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Considerations on Ground Fault Protection for Electric Vehicles

<u>Introduction</u>

The emergence of Electric Vehicles (EV's) and Plug-in Hybrid Electric Vehicles (PHEV's) has provided the possibility of utilizing energy stored in the vehicle's battery to power AC equipment from the vehicle (referred to as export AC power), or recycling power from the vehicle's battery back to the utility grid (referred to as Grid-tie power). With these opportunities come new considerations for personnel safety in the situation where there are unintentional faults from the power lines to ground. This paper analyzes various scenarios, pointing to viable solutions for personnel safety assurance circuits.

<u>Background</u>

The general electric vehicle charger / export power topology under consideration is presented in Figure 1.

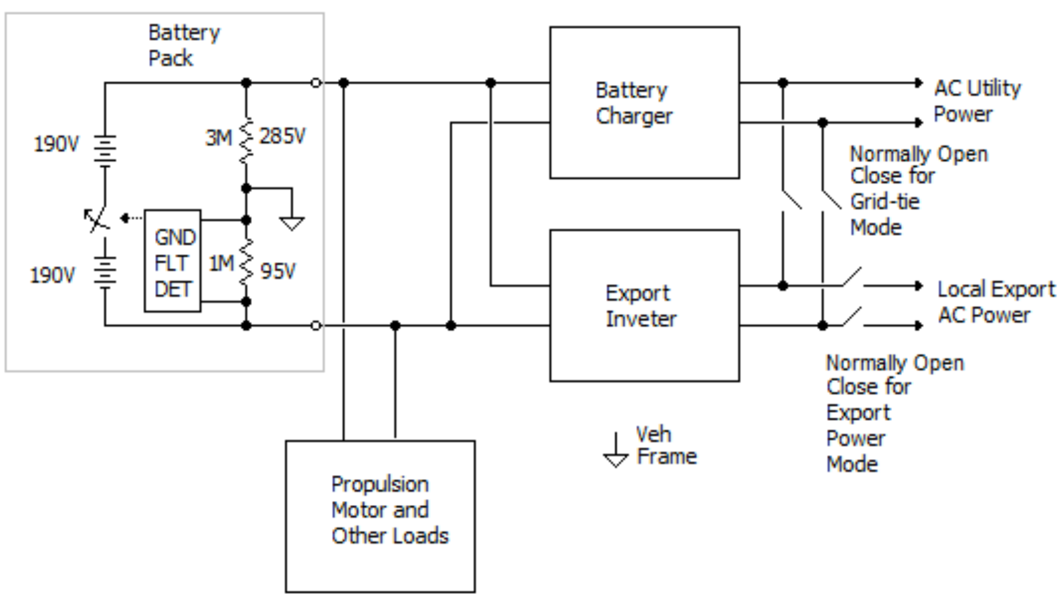

Figure 1 – General Vehicle Electric Power Circuit

The battery charger takes AC power from the utility grid and converts it to a DC voltage suitable for battery charging. The Export Inverter takes DC voltage from the battery and converts it to an AC voltage compatible for local AC powered equipment (export mode), or synchronizes the output to same voltage and frequency as utility power so as to deliver power back to the AC power grid (Grid-tie mode).

It is possible to realize the battery charger and export inverter as a single bi-directional converter that can operate in either direction. This converter may feature galvanic isolation between its AC and DC terminals through use of an internal isolation transformer, or the converter can feature a non-isolated design that provides a relatively low impedance path between the vehicle battery and AC power.

Battery Isolation Detection

The general practice in EV's and PHEV's is to provide robust insulation between the battery's high voltage terminals and the rest of the vehicle. As depicted in Figure 1, insulation integrity is often monitored by connecting relatively high impedance sampling resistors from the battery's positive and negative terminals to the vehicle's frame ground and then monitoring the voltage on one of these resistors to verify it is at a voltage compatible with no unexpected impedances connected from the battery bus to ground. If a fault to ground is detected, a contactor in series with the battery is opened to prevent dangerous currents from flowing into ground. Monitoring impedances may be symmetrical or, as shown in this example, unsymmetrical.

