

Selected issues related to diagnostic testing of hybrid vehicles

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Abstract. The increasing emphasis on ecology by the governments of particular countries makes vehicle manufacturers to look for alternative sources of propulsion to meet increasingly stringent exhaust gas emission standards. One of such solutions is the use of a hybrid system in the form of a combination of a combustion engine and an electric motor. Such a combination, together with the possibility of recovering the kinetic energy during braking, makes the vehicle, comparing to the conventional drive, much more friendly to the environment. This technology poses the new challenges in the terms of operation, testing and diagnostic measurements of the hybrid vehicles. Because of the electrical system operating under a high voltage, many service and repair facilities are still afraid of repairing the above vehicles. In this article are discussed the basic safety and diagnostic procedures during vehicle tests on the example of the Toyota Prius of the second and third generation. The following procedures have been discussed: analysis of the operation of the high voltage battery with a diagnostic tester, the recommendations during measurements by means of an oscilloscope for low voltage sensors and the procedure related to disconnecting the power supply of the hybrid system in case of an accident. In addition, more and more specialised measuring devices, dedicated to laboratory units and services, appear in the market every year. Therefore, this article reviews the devices dedicated to repairs of vehicles with the hybrid and electric drive.

1. Basic service of hybrid vehicle

Because of the operation of their particular high voltage systems, the hybrid vehicles may can pose a great danger even for trained employees if they do not maintain the appropriate security procedures. According to regulations in Poland, any work, executed

on the hybrid vehicles (combustion engine + electric motor) may take place after passing the appropriate training in the field of work at the voltages up to 1000 volts. Such a trained person has to be equipped with the appropriate accessories to ensure his / her safety [1]. Before starting the testing or service work, a stand should be properly marked with the appropriate warning boards (Figure 1).





Figure 1. An example of the warning board and 1000V protective leather insulated gloves [2, 3]

In addition, the stand, where the vehicle is located, shall be separated from unauthorized persons.

Before undertaking any work on the systems and components of the hybrid vehicles that are under the high voltage, it is mandatory to follow the safety guidelines. They are specified as follows [4]:

- 1) The personnel, working directly on the hybrid - electric vehicles shall undergo appropriate training.
- 2) The warning signs, informing about the work under the high voltage in, on and around vehicle, shall be provided. It is recommended to restrict access to the vehicle under repair to the untrained persons by means of barriers, on which there are mounted the signs indicating the high voltage.
- 3) Always wear insulated gloves suitable for work with the voltage up to 1000V. It is worth noting that such gloves should be every certain time, predetermined by the producer, sent for re-verification in order to determine whether they meet the relevant safety requirements.
- 4) Disconnect the power supply on the hybrid vehicle by pulling out the safety plug, located in the high voltage battery.
- 5) After disconnecting the high voltage, it is necessary wait the recommended time before proceeding with any work on the hybrid vehicle. The assumed waiting time is about 15 - 20 minutes.
- 6) Before starting the work, check whether the residual voltage is lower than the recommended safety level.
- 7) All the tools and diagnostic equipment shall be adapted to work at high voltage.

In both, the Toyota Prius of the second and third generation, the battery is located in the luggage compartment under the floor. In case of the Toyota Prius of the second generation, the plug is located on the left-hand side, whilst in the Toyota Prius of the third generation, the plug is located on the back wall of the battery on its right-hand side. The plug is marked with the bright red colour. The procedure for disconnecting the power supply shall be executed as follows [4]:

- 1) Wear protective gloves designed for work at 1000 V
- 2) Remove the luggage compartment floor
- 3) Disconnect the minus 12V battery clamp.
- 4) Pull out the service plug as follows (Figure 2)
 - 4.1) Pull the switch up
 - 4.2) Turn it clockwise by 90 degrees
 - 4.3) Pull out the service plug
- 5) Wait for minimum 5 minutes (the Toyota Prius of the second generation) or 10 minutes (the Toyota Prius of the third generation), to make the capacitors, located in the inverter able to discharge.
- 6) Start the maintenance / repair work after expiration of the above specified time.

