Application Note

Application of Class-D Amplifiers in Resolver and LVDT Exciters

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ABSTRACT

Resolvers and Linear Variable Differential Transformers (LVDTs) are inductive transducers for position sensing in applications where robustness and reliability are key. LVDTs withstand extreme temperatures, vibrations, shocks and even radiation. Resolvers measure the angle of rotation. LVDT sensors linear movement. Both types of sensors require a single-tone sinusoidal excitation signal for the operation. Using linear amplifiers for this purpose is the most common design. However, in safety critical applications that require additional protection and diagnostic mechanisms, the system design becomes quickly complex. Alternatively, one can use switch-mode Class-D power amplifiers that integrate additional circuitry. This report debriefs application of the TSD5402-Q1 Class-D sensor driver amplifier that drives the resolver excitation winding.

Table of Contents

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1 Introduction TO RESOLVER and LVDT sensors

Figure 1-1 shows LVDT sensors for industrial applications. Figure 1-2 helps to understand the construction and the theory of operation. The sensor is essentially a transformer with one primary winding and two secondary windings connected in series. Excitation signal V_{EXC} drives the primary winding. The movable magnetic core couples the signal to secondary windings V_1, V_2. The amplitude is proportional to the position (displacement) of the core.

source: megatron.de

Figure 1-1. LVDT Sensor

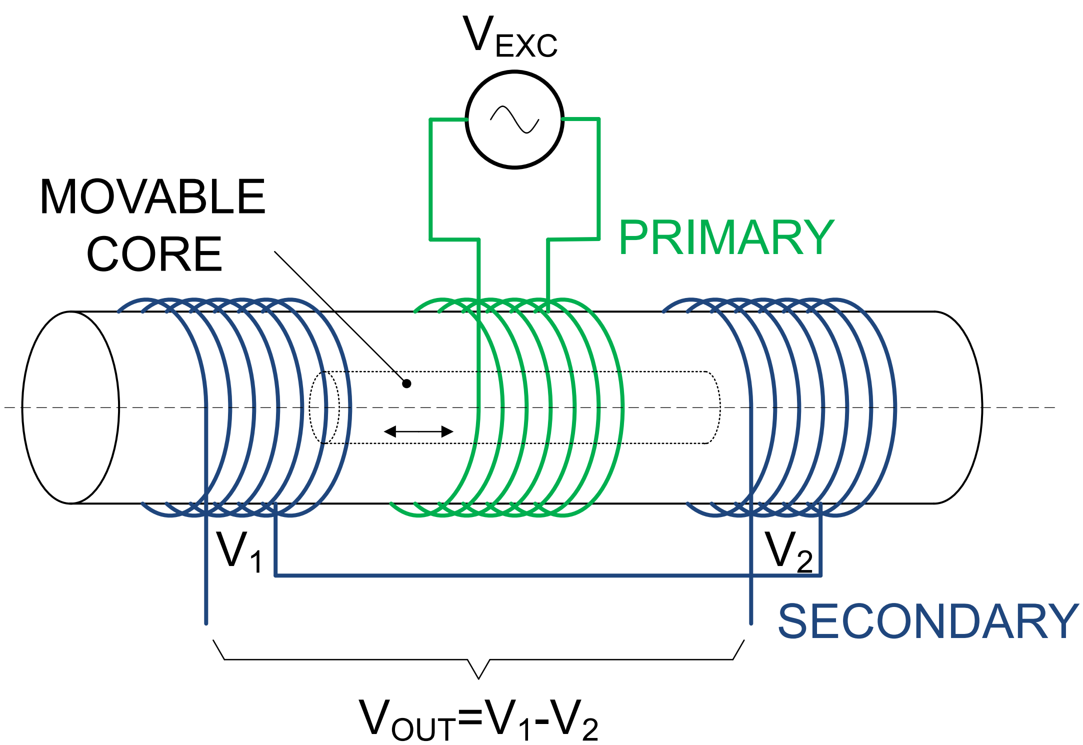

Figure 1-2. LVDT Sensor Principle

Figure 1-3 shows a variable reluctance resolver used typically in motor control applications. Figure 1-4 reveals that the construction and the operating principle is very similar to LVDT sensors. Resolvers have one primary and two independent secondary windings SIN and COS. The secondary windings are electrically in right angle from each other. The excitation signal V_{EXC} drives the primary coil. The magnetic core distributes the signal between secondary windings with respect to the magnetic core position (angle). The host system decodes the angle from secondary windings voltages V_{SIN} and V_{COS}.

Figure 1-3. Variable Reluctance Resolver

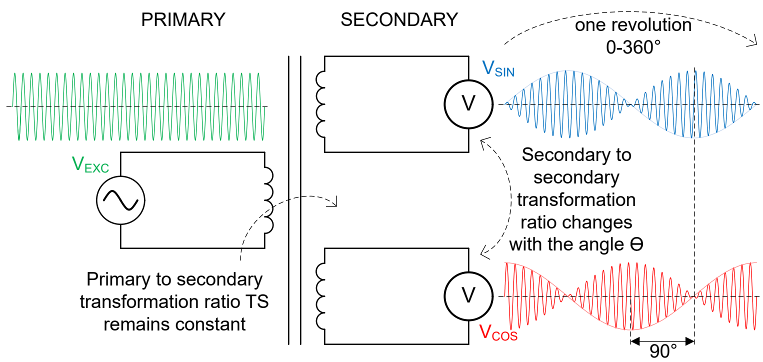

Figure 1-4. Resolver Sensor Principle

Table 1-1 compares common excitation signal requirements.

Table 1-1. Resolver and LVDT Exciter Requirements

Exciter	LVDT	RESOLVER	Unit
Frequency	1 to 20	1 to 10	kHz
Voltage	1 to 24	4 or 7	V_{RMS}
Current	20 to 100	20 to 200	mA_{RMS}

The analog front-end, that senses voltages on secondary windings, has high input impedance. This means that secondary windings are not loaded and the sensor does not transfer any real power. For this reason, the primary winding appears mainly as an inductive load to the excitation amplifier. Also, the amplifier delivers only reactive power.

2 Conventional Excitation Amplifier

Conventional excitation amplifiers use discrete linear amplifiers or integrated power operational amplifiers (OPAMPS) such as the ALM2403-Q1 device. Figure 2-1 shows a simplified block diagram of the excitation amplifier.

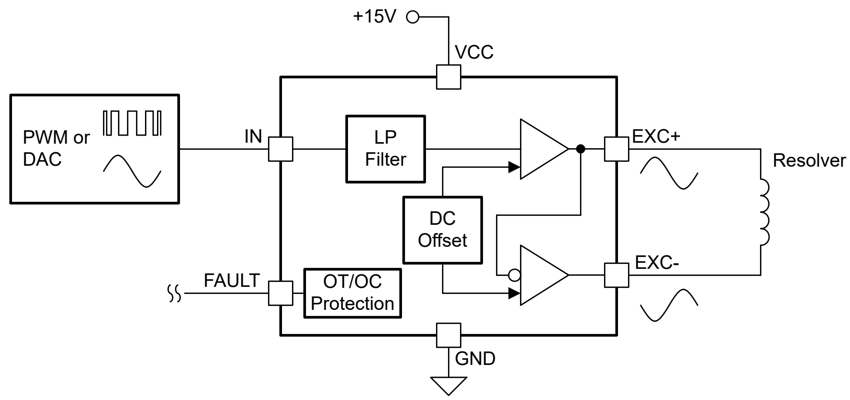

Figure 2-1. Resolver Excitation Amplifier (Simplified Diagram)

The host system generates the reference signal V_{REF}. There are two practical methods to generate this reference signal.

- Using modulated PWM signal
- Using external D/A converter (for example, in the host microcontroller)

The low-pass filter extracts the fundamental frequency and passes the signal to the power stage. The power amplifiers adjust voltage and current levels to match the resolver sensor specification. The output is differential with DC coupling. This eliminates the need for a bipolar power supply. The amplifier must have low offset. Any DC voltage between the outputs generates DC current through the sensor. This current can compromise sensor performance and lifetime.

Figure 2-1, Figure 2-2, and Figure 2-3 show design iterations for the excitation amplifier using the ALM2403-Q1 device. The simple design from Figure 2-1 becomes more complex when there is a need for adjustable over-current protection. Figure 2-3 shows the last iteration with two INA381-Q1 current sense amplifiers. Refer to [1] for more details on how to implement ALM2403-Q1 device in resolver excitation amplifier circuits.

Figure 2-2. Resolver Excitation Amplifier With ALM2403-Q1 (Basic Circuit)

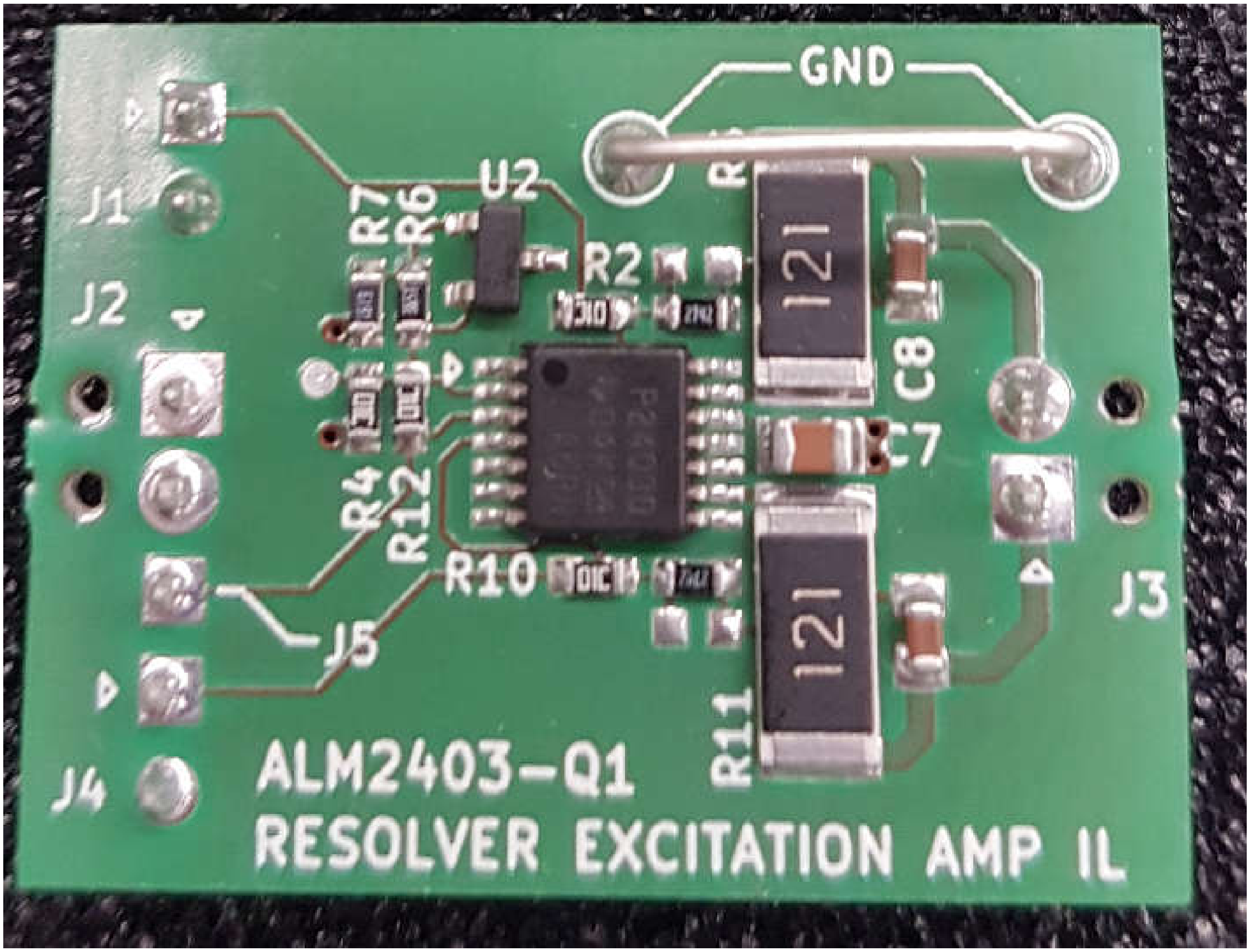

Figure 2-3. Resolver Excitation Amplifier With ALM2403-Q1 (With Output Current Limit)

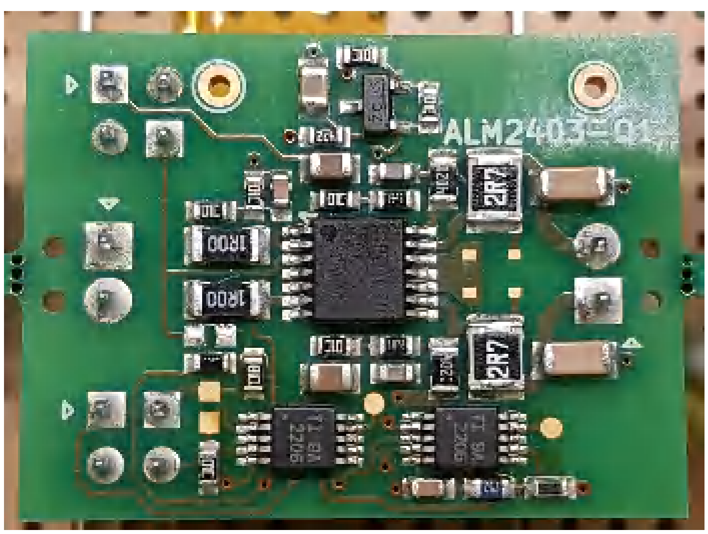

Figure 2-4. Resolver Excitation Amplifier With ALM2403-Q1 (With Advanced Overcurrent Protection)

3 Excitation Amplifier Using Class-D Amplifiers

Figure 3-1 shows a simplified block diagram of the excitation amplifier with the Class-D sensor driver amplifier. The mixed-signal amplifier core generates pulse width modulated (PWM) signals for the power stage with regards to the input signal. The output LC filter removes high frequency content and passes only the signal of interest. The amplifier operates in the bridge-tied load (BTL) mode with two outputs per channel. This eliminates need for bipolar power supply or AC-coupling of the load.

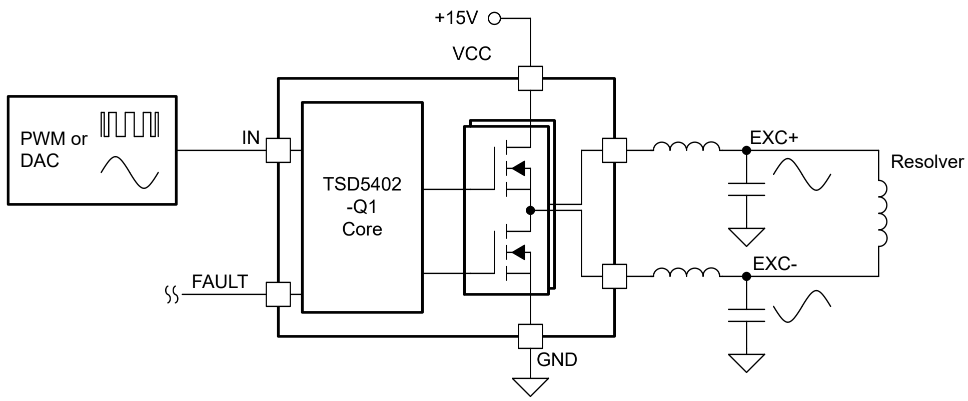

Figure 3-1. Resolver Excitation Amplifier With Class-D Amplifier (Simplified Diagram)

The example design in Figure 3-2 uses the TSD5402-Q1 device. The design size is similar to the linear version with the ALM2403-Q1 device.

