

A Plug-In Electric Vehicle Simulator for Electric Vehicles Supply Equipment Evaluation

2010 TECHNICAL REPORT

A Plug-In Electric Vehicle Simulator for Electric Vehicle Supply Equipment Evaluation

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ABSTRACT

The Electric Power Research Institute (EPRI) is developing a portable plug-in electric vehicle simulator to support laboratory testing and evaluation of electric vehicle supply equipment. The device implements the signaling required in the Society of Automotive Engineers J1772™ Recommended Practice, SAE Electric Vehicle Conductive Charge Coupler, and provides connection of power quality monitoring and simulated load equipment. The complete unit is self contained and battery powered for ease of field use, but can be used in the lab with an external load bank.

Keywords

Vehicle simulator

SAE J1772

Electric vehicle supply equipment

Charging

Plug-in electric vehicle

CONTENTS

- 1 INTRODUCTION 1-1**
 - Design Goals..... 1-1

- 2 AN OVERVIEW OF J1772 2-1**
 - System Overview 2-1
 - The Control Pilot (Pin 4) 2-3
 - The Proximity Detection Function (Pin 5)..... 2-5
 - Compatibility Issues with J1772 2-5

- 3 DESIGN AND IMPLEMENTATION OF THE SIMULATOR..... 3-1**
 - Packaging 3-2
 - Electronics..... 3-3
 - Simulator Operation 3-5

- 4 SUMMARY 4-1**

LIST OF FIGURES

Figure 2-1 Pin-out of J1772 Connector Showing Mating Sequence	2-2
Figure 2-2 Photos of J1772 Plugs from Three Different Manufacturers and a Receptacle.....	2-3
Figure 2-3 Control Pilot Circuit.....	2-4
Figure 2-4 Pulse Width Modulation Signal Parameters	2-4
Figure 2-5 Schematic of Proximity Circuit (Plug Side of Circuit).....	2-5
Figure 3-1 Block Diagram of the Simulator	3-1
Figure 3-2 External Connections to the Simulator	3-2
Figure 3-3 Photo of the Complete Simulator Unit	3-2
Figure 3-4 Simulator Block Diagram	3-3
Figure 3-5 Rear View of the Main Custom Printed Circuit Board Assembly	3-4
Figure 3-6 The Simulator Display and Keypad Module	3-4
Figure 3-7 Menu 1- Simulator Information Display	3-6
Figure 3-8 Menu 2 - Control Pin Information.....	3-6
Figure 3-9 Menu 3 - Power Information	3-7
Figure 3-10 Menu 4 - Load Control.....	3-7
Figure 3-11 State Display at Left of LCD	3-8

LIST OF TABLES

Table 2-1 Defined EVSE/PEV States2-3

1

INTRODUCTION

In January of 2010, the Society of Automotive Engineers (SAE) approved Recommended Practice J1772™ “SAE Electric Vehicle Conductive Charge Coupler”¹. J1772 defines the protocol to allow for the safe delivery of AC power to plug-in electric vehicles (PEV). Electric Vehicle Supply Equipment (EVSE) in the US, Japan and Korea will use the J1772 protocol for vehicle charging. In support of EPRI evaluation of EVSE hardware that implements the J1772 interface; EPRI has developed a Plug-in Electric Vehicle Simulator . This simulator provides responses to the EVSE interface that would normally occur when an electric vehicle is plugged in as specified by the J1772 recommended practice. The primary purpose for this device is to verify function of EVSE and to allow for laboratory and field evaluation of the EVSEs.

Whereas it is expected that the PEVs and EVSEs will be inter-operable in terms of the conductive coupler, this has not been the case in some instances and testing of the physical and electrical interoperability nevertheless has to be performed. It is also possible to apply the simulator to the task of evaluation of compatibility issues for PEV/EVSE connections. Compatibility refers to the ability of multiple brands of vehicles and EVSE to be paired with the interface working as expected. This is discussed in more detail in section 2.

There are three primary objectives for this project:

1. Design and develop a plug-in vehicle simulator that can be used to evaluate the function of an EVSE in the lab or field
2. Build a set of 5 prototype units
3. Develop a set of build ready documentation for the plug-in vehicle simulator including, but not limited to, schematics, mechanical drawings, firmware, and specifications for the unit

Design Goals

A number of design goals which were proposed at the start of the project. These define both packaging and functional aspects of the simulator:

- Unit to be housed in a weatherproof enclosure. Approximate enclosure dimensions of 10” x 10” x 5”. This will enable testing of the outdoor equipment under varying weather conditions.
- The unit is to have an internal battery power source. The use of standard form, alkaline primary batteries (type AAA, AA, C, D or 9V) is preferred. Rechargeable batteries will be considered if they do not add a large cost premium to the unit. This enables the unit to be portable.

