

# Introduction

This document is meant as a short introduction in the methods to compensate for cogging in the conversion of motors to generators. It's not meant to be a complete course on making motor conversions. There are other documents (especially those by Zubbly) that deal with that.

After discussions on the Fieldlines forum and Otherpower IRC it turned out that there are still people who have difficulty understanding the principle of cogging and its remedies. The information is available out there, but it's scattered in various discussion threads.

The goal of this paper is to collect a few of the methods that I have personally used, with good success, and to explain in a short, concise and practical way how to compensate for the cogging phenomenon. It tries to give a practical description of the solutions, not an exhaustive theoretical analysis.

None of these methods were invented by me and I don't consider myself to be an expert on the subject. The text below is just a summary of what I know, written down in such a way that it hopefully will help others to understand how to correct for cogging.

I hope it can make a small contribution to the popularizing of motor conversions.

Peter Dingemans,

May 31, 2007

The Netherlands.

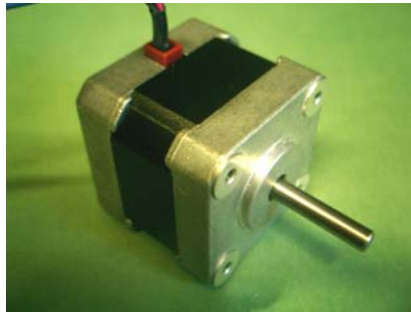
Version 1.0

# What is cogging?

Cogging is the felt unequal force of rotation as one turns the shaft of the motor or generator.

Cogging is caused by the difference in attraction of the magnets of the rotor to different parts of the stator, as the rotor rotates. This difference in attraction can be felt as little 'shocks' as one rotates the shaft.

It's easier to feel cogging than it is to describe how it feels. A clear example of how cogging feels can be found in a stepper motor. Stepper motors can be found in old printers and scanners.



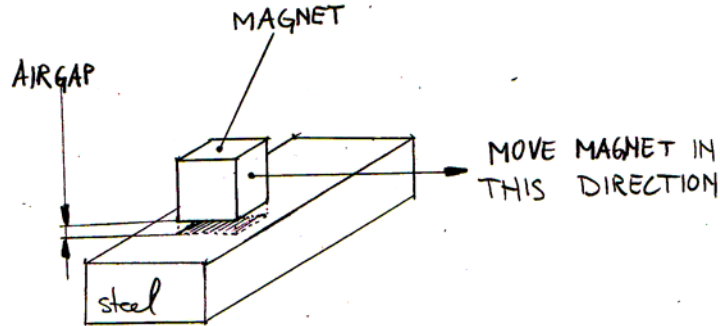
If one turns the shaft of a stepper motor one can feel tiny shocks or 'hiccups'. This is caused by the unequal attraction of the magnets on the rotor to different parts of the stator.

Notice that in the case of stepper motor this cogging is only minute. In a poorly done motor conversion it can be so bad as to make it virtually impossible to turn the shaft.

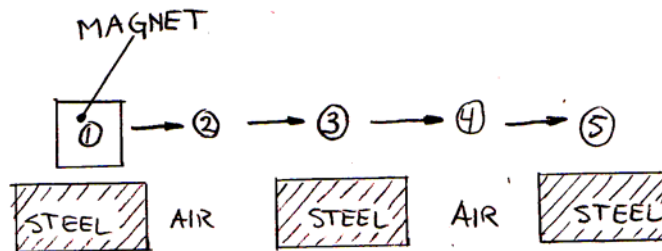
A common misconception is that cogging is caused by the interaction of the magnets with the coils. In reality cogging will also be present in the case of an empty stator core, without any windings in them. It has absolutely nothing to do with the coils. Cogging is caused only by the unequal attraction of the magnetic rotor to the iron of the stator.

### Simple explanation of cogging.

Imagine for a moment a situation as shown in the figure below.



We have a bar of steel with a magnet floating above. If we try to move the magnet to the right, away from the steel block, we'll notice that this takes a force; the magnet prefers to be over the steel block and not over the air. This is because the magnet is attracted to the steel.

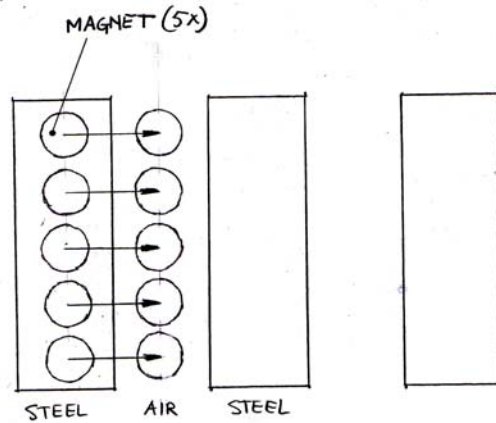


Now imagine that we have several of such bars of steel and that the magnet has to travel over them, from position 1 to position 5. It will take a force to move the magnet from position 1 to 2. As we move it further along to the right the magnet will be attracted to the steel bar; the magnet will want to go from position 2 to position 3; we'll have to slow it down as opposed to trying to push it to the right. To move to position 4 will require a push to move it out of the attraction zone of the middle bar of steel. Etc.

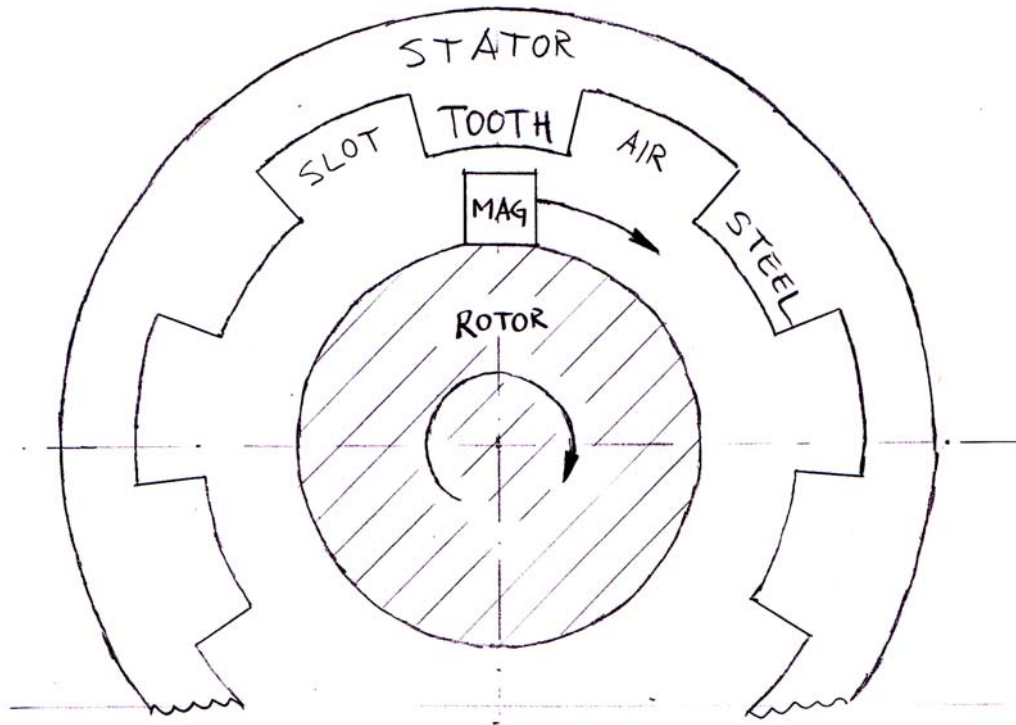
In the figure above, the magnet would want to try to move into position 1, 3 or 5, but would dislike being in positions 2 and 4.

So we see that, in effect, we have to push and pull the magnet, as we move to the right. It is this pushing and pulling that also occurs in a motor or alternator that can be felt on the shaft. It's this what we felt as we turned the shaft of the stepper motor.

Now, imagine for a moment that we are not just dealing with one magnet but a whole row of magnets, as is the case in a motor conversion, where there are many magnets on a row. It'll immediately be obvious that the cogging forces multiply by the number of magnets; 5 times as many magnets as in the example below means 5 times as strong cogging:



The above illustration shows the cogging effect projected on a flat surface. In reality, in a motor conversion, the situation would be as in the illustration below.



The above figure shows a highly simplified situation with just a few stator teeth/slots (as opposed to the usual 24, 36 or even more) and just one pole on the rotor. In reality there would be at least 2 but more likely 4 or even more poles on the rotor.

In the position with the magnet at 12 o'clock, the magnet is attracted to the steel of the extruding stator tooth. It would resist moving to the right, to the area of the slot, filled with 'air' (or more likely in reality, the copper wire of the coils).

Not only that, but since we have multiple poles (2, 4 or more) as opposed to the above illustration of just one pole, the cogging forces will multiply again by the number of poles we have. For example, in the rotor shown below we have 7 magnets per row, 3 rows per pole and a total of 4 poles. That means  $7 * 3 * 4 = 84$  magnets trying to oppose rotation, if countermeasures hadn't been taken.



The cogging would become so strong that it would make the alternator unusable in low-wind conditions; only strong winds would be strong enough to overcome it. Hence, decogging measures improve the low wind and startup performance of a motor conversion.

Since air-cored wind alternators, such as axial fluxes, don't have iron in the stator, they don't cog and thus have excellent startup performance.