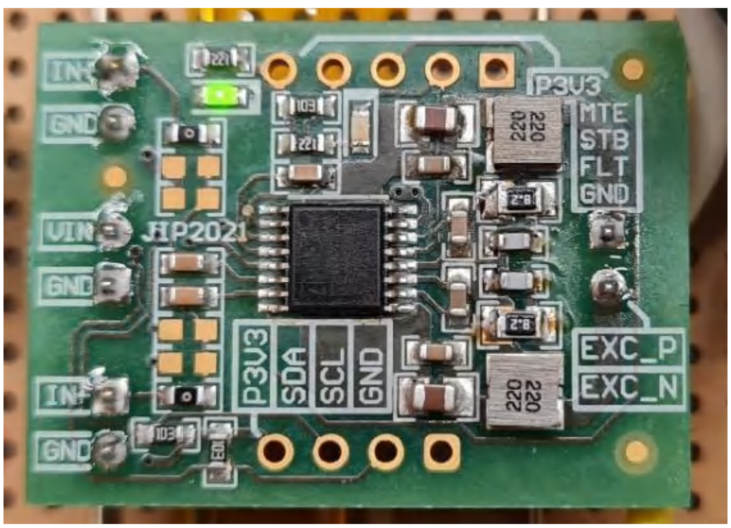

Figure 3-2. Resolver Excitation Amplifier With TSD5402-Q1 Class-D Sensor Driver Amplifier

Additionally, the integrated mono Class-D amplifier offers useful features for resolver applications such as:

- Integrated load diagnostics
- Wide input voltage operating range
- Designed to match EMC requirements
- Comprehensive protection mechanisms (short to ground, short to VCC, mutual short, and more)

Note

The I^2C communication interface can remain unused as the configuration of the IC fits resolver applications by default. However, the I^2C is beneficial for obtaining detailed diagnostic data.

4 Class-D Resolver Excitation Design Details

Table 4-1 lists input design parameters for the excitation amplifier.

Table 4-1. Excitation Amp Input Parameters

Parameter	Value	Unit
Excitation frequency	5 to 10	kHz
Excitation voltage	4 to 7	V_{RMS}
Resolver excitation winding inductance at 10kHz	1.05	mH
Resolver excitation winding equivalent series resistance	14.42	Ω
Input voltage range	9-18	V

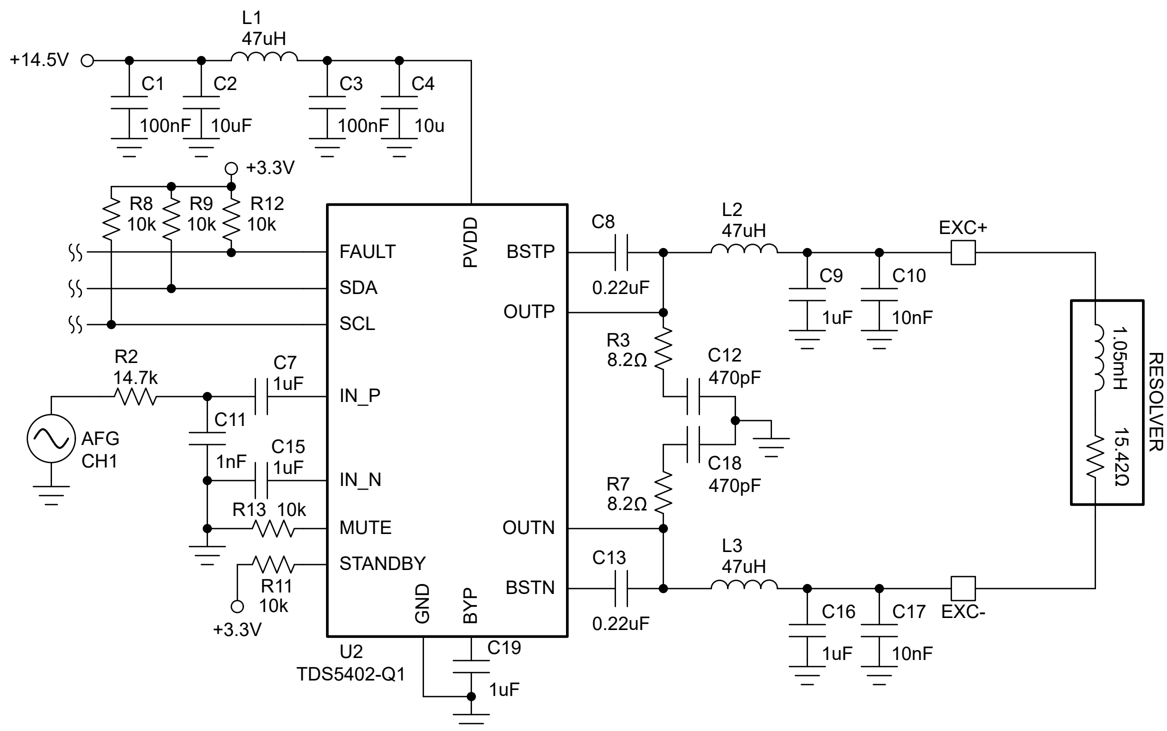

Figure 4-1. TSD5402-Q1 Resolver Excitation Amplifier Schematic

Figure 4-1 shows more detailed circuit diagram of the Class-D excitation amplifier. This circuit diagram is identical to the tested board except a few parts missing (LED, LDO). Capacitors C1 through C4 and inductor L1 form an input PI filter. This filter reduces switching noise spreading to the rest of the system. In most situations the filter is not necessary as the amplifier connects to a noisy DC/DC converter anyways. Resistors R8, R9, and R12 are pull-up resistors for the optional I^2C bus and the FAULT signal. The input reference signal from the generator AFG enters the low-pass filter R2, C11. Amplifier input pins IN_P, IN_N use capacitors C7, C15 for AC-coupling. The resolver application uses single-ended input. For this reason, the other leg of the capacitor C15 connects to the ground. Resistors R13, R11 set the default configuration for Hi-Z and STANDBY input pins. The capacitor C19 is a bypass capacitor for the integrated voltage regulator. The power stage is symmetrical for both outputs. Capacitors C8, C13 are bootstrap capacitors that allow for internal biasing of the power stage. Resistors R3, R7, and capacitors C12, C18 form two snubber circuits that reduce inductive ringing at switch nodes. Snubber component values are different for each design and are the result of laboratory experiments. Components selection for the ouptut filter is critical. The output LC filter L2 (L3), C9 (C16), C10 (C17) values are different to the data sheet recommendation. This resolver design implements 47uH inductor and 1uF capacitor values. This combination sets the cut-off frequency to 23.2kHz. The main reason for this change is reducing the power dissipation by adjusting the overall load impedance.

4.1 Components Selection for the Power Stage

Resolver secondary windings operate unloaded. For this reason, the resolver primary (excitation) coil appears mainly as an inductor. Inductors and capacitors cannot dissipate any power. For this reason, the resolver excitation operates with power factor close to zero, drawing only reactive power. The reactive power heats up the source – the amplifier.

There are multiple ways to analyze the power stage:

- Considering power factor
- Analyzing impedance network
- Frequency domain analysis, but all result in the same outcome.

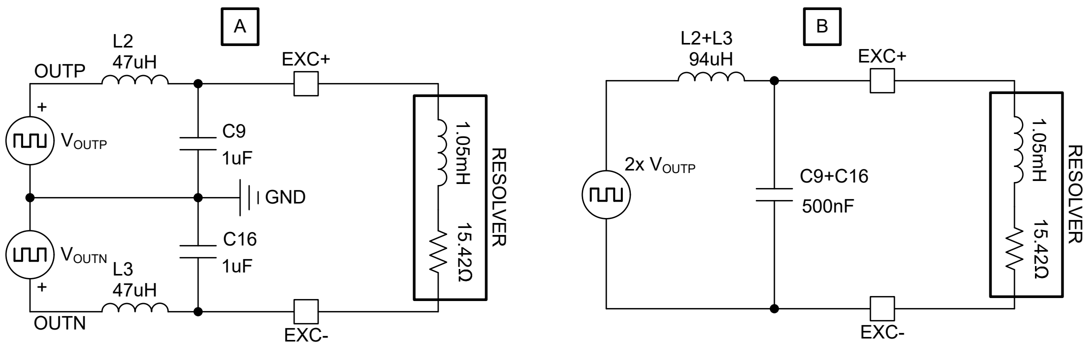

Figure 4-2. Class-D Power Stage Analysis

Figure 4-2 – Circuit A simplifies the power stage for the analysis. Capacitors C10, C17 are significantly smaller value and we can ignore them for the analysis. Additionally, the power stage is symmetrical therefore inductor values L2, L3 and capacitor values C9, C16 are same. Voltage sources V_{OUTP} and V_{OUTN} are always positive with reference to ground. This effectively doubles the voltage seen by the resolver. Figure 4-2 – Circuit B further simplifies the circuit for the analysis. The series combination of output capacitors C9 and C16 and the resolver winding form a parallel resonant circuit (tank).

Understanding the concept of a parallel resonant tank in the context of resolver excitation is important. At the resonant frequency, the current through the capacitor cancels out the current through the inductor. The impedance of the resonant circuit becomes infinite and the current supplying the resonant tank drops to zero. Using the resonance is beneficial in the resolver applications as the excitation frequency remains constant. By careful selection of the parallel capacitor, engineers can reduce the power consumption of the resolver excitation amplifier and significantly improve thermals. Figure 4-3 shows the impedance plot for the circuit example in Figure 4-4. The resonant peak occurs at 6.9kHz where the impedance increases to 144Ω. At the nominal excitation frequency f_{EXC}=10kHz the impedance is 57Ω.

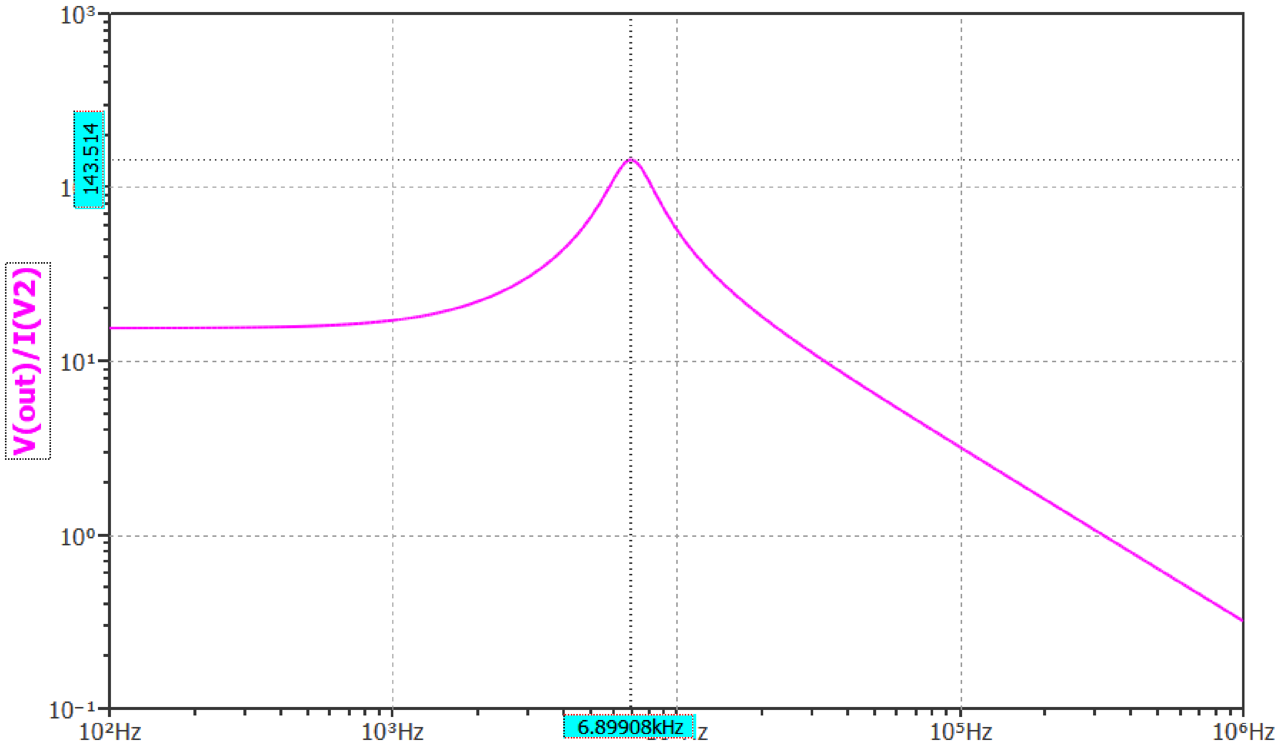

Figure 4-3. Impedance Plot for the Parallel Resonant Tank

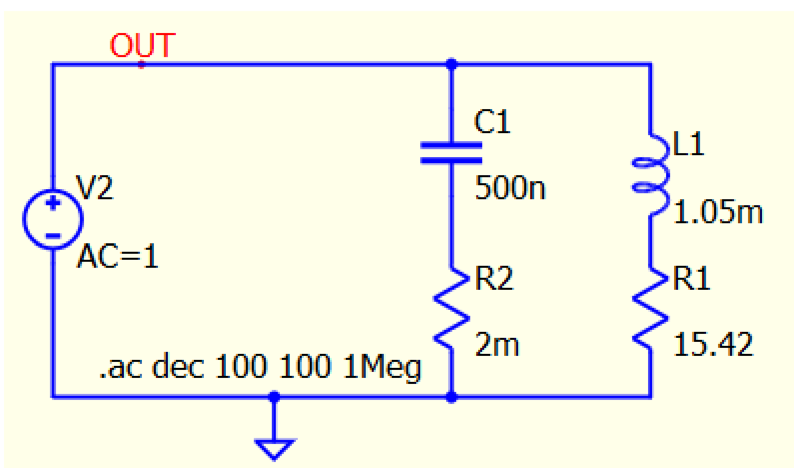

Figure 4-4. Parallel Resonant Tank Simulation Circuit (QSPICE)

The parallel capacitance is set the way the resonance occurs at excitation frequency. However, there are additional considerations. The value tolerance moves the resonant frequency up and down. Additionally, multi-layer ceramic capacitors (MLCC) have DC bias derating. The output capacitance of the power stage also defines the output ripple. Reducing the capacitance increases the output ripple. To maintain the output ripple, the inductance of L2, L3 has to be proportionally higher. Higher inductance decreases ripple current through the power stage and maintains similar cut-off frequency as the circuit in device data sheet. Current values of inductors L2, L3 and capacitors C9, C16 are the result of a good compromise between the output ripple, cut-off frequency and the inductor size. The resonant peak at approximately 6.9kHz is right in the middle of the desired excitation frequency range from 5 to 10kHz.