The battery isolation detect circuit is utilized to detect a single fault of the battery circuit to chassis and open circuit the batteries if a fault condition is detected. A single fault of the battery bus to chassis does not normally result in a personnel safety issue as in order to be shocked, a person would have to come in simultaneous contact with the non-faulted lead and the vehicle chassis. This allows the isolation fault detection circuit to be designed to be fairly slow and deliberate.

If this circuit were to be employed for personnel safety purposes in supplying export AC power, it would have to be carefully considered from the viewpoints of trip points, accuracy and speed. These parameters are normally inconsistent with other vehicle considerations and this paper assumes that battery fault isolation circuits will not be counted on to provide personnel safety for exported AC power. However, it will consider the effects of external ground faults on the normal functionality of battery isolation monitor and protection circuits.

Export Power Considerations

Figure 2 presents a model focused on export power considerations for a non-isolated converter. With a non-isolated converter, the vehicle's on-board fault monitoring circuits may be affected by external grounding. In the case of a fully isolated converter, these monitoring circuits would be fully isolated from any external connections. In either case, this model is useful for the analysis of monitoring and protecting external AC circuits from fault currents for any type of converter.

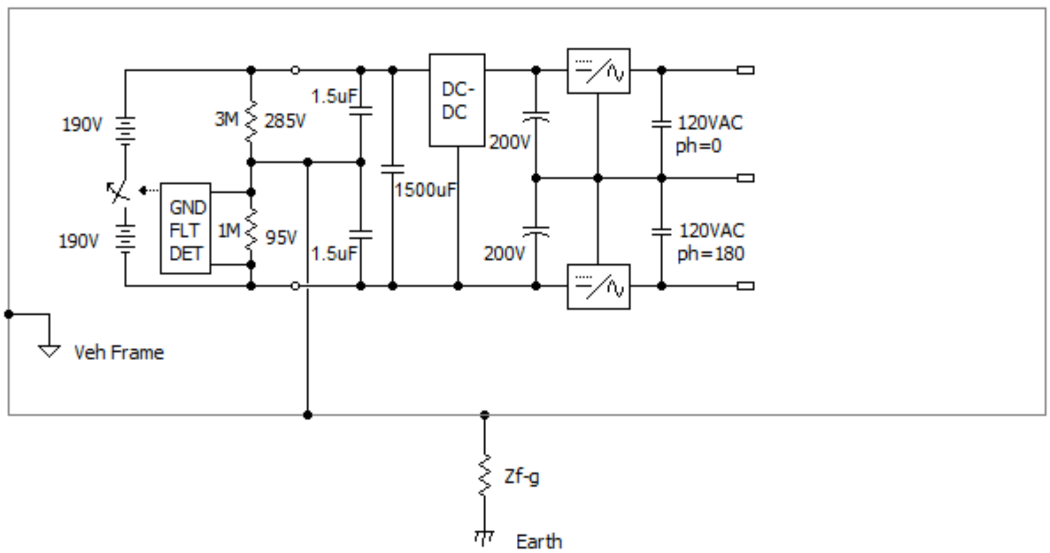

Figure 2 – Vehicle Power System Model for Export Power with a non-isolated converter

In Figure 2, the vehicle frame ground (represented by a triangle symbol) is connected to earth ground by an impedance designated Zf-g. This impedance can be very high in the case where there are clean, dry rubber tires; or can be fairly low in the case where there are wet, dirty tires; or very low, where there is an intentional safety ground connection made between the vehicle frame and earth ground.

The model in Figure 2 also presents typical distributed impedance values for both line to line and line to chassis capacitances generated by the various load circuits in the vehicle. These are set as 1.5uF for line-to-ground and 1500uF line-to-line, which are typical for EV and PHEV systems.

The converter topology in Figure 2 is set to provide split 120/240VAC power to external equipment. Battery voltage is boosted to 400VDC and then split on two capacitors.

Typical capacitance for these DC-link capacitors is on the order of 10,000uF. These form the source for two inverter circuits that are set to deliver 120VAC (170Vpk) and which are set to operate 180° out of phase from each other. In this manner, the voltage from line to line is 240VAC, and the voltage from line to the center of the two capacitors (designated as the neutral terminal) is 120VAC.

