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Potential Use of Field Programmable Gate Array (FPGA) for Electric Vehicle's Battery Swapping Station (BSS): A Simulation Approach

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Abstract. With the increasing adoption of Electric Vehicles (EVs) in recent years, there is a growing demand for efficient charging solutions. In addition to conventional charging stations, Battery Swapping Station (BSS) has emerged as an alternative solution for recharging EV batteries. Despite having several advantages over conventional charging stations, the development of BSS faces obstacles, including capital investment and operational challenges. The main objective of this paper is to explore the potential application of Field Programmable Gate Array (FPGA) as a centralized control and monitoring unit in BSS. The study uses a simulation approach, and the result demonstrates that FPGA has the potential to be used in BSS. Its parallel processing capabilities can potentially reduce the development cost of BSS and address operational challenges, such as charging scheduling and battery management system.

Keywords: Battery Swapping Station; Battery Management System; Controlled Charging; Field Programmable Gate Array

1. Introduction

By the end of 2022, over a total of ten million units of Electric Vehicles (EVs) were sold, and this number was expected to increase by approximately 40% to fourteen million units sold by the end of 2023 (International Energy Agency, 2023). The amount of EVs sold shows that the adoption of EVs has become increasingly popular in recent years. As the number of EV users continues to grow, the demand for publicly accessible and efficient charging systems is proportionally rising. Despite the increased deployment of EV charging stations to meet the demand, it still struggles to efficiently handle some critical aspects that pose obstacles to the wider adoption of EV technology. One of the most notable disadvantages of EV charging stations, compared to conventional vehicle fuel stations, is the time-consuming battery charging process that can cause inconvenience for the users and may discourage individuals from transitioning to EV. To address the problem of conventional charging stations, Battery Swapping Stations (BSSs) have emerged as a promising alternative for higher operational efficiency.

Unlike conventional charging stations where to replenish the EV's battery, the driver needs to drive the vehicle to the charging post, then plug the charging outlet's connector into the vehicle's charging inlet, and wait until the battery finally can be used, at the BSS the recharge process is carried out by directly swapping their EV's discharged battery with a fully charged battery. This type of station offers advantages over conventional EV charging

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stations, such as being less time-consuming since it only takes a few minutes to swap the vehicle battery, and more flexible, as it does not require the physical presence of the EV during the swapping ('charging') process (Horak et al., 2024). The BSS model also introduces various potential commercial applications, such as 'battery renting' that enables drivers to rent another fully charged battery to extend the driving range of the EV or simply servers as a backup battery, and 'battery trading' so that driver can choose and trade specific sized battery based on their driving needs. However, there are two main concerns in developing the BSS infrastructure. The first concern revolves around capital investment that includes development cost, labor, and maintenance (International Energy Agency, 2023), and the second is the operational-related challenges such as battery life management and charging schedule optimization (Gueller et al., 2023).

Given the challenges of the BSS infrastructure development, the potential solution proposed in this paper is to use a centralized charging control and monitoring system to address both the capital investment and operational challenges. The method used in this work to implement the proposed centralized system is by utilizing Field Programmable Gate Arrays (FPGA). FPGA is pre-fabricated Integrated Circuits (ICs) containing arrays of configurable logic blocks and interconnects that can be electrically configured to serve as various digital circuits and systems (Maxfield, 2004). FPGA offers advantages such as reconfigurability, flexibility, the ability to implement complex algorithms, and high-speed parallel processing. FPGA has a promising potential to serve as an efficient centralized control and monitoring unit for the BSS infrastructure due to its parallel processing capacity. With a single FPGA device controlling several batteries' charging processes and monitoring their states, the centralized system may lower the cost of developing and maintaining the BSS infrastructure. The second BSS concern is simultaneously addressed by the proposed solution. The system can implement different controlled charging methods to extend the battery life and control when the charging process of the battery should begin. In this work, we study the potential application of FPGA through several simulation approaches. Specifically, we model the charging process from a single battery to several batteries simultaneously using a controlled charging method and then integrate the model into the FPGA device itself.

