METU – EEE

Middle East Technical University – Electrical Electronics Engineering Department

PROJECT REPORT

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within the scope of the course

EE568

SELECTED TOPICS ON ELECTRICAL MACHINES

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Introduction

In this report, we assume have a 20-pole, 120 slot, 3-phase machine for integral slot winding and for 20 or 22 pole number, we choose a slot number between 20 and 30 for fractional slot winding. Integral and fractional slot windings are investigated and designed. Also 2D FEA model of the fractional winding is simulated and analyzed. Winding diagrams are drawn. Distribution factor and pitch factor of the each winding are calculated. Also, 3rd and 5th harmonics winding factors are calculated.

1. Integral Slot Winding Design

We assume we have a 20-pole, 120 slot, 3-phase machine.

q is the slot number per pole per phase:

$$q = \frac{120}{20 \times 3} = 2\ slot/pole.phase$$

α is the electrical angle between two consecutive slot:

$$\alpha = \frac{360^o}{120} \times \frac{20}{2} = 30^o electrical$$

Assume each coil has 1 turns and full pitched. So, winding will be single layer.

slot	1	2	3	4	5	6	7	8	9	10	11	12
winding	A	A	-C	-C	B	B	-A	-A	C	C	-B	-B

Fig. 1: Winding diagram of the given integral slot machine for one pole pair (12 slot)

Winding Factor

Winding factor ($k = k_d \times k_p$) of a winding includes two main parts as known distribution factor (k_d) and pitch factor (k_p).

Distribution factor: $k_d = \frac{\sin\left(q\frac{n\alpha}{2}\right)}{q\sin(\frac{n\alpha}{2})}$ → for 1st fundamental component $k_d = \frac{\sin\left(2\frac{30}{2}\right)}{2\sin(\frac{30}{2})} = 0.96$

Pitch factor: $k_p = \sin\left(\frac{n\lambda}{2}\right)$ → for 1st fundamental component $k_p = \sin\left(\frac{180^o}{2}\right) = 1$

Where n is harmonic order, λ is pitch angle (for full pitch, $\lambda = 180^o$).

Winding factor for 1st fundamental component: $k = k_d \times k_p = 0.96$

3^{rd} and 5^{th} harmonics winding factors

Distribution factor: $k_d = \frac{\sin\left(q\frac{n\alpha}{2}\right)}{q\sin\left(\frac{n\alpha}{2}\right)}$ → for 3rd harmonic component $k_d = \frac{\sin\left(2\frac{3\times 30}{2}\right)}{2\sin\left(\frac{3\times 30}{2}\right)} = 0.7$

Pitch factor: $k_p = \sin\left(\frac{n\lambda}{2}\right)$ → for 3rd harmonic component $k_p = \sin\left(\frac{3\times 180^o}{2}\right) = -1$

Winding factor: $k = k_d \times k_p = -0.7$

Distribution factor: $k_d = \frac{\sin\left(q\frac{n\alpha}{2}\right)}{q\sin\left(\frac{n\alpha}{2}\right)}$ → for 5th harmonic component $k_d = \frac{\sin\left(2\frac{5\times 30}{2}\right)}{2\sin\left(\frac{5\times 30}{2}\right)} = 0.25$

Pitch factor: $k_p = \sin\left(\frac{n\lambda}{2}\right)$ → for 5th harmonic component $k_p = \sin\left(\frac{5\times 180^o}{2}\right) = 1$

Winding factor: $k = k_d \times k_p = 0.25$

As a result of this part, for selected full pitch winding the fundamental component winding factor is obtained as 0.96, 3rd harmonic component is -0.7 and 5th one is 0.25. When we plot the magnetic loading distribution (B):

plot (0.96*sin(x)-0.7*sin(3*x)+0.25*sin(5*x))