Figure 3 presents a scenario where 240VAC is exported to an off-board load that is housed in a metallic chassis. For 240VAC applications, the export power connection provides three terminals: L1, L2 and GND, where GND is a connection to the vehicle's frame ground.

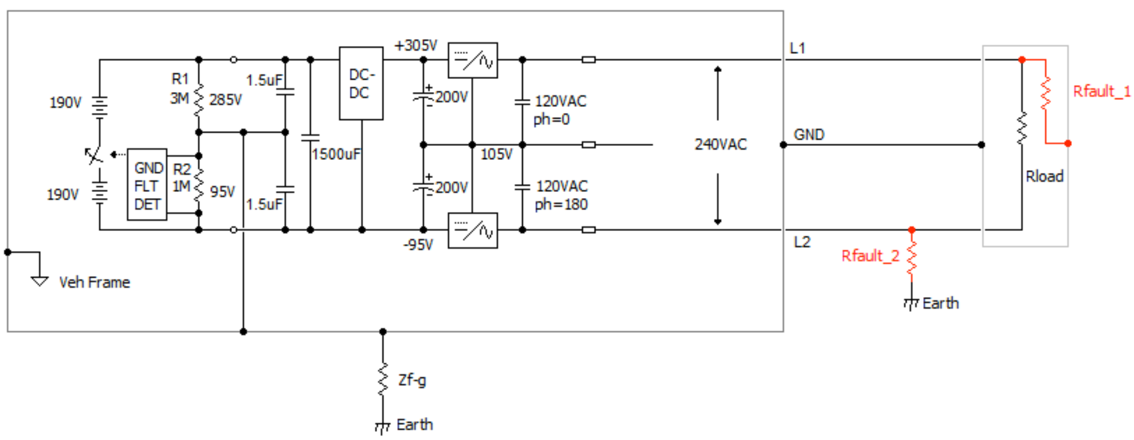

Figure 3 – Export 240VAC Power

In Figure 3, two potential fault scenarios are provided. In the case of Rfault_1, a low-impedance resistor is connected from one of the power terminals to the chassis of the load equipment. In this scenario, the battery's impedance to ground monitoring circuit will detect the impedance that shunts current away from monitor resistor R1, and will eventually open the battery disconnect contactor.

In the case of Rfault_2, a low-impedance resistor is connected from one of the power lines to earth ground. If Zf-g (connection between the vehicle's frame ground and earth) is very high, then this will limit current flow and no fault will be detected, nor will a potential safety issue exist. If Zf-g is low enough to flow a significant current, the battery's impedance to ground monitoring circuit will detect the impedance that shunts current away from the monitor resistor R2, and will eventually open the battery disconnect contactor. As noted earlier, the battery isolation fault monitor should not be relied upon to provide for personnel safety with respect to exported AC power.

Figure 4 presents the condition of 120VAC export power. For 120VAC applications, the export power connection provides three terminals: L1, N and GND, where GND is a connection to the vehicle's frame ground and N is the "neutral" terminal.

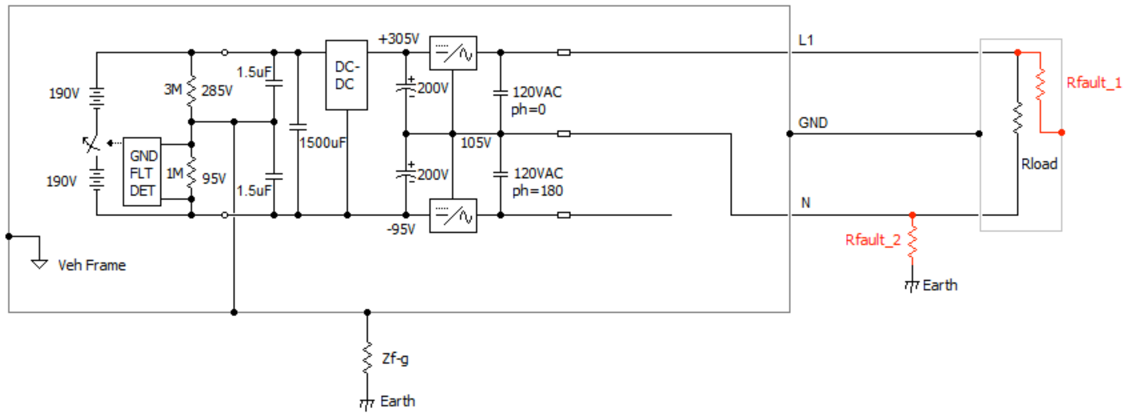

Figure 4 – Export 120VAC Power

Much the same as for the 240VAC case of Figure 3, if there is an external fault that presents low impedance to the vehicle's frame ground, the vehicle's on-board impedance to ground monitoring circuit will react to it.