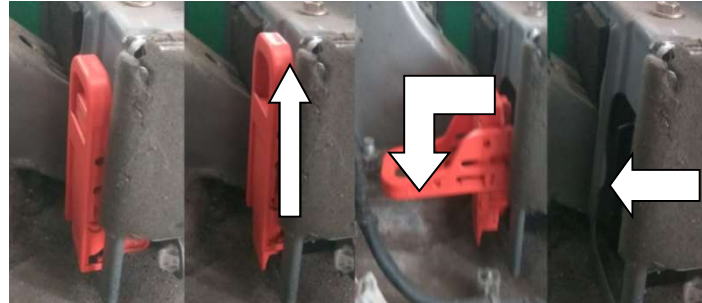


Figure 2. Service diagram for service plug

The procedure for restoring the main power supply is described as follows [4]:

- 1) Wear protective gloves to work at high voltages (1000V).
- 2) Connect the minus 12V battery clamp.
- 3) Insert the service plug into the socket, located in the battery.
- 4) Turn the switch up by 90 degrees.
- 5) Press the lever down.
- 6) Start the engine after restarting the power supply.
- 7) Program the electric windows by opening and closing each of them.

The improper placement of the service plug by, for example, not pressing the switch to the secured position, results in the P0A0D error in the system responsible for controlling and monitoring of the battery operation. Starting the vehicle in such a situation is not possible.

2. Diagnostic mode and starting combustion engine for testing and diagnostics

Operation of the combustion engines is often required during tests and diagnostic work. In case of the hybrid vehicles, after starting the drive system, the combustion engine does not always start, and if the ECU control unit starts the above unit, the combustion engine is switched off after the battery has been charged. However, the manufacturers of such vehicles foresaw such a situation during the design work and enabled the mechanics to set the vehicle in the diagnostic mode.

In case of the Toyota Prius of the second generation, the diagnostic mode is activated as follows [4]:

- Press the POWER button twice (without touching the accelerator and brake pedals).
- Press the accelerator pedal fully to the end twice.
- Place the transmission in the NEUTRAL position while holding the brake pedal.
- Press the accelerator pedal twice.
- Press the PARK button located above the gear lever.
- Press the accelerator pedal twice.
- Press the brake pedal and the POWER button.

After completing the above combination, the vehicle should enter the diagnostic mode. The above function is switched off after switching off the entire drive system with the POWER button.



Figure 3. Information on the diagnostic mode on the on-board computer of the Toyota Prius of the second generation

In case of problems with switching on the diagnostic mode, there is also another way to start the combustion engine. It works in both the Toyota Prius of the second and third generations. Shift the gearboxes in parking mode and with the ignition switched on (the word "READY" appears on the display) press the accelerator pedal lightly. This will start the combustion engine, which will run as long as the accelerator pedal is pressed. The disadvantage of this method is that two persons are often required – one, who presses the accelerator pedal and the other, who executes the diagnostic procedures.

3. Diagnostics of hybrid vehicles with the use of multimeter and oscilloscope

In practice, all the controllers, situated outside the control system located in the inverter and in the battery, operate under 12V voltage. All kinds of the electrical components (operating under 12V voltage) may be checked with the use of the multimeter with an impedance of min. 10 k Ω . The manufacturer does not predict measurements with the use of measuring instruments other than the diagnostic tester used to test the hybrid system, which operates at the voltage of up to 650 V AC. All the diagnostic work on the drive system, which operates under the high voltage shall always take place when the power supply is disconnected [4].

During the diagnostic work, it is sometimes necessary to connect to individual sensors with the oscilloscope in order to check them. When analysing the technical documentation made available by Toyota, there are no contraindications to test measuring elements. For safety, before making measurements, make sure that the voltage in the cable, to which we want to connect, is not higher than 16V [4]. Figure 4 shows the screenshots of the characteristics of two electrical components of the Toyota Prius of the second generation obtained on the oscilloscope.

