Ground Fault Diagnostics for Automotive Electronic Control Units

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ABSTRACT

An electronic control unit (ECU) with a floating ground is not able to receive or transmit messages or participate in controller area network (CAN) communication. The absence of any ECU, either temporarily or permanently, negatively impacts vehicle functionalities. The offset ground, which by itself won't affect bus functionalities if the grounding resistance is small, however, may evolve into a floating ground or behave similarly if the resistance is large. In this work, the correlation among ground faults, either offset or floating, and CAN bus voltage or messages are analyzed based on the equivalent circuit models and the bus protocol. A voltage-based solution to detect ground faults is proposed. With the help of bus messages, both faults can be isolated at the ECU level. Considering the inherent system delay between the message fetching and voltage measurement, a normalized voltage-message correlation approach with the bus load estimation is developed as well. All proposed approaches are implemented to an Arduino-based embedded system and validated on a vehicle frame.

1. INTRODUCTION

In-vehicle electronic control units (ECU) play a vital role to control the vehicle. Growing customer demands for new features have led to the proliferation of ECU. As a result, diagnostics and prognostics for ECU failures become more and more critical and challenging (Du, Jiang, Nagose, Zhang, & Wienckowski, 2016). Among all ECU failures, ground connection faults are common, and often cause unnecessary ECU replacement. The ground wire and/or connectors may be damaged, due to quality issues, design defects and inappropriate assembly operations. They can wear out in harsh environments as well. The ECU ground resistance is, therefore, increased which is commonly referred to as offset ground, or the ECU is even disconnected from the ground, *i.e.* floating ground. An ECU with an offset ground may evolve into a floating ground, and subsequently cutting off itself from the network, and cease its normal operation. The ECU ground faults generally are diagnosed by service technicians manually, however, the trouble-shooting process is complicated and time-consuming (Robertson, 2014). The ECU ground faults, especially the intermittent faults, are challenging to be isolated and located, which may result in unnecessary ECU replacement. Therefore, it increases the repair cost and reduce the customer satisfaction. The fault diagnostics for ECU ground faults are strongly desired for customers, field engineers, and service providers.

Ground faults remain as a common topic for all electric/electronic systems (Guerrero, Mahtani, Serrano-Jimenez, & Platero, 2021) (Martin, Guerrero, Mourelo, & Platero, 2021) (Ray, Chattopadhyay, & Sengupta, 2020). Various diagnostic approaches for ground faults have been proposed by other researchers. Tornare *et al.* developed a device that can detect loss of ECU ground connection, but a secondary diagnostic circuit is required to integrate into each ECU (USA Patent No. US20140375326 A1, 2014). For the highly cost-sensitive automotive industry, the cost of implementing this solution is an obstacle. Muth invented a circuit for detecting ECU offset ground, but not isolating the fault (USA Patent No. US20050268166 A1, 2005). Gauna et al. employed the voltage harmonics analysis to detect and locate ground fault within synchronous machines with static excitation systems (Gaona , Blázquez , & Frías , 2010). However, the method is exclusively developed for a specific type of systems, and not suitable for ECU applications. Baldwin et al. proposed a method using relays and zero-sequence signal generators to diagnose ungrounded faults and high ground impedance faults for power systems (Baldwin, Renovich, Saunders, & Lubkeman, 2001).

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Evidently this approach cannot be applied to ECU ground faults diagnostics. Li *et al.* proposed a fuzzy-integral decision fusion technique to detect single-line-to-ground fault (Li, Liu, & Meng, 2016). Each criterion is fuzzy-integrated to generate diagnostic decision. The approach is promising to be employed for ECU ground fault isolation, however, neither the ECU floating ground nor the offset fault is mentioned in the paper.

For network applications, the ECU failures can be diagnosed from various features of the network. In a vehicle, almost all ECUs are connected through various types of networks where the controller area network (CAN), originally developed in the 1980s (Farsi, Ratcliff, & Barbosa, 1999), is widely adopted in the automotive industry (Asaduzzaman, Bhowmick, & Moniruzzaman, 2014). The message-based approaches utilizing CAN message or message error counters generated by the CAN transceiver are widely applied in CAN bus fault diagnostics (Hu & Qin, 2011) (Kelkar & Kamal, 2014). The message-based approaches, while able to easily detect inactive ECUs, are not capable of identifying the root cause, *e.g.* software issues, power connection, ground connection, CAN connection or circuit issues. Furthermore, when an ECU has an offset ground, the offset ECU may still transmit messages when the grounding resistance is small. The existing error frame counter can't provide enough information to isolate the ground fault. An alternative way to detect ground offset would be tracking the local voltage within an ECU. However, the need of numerous voltage sensors makes this approach less attractive.

In summary, there is no mature production solution so far to detect and isolate ECU ground faults. This paper will bridge that gap. A low-cost, feasible, and accurate diagnostic approach for ECU ground faults will be developed. The proposed approach integrates the bus messages and the bus voltages to detect and locate offset or floating ground for the ECUs connected with a CAN bus. In Section 2, two equivalent circuit models for offset and floating grounds, respectively, are presented. The detection and isolation methods for ground faults are proposed in Sections 3 and 4, followed by Section 5, where several experiments using an actual vehicle frame are conducted to validate the proposed approaches. The section 6 concludes the paper.

2. SYSTEM MODELING

In this section, the CAN bus data link and physical layers are introduced. The CAN bus, as well as the associated ECUs with the floating or offset ground, is characterized and modeled by equivalent circuit models. The models are developed according to the CAN bus specification (CAN Specification , 1991) and ISO-11898-2 (ISO, 2016).

The CAN specification for CAN data link layer defines the data format. All messages (frames) on the bus are categorized into four different types: data frame, remote frame, error frame, and overload frame. A single frame consists of multiple dominant and recessive bits corresponding to logical 0 (voltage high), and logical 1 (voltage low), respectively. A data frame is composed of seven different bit fields, and its length is at least 44-bits long. Between two frames, there must be an inter-frame space which at least possesses three consecutive recessive bits. As a result, there is a minimum possible frame length and a minimum possible inter-frame space. These two numbers are instructive in developing the diagnostic logic for ECU ground faults.

