

Ground Fault Detection for Flexible High Voltage Power Systems

2011-01-2252

Published
09/13/2011Aravind Mathsyaraja
Eaton Truck Component Operations

Copyright © 2011 SAE International

doi:10.4271/2011-01-2252

ABSTRACT

Hybrid Electric Vehicles (HEV) in the consumer and commercial vehicle sectors have seen tremendous technological advancement in the last decade. The commercial vehicle industry in particular has benefited significantly from the hybridization of the propulsion system, and unlike the automotive segment, serves a wide variety of functions. This diversity in vehicle applications drives the necessity for high voltage power systems to be flexible in nature, allowing them to adapt to different vehicle architectures while performing the intended function. As a result, diagnostic modules within the high voltage power system, such as ground fault detection circuits, are being required to operate robustly in a high voltage power system that is exposed to electrical noise and significant variation in common mode impedance characteristics.

This paper explores four different ground fault detection methodologies that exist today in the industry, and evaluates their performance in a flexible high voltage power system. A thorough comparison of these technologies is performed based on results from seven distinct test cases, followed by a recommendation for the ideal ground fault detection system.

INTRODUCTION

Depending on the manufacturer and the application type, a HEV can be constructed and configured in a variety of ways. In a typical vehicle, a High Voltage battery pack usually in the range of a 100 to 1000 Volts DC, is used to power an inverter that converts DC power to three phase AC power to drive a traction motor. The High Voltage battery pack is also commonly used to power other electrical auxiliary devices, such as a DC-DC converter for stepping down voltage to the vehicle's low voltage (12-14V) power net, or an auxiliary

inverter unit for converting High Voltage DC to 120VAC. The power is often transmitted over High Voltage lines that could be accessible to the user, and are generally shielded to shunt electrical noise to the chassis of the vehicle.

The integrity of this high voltage system is critical to the reliability and safety of the vehicle. Typically, the vehicle chassis will be electrically isolated from the terminals or conductors of the high voltage system. Under normal conditions, leakage currents in the order of micro amps exist between the conductors of the high voltage bus and the frame of the vehicle. However, as these complex systems are housed in locations that may observe exposure to harsh environments with rapidly changing temperature conditions, as well as severe vibration, there exists a potential for gradual or relatively instantaneous isolation breakdown; depending on the failure mode. This condition is hazardous to users and personnel of the vehicle, and sometimes the vehicle itself.

This phenomenon of isolation breakdown is intrinsic to the nature of machines and electronics, and has been acknowledged by the industry for many decades. Several methodologies have been invented to identify ground faults within power systems and react to prevent potential failures or hazards, such as Ground Fault Circuit Interrupters (GFCIs). Especially in the last 5 years, many ground fault detection systems have been created specifically for hybrid electric vehicle power systems, as this technology continues to advance and penetrate the market. Yet, in spite of all the development that has occurred in this field, few systems exist that are generic in nature but sufficiently robust to be able to accurately identify low impedance to ground conditions on flexible power systems, where the components that make up the system are interchangeable and hence may vary significantly in design. This is particularly true for the

commercial hybrid vehicle market, which has many differences in comparison to the passenger vehicle market.

Whereas passenger hybrid vehicles are designed for the single purpose of transportation of people, with mostly similar duty cycles and environments, commercial hybrid vehicles vary tremendously in the utility of the vehicle and in the environments within which they operate. In addition, mass production quantities of passenger hybrid vehicles are far higher in comparison to those of commercial hybrid vehicles. With applications ranging from city delivery, utility, telecommunications, and mining, to refuse, goods transportation, mass public transit systems, and many more - the hybrid power systems that have to be integrated into these vehicles will significantly differ in topology and design. It has therefore become critical to design hybrid power systems that maintain a standard framework but at the same time offer the ability to be modified as per the requirements of the application; thence the introduction of flexible hybrid power systems, and the need for a ground fault detection system that will function effectively irrespective of the devices that are connected to the High Voltage Bus.

The primary intent of this paper is to present four methods of ground fault detection for HEVs, evaluate their performance against seven distinct test cases that are representative of operating conditions in a HEV, and recommend one method for use in flexible high voltage power systems based on a pugh analysis. Performance evaluation of the four detection methods was done by circuit simulations, and the outcomes will be summarized in the paper.

SURVEY AND ANALYSIS OF EXISTING TECHNOLOGIES

Although ground fault detection units and circuit interrupters for power systems in residential and industrial applications have been available for many decades now, distinct differences in vehicle applications have created the need to develop unique diagnostic circuits for HEVs. This section will briefly discuss the operation of these systems.