4.2 Input Filter Components Selection

The input filter R2, C7, C11 passes the excitation signal and suppresses higher harmonic content. The AC coupling removes any DC voltage which is important for the input circuitry in the TSD5402-Q1 device. Typically, a microcontroller generates the reference signal for the excitation amplifier. Two methods exist.

Modulated PWM is a very common design for the reference signal generation. The PWM frequency is set as high as possible. The desired excitation frequency modulates the duty cycle. A low-pass filter passes the signal of interest but removes the PWM harmonic content. PWM generators in microcontrollers use the system clock as the input. This means the system clock and desired resolution limits the maximum PWM frequency. Changing the modulation depth allows for fine adjustment of the output amplitude. Table 4-2 lists values for the PWM modulation when testing this design.

Table 4-2. PWM Modulation

Parameter	Value	Unit
PWM frequency	312.5	kHz
Logic high voltage level	3.3	V
Logic low voltage level	0	V
Center duty (no modulation)	50	%
Modulation frequency (excitation)	10	kHz
Modulation depth (index)	24.5	%
Modulation signal shape	Sine	-

Digital to Analog Converter (DAC) is another possible design for the reference signal generation. This allows for fine tuning the signal parameters and liberates requirements for the low-pass filter. This design typically offers better performance and signal purity. However, not all systems and microcontrollers have the DAC available.

5 Practical Experiments

5.1 Test Setup

Figure 5-1 shows the test setup for next measurements. Table 5-1 lists test conditions unless otherwise noted.

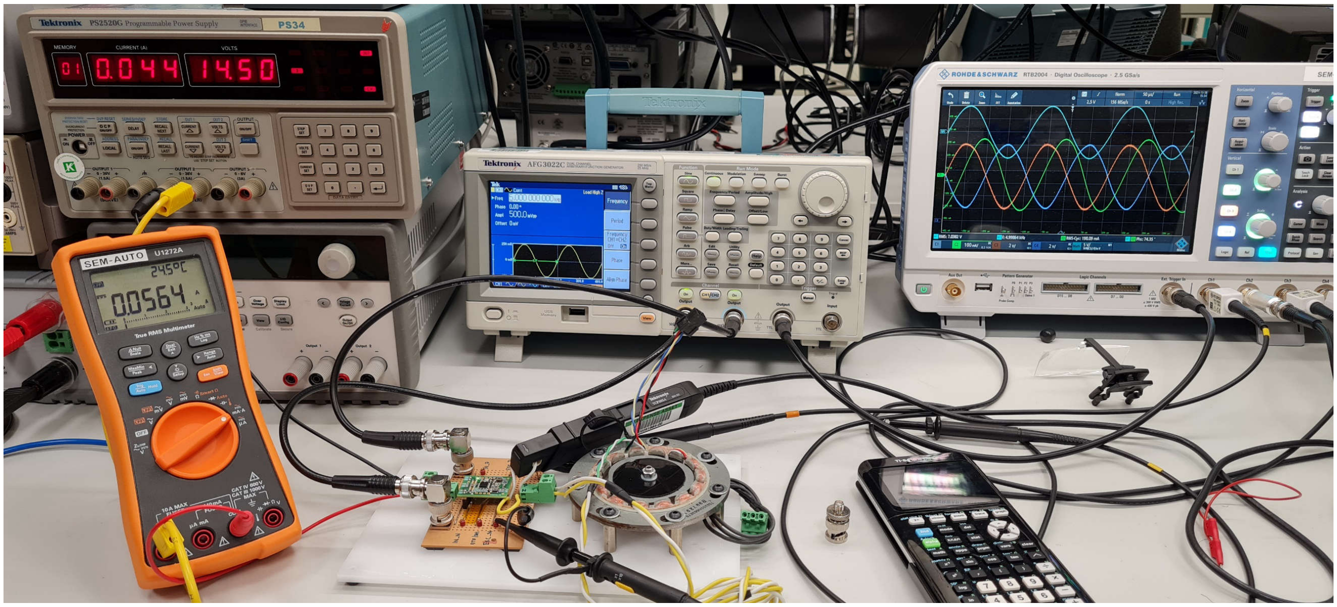

Figure 5-1. Test Setup

Table 5-1. Test Conditions

Parameter	Value	Unit
Input voltage	14.5	V
Excitation voltage	7	V_{RMS}
Excitation frequency	10	kHz
Resolver primary inductance	1.05	mH
Resolver primary resistance	14.42	Ω

5.2 Output Waveforms for Default Conditions

Figure 5-2 shows default output waveforms in normal operating conditions.

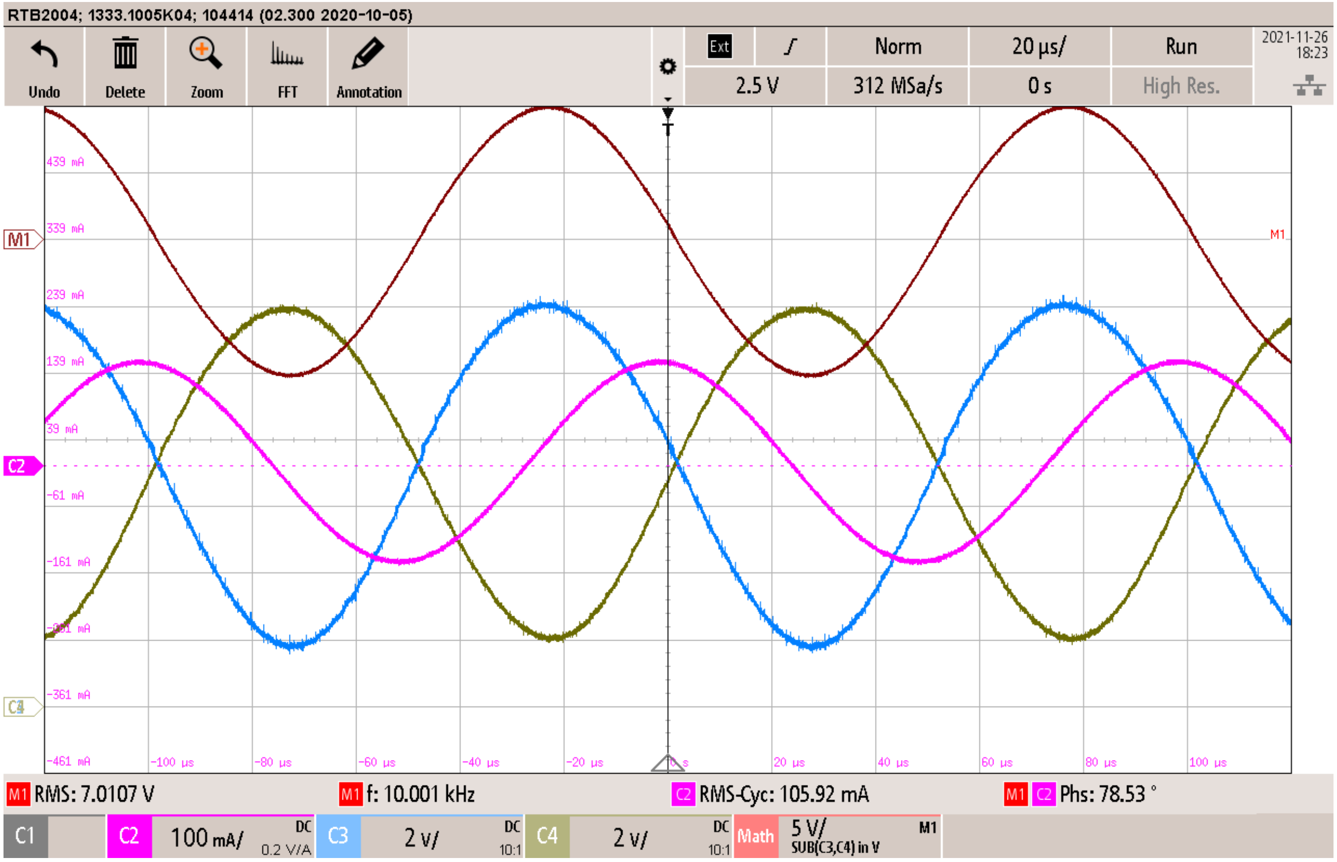

Figure 5-2. Output Waveforms

M1 – differential voltage across the resolver primary winding

CH2 – current through the resolver

CH3 – EXC- signal (single-ended)

CH4 – EXC+ signal (single-ended)

Calculations Explained

$$V_{EXC+}(t) = V_P \cdot \sin(\omega t + 000°) + V_{DC} \quad (1)$$

$$V_{EXC-}(t) = V_P \cdot \sin(\omega t + 180°) + V_{DC} \quad (2)$$

Voltage seen by the resolver is...

$$V_{EXC}(t) = V_{EXC+} - V_{EXC-} = 2 \cdot V_P \cdot \sin(\omega t) \quad (3)$$

$$V_{EXC}(RMS) = \frac{V_P}{\sqrt{2}} = \frac{9.9}{\sqrt{2}} = 7.000\ VRMS \quad (4)$$

Average responding multimeter measures the input current to the excitation amplifier.

$$P_{IN} = V_{IN} \cdot I_{IN} = 14.5 \cdot 0.0045 = 0.61W \quad (5)$$

Oscilloscope measurements allow calculating the output power (apparent)

$$S_{EXC} = V_{EXC(RMS)} \cdot I_{EXC(RMS)} = 7.01 \cdot 0.10592 \tag{6}$$

From the apparent power we can calculate real power dissipated on the resolver equivalent series resistance R_{RES}=15.42 Ω.

$$P_{EXC} = (I_{EXC(RMS)})^2 \cdot R_{RES} = 0.10592^2 \cdot 15.42 = 0.173W \tag{7}$$

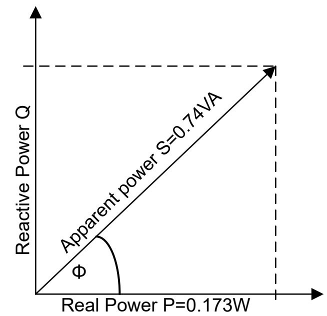

Figure 5-3. Power Vectors Plot

Phase shift between output voltage and current acts as a calculation check.

$$\cos\phi = \frac{real\ power}{app.\ power} = \frac{0.173}{0.742} = 0.233 \tag{8}$$

$$\phi = \arccos(0.233) = 76.52° \tag{9}$$

The readout value from the oscilloscope screen is ϕ=78.53°. This is a minimal error considering the test setup and oscilloscope readouts.

The power dissipation on the ampifier is the difference between peak input and output power.

$$P_{TPD} = P_{IN} - P_{EXC} = 0.61 - 0.173 = 0.437W \tag{10}$$

5.3 Amplifier Transfer Function

Figure 5-4 shows the test setup for the amplifier transfer function measurement. The output of the amplifier is differential which is unique to measure. For this reason, the amplifier input connects to the signal source through an isolation transformer (Figure 5-5). This self-made isolation transformer has flat frequency response in the band of interest (Figure 5-6, Table 5-2). For this frequency range, an oscilloscope with the built-in bode-plot function serves the purpose very well.

