New Supplier - Hardware Duplication – Some Pitfalls

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Abstract

Companies, for many reasons, often need to task a new supplier to duplicate the design and manufacture of a product that has already been qualified and flown on one of their earlier systems. This paper deals with such a situation. The conflicts that arise when required to include characteristics other than those defining the specific performance and dimensional requirements of the product is explored. While this paper uses the “reverse engineering” of a motor as the means to describe some of these problems, the basic conflicts and conditions can apply to other areas and products.

Introduction

The task was to duplicate the design of 3 different motor configurations. Although the performance specifications were clear and well written, there were no other mechanical design details provided other than the outline dimensions, winding location, and weight. The real challenge came from additional non-performance requirements that were specified. These requirements stemmed from the fact that these motors pre-existed from an earlier build cycle and the program was extremely sensitive to anything which differed from this earlier build in the new design. Winding profile, material, torque constants, resistance, inductance, harmonic distortion, detent torque, and drag torque parameters could not differ from the earlier designs. In addition some of the dimensions had tight tolerances on the OD and ID of the designs (e.g. 13 µm / 0.0005 inch). While these conditions alone might not seem to be in themselves presenting that difficult a design situation certain underlying factors proved otherwise.

In many cases, the task of “reverse engineering” is greatly simplified when there is a unit available which allows for physical inspection and disassembly of the product and the ability to make performance parameter measurements. This was not the case for this exercise.

Designing a duplicate and identical motor under these conditions is daunting at best. Attempting to get all of the performance parameters within specification is problematical. For example, one generally does not design a motor for a specific inductance. Inductance generally falls out as a by-product of the size of the motor, number of winding turns, laminations, etc. The motor’s torque constant Kt ($^{N\text{-}m}/_{amp}$) is generally determined by the motor’s dimensions, materials, air gap and winding turns. The Kt is directly proportional to the number of turns while the inductance is determined by the number of turns squared. So, one can see the dilemma of attempting to converge these two parameters. This was only one of the issues…getting a pure sinusoidal BEMF waveform (< 2% harmonic distortion for the 3, 5th and 7$^{th)}$ was another of the major difficulties to solve.

We will attempt to walk through the iterative and somewhat frustrating process of arriving at a successful series of motors. This paper is not intended as a design review but rather as lessons learned when unrelated design restrictions are added to the design process. The work began in May 2008 and was completed in January 2010.

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Description of motors

Let's call the 3 motor configurations T, G and H to depict the three different motor types. Within each configuration there were minor design changes for various applications. Every motor was to be redundant.

T – This motor configuration was a traditional design with the rotor on the inside and the stator on the outside. The design required a 0.75 slot per pole configuration, i.e. being an 18-slot, 24-pole, 3-phase, redundant machine. This configuration was necessary to meet a requirement that the phases were to be separated by 120 degrees mechanical and the primary and redundant phases to be separated by 60 degrees mechanical. The stator O.D. was given as 9.1427 to 9.1440 cm (3.5995 to 3.6000 inches) and the rotor I.D was 4.8 cm (1.9 inches). Two different stack lengths were required for two designs within this configuration. The motors were to be sinusoidally commutated using resolver and drive electronics which were not part of the task at hand.

G - This configuration was an "inside-out" design, the rotor was on the outside and the stator was on the inside. The configuration for all 3 variations of the G motor design was as above, 24 pole, 18 slot, 3 phase, and redundant. The rotor specified O.D. was 12.6 cm (4.98 inches) and the stator I.D., which mounted to the program's equipment, was given as 6.6040 to 6.6053 cm (2.6000 to 2.6005 inches). The different variations for this configuration were, again, in the stack length and motor performance parameters.

H – These motors were also of an "inside-out" configuration with the same slot design as in the G motor. The primary difference was size and performance parameters. The required rotor O.D. was 15.51 cm (6.105 in) and the specified stator I.D. was between 11.430 to 11.431 cm (4.5000 to 4.5005 inches).

Initial Major Design Restrictions and Design Concerns

Restrictions: The restrictions listed below are not necessarily required by a designer to comply with the performance parameters, and were partly responsible for some of the difficulties encountered during the design process. It was assed that these restrictions were a mandatory requirement of the customer for achieving an "identical" motor.

1 - Magnet material must be Samarium Cobalt

2 - Lamination material must be Carpenter 49 (High Nickel Steel)

3 - Primary and Redundant windings must be spaced at 120 degree intervals for each of the three phases alternating every 60 degree increment

4 - Stators were not to have a skew

5 - 0.75 slot per pole configuration with 18 slots and 24 poles was required.

