open loop control unit generates the appropriate current set values depending on the rotor position and the speed controller output for each point within the operation range in order to produce the proposed modified trapezoid torque waves. The analytical model considers only the first harmonics of the time dependent variables. Therefore it is necessary to add the third and higher harmonics of the current waveform in order to improve the control behaviour (Fig. 8).

Fig 8. shows the whole detailed control structure of the TFPM for both machine phases. The current control and the open loop torque control operate independent for each phase shifted 90 degrees electrical between phase one and two. The amplitude of the third to seventh harmonics switch on can be variated by a constant value. The harmonic wave forms are stored into a look-up table, too.

7. MEASUREMENTS AND RESULTS

In this paper an innovative method is introduced in which a constant torque can be produced by optimized current waveforms in a transverse flux machine. The needed control structure (Fig. 8) for a transverse flux motor was implemented in a microcontroller and tested on a test bench (Fig. 3) with a two phase transverse flux motor in flux concentrating configuration. Fig. 9 shows the current and torque waveform without an open loop torque control. The torque deviation in this case is in the range of ±250 Nm. Applying a rectangular current shape into the machine results in an improvement of the torque deviation which will be reduced down to ±125 Nm (Fig. 11). Fig 10 shows the measured stator current for both phases of the transverse flux motor and the measured torque using sinusoidal current (Fig. 11) in the open loop torque control block.

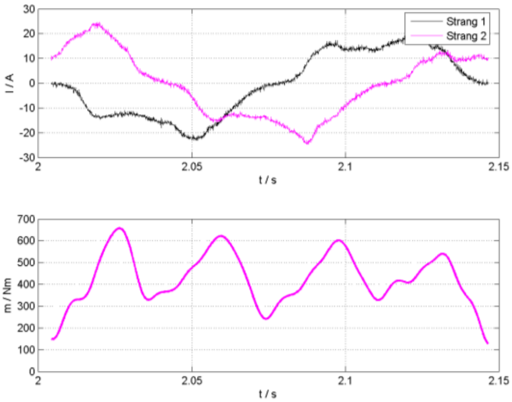

Fig. 9. Torque without open loop control at 420 Nm load

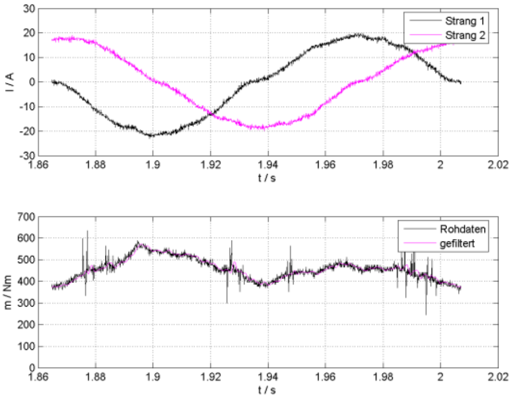

Fig. 10. Torque with sinusoidal current at 420 Nm load

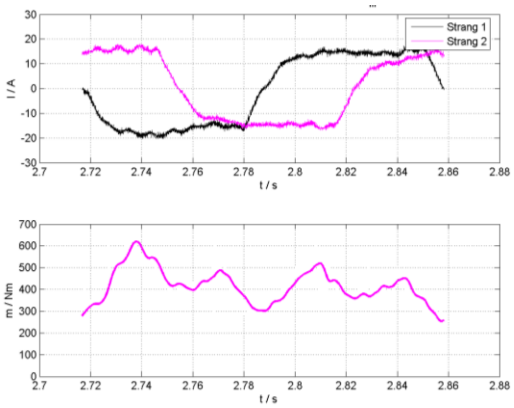

Fig. 11. Torque with rectangular current at 420 Nm load

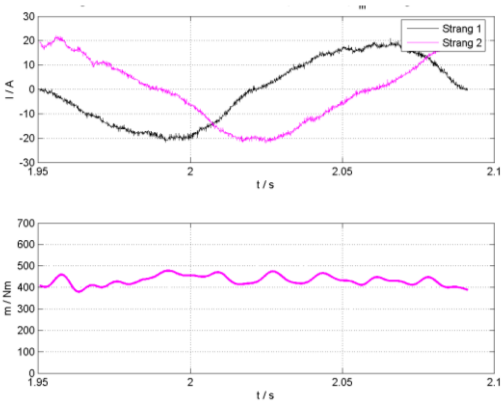

Fig. 12. Torque with optimized current at 420 Nm load

The measurements with the developed current and torque controller show a significant improvement in the shape of the produced torque. As the ripples in the torque shape increase while the speed decreases, measurements at lower speed ranges (11 rpm) have been performed to prove the proposed modified torque waveforms under worst case conditions.

Using the open loop torque control unit for generating modified trapezoid torque shapes with current harmonics switch on results in significant reduction of the ripples in the torque shape. Fig. 12 shows that the torque deviation in this case is in the range of ±50 Nm. Using this control strategy further reduction of the ripples can be observed for higher speed values where the ripples are almost 2% of the nominal torque.

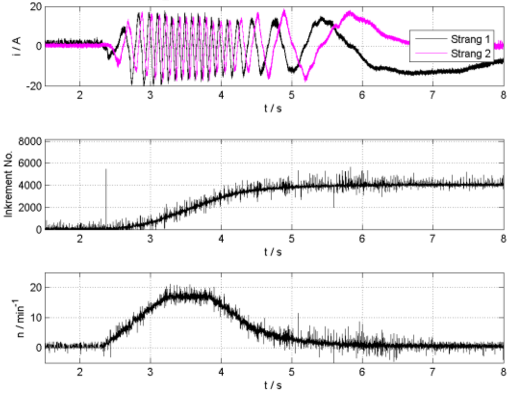

Fig. 12. Position control from 0 to 175 degree angle at no load operation

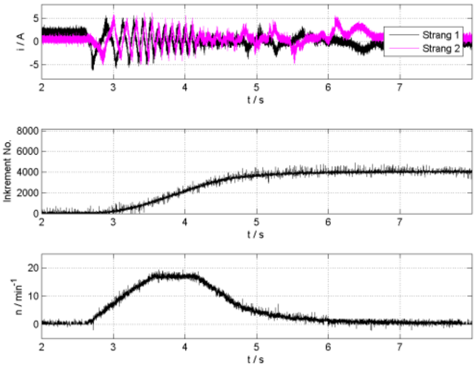

Fig. 13. Position control from 0 to 175 degree angle with 400 Nm load

The described reduction in cogging torque is the basis for an accurate speed and position control. The measured results show the speed and position behaviour and the measured phase currents under no load (Fig. 12) and under load pressure (Fig. 13). The under most plot in Fig. 12 and 13 shows the speed and the middle plot shows the position in increments (1 increment is 0.04 degree). The speed is limited to 18 rpm.

8. CONCLUSION

This paper deals with the control and operation of permanent magnet excited transverse flux machines (TPFMs). A 10 kW TPFM has been designed and manufactured as a prototype machine. Further a control strategy has been developed in order to reduce the ripples in the torque shape. The control method generates modified trapezoid torque waveforms depending on the rotor position applying appropriate current values.

The research works presented in this paper contributes to a solution of two main problems, which are the torque and normal force fluctuations, which to date prevent the use of TFMs in a wide range of applications. The achieved results are promising and show that a wider use of TFMs would be justified.

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