The characteristics for the physical layer of a CAN bus are specified in ISO-11898-2. A CAN bus consists of wires, terminators, and CAN transceivers integrated in ECUs to receive and transmit messages. To transmit messages, the CAN bus employs a single wire or dual wires for the low speed or high-speed communication, respectively. For simplicity, the CAN bus mentioned in the rest of the paper is referred to the high-speed CAN bus. The schematic of a typical high-speed CAN bus is shown in Figure 1 where the bus has three ECUs and two terminators. A CAN bus's wiring has a nominal impedance of 120 Ω (95 Ω minimum and 140 Ω maximum). Terminators are placed at each end of the bus, consist of either one resistor (standard single termination) or RC pairs (split termination) for better signal integrity. For split termination, each terminator includes two resistors of approximately 60 Ω each, and a coupling capacitor (*e.g.* 100nF) which couples high-frequency noise to the ground. According to ISO 11898-2, ECU internal resistance is 10K to 100KΩ, which is much higher than the terminator resistance. The two signal lines of the bus are called CANH and CANL, respectively. Figure 2 presents a normal CAN bus voltage trace. The communication is achieved by creating dominant and recessive states on the bus. In the recessive state, the differential voltage between CANH and CANL has to be within a predefined range ([-1, 0.5] V for input and [-0.5, 0.05]V for output (Richards, 2002). Typically, the voltages for both CANH and CANL are equal to 2.5V in the passive state. In the dominant state, CANH voltage is 3.5V, and CANL voltage is 1.5V, which create a 2V differential signal.

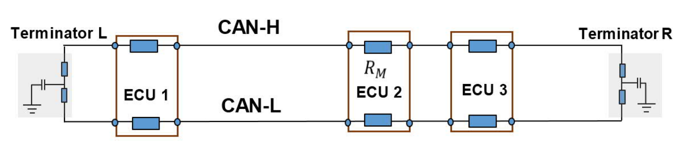


Figure 1. The schematic for a typical high-speed CAN bus with 3 ECU nodes

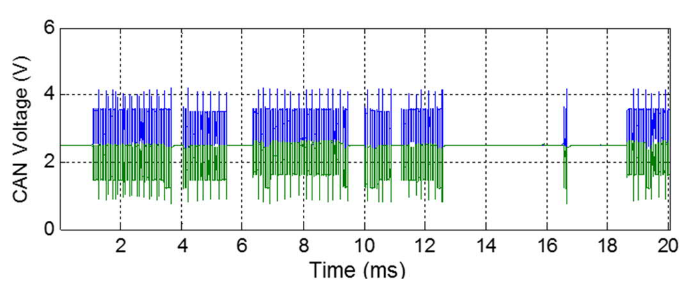


Figure 2. CAN bus voltages taken by an oscilloscope from a vehicle frame under the normal condition.

The schematic for a typical transceiver is shown in Figure 3, which is Infineon TLE 6250G CAN transceiver (Fraissé, 2006). When an ECU transmits messages, the CAN transceiver of this ECU can be modeled as a voltage source. The transmitter data input (TxD), a TTL-compatible input controls CANH and CANL pin drivers (High-Speed CAN Transceiver - MCP2551, 2003). When TxD is low, drivers are turned on and CANH is pulled up by ~1 V by enabling the upper transistor, while CANL is pulled down by ~1 V by enabling the lower transistor. When the TxD is high, the drivers are turned off so that both CANH and CANL pins float to a nominal bus voltage via biasing resistors. The input circuit is shown in the bottom of Figure 3. When an ECU receives messages, the receiver becomes high or low when there is a recessive or dominant bit on the bus, respectively. The receiver data output (RxD) generates digital signals accordingly for the CAN protocol controller so that the ECU recognizes the bus messages. When no ECU transmits a message on the bus, the drivers for all ECUs are off, and the bus voltage is 2.5 V ($V_{cc}/2$) due to internal biasing resistors.

2.1. Modeling an ECU with an Offset Ground

The ground line is of unique significance to ECUs, especially for the CAN communication purpose. For a CAN transceiver, only the differential voltage between CANH and CANL is taken into account to differentiate the dominant and recessive bits. Transceivers are designed to handle a wide range of input voltages (*i.e.* -3V and +32V ISO11898-2) and noise conditions, which means the CAN bus can still function properly without failure under a limited offset ground.

However, with an offset ground, an electromagnetic signal emits since the asymmetric voltage changes in CANH and CANL do not cancel each other, which is undesirable to the systems sensitive to emissions. Besides, an offset ground may evolve into a floating ground, which disables the ECU. This is a potential safety issue in the vehicle application. An ECU offset ground case is modeled in Figure 4, where an offset is represented by a resistor between the module and ground. When an ECU with an offset ground transmits messages, the current flows from the power source, through the offset ground resistor (indicated by the red color in Figure 4), to the ground. There will be a voltage drop across the resistor, which makes the voltage between the power source and the offset ground resistor pulled up.

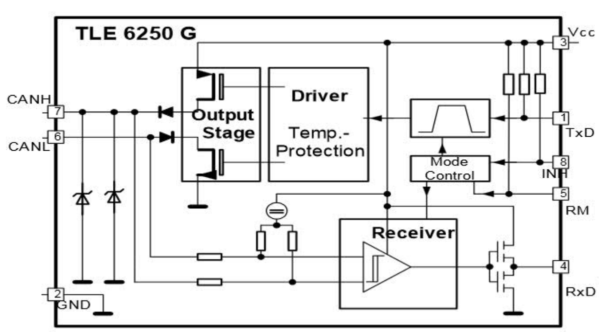


Figure 3. The schematic for Infineon TLE 6250G CAN transceiver (Fraissé, 2006).

CANH and CANL voltages over the bus are pulled up when the impacted ECU(s) transmits frame data. The larger the ground resistance is, the more the frame voltage will be shifted. A frame exhibiting this behavior is shown in Figure 5, where the highlighted frames are transmitted by the ECU with an offset ground. The voltage of the highlighted frame can be employed to detect the ECU offset ground. How much an offset ECU affects the inter-frame voltage depends on the internal ECU circuit and the level of the offset. When the ECU with the offset ground is transmitting messages, the recessive voltage is jointly determined by all transceivers (Fraissé, 2006),

$$V_{rec} = \left[\left(V_{rec}^{1}\right) + \cdots \left(V_{shift}^{1}\right) + \left(V_{rec}^{2} + V_{shift}^{2}\right) + \cdots + \left(V_{rec}^{n} + V_{shift}^{n}\right)\right]/n. \quad (1)$$

where V_{rec}^{i} and V_{shift}^{i} are the specific recessive voltage level and the ground voltage shift for transceiver i. n is the total number of ECUs. Due to the capacitor in terminators, recessive voltage takes some time to drop to its steady level.

2.2. Modeling an ECU with a Floating Ground Fault

While an ECU with a moderate offset ground doesn't impact the bus communication, a floating ground makes the ECU inoperable. An ECU with a floating ground fault is modeled in Figure 6. In such a case, the ECU is un-powered, therefore it stops transmitting messages and is lost to the CAN bus. However, the remaining healthy ECUs can still communicate with each other through the same CAN bus.