METHOD 1 - NISSAN MOTOR

Inventors Tsuyoshi Morita and Shinsuke Nakazawa from Nissan Motor Co. developed an adaptation of the popular signal injection method for detecting ground faults in an electric vehicle (or HEV). This ground fault detector system interfaces with the High Voltage Bus of the vehicle, as well as the low voltage system, via a controller [1].

The system described in the invention is designed to perform three operations:

1. Detect the presence of a ground fault within the system
2. Identify the location of the ground fault within the system
3. Identify the cause of the ground fault

The method allows for perpetual monitoring of the HV bus for ground faults, even during the operation of the vehicle. The following diagram may be used to illustrate the invention:

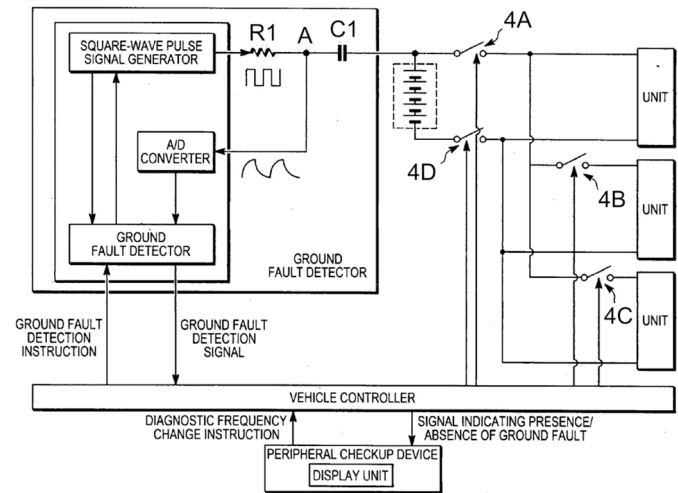


Figure 1. Schematic overview of method 1 [1]

As can be seen from Figure 1, a square wave signal generator is used to output a square pulse of amplitude V_S (e.g. 5V) and frequency f_1 (e.g. 10Hz). The output of the generator is capacitively coupled to the high voltage positive (+) rail through capacitor C_1 . Per the patent, the signal frequency of the square pulse should be significantly less than the switching frequency (usually 20 kHz to 3MHz) of power electronics components on the HV bus in order to prevent the high frequency noise from interfering with the leak detection circuit's ability to operate effectively.

The ground fault detector then measures the voltage (V_{DET}) at point A in the circuit, to determine the attenuation in the signal based on common mode impedance in the HV bus. This equivalent common mode impedance (Z_{EQ_P}) between the high voltage positive rail and chassis, and (Z_{EQ_N}) between the high voltage negative rail and chassis is a combination of all the resistive, capacitive, and inductive elements in the common mode bus.

Consider an HEV system with a HV battery source (V_{BATT}) and several fixed and variable power electronics components connected to this source (Units 1, 2, 3, 4 etc). Each component has inherent impedance between the high voltage rails and chassis (Z_{1_P} , Z_{1_N} , Z_{2_P} , Z_{2_N} etc) where:

$$Z_{EQ_P} = \frac{1}{\left(\frac{1}{Z_{1_P}}\right) + \left(\frac{1}{Z_{2_P}}\right) + \left(\frac{1}{Z_{3_P}}\right) + \left(\frac{1}{Z_{4_P}}\right)}$$

And

$$Z_{EQ_N} = \frac{1}{\left(\frac{1}{Z_{1_N}}\right) + \left(\frac{1}{Z_{2_N}}\right) + \left(\frac{1}{Z_{3_N}}\right) + \left(\frac{1}{Z_{4_N}}\right)}$$

There also potentially exists a resistive fault element R_{L_P} or R_{L_N} between the high voltage rails and chassis (ground), and R_{L_AC} between the non-isolated switched AC line of an inverter device (e.g. single phase auxiliary inverter) and the chassis.