Unlike common household situations where the neutral terminal is at zero volt potential with respect to earth ground, the export power neutral terminal may have a DC offset. In our example, parasitic impedance to earth ground will ultimately force the vehicle chassis to be at approximately 0V with respect to earth. This sets the battery positive voltage at +285V and the negative terminal at -95V (with respect to earth). The voltages that feed the inverter circuits are therefore +305V and -95V, with the center neutral point at +105V.

Figure 5 presents the voltage that would be measured across one of the 120VAC outputs with respect to earth ground. While the voltage measured from L1 to N will be fully symmetrical, the voltage measured from L1 to earth ground will not be symmetrical.

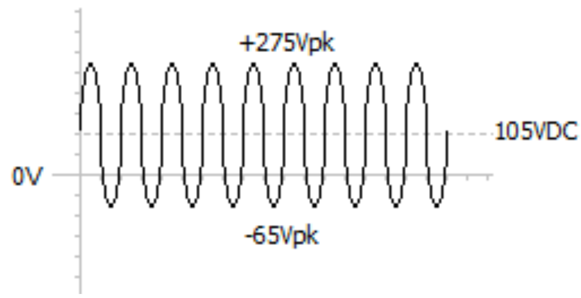

Figure 5 – Export Output voltage with respect to Earth Ground – Ungrounded Neutral terminal

As described earlier in this paper, the battery isolation monitor is not an appropriate means of assuring personnel safety for export power. This is better served with a dedicated AC ground fault detection and interruption circuit. Figure 6 presents a ground fault current interrupter (GFCI) for a 120/240 export power connection.

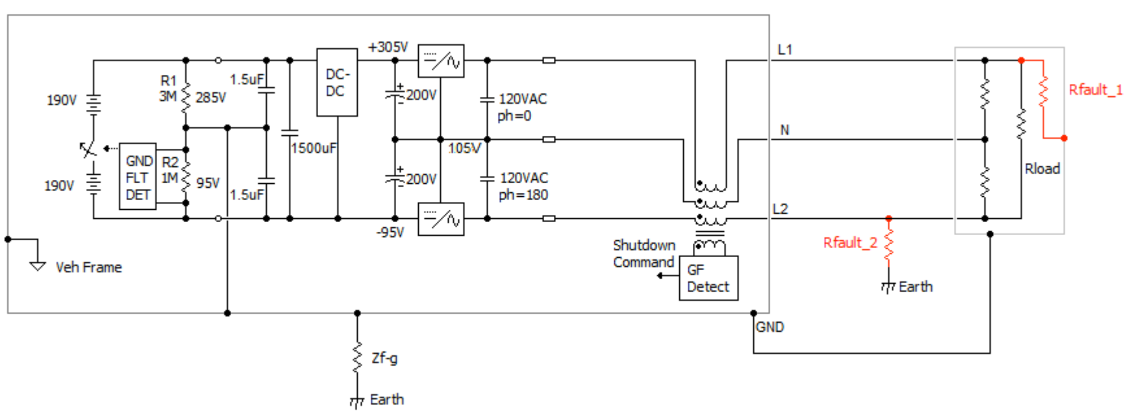

Figure 6 – AC Ground Fault Detection Circuit

In Figure 6, a monitoring circuit is added to detect that only symmetrical AC currents exist in the three output leads. Current that does not symmetrically flow out from and return to the source through these wires will be detected by the sense winding and force a system shutdown to occur, thereby limiting any further output current flow.

Examination of Figure 6 indicates the DC-DC converter sits between the neutral terminal and capacitive connections to vehicle ground. This can result in poorly defined impedance from any external fault to the export neutral terminal. In order to provide the proper precision required for the GFI circuit, definitive impedance in the form of a capacitor is connected from the neutral terminal to chassis. Figure 7 presents this connection.