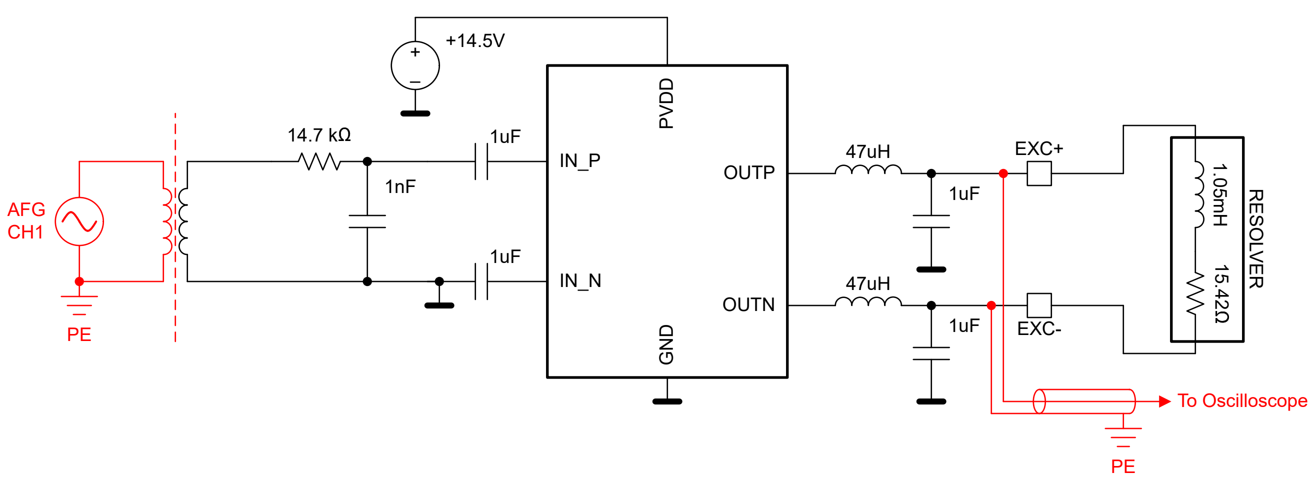

Figure 5-4. Test Setup for the Transfer Function Measurement

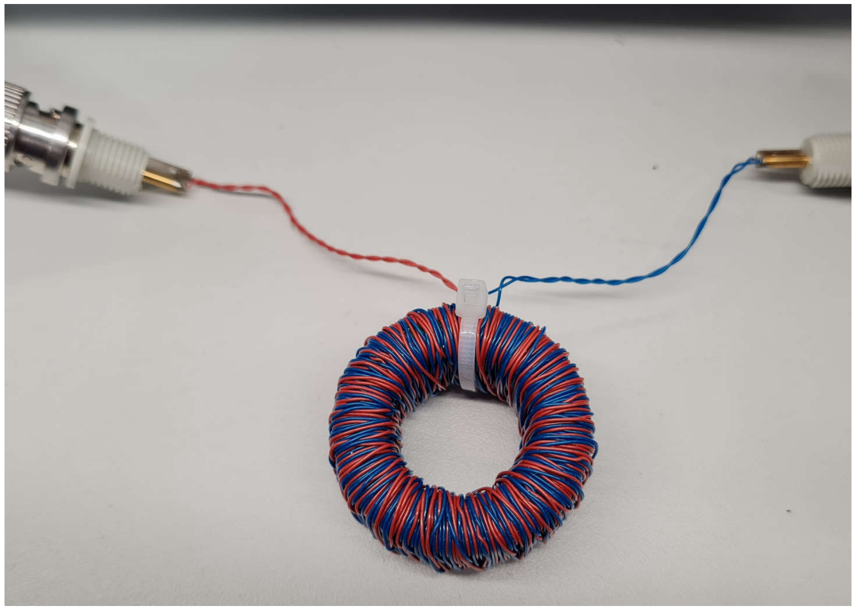

Figure 5-5. Self-Made Isolation Transformer

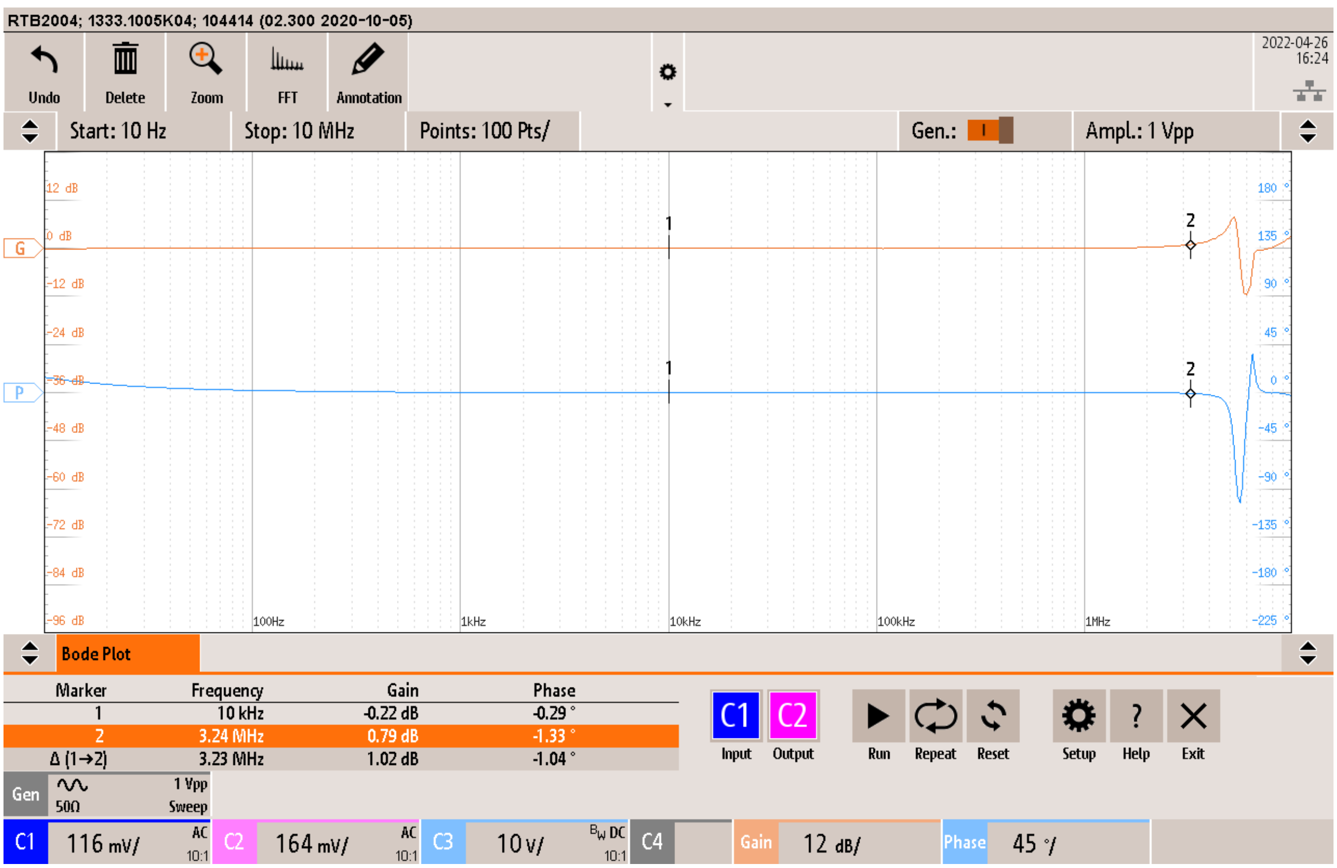

Figure 5-6. Isolation Transformer Transfer Function (High-z Loading)

Table 5-2. Isolation Transformer Frequency Characteristics

Frequency	Gain	Phase
31.6Hz	-0.09dB	4.7 °
10kHz	-0.22dB	-0.29 °
3.24MHz	0.79dB	-1.33 °

Figure 5-7 and Figure 5-8 show the transfer function of the excitation amplifier. Note the loading effect of the resolver in Figure 5-8. In the low frequency range up to about 3kHz there is noticeable gain drop. Nevertheless, for the frequency band of interest, between 5 to 10kHz, the transfer function remains constant.

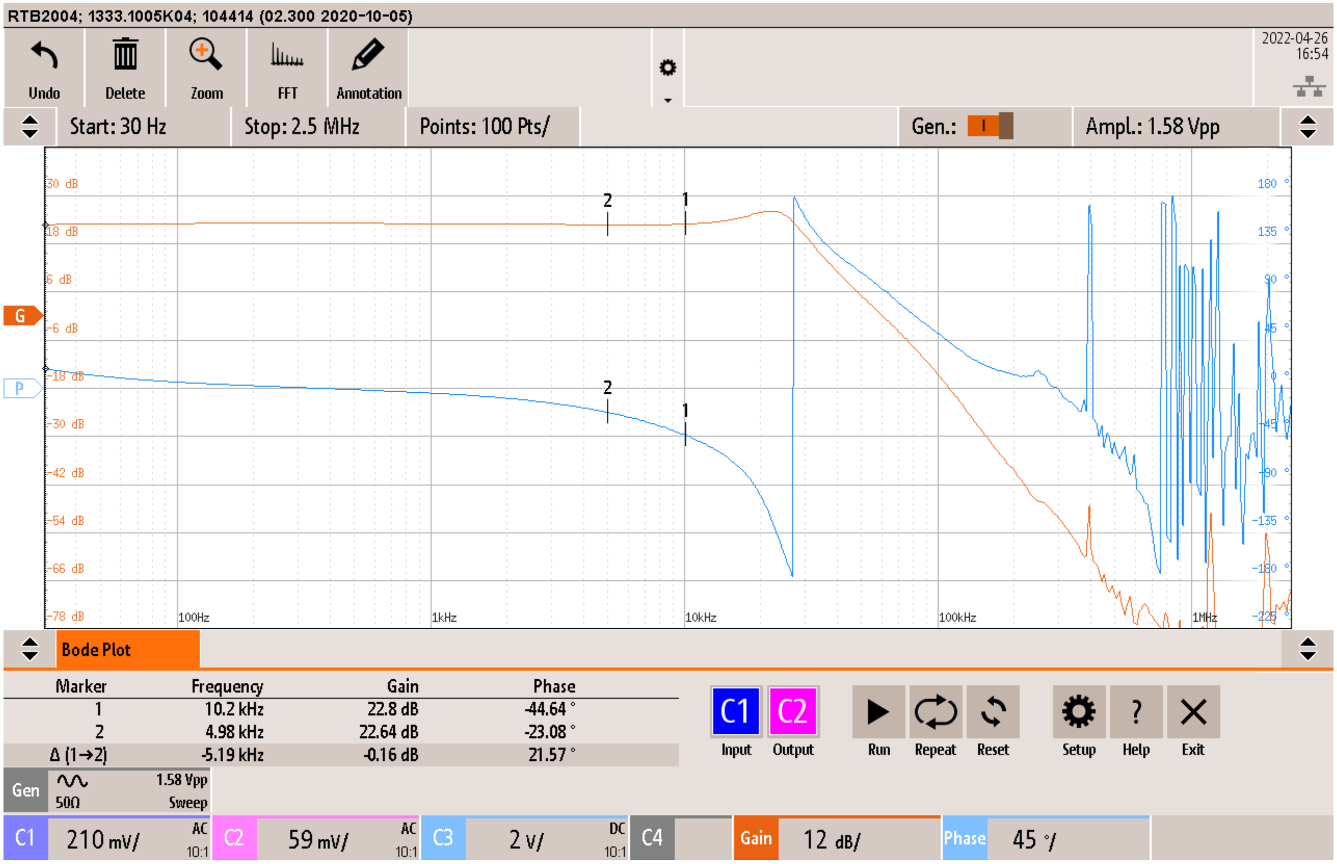

Figure 5-7. Amplifier Transfer Function (Unloaded Output)

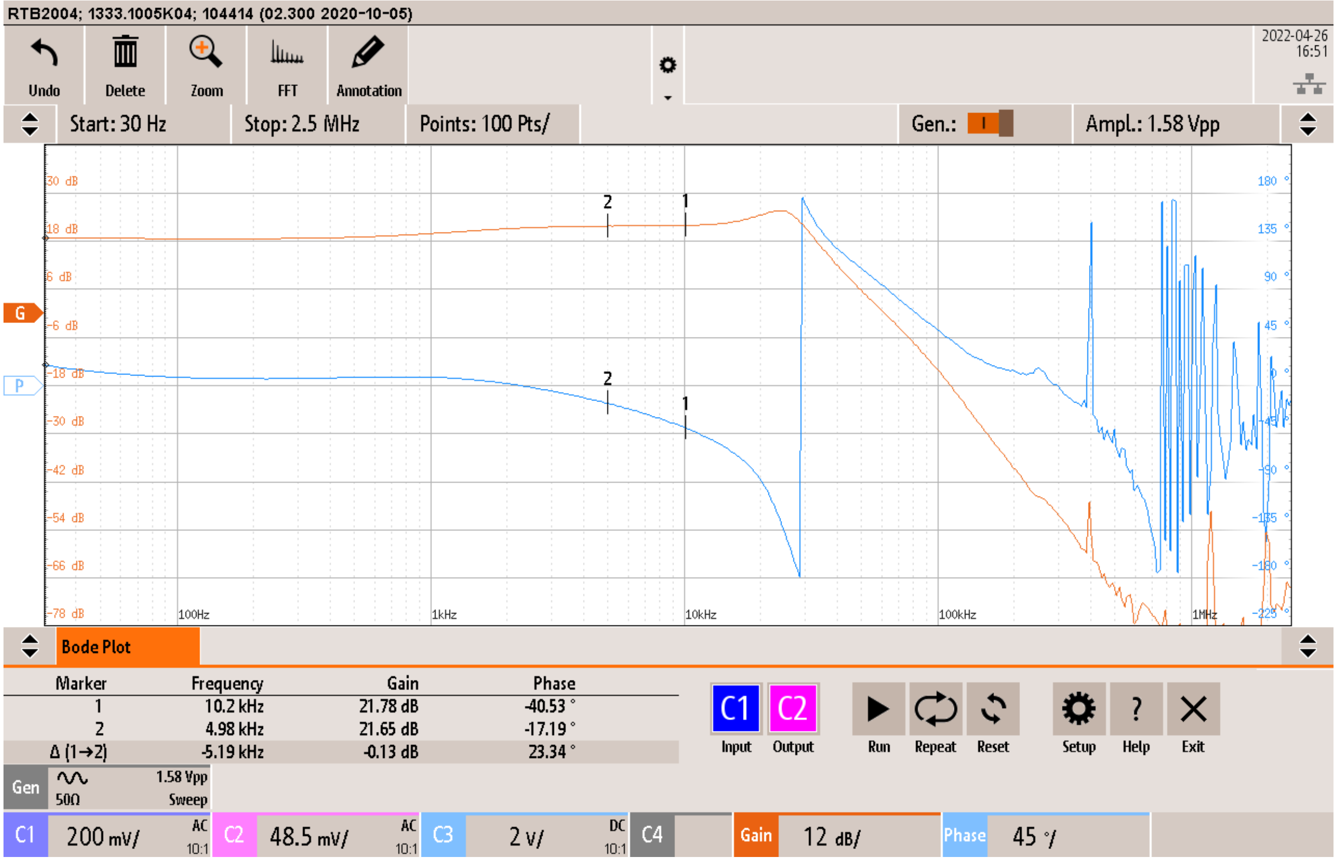

Figure 5-8. Amplifier Transfer Function (Resolver as a Load)

Note

The Class-D amplifier operates with 400KHz switching frequency. However, due to the BD mode of modulation

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5.4 Using PWM for Generating the Reference Signal

In this experiment the arbitrary waveform generator generates a PWM. The PWM signal enters the input RC filter R2, C11. Figure 5-9 shows that the 1^{st} order filter is not able to fully filter out higher harmonic content and the waveform has a lot of ripple. However, the amplifier acts as a low-pass filter. Figure 5-10 shows clean sine-wave on the output of the excitation amplifier. Some harmonic content is aliased as the Class-D amplifier is not able to pass frequencies past the Nyquist criterion. This contributes to increased total harmonic distortion (THD) as presented later.

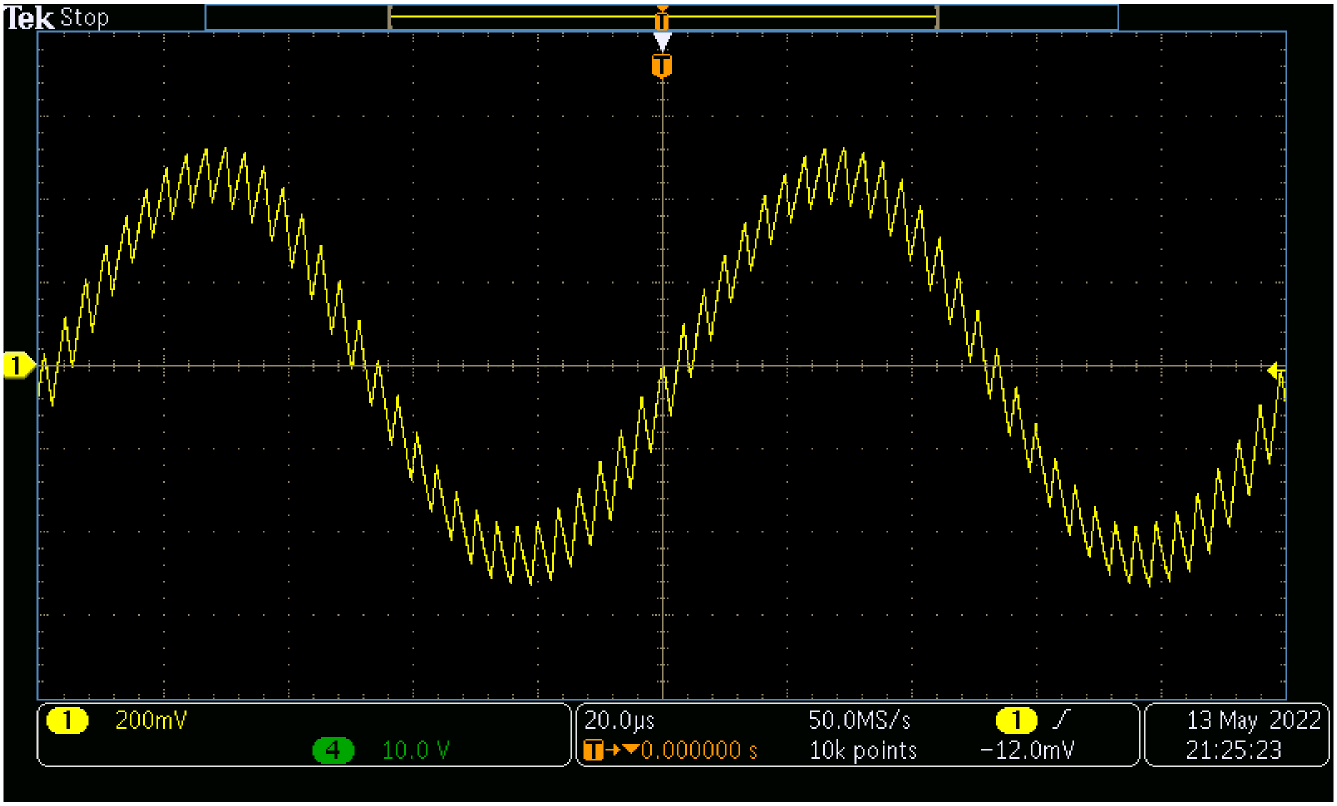

Figure 5-9. Voltage on the Input RC Filter (Across C11)