¹ http://standards.sae.org/j1772_201001/

- Where possible, all components will be contained on a single printed circuit board assembly. Point-to-point wiring is to be minimized. This ensures minimal wiring and shock/vibrations related issues that cause loose connections while transporting the unit.
- A J1772 compliant connector will be used for the primary EVSE connection point.
- Terminals will be provided for access to AC power from the EVSE in the form of intrinsically safe connections (potentially, guarded banana style jacks).
- Internal space should be provided to include a current transformer for an external current monitor to read.
- An LCD display will be provided. The display should have backlight provision and be viewable in direct sunlight. A multiline alpha-numeric or graphic display may be used. It is preferred that multiple data elements be available for viewing simultaneously.
- Using the LCD display listed above, the Control Processor will provide the capability to display the following parameters relevant to the J1772 specification:
 - Pin 4 Pilot PWM² Frequency
 - Pin 4 Pilot PWM duty cycle
 - Pin 4 Pilot PWM – current value based on the duty cycle (as per J1772)
 - AC voltage present at output of EVSE (better than 1V resolution)
 - EVSE Pin 4 Pilot high state voltage
 - EVSE Pin 4 Pilot low state voltage
 - Pin 5 Proximity Pin state
- The control processor will use the Pin 5 proximity function to detect presence of the J1772 connector.
- Selection of the simulator state should be user selectable. It is preferred that selection be accomplished using a menu input, but fixed purpose switches may also be used as appropriate.
- The control processor will manipulate the Pin 4 Pilot impedance as required to comply with J1772 specifications to enable vehicle charging. The simulator should provide for selection of State to be presented to the EVSE. The following states shall be user selectable (via menu or front panel switch control):
 - State A – EVSE has power but no vehicle connected
 - State B – vehicle connected but not ready to accept energy
 - State C – vehicle connected and ready to accept energy; no ventilation required
 - State D – vehicle connected and ready to accept energy; ventilation required

These design goals were used as the basis for development of the simulator.

² PWM – pulse width modulation; a signal generated by the EVSE which is described in more detail in Section 2.

2

AN OVERVIEW OF J1772

The primary function of J1772 is to define a standard interface that can be used by passenger car manufacturers for the safe provision of AC or DC power to a plug-in electric vehicle. It is expected that consumers will seek to charge plug-in electric vehicles in a broad variety of locations and circumstances and J1772 focuses on the signaling needed to make this happen safely. This chapter describes the basic function of the J1772 interface.

System Overview

J1772 defines the functionality of the interface between the vehicle and electric vehicle supply equipment (EVSE). For a more in-depth discussion of the safety features found in a typical EVSE, the reader is referred to Underwriters Laboratories UL 2594 “SAE Electric Vehicle Conductive Charge Coupler”³ and UL 2251 “Plugs, Receptacles and Couplers for Electric Vehicles”⁴.

J1772 defines a 5 wire interface with the following assignment of wire functions in the pin-out:

- Pin 1) – AC Line 1
- Pin 2) – AC Line 2/Neutral
- Pin 3) – Ground
- Pin 4) – Control Pilot
- Pin 5) – Proximity Detection

The control functions do not have a dedicated ground, with the ground connection being shared with the AC power delivery pins.

Handshaking, as describe in J1772, is accomplished via the Proximity Detect Wire and the Pilot wire. Signals and impedances on these wires manage the provision of AC power to the vehicle, allow the vehicle to know the ampacity of the circuit to which it is connected and for the vehicle to sense the presence of a connector plugged into the vehicle charger receptacle.

³ <http://ulstandardsinfonet.ul.com/outscope/outscope.asp?fn=2594.html>

⁴ <http://ulstandardsinfonet.ul.com/scopes/scopes.asp?fn=2251.html>

The pins of the J1772 system are staggered in height as shown in Figure 2-1. Sample photos of J1772 plugs and connectors are shown in Figure 2-2. The pin mating sequence is Pin 3; Pins 4 and 5; and then Pins 1 and 2. As such, ground is the first connection to make and the last connection to break. Pins 4 and 5 which control the charging, make before the power pins on connection and break before the power pins on disconnect. This allows for implementation of controlled shutdown of charging prior to the power pins separating if the connector is unplugged while the charging function is active.