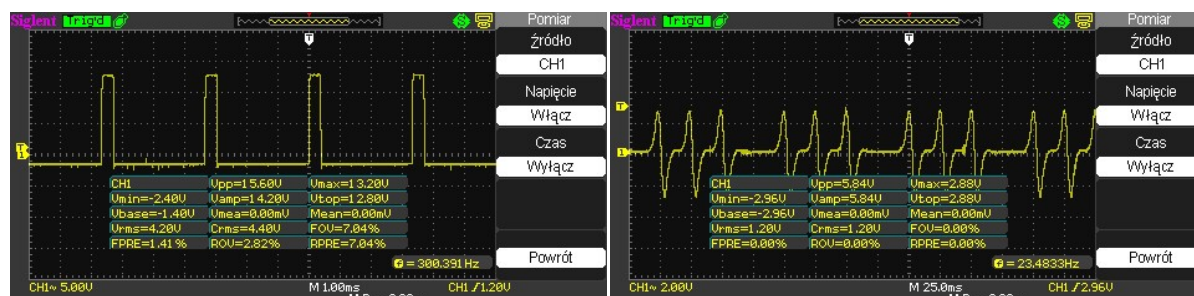


Figure 4. The oscilloscope diagrams of the timing controller – the control signal and the camshaft sensor

Making measurements with the use of the oscilloscope in the above vehicles is quite difficult because of a very limited space that often prevents the entry to the particular measuring elements of the combustion engine. The easiest access to the above elements is from the side of the injection unit, located in the passenger compartment in case of the Prius of the second generation or in case of the Prius of the third generation next to the inverter. It is worth noting that the hybrid vehicle, offered by Peugeot company and equipped with the Diesel engine is available in the market. The diagnostic procedures for these types of engines are similar to the diagnostic procedures of the vehicles with the hybrid drive with the spark-ignition engine. The difference consists in maintaining the safety measures before undertaking the diagnostic actions and checking for possible voltage in the control systems and sensors [5].

4. Electrical system of hybrid vehicles

Toyota, like many other hybrid vehicle manufacturers, has developed the repair procedures for electrical systems. There have been described all types of plugs and connectors used in hybrid vehicles as well as control and measurement equipment used to simplify the disassembly of individual elements in order to repair them. A quite common problem for all manufacturers is wear or damage to components of the broadly understood electrical system (connectors, pins, plugs) as a result of many years of operation and the impact of weather conditions. During repairs of the electrical system, the manufacturer orders to disconnect the power supply and, before starting the work, to check whether there is no voltage in the repaired cable in relation to the earthing of the vehicle. It is forbidden to repair any high voltage cables (the insulation is marked with the bright red colour). In case of finding a damage to the high voltage cable, such a cable shall be replaced into the new cable [4]. The view of the high voltage cable in the Toyota Prius vehicle of the second generation is shown in Figure 5.



Figure 5. The high voltage cable of the Toyota Prius of the second generation

5. Safety procedures after a hybrid vehicle accident

Because of equipping the hybrid vehicle with the electric drive supplied with the voltage within the range from 201.7 V to 650 V, all persons who undertake a rescue operation shall at first make sure that the power supply is turned off and will not pose a danger to all, who will perform any actions at the vehicle. Such persons are the most often representatives of the fire brigade rescue team or electrical engineers, who work in plants specialised in the work on such vehicles. Such persons shall be equipped with [4]:

- Protective clothing (protective gloves for the use at the voltage of 1000V, safety goggles, protective shoes for work at the voltage of 1000 V).
- 20 dm³ of saturated boric acid (it may be obtained by dissolving 800 grams of boric acid powder in a tank filled with water).
- Red litmus paper (otherwise known as index paper or PH paper).
- ABC fire extinguisher (also known as powder).
- Pieces of cloth (for wiping spilled electrolyte).
- Vinyl tape.
- Electrical tester.