2. System Model and Code Development

2.1. Proposed Centralized System Model

Figure 1 illustrates the block diagram of the Battery Swapping Station (BSS) structure and the proposed centralized system. Among the parts of the BSS structure, this study focused on the BSS system, mainly its charging and battery management system. The primary objective of the proposed system is to centralize the entire battery charging and monitoring process by employing a single FPGA device as the core unit responsible for controlling and monitoring the charging process of all batteries. The battery undergoing charging is connected to a different charging circuit, enhancing the system's flexibility by enabling it to accommodate the charging process for various batteries with diverse configurations and charging characteristics. The FPGA will control individual charging circuits independently to ensure that the corresponding battery is charged with the proper charging characteristic. Furthermore, each battery undergoing the charging process is connected to a voltage sensor. The purpose of this sensor is not only to provide feedback for the charging process but also to enable the user (in this context, the BSS officer) to actively monitor the ongoing battery charging process and take immediate action if anomalies arise during the charging process to ensure the safety and reliability of the overall charging process.

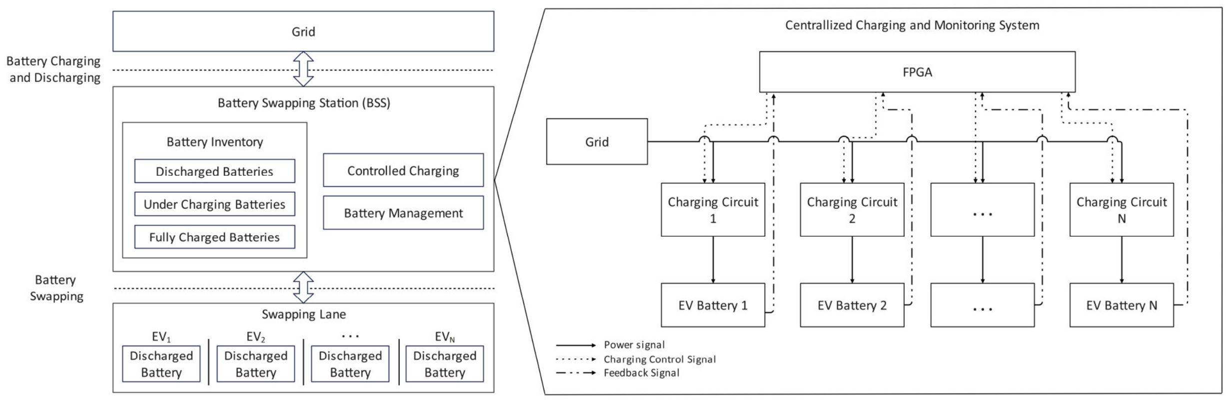

Figure 1 Topology of Battery Swapping Station (left) structure and the proposed centralized system (right)

2.2. Parallel Charging and Monitoring using Structural Modeling

To implement the centralized control and monitoring system, in this study, we will use VHSIC Hardware Description Language (VHDL) programming language for the code development. This hardware description language is chosen not only for its verbosity, which enhances the clarity and readability of the developed code but also for its support of structural modeling styles. This modeling approach allows the low-level functionalities to be treated as modular components that can easily reused within hierarchically higher and more complex digital systems (Bryan and Tappero, 2016). Structural modeling makes the development process faster since we only need to create the code for functions that are used multiple times once, rather than coding for each instance of use. Given that the proposed centralized system used similar algorithms for parallel control and charging process, therefore in this study we only need to design and develop the control and charging algorithm module once, after which the module can be concurrently used in the hierarchically top entity. The hierarchical design structure of the proposed system is depicted in Figure 2. In addition to the control and charging algorithm, we also developed several sub-modules. One of these sub-modules is a 'current mode' sub-module that utilizes a Linear Feedback Shift Register (LFSR) to generate random current increase values ranging from 4 to 6 over time. Another sub-module developed is 'page navigation' sub-module, a sub-module to change the parameter values displayed in the FPGA for monitoring purposes.

