Performance Analysis of the Tesla Model 3 Electric Motor using MotorXP-PM

Part 1

JUNE 2020

About MotorXP-PM

MotorXP-PM is a powerful software for design and analysis of modern permanent magnet (PM) machines including brushless DC (BLDC), surface-mount (SPM) and interior magnet (IPM) motors.

The software is built from ground up to address the modern PM motor design challenges as well as the motor drive aspect which is tightly linked to the high-performance motor control requirements. For more information, please visit http://motorxp.com.

In this whitepaper, a Tesla Model 3 (2018) rear drive electric motor is used as an example to highlight some of the MotorXP-PM capabilities.

This experimental study is organized into two parts: In part one (this article) exploratory research and high level conclusions are presented; In a follow up part 2 of the series, the detailed use of motorXP software during the study is presented as a tutorial.

About Tesla Model 3 IPM motor

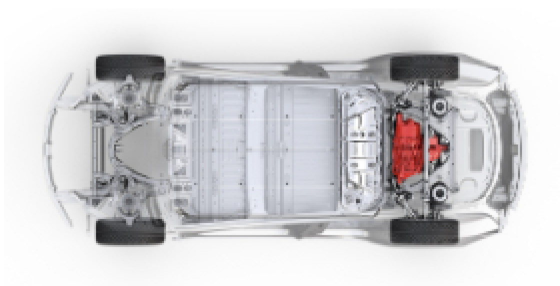

Figure 1: Tesla Model 3 Rear Motor Drive [source, tesla.com]

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The subject motor is employed in the Tesla Model 3 rear drive unit. The published data suggests the single drive system delivers 190-211kW and 420-450Nm at its peak [2][3].

This experimental study focuses on the accuracy of MotorXP-PM software when it comes to the characteristics and performance analysis of the electric motor. Both public data and experiment data were used for the comparisons and analysis. The study was carried out independently and the result is published here for references only.

Construction

The subject of the study was acquired from a used vehicle part market marked as 2018 model year long range version. To reconstruct the motor geometry to be imported to the MotorXP software, a tear-down was performed to separate the motor components from the rest of the drive system.

Figure 2: Tesla Model 3 Rear Drive Unit

The motor has been since further separated to reveal the stator and rotor assemblies.

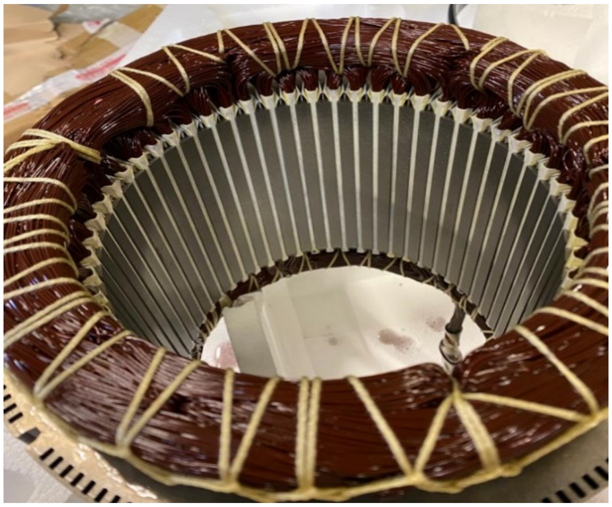

Figure 3: Stator Assembly

With proper tools, the geometry of the stator is then exported to DXF file (with cooling features around the outer perimeter reasonably simplified) and the stator parameters are tabulated as below.

Number of stator slots	54
Stator lamination outer diameter	225 mm
Stator lamination inner diameter	151.3 mm
Lamination stack length	134 mm
Lamination stacking factor (estimated)	0.95

Table 1: Parameters for stator lamination stack

The following parameters were measured from the motor with proper instruments.

End winding axial overhang	40 mm
Number of phases	3
Parallel paths	3
Number of turns	2
Phase resistance at 20°C	0.00475 Ω
Number of pole pairs	3

Table 2: Parameters measured from motor

The rotor subassembly of the Tesla Model 3 electric motor is shown in Figure 4.

Figure 4: Rotor Assembly

Further tear down reveals the lamination.