Had these restrictions not been applied, several design techniques, such as 2.25 slot per pole design (24 poles 54 slots) without the angular separations, which were a more standard configuration for us, might have been used. Another familiar configuration, like a 72 slot (3 slots/pole) with a skew, might have also been employed. Given some degree of dimensional freedom, the Aeroflex zero-cog approach might also have been used thereby guaranteeing a low distortion sinusoidal BEMF waveform with very low drag and detent results. In other words, allowing a manufacturer to use more familiar designs, techniques, and materials while meeting the specific performance and environmental conditions can often lessen problem areas encountered than with the requirement to match exactly the mechanical and material design details as manufactured by another company.

Initial Concerns

1 - In many new design cases, existing laminations and their characteristics can be referred to laminations that have already been established and proven in previous designs. In this case the lamination designs needed to be designed from scratch. The task of deriving the exact geometry of the lamination, so important to duplication, was doubtful. The 0.75 slot/pole format would require investigating the magnetic flux details of the laminations using magnetic FEA analysis tools, which unfortunately is not always that precise. How close would we come?

2 – How would the resistance vs. inductance winding parameters balance against each other, both a function of the motor geometry as well as the copper windings?

3 - What is the BEMF waveform for the specified winding profile? Will it meet the 2% distortion requirement?

Major Parameters for T Motor

The development of the T motor was moderately painless and is illustrated to show how the T motors development was hoped to have also proceeded with the G and H configurations. It was considered painless because the performance parameters were more easily obtained without major modifications to any of the restrictions outlined above. Also, the T motor being the smallest of the 3 configurations made tooling for test easier to handle than the larger motors. Anyone having the experience of mounting rotors and stator with high energy magnets has sooner or later gotten his fingers bitten during the insertion of the rotor into the stator process if the proper tooling was not available. Special tooling “jacks” needed to be designed to allow the assembly into the test fixtures. The basic performance for one of the T motors is listed below:

* Kt > 35 $^{N\text{-}cm}/_{amp}$ (49 $^{in\text{-}oz}/_{amp}$)

* R = 2.6 ohms within 10%, L = 8 mH within 25%

* Friction torque < 1.8 N-cm (2.5 in-oz) at 10 RPM

* Detent torque < 3.5 N-cm (5 in-oz)

A view of this motor is shown in Figure 1.

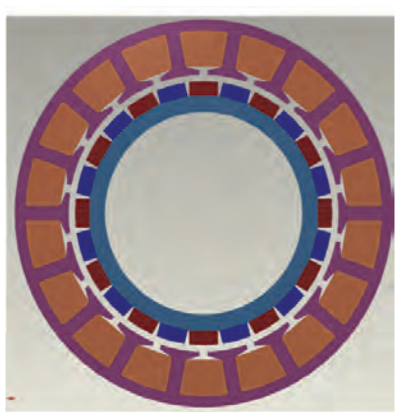


Figure 1. T Motor

A significant obstacle to the development and delivery effort was that Carpenter 49 lamination material was not available in the sheet stock we needed which required a special order with a long delivery schedule. It was decided to make the early prototypes using M-15 lamination material, which was available and whose characteristics were well known to us. The plan was to learn as much as possible before the Carpenter material was received.

The usual manufacturing procedure to make a lamination stack is to stack and bond a number of 0.18 or 0.36-mm (0.007 or 0.014-inch) thick laminations, previously punched to shape, to make the desired stack height required. Since these laminations were of a new design, the technique used for these unique shaped laminations was to bond square sheets of 0.18-mm (0.007-inch) lamination stock to produce the height needed and cut the proper shape with an electrical discharge wire machine (EDM). The sheets are welded on the edges to make the electrical contact needed for the process. The non-recast EDM process produces a lamination stack with very well defined and smooth edges to the dimensions required. Some follow up machining, is required to obtain the 13 µm (0.0005 inch) tolerances required.

As a conservative strategy the thought was to start with a projected high Kt and a high detent prediction as a conservative approach to become familiar with the 0.75 slot per pole configuration. Using the measured data from a prototype M-15 lamination motor, we would then modify the air gap and turns to bring both parameters into specification. The FEA Kt and detent predictions as well as their ultimate measured parameters are shown in Figures 2 and 3.

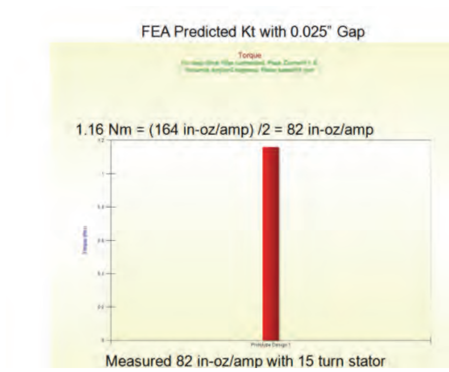


Figure 2. T Motor FEA Kt Prediction

Initial T motor Kt analysis and measurement data (Note: the program does not allow for separate primary and secondary windings so the 116 $^{N\text{-}cm}/_{amp}$ (164 $^{in\text{-}oz}/_{amp}$) value is for both primary and secondary energized).