Procedure for behaviour at the vehicle after an accident:

- 1) Wear protective clothing
- 2) Do not touch the cables with the bright red colour. However, if the cable has been touched, then:
 - 2.1) Wear protective clothing
 - 2.2) Check with an electrical tester that there is no voltage between the high voltage cable and the body of the vehicle.
 - 2.3) Secure the damaged cable by insulating it with a vinyl tape.
- 3) If there is a fire in the vehicle, use the ABC powder extinguisher and try to extinguish the fire. It should be remembered that a small amount of water can be a greater threat, because the fire may spread. If it is not possible to extinguish the fire, because a significant part of the hybrid vehicle is on fire, then it is necessary to wait for the arrival of the fire brigade.
- 4) Check the high voltage battery for any leaks of electrolyte. In case of leaks, do not touch electrolyte under any circumstances. Wear rubber gloves and glasses. Place a piece of indicator paper on electrolyte. If it turns blue, it must first be neutralised before collecting it with pieces of cloth.

Electrolyte neutralisation procedure [4]:

- Pour the solution of saturated boric acid onto electrolyte and check with the use of the PH paper whether it becomes blue. If the PH paper color is still blue, it is necessary to use more H₃BO₃ solution until the colour of the PH paper becomes red.
 - Electrolyte may be collected with pieces of cloth only when the colour of the PH paper no longer changes its colour to the blue colour.
- 5) In case of suspicion that particular elements or cables are under the high voltage, cut them off in accordance with the following:
 - 5.1) Set the gearshift lever to the "P" position.
 - 5.2) Remove the key from the ignition switch and disconnect the minus clamp from the battery (for the Toyota Prius of the second and third generation vehicles the battery is located on the right side of the luggage compartment near the rear reflector).
 - 5.3) Pull out the service plug, remembering to put on protective gloves suitable for work at the voltage of 1000 V.
 - 5.4) In case, when that pulling out of the service plug is not possible, at first remove the fuse corresponding to the HV hybrid drive (in the Toyota Prius of the second generation the fuse is located

in the engine compartment in the fuse box next to the inverter on the right side Figure 6).

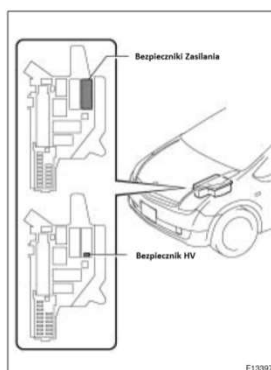


Figure 6. Location of the fuse responsible for supplying the HV hybrid drive (the Toyota Prius of the second generation) [4]

6. Diagnostic procedure for high voltage batteries

Toyota company has developed a method for testing HV batteries by means of the diagnostic tester and the Online system. Unfortunately, unauthorised services do not have access to the above diagnostic procedure. However, having a professional universal or dedicated diagnostic tester, it is possible to check the operation of individual cells. The following measurements were made by the professional Magneti Marelli Vision diagnostic tester.

Based on the tests executed on the Toyota Prius vehicle of the second generation shown in Figures 7 and 8, the following data may be found:

- The voltages of individual cell pairs are on the level 16.2 - 16.3 V.
- The resistance of individual cell pairs is 0.019 Ω

Maintain the parameter values	10:40	
V0 – Battery voltage [<i>Napięcie akumulatora – V0</i>]	16,20	V
V0 – Battery voltage	16,20	V
V0 – Battery voltage	16,18	V
V0 – Battery voltage	16,22	V
V1 – Battery voltage	16,20	V
V1 – Battery voltage	16,19	V
V1 – Battery voltage	16,21	V
V1 – Battery voltage	16,19	V
V1 – Battery voltage	16,13	V