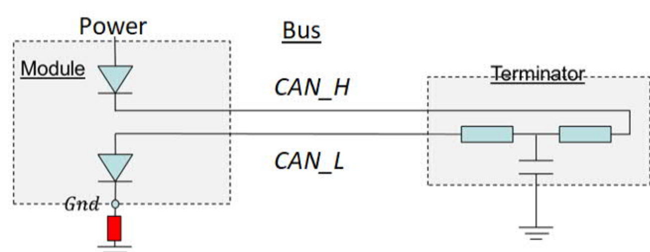


Figure 4. The equivalent circuit for the CAN bus in the scenario of one ECU with an offset ground.

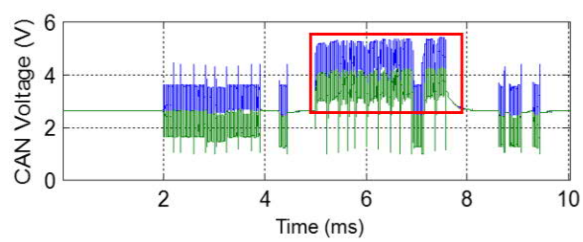


Figure 5. The actual CAN bus voltages sampled from the vehicle frame when an ECU has an offset ground fault (blue: CANH voltage, green: CANL voltage)

From the system point of view, an ECU with the floating ground is equivalent to a high voltage source connected to the CAN bus via a pull-up resistor with the extremely high resistance. Therefore, when no ECU is driving the CAN bus voltage by transmitting messages, *i.e.* during the inter-frame period, both CANH and CANL voltages are pulled up together by the floating ECU. Such behavior is totally different from the ECU software fault or the power fault. The level of inter-frame voltages depends on the internal circuit of each ECU. According to Fraisse (Fraissé, 2006), the floating ground failure potentially damages the ECU itself if an inductive load is used. A sample trace of bus voltages in the floating ground scenario is shown in Figure 7. As the ECU with the floating ground doesn't affect the voltages for the frame transmitted by other ECUs, the inter-frame voltage has to be employed to detect the ECU floating ground fault.

3. GROUND FAULT DETECTION

As discussed in the previous section, ECU ground faults can be detected by capturing changes in frame or inter-frame voltages. The overall approach to detect ECU ground faults is proposed and shown in Figure 8. First, the battery voltage is verified after the bus wakes up and all internal variables are initialized. If the battery voltage is extremely low (*e.g.* 6V when the battery charge is low), which normally doesn't meet the ECU design requirements, the bus voltage is not compliant with the CAN protocol. Therefore, any further analysis and conclusions may not be valid. When the battery voltage is normal (*e.g.* 9V to 15V), samples of bus voltages are acquired simultaneously for both CANH and CANL. A certain level of synchronized acquisition is required in order to determine frames and inter-frames. In practice, synchronization is satisfied if the gap between

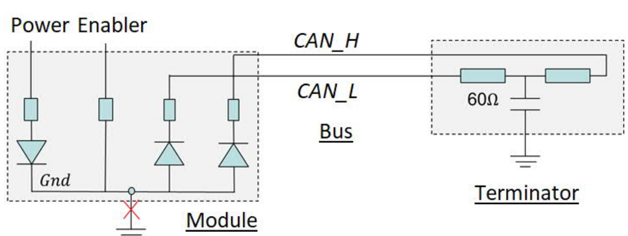


Figure 6. The equivalent circuit for the CAN bus where an ECU has a floating ground.

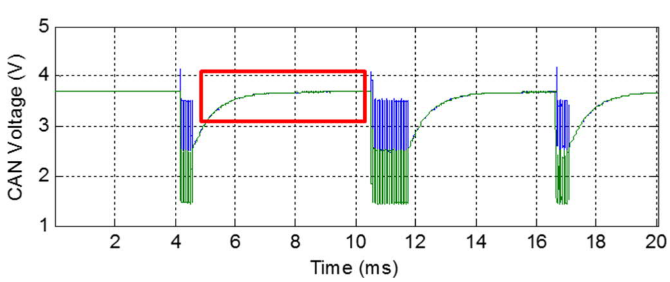


Figure 7. The CAN bus voltages are sampled from a vehicle frame where one ECU ground is floating. (blue: CANH voltage, green: CANL voltage)

CANH and CANL readings is near or lower than a bit time, *i.e.*, 2ns for a 500 Kb/s bus. Once the data has been acquired, the state estimation algorithm (shown in Figure 9) generates the maximum inter-frame voltage, count of data pairs with high average dominant voltages, and the number of inter-frame samples. These three variables are fed to the decision-making algorithm (Figure 10). If the number of data is enough to make a decision, the flags corresponding to offset or floating ground are set and all other variables are reset to 0. In cases where the information extracted from the acquired data are ambiguous, an "unknown" decision is made. In such a case, the failure type can't be isolated and a counter, C_1, for such pending faults is increased by 1 and will be used later. The internal variables are not reset and are carried over to the next cycle.

The state estimation algorithm employed to determine frames and inter-frames is shown in Figure 9. First of all, each data point is labeled as either recessive or dominant based on both CANH and CANL voltage levels. A data point is assessed as dominant if the difference between CANH and CANL is high, otherwise it is recessive. Note that a single bit lasts for only 2μs for a 500 Kb/s bus. If both CANH and CANL voltages are processed by the same analog-digital converter (ADC), absolute synchronization between two readings is not guaranteed. In Figure 9, CANL is read after CANH within each step. Therefore, the voltages from the current acquisition and the previous acquisition should be used together to determine the bit status.

An inter-frame region can be identified whenever the duration of consecutive recessive points exceeds a predefined value. Recall from the previous section that the period between the last dominant bit of a data frame, acknowledge slot, and the first dominant bit of the next data frame, start-of-frame, possesses at least 11 consecutive recessive bits. Furthermore, there cannot be more than 5 consecutive bits of the same value during a frame due to bit stuffing. Therefore, a long-enough recessive region should be able to assert that the region is an inter-frame.

The number of inter-frame samples within one dataset is recorded and will be used to determine the ECU ground state. In case of a floating ground, an inter-frame period has to be long enough to allow the recessive voltage to exhibit an evident increase in voltage. As a result, the average recessive voltage is only computed for inter-frame periods that are longer than a large threshold. The maximum average inter-frame voltage for each dataset is used by the decision-making algorithm. With the inter-frame periods determined, frames can be easily identified as the regions between two consecutive inter-frame periods. Offset ground is detected primarily based on the average dominant voltage between CANH and CANL. As such, the average dominant voltage is calculated for each frame longer than a predefined value in order to enhance precision and robustness. Then the number of frames whose average dominant voltage is high is recorded.