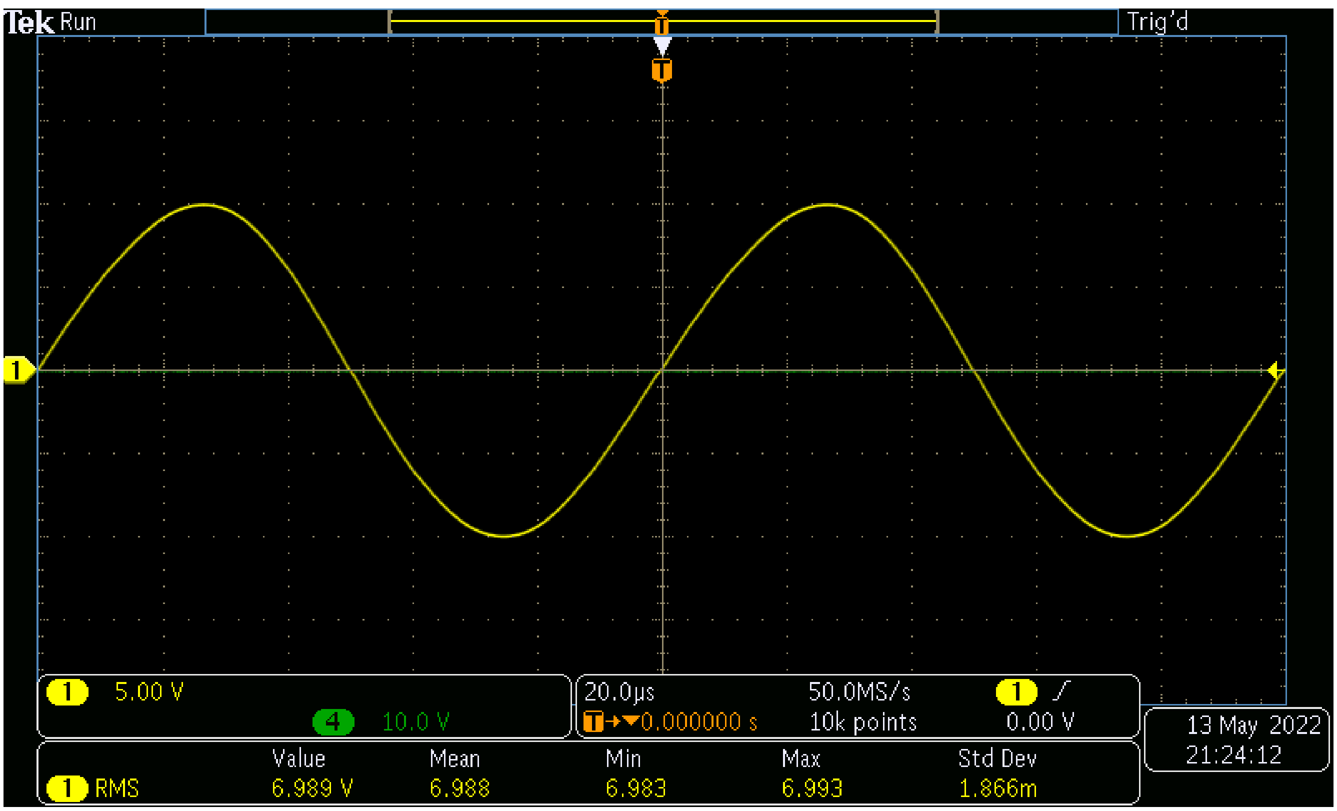

Figure 5-10. Excitation Amplifier Output Voltage

5.5 Thermal Image and Comparison Against the Linear Design

Figure 5-11 shows a thermal picture of the amplifier when driving the resolver at ambient temperature 21°C.

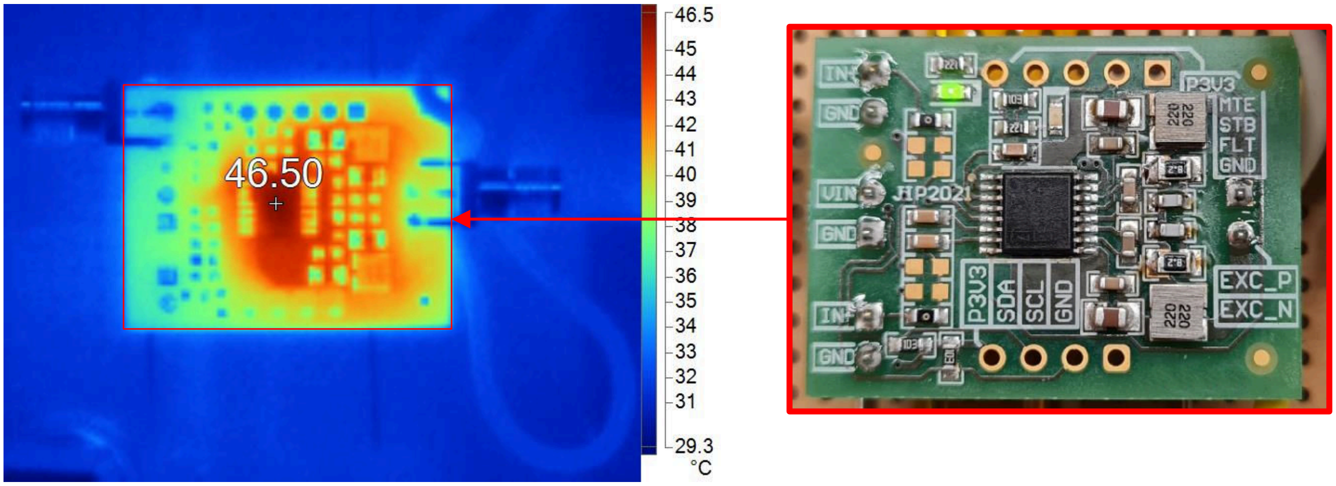

Figure 5-11. Thermal Picture of the Amplifier When Driving the Resolver

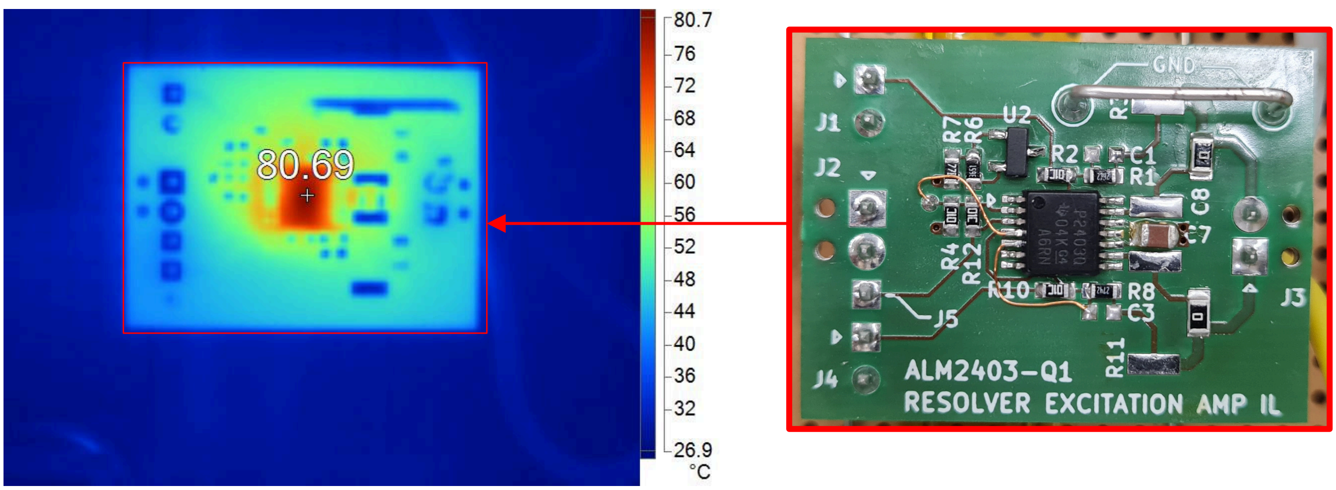

Figure 5-12. Thermal Picture of the Amplifier With Power OPAMP ALM2403-Q1

Figure 5-12 shows a thermal picture of the similar board but with the linear amplifier. The ALM2403-Q1 is a power operational amplifier with the Class-AB output power stage. Note that the excitation circuit operates with different power factor hence the high power dissipation. Adding a capacitor in parallel with the resolver primary winding reduces the input current and the power dissipation as discussed earlier. Figure 5-13 shows the improvement with the 100nF capacitor.

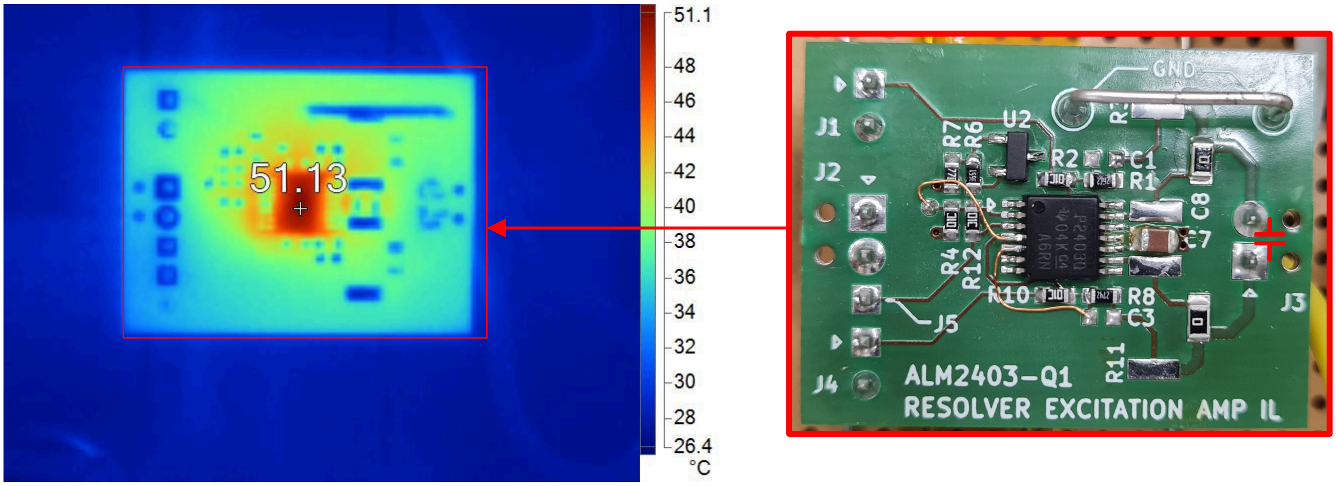

Figure 5-13. Thermal Picture of the Amplifier With Power OPAMP ALM2403-Q1 and Capacitor on the Output

5.6 Output Spectrum

The purpose of this experiment is to verify how much switching noise the switch-mode power stage introduces to the output of the excitation amplifier. Figure 5-14 shows the test setup circuit diagram for the output spectrum measurement. Similarly, to the transfer function measurement the arbitrary waveform generator is isolated from the input using the isolation transformer. This allows connecting the spectrum analyzer across the amplifier output. A passive 1:10 probe protects the spectrum analyzer input from overload.

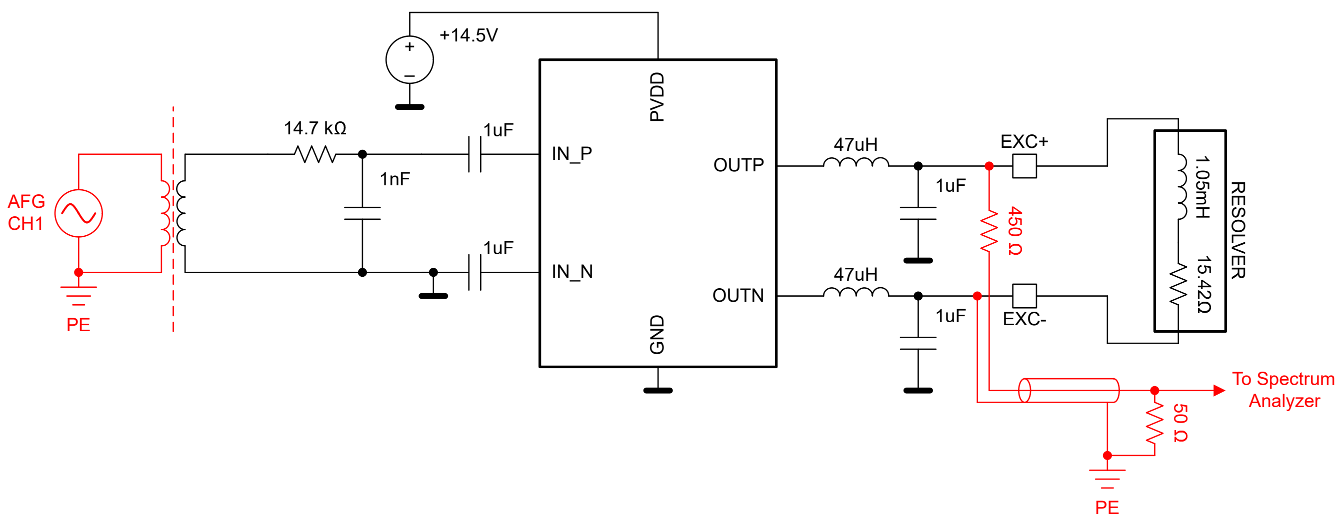

Figure 5-14. Test Setup for the Output Spectrum Measurement

Figure 5-15 shows the output spectrum from 0 to 10MHz and selected zoom window from 0 to 1MHz.

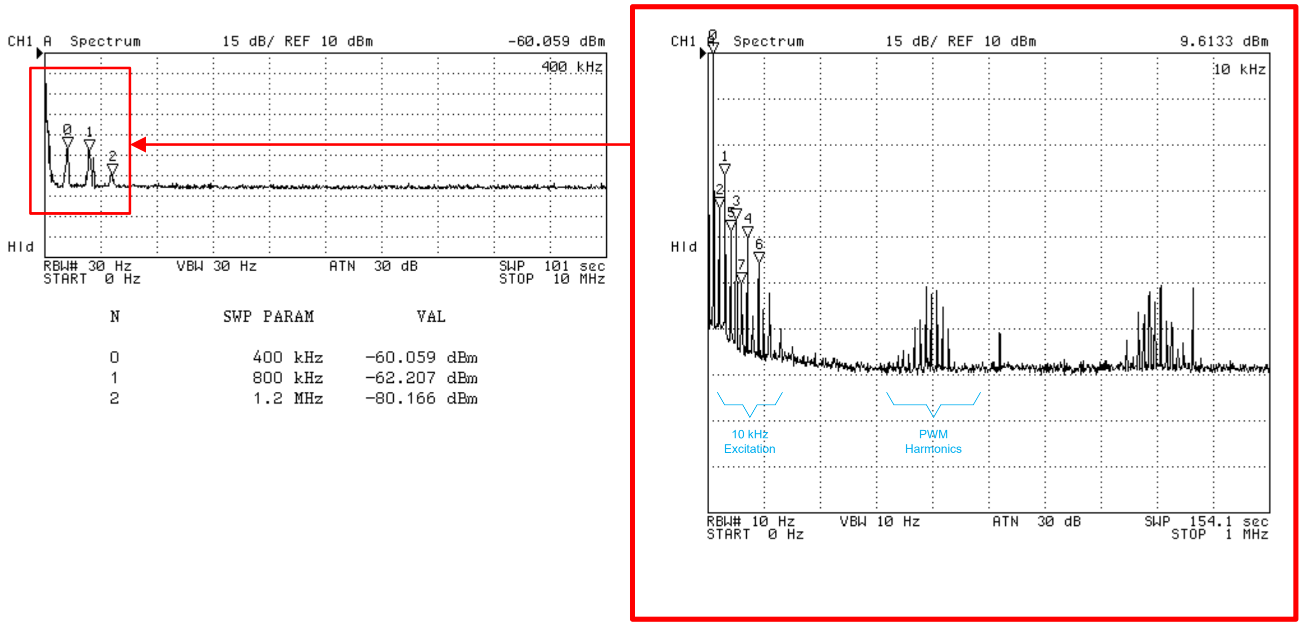

Figure 5-15. Output Spectrum of the Excitation Amplifier (Harmonic Input)

Further detailed analysis in Figure 5-16 shows first 8 harmonics. The first unwanted harmonic at 30kHz has 40dB (100x) lower amplitude to the carrier. This is a very good result.