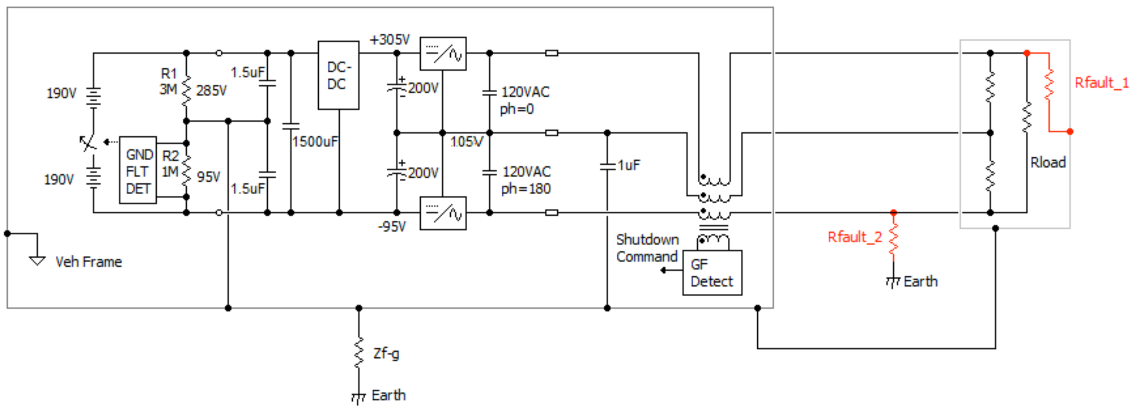

Figure 7 – AC Ground Fault Detection Circuit with Reference Impedance Neutral to Vehicle Ground

The value of the added capacitor is set at 1uF to support a protection circuit trip at around 5mA. (This is the value recommended by various safety agency standards.) At 60Hz output frequency, a current of 5mA-rms will generate 15V-rms across the 1uF capacitor. For 120VAC output voltage, this corresponds to a fault impedance of approximately 23.9k-Ohm, which is well above most human body impedance models.

Export Power to a Grounded Home Connection

A special case of export power occurs when the neutral connection is intentionally connected to earth ground, as would be found when the vehicle is used to power up a home during a utility power outage. Figure 8 presents this scenario.

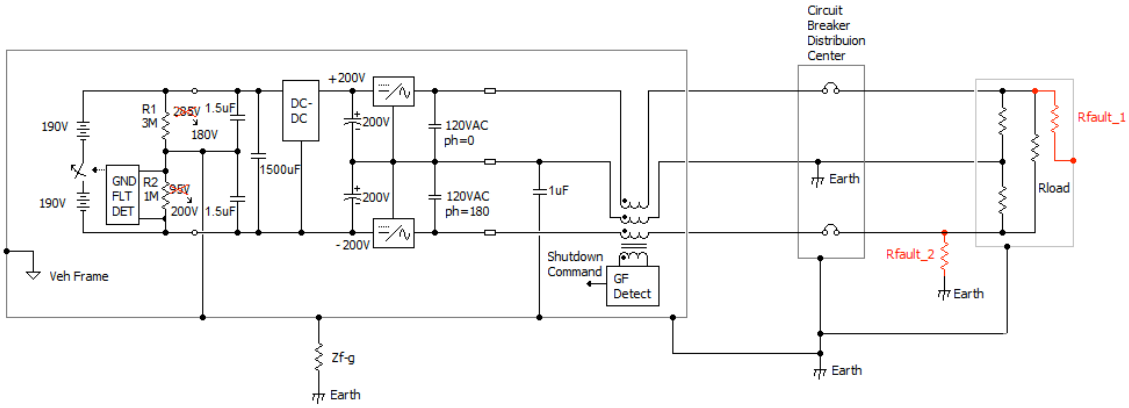

Figure 8 – Export Power with Earth-Grounded Neutral Wire

In this scenario, a hard wired connection between the vehicle chassis and earth ground is present, provided by the export power connection cable. This connection will force the neutral terminal to be at zero volts with respect to earth ground. This in turn will force the battery ground fault sensing resistors to indicate a ground fault.