Figure 7. Parameter printout from the MM Vision diagnostic tester

R01 Internal resistance	0.019	Ohm
R02 Internal resistance	0.019	Ohm
R03 Internal resistance	0.019	Ohm
R04 Internal resistance	0.019	Ohm
R05 Internal resistance	0.019	Ohm
R06 Internal resistance	0.019	Ohm
R07 Internal resistance	0.019	Ohm
R08 Internal resistance	0.019	Ohm
R09 Internal resistance	0.019	Ohm
MAINTAIN THE PARAMETER VALUES	10:41	
R09 Internal resistance	0.019	Ohm
R10 Internal resistance	0.019	Ohm
R11 Internal resistance	0.019	Ohm
R12 Internal resistance	0.019	Ohm
R13 Internal resistance	0.019	Ohm
R14 Internal resistance	0.019	Ohm

Figure 8. Parameter printout from the MM Vision diagnostic tester

The above prints were made on the Toyota Prius vehicle of the second generation during parking of the vehicle and on the efficient batteries. The increase in the resistance of the particular pairs of cells and the drop in the voltage in relation to the other testifies the worse and worse condition of the battery and the need to replace the battery soon.

The measurements of the high-voltage battery in the Toyota Prius of the third generation were performed during a road travel with the use of the dedicated tester with the Toyota TechStream software. The test results are shown in Figure 9.

Parameter	Value	Unit	Parameter	Value	Unit
MG2(Motor) Inverter Temperature High-Last Op	0		Battery Block Vol -V09	16.06	V
MG2(Motor) Inverter Temperature High-Last Trip	0		Battery Block Vol -V10	16.06	V
MG1(Generator) Inverter Temperature High-Last Op	0		Battery Block Vol -V11	16.11	V
MG1(Generator) Inverter Temp High-Last Trip	0		Battery Block Vol -V12	16.09	V
Main Battery Low Voltage-Last Operation	1		Battery Block Vol -V13	16.09	V
Main Battery Low Voltage-Last Trip	1		Battery Block Vol -V14	16.06	V
Coolant Heating-Last Operation	0		Battery Low Time	0	
Coolant Heating-Last Trip	0		DC Inhibit Time	0	
Converter Heating-Last Operation	0		Hot Temperature Time	0	
Converter Heating-Last Trip	0				
Batt Pack Current Val	42.04	A			
Inhaling Air Temp	21.8	C			
VMF Fan Motor Voltage1	2.2	V			
Auxiliary Battery Vol	14.32	V			
Charge Control Value	-25.0	KW			
Discharge Control Value	21.0	KW			
Cooling Fan Mode1	2				
Temp of Batt TB1	37.5	C			
Temp of Batt TB2	39.6	C			
Temp of Batt TB3	35.0	C			
Battery Block Vol -V01	16.04	V			
Battery Block Vol -V02	16.01	V			
Battery Block Vol -V03	16.14	V			
Battery Block Vol -V04	16.09	V			
Battery Block Vol -V05	16.04	V			
Battery Block Vol -V06	16.01	V			
Battery Block Vol -V07	15.89	V			
Battery Block Vol -V08	15.84	V			

Figure 9. The screenshot of the Techstream program during testing of high voltage batteries

The following facts could be stated during the analyse of the operation of the high voltage batteries:

- During the stoppage, the voltage of the individual cell pairs is between 16.27 and 16.32 V.
- During the acceleration of the vehicle at the current consumption of approx. 128 A, the voltage on the cells dropped to approximately 13.96 and 14.18V.
- During the recovery of energy at the current of 93 A, the voltage of particular cells increased to about 18.30 V.

Similarly to the Toyota Prius of the second generation, too big difference in the voltage between the cells indicates their consumption and the need to replace them soon in order to ensure the correct operation of the whole battery.

7. Devices dedicated to diagnostics of hybrid vehicles

The popularity of hybrid vehicles increases every year. As a result, there is an increasing demand for specialist equipment for diagnosing hybrid and electric vehicles also available for unauthorised services and laboratories.

7.1. Midtronics HYB-1000 tester for HV battery used in hybrid vehicles

Midtronics has designed a diagnostic tester dedicated to hybrid vehicles. The first most important function of this tester is to test the high voltage battery. The test is performed while driving a vehicle on the road. There is no need to disassemble the battery. All necessary data is downloaded from the OBD2 plug. This is a huge advantage of this device. In addition, the device has the ability to read error codes, delete them and perform tests on the auxiliary battery [6].