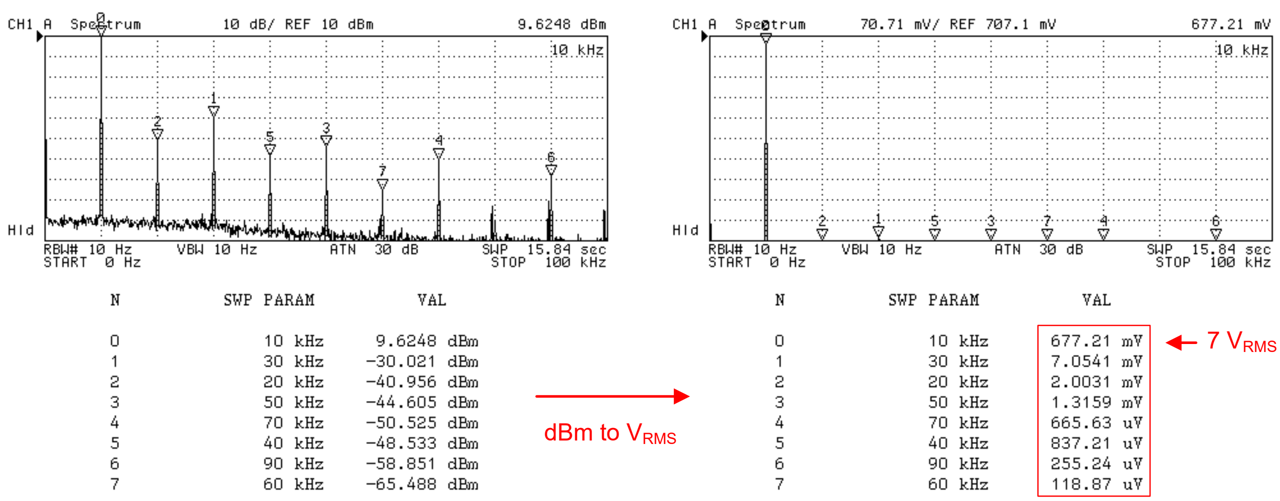

Figure 5-16. Detailed Analysis of the Output Spectrum 0-100kHz

Figure 5-17 shows comparison of the output spectrum when the signal generator drives the input with the harmonic signal (A) and modulated PWM (B). The PWM signal introduces new harmonics.

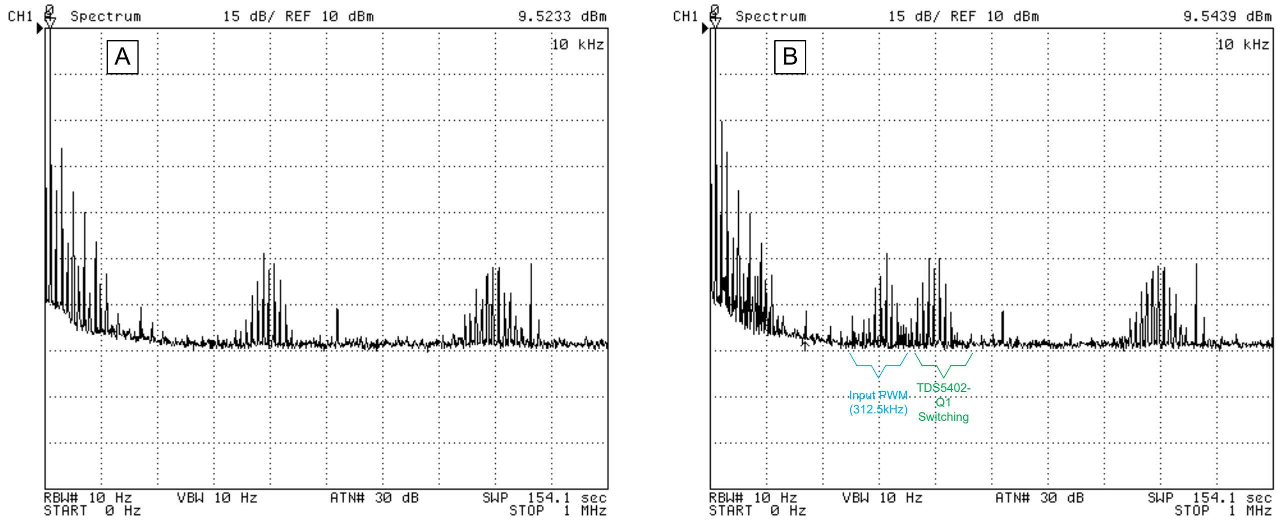

Figure 5-17. Output Spectrum Comparison for Harmonic (A) and PWM (B) Signal Driving the Input

Figure 5-18 shows detailed analysis of the output signal with the PWM signal as an input. The detail also shows aliased harmonics wrapped around 400kHz. Note that the switching frequency of the TSD5402-Q1 device is 400kHz. However, due to the BD modulation scheme the frequency practically doubles and increase the Nyquist criterion to 400kHz.

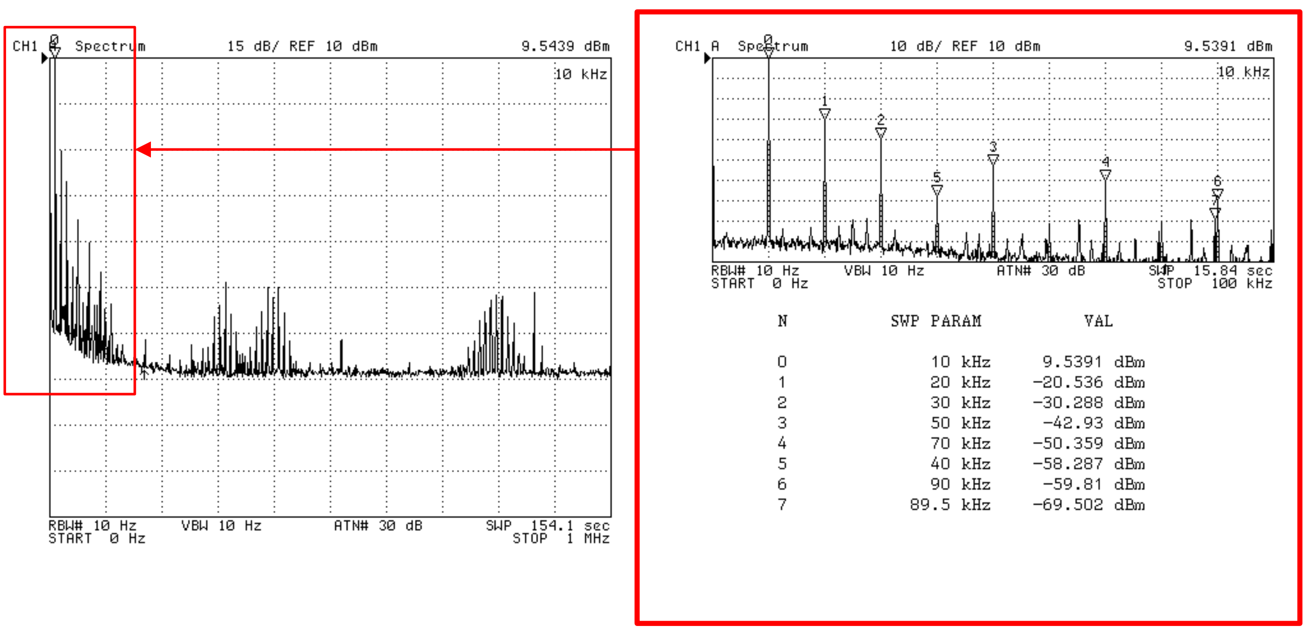

Figure 5-18. Output Spectrum of the Excitation Amplifier (PWM Input)

5.7 Total Harmonic Distortion (THD)

Total harmonic distortion is a single number that interprets output spectrum measurements from the previous chapter. Table 5-3, Figure 5-19 and Figure 5-20 document the results.

Table 5-3. Total Harmonic Distortion

Input type	Value	Unit
Harmonic signal THD	1.15	%
Modulated PWM signal THD	3.24	%

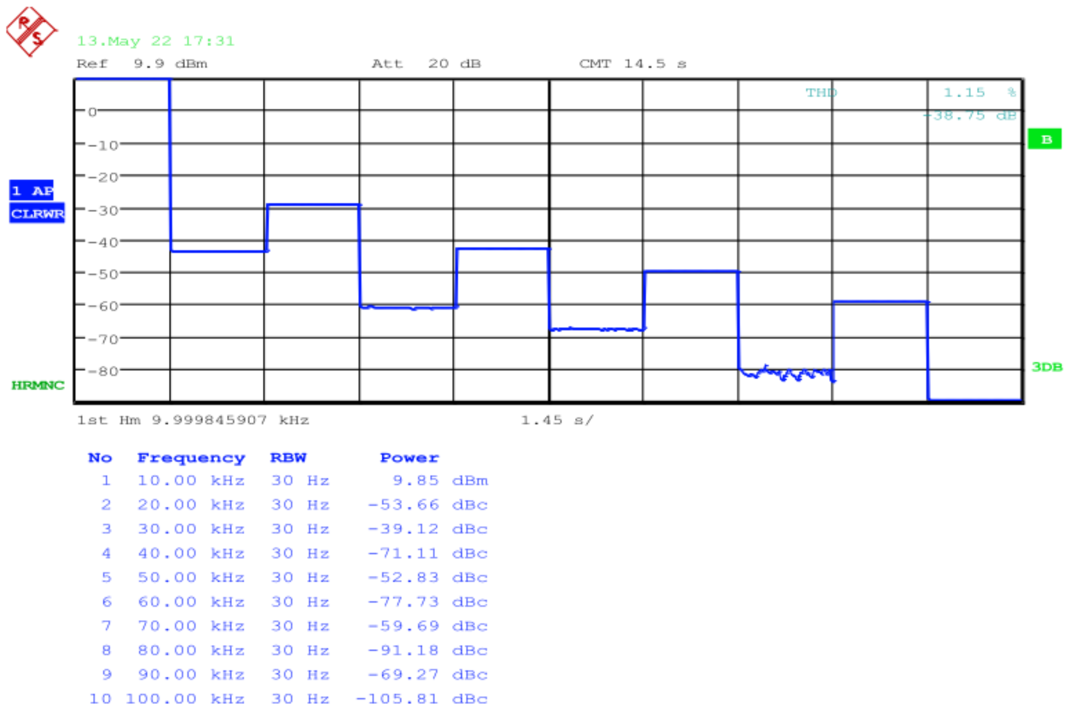

Figure 5-19. Total Harmonic Distortion (Harmonic Signal)

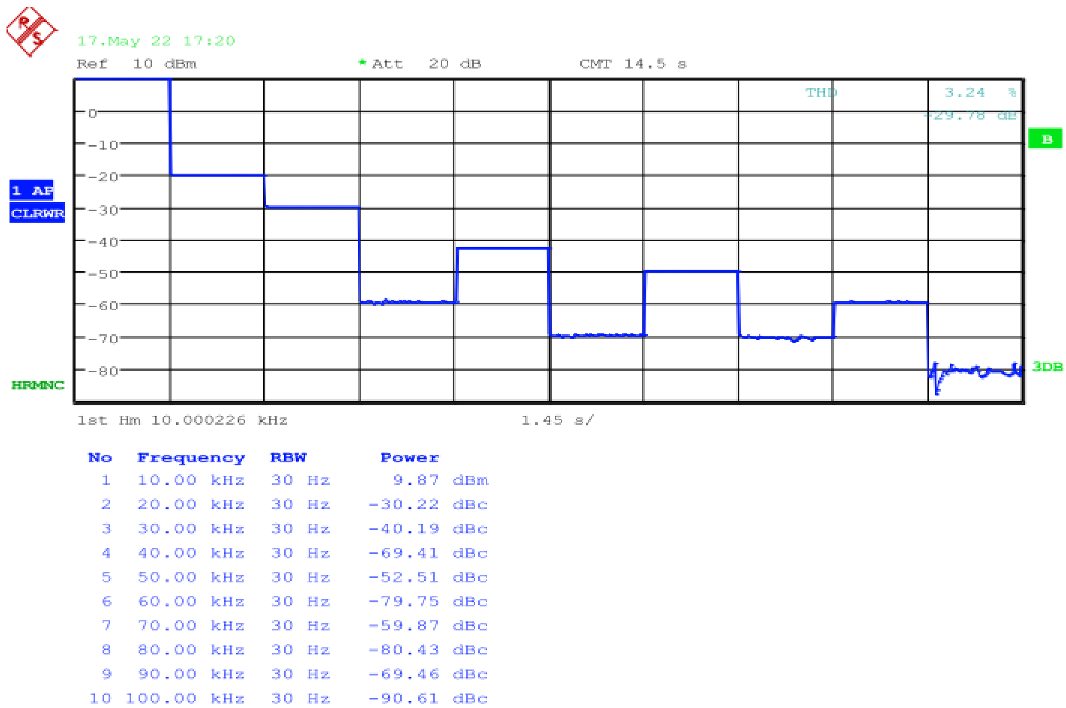

Figure 5-20. Total Harmonic Distortion (PWM signal)

5.8 Fail Events

Figure 5-21 shows the test setup and Figure 5-22 schematic for fail events. The test setup introduces short to ground or short to VCC test conditions through a fault injector. The fault injector uses a mercury-wetted relay that provides excellent, bounce-less, switching characteristics. The waveforms demonstrate that the excitation amplifier promptly reacts to the short circuit condition by disabling the output. This prevents the power supply overload and protects the system. The excitation amplifier recovers to the normal operation after the short circuit removal.