The decision-making algorithm provides an ECU offset ground decision based on the data acquired in the current loop. This algorithm employs a decision tree approach, shown in Figure 10, to sequentially evaluate each possible decision. If the average of CANH and CANL voltages within a frame is consistently greater than 2.5 V, the frame is called a high-voltage frame. If multiple high-voltage frames are detected within one loop, the algorithm asserts that an ECU ground fault is present. Since the high-voltage frames are

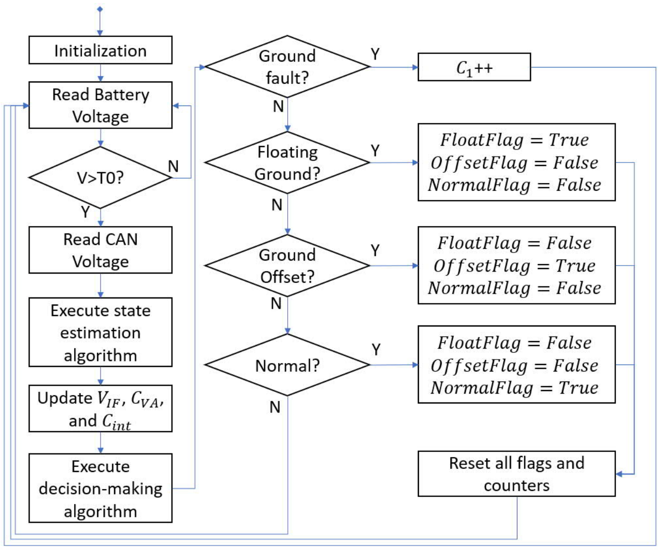


Figure 8. The overall flow chart for ECU ground fault detection.

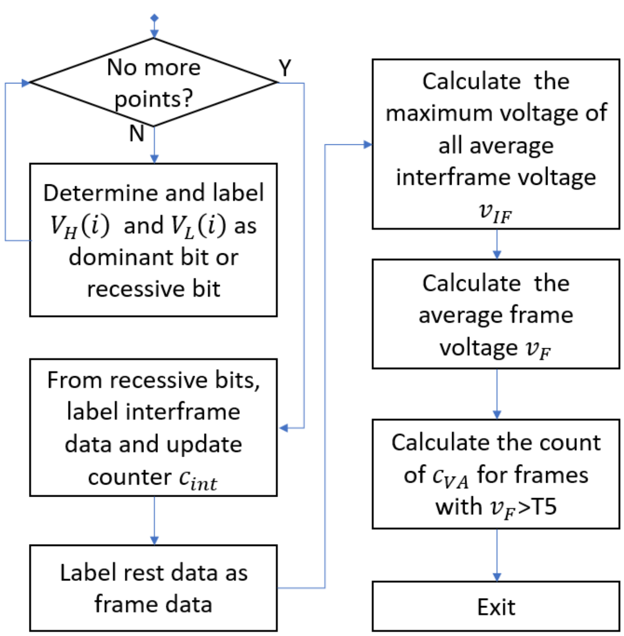


Figure 9. The state estimation algorithm for ECU ground fault detection.

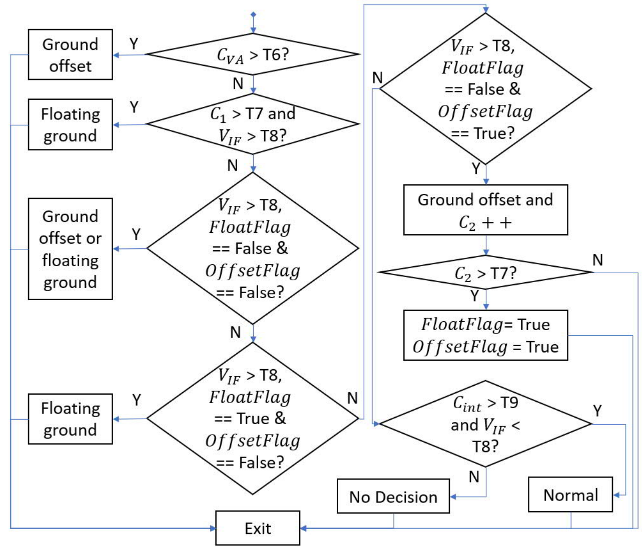


Figure 10. The decision-making algorithm for ECU ground fault detection.

only transmitted by ECUs with an offset ground and the bus voltage is not continuously monitored, it is possible that no high-voltage frame will be captured within one or more loops even if an ECU has an offset ground. The possibility to catch those high-frames depends on both the number of ECUs with an offset ground and the frequency of their associated messages. At the same time, the inter-frame voltage, which is calculated from the average of CANH and CANL voltages, may or may not exhibit an increase in cases of an offset ground (Referring to Section 2.1). Based on these two arguments, a floating ground can only be confidently decided and flagged if no high-voltage frame is found for a relatively large number of loops (T7) and the maximum average of CANH and CANL voltage within the inter-frame is evidently higher than the normal value (e.g. 2.5 V). Before exceeding the counter limit (T7), if a high average voltage of the inter-frame is detected, and no active ground fault flag is posted, an offset/floating ground decision will be made. This is reflected in the second and third steps within the decision tree in Figure 10. If the floating ground flag is true, the decision remains ECU floating ground unless the maximum average of the inter-frame voltage goes back to normal. If the offset ground flag is active but no high-voltage frame is found, the detection of the high inter-frame voltage will indicate an offset ground fault until repeated for more than T7 loops. A faulty ECU ground causes high voltages either during frames or inter-frames. If no high voltage is found during these periods, and more than T9 inter-frames are identified within one dataset, a decision of normal ground will be made. Otherwise, no decision is made for the current loop. None of flags is updated under no decision or the offset/floating ground decision.

Multiple thresholds and parameters are used in the process of ECU ground fault detection. In general, voltage thresholds are determined based on the CAN protocol and ground fault symptoms of all ECUs on the bus. The expected voltage levels under the normal condition are provided in the CAN protocol. Besides, the voltage thresholds are determined in such a way that an offset or floating ground of any ECU can be detected without ambiguity. Counter thresholds are obtained by trials and tests, until a good balance between robustness and responsiveness is achieved.

4. GROUND FAULT ISOLATION

Isolation of a floating ground fault can be gained from the bus's message data. When a floating ground fault is detected, the inactive ECU is the root cause. Isolating an offset ground fault is more challenging since an ECU with an offset ground can still participate in the CAN communication. In this section, floating ground isolation is first discussed and then two approaches to isolate the ECU(s) with the offset ground are proposed.

4.1. ECU Floating Ground Isolation

Every message on a CAN bus can be uniquely identified by its message ID. Each active ECU is assigned a unique set of message IDs, which it may transmit at different periodic frequencies. Therefore, ECU can be determined to be active by monitoring one of the messages it transmits. An ECU can become inactive because of various reasons, including loss of power, software faults, connection issues or a floating ground. As per the discussion in Section 3, once a floating ground fault is detected, the failed ECU can be isolated if the selected messages sent by them are no longer available. The timeout values are different for different ECUs. For example, a 50ms timeout is suitable for a message with a period of 20ms, but unsuitable for a message whose period is 100ms. Timeout values should be predefined for each ECU.