Ideally, Z_{EQ_P} and Z_{EQ_N} are relatively large for DC and low frequency AC. Hence, the attenuation in signal V_S (measured as V_{DET}) could be relatively small in a faultless system. The amplitude of V_{DET} is as follows:

$$V_{DET} = V_S \cdot \frac{Z_{EQ_P} - jXC_1}{Z_{EQ_P} - jXC_1 + R_1}$$

The reactance of C_1 is an order of magnitude smaller than R_1 at 10 Hz. Hence, in the case that a resistive fault R_{L_P} or R_{L_N} (e.g. 5 Ω) exists, Z_{EQ_P} or Z_{EQ_N} becomes significantly small as well, resulting in large attenuation of the 5V signal V_S . Based on this principle, an appropriate threshold impedance Z_{TH} may be chosen as a lower limit for the common mode impedance Z_{EQ_P} or Z_{EQ_N} , and the corresponding threshold voltage V_{TH} can be derived to be used as a metric for diagnosing ground faults.

This summarizes the ground fault detection methodology of the invention. The authors also discuss a simple means for detecting the location of the fault, by first detecting its presence in the system, and then isolating the fault to individual components by controlling switch circuits 4A, 4B, 4C, and 4D independently at different times.

METHOD 2 - MAXIM INTEGRATED PRODUCTS

Inventors Mark Plagens and Brian Fritz from Maxim Integrated Products, Texas developed a method to detect a resistive ground fault condition between a DC power system and the chassis of an EV or HEV. The aforementioned invention was developed to address the need for a reliable detection methodology that would not be susceptible to large amounts of noise created by parasitic or inherent capacitance in the common mode HV bus, or a failed component within the detection circuit itself [2].

The following [Figure 2](#) graphically illustrates the invention:

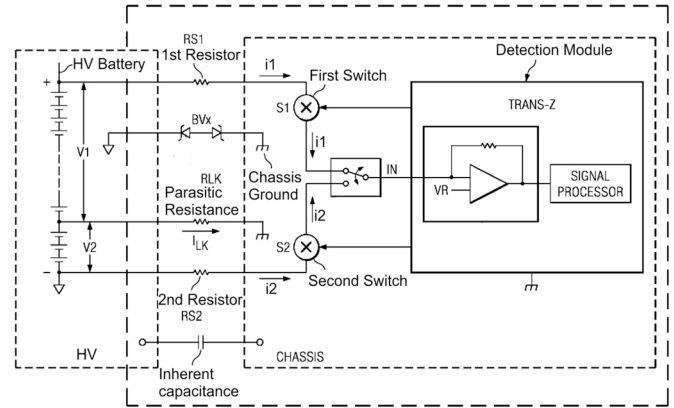


Figure 2. Schematic overview of method 2 [2]

The system described above is designed to detect the total parasitic resistance R_{LK} that exists between the High Voltage bus and chassis ground. A 1st resistor R_{S1} is connected on one end to the positive node of the High Voltage system, and to a switch S1 on the other. The switch S1 when closed allows current to flow from the positive high voltage rail to the chassis. This current I_1 is measured by a current sensor device and then sent to a microcontroller for processing. A 2nd resistor R_{S2} is connected to the High Voltage negative rail on one end and to a switch SW2 on the other. Current I_2 flows from the negative rail of the bus to the chassis ground through SW2 when it is closed, and this current is sensed and processed by the microcontroller in the system.

There also exists inherent capacitance within the system that could be a result of close proximity of high voltage conductors to the chassis of the vehicle. In addition, there are many power electronics components with Y-capacitors for EMI filtering, which could add to the inherent common mode capacitance in the system. The fault detection system functions as described below:

Switch SW1 is first closed at time T_0 , causing current I_1 to flow through the resistor R_{S1} and switch SW1 until the inherent capacitance C_N (e.g. 1nF) is charged. As C_N is charged, the value of I_1 declines, ideally approaching zero in a no fault condition due to the large value of the R_{S1} (e.g. 1 M Ω) and the parasitic leakage resistance in the system. At time T_2 , switch SW1 is opened and switch SW2 is closed. As a result, inherent capacitance C_N discharges through SW2 and 2nd resistor R_{S2} (e.g. 1 M Ω), and this current I_2 eventually approaches zero. This behavior is illustrated in [Figure 3](#), and is representative of an ideal system with very large parasitic resistance.

In the case of a true leak fault, when SW1 is closed, current I_1 does not decline because of leakage current flowing through

parasitic resistance (e.g. $I_{LK} = 10mA$ through the parasitic resistance R_{LK}). At time T_2 , when SW1 is opened and SW2 closed, current I_2 flows through the resistor R_{S2} but again does not decline due to the leakage current across parasitic resistance R_{LK} . The footprint of I_1 and I_2 in this case is shown in Figure 4.