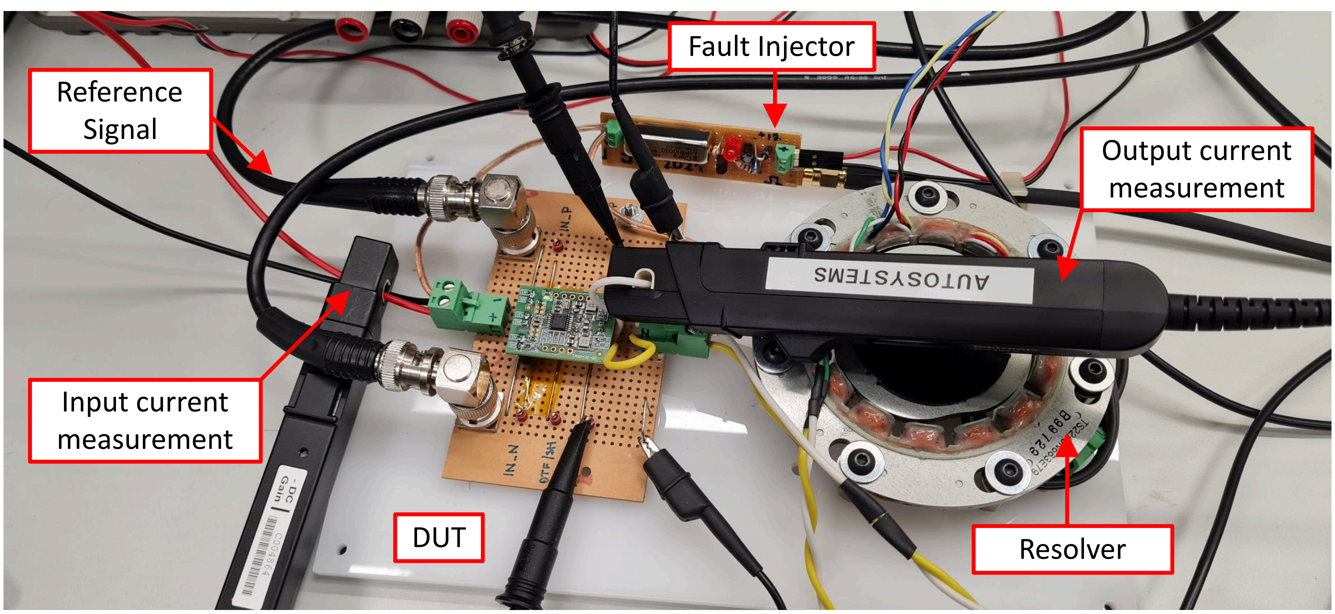

Figure 5-21. Test Setup for Fail Events

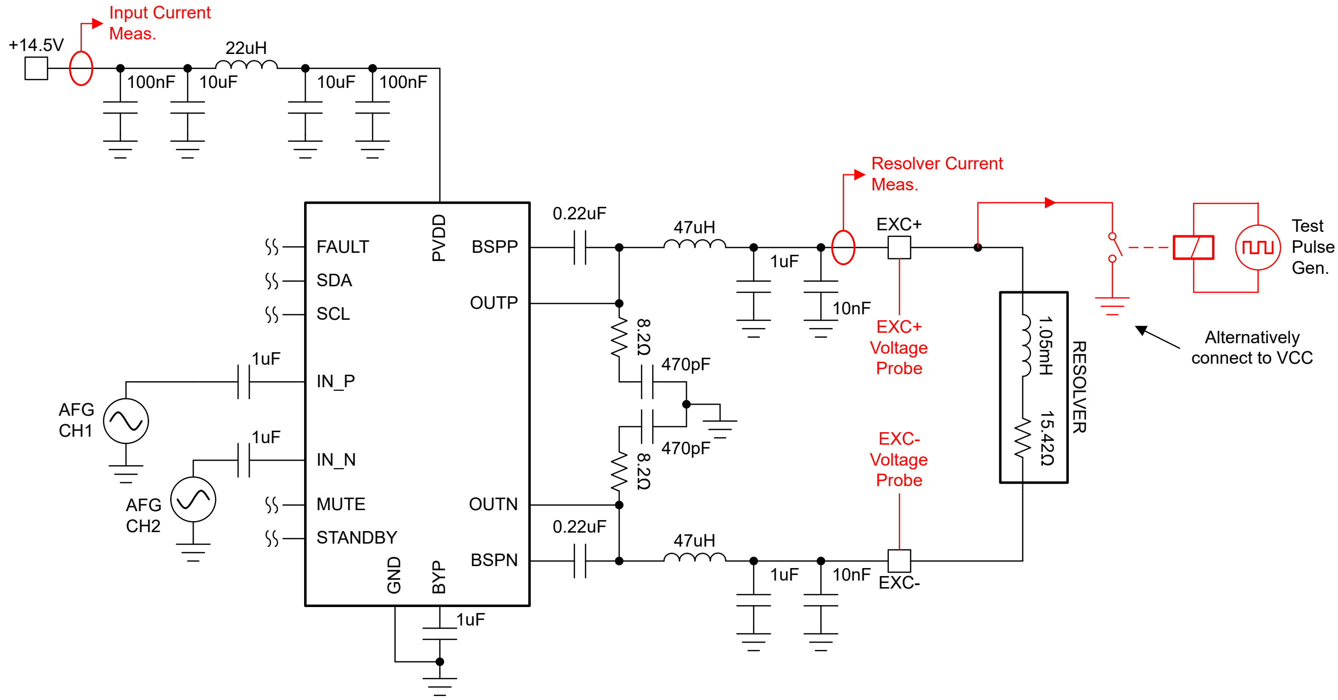

Figure 5-22. Circuit for the Test Setup for Fail Events

Figure 5-23 shows resolver waveforms for reference.

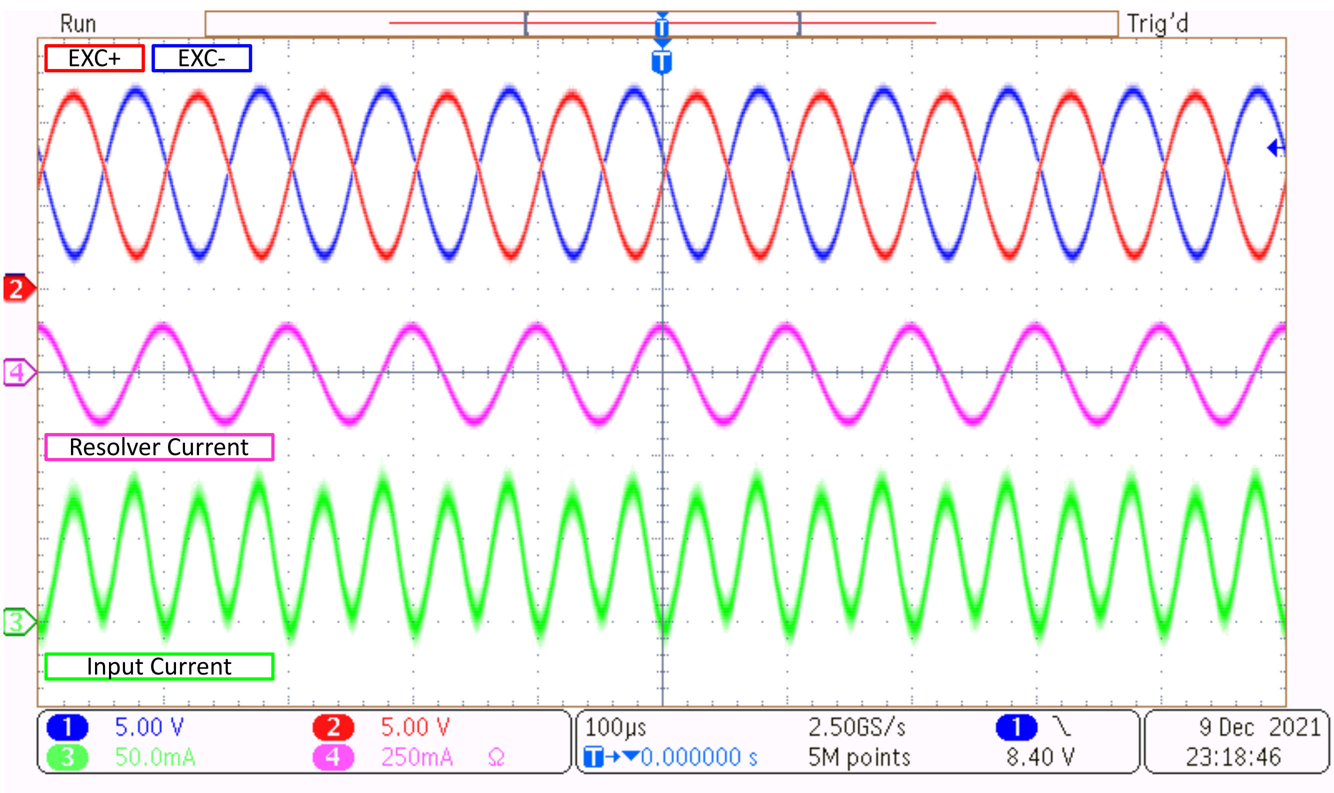

Figure 5-23. Fail Events - Reference Waveforms

CH1 – EXC+ signal (single-ended)

CH2 – EXC- signal (single-ended)

CH3 – Excitation amplifier input current

CH4 – Resolver current

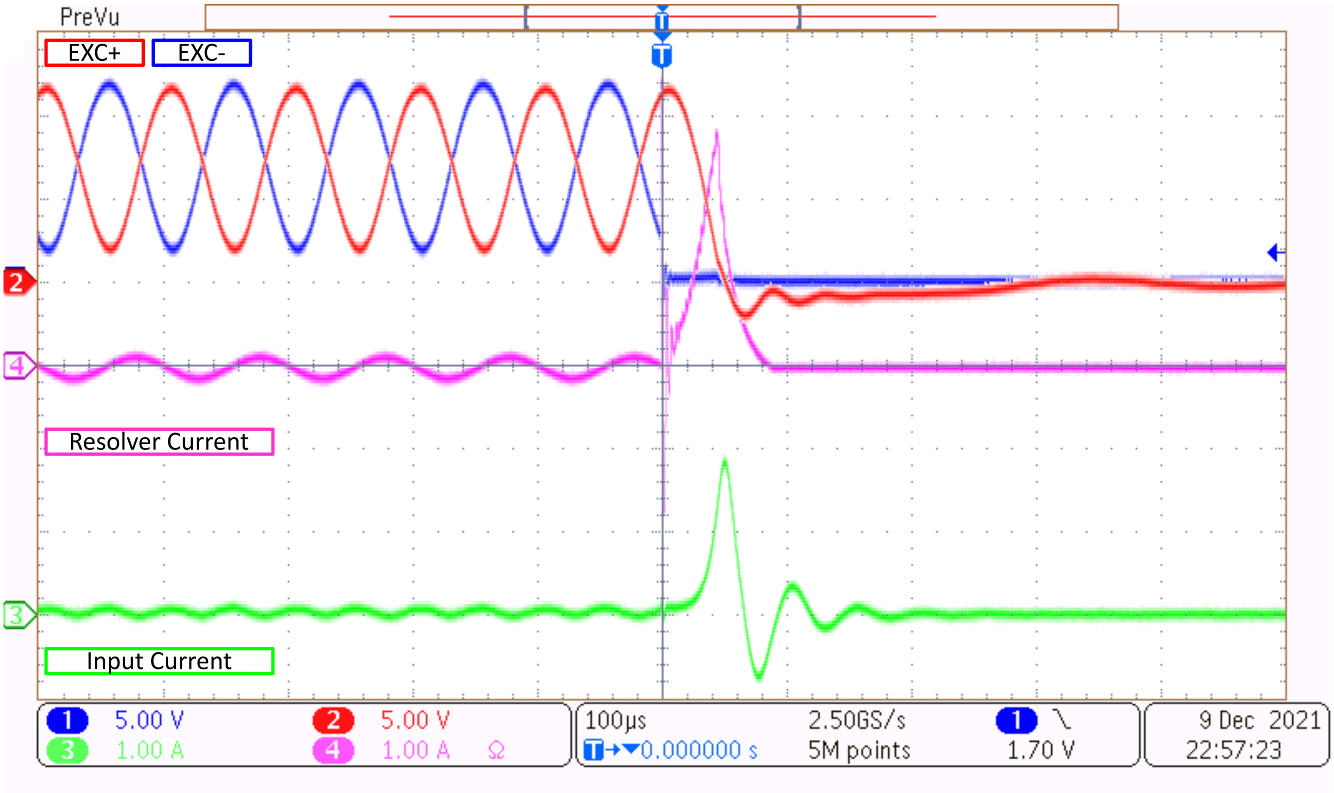

Figure 5-24. Short to Ground

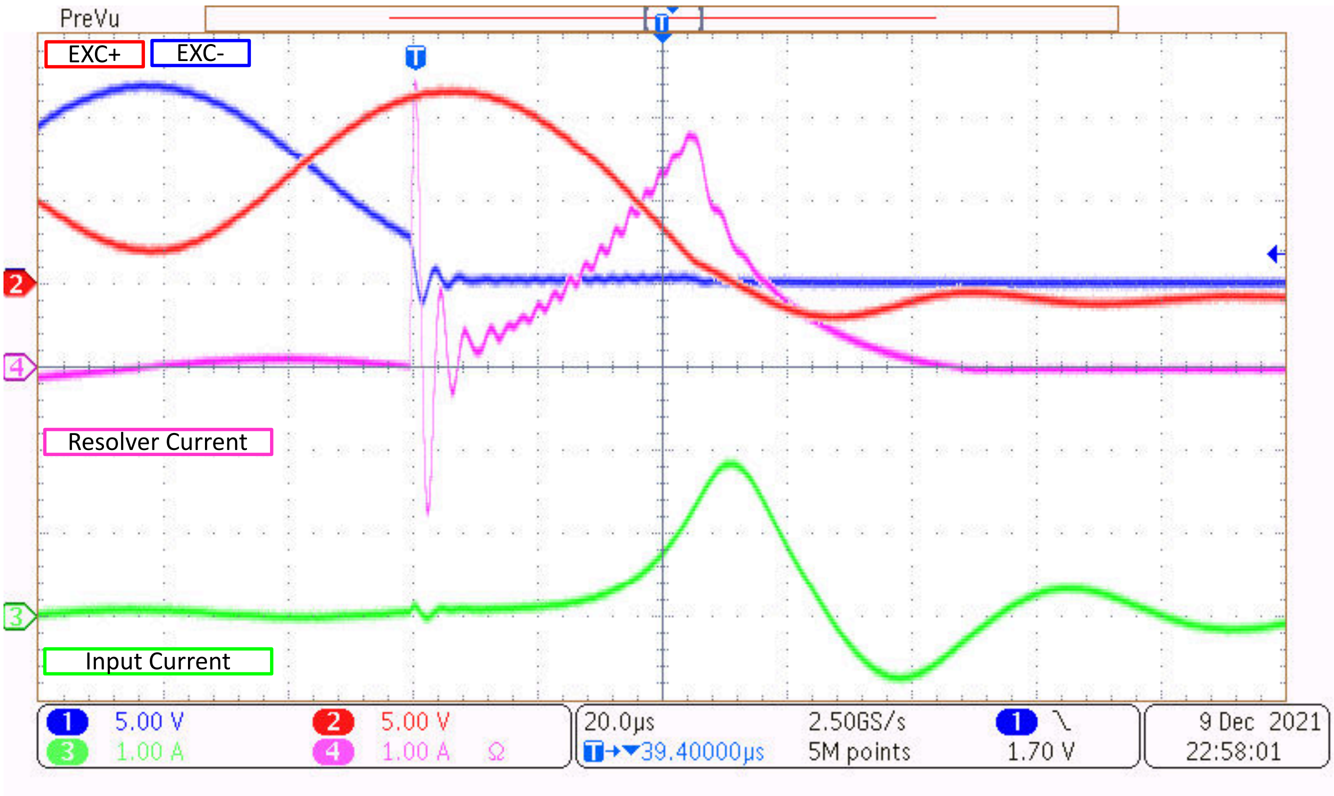

Figure 5-25. Short to Ground (detail)