4.2. ECU Offset Ground Isolation

Two methods are proposed here for ECU offset ground isolation: normalized voltage-message correlation with count pattern matching and bus load estimation. The former is preferable if the delay between voltage measurement and message fetching is small. If this delay is large, the bus load approach is a better option to provide the isolation. These two approaches are described as below.

4.2.1. The Normalized Voltage-Message Correlation with Count Pattern Matching Approach

The ECU offset ground isolation algorithm, shown in Figure 11, is initialized once an offset ground is detected. The algorithm is divided into four sequential parts: data collection, isolation using voltage, voltage/message correlation, and pattern matching. The thresholds for CANH and CANL high voltage are dynamically updated according to the current data. The high voltage points with the corresponding time stamp are stored, and the rest points are discarded. This is because only the data transmitted by offset ECUs (*i.e.* high-voltage frames) are useful for isolation. Please note that the voltage during arbitration and at the acknowledge bit is also high; but they are not very long relative to the total frame. If the voltage and the message can be monitored at the same time without any delay in between, offset ECUs can be easily located by identifying the message ID when high voltage frame is detected. In practice, the delay does exist. For example, if a single-core processor is used, there will be a processing delay between the message reading and the voltage measurement. Due to layered implementation in AUTOSAR, the delay between the time when a message is received and the time when high voltage is identified cannot be avoided. In such cases, the closest message detected to a high voltage frame may have been transmitted by another healthy ECU that sends high-frequency messages. To resolve the delay effect, a window is selected to correlate the high voltage frame and the bus message. Correlation results are used to calculate normalized offset frames transmitted by each ECU. Finally, count pattern matching is applied to identify the offset ECU(s). Each critical step will be explained below.

In order to reduce computational cost, only one message per ECU is monitored to track the ECU status. An ECU can transmit multiple messages at different frequencies. Slower message reduces the number of messages to be monitored as well as the computational cost. However, the frequency of selected messages cannot be too low, otherwise it would take long time to locate the ECU with an offset ground. In this work, messages with a period of around 100ms are selected.

To handle the delay issue, a predefined window is able to help, which is shown in Figure 12. There are two ways to find the correlation within the window, *i.e.* identify the high voltage first and then correlate messages within the time window T (named voltage-to-message correlation), or vice versa (named message-to-voltage correlation). The voltage-to-message correlation only monitors selected messages when a high voltage frame is detected. The message-to-voltage correlation has to monitor every selected message and then search for high voltage points in the neighborhood of each message. The voltage-to-message correlation is computationally less expensive when modules with an offset ground have less traffic, but more expensive with busy ECUs with an offset ground. Few high-voltage frames will be observed with less busy ECUs, which is favorable for the voltage-to-message correlation. While for busy ECUs, only high-voltage frames are required for the message-to-voltage correlation when a selected message is recognized. In this research work, the involved ECUs are not extremely busy. Furthermore, it is assumed only one ECU has an offset ground at the same time. Therefore, there are limited high-voltage frames on the bus. As a result, the voltage-to-message correlation is employed.

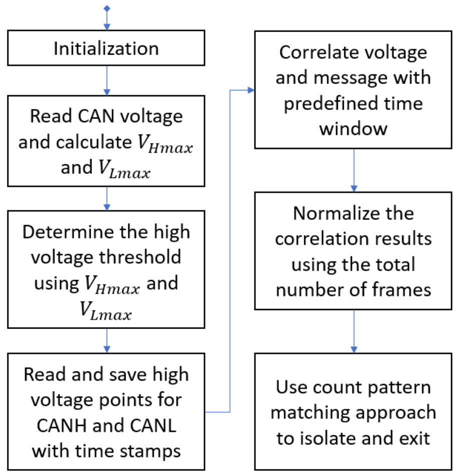


Figure 11. The overall flow chart for ECU offset ground isolation.

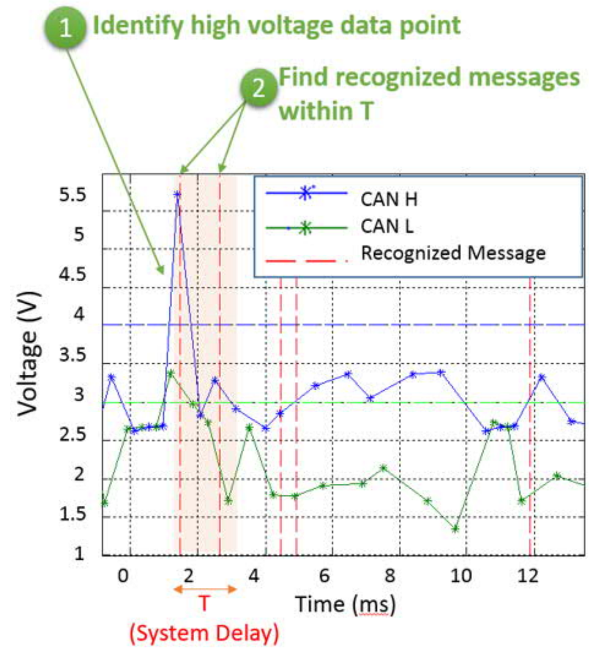
Please note that when the delay is relatively small, correlation within a time window can still provide usable information for offset ground isolation. On the other hand, if the delay is relatively large, correlation within a time window no longer generates accurate information, and the bus load isolation approach should be employed.

Based on the voltage-to-message correlation, the number of high voltage frames transmitted by each ECU can be calculated. However, the ECU with the highest number of high voltage frames cannot be directly identified as the ECU with an offset ground due to different message frequencies. For example, a busy but healthy ECU may have lots of messages falling within the window near a high voltage frame, while messages sent by the ECU with an offset ground may be much fewer if that ECU transmits data at a much lower frequency. To minimize the impact of message frequency variation, the definition of normalized high voltage frame count is introduced,

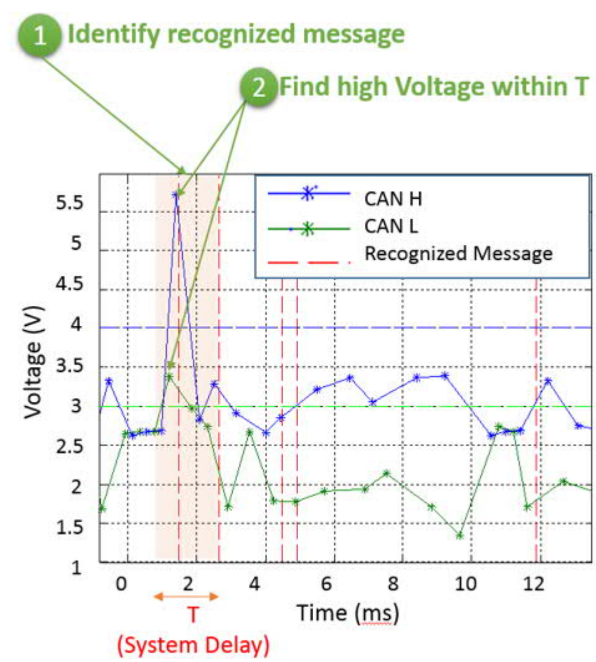
$$C_N = N_{hv}/N_{Total} \qquad (2)$$

where N_{hv} is the number of messages with high voltage and N_{Total} is the total number of messages. The ECU with the highest normalized value can be concluded to have an offset ground. The comparison to demonstrate the improvement brought by normalization is shown in Figure 13. In this example, the RDCM is the ECU with an offset ground, and the delay is 10 ms. With the raw count, both the RDCM and the TCM have comparably large number of messages near high voltage frames. With the normalized count, the RDCM's offset ground can be isolated much more easily and confidently.

