Brushed DC Motor Noise Above 1 GHz

2018 DoD E3 Review

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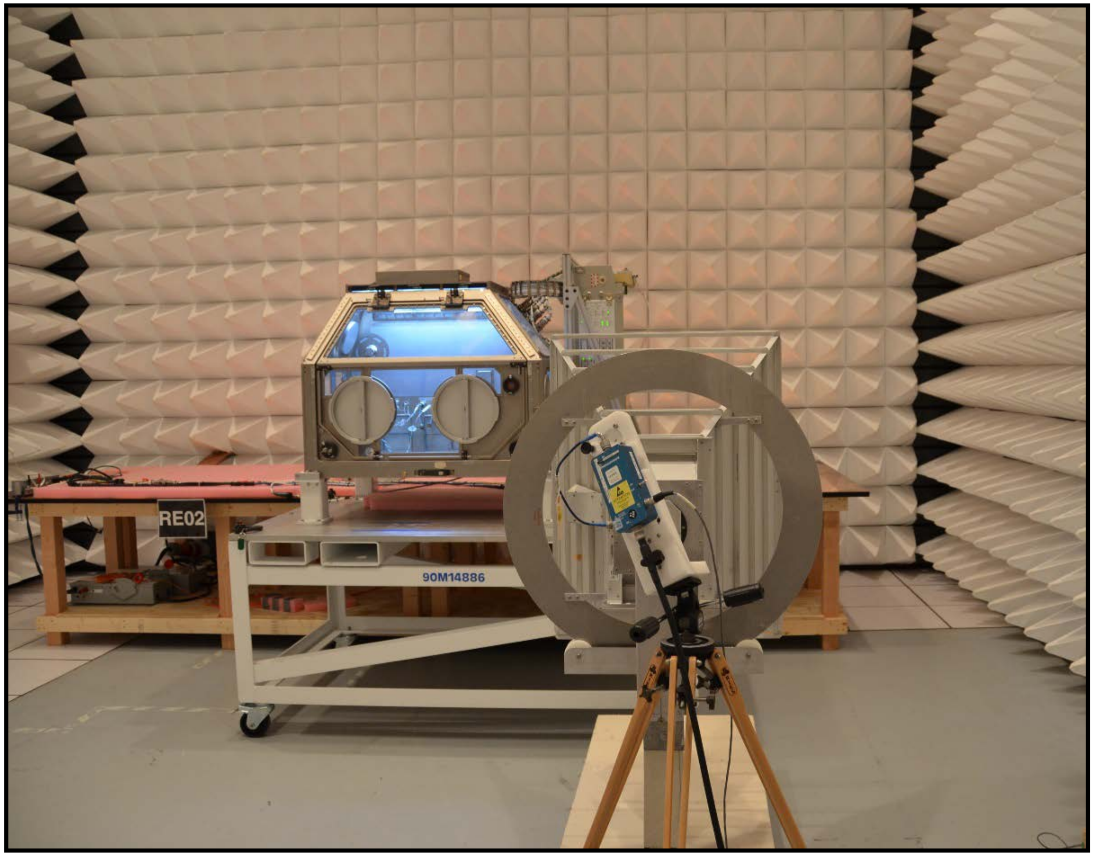
Agenda

- Marshall EMI Test Facility (METF) Overview
- Brushed DC Motor Overview
- Literature Review
- System Level Radiated Emissions
- Component Radiated Emissions
- Additional Data with COTS Hardware
- Conclusion

MSFC EMI Test Facility

Test Capabilities:

- Electromagnetic Interference (EMI)
  - MIL-STD-461C - G
- Lightning
  - RTCA DO-160 Section 22
  - MIL-STD-461G
- Electrostatic Discharge (ESD)
  - MIL-STD-461G
  - IEC 61000-4-2
- Power Quality
  - SSP 52051 (ISS Power Quality Spec)



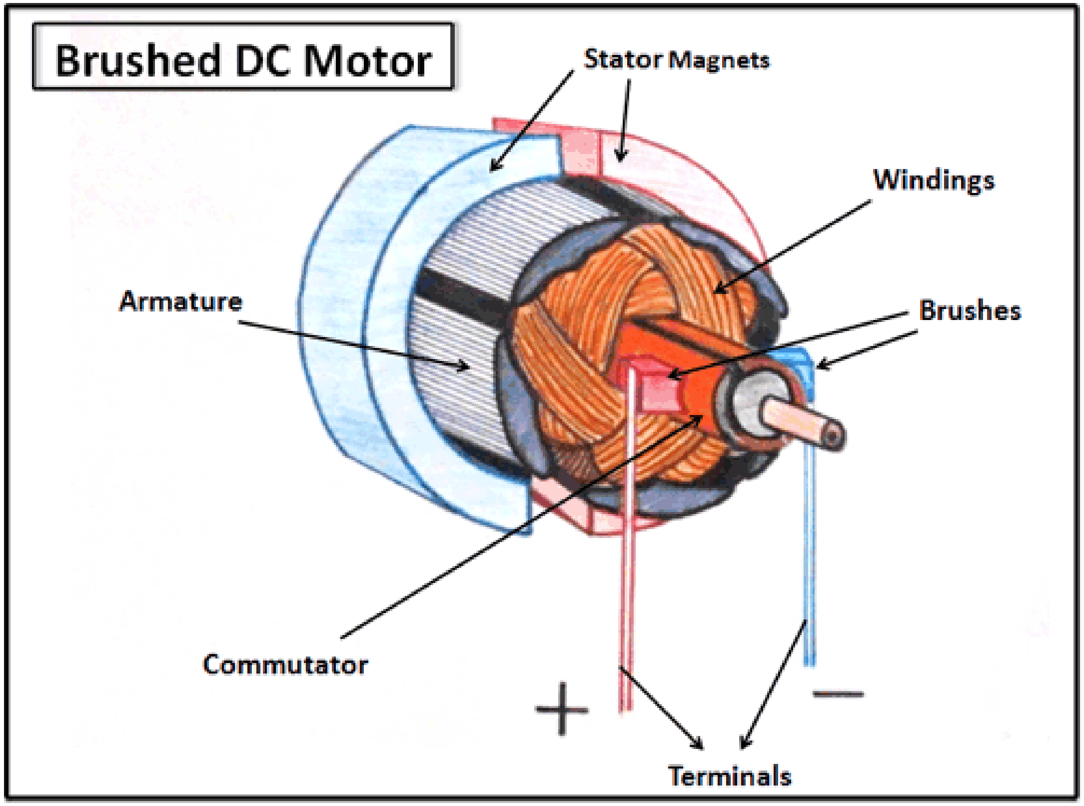
Brushed DC Motor Overview

Advantages

- Fairly inexpensive compared to other designs
- Easy to Operate / Simple Control Circuitry

Disadvantages

- Maintenance required for long term use, particularly brushes
- Electrically Noisy, both Conducted and Radiated



Literature Review

- *Radio Frequency Interference of Electric Motors and Controls*
  - M.A. Jabbar, M.A. Rahman
  - Conference Record of the IEEE Industry Applications Society Annual Meeting; 1989
- *Commutator Motors as EMI Sources*
  - F. Pavlovcic
  - SPEEDAM 2010
- *Discharging Arcs in Commutation Motors*
  - F. Pavlovcic
  - International Conference on Power Electronics; 2010
- *New Behavioral Modeling of EMI for DC Motors Applied to EMC Characterization*
  - R.Kahoul, Y. Azzouz, B.Ravelo, B. Mazari
  - IEEE Transactions on Industrial Electronics; 2013

Literature Review

- *Radio Frequency Interference of Electric Motors and Controls*
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discussed. Suppression components and their use in **HF and VHF ranges** including their dispositions are also discussed. Aspects and

RADIO FREQUENCY INTERFERENCE OF ELECTRIC MOTORS AND CONTROLS

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Abstract :

All motorized appliances are to comply with laws and rules regarding generation of radio frequency interference which can affect radio and television broadcasts. Elimination or suppression of such noise to permissible levels is difficult and expensive. Various aspects of motor design, like electric / magnetic loading ratio, commutation and sparking, brushes and brush-gears etc., which all affect R.F.I., are discussed. Suppression components and their use in HF and VHF ranges including their dispositions are also discussed. Aspects and techniques of measurement of noise level are also highlighted.