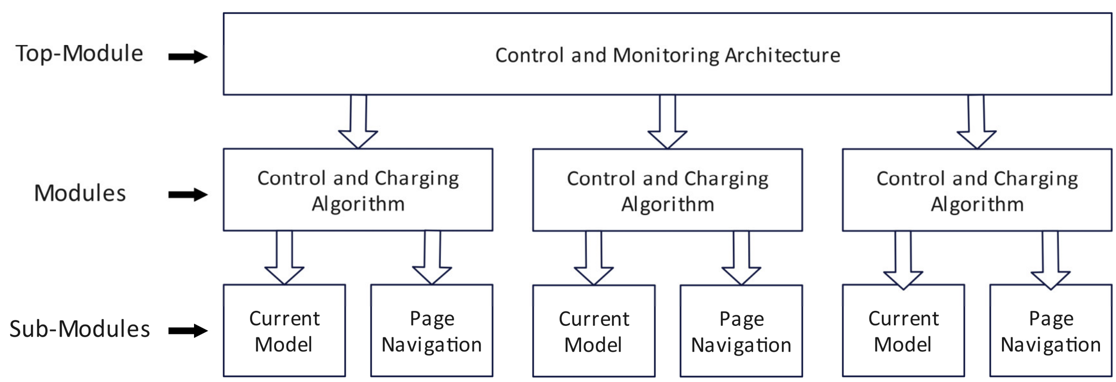

Figure 2 Hierarchical design of the centralized system

2.3. Control and Charging Algorithm Design

For control purposes, we created several input ports, namely *Start, Set_Thres, Type_Thres,* and *Inc_Dec.* The functions of all available input ports are detailed in Table 1. These input ports play an important role in modifying the charging configuration of the corresponding battery. The initial configuration state utilizes a default threshold value, which can be adjusted by manipulating the input ports. In this study, the user can modify two charging parameters which include charging voltage and charging current threshold. The parameter adjustment can be performed by either increasing or decreasing the corresponding values to meet specific charging requirements. To integrate this functionality into the proposed system, we designed a Finite State Machine (FSM) state diagram, as shown in Figure 3. The FSM consists of five states, including one default state and four other states that represent the modification states of charging parameters. Table 2 provides a detailed explanation of all the states and symbols used in the FSM. The input bits in the FSM represent all available input ports in the system, starting with the *Start* as the Most Significant Bit (MSB) to *Inc_Dec* as the Least Significant Bit (LSB).

Table 2 List of symbols representation used in the FSM of the system's charging setting

Input Port	Purpose
Start	Start or stop the charging process
Set_Thres	Enable the modification of threshold parameters
Type_Thres	Select the parameters to be modified, '0' for voltage and '1' for current
Inc_Dec	Select modification mode, '0' to increase parameter and '1' to decrease parameter

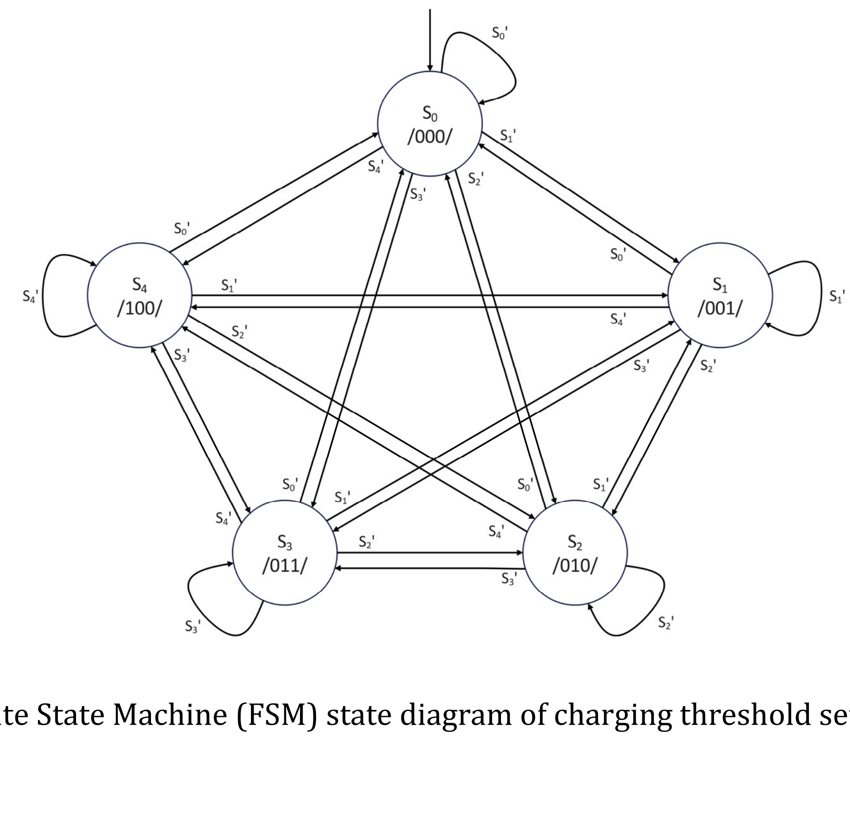

Figure 3 Finite State Machine (FSM) state diagram of charging threshold setting states