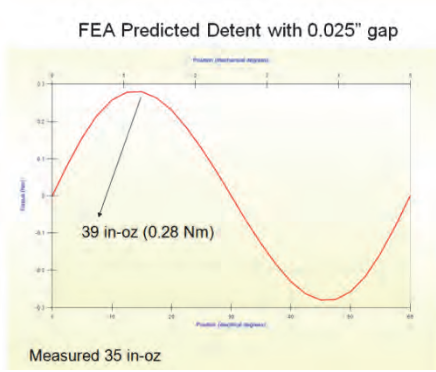


Figure 3. Initial T Motor Detent Analysis and Measurement

As can be seen the detent prediction was 28 N-cm (39 in-oz) and the measured detent on the prototype was 25 N-cm (35 in-oz). The Kt prediction and the measure Kt were spot on with 58 $^{N\text{-}cm}/_{amp}$ (82 $^{in\text{-}oz}/_{amp}$). Both of these were very high as expected compared with the required values of 3.5 N-cm (5 in-oz) and 35 $^{N\text{-}cm}/_{amp}$ (49 $^{in\text{-}oz}/_{amp}$). With these actual values increasing the air gap from 0.635 to 1.52 mm (0.025 to

0.060 inch) was predicted to achieve the detent and Kt parameters needed. The Carpenter material was now on hand and with the following air gap modification the results in Figures 4 were obtained with no surprises and were very close to the required values.

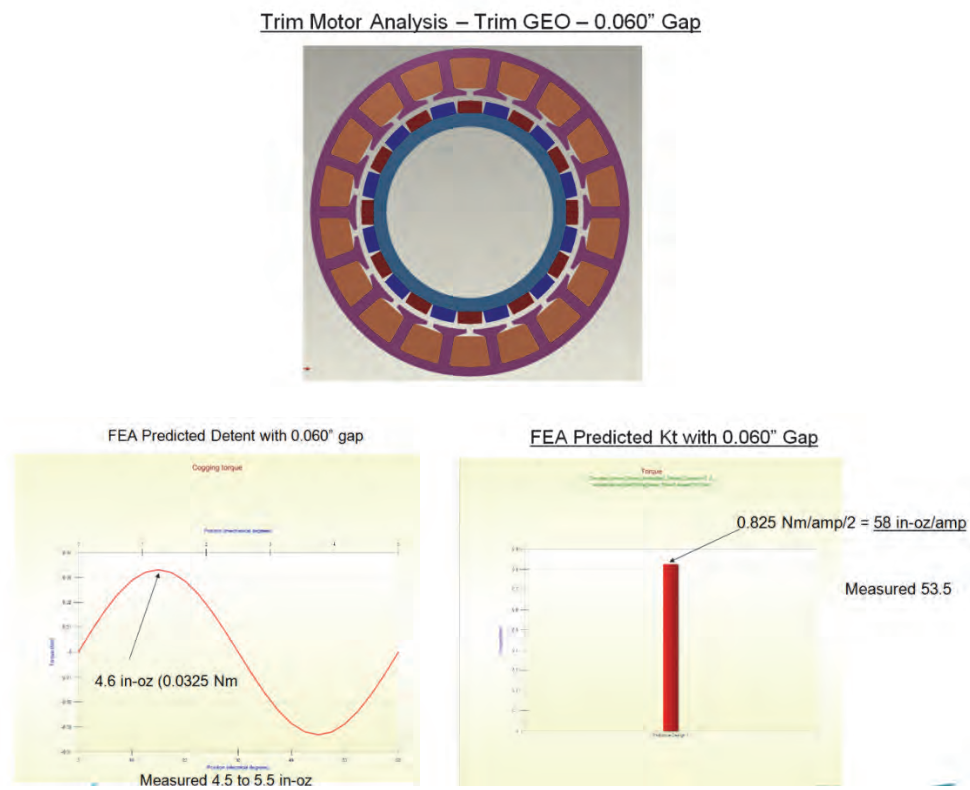


Figure 4. T motor Kt and detent with 1.52-mm (0.060-inch) mangetic air gap

To get some perspective on the windings, in order to achieve the required 2.6-ohm resistance it was necessary to use a winding of 5 wires of #29AWG and 3 of 28AWG for a total of 8 strands per coil. The inductance was fortunately within the range required (8 mH). It did, however, take several iterations of the winding turns to arrive at the final values of the design. So far so good!