I. INTRODUCTION

In recent years motorized electric appliances have found their way to household use in fast increasing numbers. Safe and sound operation of such appliances and power tools is therefore of great importance. In most countries these aspects of safety and sound operation are controlled by national and international standards prepared by standard institutions and technical approval Boards, like BS, BEAB and SISIR. All equipment and appliance manufacturers are therefore required to see that their appliance comply with the requirements of these relevant standards. Implications of complying with such requirements are increased manufacturing costs and operational complexities; and in view of the intense competition among manufacturers, these extra costs and complexities become very important in the marketing strategy.

There are two aspects of compliance with the requirements of standards mentioned above [1 - 4], legal and safety requirements. These relate to radio frequency noise generation by appliances and consumer safety relating to electric shock, hazard and mechanical accidents. This paper discusses, in general terms, problems of RADIO FREQUENCY INTERFERENCE caused by electric motors used in appliances and indicates some possible solutions.

II. R.F.I. LIMITS

All motorized appliances and power tools may cause interference with both civilian and military broadcasts and receptions of radio and television signals. This aspect is subject to legal requirements and compliance is required with limits set by laws. In many countries there are legal requirements to limit these interferences within prescribed limits over a range of frequencies.

The requirements of R.F.I. for both continuous and discontinuous interference are specified in BS800 and EEC 76/889. The noise level is to be measured in dB (uv) over 1uv for terminal voltage measurement over the frequency range 150 kHz - 30 MHz, and dB (pW) for terminal power in the range 30 MHz - 300 MHz. In the final European directive which came into effect on 1st January 1984, these limits were slightly readjusted along with changes in measuring techniques.

Techniques and methods of measurement are described in BS800 and BS727 in details and therefore not discussed in this paper. However, the requirements of R.F.I. for continuous interference over the specified frequency ranges are shown in Tables 1 and 2 in the appendix. In continuous production batch testing is required when statistical sampling is permitted, but single item test can be done in which case all required levels have to be reduced by 2 dB.

Similar requirements are also specified for discontinuous interference due to intermittent operation of tools and appliances, switches and controls etc.

III. PROBLEMS OF R.F.I.

Small commutator motors generate radio frequency interference which unless suppressed will cause interference with commercial, civilian and military broadcasts and communications. It is a very difficult problem for the motor designer to control or suppress such interference at the design stage. Fortunately, however, most of R.F.I. problems are related to commutation, brush-gears and magnetic conditions. Sources of R.F.I. noise can be associated mainly with [5]

- sparking or arcing
- rapid current commutation
- rapid change of magnetic fields
- making and breaking of contacts
- rapid switching of controllers
- bad physical contacts
- capacitor discharge

Identification of exact nature of R.F.I. generation is uncertain and therefore elimination or reduction is also extremely difficult. After extensive experimental studies, it has been established that the following measures can be effective against either generation or propagation of R.F.I. noise.

* A properly designed motor w.r.t.
  - magnetic and thermal balance
  - commutation problems
  - brush grades/types
  - brush guides and clinching
  - brush spring loading
  - commutator type and finish
  - dynamic balance of the rotor
  - operating speed of the motor

Literature Review

- *Prediction of Radiated Emissions From DC Motors*
  - C. Suriano, J. Suriano, G. Thiele, T. Holmes

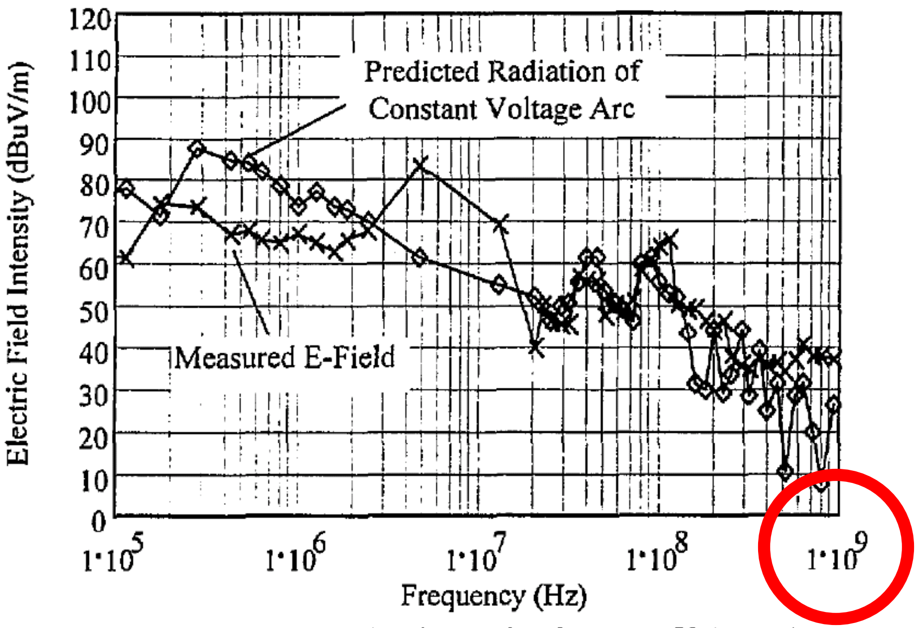

Figure 15. Comparison of Radiation for Constant Voltage Arc

Prediction of Radiated Emissions From DC Motors

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Abstract: DC motors are known sources of radio frequency electromagnetic noise produced by arcing at the motor brushes. A simplified model of electromagnetic radiation from a DC motor and associated wiring harness is introduced and compared to measurements. This model relates motor arc characteristics to the radio frequency emissions of the motor and wiring circuitry which can be used to guide engineers in the design process. This technique is intended to form the basis for a motor design aid.

INTRODUCTION

By the nature of their operation DC motors are notorious sources of RF emissions. Radiation at a fixed frequency from a typical small DC motor is shown in Figure 1. This particular motor has ten commutator bar segments and should undergo ten distinct arcing event cycles during one revolution. As can be seen in the trace, there are twenty distinct regularly spaced events during a single revolution of the armature. A single commutation cycle has two transient spikes either because of lack of synchronism in the commutation from the two brushes or because one set of spikes represents the start of commutation and the other the end of commutation. Commutation arcing results in broadband coherent noise which can impact a variety of electronic systems.

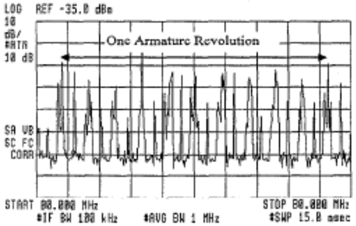

Figure 1. Trace of DC Motor Radiation at Fixed Frequency

Previous studies have characterized the conditions that are present during commutation [1-3] and have examined the arcing using empirical methods [4-6]. Studies of radio frequency noise have been limited to empirical studies [7] and predictions of conducted emissions [8]. This study examines the radiated emissions using simplified mathematical models of the commutation process, the arcing characteristics, and the radiation characteristics of the motor and wiring harness. Suppression components for filtering RF emissions can also be included in the model.

This model incorporates three stages as shown in Figure 2. The motor/commutation model determines the arc duration from a time domain solution of the motor electrical equations. A fourier transform of the arc voltage is supplied to the radio frequency model where it is used with an impedance model of the wiring harness to compute common mode current from the motor. The common mode current is used with a simple monopole antenna model of the wiring harness to predict the radiation intensity. This study explains the mechanisms by which DC motors radiate RF noise, the relationship of design parameters to the noise, and is useful for optimization of both the motor and suppression circuitry.

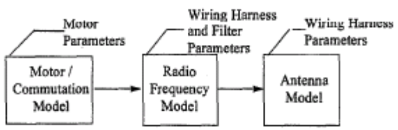

Figure 2. Block Diagram of Motor Radiation Model Stages

COMMUTATION MODEL

Arcing between brushes and commutator bars in a DC motor provides a broadband forcing function which results in radiated emissions from the motor. To predict the duration of the arc which exists during the period of abrupt current reversal, this study utilizes a numerically solved time domain circuit network model similar to [2]. This model includes information on the motor design and operating conditions. Modifications to the motor design impact the solution of the commutation current and the arc characteristics, and hence the radiated noise.