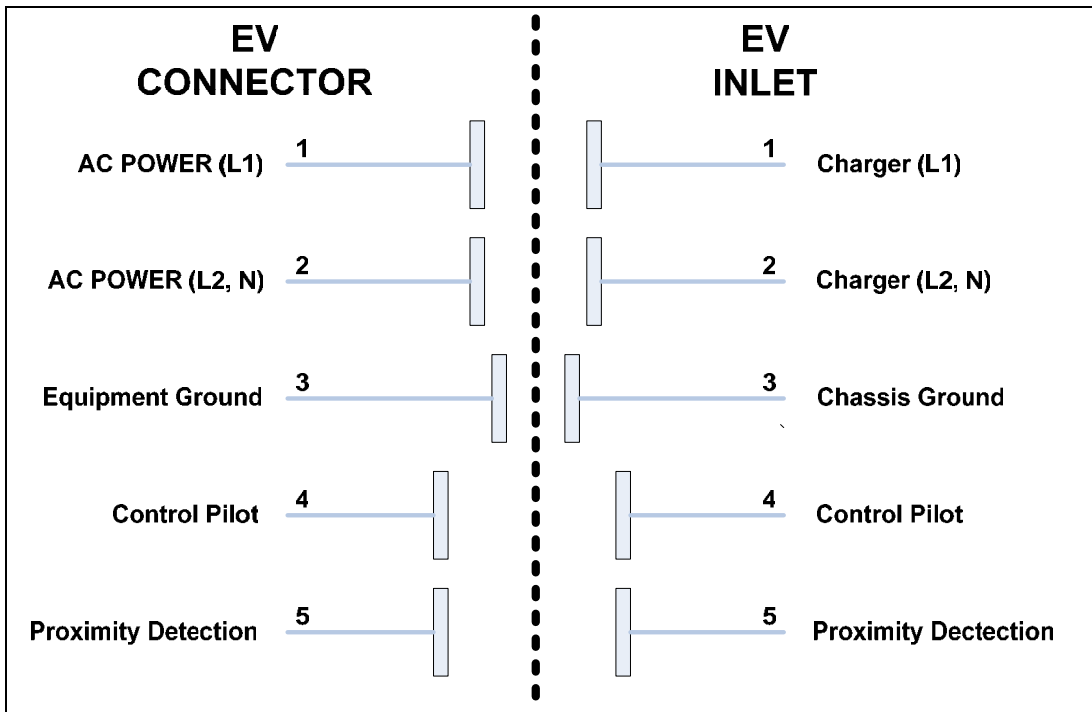


Figure 2-1
Pin-out of J1772 Connector Showing Mating Sequence

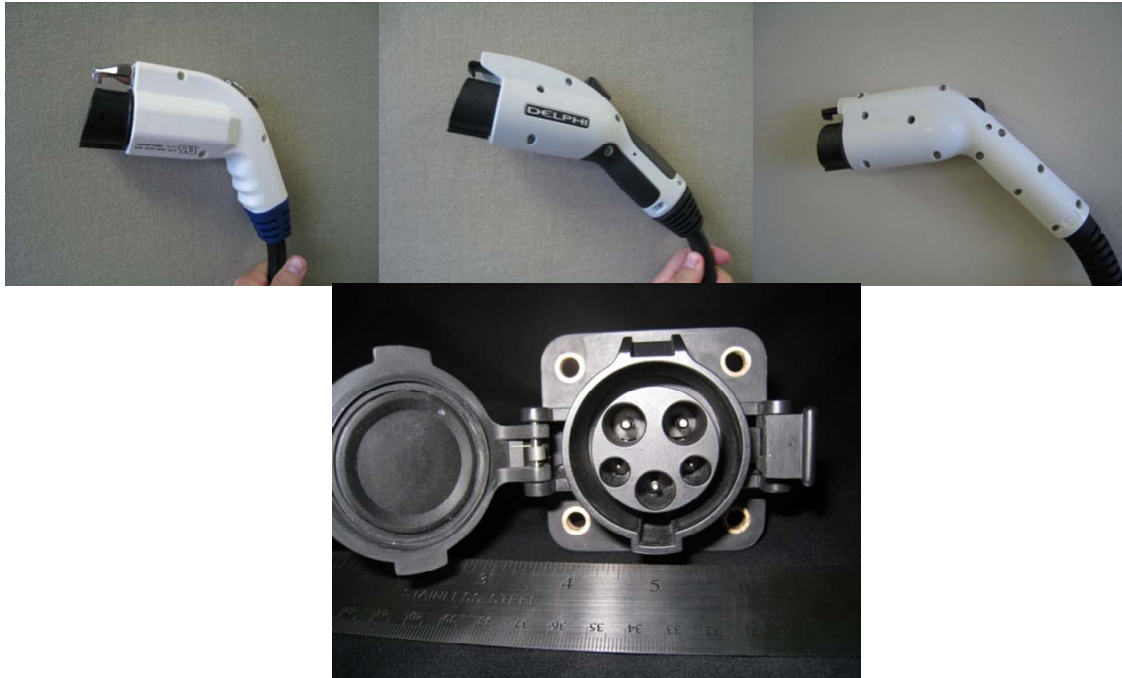


Figure 2-2
Photos of J1772 Plugs from Three Different Manufacturers and a Receptacle

The Control Pilot and the Proximity Detection pins provide for the primary charge control functions between the vehicle and EVSE.

The Control Pilot (Pin 4)

The Control Pilot wire performs two primary functions: the PEV uses this wire to signal the EVSE as to its current state by varying the load resistance on the wire; and the EVSE uses the wire to communicate the circuit ampacity to the PEV by applying a pulse width modulation waveform (PWM) with a duty cycle that signals the circuit ampacity. Table 2-1 shows the states as defined in J1772.

Table 2-1
Defined EVSE/PEV States

State A	Vehicle not connected
State B	Vehicle connected/not ready to accept energy
State C	Vehicle connected/ready to accept energy/indoor charging area ventilation not required
State D	Vehicle connected/ready to accept energy/indoor charging area ventilation required
State E	EVSE disconnected, utility power not available, or other EVSE problem
State F	EVSE not available, or other EVSE problem

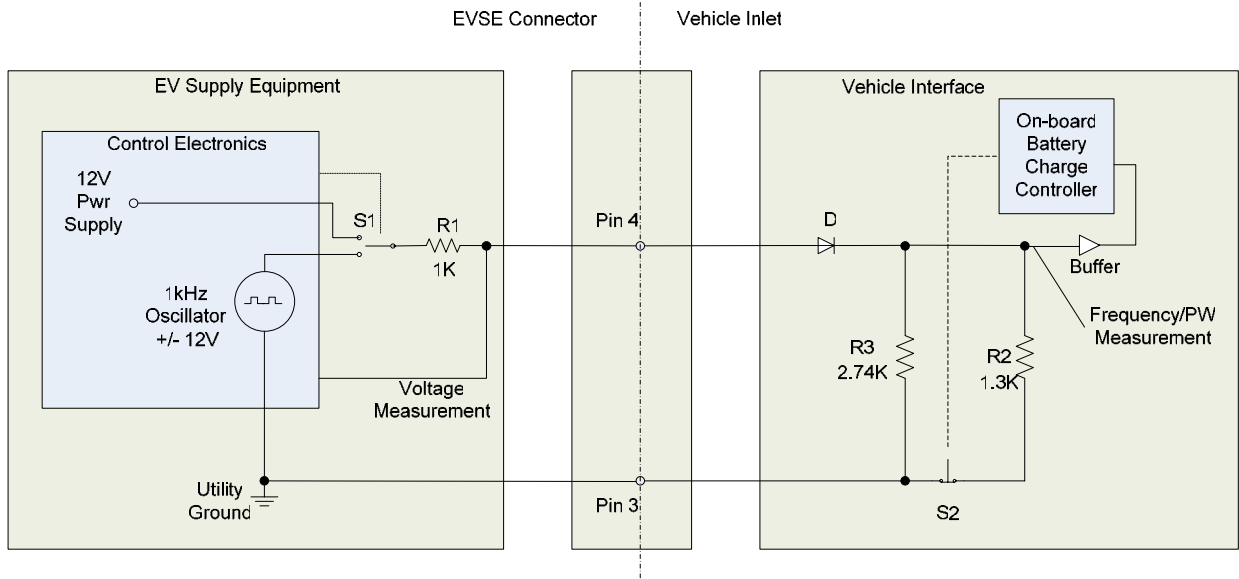


Figure 2-3
Control Pilot Circuit

There has been some discussion within the SAE committee working on the communications implementation for PEVs (J2836™/J2847) to superimpose a communications signal over the Control Pilot wire, sometimes referred to as “in-band” communication. The plug-in vehicle simulator as designed does not implement this capability.

