Application of Response Surface Methodology in Torque Ripple Reduction of a Transverse Flux Rotary Motor

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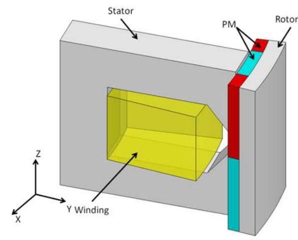
Abstract — **This paper presents a process using response surface methodology (RSM) for torque ripple reduction of three-phase transverse flux rotary motor (TFRM) with surface mounted permanent magnet type of mover. The analysis is based on three-dimensional finite element method (3D FEM). Several variables are chosen to minimize torque ripple under the constraint of getting an acceptable mean torque which is higher than 70Nm. The optimal design is obtained with the use of response surface methodology (RSM). The target is to get torque ripple of lower than 1.5%.**

I. Introduction

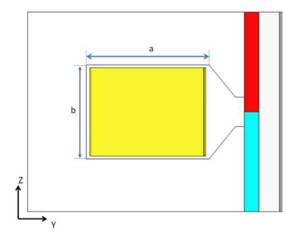
A transverse flux machine (TFM) which was first proposed by Weh and May [1] has been emerging as an excellent candidate and very attractive to industrial applications with high torque density, high power density and high efficiency [2]. However, like any kind of permanent magnet machine, TFM owns a fairly high torque ripple which is caused by fluctuation of the field distribution and the armature magneto-motive force. Generally, torque ripple is caused by contributions from cogging torque, harmonics from pulse width modulation (PWM), non-ideal back EMF waveform…This undesirable effect will result in acoustic noise, vibration and reduce the accuracy of positioning [3] especially with low-speed application like the case of TFM, it becomes a critical concern for designers.

Many efforts and techniques were made in order to reduce torque ripple, ways to minimize torque ripple can be divided into two groups. The first one is controlling for example using complex control concepts; the control of the motor is realized through the application of optimized voltage or current waveform. And the second one is structural design in which suitable arrangements of either stator poles, permanent magnets (PMs) or phases are made to influence torque ripple [4].

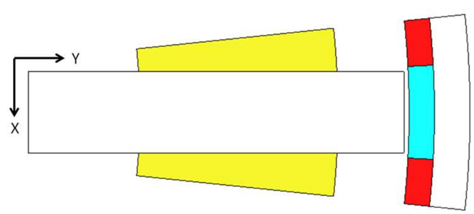
This paper is to use response surface methodology (RSM) focus on torque ripple minimization with structural design for TFM with surface mounted permanent magnet type of mover (SPM TFM) shown in Fig. 1. This type of motor is known to have lower torque ripple in comparison with flux concentrating type of TFM. The process is carried out with the use of response surface methodology (RSM) with two steps: In the first step, several variables are chosen in design of experiment (DoE) to see how important they are in the optimization process - screening step. Second, central composite design (CCD) will be applied to figure out the optimal design with minimum torque ripple (less than 1.5%) and acceptable mean torque which is desired to be higher than 70Nm. All the model computations are derived from using three-dimensional finite element method (3D FEM) with Ansoft Maxwell.



a) 3D modeling



b) Viewed on Y-Z plane



c) Viewed on X-Y plane

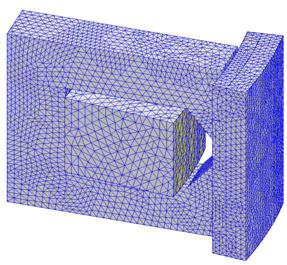
Fig 1. Model for one pole-pair of a phase.

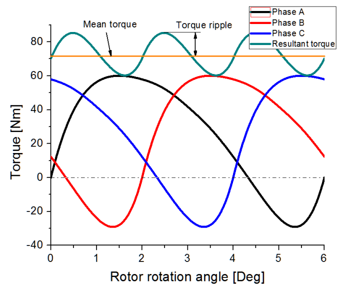
II. Initial Design

In order to approach the given target, in table 1, a somewhat arbitrary model of SPM TFM is designed for the first investigation on torque profile and suggestion of variables needed for the optimization process. One should be noted that because the air-gap flux density distribution is sinusoidal so that a sinusoidal current is required to lower torque ripple. Figure 2 is for result at the initial step with 3D FEM mesh and torque profile. The torque ripple is really big which is 17.21% at the output torque of 72.78Nm.