In the next part, we will take a closer look at several methods of decogging:

- 1) helix method
- 2) offset method
- 3) offset method 2
- 4) skewing the stator
- 5) two skewed rotors on one shaft

# Helix method

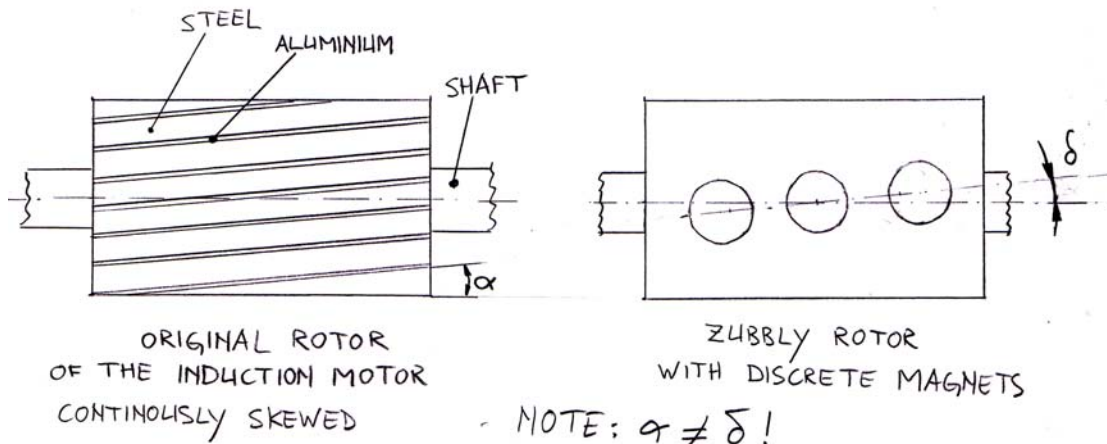
If done correctly this method will result in a motor conversion that doesn't have the slightest hint of cogging left. Many people have used it with good results. I personally have made two conversions using it.

It can be seen that the magnetic poles on the rotor are not in line with the longitudinal axis but at a slight incline. The reason the manufacturer skews the rotor bars has nothing to do with decogging but with the control of starting torque.



This angle has nothing to do with the angle of our future row of magnets. They are unrelated. It is a common misconception that if one skews the converted alternator rotor by the same amount as the original motor rotor that it will not cog. This is incorrect, as in the case of motors and alternators the goal and principle of the skew is fundamentally different.

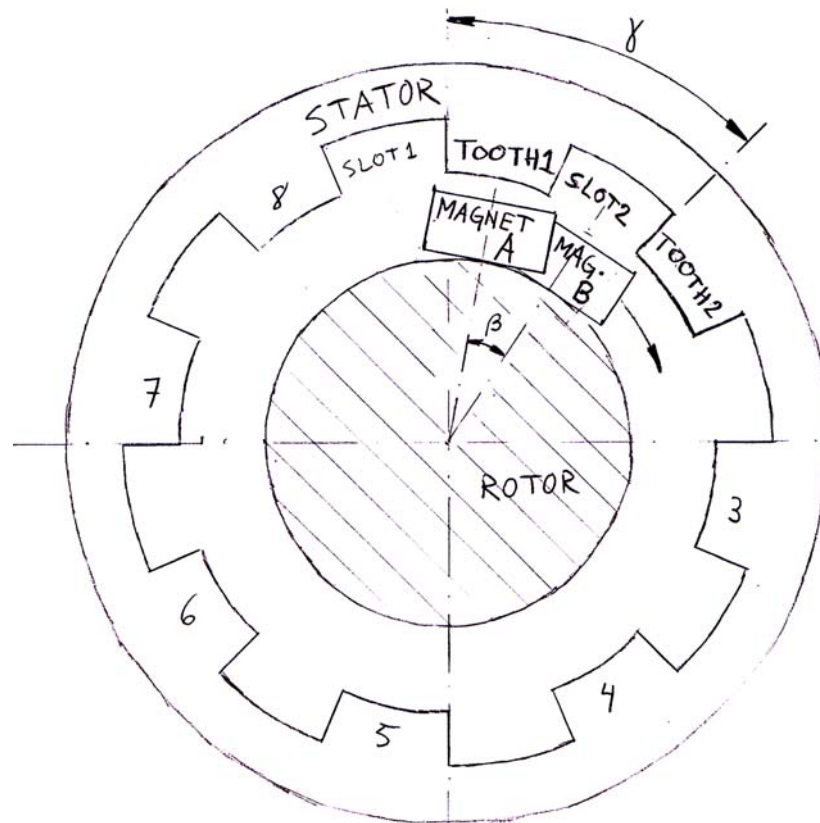
The two angles in the drawing below should not be equal to each other, unless by coincidence.



If we take the original angle  $\alpha$  and line up the magnets on the new rotor at the same angle, i.e. make  $\delta$  equal to  $\alpha$  we would make an error because of the fact that the two rotors are fundamentally different.

### The principle

The idea behind this helical method of skewing the magnets is that, as one magnet is still attracted to a certain stator tooth and resists movement, another magnet is attracted to the next stator tooth. The two forces compensate each other, cancel each other out, so we end up with a rotor that doesn't cog.



STATOR WITH 8 SLOTS  
ROTOR SHOWING ONE POLE WITH  
2 MAGNETS ON A ROW

In the illustration above we have a rotor with just one pole (for simplicity) and with just two magnets on it, magnet A and B. Magnet A is attracted to stator tooth 1, while magnet B is in the airgap (slot) between two teeth. As the rotor rotates to the right, magnet A

will try to resist movement, whilst magnet B is attracted to tooth 2 and enhances rotation of the rotor.

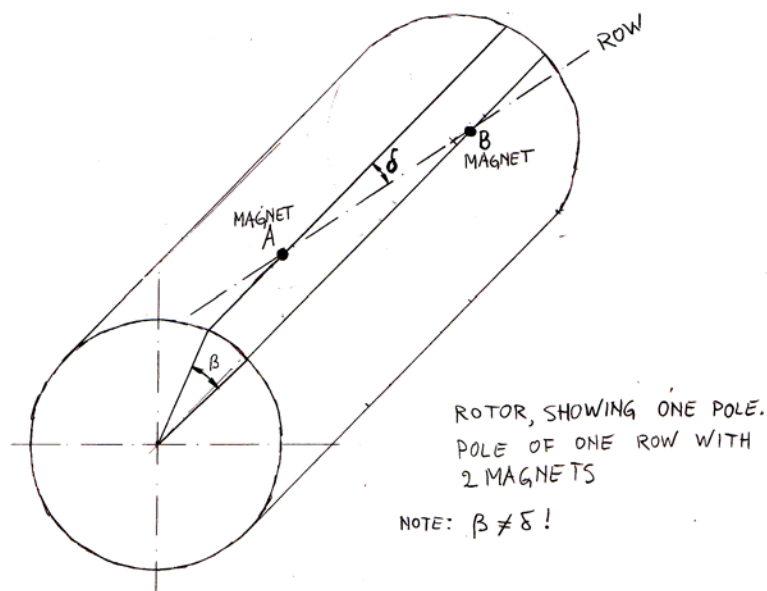
We see that even in this simple case, the forces on the rotor (mostly) cancel out. The more magnets we use, the better. In this simple case of 2 magnets per row there would still be some cogging left, but it is much smaller than it would have been if magnet A and B were on the same position.

The trick now is to find out by how much we should displace the magnets.

In the simple case above we have eight stator slots and teeth. This means each slot/tooth pair occupies  $360 \text{ deg} / 8 = 45 \text{ deg}$ .

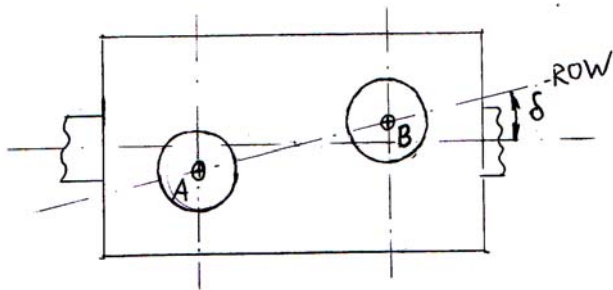
That is,  $\gamma = 45 \text{ deg}$ .

Angle  $\beta$ , the angle between the two magnets, should be half that, in this case,  $22.5 \text{ deg}$ . But –only- in this special case of two magnets per row.

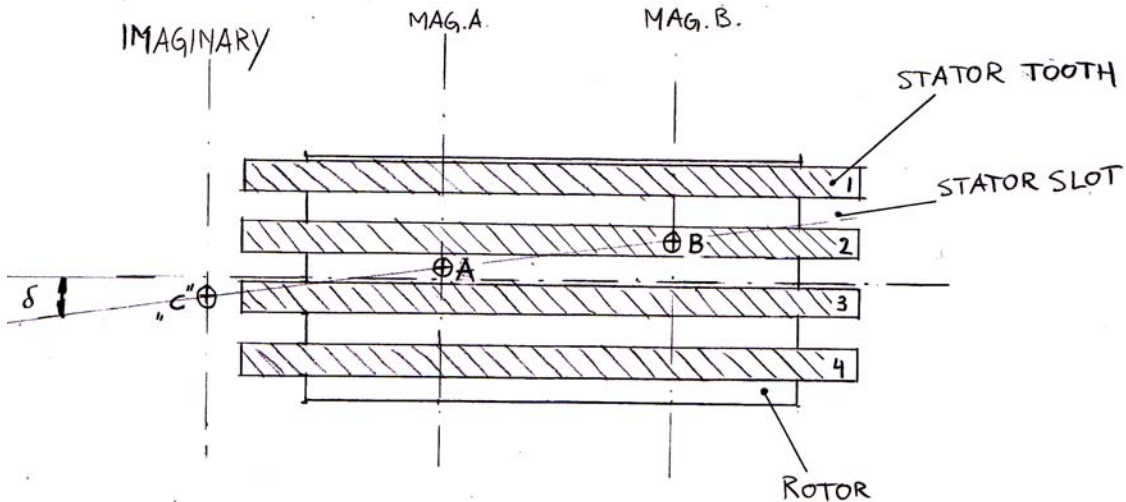


$\beta$  is only of limited use; we want to know angle  $\delta$ , as it is this angle we will have to mark out on the surface of the rotor.