Since the sampling frequency may be low, a longer message gives a better chance of capturing a sample corresponding to that message frame. More precisely, more dominant bits in an offset message frames makes it easier for the voltage sensor to capture the voltage-message correlation for this message. For example, the message, $199 (25-ms period, 64 data bits), is more favorable over the message, $0C7 (12.5-ms period, 32 data bits), for TCM. If longer messages are monitored, normalized counts for healthy ECUs are further



(a)



(b)

Figure 12. Correlation between voltage and message. (a) Voltage-to-message approach (b) Message-to-voltage approach

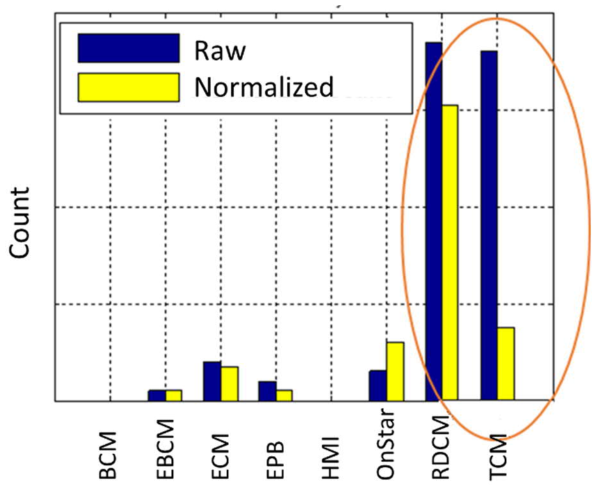


Figure 13. Normalization improves offset ground isolation: the raw count is the count of high-voltage frames correlated to each ECU; the normalized count is the ratio of high-voltage frames count to the total frame count for a message. In this case, the RDCM has the offset ground fault and other modules are healthy. EBCM stands for the electronic brake control module.

separated from the counts for ECUs with an offset ground. This clear separation makes it easier to isolate faulty ECUs. As the correlation method and monitoring messages for all ECUs are determined, a remaining question is the choice of the window size. Using the voltage-to-message correlation as an example, the window cannot be too wide, otherwise messages transmitted by healthy modules will be incorrectly correlated to a high voltage frame. On the other hand, due to the delay effect the window cannot be too narrow either. A narrow window may miss the message that caused the high voltage frame. Based on this, a window slightly larger than the maximum delay is a good option.

4.2.2. The Bus Load Approach

The voltage and message correlation approach will not work when the system delay becomes very large. Under high delay, the correlation window has to be very large to mitigate the delay effect. This leads to more messages, which are actually not correlated to the high voltage frame, getting enclosed by the window. As a result, the isolation accuracy deteriorates. Instead of correlating voltage samples with CAN frames, isolation can be performed with voltage samples alone. This concept is introduced here to handle high-delay cases. The frequency of high voltage frames equals to the message frequency of the faulty module(s). The message frequency of an ECU can be calculated based on the bus signal database,

$$f_{ECUi} = \sum_{k=0}^{N_i} C_{ik} \times f_{ik} \quad (3)$$

where C_{jk} is the number of messages with frequency of f_{ik}.

The frequency of high voltage frame on a bus can be estimated by,

$$f_V = C_h / W \quad (4)$$

where C_h is the high voltage frame count and W is the window size. Obviously, this approach is effective when message frequencies for two or more ECUs on the same bus are not close. Otherwise, an ECU candidate set can be generated.

5. VALIDATION

In this section, the proposed algorithms are compared and validated using a vehicle frame. As shown in Figure 14, a high-speed (HS) GMLAN bus, a low-speed (LS) GMLAN bus, and a Chassis Expansion (CE) bus were taken off the car and attached to the yellow frame. Since our ground fault algorithm does not depend on the data speed of the bus, the HS bus is employed. There are eight modules on the bus being monitored, including ECM, TCM, EBCM, BCM, HMI, RDCM, and EPB. The bus topology is shown in Figure 15. The bus is connected to an Arduino-based test box through the Diagnostic Link Connector (DLC). The test box is the off-board platform to collect the data, process the data, and make diagnostic decisions. For test purposes, a connector has been added between the ground pin of each module and true ground to inject ground faults. The ECM and TCM share the same ground. Therefore, one connector is shared for these two modules. In this work, the CANH and CANL voltages are measured by an oscilloscope through the exposed connectors. Bus messages are monitored by Vehicle Spy through the DLC. Disconnecting the connector between a module and the ground will make that module ground floating. To inject offset ground, disconnect the connector and add a resistor in between. Voltage drop across the added resistor can be measured if desired.

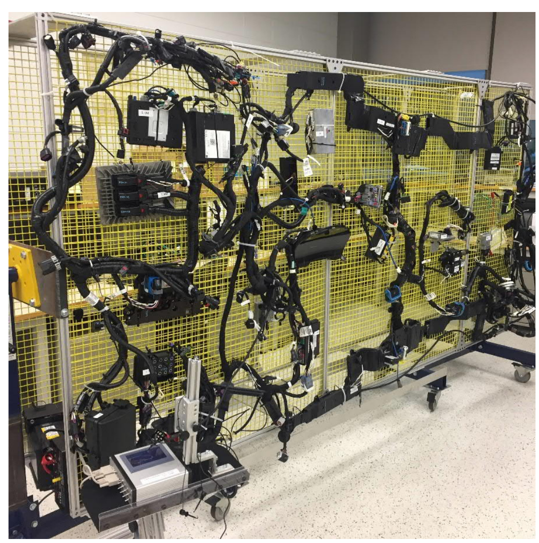


Figure 14. The vehicle frame from a GM vehicle.

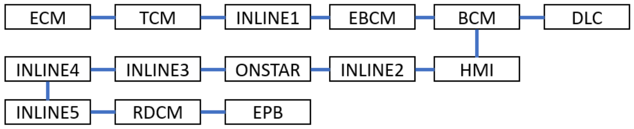


Figure 15. The topology of the high-speed bus on the vehicle frame.