An initial steady state current level is determined based on the emperical and theoretical parameters of the DC motor. This provides the initial condition which is used to calculate the currents when the motor begins commutating as shown in

Literature Review

- *New Behavioral Modeling of EMI for DC Motors Applied to EMC Characterization*
  - R.Kahoul, Y. Azzouz, B.Ravelo, B. Mazari

and speed. EMIs are measured and analyzed in radio frequencies from 100 kHz to 108 MHz. The behavioral model proposed is

New Behavioral Modeling of EMI for DC Motors Applied to EMC Characterization

Rami Kahoul, Yacine Azzouz, Blaise Ravelo, *Member, IEEE*, and Belahcene Mazari

Abstract—**This paper is dealing with the characterization of the electromagnetic compatibility of the direct current (dc) motors. It acts as the complements of the works achieved recently for the modeling of dc motor impedances. The contact mechanisms between the brushes and the collector blades which cause the electromagnetic interferences (EMIs) are explained and modeled. Knowing the operating conditions of the current intensity, voltage, and speed, EMIs are measured and analyzed in radio frequencies from 100 kHz to 108 MHz. The behavioral model proposed is based on Norton's equivalent circuit where the motor is assumed as a current generator representing the EMI source, associated in parallel with its impedance model. Specific identification methods are used to quantify the EMI model parameters. It is shown that the model is in good correlation with the measurement. The model was applied for estimating the conducted EMI generated by a dc motor with its filters, and then, validations with different dc motors were performed.**

Index Terms—**Behavioral model, direct current (dc) motor, electromagnetic compatibility (EMC), electromagnetic interference (EMI), frequency modeling, low frequency (LF)/high frequency (HF)/radio frequency (RF) spectrum, validation process.**

I. Introduction

DESPITE the thermal, mechanical, and electromagnetic constraints, the direct current (dc) motors remain the most used machines in the industry [1], as is the case of automotive applications. Basically, the dc motor with separate excitation is modeled by the serial equivalent circuit R_w–L_w–E shown in Fig. 1, where R_w and L_w represent respectively the lumped resistance and inductance of the rotor windings and E is the back electromotive force (EMF) induced by the stator.

Such a model is only valid in low frequencies (LFs), less than 1 MHz, for functional simulations where the electromagnetic, thermal, and mechanical constraints are not critical. In fact, the mechanical commutations of the collector blades, fixed to the rotor, through the carbon brushes, fixed to the stator, are the

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Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

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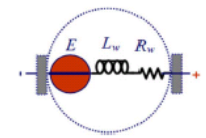


Fig. 1. Usual model of dc motor with separating excitation (functional representation).

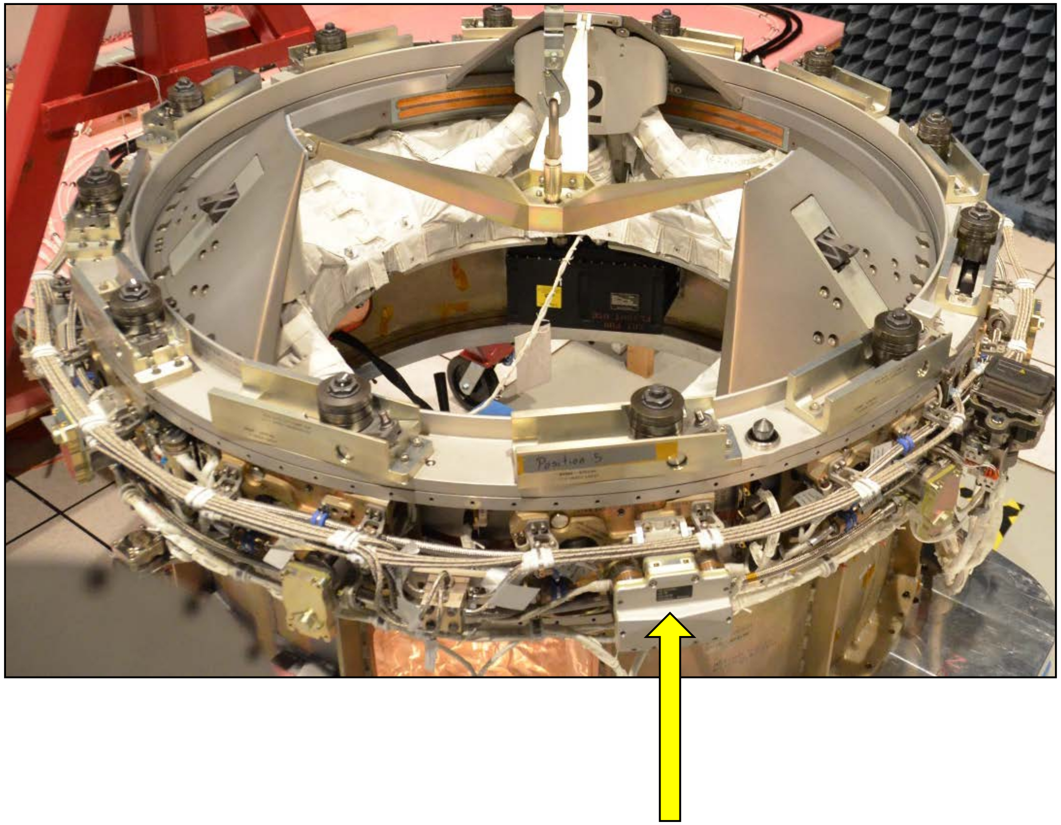
critical points of these constraints [2]. On the one hand, they cause brush usury and make it as the hottest area of the motor. The current intensities are very important in that area and create then an additional heating [3]. On the other hand, they affect the electrical behavior of the motor and, thus, the electromagnetic compatibility (EMC) at different frequency bands from diverse ways.

The second issue attracted particularly our interest. As stated in [4], a first aspect of the motor EMC, namely, the evolution of its impedance at high frequency (HF), was investigated. The motor was assumed as a passive circuit regarding the electromagnetic interference (EMI). Its armature was modeled owing to a behavioral approach based on the fitting with the impedance measurement at different positions along one complete revolution (2π) and with different conditions of voltage and current. The proposed model combines RLC resonant cells where the parameter calculation was optimized using appropriated numerical methods. Such an RLC circuit is sufficient to model the typically brushless motors such as permanent-magnet synchronous motors and induction motors. However, in the case of brushed motors, the second aspect of EMC as the generation of microarcs (microdischarges) that propagate in conducted mode and radiate undesirably in the radio frequency (RF) band [100 kHz–108 MHz] cannot be provided by such a circuit. A rigorous analysis of the EMI spectrums is necessary in this band, where the Automotive EMC standards are very critical. In the same paper, we briefly introduced this aspect through a simplified model of the EMI source and without presenting the approach followed.