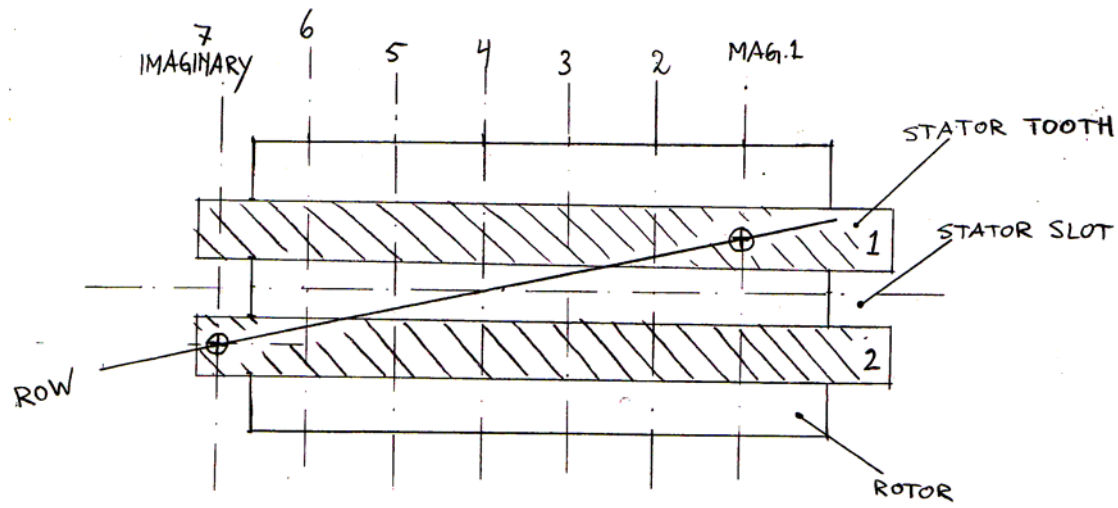
To determine the correct angle  $\delta$  to mark out on the rotor, we need another projection of the situation.



ROTOR WITH 2 MAGNETS A & B.  
STATOR TEETH PROJECTED OVER ROTOR

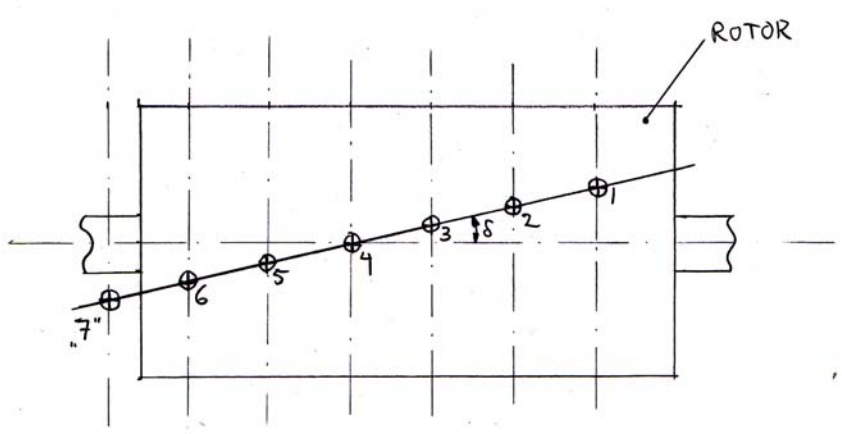
The illustration above shows a projection of a few stator teeth over the rotor. Notice that magnet B sits exactly under a stator tooth, whereas magnet A is exactly under a stator slot (that is, 'air'). An imaginary extra magnet C would again sit exactly under a stator tooth, just like magnet B. The line on which the magnets sit is at angle  $\delta$  with the longitudinal axis of the rotor.

The trick is to determine the correct angle  $\delta$ . To determine that, we can make a to-scale drawing of our rotor, with two stator teeth projected on the rotor:



ROTOR WITH 6 MAGNETS PER ROW

Magnet 1 should sit exactly under a stator tooth, and the imaginary (it will not be present in the real rotor) magnet 7 sits under the next stator tooth. The other magnets should sit on a line between magnet 1 and 7. We added the imaginary magnet 7 in the drawing so we can draw a straight line, on which the other magnets will sit.



ROTOR. MAGS 2-6 ARE ON A LINE DRAWN BETWEEN MAG. 1 AND IMAGINARY MAGNET 7

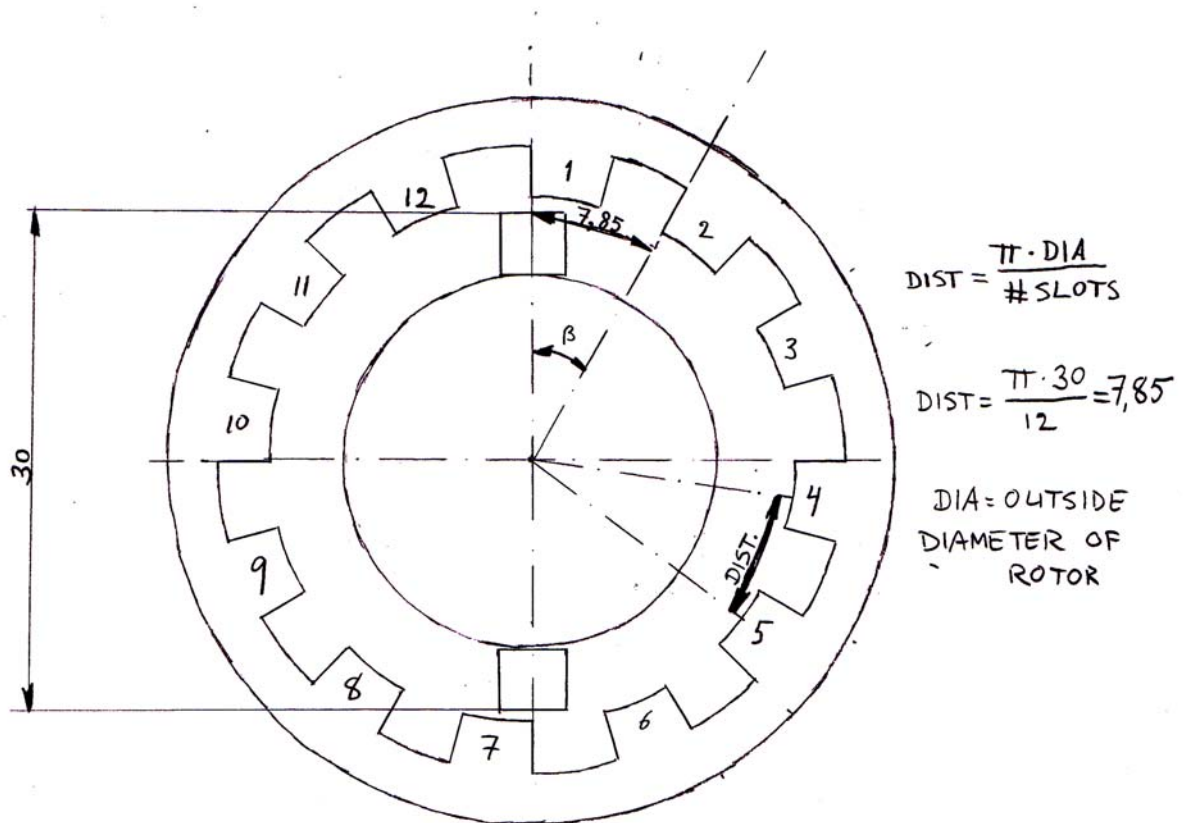
Notice that the last real magnet, number 6, does -not- sit exactly under the next stator tooth; it comes a little short. Only magnet 7 would sit exactly under the next stator tooth.

By positioning the magnets like this we will ensure that the pole, as it rotates, is equally attracted to the stator at all positions. In effect, we have completely decogged this row of magnets.

We could add more rows to the same pole, and we can add more poles to the rotor; if we mount them at the same angle as our previous row of magnets, they too will not cog.

So, one makes a drawing (scale 1:1) of the rotor and then projects an image of the stator core on top of that. Only two stator teeth would be enough. The distance between the heartlines of the two stator teeth can be calculated using this equation:

$$\text{Distance} = \pi * \text{diameter} / \text{slots}$$

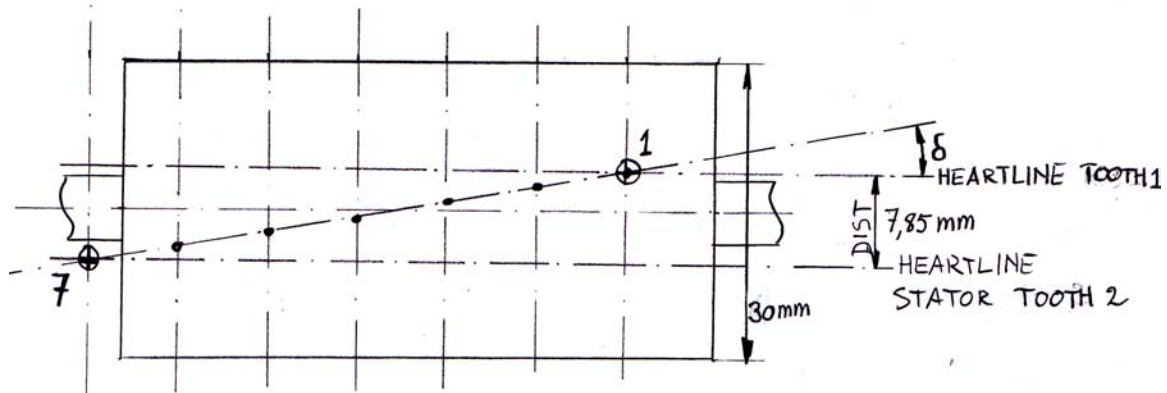


If, for example, the diameter of the inside of the stator is 30 mm and the motor has 12 slots, then the distance between the (heartline) of the slots would be

$$\text{Distance} = \pi * 30 / 12 = 7.85 \text{ mm}$$

We then make a drawing of the rotor and 2 lines that symbolize the heartlines of the stator teeth, at a distance of 7.85 mm.