Table 2 List of symbols representation used in the FSM of the system's charging setting

Symbol	State or Definition of Symbol
S_0	Default Threshold State
S_1	Increase Voltage Threshold
S_2	Decrease Voltage Threshold
S_3	Increase Current Threshold
S_4	Decrease Current Threshold
S_0'	Transition to S_0 (00XX/000)
S_1'	Transition to S_1 (0100/010)
S_2'	Transition of S_2 (0101/010)
S_3'	Transition to S_3 (0110/011)
S_4'	Transition to S_4 (0111/011)

To address concerns related to battery life management in BSS, this study implements a controlled charging method. The objective of the implementation is to demonstrate the capability of the proposed system in implementing such a method to extend the battery life. The controlled charging method employed in this study is the traditional Constant Current Constant Voltage (CCCV) method. The motivation behind the choice is even though the method is simple, it comprises distinct charging states. These states can be used to assess the capability of the proposed system in handling parallel charging with different states for each battery ongoing the charging process. The FSM state diagram designed for the CCCV algorithm is presented in Figure 4. The designed CCCV algorithm charging consisted of four primary states including bulk charging (Constant Current), absorption charging (Constant Voltage), float charging (CCCV with low current and voltage), and 'completed state.' Given the need to maintain constant values in each state, the state alternately increases and reduces the current value. Consequently, in the designed FSM, the first three charging states are further divided into two sub-states each, resulting in a total of six states. The transitions between states depend on various charging parameters as shown in Table 3.

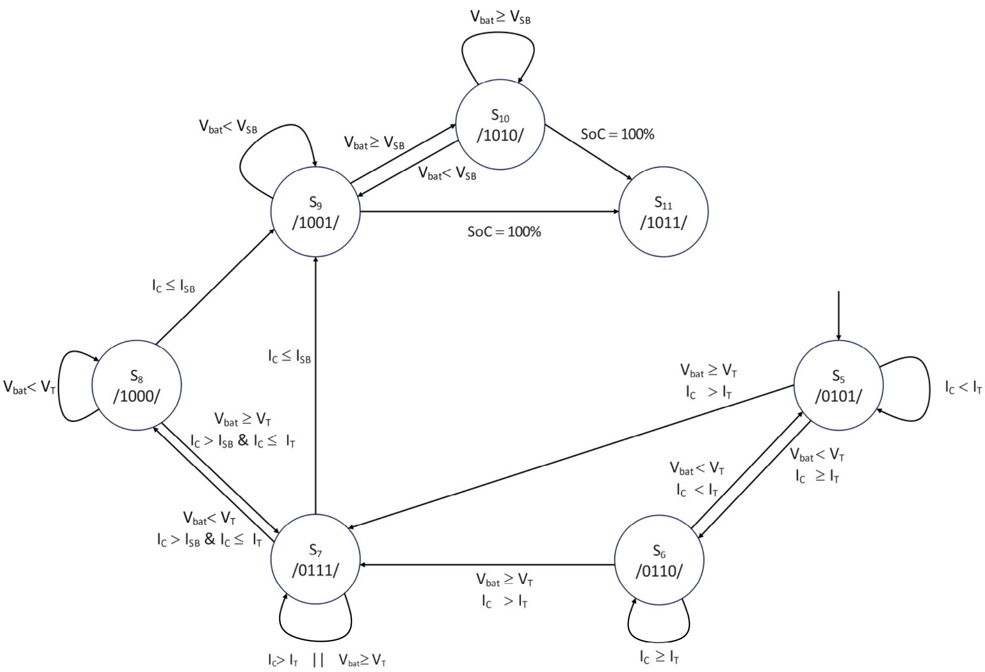

Figure 4 FSM state diagram of CCCV charging as controlled charging method in the proposed system