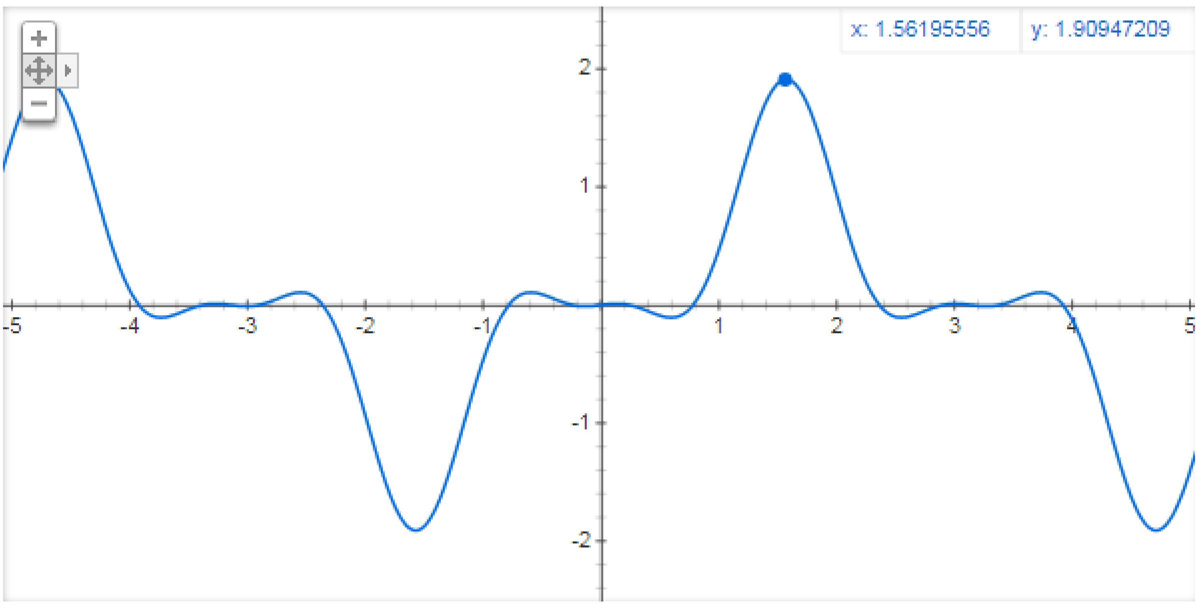

Fig. 2: Magnetic loading B of the selected integral slot winding

As seen from the figure 3rd harmonic negative winding factor causes sharpen the peaks of the total B. This effect creates long width zero crossing and smaller area under the curve that means smaller flux (ϕ) and energy. This type winding design creates nearly 70% 3rd harmonic component so it is inefficient design. Overcome this situation we can use fractional slot that is analyzed in next section.

2. Fractional-Slot Winding Design

In this part, we are going to analyze a 3-phase permanent-magnet synchronous machine with a fractional-slot winding.