Magnet 1 should sit one line, imaginary extra magnet 7 on the next line. We now draw a line between these two positions and fill in the places of the other 5 magnets.



And so we have found out the correct skewing angle for the rotor.

We can now mark out this angle on the real rotor and machine the pockets for the magnets.

### Shortcut

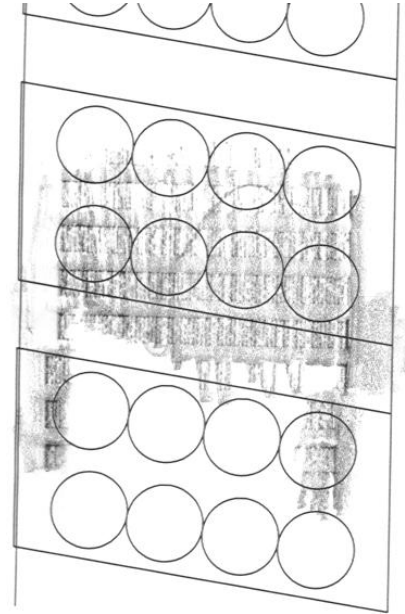
A simpler method, though theoretically less correct, is to skip the previous steps and simply line up the first and last magnets under different stator teeth. In the case above, magnet 6 would sit exactly under stator tooth 2, and magnet 1 under tooth 1. The other magnets would be in between. As said this is theoretically less correct but yields, in 'normal' cases, a good conversion with little cog. In cases where there are relatively few magnets on a row, however, the error becomes progressively large; in the extreme case of 2 magnets, for example, the rotor would cog twice as much because both magnets are under a stator tooth; when using two magnets, one magnet should really be under a tooth and the other magnet under a slot, as seen on page 7.

In the case of 3 magnets it would also cog. Only as the number of magnets per row approaches larger numbers does the error become relatively small. The detailed method, as explained previously, will always yield a good conversion, even with few magnets per row; the shortcut may work in cases where there are many magnets per row. I prefer to use the detailed method, as it's not much harder and theoretically the correct way to arrive at a cogless conversion.

Appendix B describes another way of calculating the correct skew angle. I find it the quickest and easiest way but it requires a little math.

## Verification

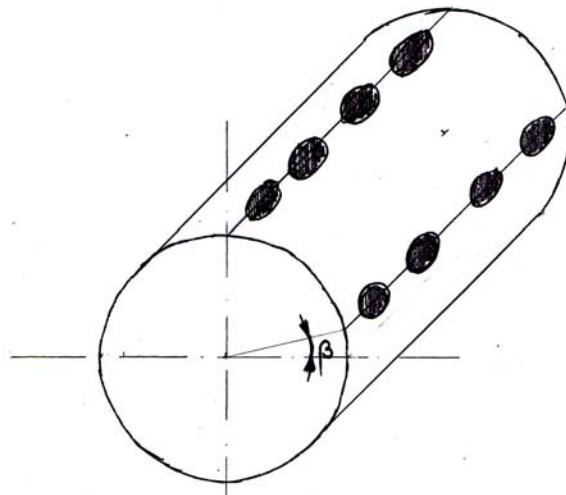
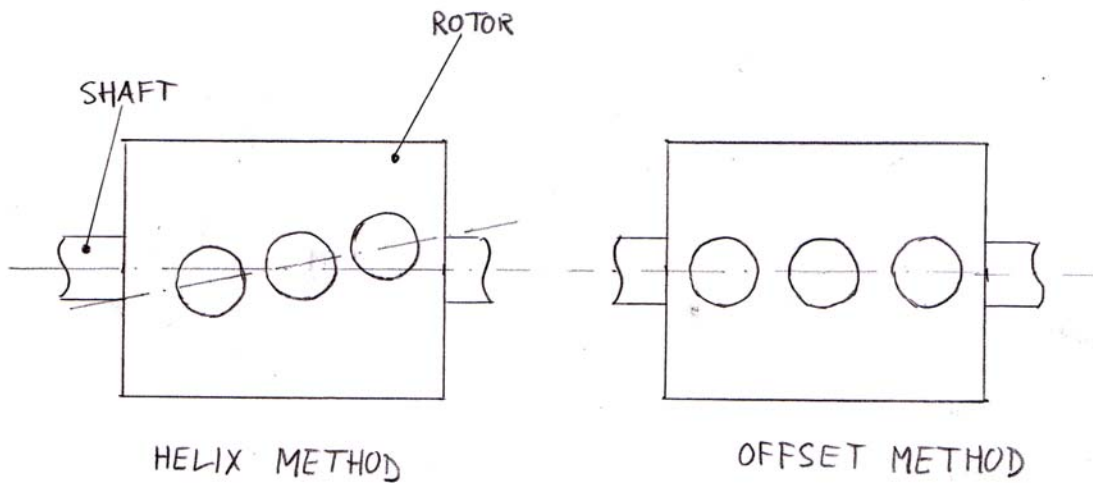
A simple way to verify whether the designed skewing angle is correct is by drawing the magnets, scale 1:1, on a piece of paper. Then put the paper in the stator and rub with a pencil (as is done by children for copying/tracing coins on paper). The stator slots and teeth will be marked on the paper and at a glance one can see whether the skew angle is correct and whether the magnets would extend outside of the stator.



## Offset method

Another method of compensating for cogging is done not within a pole (as is the case with Zubbly's helix method), but for the rotor as a whole by offsetting the position of the various poles.

With this method of decogging all magnets are on a straight line that is parallel to the axis of the shaft, as can be seen in the next figures.

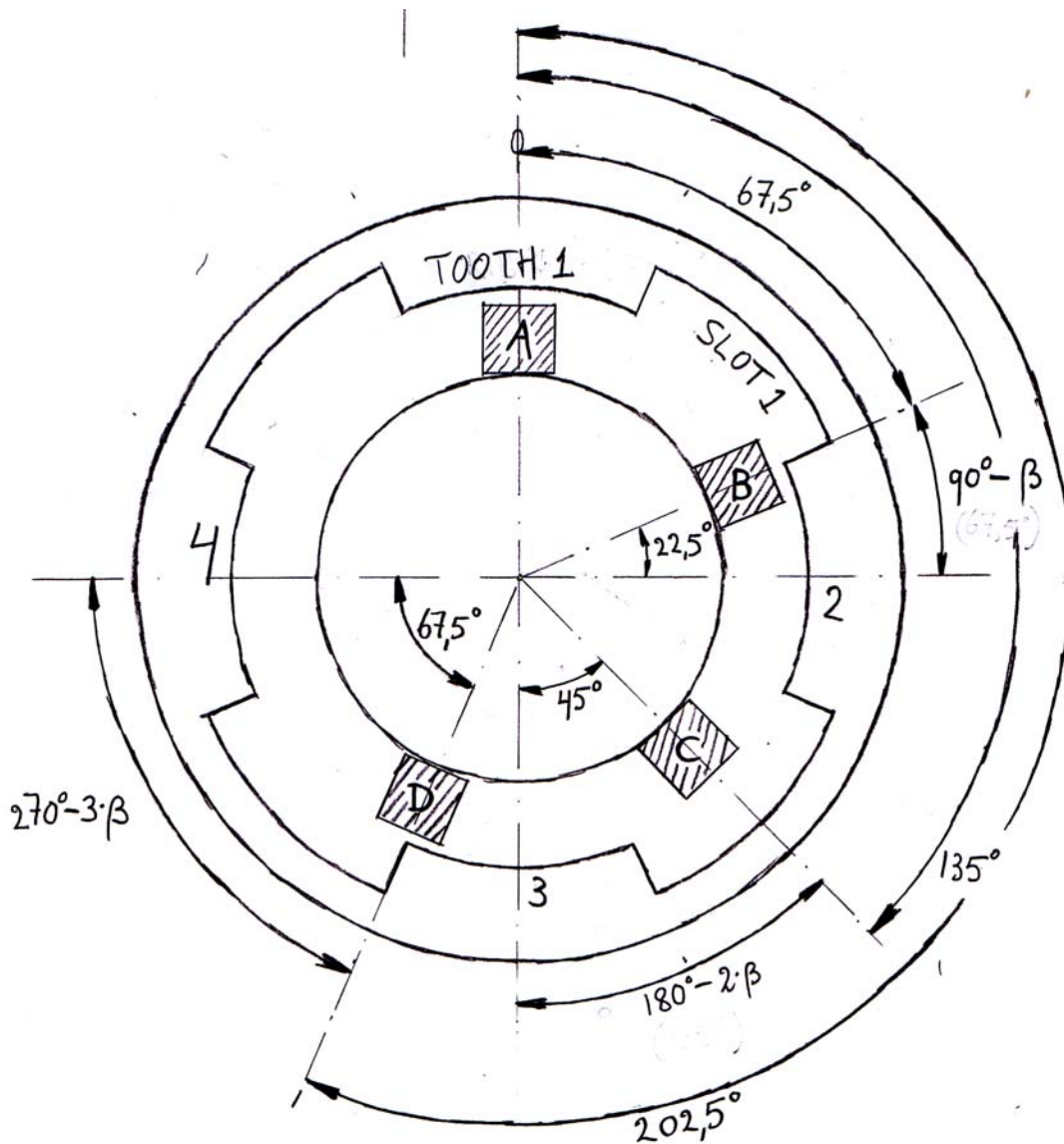


The above figure shows a 4 pole rotor; the magnets are however not at 12 o'clock, 3 o'clock, 6 o'clock and 9 o'clock but at a corrected angle. The correction is, in the above image, denoted by angle  $\beta$ .