Table 3 List of symbols representation used in the FSM of CCCV charging

Symbol	State or Definition of Symbol	Process
S_5	Initial Charging State, Bulk Stage/Constant Current (CC)	Increase current
S_6	Bulk Stage/CC	Reduce current
S_7	Absorption Stage/Constant Voltage (CV)	Reduce current
S_8	Absorption Stage/CV	Increase current
S_9	Float Stage	Increase current
S_{10}	Float Stage	Reduce current
S_{11}	Completed Charging State	Stop charging process
V_{bat}	Battery Voltage/Charging Voltage	-
V_T	Charging Voltage Threshold	-
V_{SB}	Standby Voltage	-
I_C	Charging Current	-
I_T	Charging Current Threshold	-
I_{SB}	Standby Current	-
SoC	State of Charge of Battery	-

In addition to monitoring charging parameters such as voltage, current, and charging state, we add battery State of Charge (SoC), a more user-friendly parameter. This parameter enhances the comprehensiveness of battery energy level monitoring and serves as a trigger to stop the charging process once the battery reaches full capacity. This optimization prevents overcharging and can ensure an efficient charging process. The SoC of a battery is estimated using the following equation:

$$SoC_t = \begin{cases} \dfrac{V_{bat} \times 8000}{V_T} & \text{for bulk stage,} \\ SoC_{t-1} + \dfrac{(I_{hold} - I_C) \times 1500}{I_{hold} - I_{SB}} & \text{for absorption stage,} \\ SoC_{t-1} + \dfrac{(V_{hold} - V_{bat}) \times 500}{V_{hold} - V_{SB}} & \text{for float stage} \end{cases} \tag{1}$$

In (Equation 1) we derive the SoC value estimation based on the battery's charging states. In the above equation, we assumed that the battery reaches an SoC of 80% when transitioning from bulk charging to absorption charging. Additionally, during the absorption and float stages, the battery is assumed to be charged for the remaining 15% and 5%, respectively. The accuracy of the SoC estimation is not the primary focus of this preliminary study since the main objective is to demonstrate the potential of FPGA parallel processing for BSS battery life management. Therefore, for this purpose, a simple SoC estimation method is sufficient.

3. Simulation Results and Implementation to FPGA

3.1. Single Battery Charging Simulation

The simulation of the proposed system started with the simulation of the control and charging process of a single battery using Modelsim software. The main objective of this simulation is to verify the functionality of the developed intermediate-level module for control and charging processes. The simulation results are presented in Figure 5. In this testbench simulation, we modify the charging threshold of the battery, changing it from initial values of 14600 mV for voltage and 1500 mA for current to new values of 14100 mV and 2000 mA for both voltage and current thresholds, respectively. Subsequently, we initiate the charging process by changing the state of the *Start* switch. Based on the result of the initial simulation, it is safe to assume that the developed control and charging module performs properly and can be integrated into the top-level centralized control and monitoring system.