1st selection for design: 20 poles, 24 slots

Using the Emetor Winding Design,

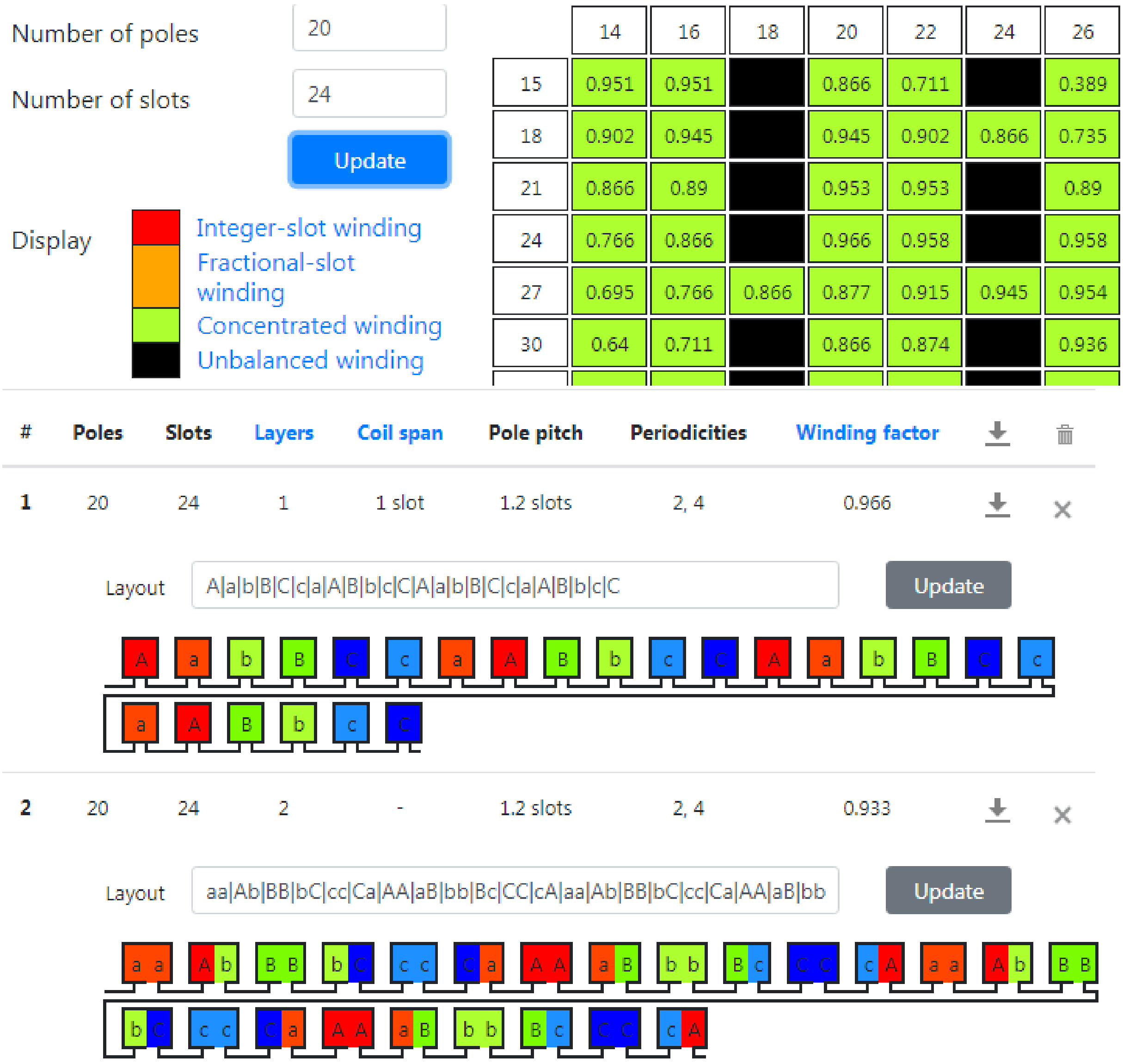

Fig. 3: Emetor Winding Design page, selected pole 20, slot 24 returns 1.2 slots pole pitch (5/6), 0.966 winding factor for 1 layer and 0.933 winding factor for 2 layer concentrated winding

q is the slot number per pole per phase:

$$q = \frac{24}{20 \times 3} = 0.4\ slot/pole.phase$$

α is the electrical angle between two consecutive slot:

$$\alpha = \frac{360^o}{24} \times \frac{20}{2} = 150^o electrical$$

Table 1: phase angle of the induced voltage in each slot

1st slot	2	3	4	5	6	7	8	9	10	11	12
0°	150°	300°	90°	240°	30°	180°	330°	120°	270°	60°	210°

13	14	15	16	17	18	19	20	21	22	23	24th slot
0°	150°	300°	90°	240°	30°	180°	330°	120°	270°	60°	210°

Then the phasor diagram for one phase is drawn by using Dolomites software:

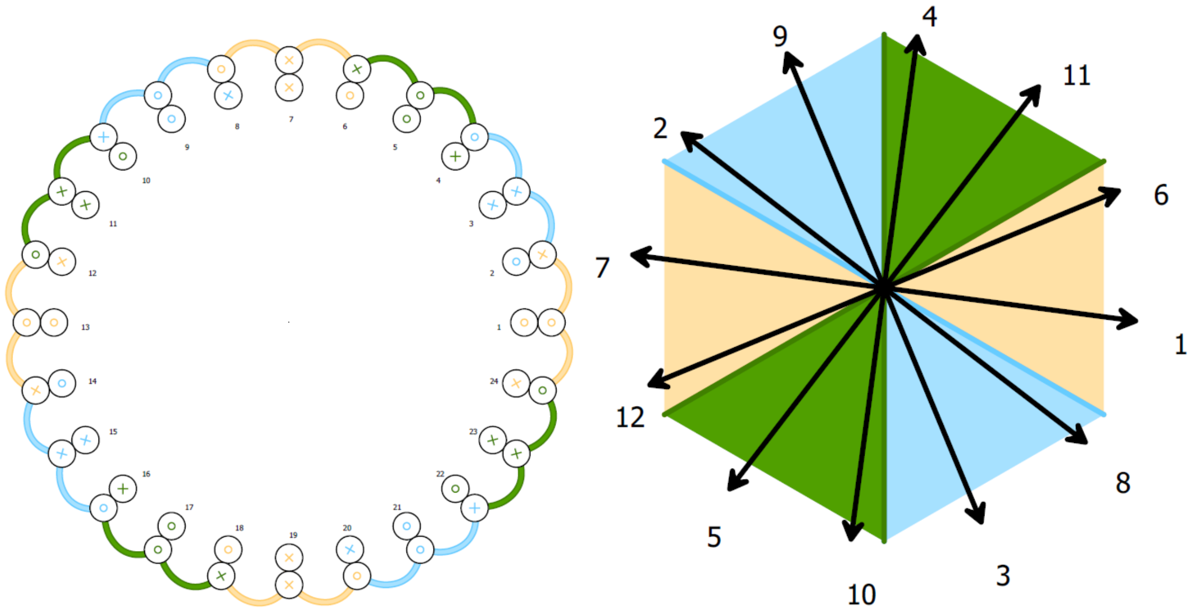

Fig. 4: Phasor diagram of 20 pole, 24 slot, 5/6 pitched winding

Winding Factor

Distribution factor: $k_d = \frac{\sin\left(q\frac{n\alpha}{2}\right)}{q\sin(\frac{n\alpha}{2})}$ → for 1st fundamental component $k_d = \frac{\sin\left(0.4\frac{30}{2}\right)}{0.4sin(\frac{30}{2})} = 1.009^*$

**For reducing the end winding, we can use phasor 1 and 6. In that way $\alpha = 30^o$.*

Pitch factor: $k_p = \sin\left(\frac{n\lambda}{2}\right)$ → for 1st fundamental component $k_p = \sin\left(\frac{150^o}{2}\right) = 0.96$

Where n is harmonic order, λ is pitch angle (for 5/6 pitch, $\lambda = \frac{5}{6} \times 180^o = 150^o$).