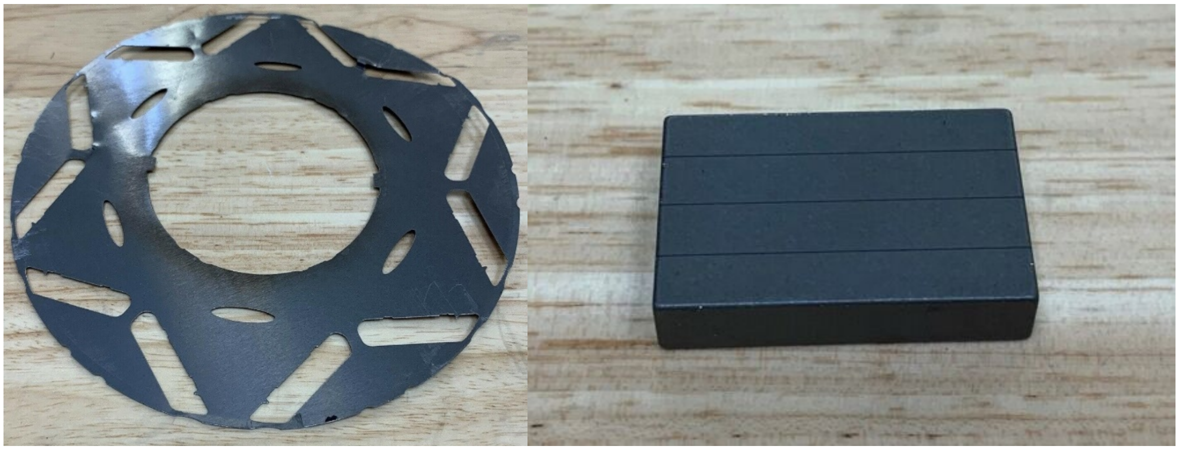

Figure 5: Rotor Lamination and Magnet

The following parameters were measured from the rotor lamination sheet and the magnet. A DXF file then is derived for later steps. It is interesting to mention that the 4 segments in the magnet does NOT form a Halbach array; Both sides of the magnet measured the same magnetic field evenly. The segmentation of the magnet helps reduce the eddy current thus self-heating of the magnet themselves.

Rotor lamination outer diameter	149.9 mm
Rotor lamination inner diameter	70 mm
Magnet dimension	33x21.5x6.5mm

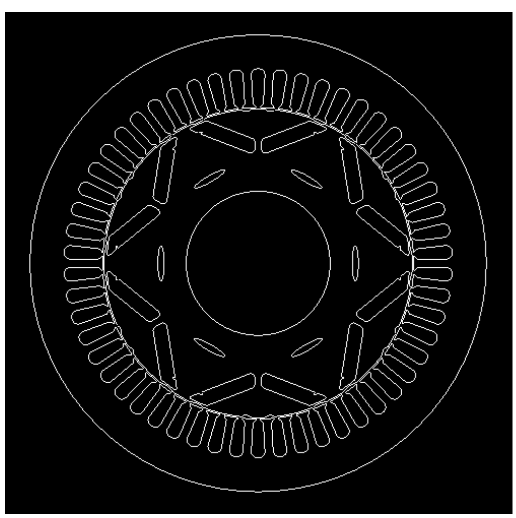

Figure 6: Combined DXF of the Stator & Rotor Geometry

Project Setup

The DXF files obtained during the teardown are then imported in the MotorXP Design Studio. The winding information, rotor skew information is manually put in to complete the problem setup. The complete procedure will be presented in the part 2 of the white paper series.