The T motor BEMF curves are shown in Figure 5. The harmonic content was measured using the FFT functions of the scope (not shown).

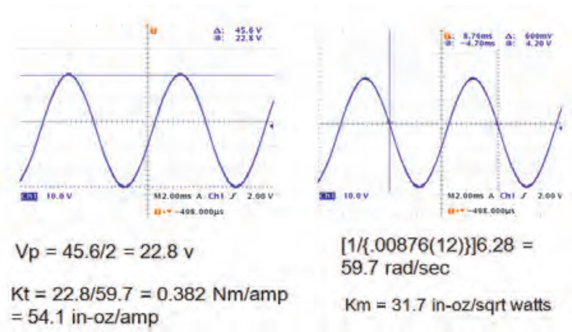


Figure 5. BEMF waveforms with 1.52-mm (0.060-inch) magnetic air gap

The spectrum analysis showed the harmonics to be less that the 2% limit. This motor performed as expected and promised similar expectations that the G and H motors would be equally accommodating…so it was hoped.

Major Motor Parameters for G Motor

The G and H motors were of an inside out design (rotor on the outside). This was not considered as an obstacle for obtaining the same results as was obtained for the T motors. The form factor for the G motors is illustrated in Figure 6.

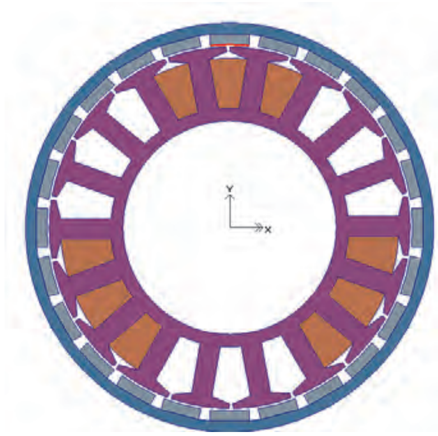


Figure 6. G motor

Major Specification Parameters

* Kt > 61 $^{N\text{-}cm}/_{amp}$ (87 $^{in\text{-}oz}/_{amp}$)

* R = 1.17 ohms within 10%, L = 3.58mH within 30%

* Friction torque < 11 $^{N\text{-}cm}/_{amp}$ (15 $^{in\text{-}oz}/_{amp}$) at 105 RPM

* Detent torque < 19 N-cm (27 in-oz)

* % Harmonic Distortion < 2%

The initial lamination stack was already made with M-15 material and was not used since the Carpenter material had now arrived. (This becomes significant later on.)

The G motor, as with the T motor, began with a known smaller than expected air gap of 0.635 mm (0.025 inch). The FEA Kt was predicted to be 79.44 $^{N\text{-}cm}/_{amp}$ (112.5 $^{in\text{-}oz}/_{amp}$) and the measured was 80.36 $^{N\text{-}cm}/_{amp}$ (113.8 $^{in\text{-}oz}/_{amp}$) on this first prototype. The detent was predicted as 65 N-cm (92 in-oz). and the detent was measured at 64 N-cm (90 in-oz). The wave form, however, was not looking too good as seen in Figure 7:

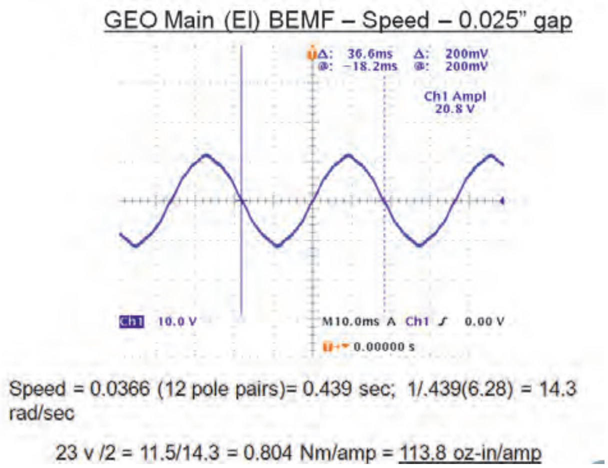


Figure 7. G motor BEMF waveform

The shape of the BEMF wave looked less like a perfect sine wave and harmonic distortion was viewed as a potential problem. The gap was then opened to 1.27 mm (0.050 inch) to lower the detent as well as the Kt with the hope this would also improve the distortion issue. The results were as follows:

Kt dropped 80.36 $^{\text{N-cm}}/_{\text{amp}}$ (113.8 $^{\text{in-oz}}/_{\text{amp}}$) to 65.2 $^{\text{N-cm}}/_{\text{amp}}$ (92.4 $^{\text{in-oz}}/_{\text{amp}}$)

Detent dropped from 69 N-cm (98 in-oz) to approximately 18 – 20 N-cm (25 – 28 in-oz)

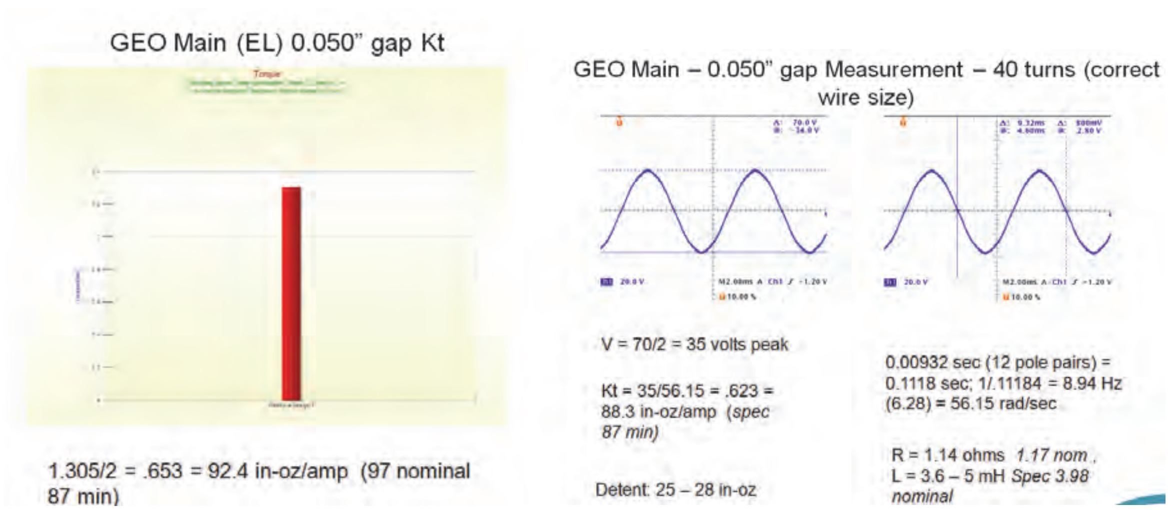
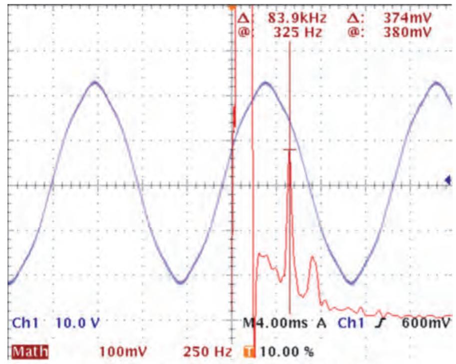


Figure 8. Motor with 1.27-mm (0.050-inch) air gap

The waveform became a little less peaked but nevertheless was still apparently distorted and a concern. This was caused by the 5th harmonic and was above the 2% spec and was unacceptable.



Scale expanded: Fifth Harmonic = 0.380 volts

% distortion = 0.380/ 13.6(100) = 2.79 %

Figure 9. G motor Harmonic distortion

It was postulated that the lamination shape was perhaps deficient and that also shaping of the rotor magnets would perhaps contribute to improving the harmonic distortion. Inspection of the FEA analysis (Figure 10) did not show magnetic saturation in any part of the lamination material.

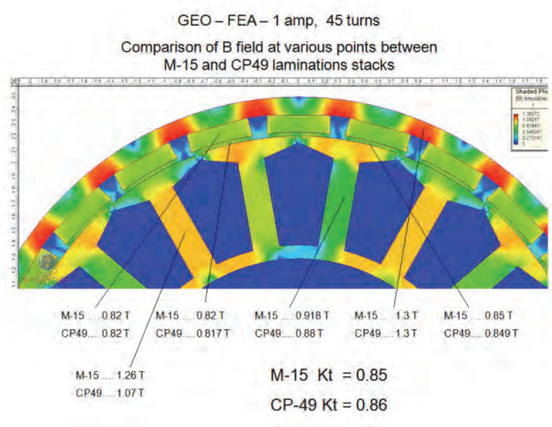


Figure 10. Flux Density Comparison of Lamination Materials

There were several other issues other than the distortion to address such as inductance and detent. It was hoped that correcting these deficiencies would help correct the distortion issues. A brief description of the inductance and detent improvement efforts are summarized in bullet form:

- The inductance was too high so the turns were reduced from 45 to 38 (inductance is a function of the turns squared). To compensate for the loss of Kt due to the turns reduction, decrease the air gap. This worked as intended for the inductance and Kt, but the detent was now 3 times higher than required due to the air gap reduction.
- A small skew was introduced into the lamination structure which reduces detent. The detent was now OK but the Kt dropped below the desired level due to the skew.
- Used higher energy product Neodymium magnets instead of samarium cobalt. Kt improved but still too low
- Bring coils to 40 turns to improve Kt with inductance still OK; attempt to go back to Samarium Cobalt magnets…Kt just 0.7 $^{N\text{-}cm}/_{amp}$ (1 $^{in\text{-}oz}/_{amp}$) below the minimum; inductance marginal….parameters too marginal to attempt production. Went back to180 C Neodymium, ultimately used for production.
- Back to distortion issue, solving may resolve the Kt, detent and inductance issues.

- Distortion remained above the 2% level for all of the above modifications

Some of the lamination styles that were tried to reduce the harmonic distortion are shown in Figure 11. Recognize that this is a time consuming process to build the stacks, EDM the laminations, machine, and coat with an insulator as well as wind and insert the coils.

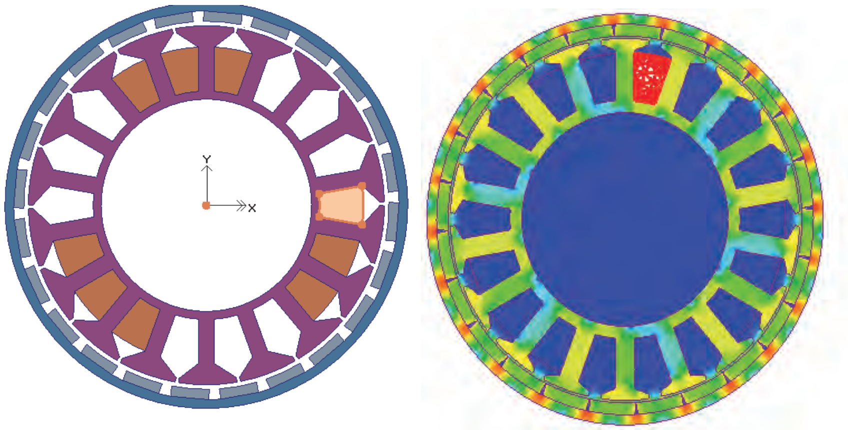


Figure 11. Pole shoe shaping, tooth gap, and magnetic span variations were tried.

FEA analysis alone was not considered a viable approach alone in that the difference of distortion was only about 1%. Shapes tried were: wide boot height to narrow boot height, wider tooth widths, wide tooth to tooth gap to narrow tooth to tooth gap, wide magnet to magnet spacing to narrow magnet to magnet spacing - all provided no change in harmonic distortion to bring values below the 2% limit. There were also models made with the edges of the magnets rounded.

At some point defeat must be acknowledged and a call for help initiated, be it self imposed or externally suggested. The suggestion was to call in help from an recommended and established consultant. This was accomplished and was followed by an impressive 14-page report from the consultant. The report offered a solution. The proposed solution was so deceptively simple that it was welcomed with great enthusiasm. At the same time, the report gratifyingly duplicated the non-sinusoidal BEMF results we were observing, as well as duplicating other motor parameters, so high expectations were anticipated.

The solution based on a detailed FEA analysis (using a different analysis tool than the ones we were using) was to make the magnets as flat rectangles rather than the having the normal surface curvature mirroring the stator curvature as in traditional designs.

A test motor was then wound, magnets purchased, and tested with the wonderful results that all of the parameters, including harmonic distortion were now within specification. A bonus feature was the detent was reduced from 18 to 9 N-cm (25 to 13 in-oz) giving a good margin.

What then followed was the production manufacture and testing of the modified rotor design. *Total disbelief*….the motor performed as poorly as it had before the rotor magnet change. What had happened? Our thoughts went back to the CP49 and the M-15 materials. We always felt (just experience), despite the FEA analysis showing the reasonable flux paths within the two materials (Figure 10) that the M-15 was the proper way to go given past experience with the CP49 Hi nickel materials annealing variations.

What had happened is that the flat magnets were mistakenly tested with the original M-15 stator that, as you recall, was originally made but never used. The M-15 lamination stack had gotten mixed up with the CP49 lamination stack. To prove that the model that was successful with the flat magnets was using M-15, a known M-15 stator stack was then wound and tested. Back to the good results tested!