Winding factor for 1st fundamental component: $k = k_d \times k_p = 0.97$

3^{rd} and 5^{th} harmonics winding factors

Distribution factor: $k_d = \frac{\sin\left(q\frac{n\alpha}{2}\right)}{q\sin(\frac{n\alpha}{2})}$ → for 3rd harmonic component $k_d = \frac{\sin\left(0.4\frac{3\times30}{2}\right)}{0.4\sin(\frac{3\times30}{2})} = 1.09$

Pitch factor: $k_p = \sin\left(\frac{n\lambda}{2}\right)$ → for 3rd harmonic component $k_p = \sin\left(\frac{3\times150^o}{2}\right) = -0.707$

Winding factor: $k = k_d \times k_p = -0.77$

Distribution factor: $k_d = \frac{\sin\left(q\frac{n\alpha}{2}\right)}{q\sin(\frac{n\alpha}{2})}$ → for 5th harmonic component $k_d = \frac{\sin\left(0.4\frac{5\times30}{2}\right)}{0.4\sin(\frac{5\times30}{2})} = 1.29$

Pitch factor: $k_p = \sin\left(\frac{n\lambda}{2}\right)$ → for 5th harmonic component $k_p = \sin\left(\frac{5\times150^o}{2}\right) = 0.25$

Winding factor: $k = k_d \times k_p = 0.33$

plot (0.97*sin(x)-0.77*sin(3*x)+0.33*sin(5*x))

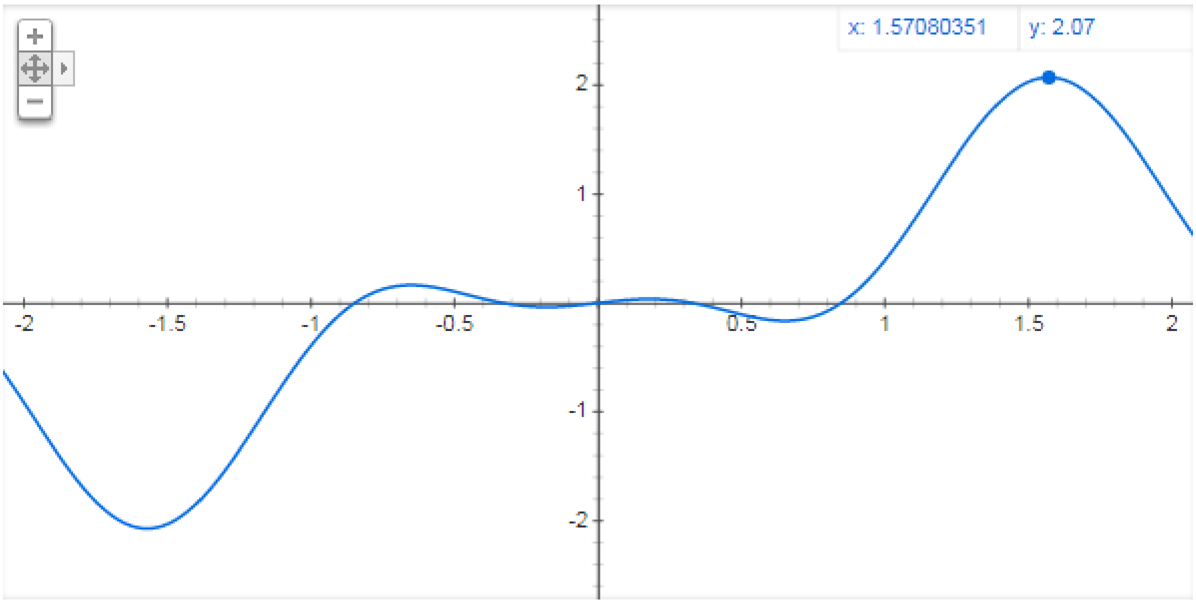

Fig. 5: Magnetic loading B of the selected fractional slot winding

Comments: 0.97 winding factor is obtained from 20 poles, 24 slots winding. It seems enough high for a design but, when we look the 3rd and 5th harmonic winding factors, we can see the 77% of 3rd effect and 33% of 5th harmonic effect. So, the total magnetic loading wave form of this type winding looks like in fig. 5. Because of the 3rd and 5th harmonics, total magnetic loading has not got pure sinusoidal shape and this causes less effective results in frame of harmonic contents.