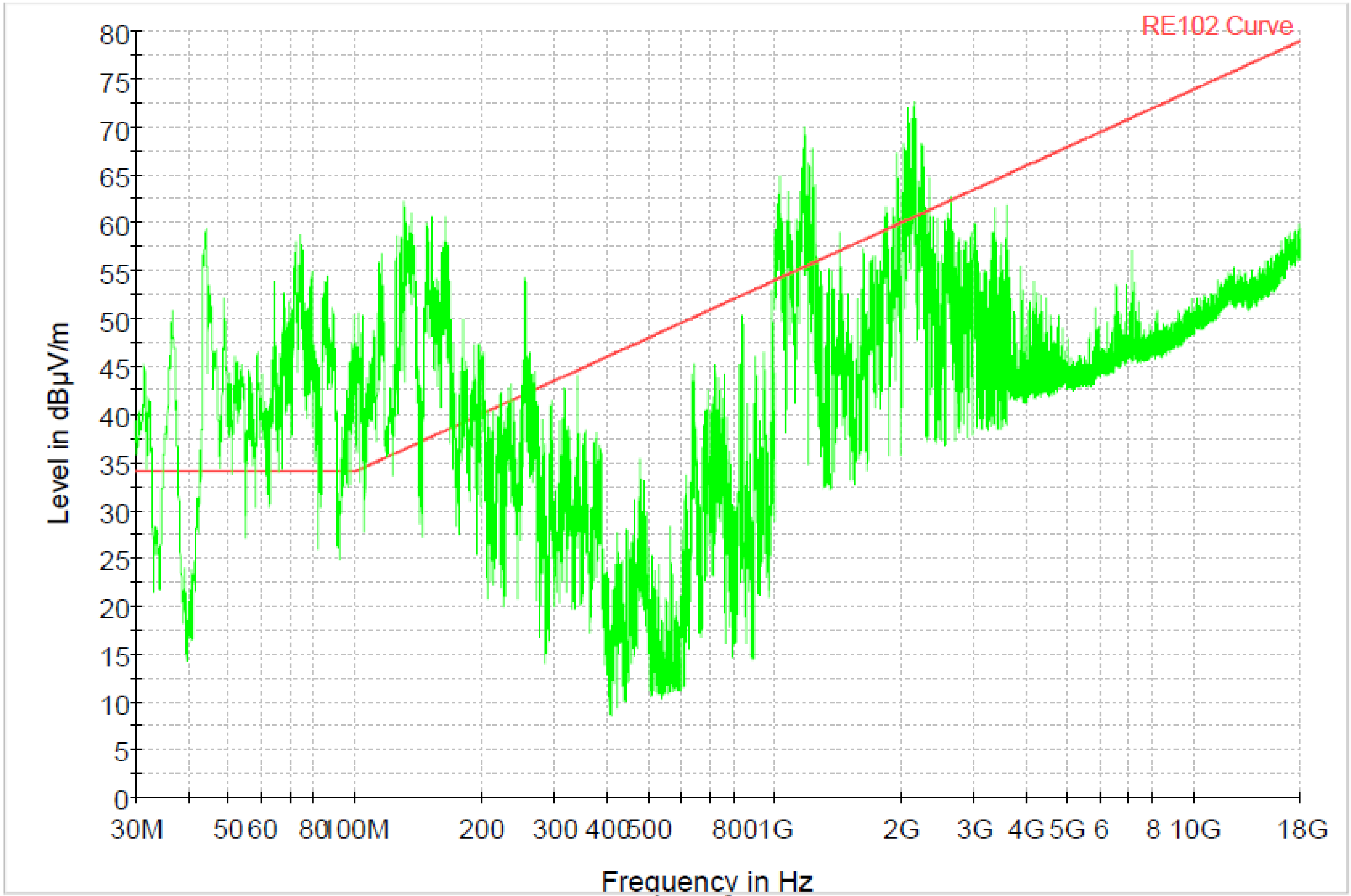
In this paper, we develop the systematic approach followed for an empirical modeling reliable of the EMI generation. Initially, this behavioral approach, based on the RF EMI measurement, was justified by the limitations and difficulties that we have encountered during the application of a purely physical approach to modeling a complex phenomenon such as the generation of microarcs. However, as illustrated in this paper, the

System Level Radiated Emissions

- Test Setup
  - MIL-STD-461F Test Setup
  - RE102 Performed:
    - 30 MHz – 18 GHz
  - Max hold, Multiple Fast Sweeps Method used
  - Brushed DC Motors (all 4) exercised throughout full range of travel while capturing emissions data



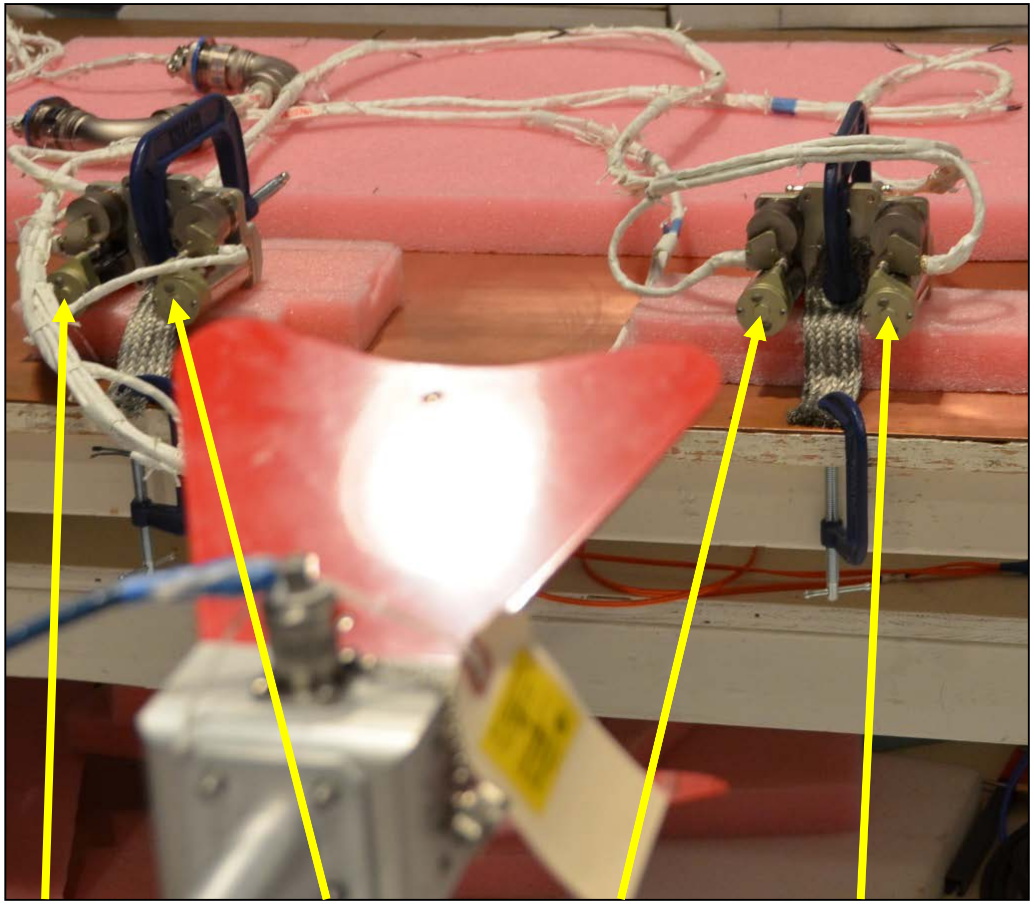
1st Qual System RE102 Results: 4 motors operating



- Multiple Troubleshooting steps taken
  - Shielding integrity of Motor Cabling
  - Bonding integrity of Motor housing/assembly
  - Added 10 dB attenuator at Preamp to verify no Overload condition existed
  - Removed Preamp to verify broadband noise not causing oscillations
- Probing revealed most RF energy coming from motor housing assembly