The PWM signal is defined as in Figure 2-4, where the duty cycle is given by the ratio of T1 to Ttot in the diagram (showing an approximate 33% duty cycle). Vhigh and Vlow and the high state and low state voltages of the PWM signal and are shown as they would appear on the pilot wire at the J1772 plug (upstream of the control pilot diode, D1).

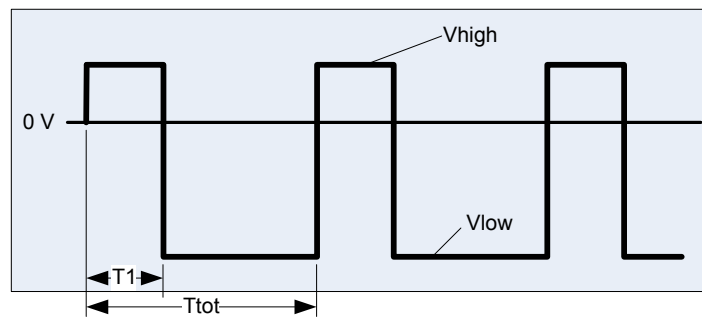


Figure 2-4
Pulse Width Modulation Signal Parameters

The PWM duty cycle provides state and ampacity information. If the duty cycle is 5%, this indicates that digital communications is needed to perform charging. For duty cycles from 10% to 85%, this indicates a circuit ampacity of 0.6 times the duty cycle amps are available to the

vehicle. For duty cycles from >85% to 95%, this indicates an ampacity of 0.25 times the duty cycle amps are available to the vehicle.

The Proximity Detection Function (Pin 5)

This pin is used by the PEV to detect the presence of a J1772 plug in the vehicle receptacle as shown in Figure 2-5. It can be used by the vehicle for a number of functions, the primary one being prevention of vehicle drive away while a plug is present. The resistive loading of this wire also allows the vehicle to sense the position of the pushbutton latch on the J1772 connector.

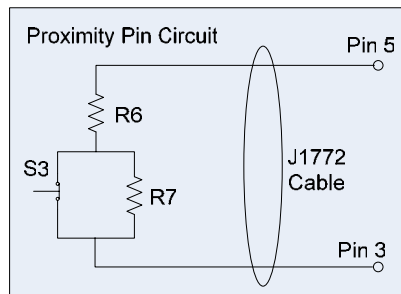


Figure 2-5
Schematic of Proximity Circuit (Plug Side of Circuit)

Compatibility Issues with J1772

It is expected that a broad range of companies will produce EVSE hardware and that a number of different automobile original equipment makers (OEMs) will produce plug-in electric vehicles. For this reason, the PEV to EVSE connection must function properly independent of these combinations in the field. Tolerances for parameters such as the Control Pilot load resistance values and the PWM frequency will require both the EVSE and PEV to be able to deal with values that might fall near the limits of the specified value boundaries.

Referring back to Figure 2-3, there are 4 variables that determine the voltage on the pilot wire at the J1772 plug: the value of R1, the characteristics of diode D, the parallel value of R2 and R3 and the actual 12V power supply voltage output provided by the Control Electronics in the EVSE. For each of these 4 variables there is a max and a min value. This gives a set of 16 possible combinations and permutations of the values. The value of resistance to the right of the diode in Figure 2-3 is used to determine one of three states: State B, State C, and State D. The states are defined as:

State	Pin 4 Nominal Voltage
B – Vehicle connected/not ready to accept energy	9.0V
C – Vehicle connected/ready to accept energy/ventilation not required	6.0V
D – Vehicle connected/ready to accept energy/ventilation required	3.0V

The worst case voltage and current values can be calculated for Pin 4 based on all of these parameters:

State	Pin 4 Voltage	Pin 4 Current
B	8.370 to 9.594 V	2.739 to 3.321 mA
C	5.474 to 6.531 V	5.444 to 6.599 mA
D	2.642 to 3.173 V	8.268 to 9.967 mA

These calculations are based on the EVSE and vehicle as a system and represent a worst case set of conditions. An EVSE's voltage sensing circuit for Pin 4 may use a digital to analog converter that is ratio metric with the 12V supply in the EVSE. This would act to remove the much of the effect of the possible 11.4 to 12.6 V rail difference when computing voltage extremes for the different states.

Since the EVSE is designed to detect ground fault currents in the ground circuit that are greater than 20mA, it is expected that the difference in voltage between the vehicle and EVSE ground reference points would be within millivolts.

For example:

Assume a ground current of 20mA and a ground return resistance of 0.1 ohms:

$$\Delta V_{\text{ground}} = 2\text{mV}$$

Thus the ground differential is ignored in the calculations used for the EVSE Compatibility document.

These calculations suggest that two tests should be conducted to ensure EVSE compatibility with multiple vehicles:

- 1) Apply a variable resistor in place of R2/R3 and use it to set the Pin 4 voltage to the tabulated extremes and verify proper behavior on the part of the EVSE for each given vehicle state.
 - a. This verifies that the voltage detection range within the EVSE can handle all anticipated values of Pin 4 voltage for the given states.
- 2) Measure the EVSE positive 12V rail value and the output resistance of the EVSE to verify that they are in range of the specified limits.
 - a. This verifies that the EVSE is within the requirements of J1772 for output impedance and output voltage.