2^{nd} selection for design: 20 poles, 30 slots

Using the Emetor Winding Design,

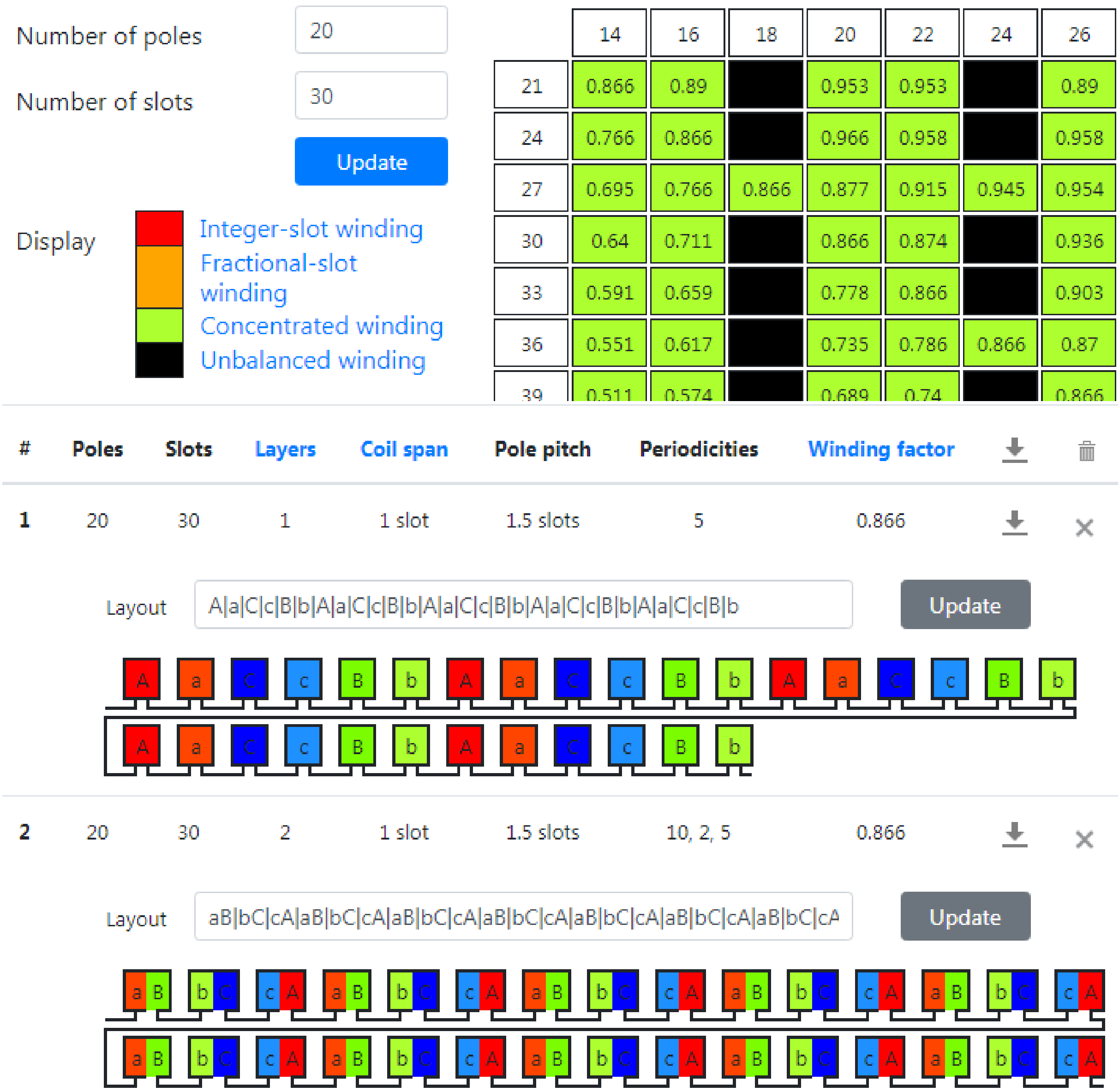

Fig. 6: Emetor Winding Design page, selected pole 20, slot 30 returns 1.5 slots pole pitch (2/3), 0.866 winding factor for 1 layer and 2 layer concentrated winding

q is the slot number per pole per phase:

$$q = \frac{30}{20 \times 3} = 0.5\ slot/pole.phase$$

α is the electrical angle between two consecutive slot:

$$\alpha = \frac{360^o}{30} \times \frac{20}{2} = 120^o electrical$$

Table 2: phase angle of the induced voltage in each slot

1st slot	2	3	4	5	6	7	8	9	10	11	12
0^o	120^o	240^o	0^o	120^o	240^o	0^o	120^o	240^o	0^o	120^o	240^o

13	14	15	16	17	18	19	20	21	22	23	24th slot
0^o	120^o	240^o	0^o	120^o	240^o	0^o	120^o	240^o	0^o	120^o	240^o

Then the phasor diagram for one phase is drawn by using Dolomites software:

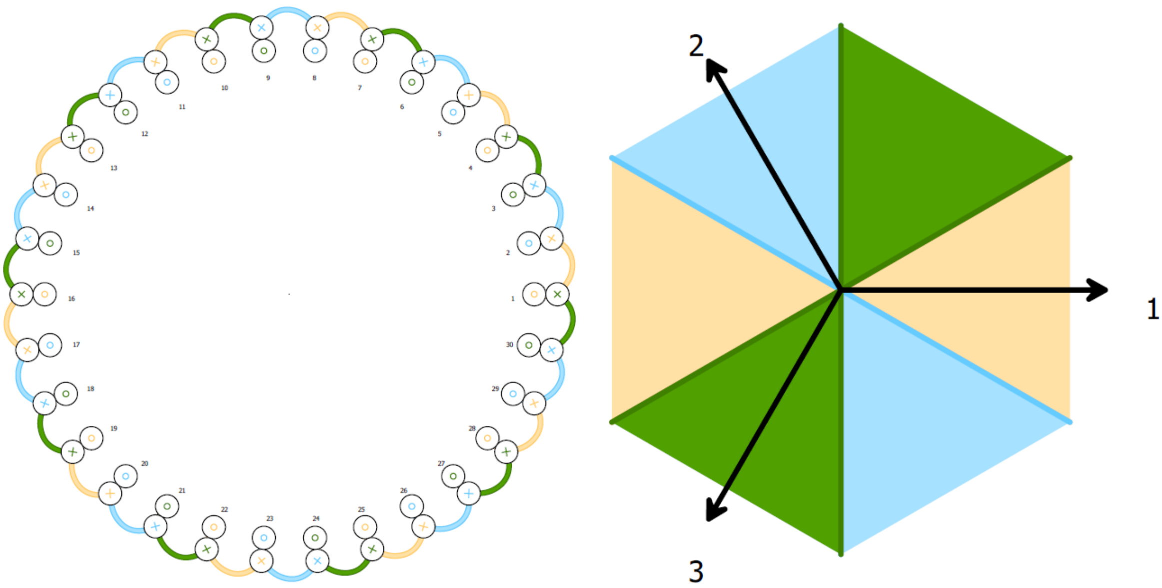

Fig. 7: Phasor diagram of 20 pole, 30 slot, 2/3 pitched winding

Winding Factor

Distribution factor: $k_d = \frac{\sin\left(q\frac{n\alpha}{2}\right)}{q\sin(\frac{n\alpha}{2})}$ → for 1st fundamental component $k_d = \frac{\sin\left(0.5\frac{120}{2}\right)}{0.5\sin(\frac{120}{2})} = 1.00$

Pitch factor: $k_p = \sin\left(\frac{n\lambda}{2}\right)$ → for 1st fundamental component $k_p = \sin\left(\frac{120^o}{2}\right) = 0.86$

Where n is harmonic order, λ is pitch angle (for 2/3 pitch, $\lambda = \frac{2}{3} \times 180^o = 120^o$).

Winding factor for 1st fundamental component: $k = k_d \times k_p = 0.86$

3^{rd} and 5^{th} harmonics winding factors

Distribution factor: $k_d = \frac{\sin\left(q\frac{n\alpha}{2}\right)}{q\sin(\frac{n\alpha}{2})}$ → for 3rd harmonic component $k_d = \frac{\sin\left(0.5\frac{3\times120}{2}\right)}{0.5\sin(\frac{3\times120}{2})} = 1.00$

Pitch factor: $k_p = \sin\left(\frac{n\lambda}{2}\right)$ → for 3rd harmonic component $k_p = \sin\left(\frac{3\times120^o}{2}\right) = 0$

Winding factor: $k = k_d \times k_p = 0$

Distribution factor: $k_d = \frac{\sin(q\frac{n\alpha}{2})}{q sin(\frac{n\alpha}{2})}$ → for 5th harmonic component $k_d = \frac{\sin(0.5\frac{5\times120}{2})}{0.5 sin(\frac{5\times120}{2})} = -1.00$

Pitch factor: $k_p = \sin(\frac{n\lambda}{2})$ → for 5th harmonic component $k_p = \sin\left(\frac{5\times120^o}{2}\right) = -0.86$

Winding factor: $k = k_d \times k_p = 0.86$

plot (0.86*sin(x)-0*sin(3*x)+0.86*sin(5*x))

