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Safety Design for Smart Electric Vehicle Charging with Current and Multiplexing Control

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***Abstract*—As Electric Vehicles (EVs) increase, charging infrastructure becomes more important. When during the day there is a power shortage, the charging infrastructure should have the options to either shut off the power to the charging stations or to lower the power to the EVs in order to satisfy the needs of the grid. This paper proposes a design for a smart charging infrastructure capable of providing power to several EVs from one circuit by multiplexing power and providing charge control and safety systems to prevent electric shock. The safety design is implemented in different levels that include both the server and the smart charging stations. With this smart charging infrastructure, the shortage of energy in a local grid could be solved by our EV charging management system.**

I. Introduction

As EVs on the roads increase, charging stations in both parking structures and garages will become more important for longer distance commuters. For those long distance commuters, an available charging station may be a critical requirement to ensure the ability to finish the round trip and make it home. They will have to charge during peak hours that will stress the grid. In order to satisfy the demand of EV charging requests, an EV charging management system needs to be implemented to handle the peak time EV charging, regardless whether charging takes place in a parking garage or at home. Charging stations that service multiple vehicles simultaneously with a given infrastructure need to be implemented in order to meet the increasing demand for charging infrastructure. The station needs to share the plug point by safely plugging in multiple vehicles at once, it needs to share the circuit by rationing the available power in order to not overload the circuit, and it needs to share the grid capacity by intelligently scheduling charging in order to avoid peak consumption. A smart grid requires a safe and reliable infrastructure which controls the current to these EVs. This paper presents the safety design of a software-based EV monitoring, control, and management system, WINSmartEV™[1][2], which allows remote monitoring and variable current control of EV charging. This smart charging infrastructure is capable of providing power to several EVs from one circuit with multiplexing and variable current controlled charging. Since WINSmart EV is a software based control system that can take input data from any relevant source on the internet, it has the capability using complex algorithms that take into account external factors and predictive models in order to balance the requirements of EV charging and the demands of the grid. By using this smart charging infrastructure to manage EV charge scheduling and current flow, energy shortage in local grids can be prevented.

The prevention of electrical shock is of critical importance to any EV charging system. A software based EV charging system with multiplexing capabilities must have a unique safety system that integrates safety on all levels of control. Safety designs have been implemented inside some basic, unnetworked, commercial charging stations like Leviton[3] and ClipperCreek[4]. It is uncertain if the commercial charging stations with proprietary networks like Coulomb[5] and Blink[6], have an integrated safety design. In [7][8][9][10], several charging algorithms and results are presented. However, none of them address the unique safety requirements of a software based charging system with variable current and multiplexing control that is introduced in this paper. In section II of this paper, a brief description of the smart charging infrastructure, WINSmartEV™, is introduced, followed by the safety design for the smart charging infrastructure at each level.

II. System Architecture

The smart charging infrastructure, WINSmartEV™, is illustrated in Fig. 1.

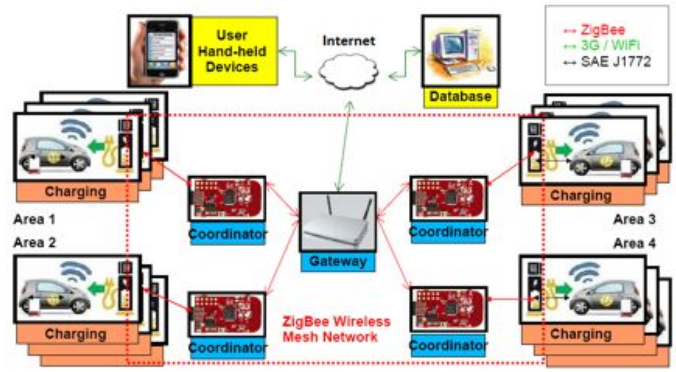

Figure 1. WINSmartEV™ Infrastructure

The Station Controller and Data Collector with the EV database sends commands to the charging station to control the charging while gathering and accumulating all the power information. The server sends the commands to the charging station through the multiple protocol gateways with 3G communication. 3G communication is required due to its flexibility and accessibility to be everywhere as long as the cellular signal exists, especially where wired or WiFi communication is unavailable. Based on user preference and the local power capacity, efficient control schemes will be executed by sending commands to the charging station through a multiple protocol gateway. Inside the charging box there are a gateway, 4 meters, 4 safety relays, and a control unit. The detail schematics of a four-channel metering system are shown in Fig. 2. Since the National Institute of Standards and Technology (NIST) has announced the first draft of the framework and roadmap to coordinate the interoperability and standards for the smart grid[11], in which ZigBee is specified for its low power and mesh network capabilities, ZigBee has been adopted in our system. Because a number of the control devices in each charge box can communicate using ZigBee mesh network capabilities, the charging boxes can communicate with each other. Therefore, only one gateway is required in each localized area to access the internet.