Note that a reciprocal test could be defined for the PEV, where worst case values are assumed and the PEV must also properly detect the charge state and PWM duty cycle.

A final consideration for the EVSE/PEV connection is the effect of noise on the interface. One critical function that the PEV must perform is the measurement of the EVSE provided PWM signal to determine ampacity. With a shared ground connection between the signaling functions and the AC interface, it is possible that the control pilot wire will have external noise present which may make it difficult for the PEV to determine the duty cycle of the PWM signal. Since J1772 has no provision for time out limits for any of the defined states, if a PEV is unable to determine the duty cycle, then the interface can become “stuck” in state B, where the vehicle never asserts state C or D and the user receives no feedback as to the problem.

3

DESIGN AND IMPLEMENTATION OF THE SIMULATOR

The plug-in vehicle simulator is designed to be a portable instrument that enables easy evaluation of EVSE in the laboratory or field. Figure 3-1 shows a simple block diagram of the simulator. An embedded microprocessor is used to implement the J1772 interface requirements. The microprocessor provides for both control of the simulated state of the PEV and analysis of the PWM signal being provided by the EVSE. The internal wiring of the simulator provides for ease of connection of an external power quality (PQ) monitor by providing a permanently installed current transformer and a voltage tap. While not implemented in the first design iteration of the simulator, the design provides for future addition of a communications link to an external electronic load as shown in Figure 3-2. This would be used to implement a vehicle simulation where power loading of the EVSE would vary with time and could be programmed to simulate a particular vehicle's charging behavior.

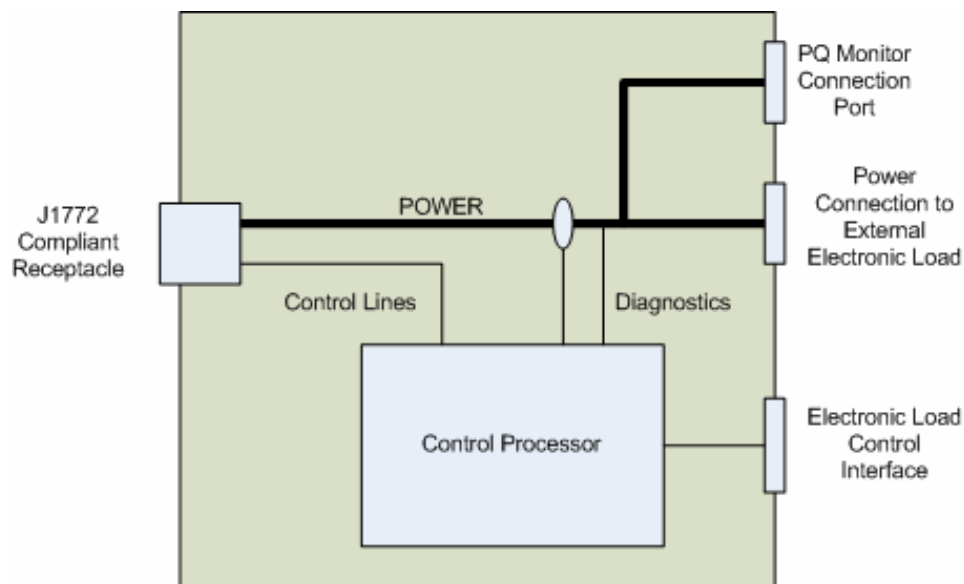


Figure 3-1
Block Diagram of the Simulator

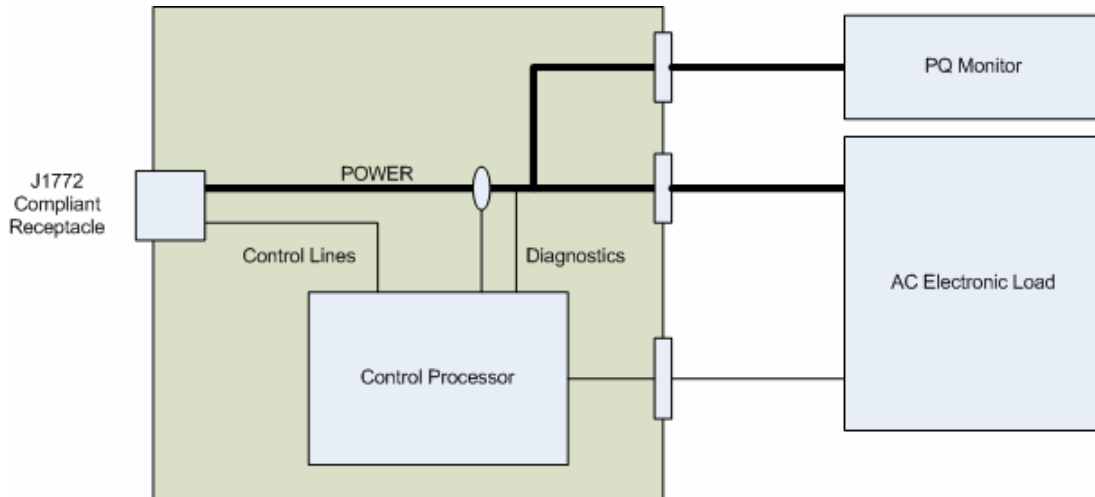


Figure 3-2
External Connections to the Simulator

Packaging

The plug-in vehicle simulator is designed to provide for portable operation. As such, it is packaged in a weather proof lidded enclosure resembling a small suitcase case. Figure 3-3 shows a front view of the simulator enclosure.