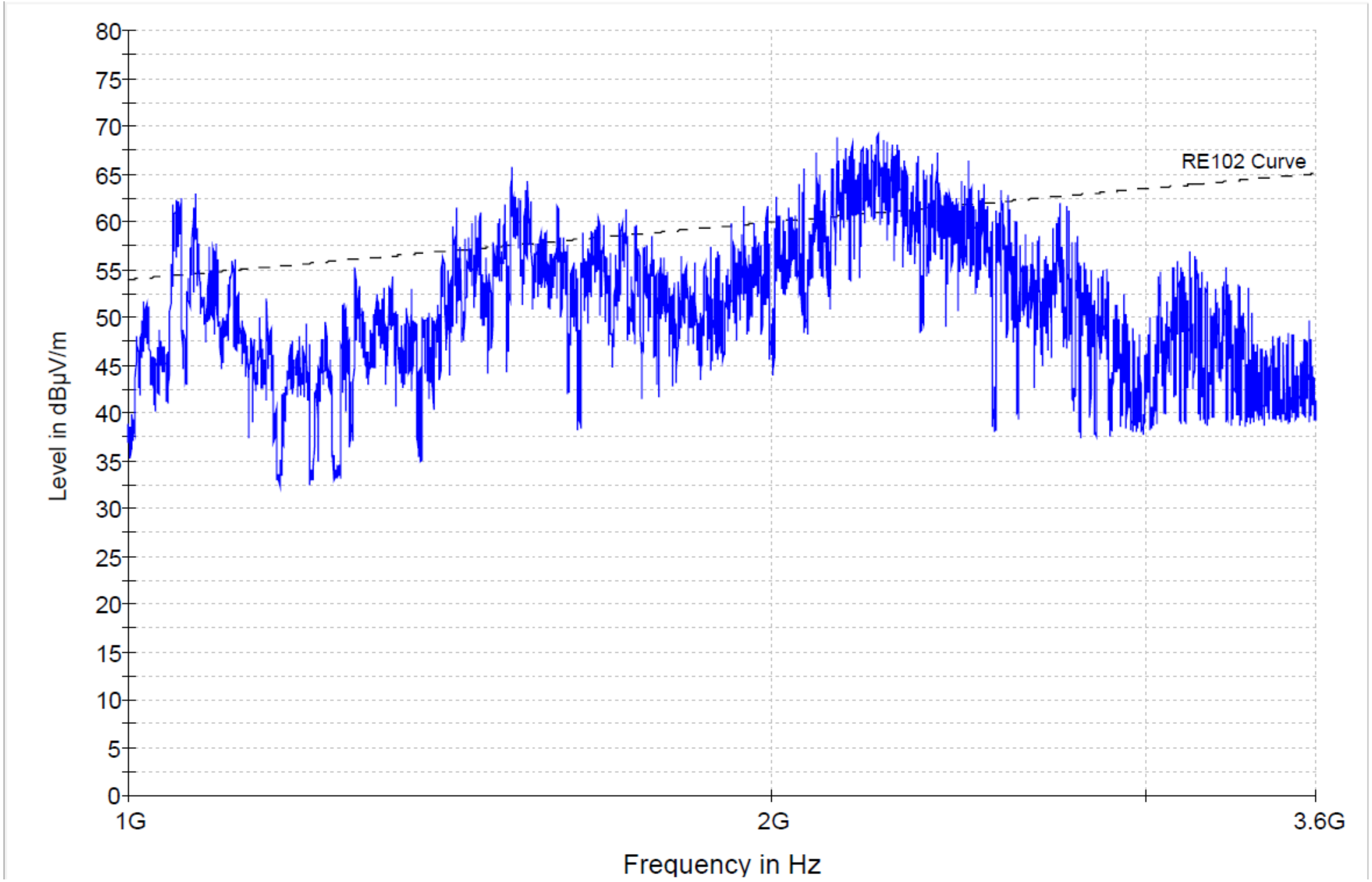
Component Level Radiated Emissions

- Motor Only Testing
  - 2 sets of Motor Assemblies
  - Independent motor control (A1, B1, A2, B2)
  - Radiated Emissions data taken 1 – 3.6 GHz
  - Significant over-limit emissions observed