As one pole is attracted to a stator tooth, another pole is attracted to another stator tooth. By correctly positioning the poles one can let these two forces cancel out which results in a cogless conversion.

If the rotor is so small (or the magnets that large) that there is only room for one magnet per pole, then this method is the only possible way to decogg. The other methods require several magnets per pole in order to work or specially shaped magnets (trapezoid).

To give an idea of how this method works we'll take a look at a hypothetical 4 pole motor that has only 4 stator teeth:



4 POLE ROTOR ; 4 SLOT STATOR

We can see that magnet A is fully attracted to tooth 1, whereas magnet C is exactly in between teeth. Magnet A and C thus compensate each other as the rotor rotates.

Magnet B is attracted to tooth 2 and wants to rotate the rotor clockwise. However, magnet D is attracted to tooth 3 and wants to rotate the rotor counterclockwise. Hence, magnet B and D compensate each other too. As the rotor rotates the various magnets will thus compensate each other.

It's immediately obvious in the above picture that the rotor is not balanced; the center of mass is not at the center of rotation. The unbalance is a downside of this method and something we will have to compensate for.

The trick with this method is to find out the correction angle  $\beta$ . It describes the amount by which we have to offset the magnet poles from their 'normal' position (in this case for a four pole motor the normal position is at 0, 90, 180 and 270 degrees).

There's a simple equation for that:

$$\beta = 360 / (\text{\#stator teeth} * \text{\#poles})$$

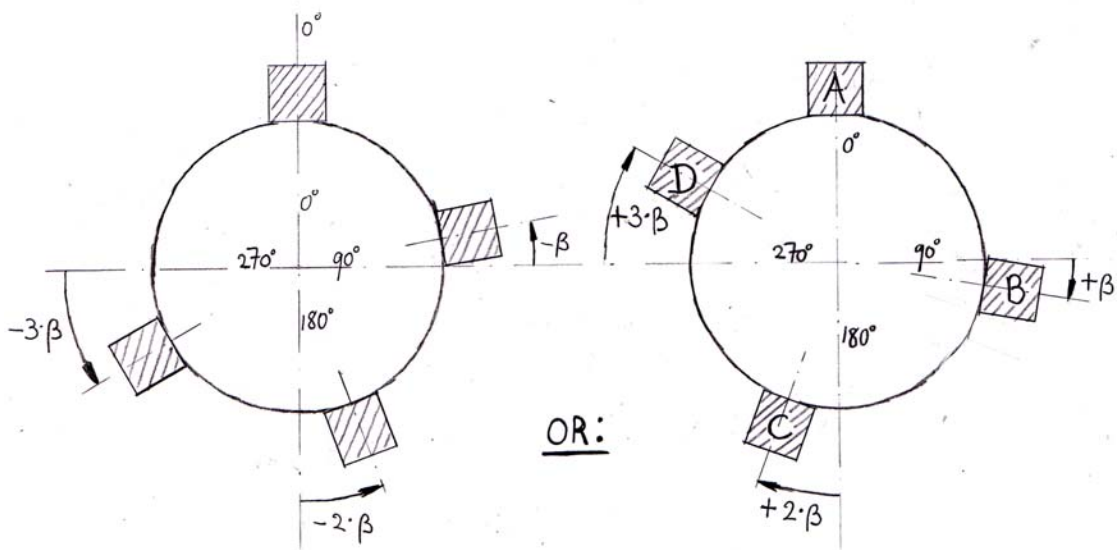
In the above case, with four stator teeth and four poles,  $\beta$  would be:

$$\beta = 360 / (4 * 4) = 360/16 = 22.5 \text{ degrees}$$

Magnet A will be compensated for by 22.5 degrees; magnet B by  $2*22.5 = 45$  degrees; magnet C by  $3*22.5 = 67.5$  degrees.

In the above figure the compensations are done in counter-clockwise direction. We could equally well have done it the other way around, in clockwise direction. See figure below for that.

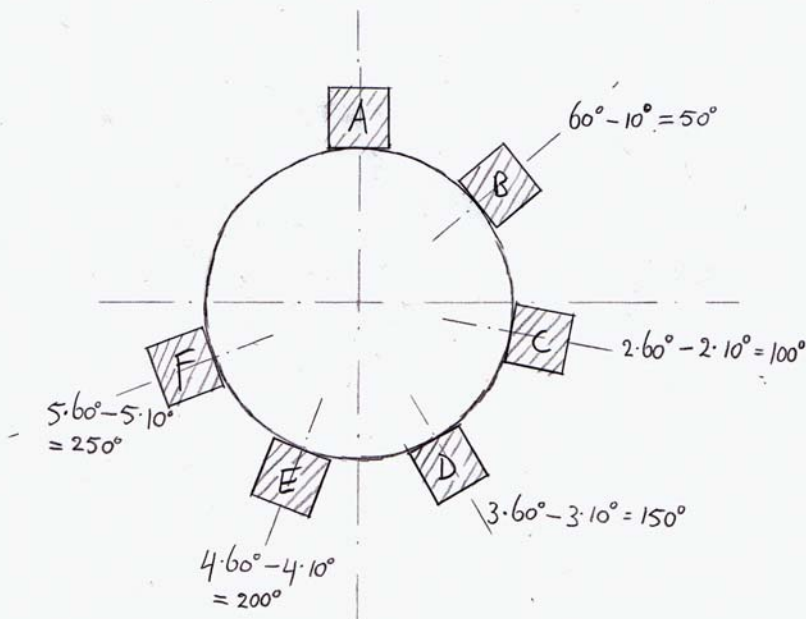




4 POLE ROTOR

The net result should be the same, but it should be noted I have never used the method on the right; I have compensated counter-clockwise so far only.

Another example. A 6 pole rotor with a 6 slot stator.



6 POLE ROTOR; 6 STATOR SLOTS ( $10^\circ$ )

In this case,  $\beta = 360 / (6 * 6) = 10$  degrees. So each magnet has to be compensated by 10 degrees, in the drawing above it was done in the counter-clockwise direction.

Magnet A is our starting point, at 12 o'clock (0=360 degrees).

Magnet B would originally be at  $360/6 = 60$  degrees, but we subtract the 10 deg correction from that:  $60-10 = 50$  deg.

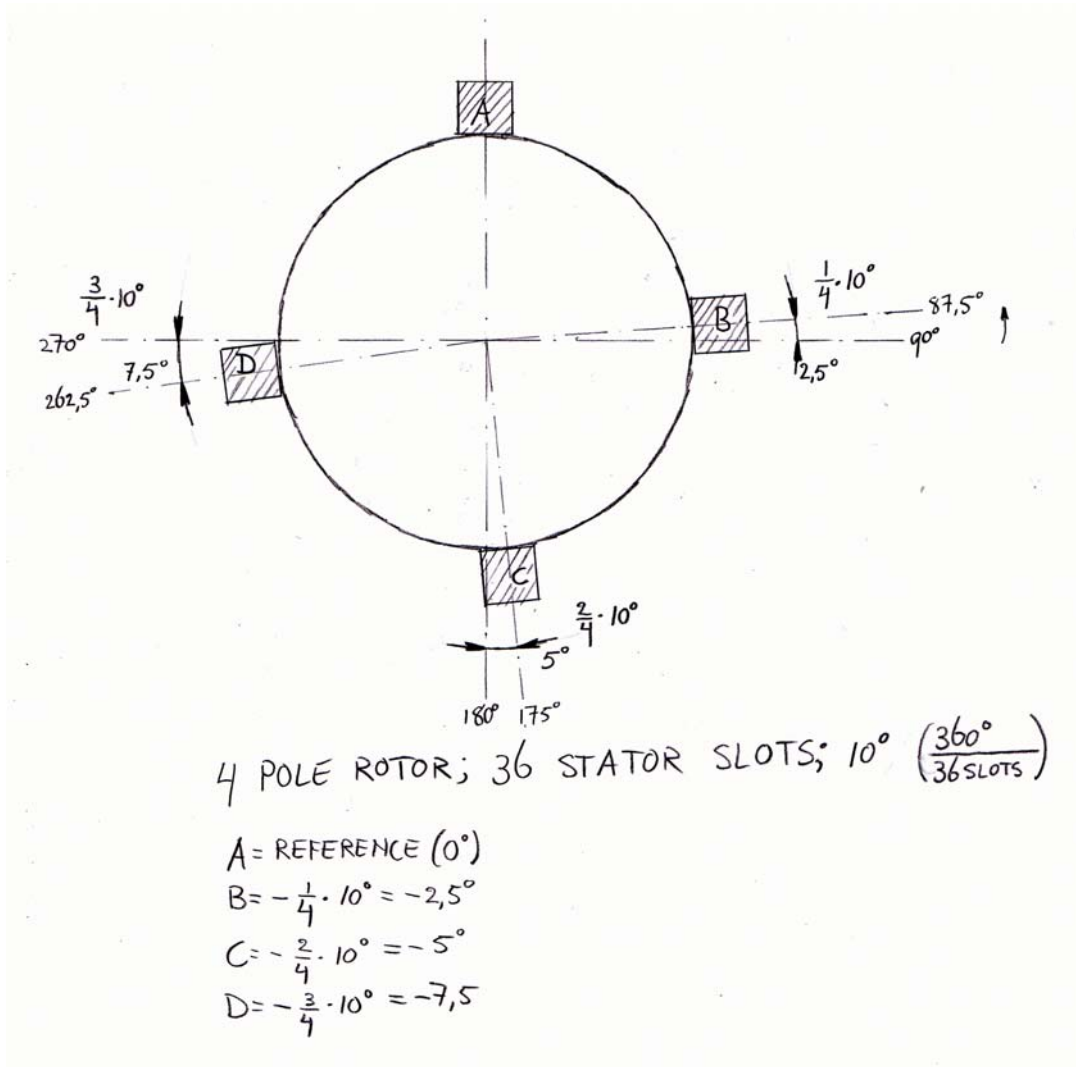
Magnet C would be at  $2 * 60$  degrees, but we subtract twice the correction from it:  $120 - 20 = 100$  deg.

