

Development of a Diagnostic Procedure for Vehicle's Built-in Electric Motors [†]

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Abstract: Electric and hybrid vehicles, similarly to combustion engine ones, can experience malfunctions, yet preventive diagnostics for their electric motors are underdeveloped. While many methods exist for testing electric motors in heavy industry, they are not commonly applied in the vehicle industry. Our study aims to develop a real-time, non-invasive fault detection procedure for electric motors in these vehicles. Previous research has focused on simulations, but our work involves real measurements conducted in a controlled laboratory using a two-axle chassis dyno. We present the hybrid vehicle's drivetrain, our equipment, and the feasibility of simulated methods, and we also detail the evaluation method used.

Keywords: high voltage; hybrid powertrain; inverter; frequency; signal testing

1. Introduction

Our work was inspired by a 2015 study that introduced a combinational logic-based approach to fault identification in electric vehicle drivetrains. This study used a real-time simulation model to analyze sensor signals and control commands, such as phase currents, a DC bus current, and motor speed averages, without the need for additional expensive devices. These parameters contain information about errors and disturbances under faulty conditions compared to a rated operation. The proposed method diagnoses faults at any time during the vehicle's driving cycle using simple combinational logic and thresholds. The results from real-time simulations demonstrate the method's reliability and success in diagnosing various faults, regardless of their occurrence time [1].

Since most similar diagnostic approaches are based on measuring parameters of the battery pack to filter out faults rather than on direct monitoring of E-motors [2,3].

Our goal was to test the motor diagnostic-based method in real-life tests, not just in a simulation environment, like others have achieved. During our measurements, we recorded the currents flowing into the vehicle's electric motor units and subsequently used different electric motor diagnostic methods to check whether a fault could be detected in the vehicle's drive chain.

1.1. Presentation of the Test Vehicle and Its Drivetrain

For our measurements, we used a third-generation Toyota Prius from 2010, which had covered 244,000 km. In addition to its 1800 cm³ gasoline engine, the vehicle is equipped with a hybrid drivetrain, featuring a unique eCVT (electronically controlled continuously variable transmission). The vehicle's electrical supply is provided by a high-voltage battery, which is placed in the luggage compartment.

In the third-generation model, we have a reduced voltage battery unit compared to previous models [4]. The entire electrical system of the vehicle, including low-voltage consumers, is supplied by this battery pack through the DC/DC converter built into the inverter. The unit is a nickel-metal hybrid (NiMH) battery with a nominal voltage of 201.6 V, consisting of 28 cells connected in series with a low voltage of 7.2 V each [5,6].



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A special feature of the eCVT transmission is that the planetary gear inside is not controlled by any kind of mechanical connection but by the excitation of electric motors. The vehicle has two motor-generator units (MG1 and MG2 later) which, as their names reflect, are capable of both driving the vehicle and recharging the battery. The internal combustion engine does not have a separate starter and generator unit; it is started by MG1, and the battery is recharged by both MG1 and MG2 units.

MG1 drives the sun gear of the planetary gear, MG2 drives the ring gear, and the common shaft of the planetary gears is connected to the internal combustion engine via a clutch (Figure 1) [7]. This clutch cannot be disengaged, nor was it designed and installed for this purpose; it is simply meant to balance the vibrations resulting from the engine's ignition timing, just like a double-mass flywheel.

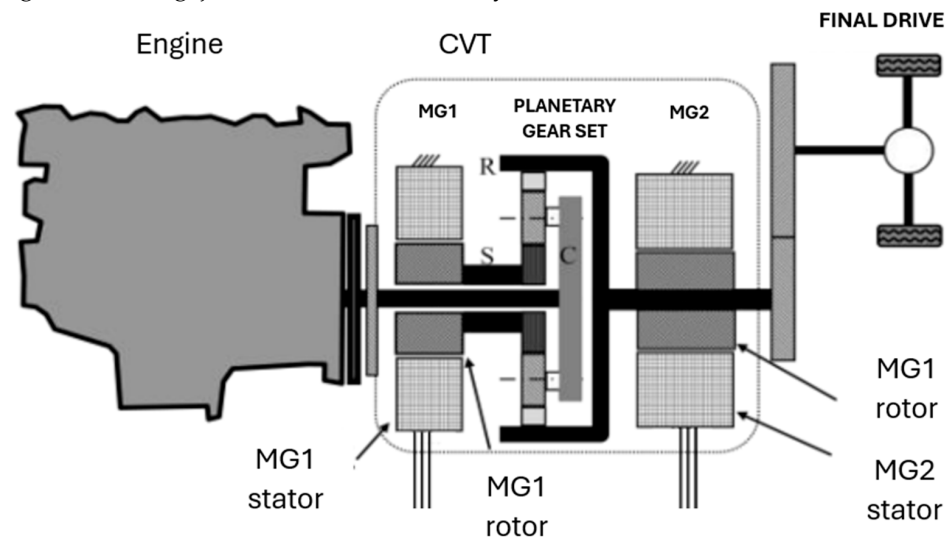


Figure 1. Toyota Prius Gen3's eCVT transmission structure.