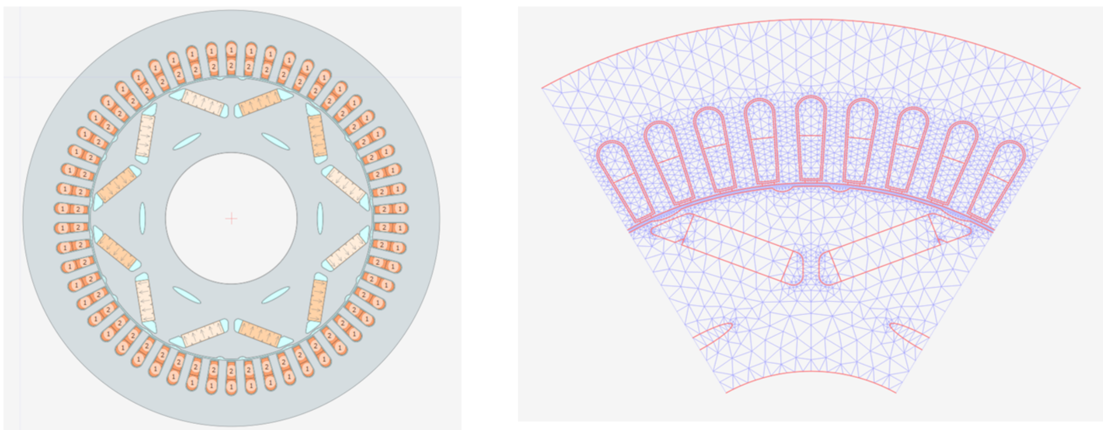

Figure 7: Imported motor cross section and mesh in MotorXP Design Studio

No Load Characteristics Measurement

Without proper signal setup it is not possible to perform the full dyno test on the motor using its original motor drive. However some characters of the motor, like the back emf constant, can be derived from the no load tests to determine winding patterns and the materials for laminations and magnets.

The back EMF of the motor was measured by spinning the motor using a third-party motor drive in open-loop mode. The measurements were performed at 222 RMP with magnet at room temperature of 20°C. The measured peak of line-to-line back EMF is determined to be 42 Vp/kRPM.

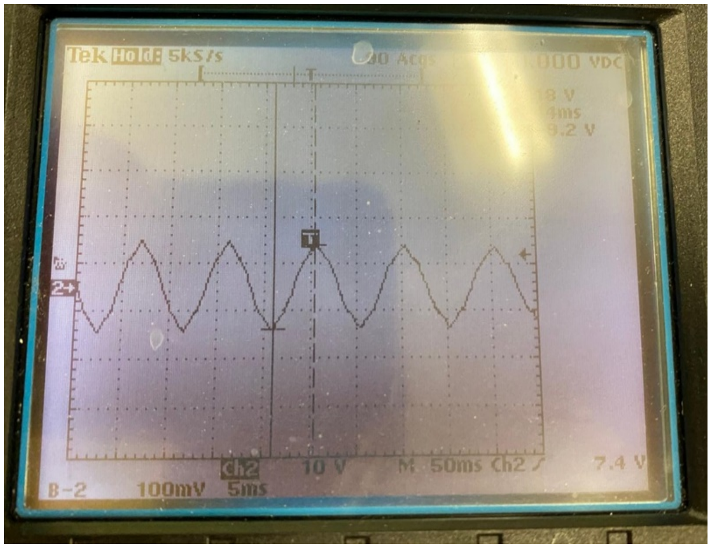

Figure 8: Measured back EMF waveform at 222 RMP

In Motor XP-PM it is easy to calculate line-to-line back EMF by just subtracting one phase value from another. Figure 9 represents simulated line-to-line back EMF waveform at 1000 rpm. The simulated waveform matches the measurement both in waveform shapes and the peak quantity. This test, in junction with the DC resistance measurements, verifies that the basic information (geometry, winding pattern, material) that were used in the problem setup are close to the actual design.

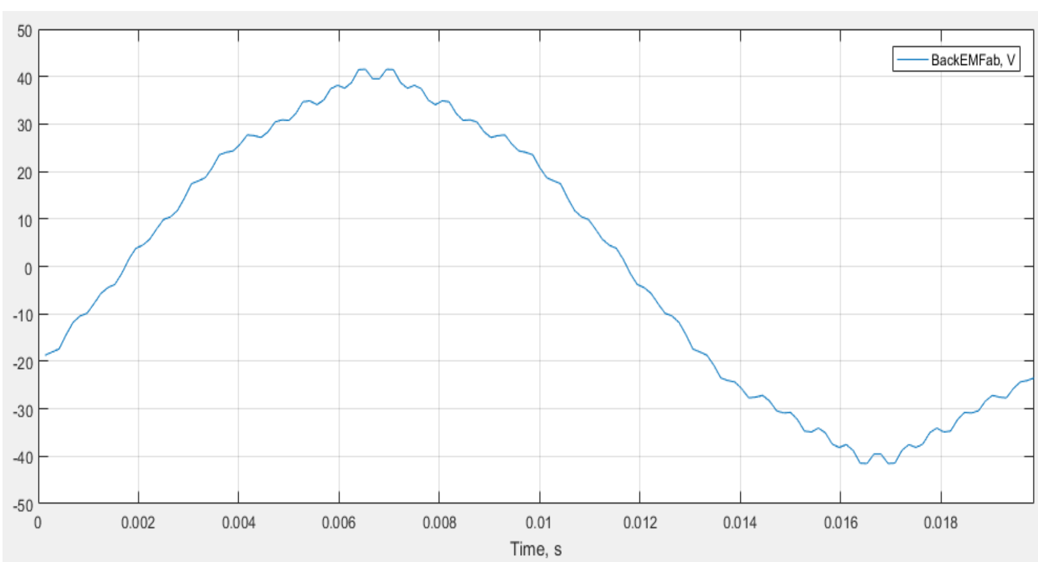

Figure 9: Simulated line-to-line back-EMF waveform at 1000 rpm

Simulation Under Load

With the back emf and dc resistance verified by the static analysis, further simulations can be carried out with confidence.