In the case where the parasitic resistance R_{LK} is not very low, but is approaching the threshold of $120k\Omega$ (e.g. $300k\Omega$), current I_1 declines rapidly but does not approach zero due to the leakage across R_{LK} .

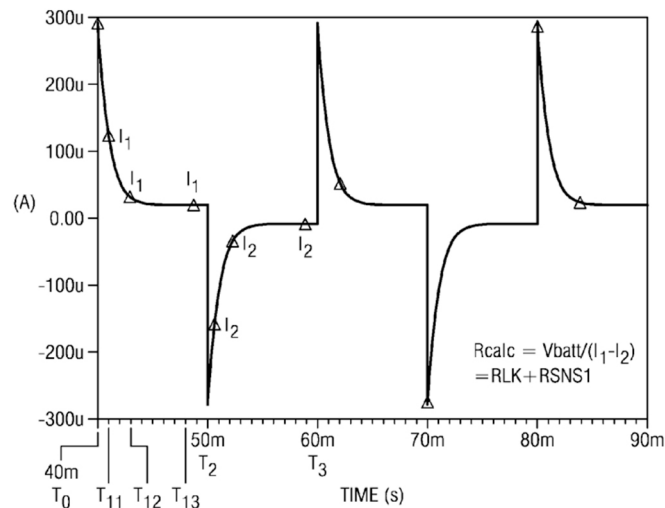


Figure 3. Response of I_1 and I_2 in a no fault condition [2]

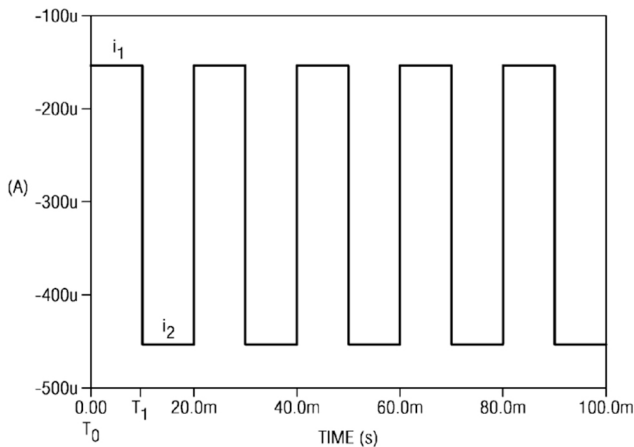


Figure 4. Response of I_1 and I_2 in a true fault condition [2]

Similarly, in the case of a damaged component in the test circuit, such as an open resistor R_{S1} , no current I_1 will flow through the switch SW1 since the circuit is open. Therefore, the signature of current waveforms I_1 or I_2 are sufficiently unique to diagnose that the detection system has failed. This is one positive aspect of the described invention, where every perturbation in the hybrid power system results in a response with a unique signature that can be processed for reliable diagnostics. This can be achieved by increasing the sampling rate of the current waveform, programming the microcontroller to be able to identify its signature footprint, and then correlating the footprint to a certain operating condition of the system. The patent for the invention provides more detail on the mechanics of this function, which is not within the scope of this paper.

As the microcontroller acquires measurement data for I_1 and I_2 , It processes the information to calculate the leakage current I_{LK} in the system (equations may be found in the patent). The derived value of I_{LK} may then be compared to a threshold leakage current value (e.g. $5mA$) to diagnose a ground fault.

This summarizes the ground fault detection methodology of the invention.

METHOD 3 - LEAR CORPORATION

Inventors Miguel Angel Acena and Jordi Escoda from Lear Corporation, Michigan developed a method to detect loss of electrical isolation in a vehicle that uses a HV power net [3]. This is achieved by charging HV capacitors, then connecting them at different times between the HV positive and negative rails and the vehicle chassis, and measuring the remaining charge after a fixed period of time. The amount of energy lost in the capacitors reflects the level of isolation of the floating HV power system to chassis ground. If the discharge is low (shallow), the equivalent resistance to ground is high and the isolation can be characterized as proper. If the discharge is above some nominal level, the equivalent resistance is lower and isolation can be characterized as improper [3]. Once again, the primary purpose of the proposed methodology is to detect resistive leak faults in the system, in both energized and non-energized states. There are minor variations in the implementation of the fault detection system for a vehicle in the off-state (when the HV batteries are disconnected) in comparison to a system for a vehicle in the on-state (HV batteries are connected). However, the design principle behind both systems is the same, and for the purpose of evaluating this method, the fault detection method designed for an energized system was used.