Figure 1 above shows that MG2 is in direct contact with the wheel of the vehicle; therefore, MG2 will always be in motion as soon as the vehicle starts to move. In the parking position, if the vehicle's battery is halfway down, the internal combustion engine starts. In this case, only the MG1 unit, i.e., the sun gear, is driven to be able to recharge the battery, while the vehicle is stand still [7–9]. Since one of the MG units is in motion in every case (MG1 for recharging in the stationary position, MG2 for internal combustion drive, and MG1 and MG2 for pure electric drive), we can always test at least one of the MG units during different operations. The perfect operation of this type of converter depends on timing, so a high-voltage inverter is responsible for their controlling, which supplies the right voltage and current to MG1 and MG2 at the right moment.

The high-voltage motor control unit (inverter) in the vehicle amplifies and inverts the high-voltage direct current energy from the HV battery into a three-phase alternating current that drives the electric motors. The inverter also converts the alternating current from the electrical generators into a direct current, which recharges the HV battery [4]. Since the vehicle does not have a separate generator unit, the low-voltage battery is also charged by this unit [10].

1.2. The Applied Diagnostic Procedure

We aimed to perform diagnostics without disassembling the vehicle's drivetrain, using the Motor Current Signature Analysis (MCSA) method. This approach allows for an easy current measurement with minimal disruption, even using a clamp meter. The method involves transforming the measured time signal into a frequency domain using Fast Fourier Transform (FFT), enabling an effective and intuitive signal analysis. By analyzing the periodic components and their harmonics, we can identify faults in the electrical machine based on their unique “signatures” [11–13].

The faults that can be filtered out by monitoring currents are as follows:

- Static or dynamic air gap irregularities;
- Broken rotor bar or cracked rotor end rings;
- Stator faults (opening or short-circuiting of one or more phase windings);
- Bent shaft;
- Bearing and gearbox failures [12].

2. Material and Methods

The device we use is an 8-channel Pico Scope 4823-type oscilloscope (Figure 2), with 12-bit hardware resolution (up to 16-bit hardware resolution using resolution enhancement), 256 MS deep recording memory, 20 MHz bandwidth and 80 MS/s as a sampling rate. It also boasts a built-in 14-bit triggerable signal generator and 80 MS/s AWG. The power supply and data transfer are provided by the SuperSpeed USB 3.0 interface, which provides communication at a speed of up to 160 MS/s [14].

To perform the measurement, we used two clamp meters operating in different ranges, which also belong to the Pico Technology product family (Figure 4). One type is the TA019, which can be used to measure both AC and DC currents and operates in the 0–600 A measurement range and 50–400 HZ frequency range [15]. The other one is also suitable for measuring both current types; it is the TA167 model with a measurement range of 0–2000 A and 0–20 KHz [16].

The diagnostic method we have chosen must be carried out with a load of at least 70%, so we defined the method as an acceleration to 100 km/h with full throttle. The measurement was performed in a laboratory environment on a Chassis dynamometer as this was the safest solution, and we had such equipment in our laboratory building.

2.1. Installation of the Measuring Device in the Vehicle

Before testing the vehicle's high-voltage system, we removed the high-voltage fuse to de-energize the system. After that, we disconnected the shielding cover from the connectors of the MG units, which also served as the negative ground. This had to be triggered with a wire to ensure it did not interfere with the vehicle's operation. The wire is attached to one of the phases of the electric motors via the circuit of the clamp meter (Figure 2), according to its direction.