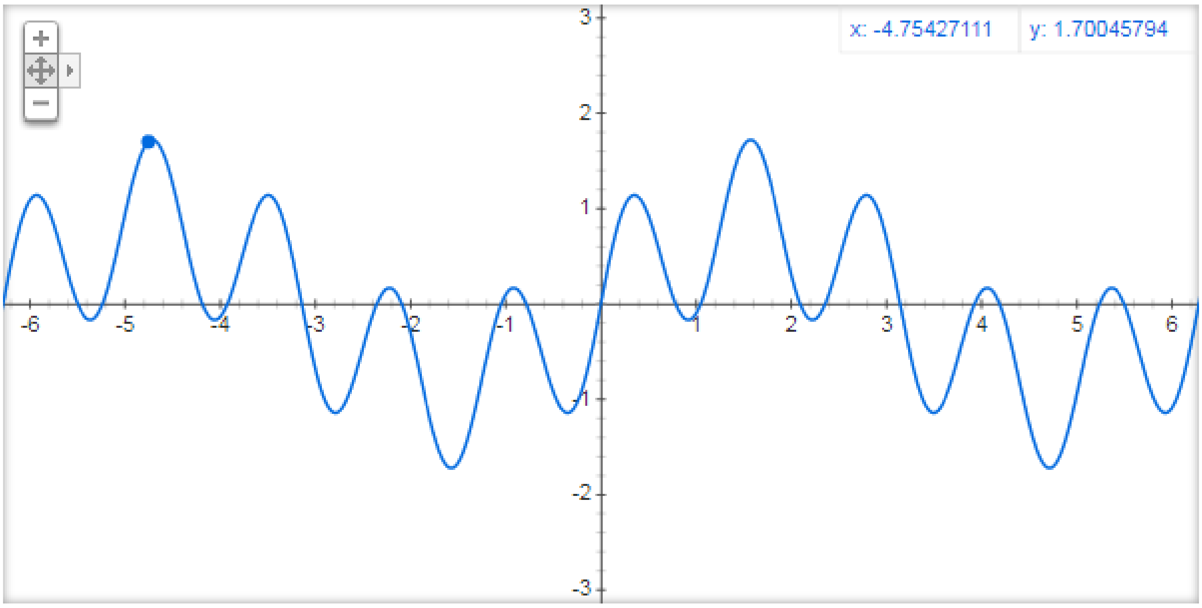

Fig. 8: Magnetic loading B of the selected fractional slot winding – 5th harmonic causes ripples

Comments: Comments: 0.86 winding factor is obtained from 20 poles, 30 slots winding. It seems little lower than previous one but still enough high for a design but, when we look the 3rd and 5th harmonic winding factors, we can see the 0% of 3rd harmonic effect (2/3 pitched coil – 120^o/180^o eliminates the 3rd harmonic) and 86% of 5th harmonic effect. So, the total magnetic loading wave form of this type winding looks like in fig. 8. Because of the 5th harmonic, total magnetic loading has not got pure sinusoidal shape and this causes less effective results in frame of harmonic contents.

3. FEA Modelling (2d) – fractional winding

In FEA (2d) model, we selected the 24 slots, 20 poles machine, which was analyzed in section 2. For the model, "Study of a Permanent Magnet Motor with MAXWELL 2D: Example of the 2004 Prius IPM Motor" document is used with some modifications (Optimizing is neglected, only suitable geometry considered). So, the designed geometry of FEA model is given in figure 9.

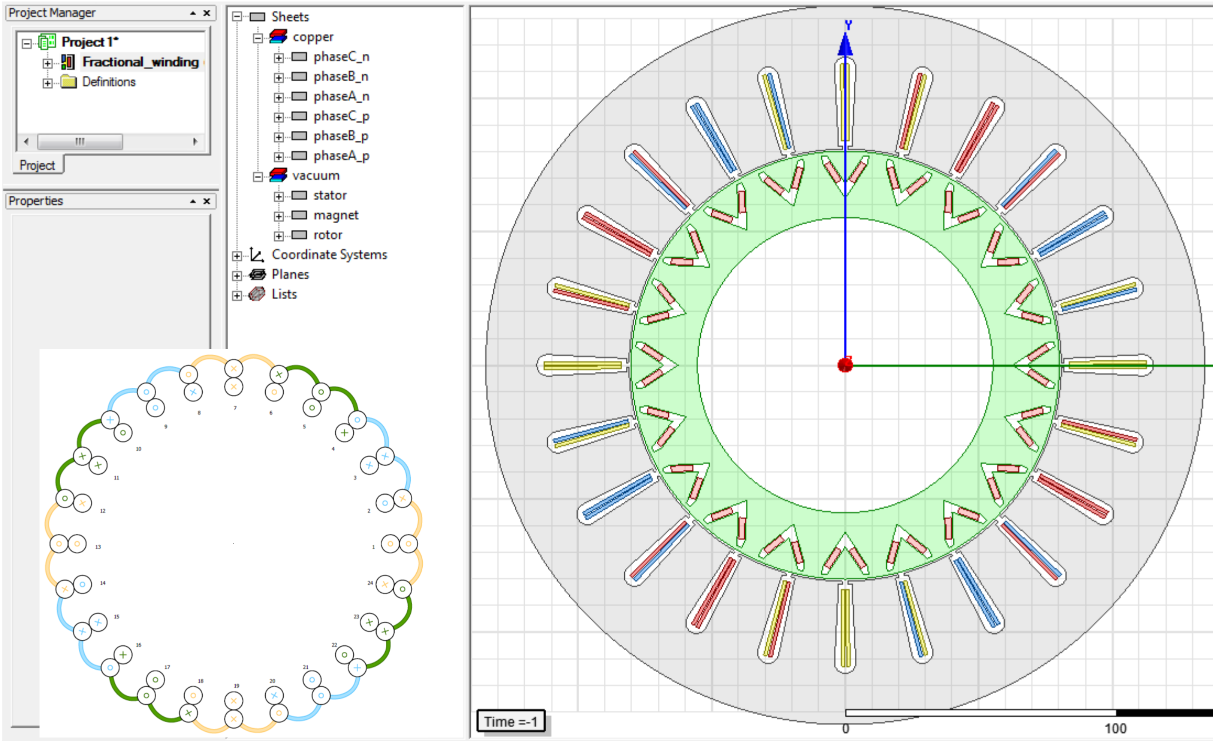

Fig. 9: Maxwell 2d FEA model of the 24 slots, 20 poles fractional winding machine.