Beyond forcing a battery isolation fault indication, the external ground connection will most likely cause a fault of the output GFI circuit, as illustrated in Figure 9.

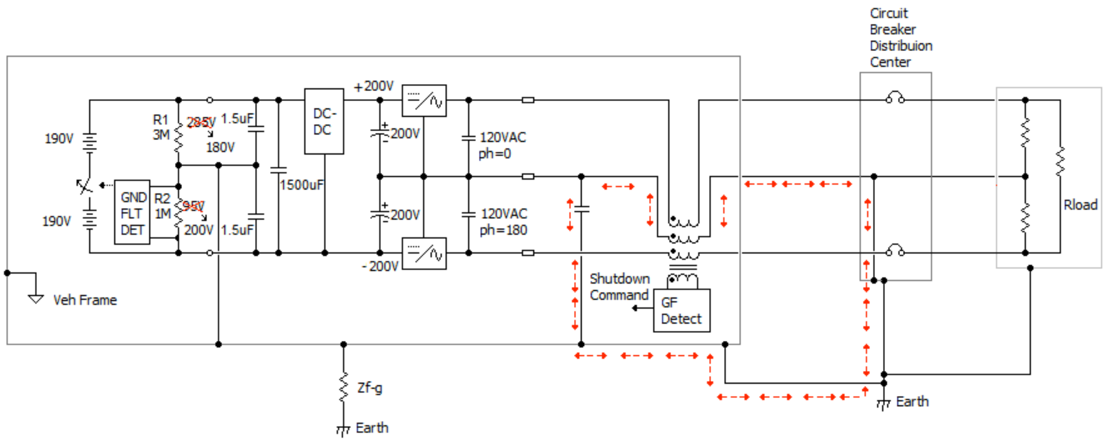

Figure 9 – Export Power with Grounded Remote Neutral

Figure 9 illustrates how there is a parallel path for load current to return to the converter formed by the remote neutral connection to earth. Depending on impedances, this will instigate a GFI shutdown.

Given the uncertainty of protection circuits, depending on grounding impedances, in export power scenarios that connect to a grounded load circuit, it is good practice to prohibit this sort of connection. In Export Power mode, onboard GFI circuits should detect a remotely grounded neutral and shut the converter down if one is detected.

In order to assure an externally grounded neutral is detected, a supplementary "grounded neutral detector" circuit is recommended. As shown in Figure 10, this can be realized by injecting a low current AC signal from Frame Ground to the output neutral terminal and then measuring the resultant voltage on the neutral to Frame Ground capacitor. If a conductive path sufficient to disrupt normal GFI operation is present, the voltage on the 1uF capacitor from neutral to Frame Ground (typically 6V-rms) will collapse and a GFI shutdown will be initiated.