Magnet D =  $3*60 = 180$  deg; minus  $3 * 10$  deg;  $180 - 30 = 150$  deg.

And so on for the other magnets.

Notice that in the above examples the magnets are shifted by a lot; it's easy to see in the above pictures that the center of mass is far from the center of rotation. This is due to the artificialness of the examples (done so that the pictures would be exaggerated but clearly show the principle). In reality the corrections are much smaller due to the fact that real motors have many more stator slots; usually 24, 36 or even more.

The next example shows a more practical situation. It deals with a 4 pole motor with 36 slots in its stator.



The correction angle  $\beta$  is (for 36 stator slots and 4 poles) :

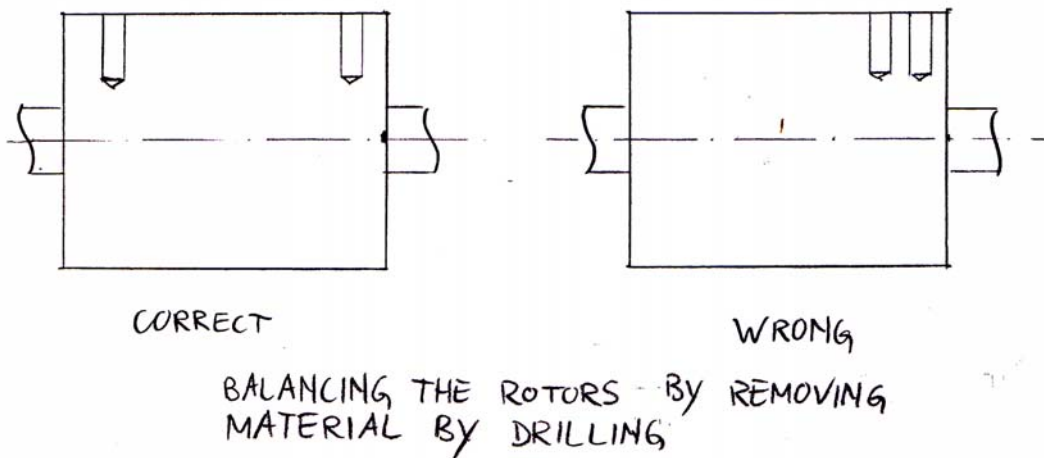
$$\beta = 360 / (36 * 4) = 2.5 \text{ degrees.}$$

Magnetic pole A is our reference and remains at its position. Pole B is moved in counter-clockwise direction by 2.5 degrees; pole C by  $2 * 2.5 = 5$  degrees; pole D by  $3 * 2.5 = 7.5$  degrees.

As can be immediately seen in the above figure, the resulting imbalance is much smaller than in the previous example. The general rule is that the more stator slots the motor has, the smaller the correction angle of the poles on the rotor will be, and thus the smaller the imbalance in the rotor will be.

In appendix C are the calculated values for  $\beta$  for the most common motor configurations. The values were calculated using the above equation.

Because the offset method creates an imbalance, this has to be corrected for in order to reduce vibration and increase the service life of the alternator, especially of the bearings. One could remove material from the side that is too heavy, or add material (e.g. lead plugs) to the side that is too light. It's a trial-and-error method to get the balance of the rotor right. One has to be careful to balance in such a way that it doesn't upset the dynamic balance; if one adds or removes material from the rotor, one should do it equally at both sides. Otherwise the rotor could be statically balanced but end up with a dynamic imbalance which still leads to vibration and extra wear of the bearings.

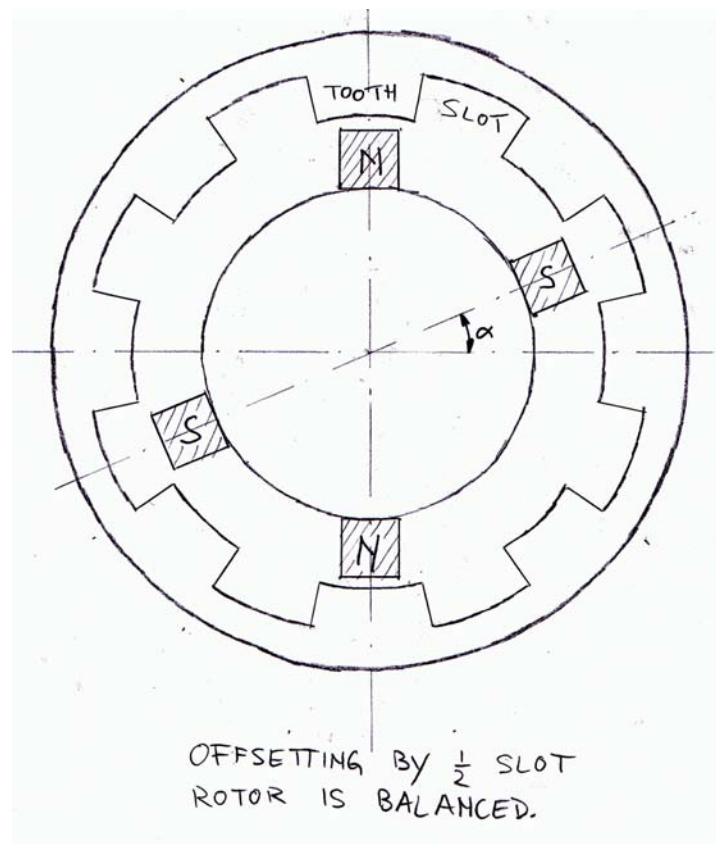


## Offset method 2

Another possible way to offset the magnets on the rotor is described below. Unlike the previous method it results in a rotor that will be balanced. The downside is that it only works with rotors that contain more than 2 poles; it does not work with 2 pole motors as the rotor will be unbalanced.

I have never used this method myself yet but it should work. A major advantage is too that it's much easier to machine (mill) the rotor, unlike the helix method.

Below is a very simplified drawing that shows the principle.



In this four pole example, the two N magnets are exactly on their normal position (0 and 180 deg), but the two south poles are rotated counter-clockwise (in this example; clockwise rotation would also work) by angle  $\alpha$ .

As can be seen, the N magnets are under a stator tooth whereas the S magnets are under a stator slot. As the rotor would rotate a little clockwise, the N magnet would pull the rotor back counter-clockwise where the S magnet would want to pull it further along in the clockwise direction. In effect, the two forces compensate each other resulting in a cogless rotor.

It works with 6, 8, 10, ... pole motors too and the principle is the same; all the N pole magnets are in their normal position, whereas the S magnets are offset by a certain amount. This results in each N-S pole pair on the rotor compensating itself for cog.

What is also immediately obvious in the above image is that the rotor will be balanced, unlike the offset method that was explained in the previous chapter.

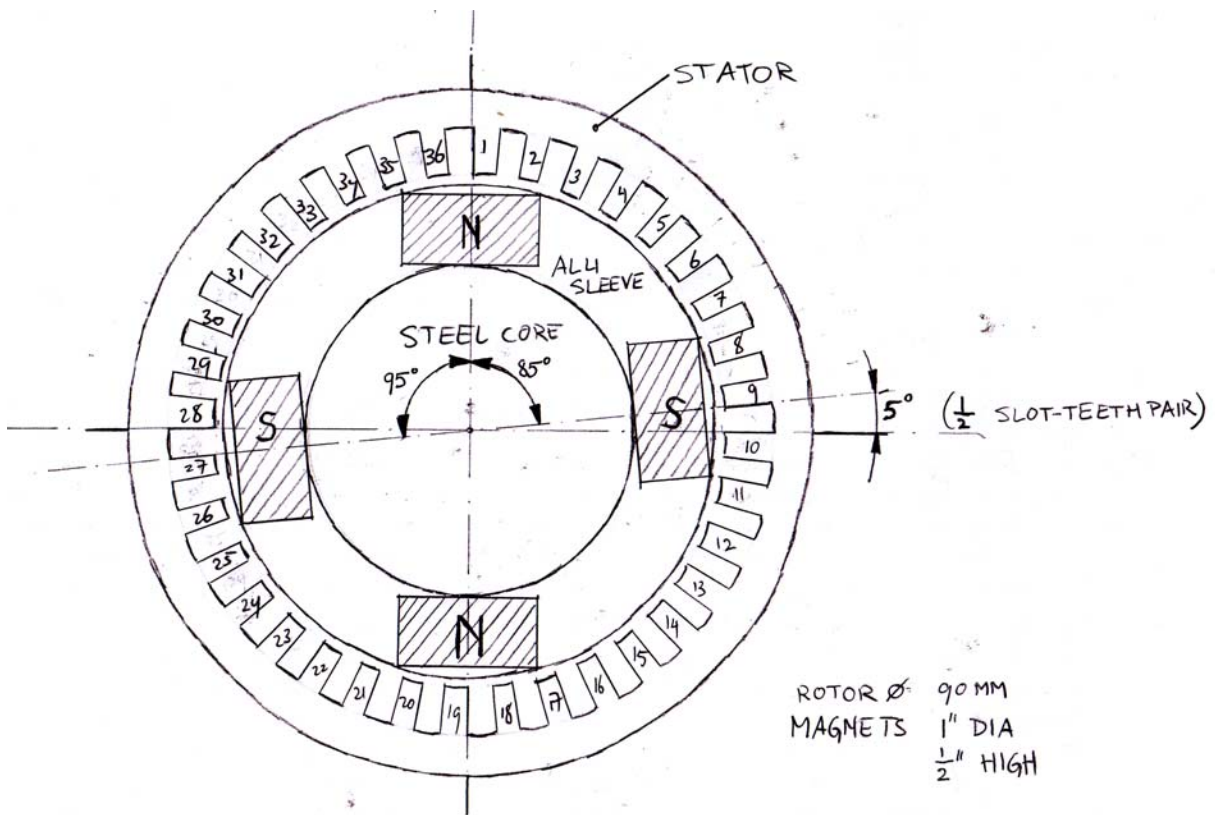
Determining the angle  $\alpha$  is simple; the correction angle should be:

$$\alpha = 360 / (\#slots * 2)$$

In the above case we have 8 slots so  $\alpha$  would be  $360 / (8 * 2) = 360/16 = 22.5$  degrees.