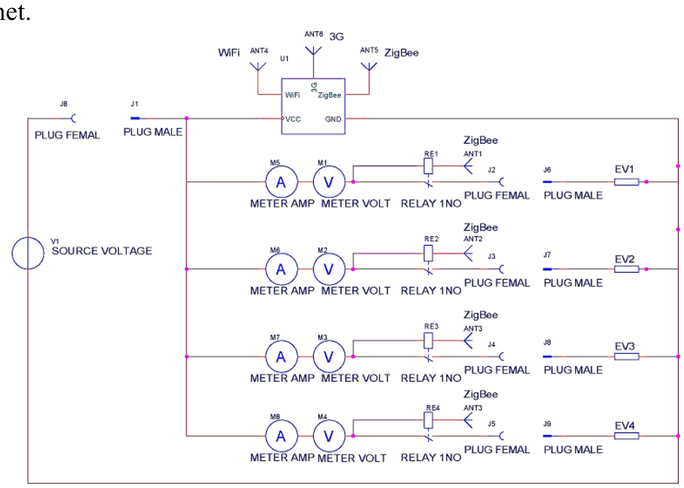

Figure 2. Schematics of metering system

The relays of each channel can be turned on/off by the web server, the control unit of the charging station, or the GFCI circuit of the charging station. Fig. 3 shows the realization of the four-channel smart charging box.

Figure 3. Realization of 4 channel smart charging box

To safely control EV charging, the safety design should be distributed to every level of the system, from the top level to the bottom level, including the web service and the control unit of the charging station. In case of emergency, the charging can be turned off at every level. The detailed safety design will be depicted in the following sections.

A. Safety design in Web based EV charging control system

There are four major software components in the web based EV charging control system including: Database, Station Controller and Data Collector, System Monitoring and Control Center, and User Control Center. When exceptional conditions occur, the station controller detects the abnormal status and automatically stops EVs from charging. For example, if the EV ignores the charging stations pilot signal and uses more power than the charging station allotted to it, the station controller can remotely stop the EV from charging. The system administrator can manually control the charging stations through the Monitoring and Control Center as shown in Fig. 4. The authorized user can stop charging via mobile device through the user control center as shown in Fig. 5.

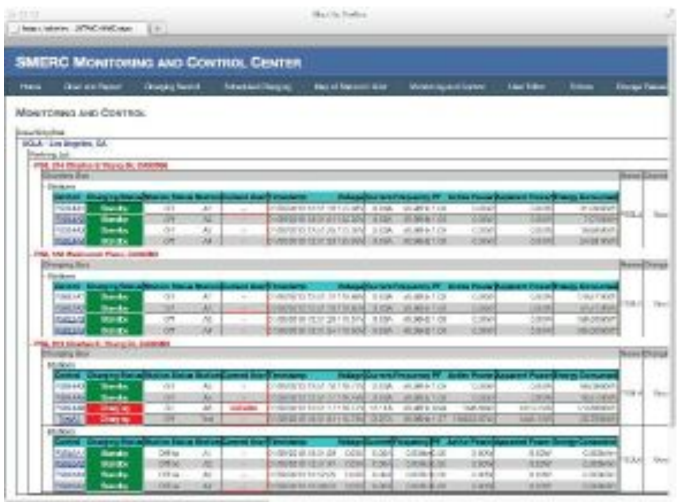

Figure 4. Screen shot of Monitoring and Control Center

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Figure 5. Screen shots of User Control Center: Map of stations

The server is capable of controlling the stations by sending out the command in the format: ***comd [command] [channel] [parameter*]**. The commands and returns are summarized in Table 1.