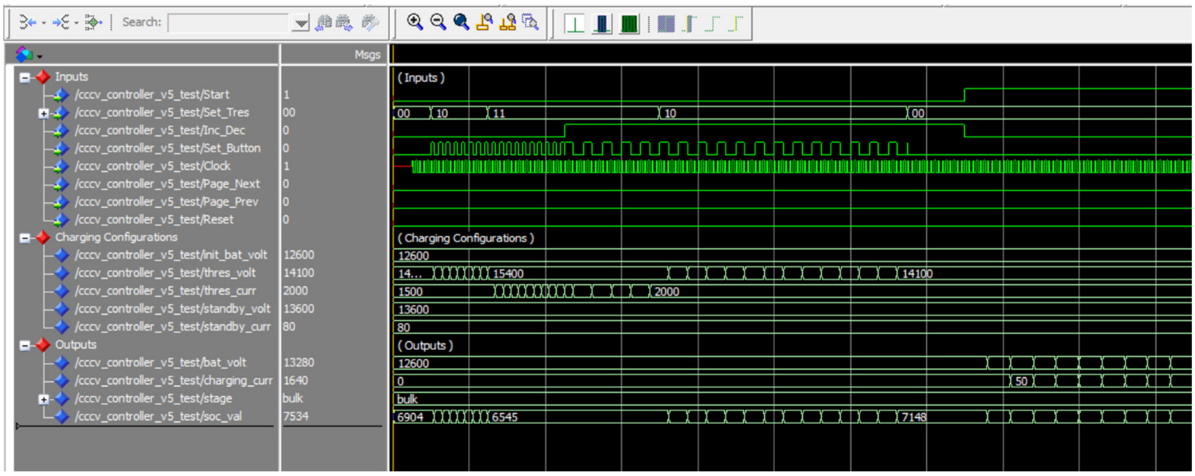

Figure 5 The Simulation results of single battery charging using the control and charging module

3.2. *Parallel Charging* and Monitoring *Simulation*

The subsequent simulation involves the simulation of the proposed centralized system. The main objective of this simulation is to demonstrate the system's ability to concurrently control distinct charging processes, calculate each battery's SoC, and present all relevant charging parameters to the user. In the testbench simulation, we emulate the charging processes of six batteries, each with a distinct initial voltage. The result of this simulation is presented in Figure 6.

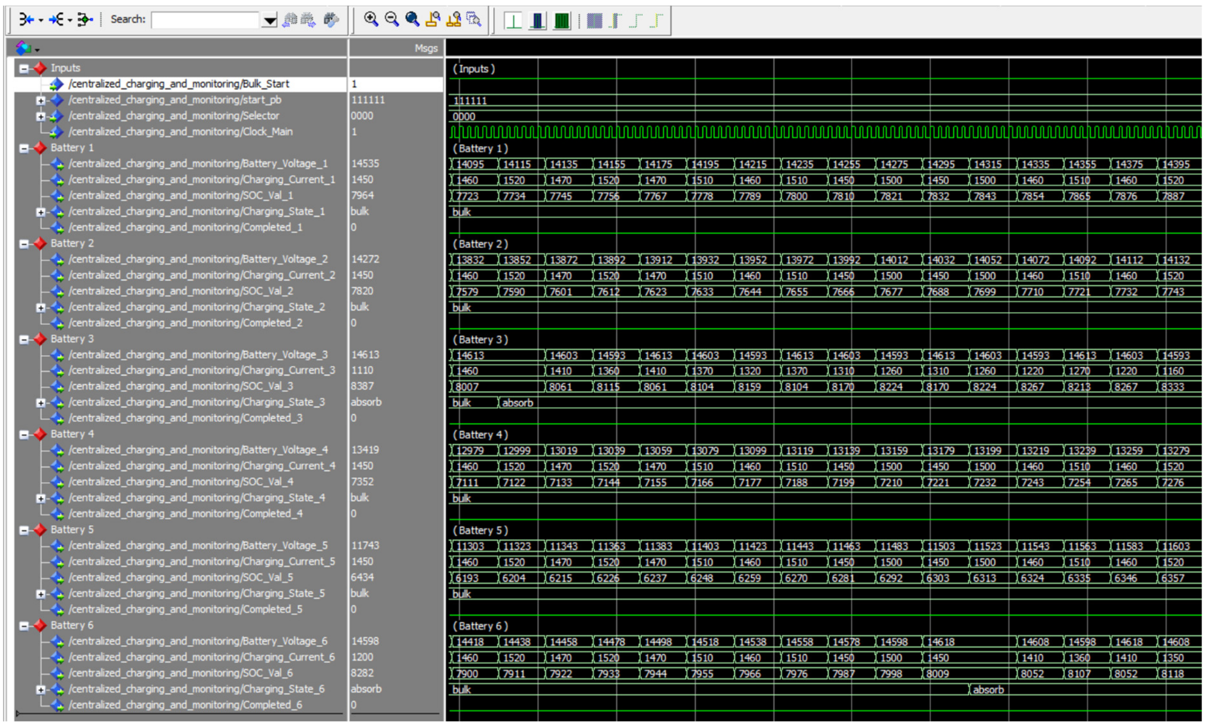

Figure 6 The simulation results of charging six batteries simultaneously using the proposed centralized system

By observing the result of the simulation, we can infer that batteries with varying initial voltages undergo different charging stages. However, despite the differences in the charging process, the proposed centralized system is able to manage all the charging processes without problems. This capability shows the system's potential to serve as a centralized control and monitoring system for BSS battery management.