Below is a more realistic example, with the dimensions of a 3 hp motor in mind, consisting of 36 stator slots and being a 1500 RPM (4 pole) motor.

In the example below,  $\alpha = 360 / (36 * 2) = 360 / 72 = 5$  deg.



LILR METHOD; ROTOR IS BALANCED  
4 POLE MOTOR; 36 SLOTS

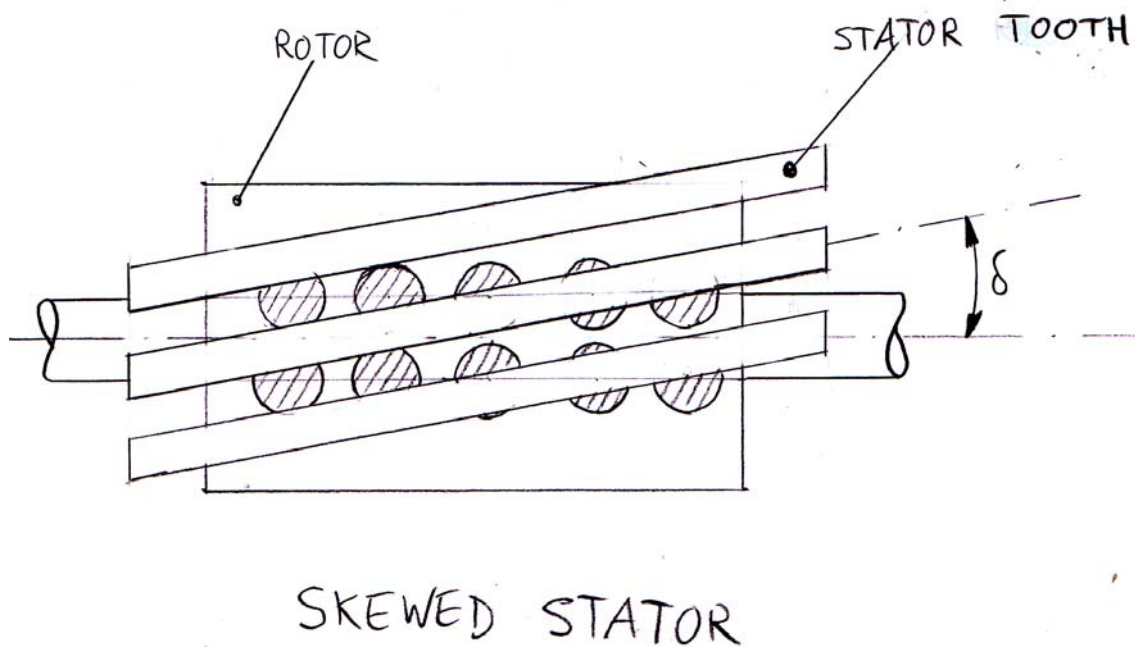
$$\frac{360}{36 \text{ SLOTS}} = 10^\circ \quad \text{S-MAGNETS ARE } \frac{1}{2} \text{ SLOT/TEETH PAIR}$$

$$\text{OFFSET} = \frac{1}{2} \cdot 10^\circ = 5^\circ$$

## Skewing the stator

This is a method I haven't used myself yet but others have used it successfully. In this case the stator slots are skewed whilst the magnet poles on the rotor are straight.

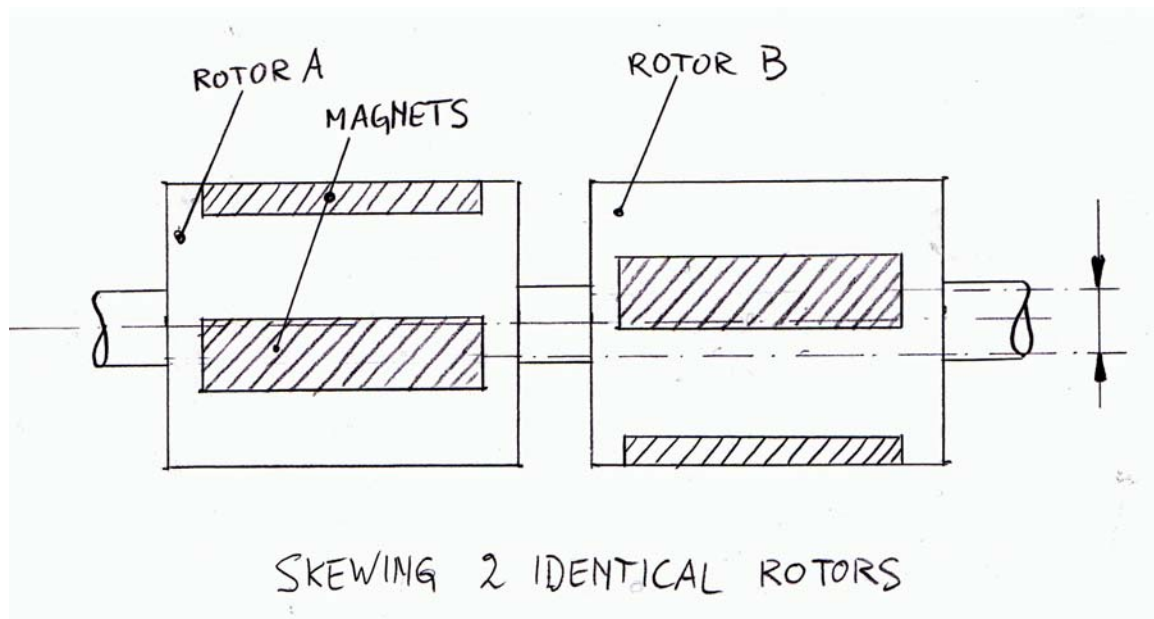
The correct angle delta is not equal to the skewing on the original rotor of the motor, as explained in the chapter on the helical method. The determination of the correct angle  $\delta$  is the same method as was explained in that chapter.



## Skewing two rotors on one shaft

This method is one I haven't used yet either. It's basically the same principle as skewing two magnets on one rotor (see a previous example in the chapter 'helix method'). The method is the same but on another scale; compensation is not done within a rotor (or even within a pole), but the two rotors compensate each other.

As the magnets of rotor A sit exactly under a stator tooth (and are thus more attracted to the stator), the magnets of rotor B should sit exactly under a stator slot. See pages 7 and 9 for an illustration.



This method is especially useful when one wants to convert a larger motor using, for example, 2"x1"x.5" magnets, where the usual method of helical skew may not work.

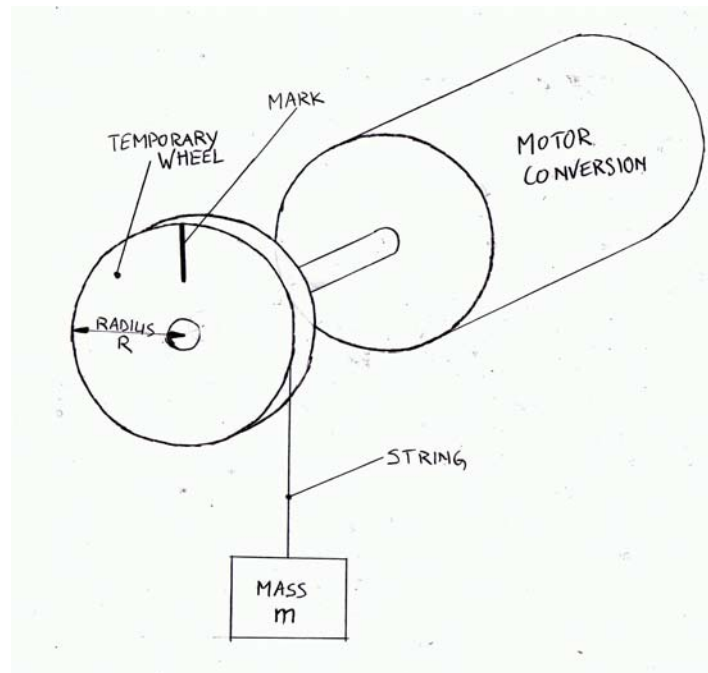
Unlike the case of offsetting the magnets, it will not result in an imbalance in the rotor.



## Appendix A: determining stator losses

Unlike axial flux generators motor conversions have an extra loss in the stator, due to the hysteresis of the magnetization and de-magnetization of the iron. These losses reduce output. There is a simple method to determine these losses for a motor conversion.

(note that the losses, measured in this way, include bearing losses as well; I assume that the bearing losses are negligible in comparison to the iron losses in the stator.)



For this method to work it's important that the motor conversion has as little cogging as possible. I have used it to measure the stator losses on the mini-induction conversion. The calculations in the rest of this appendix are made using the values for that generator.