Figure 3-3
Photo of the Complete Simulator Unit

Electronics

The simulator electronics are mounted to the underside of the front cover of the suitcase style enclosure. An overall block diagram for the electronics is shown in Figure 3-4.

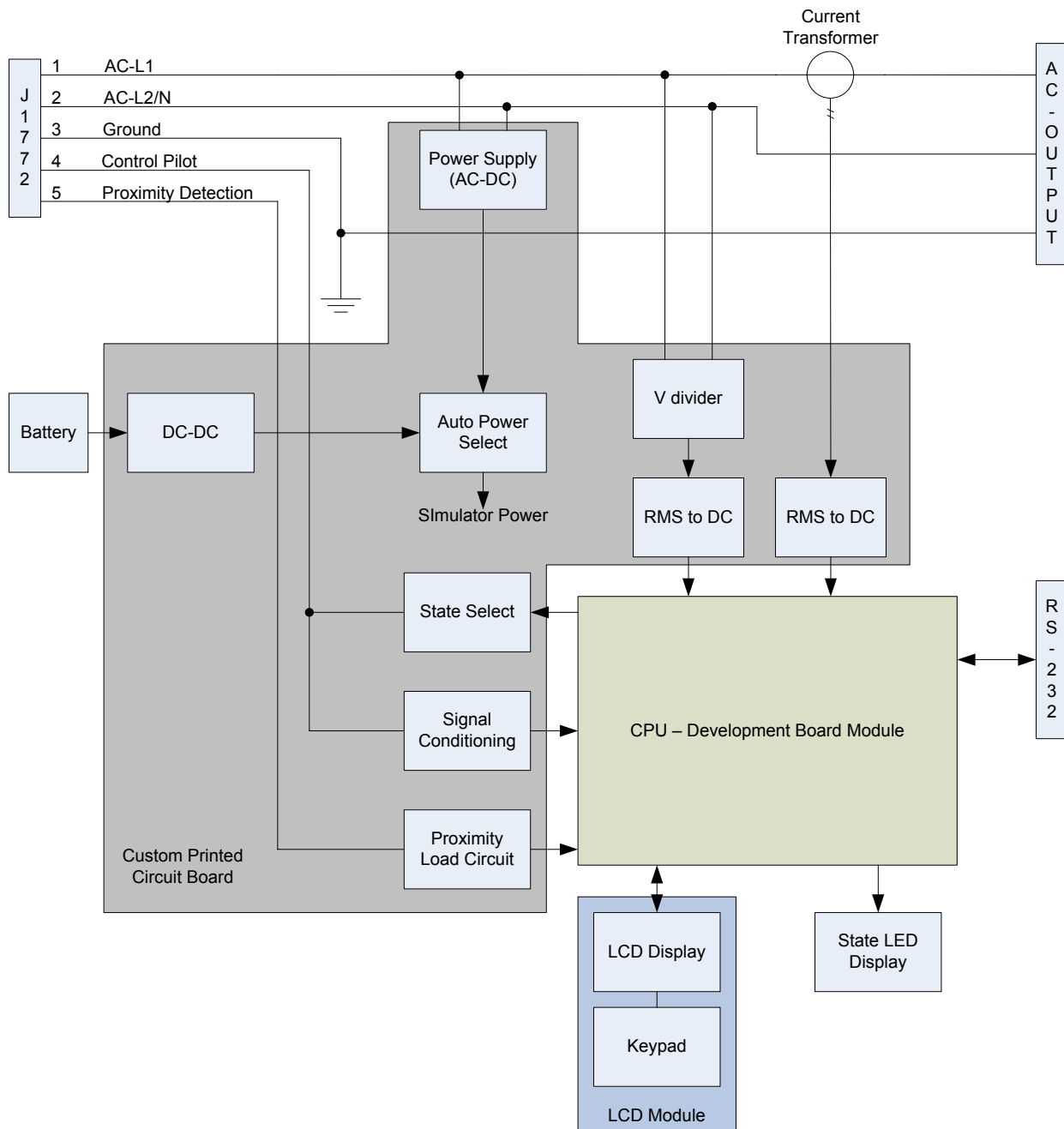


Figure 3-4
Simulator Block Diagram

Three modules make up the simulator active electronics. The main circuit card is a custom designed printed circuit board and houses the signal processing circuitry used to measure the operating parameters of the J1772 interface and to set the current state of the system. Two external modules are plugged into the main circuit board: The front-panel LCD display module and a microprocessor development board. The signals from the LCD module are directly routed through the custom printed circuit board directly to the CPU board which is reflected in the block diagram of Figure 3-4. Figure 3-5 shows a view of the rear of the main custom printed circuit board assembly.

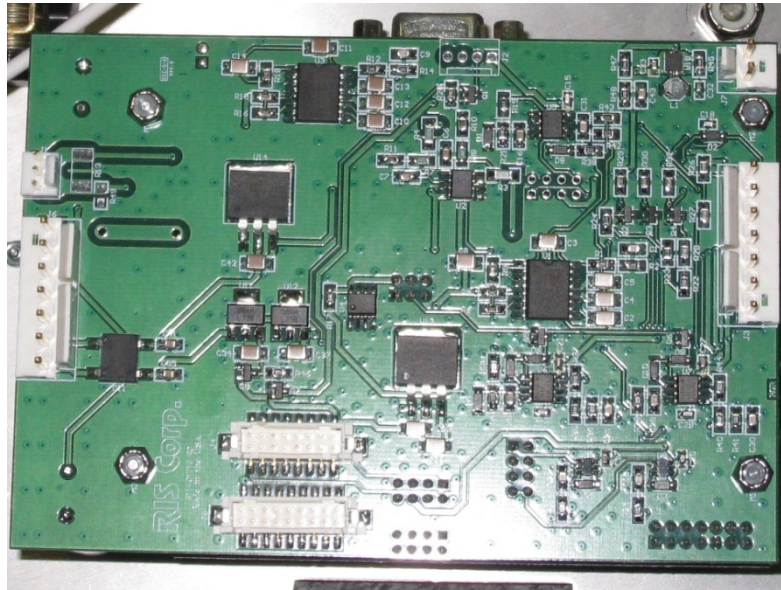


Figure 3-5
Rear View of the Main Custom Printed Circuit Board Assembly

The LCD assembly, shown in Figure 3-6, has an integrated keypad for user input and provides a 4 line by 40 character display.