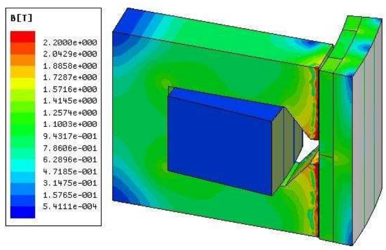
TABLE 1. SPECIFICATION OF THE INITIAL DESIGN.

Parameter	Value
Number of phases	3
Number of coil turns/phase	80
Designed current (rms)	7.8A (Sinusoidal)
Air-gap length	0.5mm
Number of pole pairs	30
Stator tooth width	8mm
Inner stator diameter	83mm
Outer stator diameter	165mm
Outer rotor diameter	185mm
PM height	2.5mm
PM arc	6^0
Material	Rotor & Stator: S23
	PM: Nd-Fe-B, μ_r= 1.05, B_r = 1.2T





a) 3D FEM mesh b) Torque profiles and resultant torque.



c) Flux density distribution.

Fig 2. Result for the initial design.

III. Optimization Process.

In order to minimize torque ripple, several variables which are expected to influence torque generation will be chosen and investigated. Variables are shown in Fig. 3.

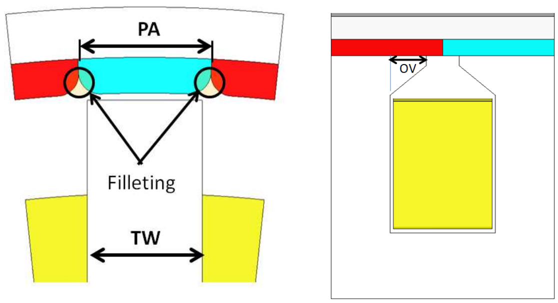


Fig 3. Variables for the minimization process

As shown in Fig. 3, four variables are chosen which are TW (stator tooth width), OV (overhang), PW (PM width) and FR (filleting radius – PMs are rounded at the corners). Design of experiment (DoE) will be performed to investigate effects of variables.

TABLE 2. VARIABLES FOR DoE

Level	FR [mm]	TW[mm]	OV [mm]	PA [Deg]
-1	1	5.5	5.5	5
1	2	8	7.2	6

Based on the result from this DoE, it is found that, overhang (OV) has almost no effect in torque ripple but it increase output torque, so that, OV is set to be maximum as 7.2mm for the next step which is central composite design (CCD) with three other variables (FR, TW and PA). CCD includes 8 full factorial design (for 3 variables), 6 star points with α = 1.68 to make the design rotatable, and 6 center points. Levels for CCD are shown in table 3 and Fig. 4 is for surface plot of torque ripple.

TABLE 3. LEVELS OF VARIABLES IN CCD.

Level	FR [mm]	TW [mm]	PA [Deg]
-α	1.30	6.53	5.0
-1	1.50	6.80	5.2
0	1.80	7.20	5.5
1	2.10	7.60	5.8
α	2.30	7.87	6.0

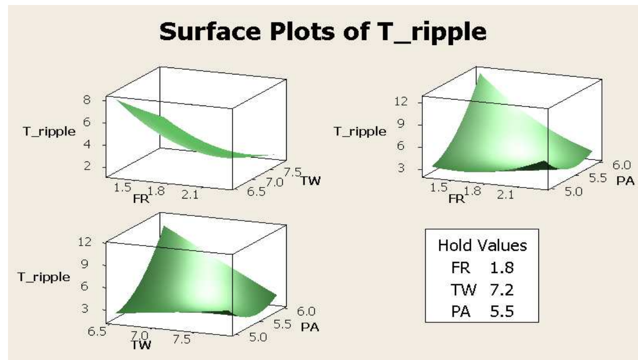


Fig 4. Surface plot of torque ripple for each 3 pair of variables (while another variable is held at center value).

From CCD results, with the aid of Minitab, an optimal design is obtained based on the criterion that output torque is higher than 70Nm and torque ripple should lower than 1.5%. The suggested design offers output torque of 73.15 Nm and torque ripple of 1.37%. By a small modification from this design, the final one got torque ripple of 1.17% at output torque of 72Nm which is satisfied.

IV. Conclusion

An optimization design has been done for the torque ripple minimization of SPM TFM. With the use of response surface methodology, a satisfactory design is obtained with torque ripple of 1.18% and output torque of 72Nm. In the extended paper, the detail process will be explained and experiment results will be added for the verification of accuracy.

V. References

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