To determine the optimal operating point to achieve the peak torque/power of the machine, a DQ analysis was first carried out (see DQ Analysis section) to determine the optimal current and angle to achieve these goals listed in the public data. This operating point is then fed back to the Magnetostatic analysis for more accurate FEA analysis.

Figure 10 shows simulation results for operation with maximum output power and maximum torque according to [1]. Advance angle was adjusted so the maximum torque is produced with minimum possible current of 953 A. The resulting optimum advance angle value is 53.5 electrical degrees.

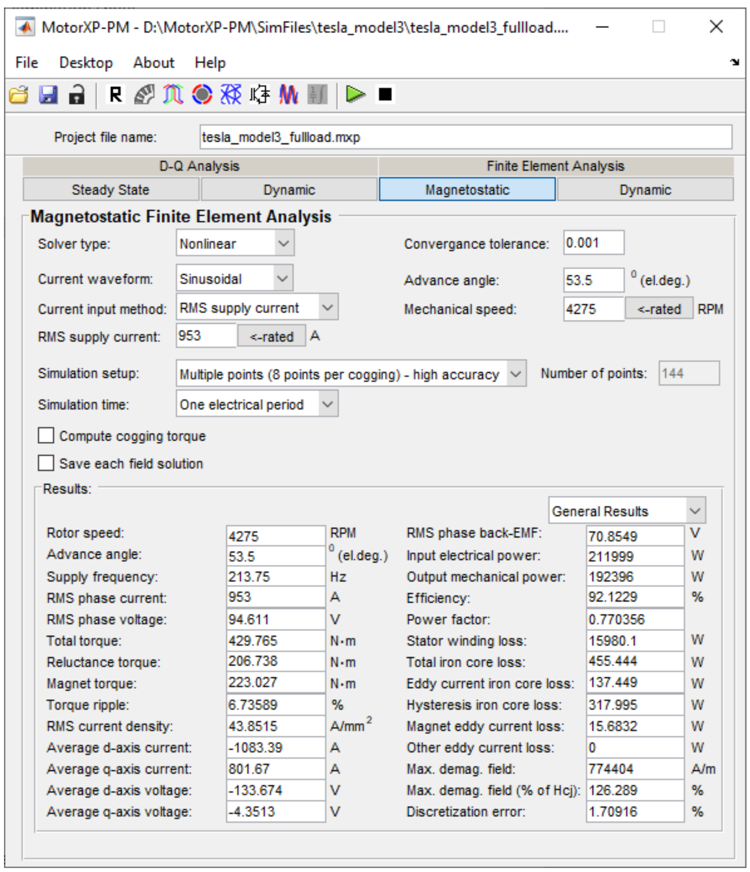

Figure 10: Magnetostatic Analysis setup and simulation results of Tesla Model 3 motor for operation with maximum output power and maximum torque

This simulation verifies the published data on [2][3] about the peak power and peak torque to a very close proximity. The predicted 430Nm and 192kW can be achieved at close to

1000Arms phase current under 94.61V of RMS voltage, which translates to 231Vdc minimum bus voltage.

Magnetostatic Analysis

Most of the characters of the motor can be determined by fast Magnetostatic analysis for a first principle examination. Besides the torque, voltage, current and loss information, some underlying quantities can be extracted from this type of analysis too. For example, the flux density distribution plot is calculated to make sure that the motor is not saturated during operation. Figure 11 represents the flux density distribution. It aims to study the flux distribution at different parts of the motor and to predict safety and efficiency of the motor by increasing torque and current accordingly.