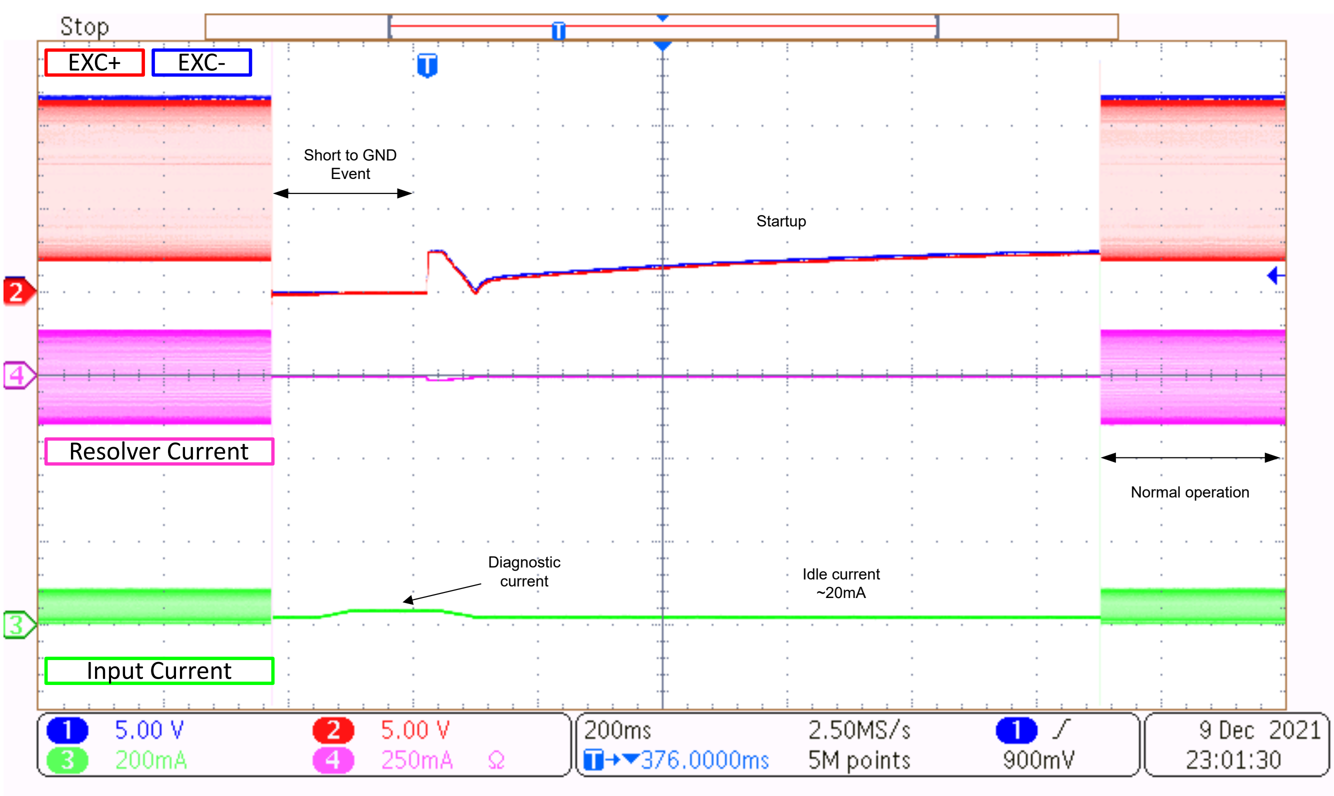

Figure 5-26. Recovery from Short to Ground

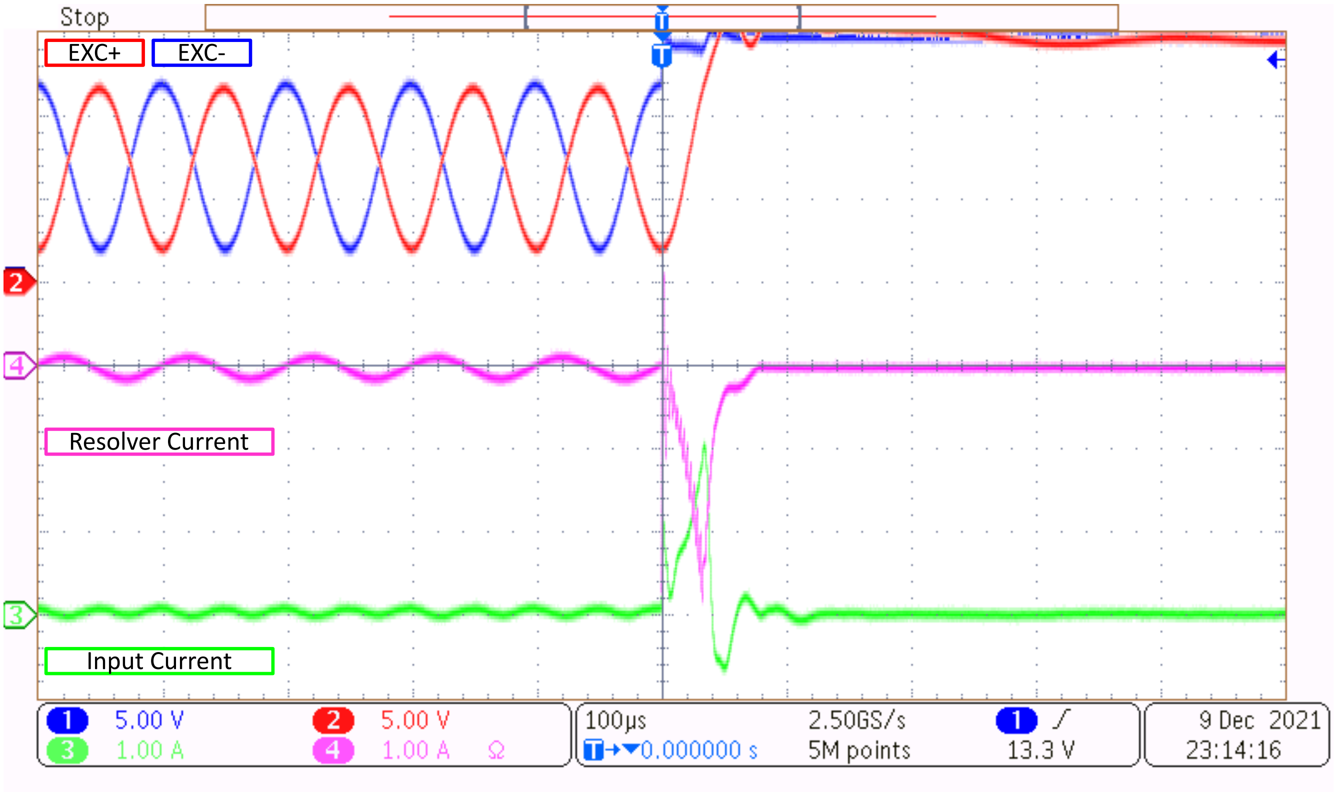

Figure 5-27. Short to VCC

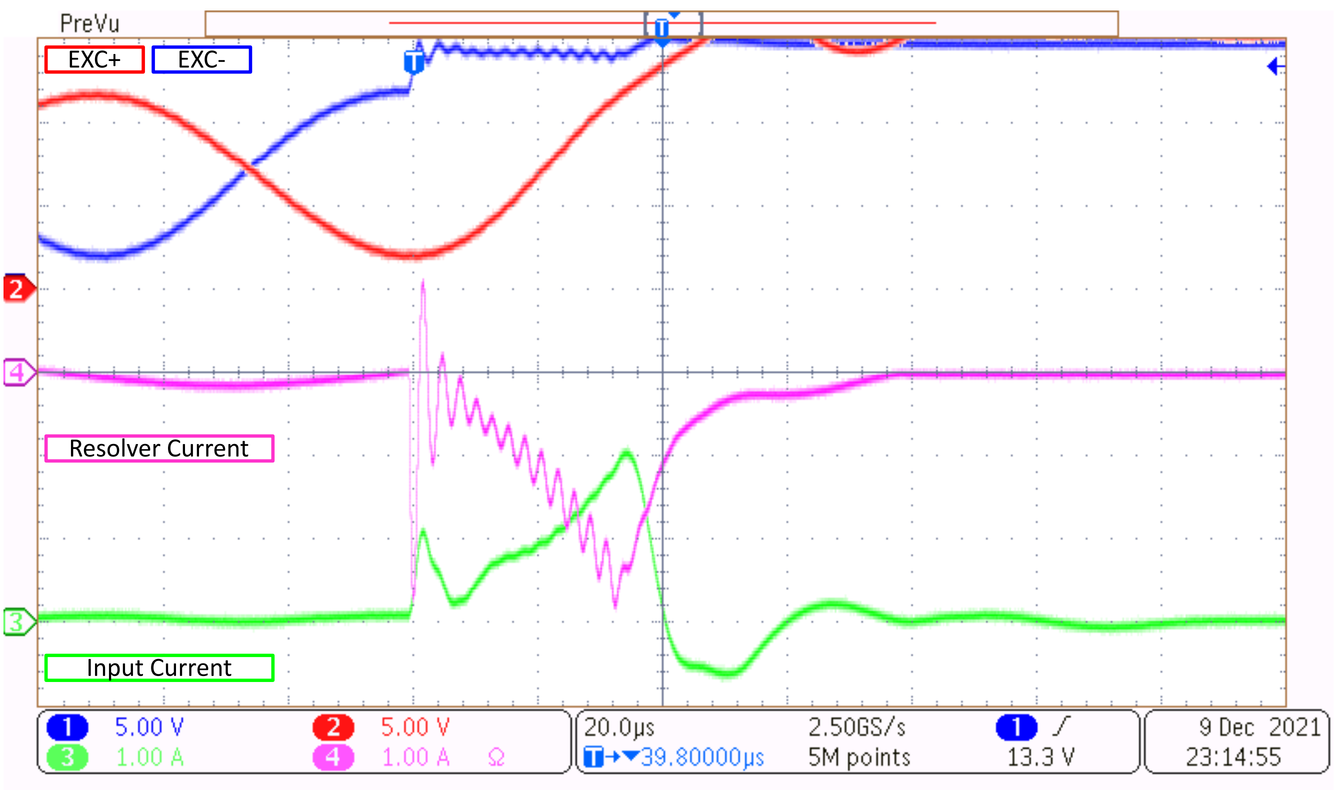

Figure 5-28. Short to VCC (Detail)

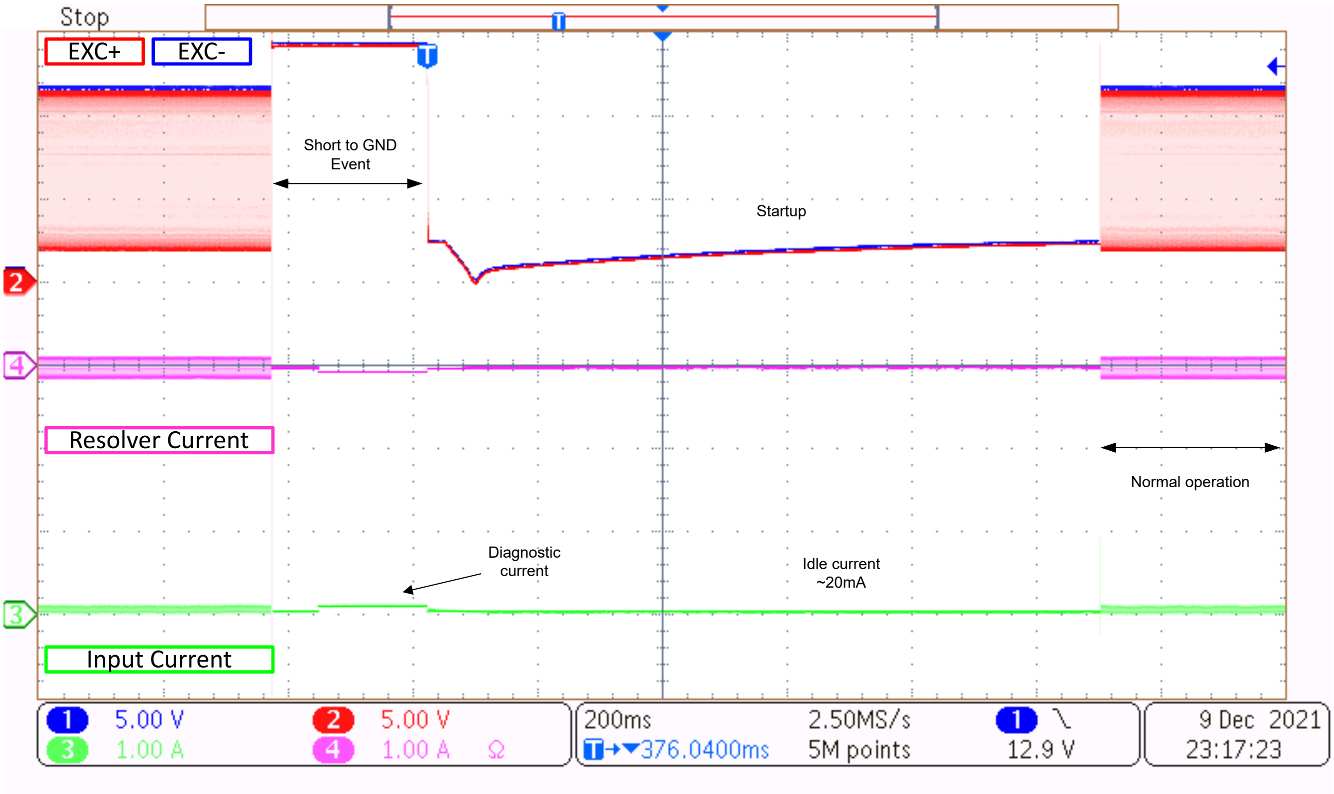

Figure 5-29. Recovery from Short to VCC

6 Summary

Engineers recognize Class-D amplifiers mainly for high efficiency and resulting lower power dissipation. Seemingly same operation in the resolver excitation amplifier leads however to different results. Resolvers transfer negligible power therefore the primary winding acts as a reactive load. Improved efficiency compared to the basic analog circuit is the result of the parallel resonant tank that the output capacitance forms together with the resolver. Resolver excitation with the TSD5402-Q1 Class-D amplifier offers wide range of protection mechanisms and significantly improves system behavior during fail events.

7 References

- Texas Instruments, *Applying the ALM2403-Q1 Single-Chip Resolver Solution to Reduce System Costs, and Improve the Reliability and Performance of Automotive and Industrial Applications* application report.