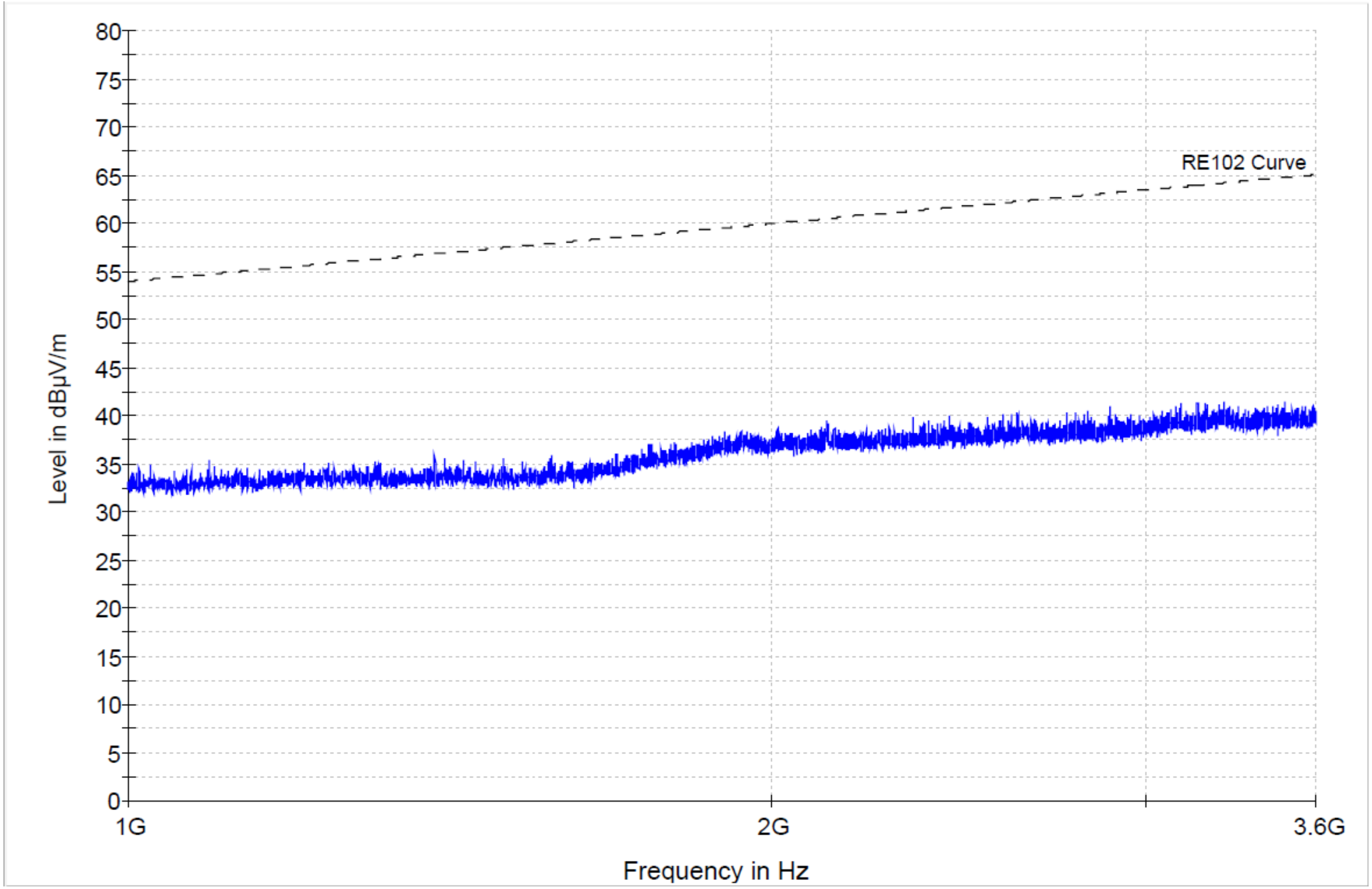


Component Level Radiated Emissions

Single Motor Results: B2 Motor Operating

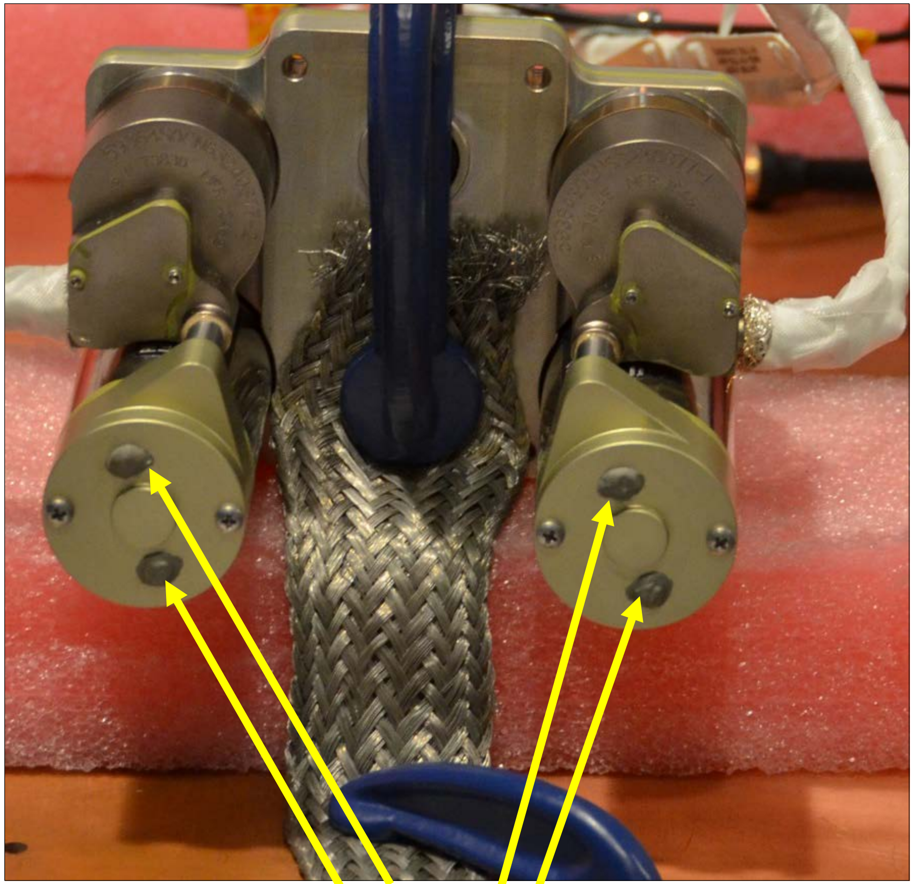


Single Motor Results: A2 Motor Operating



Component Level Radiated Emissions

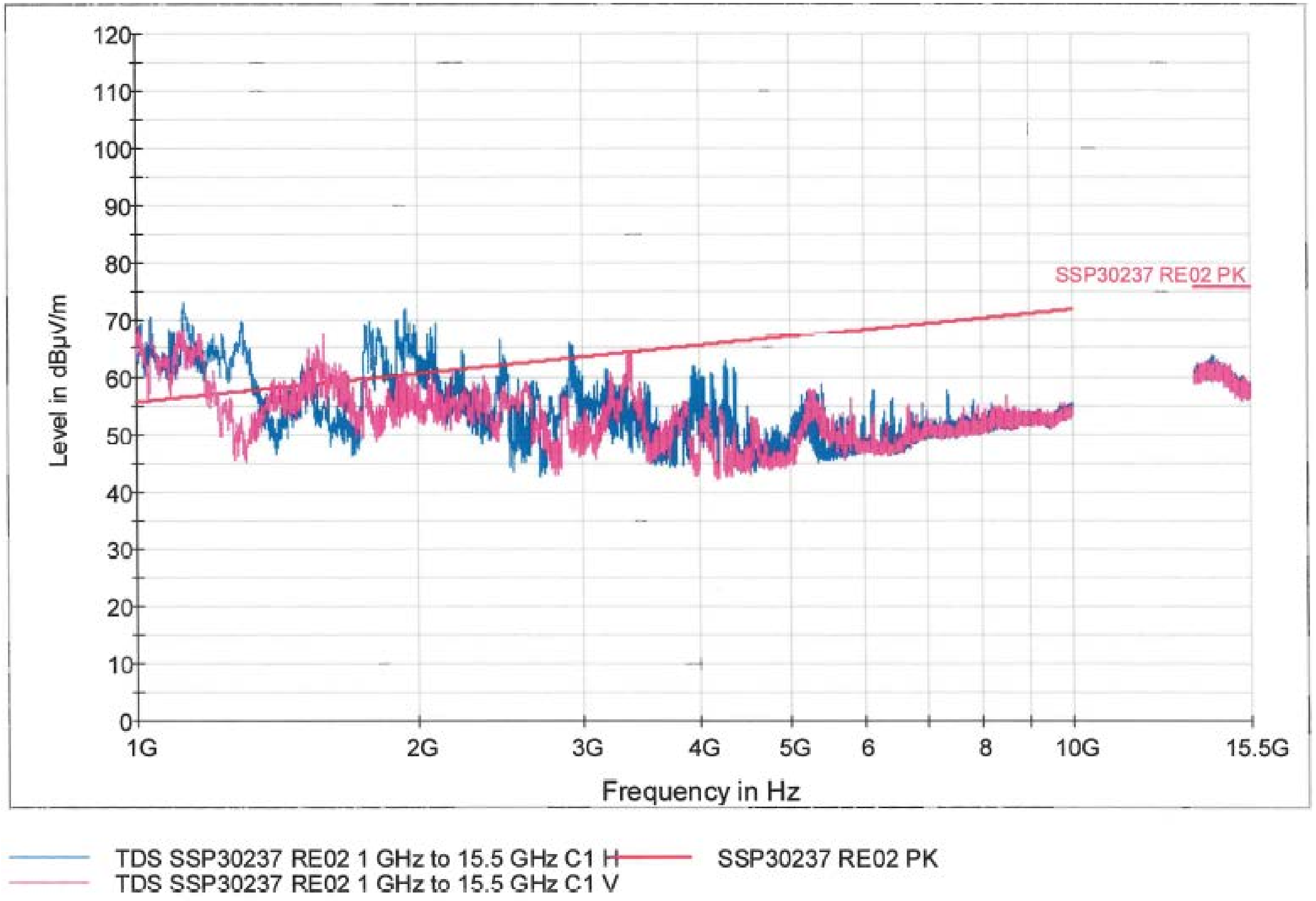
- Results
  - Each Motor tested exhibited different RE Characteristics
  - Only 1 (possibly) significant difference in motor to motor construction
    - Bonding Measurements – Very little difference
    - Nominal Current Draw – Very little difference
    - ***Brushes – Hand-tuned after construction, Possible Differences in Construction between motors***



Tuning Slots for Brushes

Additional Data with COTS Hardware

Radiated Emissions Data taken by a Different NASA EMI Facility on a COTS Item with Brushed Motor