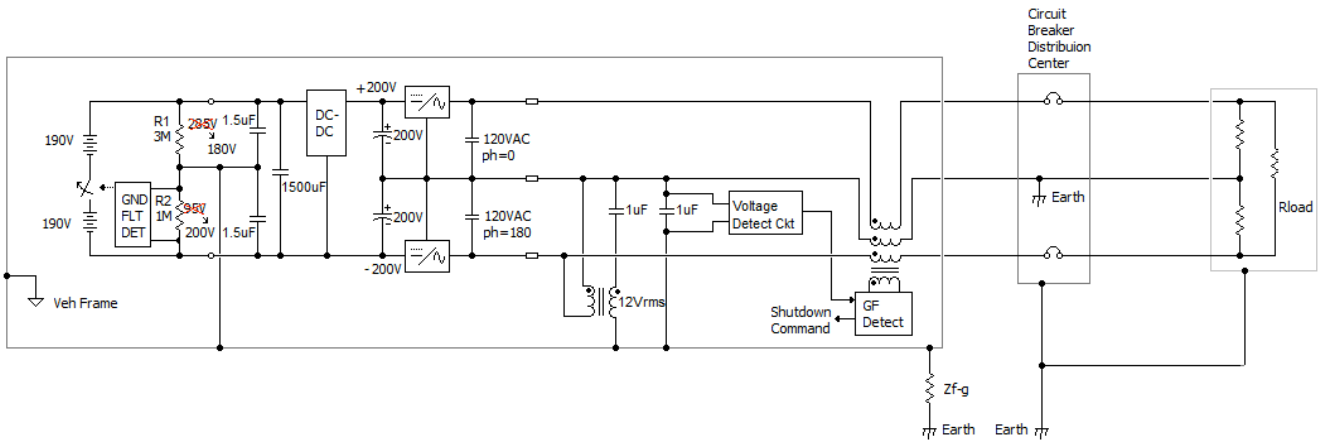

Figure 10 – Supplementary Grounded Neutral Protection

As the addition of a remotely grounded neutral affects both the battery isolation monitor and the AC GFI circuits, it represents a disruptive and potentially unsafe operating mode for export power. However, as will be shown in the next section of this paper, the charge port connection provides a viable means of providing either grid tie power or export power to an external grounded neutral system.

Grid-tie Power Considerations

For analysis purposes, this paper assumes any Grid-tie or Externally Grounded Neutral Export operation will be back through the vehicle's charging input port via a land based Electric Vehicle Safety Equipment ("EVSE") compliant connection. As of this writing, EVSE charging ports provide 220-240VAC without a neutral connection. Figure 11 presents an AC Level 2 system configuration diagram for a typical EVSE charger.

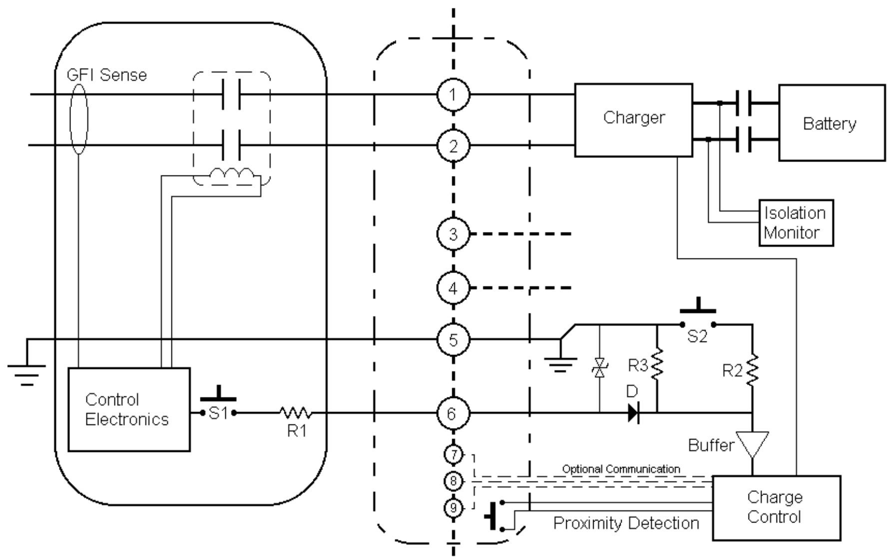

Figure 11 – AC Level 2 EVSE System Diagram

Figure 12 illustrates this system expanded to include the details on the bidirectional charger/inverter.