TABLE I

COMMANDS OF THE CHARGING STATION

Command	Description and Example
atrs	Auto-reset the whole system, including gateway, meters, relays, and control unit
	comdatrs0000 [return]: N/A
rely	Turn on/off the relay manually
	Ex1: comdrely0101 [describe]: turn on relay at channel 1 [return]: duty0150rely0101plug0101stat0100 Ex2: comdrely0100 [describe]: turn off relay at channel 1 [return]: duty0150rely0100plug0101stat0100
stat	Request charging station's channel status
	Ex1: comdstat0100 [describe]: request channel 1 status [return]: duty0150rely0101plug0101stat0100

The administrator can turn the relays on or off and check the on/off status of each channel by sending out the "stat" and "rely" commands. The command "rely0101" signifies that the channel 1 relay is on, while "rely0100" signifies it is off. Meanwhile, as long as the connection between the server and the charging station exists, the charging station can be reset manually or automatically on a schedule by having the administrator send out the "atrs" command.

Because of the lag in relevant forms of communication, including 3G, WiFi, ZigBee, and Cloud, any emergency action taken at the top level will have a delay time of $T_{Delay\_TopLevel}$ that depends on the conditions of the wireless communication. Therefore, a fast acting local unit should be implemented to stop charging in case of emergency. This local control unit will be described in section B.

B. Safety Design in the Charging Station's Control Unit

A control unit located within each charging station controls it. The control unit carries out commands from the server and transmits information back to the server. The schematic of the peripheral circuit in Fig. 6 is proposed to make pilot signals with variable duty cycles.

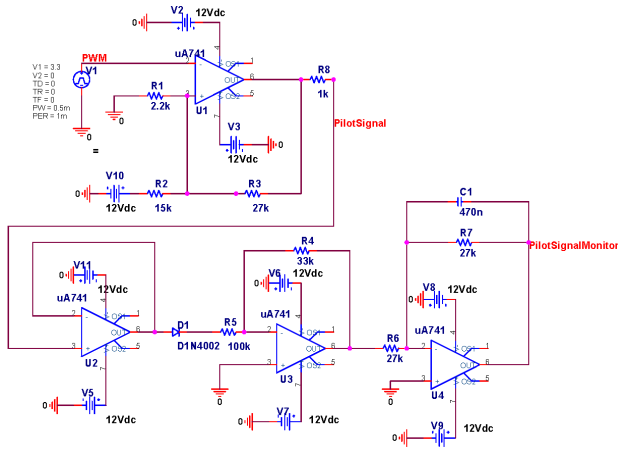

Figure 6. Peripheral circuit of Pilot Signal Monitor

The Pulse Width Modulation (PWM) signal produced by the pilot signal generator is amplified from 3.3V/GND to +/-12V by the Schmitt trigger and fed to the EV. After the Schmitt trigger is the unit gain buffer. The unit gain buffer separates the circuits so that the pilot signal monitor can observe the pilot signal without adding load effect to it. Note that a Schottky diode is inserted after the unit gain buffer because only the positive part of the signal will be monitored. To shrink the pilot signal to the A/D conversion range, an inverting amplifier with 1/3 gain is used. The peak value detection method is not utilized because it tends to be affected by unexpected spikes which make the measurement unreliable. Instead, an inverting active low pass filter (LPF) is used to average out the pilot signal so that a DC voltage can be measured by the pilot signal monitor. The realization of the control unit of the smart charging station is shown in Fig. 7.

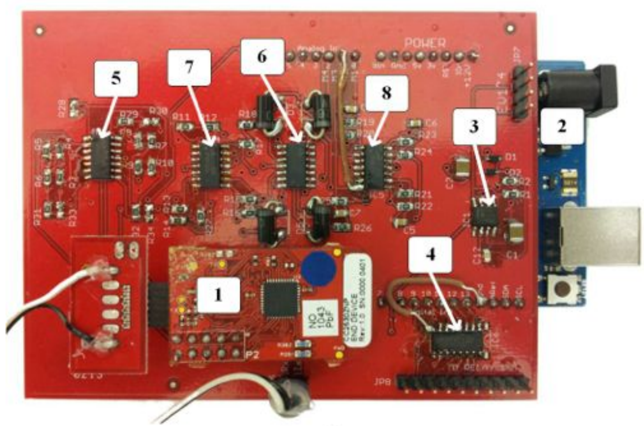

Figure 7. Realization of the control unit: (1)Pilot Signal Generator (2)Pilot Signal Monitor (3)555 counter. (4)Relay Driver. (5)Schmitt Trigger. (6)Unit Gain Buffer. (7)Inverting Amplifier. (8)Inverting LPF.