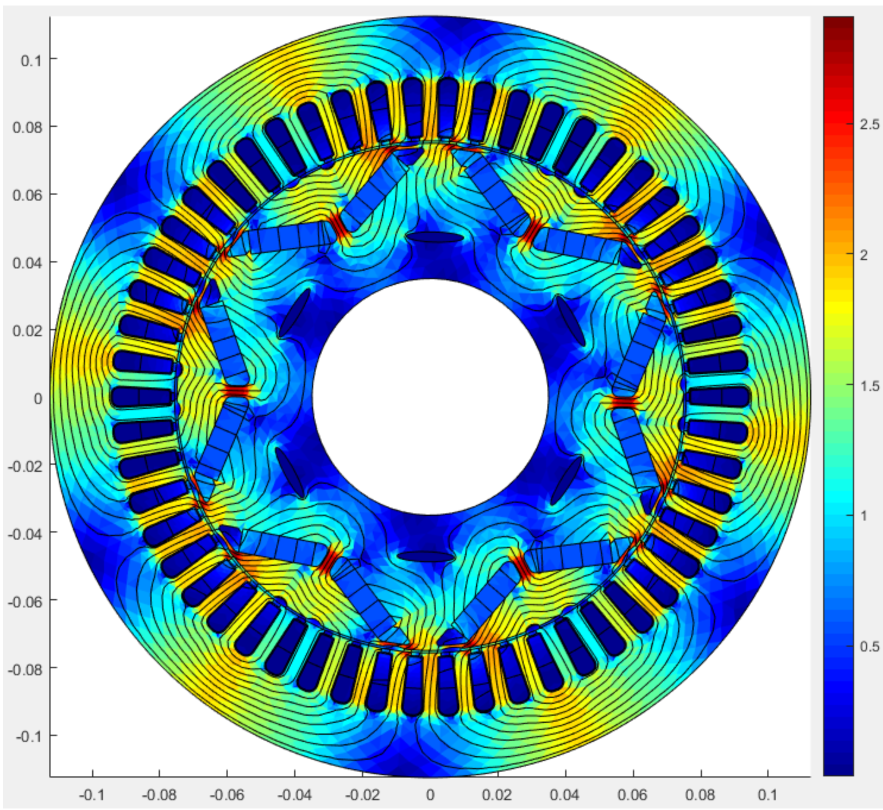

Figure 11: Flux density distribution of Tesla Model 3 motor for operation with maximum output power and maximum torque

DQ Analysis

DQ models are used widely by control engineers for algorithm design and stability analysis. One of the distinguishing features of the MotorXP is the capability to map out the full DQ parameter spectrum across the full operational range. By building the DQ parameter map once using the highly accurate FEA engine, it would allow the easy generation of the efficiency maps and variety of operational charts and envelopes at any operating points with superior accuracy. Control engineers can also export the DQ parameters or Id / Iq tables to easily build control algorithms with maximum torque per amp or max efficiency at each operation point.

Some exemplary charts are presented below.

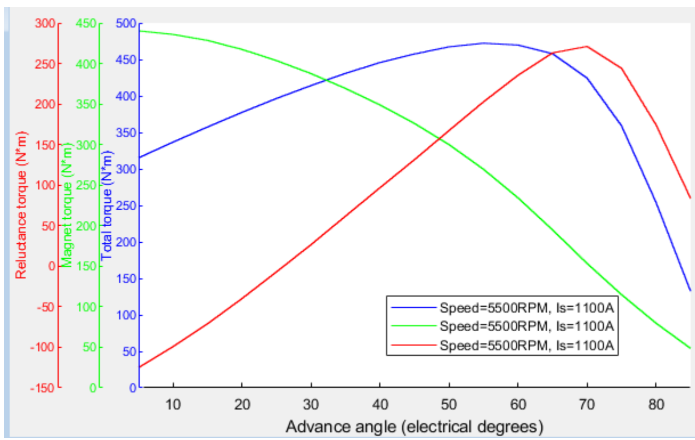

Figure 12: Analysis chart: Magnet Torque, Reluctance Torque and Total Torque vs. Advance Angle