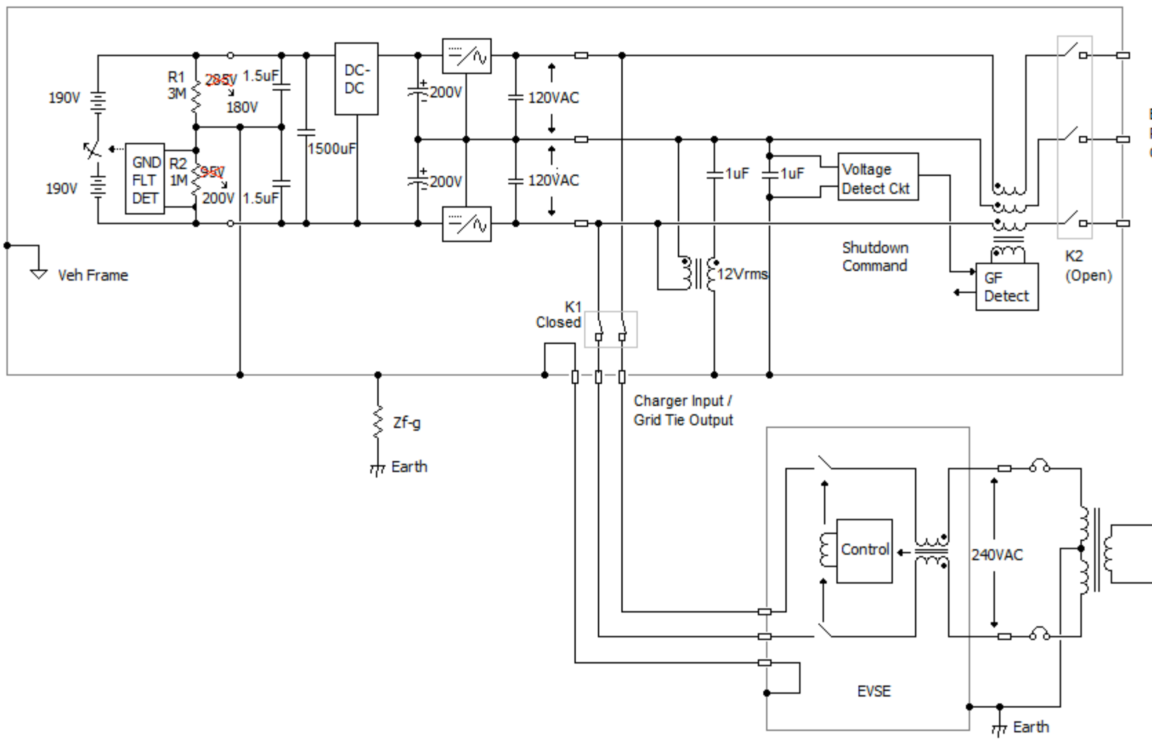

Figure 12 – Grid-tie Power Mode

In Figure 12, the connection back to the power grid 220/240V distribution network is generated via a split connection with respect to earth ground, as would be the case for most North American households.

The utility grid acts as a very low impedance voltage source. In Grid-tie mode, the export inverter is set to act as a current source, with its output voltage slaved to that of the power line. For a non-isolated solution, as shown in Figure 12, this type of connection will force the neutral terminal of the export inverter to a voltage near zero. This in turn will disrupt the voltages normally seen on the battery's ground fault detection resistors. If this type of operation is to be allowed, accommodation of the changed ground fault sensing levels will have to be made in the battery protection circuit and AC ground fault protection at the output of the inverter must be utilized.

The EVSE provides the required ground fault protection between the external power grid connection and the vehicle. If there is a non-symmetrical impedance connection between the onboard power electronics and vehicle frame ground, this will be picked up by the GFI sense coil in the EVSE. If this connection generates a current that is above a predetermined safety threshold, then the EVSE will open its contactor to break the connection between the vehicle and the power grid.

Battery Charging Considerations

The analysis put forth for Grid-tie export inverter operations holds true for battery charging mode.

If there is no earth ground connection on the utility power side (i.e., power is supplied from an electrically floating winding or generator), then for either a non-isolated or isolated converter there is no compromise to battery ground fault sensing circuits.

If the utility line connection has an earth ground reference, as is often found in common household situations, a fully isolated converter will prevent battery isolation fault sensing circuit from being affected. Non-isolated converters may result in the battery isolation fault detector being affected and requiring active adjustment for this condition.

The EVSE's GFI protection circuit will support personnel safety and other AC ground fault issues on the vehicle.

Conclusions

Eliminating the isolation barrier between the utility grid and an EV or PHEV battery offers advantages in terms of power converter size, complexity and cost. This paper shows how this approach can be realized while providing full safety considerations for external personnel. For such a converter, care must be taken in addressing such issues. A non-isolated converter will require battery ground fault detection circuits be tailored to different operating modes.

Likewise, either non-isolated or isolated converters that provide AC power back to individual equipment, or act as a backup generator to a household environment, or are tied back to the utility grid, must be carefully designed to address the issues that each of these different applications present.

This paper suggests that any connection to the power grid or to a grounded neutral external power distribution network be only via properly rated EVSE equipment, and prohibited from the vehicle's export power connection. EVSE compliant utility line connections will provide full protection to the vehicle from all possible faults to ground.