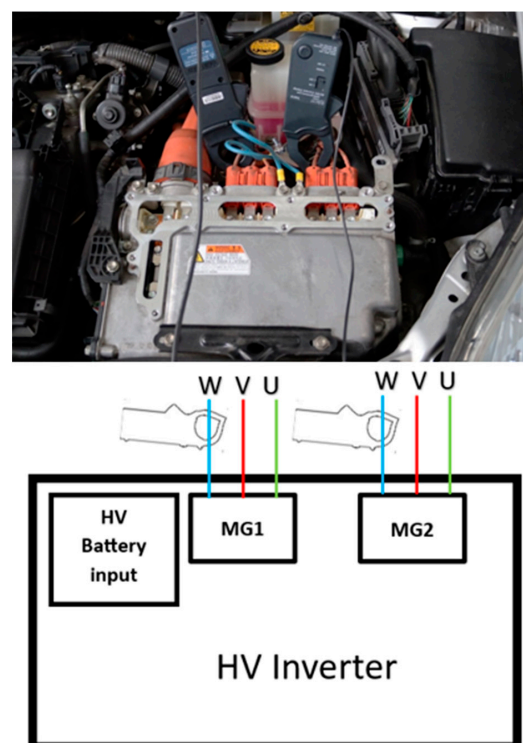


Figure 2. Clamp meters connected to the vehicle's high-voltage inverter.

2.2. Software Configuration

On the PicoScope's software (PicoScope 7.1.29 Stable), it was necessary to configure the following values (Figure 3) for the vehicle's system:

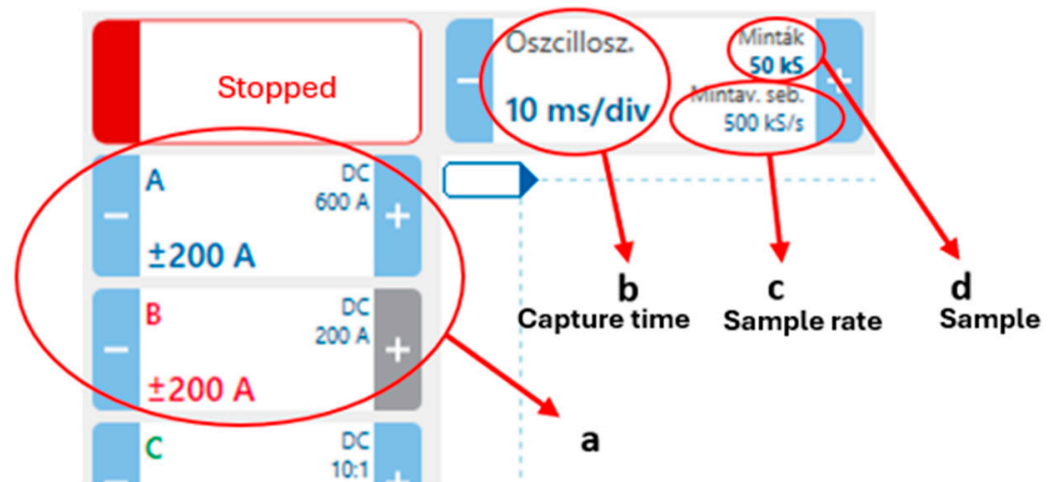


Figure 3. Software configuration.

- (a) A selection of channel assignment, measuring head type, current type, and measurement range (in our case, channels A and B, measuring heads TA167 and TA019, DC current, and measuring range ± 200 A);
- (b) Data recording range: 0.01 s/div;
- (c) Sampling speed (S): 500,000 S/s;
- (d) Fixed samples during the measurement cycle: 50,000 S.

The figure shows the details of the configuration settings that were necessary for accurate data capture and analysis. The correct configuration ensures that measurements are accurate and reproducible during vehicle testing.

The increase in the volume of recorded data presented a significant problem, as most of the software available online was unable to handle such large datasets.

Consequently, it was necessary to develop custom software, for which we used the Python programming language. Utilizing the functions available in the NumPy mathematical library in Python, we were able to efficiently perform the required data transformations on datasets comprising millions of entries. The developed software also possesses an additional crucial feature: any new data to be monitored can be easily integrated into the system, thereby enabling more precise and detailed observations.

3. Results

With the software configuration shown on Figure 3, we were able to record data for 100 s in each case, but out of that, only 25 s was necessary for the actual measurements. All the data were saved in CSV format, which can be handled by most software; however, there were many problems with the amount of data. During one measurement, we recorded about 50 million data, which not all programs could display in such a large amount, but reducing the recorded data would not have been a solution in our method since the extent of the error could be determined more accurately as more data were available (Figure 4).

Both functions are suitable for detecting possible electric motor failures, but we focused mainly on the frequency range. With the help of transformed values, today's technology can detect abnormalities much faster and more easily. In the program, it is possible to zoom in (Figure 5) at any point of the function so that possible error "signatures" become visible.