5.1. Validation of ECU Floating Ground Detection

As discussed in the section 2, an ECU with a floating ground no longer participates in CAN communication, and only affects the inter-frame bus voltage. The inter-frame voltage ultimately settles down to a constant value during long idle periods. The steady level and settling time depend on the faulty module. Table 1 shows that the average voltage of CANH and CANL within a frame remains around the same as a healthy bus if an ECU has a floating ground (2.5 V for the HS bus), while the passive voltage goes up.

From Table 1, it can be clearly seen that a floating ground is able to cause bus voltage to increase in the inter-frame region. The increase in idle voltage depends on the faulty ECU. Specifically for this HS bus, 2.65 V is a good choice for the floating ground detection threshold. A general procedure to determine the inter-frame voltage threshold is as follows, (1) measure the steady inter-frame voltage for each ECU with the floating ground fault (*e.g.* Table 1) as V_F; (2) measure the inter-frame voltage when all ECUs are normal as V_N; (3) set the threshold between the minimum V_F and V_N.

5.2. Validation of ECU Offset Ground Detection

As discussed in the section 3, the ECU offset ground will always affect in frame voltage, and for some cases also inter-frame voltage. The diagnostics of the ECU offset ground enables the ground fault prognostics to predict the possibility of an ECU becoming floating ground. Figure 16 reveals the transition from a normal ground, an offset ground, to a floating ground. When the ground resistance is very low (smaller than 1 Ω), the ECU is normal, and the maximum average voltage of CANH and CANL within frames is around 2.5 V. As the ground resistance gets larger, the ECU is still able to transmit messages, and the maximum average dominant voltage gets larger. At some point such as 10 KΩ, the ground resistance becomes so large that the affected ECU stops transmitting any messages. The maximum average dominant voltage returns to the normal level because all the remaining messages on the bus are sent by healthy ECUs.

Similar to floating ground detection, the determination of a general voltage threshold needs baseline information for all ECUs. Specifically for this test bench, a threshold of 3 V is a good choice, as all average dominant voltages under certain ECU ground offset are greater than 3.2 V. Normally this value should be around 2.5 V.

Validation of the floating ground detection algorithm was performed using with the Arduino box on the HS bus (Figure 17). EBCM, HMI, OnStar, RDCM, TCM&ECM, or EPB

Affected Module	Passive Voltage (V)	Active Voltage $(V_h + V_l)/2$ (V)
BCM (both X1 & X2 floating)	2.90-3.70	2.51
EBCM	2.90	2.52
EPB	3.05	2.52
HMI	2.88	2.51
RDCM	6.35	2.48
ECM/TCM (TCM bypassed)	4.15	2.6

Table 1. Bus voltage features under ECU floating ground.

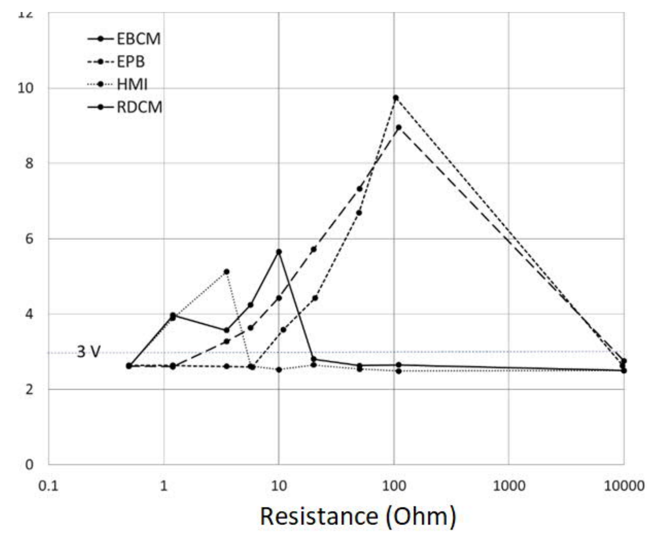


Figure 16. The transition from a normal ground, an offset ground, to a floating ground as the ground resistance increases. The y axis is the maximum average dominant voltage (V)

were disconnected from ground. A floating ground decision was correctly made in all the tests.

5.3. Validation of ECU Floating Ground Isolation

Each ECU on the CAN bus is being monitored by a unique message. Therefore, an ECU can be isolated immediately if this message is lost on the bus. Loss of an ECU communication does not necessarily mean that the ECU's ground is floating. So, this floating ground isolation method has to be applied along with floating ground detection. For the tests with EBCM, HMI, OnStar, RDCM, TCM&ECM, and EPB, faulty ECUs were successfully identified by the Arduino diagnostic box (Figure 18).

5.4. Validation of ECU Offset Ground Isolation

5.4.1. Validation of the Normalized Voltage-Message Correlation with Count Pattern Matching Approach

In this validation test, an offset ground was injected to one ECU at one time. For small delays, isolation by both the raw count and the normalized count showed good results as shown Figure 19 (a). While the normalized voltage-message correlation count within a time window is proved to be effective on the test bench for low delays, it is not able to handle higher delays. A higher delay requires a wider window, and more messages transmitted by healthy modules are correlated to high voltage frames. Normalized correlation counts under 250 µs delay and 250 µs window stood out in all cases in Figure 19 (a). With 10,000 µs delay, this correlation approach is not effective on BCM, EBCM, TCM, and ECM even with a 10,000 µs window (Figure 19 (b)).

Figure 20 shows the impact of the window size, normalization and system delay, when the EBCM had an offset ground. When the delay is near zero, the EBCM is located accurately as expected. When the delay increased to 2ms, the correlation without accounting for the delay (the window is very low compared to delay) results in a faulty decision (TCM). Normalized correlation accounting for the delay (with a window of 2 ms) is able to isolate the EBCM from the healthy modules.

5.4.2. Validation of Bus Load Approach

Bus load approach is proposed to handle some of the high-delay cases that cannot be solved by the correlation approach. In the validation test for the bus load approach, the fault signature for an ECU is chosen as the bounds of the number of frames sent by that ECU per second. Then, high voltage frames on the bus per second are also identified. Figure 21 shows that fault signatures for all ECUs, except for EPB and RDCM, do not overlap. BCM, EBCM, and HMI are successfully isolated from the rest healthy ECUs using the bus load approach. For the case of f_v = 21 high voltage frames are detected, EPB and RDCM are identified as two candidates with an offset ground, since their fault signatures are the same. Even though EPB cannot be isolated from RDCM, the approach is still valuable since it dramatically reduced the candidate root causes from 8 to 2.