According to the J1772 standard[12], the control unit should handle the pilot signal and Ground Fault Circuit Interrupter (GFCI) as shown in Fig. 8. Therefore, to meet the requirement, the schematic for a safety control for the relay is proposed in Fig. 9.

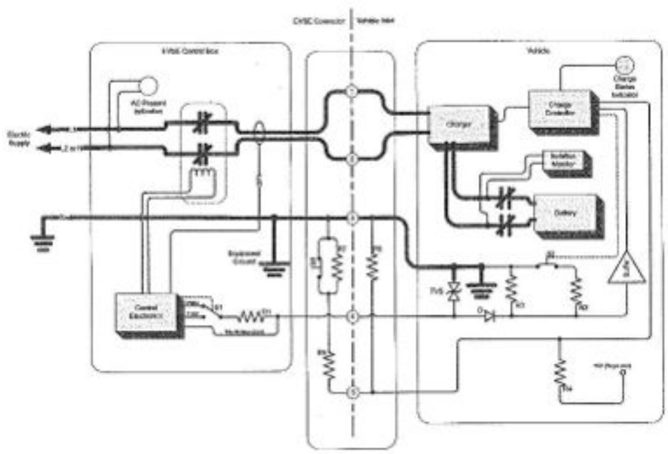

Figure 8. AC Level 2 system configuration[12]

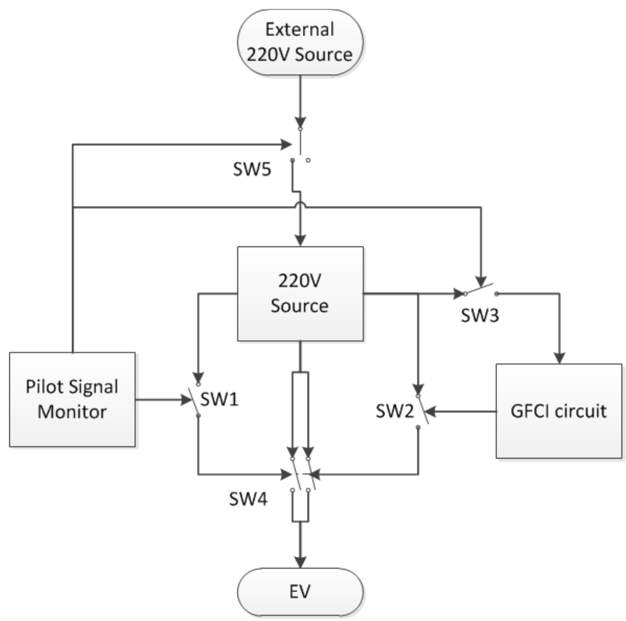

Figure 9. Schematic of Safety Control for the Relay

The pilot signal monitor controls one leg the safety relay's (SW4) coil power directly, while GFCI controls the other leg. When no EV is detected or the user unplugs the EV, one leg of the coil power of SW4 will be shut off by the Pilot Signal Monitor, shutting off power to the EV. The GFCI can be reset by the Pilot Signal Monitor with SW3. The system can be reset by SW5 when the Pilot Signal Monitor receives the "atrs" command from the server as described in Table 1.

1) Detection of EV Plug-in Status

In order to prevent electrical hazards, there should be no voltage on the handle until it is connected to an EV. According to J1772 specification[12], the EV plug-in status is detected with the pilot signal generated in the charging station. When there is no EV connected to the charging station, the voltage of the pilot signal pin on the handle should be DC +12V. After the user plugs in the EV, the voltage of the pilot signal pin should be +9V or +6V, depending on whether or not the EV is ready to accept the energy. The charging station will start to generate the pilot signal with a duty cycle that indicates the allotted power of the charging station. When the EV is full charged, the positive part of the pilot signal will be from +6V to +9V. When the user unplug the EV, the positive part of the pilot signal will be from +6V to +12V. According to these characteristics, the EV plug-in status detection is executed in the state machine of EV charging procedure in the firmware flow. The Timer Flag is set to 1 in the timer interrupt loop. After the detection of EV plug-in status process is finished, the Timer Flag will be set to be 0. Currently, the timer interrupt interval is set to 1 second in the firmware, which means the detection process is handled every 1 second. Note that the detection process time needs to be less than the interval of the timer interrupt so that the detection process can be handled correctly. Fig. 10 shows the firmware flow of the pilot signal monitor.