In our case, accessing the electric motor units would have involved a significant disassembly of the vehicle, so we did not inject errors during the measurement, and therefore, no detectable failure occurred from the measured data. Despite all this, it can be concluded that the tested method is functional and that the diagnostics of the electric

motor units can be solved with minimal disassembly. Similar to the simulation, the electric motor current waveforms can be easily extracted, and with further analyzes, the extent of the motor's failure can be determined.

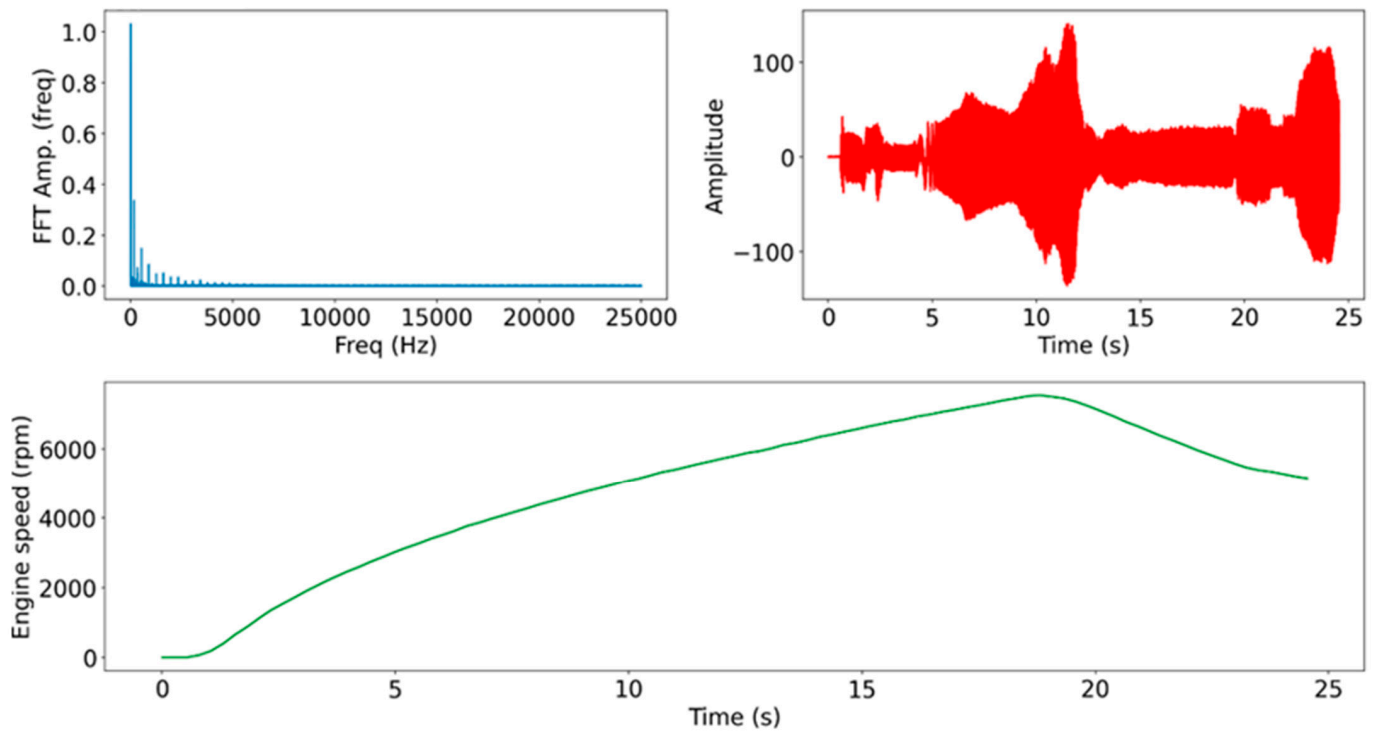


Figure 4. Evaluation for the 'A' channel using our program.