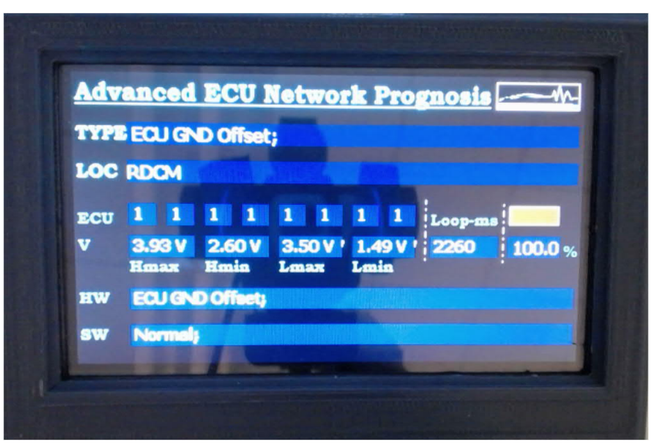


Figure 17. The Arduino diagnostic box indicates the RDCM has an offset ground.

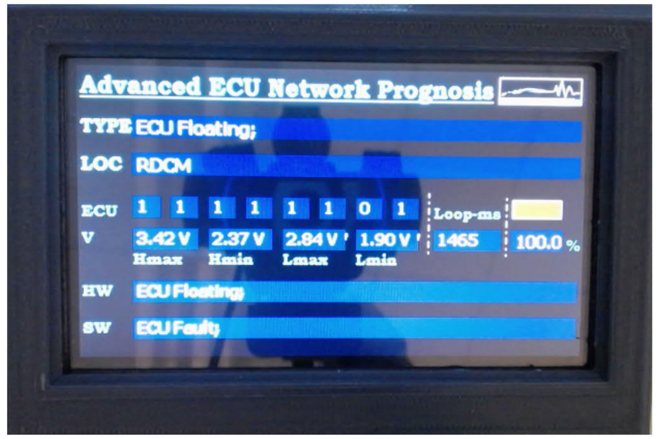
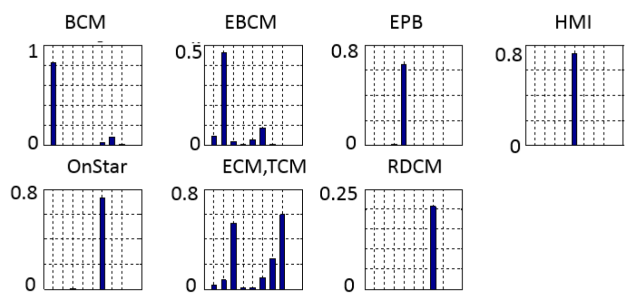
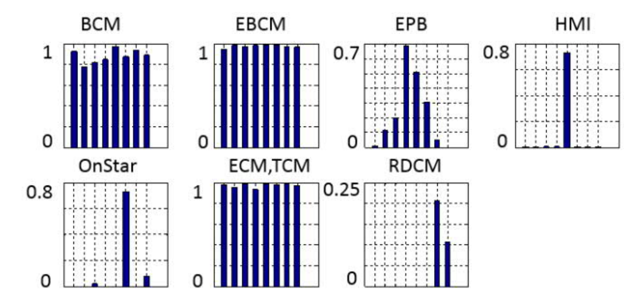


Figure 18. The Arduino diagnostic box indicates the RDCM has a floating ground.



(a)



(b)

Figure 19. Normalized correlation count for different ECUs with the offset ground fault. The ECU name shown on the top of each figure is the fault root cause. The bars from left to right correspond to BCM, EBCM, ECM, EPB, HMI, OnStar and TCM, respectively. (a) The system delay is 250 us. (b) The system delay is 10,000 us.

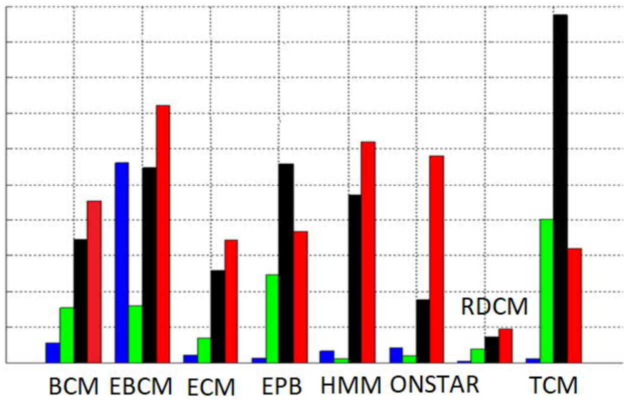


Figure 20. The effect of delay on offset ground isolation. Y-axis is the frame count. The blue bar indicates 0ms delay and 0.25ms window, the green bar indicates 2ms delay and 0.25ms window, the black bar indicates 2ms delay and 2ms window and the red bar indicates normalized 2ms delay/window.

Module	Fault Signature
BCM	[263.88, 322.52]
EBCM	[849.6, 1038.4]
ECM, TCM	[1082.7, 1323.3]
EPB	[18.9, 23.1]
HMI	[45.9, 56.1]
ONSTAR	[3.6, 4.4]
RDCM	[18.9, 23.1]

Test Cases
947
306.8
21
52

Figure 21. Fault signature and test results for ECU offset ground isolation using bus load.

6. CONCLUSION

Healthy operation of each ECU is critical to vehicle driving. With a floating ground, the ECU stops receiving or transmitting messages, no longer participates in the CAN bus communication, and can no longer perform its other normal operations. A floating ground is normally evolved from an offset ground due to corrosion, damages, or manufactured/assembly issues. Therefore, the ability to predict when a ground will become floating by diagnosing offset ground is highly desirable for customers. In this work, we propose a feasible production solution for ECU ground fault diagnostics. The offset and floating ground can be detected by monitoring bus voltages within frames and inter-frames, respectively. The floating ground fault can be further isolated at the ECU level with additional ECU activity information based on bus messages. To isolate the offset ground fault, a normalized correlation approach can be employed for systems with a small delay between the voltage measurement and message reading. For systems with a large delay between the voltage measurement and message reading, the approach of bus load estimation is effective to isolate the offset ground fault. The proposed solutions provide a cost-effective way to detect and isolate ground faults compared to the state-of-art solutions, *e.g.* adding voltage sensors to each ECU. More validation and refinement using different vehicle models or CANFD bus data will be our next focus.

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NOMENCLATURE

BCM	body control module
CAN	controller area network
CANFD	controller area network flexible data-rate
CANH	controller area network high voltage wire
CANL	controller area network low voltage wire
DLC	Diagnostic Link Connector
ECU	electronic control units
EBCM	electronic brake control module
ECM	engine control module
EPB	electric park brake
HMI	human machine interface
RC	resistor and capacitor
TCM	transmission control module
V	voltage
Ω	resistance ohm

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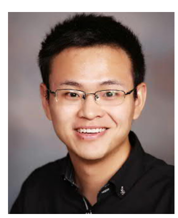

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