I've temporarily installed a small wheel (diameter 22 mm; radius 11 mm) on the shaft. A mark was made on the white nylon wheel. The mark is there to make sure that the wheel turns at constant speed as the weight drops. A piece of string of about 1 m long is wound over the wheel. To the end of the string the weight is added.

The trick here is to add so much weight that it unwinds slowly and evenly. It shouldn't accelerate or decelerate. The weight should be just enough to overcome the various mechanical resistances to let it slowly rotate at a constant speed.

I used various Neo magnets as weights, they're easy to clamp onto the string. In this case, 2 20x20x10mm neos were needed, that's 70 gram of weight.



Below follows the mathematical derivation of the equation we will use; for those not interested in the derivation, skip the part between '\*\*\*\*\*'.

\*\*\*\*\*

$$1) P = F * v$$

P [W] (power)

F [N] (force)

v [m/s](velocity)

$$2) v = \omega * r$$

$\omega$  [rad/s] (angular velocity)

r [m] (radius of the wheel)

Combining 1) and 2) gives

$$3) P = F * \omega * r$$

$$4) F = m * g$$

m [kg] (mass of the weight)

$$g = 9.81 \text{ m/s}^2$$

Combining 3) and 4) gives

$$5) P = m * g * \omega * r$$

$$6) \omega = 2 * \pi * f$$

$$\pi = 3.141$$

f = frequency of the shaft [Hz]

$$7) f = n/60$$

n = revolutions per minute of the shaft [RPM]

combining 6) and 7) gives

$$8) \omega = 2 * \pi * n / 60$$

combining 8) and 5) gives

$$9) P = m * g * r * 2 * \pi * n / 60$$

This last equation (9) is the one we shall be using.

\*\*\*\*\*

$$P_{\text{loss}} = m * g * r * 2 * \pi * n / 60$$

or

$$P_{\text{loss}} = 1.027 * m * r * n$$

m = mass of the weight [kg]; in this example, m = 0.07 kg (70 gram)

g = 9.81

r = radius of the wheel [m]; in this example, r = 0.011 m (11 mm)

n = RPM of the shaft [RPM]

For various RPMs we can now calculate the power loss in the stator:

n = 100 RPM ;  $P_{\text{loss}} = 0.08 \text{ W}$

n = 200 RPM ;  $P_{\text{loss}} = 0.16 \text{ W}$

n = 500 RPM ;  $P_{\text{loss}} = 0.40 \text{ W}$

n = 1000 RPM ;  $P_{\text{loss}} = 0.79 \text{ W}$

n = 1500 RPM ;  $P_{\text{loss}} = 1.18 \text{ W}$

n = 2000 RPM ;  $P_{\text{loss}} = 1.58 \text{ W}$

The above table shows the various stator losses for different RPMs. As RPM goes up, so does stator loss. The actual force (resistance, drag) remains the same but because of the higher speed at high RPMs, the power dissipated increases. It's immediately obvious there is a linear relationship between RPM and stator losses.

If we also measure the electrically generated power at, say, 500 RPM, we can express the stator losses as a percentage of output power:

At 600 RPM I got about 5 W electrical output power from the generator. At 600 RPM, the stator loss would be:

$$P_{\text{loss}} = 0.07 * 9.81 * 0.011 * 2 * 3.141 * 600 / 60 = 0.47 \text{ W}$$

Hence stator loss as a fraction of output power is  $0.47 / 5 = 0.09$  (9 % of output power.)

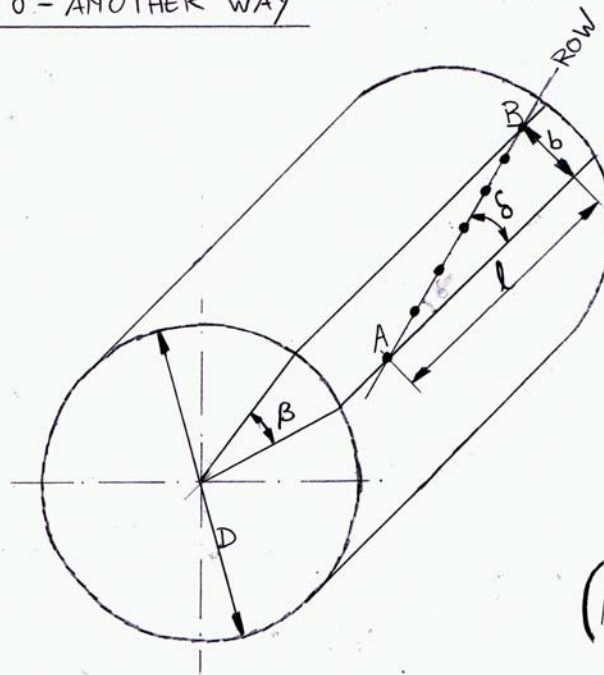
I assume that this is a linear function of output: I.e., double power output (because of double RPMs) leads to double stator losses, but the stator loss stays the same percentage of total output, so it would remain 9 % of output power over the entire RPM range.

In conclusion, it's a pretty simple measurement technique and quick to set up. The calculations are also straightforward yet gives some valuable information into the performance of the generator.

## Appendix B Another way to determine skew angle

CALCULATING  $\delta$  - ANOTHER WAY

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# MAGNETS ON ROW  
 $\delta$  = SKEW ANGLE

A = FIRST MAGNET  
 B = LAST MAGNET

$$b = \frac{\pi \cdot D}{\# \text{SLOTS}}$$

$$\left( \beta = \frac{360^\circ}{\# \text{SLOTS}} \right)$$

$$l^* = l \cdot \frac{\# \text{MAGNETS}}{\# \text{MAGNETS} - 1}$$

$$\tan \delta = \frac{b}{l^*}$$

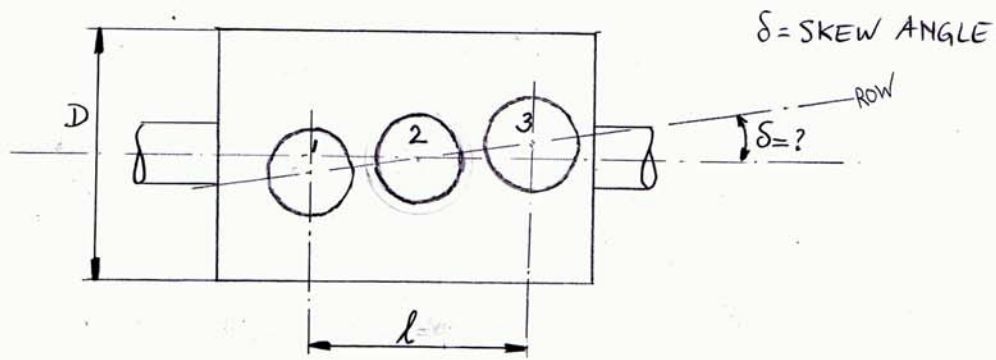
OR:

$$\delta = \text{ARCTAN} \frac{b}{l^*}$$

NOTE: THERE IS A SMALL ERROR SINCE WE TREAT  $b$  AS A STRAIGHT LINE WHERE IN REALITY IT IS AN ARC SEGMENT.

FOR SMALL  $\beta$  AND LARGE  $D$  THE ERROR IS MINIMAL AND NOT WORTH THE COMPLEXITY OF SPHERICAL TRIGONOMETRY.

USING JUST 4 INPUT PARAMETERS (#SLOTS; #MAGNETS PER ROW; ROTOR DIAMETER; DISTANCE  $l$  BETWEEN CENTERS OF THE EXTREME MAGNETS) WE CAN DIRECTLY CALCULATE SKEW ANGLE  $\delta$ .



$D$  = ROTOR DIAMETER<sup>1</sup> (DIAMETER OF MARKING)  
 $l$  = DISTANCE BETWEEN CENTER OF EXTREME MAGNETS

1) DIAMETER ON WHICH THE MARKINGS WILL BE MADE

TASK: DETERMINE CORRECT ANGLE  $\delta$

STEP 1 - CALCULATE THE DISTANCE BETWEEN 2 STATOR TEETH: (b)

$$b = \frac{\pi \cdot D}{\# \text{SLOTS}}$$

EXAMPLE:  $D = 40 \text{ mm}$   
 24 SLOTS/TEETH

$$b = \frac{\pi \cdot 40}{24} = 5,23 \text{ mm.}$$

STEP 2 - CALCULATE THE CORRECTED  $l$  ( $l^*$ ):

$$l^* = l \cdot \frac{\# \text{MAGNETS}}{\# \text{MAGNETS} - 1}$$

WHERE #MAGNETS IS THE NUMBER OF MAGNETS PER ROW

EXAMPLE:  $l = 30 \text{ mm}$   
 #MAGNETS = 3

$$l^* = 30 \cdot \frac{3}{3-1} = 45 \text{ mm.}$$

STEP 3 - CALCULATE ANGLE  $\delta$ :

$$\tan \delta = \frac{b}{l^*} \quad \text{OR}$$

$$\delta = \text{ARCTAN} \frac{b}{l^*}$$

$$\delta = \text{ARCTAN} \frac{5,23}{45} = 6,6^\circ$$

$$\underline{\underline{\delta = 6,6^\circ}}$$

## Appendix C Offset angle for the most common motors

In the table below are the values for the offset angle  $\beta$  when using the offset method. Note these values are for the 'normal' offset method, not offset method 2.

For example, with the offset method, a 4 pole motor that has 36 stator slots should be offset at an angle of 2.5 ° per pole.

# poles	# stator teeth	$\beta$
2	16	11.25 °
2	24	7.5°
2	36	5 °
2	48	3.75 °
4	16	5.625 °
4	24	3.75 °
4	36	2.5 °
4	48	1.875 °
6	16	3.75 °
6	24	2.5 °
6	36	1.67 °
6	48	1.25 °