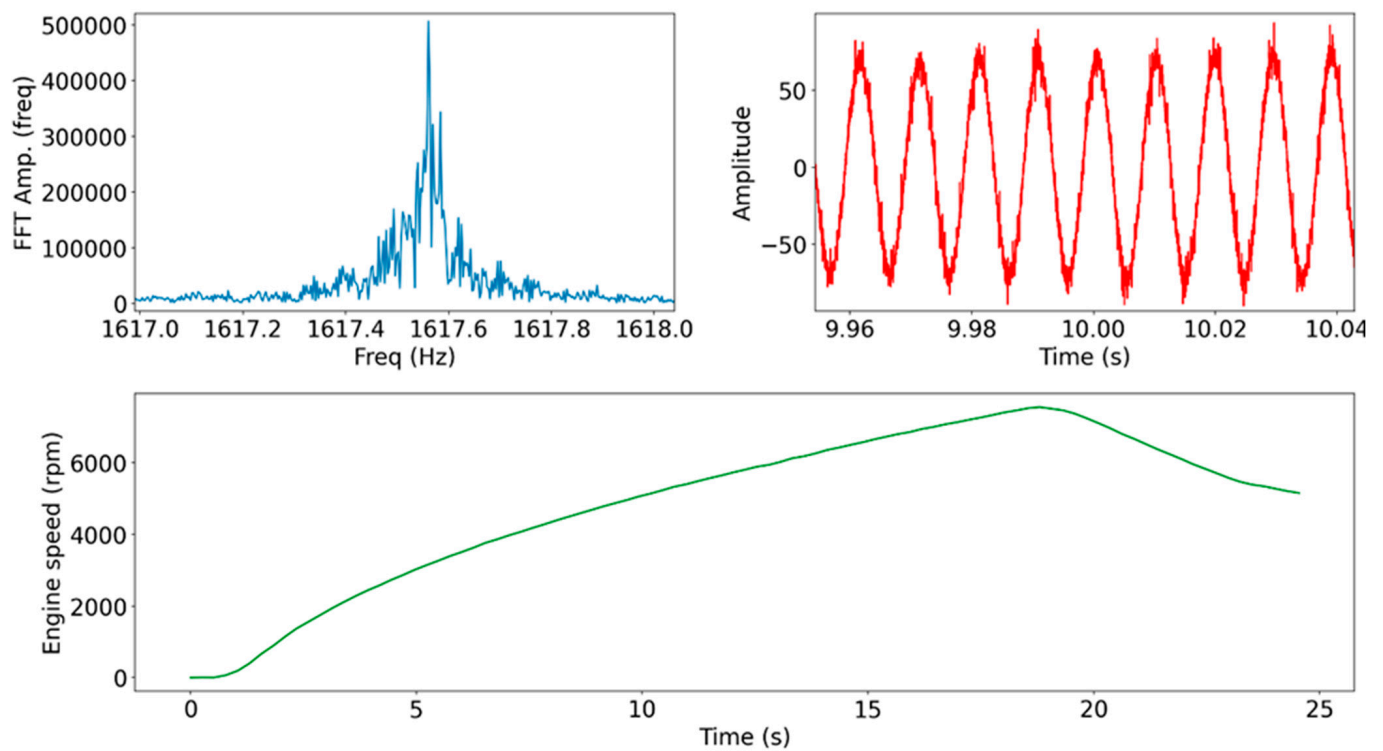


Figure 5. Zoomed-in function.

4. Conclusions

Our study aimed at developing a diagnostic procedure for electric motors built into vehicles, representing a significant step forward in the preventive maintenance of electric and hybrid vehicles. During our study, we presented in detail the applicability of diagnostic methods, especially the MCSA (Motor Current Signature Analysis) process based on monitoring currents, which requires minimal dismantling operations, thus offering a time- and cost-effective solution. We performed our measurements in laboratory conditions on a Chassis dynamometer, which made it possible to minimize external factors and closely follow the measurement process. With the help of the used automotive oscilloscope and high-voltage lock arresters, it was possible to record an accurate and adequate amount of data for the currents of the electric motor, which could later be subjected to a detailed signal shape analysis. By using FFT (Fast Fourier Transformation), the analyzes in the frequency domain provided data on the state of the electrical machines in a fast and visual way, enabling the fast and accurate diagnosis of faults. Based on these results, we can state that the developed diagnostic procedure can be useful not only in the vehicle industry, but also in other industrial applications where the diagnosis of electric motors is needed. Due to the simplicity and efficiency of the method, it can be a significant advantage during preventive maintenance activities, reducing the risk of unexpected failures and increasing the operational safety of the equipment.

In the course of our future research, we plan to conduct measurements and analyzes on different types of electric motors and drivetrains in order to obtain an even more comprehensive picture of the applicability and limitations of the diagnostic method. Furthermore, our goal is to integrate real-time monitoring systems, which enable continuous status monitoring and immediate intervention when errors are detected.

Overall, this study contributes to the development of diagnostic methods for electric motors, and we hope that our results will stimulate further research and development in this area, helping to develop more reliable and sustainable vehicle systems.

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