7.2. Midtronics GRX-5100 EV/HEV Battery Service Tool

Another tool designed by Midtronics and dedicated for hybrid vehicles. This device may be used by services, transport companies and vehicle utilisation plants. It has three modes: De-Power, Selection Balance and View Pack Info.

De-Power - this is the mode that allows to discharge the battery in a safe way, or to prepare the battery for transport. This mode is used in case of a need to remove the battery from vehicle and ensures the highest possible level of safety.

Selection Power - this mode is used to balance the particular battery sections. Individual sections can be charged or discharged.

View Pack Info - This mode allows to read the VIN number and to print a report on the high-voltage battery, located in vehicle along with its temperature from individual sensors placed inside and the voltage of the particular cells [7].

7.3. FSA 050 Hybrid Insulation Tester

Bosch, one of the leading manufacturers of professional diagnostic equipment, also designed the devices dedicated for hybrid vehicles. One of them is the FSA 050 Hybrid multimeter. The name of the device is misleading, because the device allows not only for the insulation test of, for example, the electric motors, mounted in the vehicle, but also for the measurement of the voltage, resistance, capacity, continuity test and the high-voltage test. The device is also equipped with the test mode for electric motors. The above tester can be connected wirelessly to a computer with Windows system and print all measurement and test results [8].

7.4. 25 MHz 1400 V Differential Oscilloscope Probe x20/x200

Pico Technology company is a producer of one of the most complex oscilloscopes designed for service and laboratories testing passenger vehicles. The above adapter extends their oscilloscopes with the possibility of connecting to a high voltage installation in a safe manner up to 1400 V DC / AC [9]. This is a very good proposition for laboratories and universities studying hybrid vehicles and simultaneously already possessing the oscilloscopes of the above manufacturer.

7.5. EVC- 30 – Multi-channel test stand for testing and regeneration of HV batteries

The multi-channel EVC-30 device for testing and regenerating HV batteries enables the accurate examination of each cell by measuring the resistance, voltage, capacity and graphical representation of all parameters in the graph when charging or discharging the battery. Thanks to the above device it is possible to detect defective cells and replace them if necessary [10].

7.6. HBM eDriving Testing

HBM eDriving Testing is a modern measuring device for testing inverters and electric motors. The device has great possibilities in the terms of measurements. It not only collects the data from the range of electrical signals (voltage, current), but also has the ability to record mechanical signals (e.g. torque). This allows a much better understanding of what happens in the system under study. The device has the ability to measure the electrical signals up to 51 channels simultaneously, also 6 torque / speed signals. The data is stored and presented in real time. The device also allows to read data from the CAN system. Data created during measurements can be read by programs such as Matlab or LabView. One of the companies using the above solution in testing hybrid electric systems is the French company GreenMot, which is specialised in testing combustion engines, propulsion systems and energy systems, in particular in the automotive industry [11].

Summary

The above article proves that the diagnosis and testing of hybrid vehicles is not dangerous as long as a given person possesses the necessary knowledge, skills and training in the field of diagnostics and procedures of hybrid vehicles. Many solutions come from the conventional drive vehicles, which makes most diagnostic procedures identical. Despite the lack of access to the original online software provided by the manufacturer, it is possible to pre-diagnose the high voltage battery either by the diagnostic tester or by the device designed by Midtronics to test the HV battery. The bright colour of the high voltage cables allows to assess in an easy way whether we are dealing with an element working under the high voltage.

It is important that the person, who undertakes repairs with a hybrid vehicle is trained in the scope of works on the devices with the voltages up to 1000 V and is equipped with the necessary equipment, which guarantees his / her safety. The growing number of hybrid vehicles in the market means that different manufacturers offer diversified, specialised devices, which enable diagnostics and testing of the high voltage systems.

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