Tests with older curved rotors using the M-15 stator also showed the same excellent results indicating that the issue was with the CP49 material and not anything else. The lesson learned here is that FEA analysis is a path towards good designs but is not the end all. Practical machines with practical materials must ultimately be the final say. We stayed with the flat magnets because we had purchased the entire programs supply. In retrospect, had we had been able to have gone with the M-15 material (usually our preferred material for this type of motor) most of these delays and perturbations relative to the harmonics would not have occurred or been necessary. A photo of the G motor is shown in Figure 13.

The data in Figure 12 shows the distortion improvement with the M-15 material from 2.79% to 1.57%.

Fundamental 18.4 volts; 5^{th} Harmonic at 0.26 volts

Harmonic distortion = 0.260/18.4 = 0.0157 = 1.57%

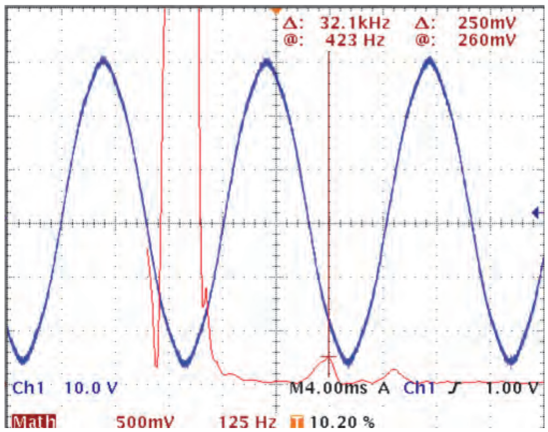


Figure 12. M-15 Harmonic Distortion Data for the M-15 Material

Figure 13. Photo of the G Motor - Rotor is encapsulated in titanium ring

Major Motor Parameters for H Motor

The H motor, also an inside out design, presented with a whole different set of issues. The initial design using CP49 and Samarium Cobalt magnets resulted so enormous a difference between performance and requirements that an initial drastic step needed to be taken before any iteration would be possible.

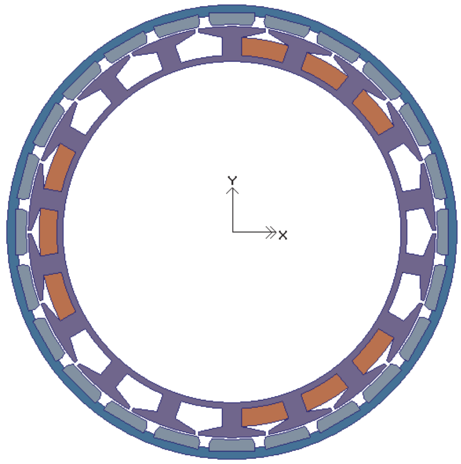


Figure 14. Geometry of the H motor

The Kt, detent and distortion below represent the performance requirements:

* Kt > 56 N-cm/amp (80 in-oz/amp)

* R = 0.84 ohms within 7%, L = 2.28 mH within 30%

* Friction torque < 19 N-cm (27 in-oz) at 272 RPM

* Detent torque < 15 N-cm (21 in-oz)

* % Harmonic Distortion < 8%

The initial lamination stack was made with CP49 material. The waveform and detent were much worse than seen of the G motor and the decision to use M-15 at the outset was immediately made. The result for the first CP49 H motor is shown in Figure15.

The Kt was measured at 183 N-cm/amp (259 in-oz/amp) and the detent was over 141 N-cm (200 in-oz).

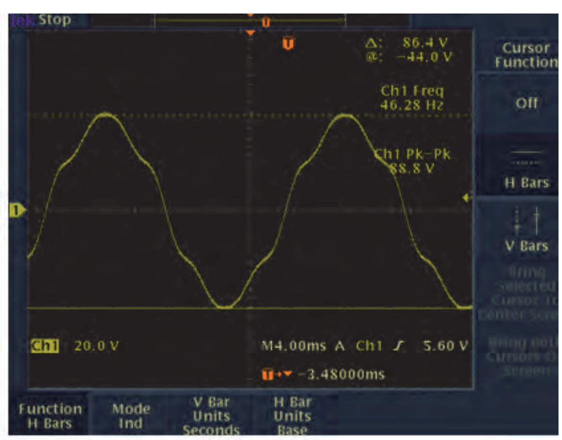


Figure 15. BEMF Curve with CP 49 and 0.635-mm (0.025-inch) air gap

The first attempt using M-15 material resulted in a Kt of about 79.8 N-cm/amp (113 in-oz/amp) with the detent being approximately 64 N-cm (91 in-oz). The decision to skew the stator was made to reduce the detent and smooth the waveform with the results shown in Figure 16.