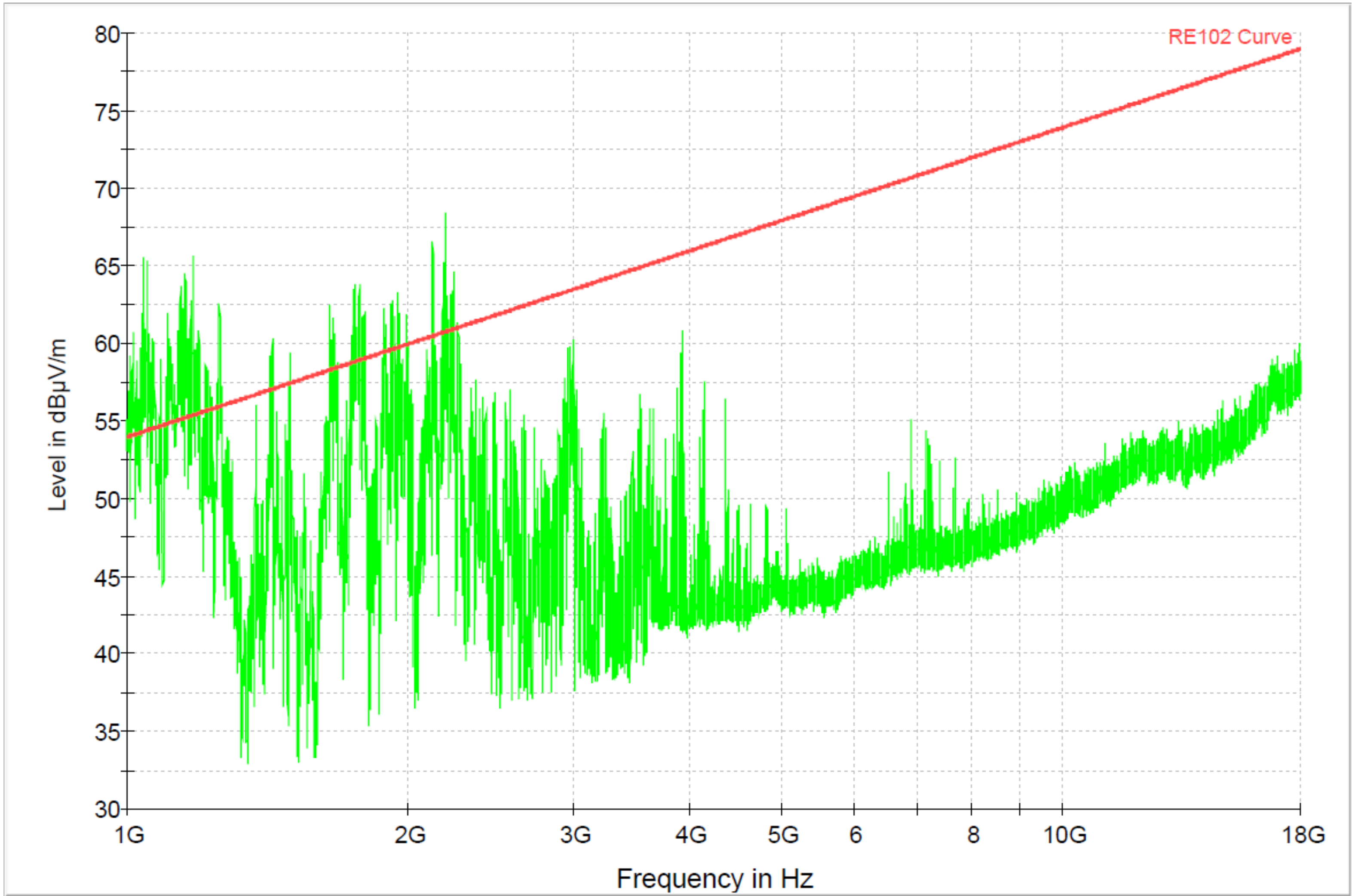


Conclusion

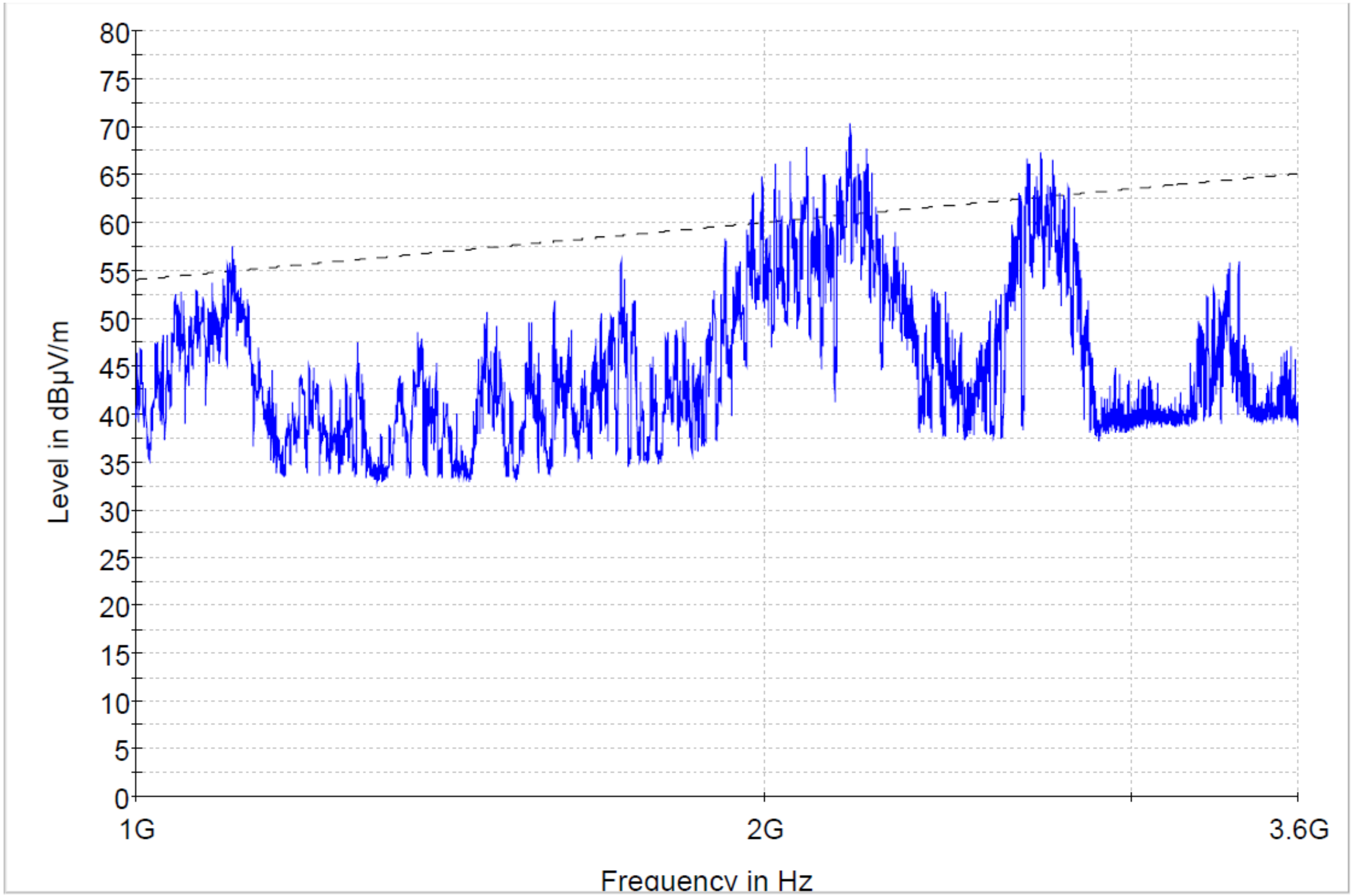
- No publications found that address Brushed DC Motor Radiated Emissions above 1 GHz
- Overcoming beliefs / "Common Knowledge" that Brushed DC motor radiated noise attenuates as frequency approaches 1 GHz and beyond proved difficult
- Data Presented shows significant radiated emissions above 1 GHz, particularly in L and S Bands, from Brushed DC Motors
- If MIL-STD-461F guidance had been followed, Radiated Emissions testing would have stopped at 1 GHz (Highest intentional generated frequency was on the order of 40 MHz)

Backup

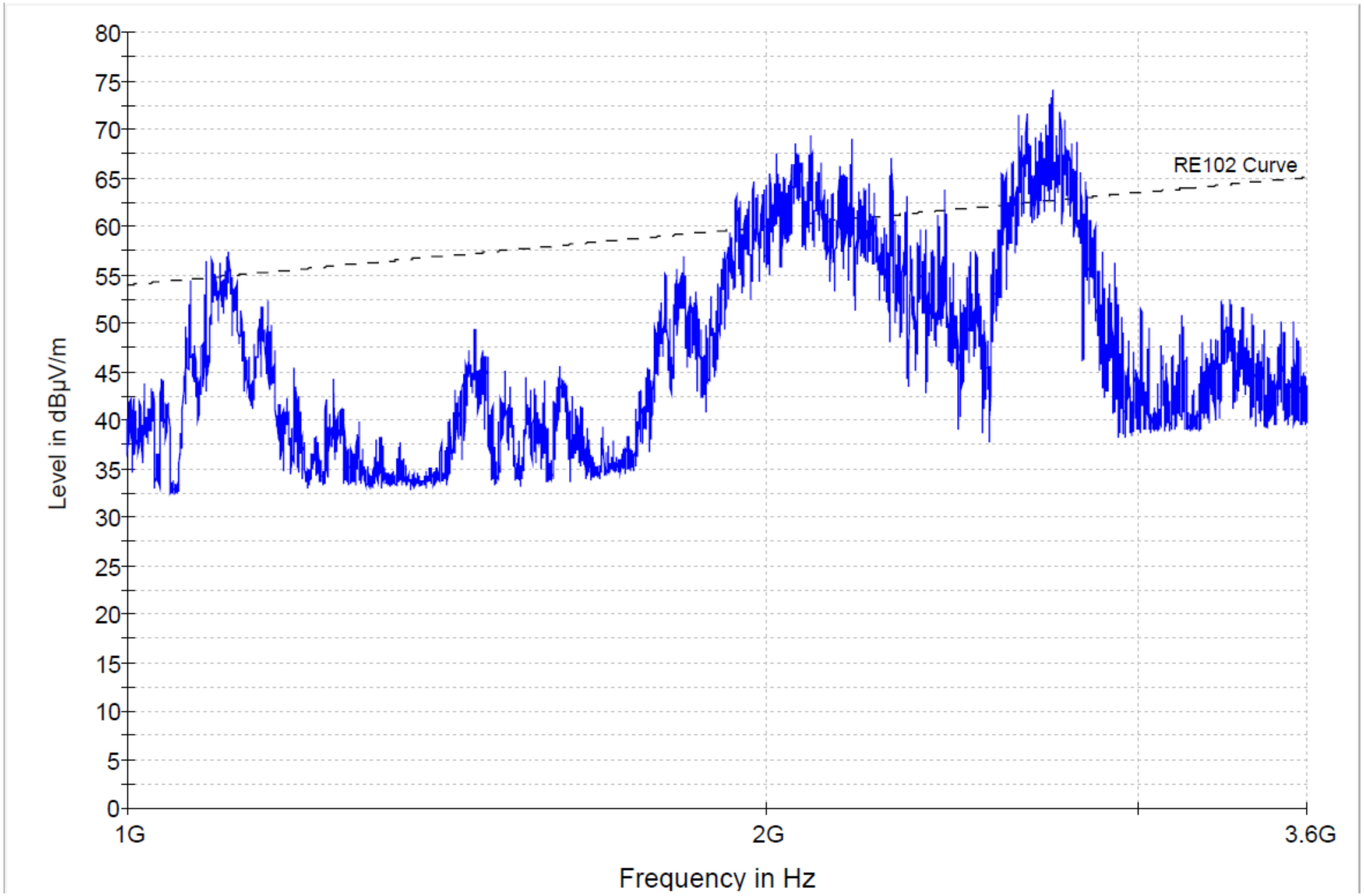
1st Qual System Additional RE102 Results: 4 motors operating