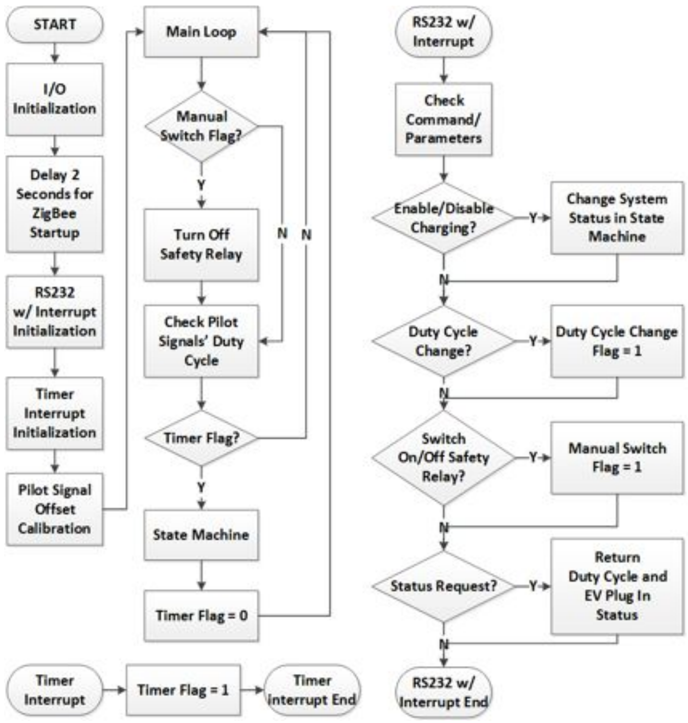

Figure 10. Firmware Flow of Pilot Signal Monitor

2) Ground Fault Circuit Interrupter (GFCI)

When there is an abnormal diversion of current from one of the hot wires, the charging station is required to shut off the power immediately to prevent the hazard of electric shock. The GFCI circuit fulfills this duty by detecting the difference of current between two hot wires and shutting off the safety relay, SW4 in Fig. 9, when the difference has crossed threshold amperage. In [13], a GFCI is proposed with a microprocessor. To reduce the bill of material cost and increase the reliability, a pure hardware GFCI with remote reset function is proposed in Fig. 11.

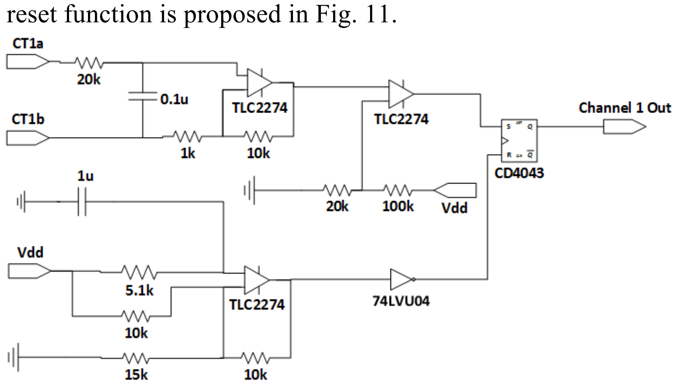

Figure 11. Proposed GFCI circuit

This model features six major components: current transformer (CT), low-pass filter (LPF), non-inverting amplifier, voltage comparator, S-R latch, and Schmitt delay trigger circuit. The current transformer takes the difference between two hot wires and outputs a corresponding voltage. The LPF filters out undesired noise from the mechanical relay. The non-inverting amplifier magnifies the signal from the CT. The voltage comparator functions as an A/D converter that converts the amplifier's sinusoidal signal into a digital signal. The S-R latch starts off with an initial LOW state, and then once a HIGH input signal is received, the latch switches to a HIGH state and maintains it until the GFCI circuit is reset. The Schmitt delay circuit is needed to generate a short pulse signal provided to the S-R latch's reset pin so that every time the GFCI resets, the S-R latch returns to the initial state (LOW). Unlike the traditional GFCI which requires a manual press of the reset button, this GFCI simply needs a reset on its power source. Fig. 12 shows the realization of the GFCI circuit.