3.3. Implementation of the System to FPGA

The final step in this preliminary study is the implementing of the developed system onto the FPGA. This step aims to validate the functionality of the proposed system's code within the FPGA hardware. The implementation onto the FPGA involves compilation and several hardware configurations, which will be carried out using Intel Quartus Prime Software. The Terasic DE-10 Standard FPGA is utilized as the hardware for this step. The validation process will be done by doing fundamental control, including the adjustment of battery charging configurations and the initiation of the charging process from the start until the model battery reaches its full capacity. Another important aspect of this process is to ensure that the FPGA can accurately display the charging parameters that change over time. Figure 7 shows the input and outputs configuration implemented in the FPGA.

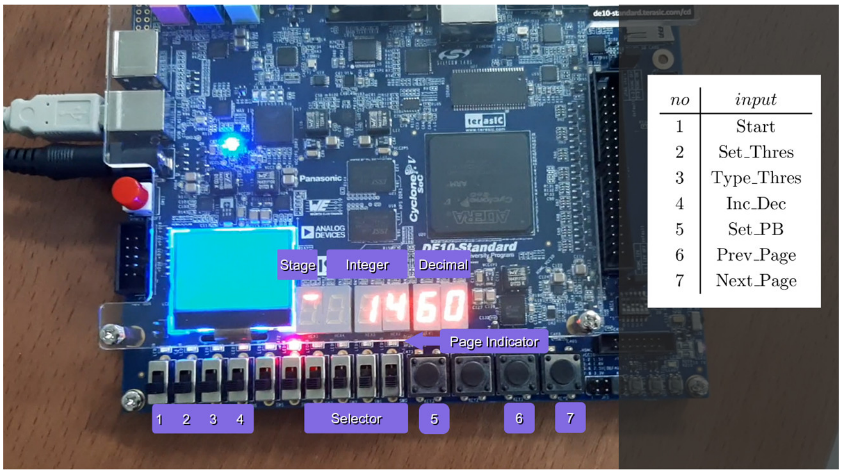

Figure 7 Pin configuration of the implemented system in Terasic DE-10 Standard FPGA

The complete CCCV charging process includes bulk charging, absorption charging, and float charging implemented in FPGA is presented in Figure 8. The implementation results suggest that the developed system is capable of executing the entire charging process properly. Hence, based on the validation, we can confirm that it is feasible to use FPGA as the centralized control and monitoring unit for the BSS by utilizing its parallel processing capabilities.

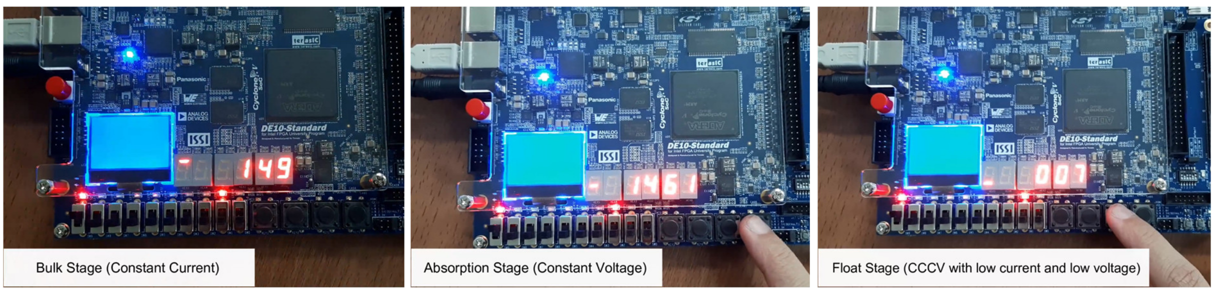

Figure 8 CCCV charging process carried out by the implemented system in the FPGA

4. Conclusions

In this study, a centralized control and monitoring system for BSS was developed and implemented by utilizing various advantages of FPGA, such as structural modeling and parallel processing. VHDL has been used in this paper to implement the developed algorithm on the FPGA. The simulation of the developed system demonstrates that the proposed system capable of carried out all the charging processes both for single battery and parallel battery charging. The study shows that the FPGA has a great potential to be used in the BSS as the control and monitoring unit.

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