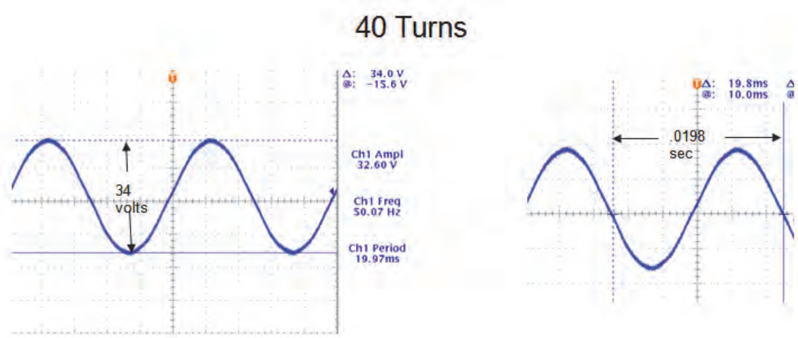


Figure 16. BEMF for H motor with M-15 Material

Again, exploring the flux density differences between the FEA analyses of the materials (Figure 17), there again did not seem to be much difference to cause this great disparity of performance for the H motor due to material as seen between Figures 15 and 16.

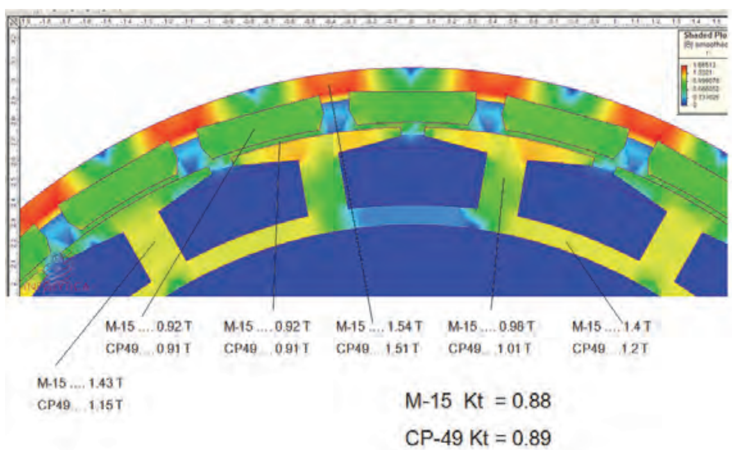


Figure 17. Comparison of lamination material for the H motor

This motor was most critical in terms of balancing the flux carrying capability of the laminations with the amount of copper area available affecting Kt, inductance and resistance. The motor needed a full complement of 40 turns (6 of #28 and 2 of #29 AWG wire) to conform to the specification requirements (Kt, resistance and inductance). A bonus of the skew was that the detent torque was reduced to about $^{1}/_{3}$ of specified allowable which was well received.

The wire would not fit within the area needed for the lamination design. (Several tooth widths were tried to arrive at the final configuration). Not a quick task when the programming, EDM process, lamination coating and winding time factors are considered. As a result, the motor could not be wound and inserted in the normal production manner. Normally, a string of coils per phase is wound on a mandrel, loosely tied to hold each coil of 40 turns together and then inserted into the stator as whole coils placed wire by wire into each stator slot. In this case the slot fill factor is so high that this would not allow the coil bundles to fit into the slots, just missing by a few percent. The stator needed to be hand wound, turn by turn, into the slots allowing each turn to be tightly fit into the slot maximizing the space available with just the right length of wire to make the resistance specified. Under these conditions it is necessary to have a very patient and amiable technician in your employ!

Figure 18. Photograph of the H motor with the lamination skew

Summary

With the above trades and compromises, all of the motors styles ultimately made their way into successful production cycles.

In summary, what was needed to be changed from the 5 initial restrictions (which were not specific to the performance requirements) in order to meet the performance criteria is as follows:

1 - Magnet material must be Samarium Cobalt - In one case (G motor) higher energy product Neodymium magnets needed to be substituted.

2 - Lamination material must be Carpenter 49 (High Nickel Steel) – In two cases silicon steel was needed to replace the high nickel steel.

3 - Primary and Redundant windings to be mechanically spaced at 120 degree intervals for each of the three phases alternating every 60 degree increment - Preserved

4 - Stators were not to have a skew – In one case (H motor) a partial skew was required for detent and waveform conformance.

5 - Parameters must meet the tight specification values – In one case some relief was required for the inductance values

6 - 0.75 slot per pole configuration with 18 slots and 24 poles was required. - Preserved

The major lesson learned from this project is to have give and take discussions between parties to determine which of the specification requirements are truly pertinent to the performance as opposed to those which would be nice to have based on existing hardware.