Figure 3-6
The Simulator Display and Keypad Module

When the unit is not connected or the EVSE power is not available, power for the unit is provided from an on-board battery. When AC power is available, the Auto Power Select circuit switches to an AC to DC power supply that is contained in the simulator. This is done to extend battery life for field use.

The current transformer (CT) and voltage monitors are processed by separate RMS to DC conversion circuits, allowing a simple analog converter on the CPU board to process the current and voltage signals on the AC line. The state display LEDs are driven directly from the CPU.

The signal conditioning block on the control pilot filters and extracts the PWM signal timing for measurement by the CPU.

An RS-232 port is provided to enable control of an external programmable load. The firmware needed to implement this feature is not included on the prototype unit but is the hardware is provided for future expansion of the simulator's capabilities.

The proximity load circuit terminates the proximity detection wire. The proximity detection function is then monitored by the CPU.

Simulator Operation

The simulator is designed to be connected to an EVSE in place of a vehicle. The J1772 connector from the EVSE is plugged into a front panel receptacle on the simulator. A typical operation sequence would be:

- 1) The simulator is powered on.
- 2) EVSE J1772 connector is plugged into the simulator.
- 3) The simulator remains idle until commanded to assert State B (connected but not ready to charge).
- 4) The simulator displays the PWM parameters and voltage parameters measured on EVSE pilot
- 5) At user command, the simulator changes from State B to State C (ready to charge without ventilation) or State D (ready to charge with ventilation).
- 6) The simulator displays system parameters.
- 7) At user command the simulator changes from State C or D to State B

As stated previously, an external power quality monitor can also be attached to the simulator to allow monitoring of detailed performance of the EVSE. The unit is battery power when not connected to an active EVSE. An on-board circuit allows the simulator to take power from a connected EVSE to extend the unit's battery life.

User input to the simulator is via the front panel display and keypad shown in Figure 3-4. The display is a 4 line liquid crystal display with 40 characters available per line. A 6 button keypad located to the left of the display is provided for user input to the simulator. The arrow keys are used to navigate through the menu structure; the check key is used to enter data and the red X key is used to cancel a user input. There are four defined menus.

Menu 1, shown in Figure 3-7, displays information about the simulator, including the firmware version and battery voltage of the internal battery. Valid controls for Menu 1 are left and right arrows (change menu), and the X button. Pressing X will cycle the backlight through: all off; display on/keypad off; all on; all off.

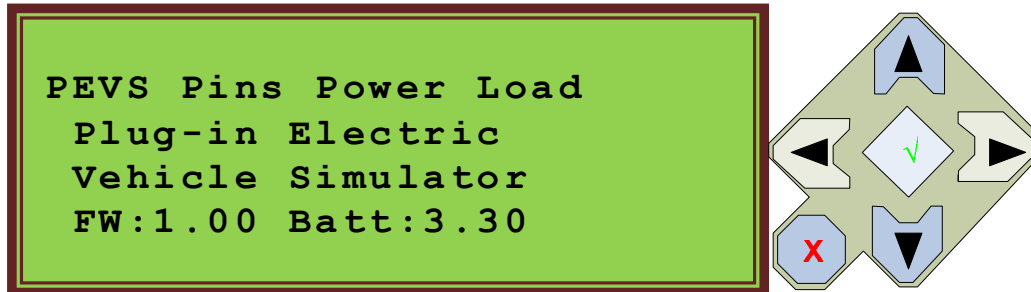


Figure 3-7
Menu 1- Simulator Information Display

Menu 2, shown in Figure 3-8, displays information about the Pilot and Proximity pins. The Frequency, Duty Cycle, High Voltage and Low Voltage of the Pilot pin is displayed. The State of the Proximity pin is displayed (Disconnected, Unlatched, Latched). Valid controls for this menu are left/right to change menus, and Up, Down, and the check mark button to change state. See Changing State after menu descriptions.

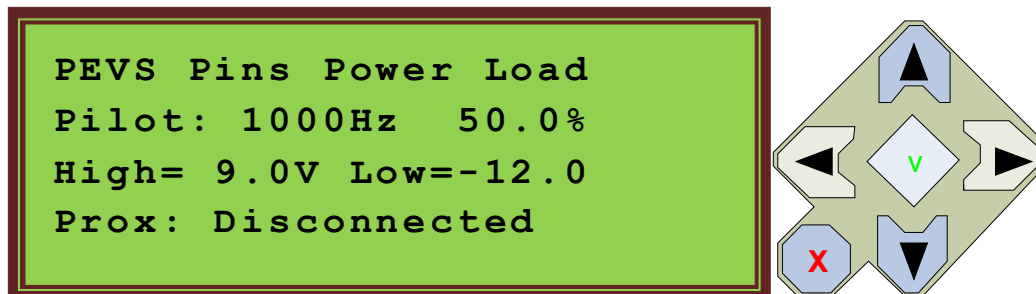


Figure 3-8
Menu 2 - Control Pin Information

Menu 3, shown in Figure 3-9, displays information about the line power coming from the EVSE. It shows the voltage of the EVSE, and the maximum current draw the EVSE allows (based on the duty cycle). Current Draw is the amount of current flowing through L1. Valid controls for this menu are left/right to change menus, and Up, Down, and the check mark button to change state. See Changing State after menu descriptions