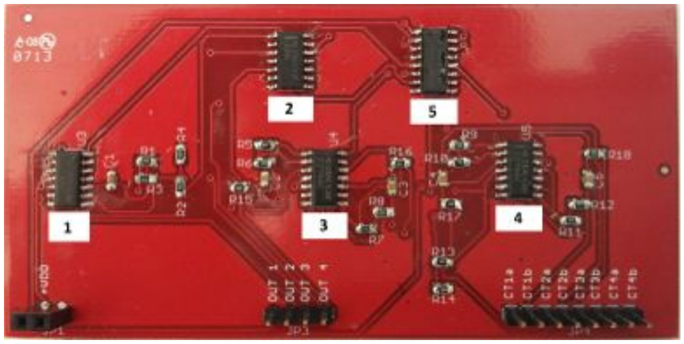

Figure 12. Realization of 4-channel GFCI circuit: (1)Schmitt Delay Trigger (2)Invertor (3)Voltage Comparator. (4)Non-inverting Amplifier. (5)SR Latch.

III. EXPERIMENTS AND RESULTS

The experiments on the detection of EV plug-in status and the test of GFCI are performed and verified in the following sections.

1) EV plug-in status detection

In this experiment, the A/D values at the pilot signal monitor are measured with different duty cycles under two cases: EV charging and EV disconnected. The test-bed is a Nissan Leaf with 110V charging cable. Fig. 13 shows the setup of the experiment and Fig. 14 shows the results of the experiment.

Figure 13. Setup of experiment of changing current by duty cycle

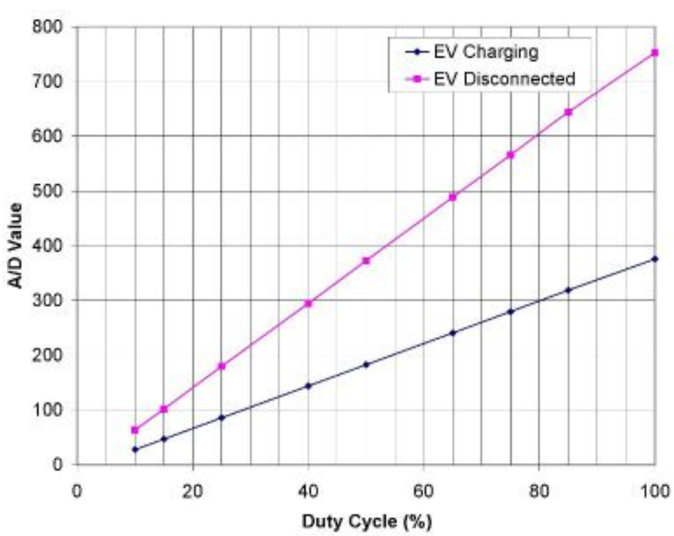

Figure 14. A/D Value v.s. Duty Cycle of Pilot Signal

The results show that the A/D values of these two cases are clearly distinguishable and have good linearity. Even when the duty cycle is around 10%, which is 6A, (the minimum charging current of the J1772 specification), the pilot signal monitor's resolution is still more than sufficient to detect the EV's plug-in status. The threshold value for EV plug-in status detection is set to be the average of these two cases.

2) Test of GFCI

The trigger level and delay of the GFCI circuit are measured in this experiment with the schematics in Fig. 15. and setup in Fig. 16.