2nd Qual System Additional RE102 Results: 4 motors operating



2nd Qual System RE102 Results: A1 motor operating



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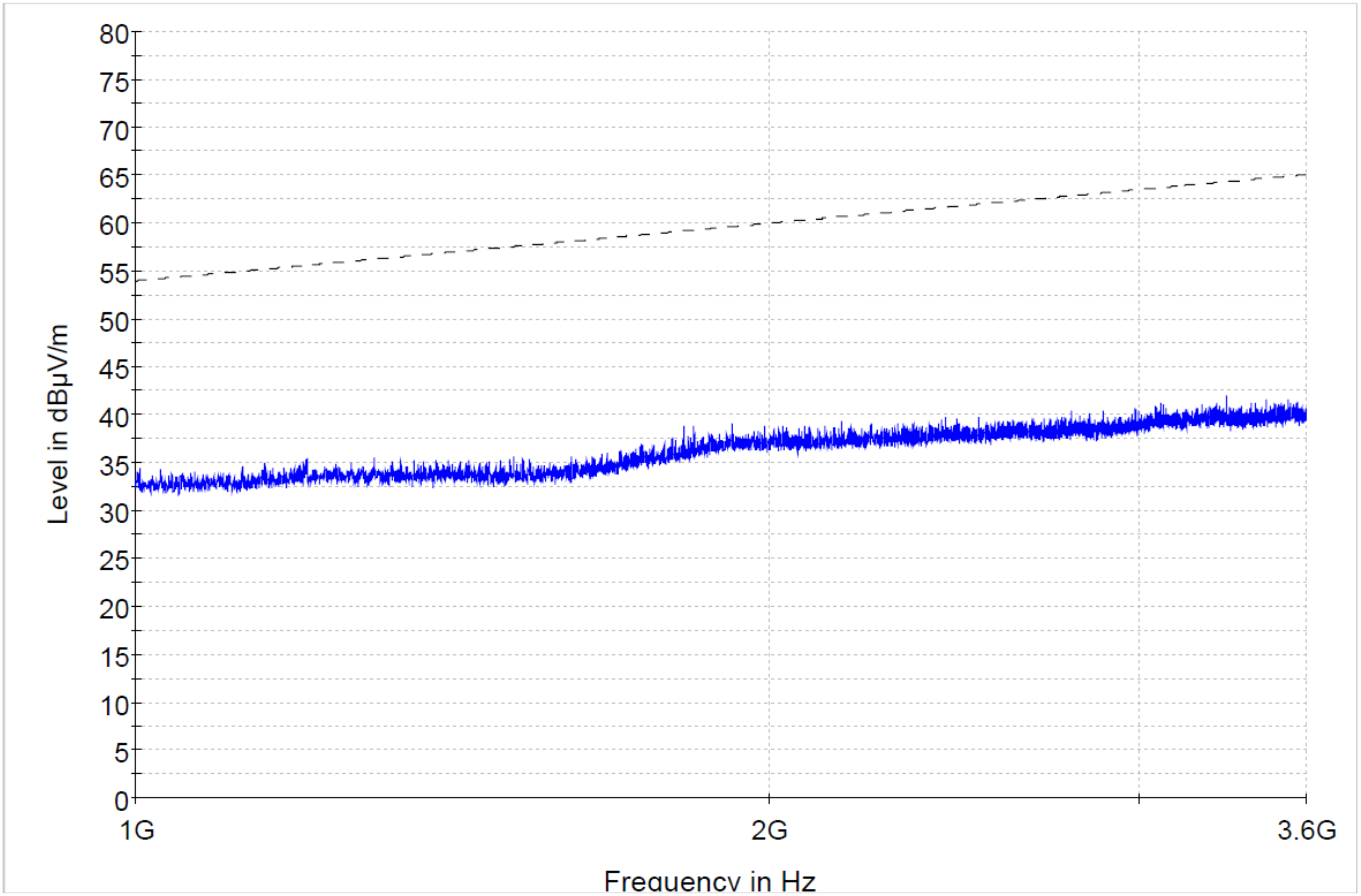
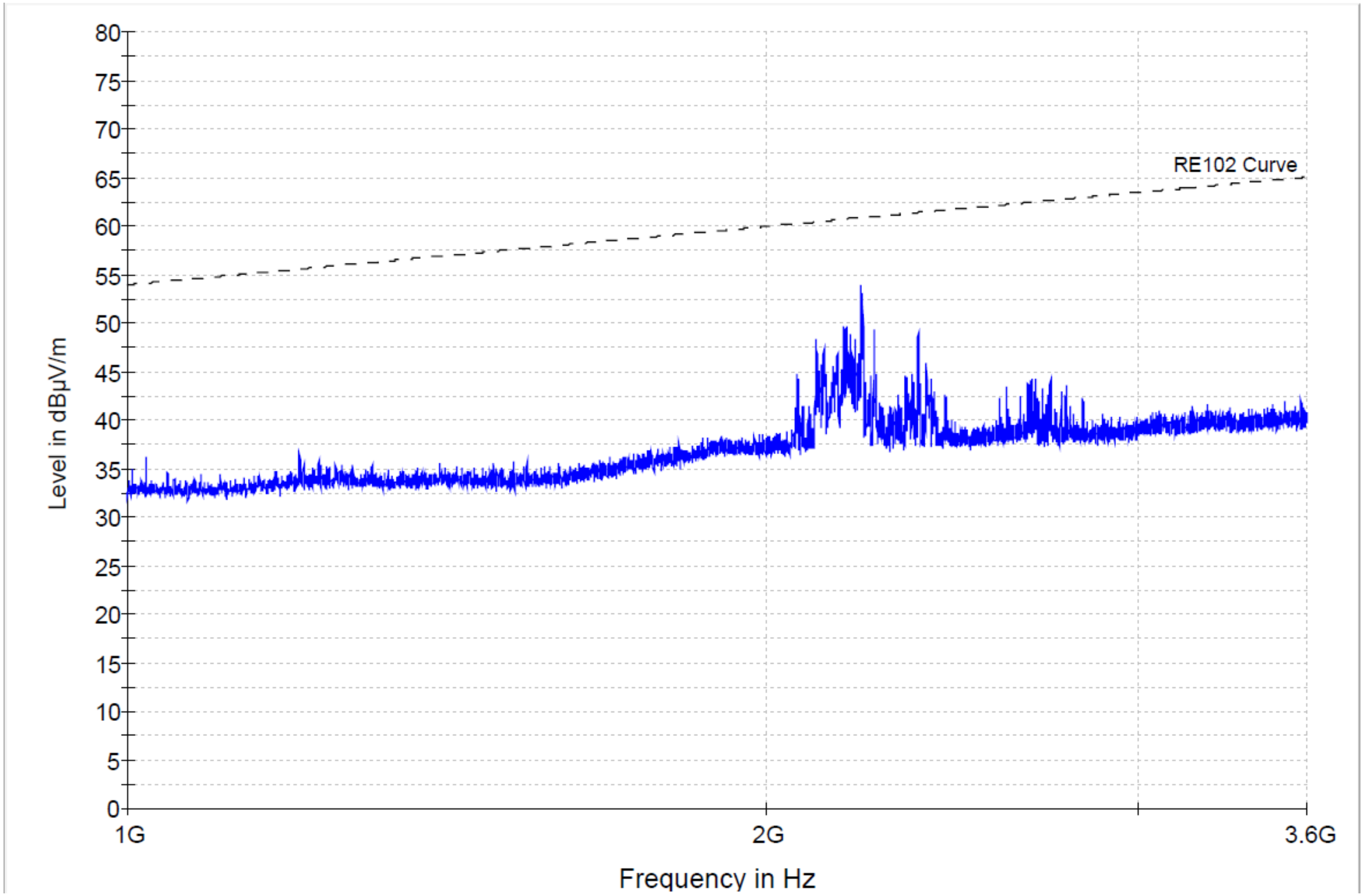
2nd Qual System RE102 Results: A2 motor operating



System Level Radiated Emissions

2nd Qual System RE102 Results: B1 motor operating



2nd Qual System RE102 Results: B2 motor operating