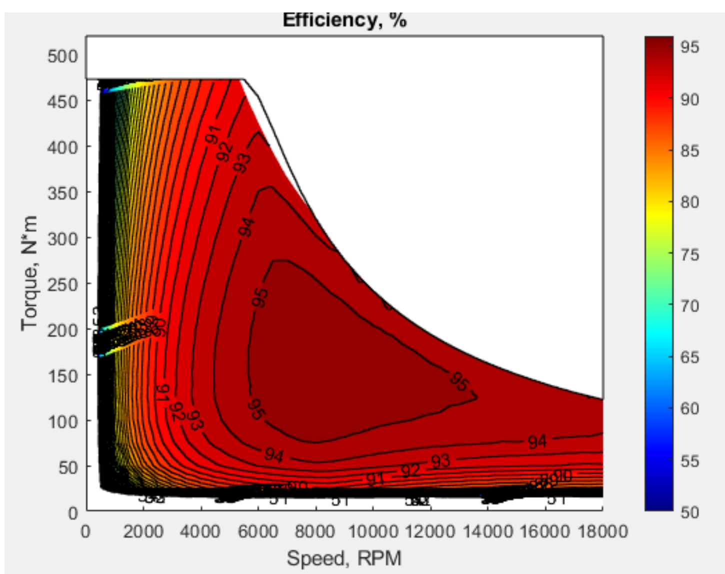

Figure 13: Analysis chart: Efficiency

Dynamic Finite Element Analysis

Dynamic FEA option provides the most accurate details of the machine simulation. It provides the extra accuracy (comparing to magnetostatic analysis) by considering the dynamic terms in the Maxwell equations.

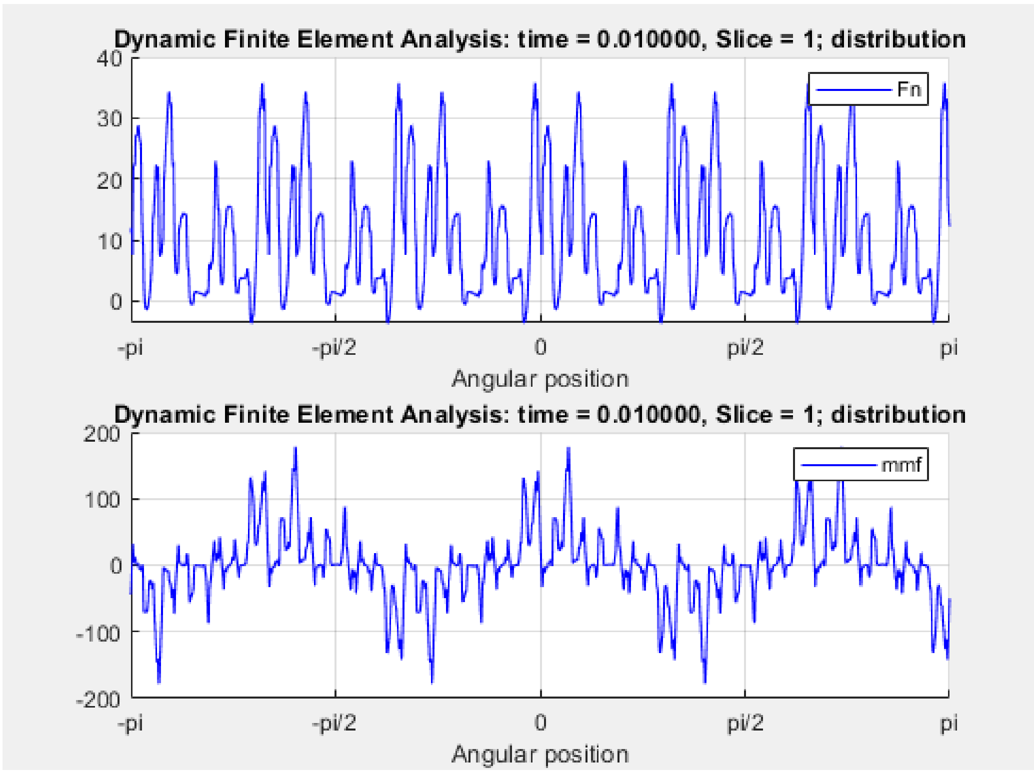

Figure 14: Example of Dynamic FEA results – radial force and airgap mmf

Summary

In this first part of the 2-part series of the Tesla Model 3 rear motor analysis using MotorXP-PM, high level capability of the software is demonstrated by comparing the simulated results with the available motor data from publication and measurements. Some simulation results are presented as an example to predict the operational envelope of the model 3 drive system.

The project used in this whitepaper is available as a part of examples in the MotorXP-PM software package. A trial version of the software can be requested from https://motorxp.com/downloads/.

References

[1]. MOTORTREND - 2018 Tesla Model 3 Dual Motor Performance Quick Test Review. https://www.motortrend.com/cars/tesla/model-3/2018/2018-tesla-model-3-dual-motor-performance-quick-test-review/

[2]. New Tesla Model 3 details revealed by EPA: ~80 kWh battery pack, 258 hp, and more. https://electrek.co/2017/08/07/tesla-model-3-new-details-revealed/#jp-carousel-49431

[3]. Wikipedia https://en.wikipedia.org/wiki/Tesla_Model_3