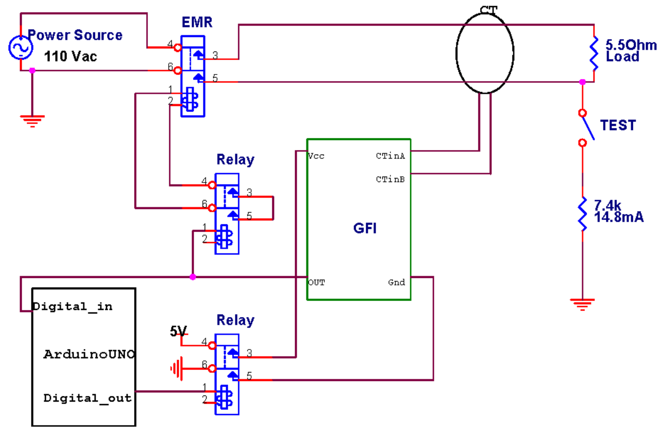

Figure 15. Schematics of GFCI test

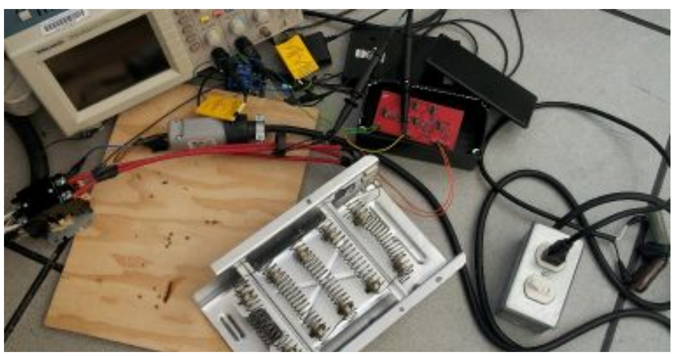

Figure 16. Setup of experiment on GFCI circuit

In order to see the trigger level and delay time, in stead of flipping the TEST switch, which will cause a larger signal to trigger the circuit, the experiment procedure is as follows: (1) TEST switch ON; (2) GFCI is ON; (3) Relay, SW2 in Fig. 9, is ON. Fig. 17 shows the result of the experiment.

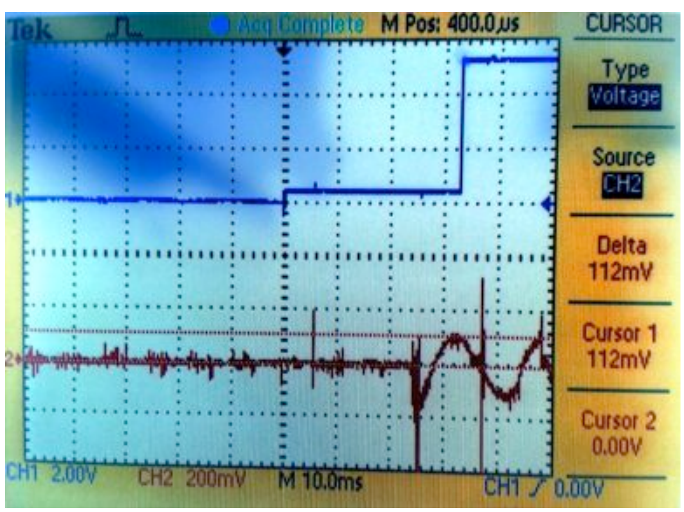

Figure 17. Result of GFCI test

Channel 1 (Blue) is the GFCI trigger signal, and channel 2 (Red) is the output of Current Transformer (CT). The result shows that the SW2 in Fig. 9 has approximately 25ms delay after GFCI is ON. When there is 14mA difference between the hot wires (which is 110mV here according to the specification of CT), the GFCI triggers on the positive cycle. The results also show that the GFCI circuits has approximately 1ms delay. The GFCI needs to be enclosed in a grounded metal surface box in order to negate the magnetic disturbance from the electro-magnetic relay. The GFCI only works for positive cycle of the AC. If an abnormal diversion of current from a hot wire happens on the negative cycle, the GFCI trigger will be delayed by 8.33ms. The GFCI was tested at least 300 times on each of four channels with no failure. These tests were done with 21A load current, channel by channel.

IV. CONCLUSION

WINSmart EV not only provides a safe, energy efficient, economical, and user friendly smart technology for charging EVs, but also enhances the stability and reliability of the local power system by managing EV charging while taking into account all available and relevant information including user requirements and the demands of the electrical grid. With algorithms for intelligently scheduling EV charging implemented in the control server, this proposed EV charging infrastructure could serve as an important component in the nationwide smart grid. This paper presents a design for the safety system for WINSmart EV, where safety is implemented on all levels of control.

V. ACKNOWLEDGEMENT

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