After that, I created 1/4 model of the design (in figure 10) but I got mesh error that I can not found the solution of Maxwell error (I spent my 4.5-5h for handle it but I can not. (I selected coil pitch 0.4 but in Maxwell, I think it must set 5/2 instead of 2/5)).

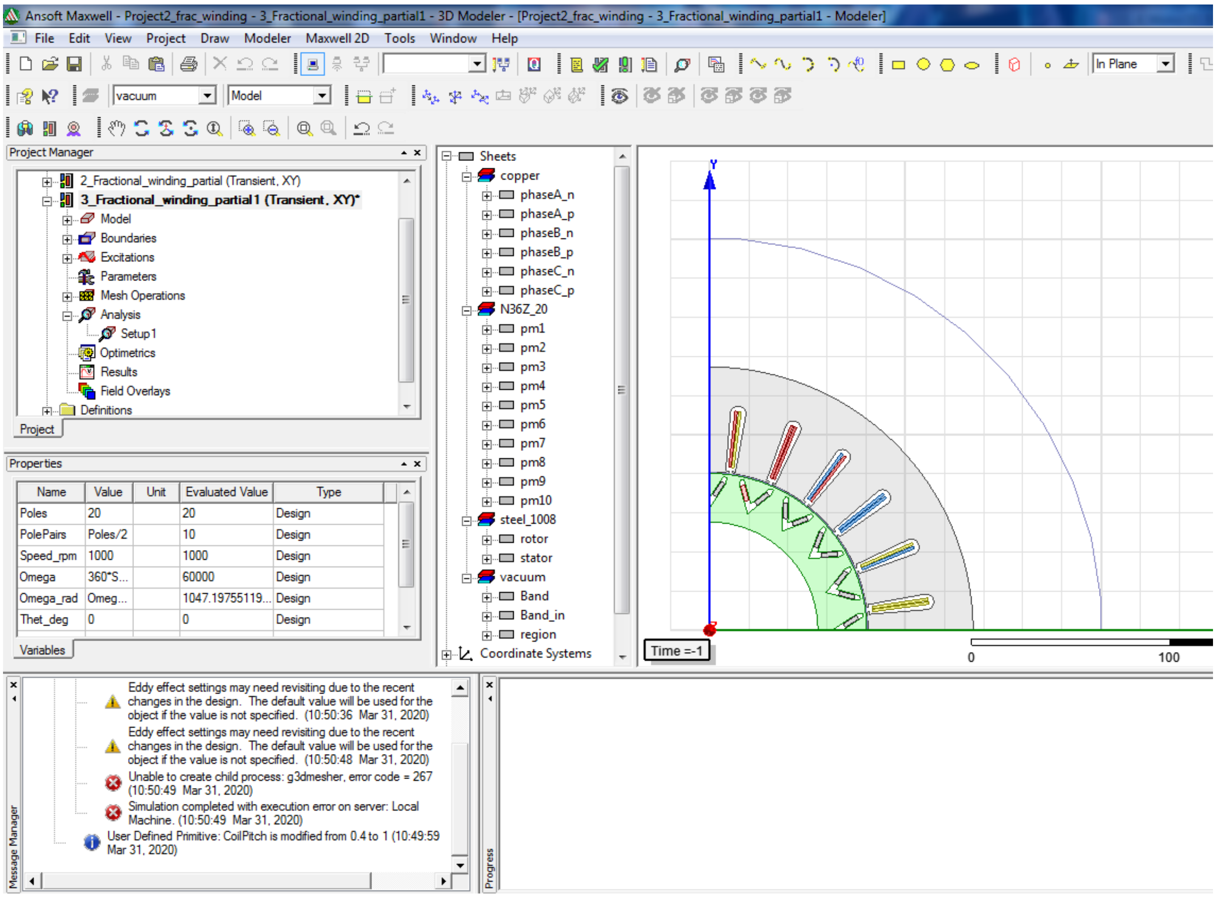

Fig. 10: Maxwell error

REFERENCES

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2. http://keysan.me/ee568/

3. ANSYS Maxwell 2D Field Simulator v15 User's Guide 11.4, Study of a Permanent Magnet Motor with MAXWELL 2D: Example of the 2004 Prius IPM Motor

4. https://www.emetor.com/windings/

5. https://sourceforge.net/projects/dolomites/

6. Brushless Permanent Magnet Motor Design, D. Hanselman