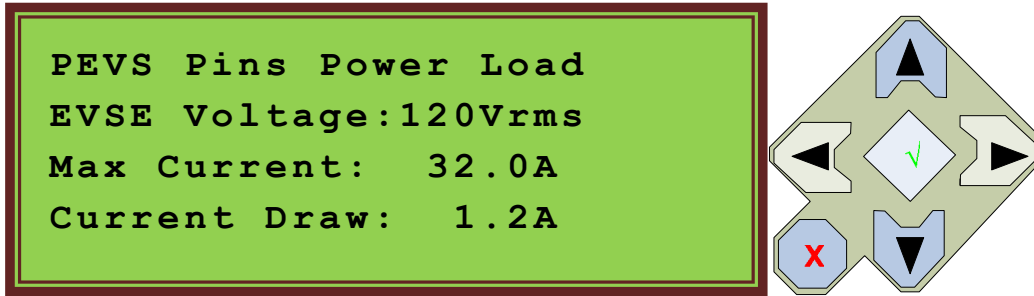


Figure 3-9
Menu 3 - Power Information

Menu 4, shown in Figure 3-10, controls the Electronic Load. This menu will have a more advanced control scheme once the load is fully designed. Currently, hitting X on this menu will toggle the internal relay. The relay starts Disconnected and will automatically Disconnect if the Proximity pin goes from Latched to Unlatched. Valid controls for this menu are left/right to change menus, and Up, Down, and the check mark button to change state. See Changing State after menu descriptions. The ability to change state in this menu may be removed in the future if the electronic load needs a more complicated control scheme.

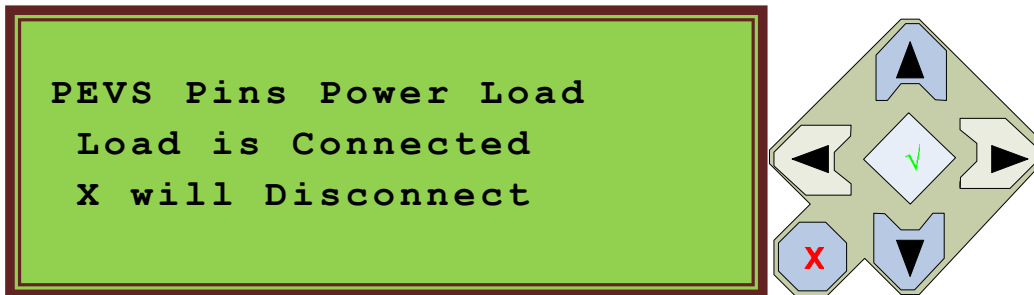


Figure 3-10
Menu 4 - Load Control

The load control feature is not fully implemented in this first prototype run of units and is considered a feature to be implemented in a second revision of the simulator.

The current state and state selection of the simulator/EVSE pairing is indicated on a set of LEDs located to the left of the main LCD display.

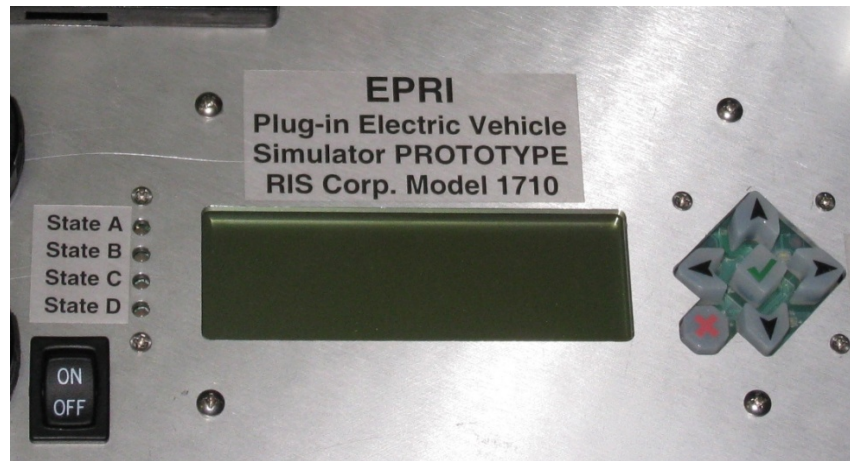


Figure 3-11
State Display at Left of LCD

The upper most LED is State A progressing down through State D. When the simulator is switched on, it comes up in State A. For a true PEV, transition from State A to State B would be automatic when the J1772 connector is attached to the vehicle. For the simulator this automatic transition from State A to State B is disabled allowing the user to measure information about the EVSE while the EVSE believes it is not connected.

The state LEDs are bi-color, with the current selected state being shown as a green LED. Pushing Up or Down arrows on the keypad will cycle between valid state transitions, highlighting the selected state by showing it as a red LED. After the desired state is selected, pushing the Checkmark button will switch the simulator to the newly selected state. Only valid state transitions, based on the J1772 document are allowed. In addition, the Proximity pin can force the simulator to transition to the appropriate state and control the relay as needed.

4

SUMMARY

The design and initial assembly of the simulator has been completed. The device is currently undergoing lab testing with emphasis on ensuring that the firmware is bug free during operation. The unit will provide for laboratory or field evaluation of EVSE, greatly simplifying the task of performing power quality monitoring of the equipment.

The current custom printed circuit board layout required some trace cutting and hand modification to make the unit functional. A second generation board layout is in process and will be used for an additional run of four prototype units.

The first set of prototype units will be fully tested and the lessons learned will be used to update the final simulator design.

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