

EMPIRICAL VERIFICATION OF REAL-TIME CHARGING RESPONSES FOLLOWING LONGTERM SCHEDULING FOR ELECTRIC TWO-WHEELER CHARGING STATIONS

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| ARTICLE INFO | ABSTRACT |
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| Received: 01/11/2023 | In Vietnam, the potential of electric two-wheelers in urban traffic necessitates the need for charging infrastructure as well as charging solutions for this means of transportation. Studies show that the optimal charging scheduling algorithms for electric two-wheeler charging stations often output charging schedules for each vehicle over multiple timesteps. To realize the charging schedule, research on charging and discharging responses following optimal charging commands at timesteps should be implemented. This study aims to empirically verify the real-time responses following long-term optimal charging schedules in experimental conditions. Through empirical testing, this research complements and affirms the practical feasibility aspect of long-term optimal charging schedules for electric two-wheeler charging stations in Vietnam. The processes involved in developing the testing workbench of the charging station and measuring the charging/discharging responses are also discussed in the study. The research results realize that electric two-wheeler charging stations can feasibly meet long-term optimal charging schedules in real-world conditions. |
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| KEYWORDS | |
| Charging stations | |
| Electric two-wheelers | |
| Testing workbench | |
| Charging algorithms | |
| Empirical research | |

KIỂM CHỨNG THỰC NGHIỆM ĐÁP ỨNG SẠC THỜI GIAN THỰC THEO KẾ HOẠCH SẠC DÀI HẠN CHO TRẠM SẠC XE ĐIỆN HAI BÁNH

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Trường Đại học Điện lực

| THÔNG TIN BÀI BÁO | TÓM TẮT |
|-----------------------------------|--|
| Ngày nhận bài: 01/11/2023 | Tại Việt Nam, tiềm năng của xe điện hai bánh trong giao thông đô thị dẫn đến nhu cầu về hạ tầng sạc cũng như giải pháp sạc cho loại phương tiện này. Các nghiên cứu cho thấy giải thuật lập kế hoạch sạc tối ưu cho trạm sạc xe điện hai bánh thường đưa ra kế hoạch sạc cho từng phương tiện tại nhiều bước thời gian. Nhằm hiện thực hóa kế hoạch sạc, các nghiên cứu về đáp ứng sạc/xả theo các lệnh sạc tối ưu tại các bước thời gian cần được thực hiện. Nghiên cứu này nhằm kiểm chứng đáp ứng thời gian thực theo kế hoạch sạc tối ưu dài hạn trong điều kiện thực nghiệm. Bằng phương pháp thực nghiệm, nghiên cứu này bổ sung và củng cố về mặt thực tiễn tính khả thi của kế hoạch sạc dài hạn đối với trạm sạc xe điện hai bánh tại Việt Nam. Các quy trình phát triển mô hình trạm sạc thực nghiệm, đo lường đáp ứng sạc/xả cũng được đề cập cụ thể trong nghiên cứu. Kết quả nghiên cứu cho thấy trạm sạc xe điện hai bánh hoàn toàn có thể đáp ứng kế hoạch sạc tối ưu dài hạn trong điều kiện thực. |
| Ngày hoàn thiện: 22/3/2024 | |
| Ngày đăng: 22/3/2024 | |
| TỪ KHÓA | |
| Trạm sạc xe điện | |
| Xe điện hai bánh | |
| Mô hình thực nghiệm | |
| Giải thuật sạc | |
| Nghiên cứu thực nghiệm | |

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1. Introduction

In Vietnam, the promotion of electric mobility is one of the immediate tasks aiming at sustainable development in both transport and energy sectors [1]. In addition, with high potential of renewable energy sources (RESs), energy transition promotion, proactive and effective RESs exploitation can be considered as key factors to realize the Vietnam's commitments made at the 2021 United Nations Climate Change Conference (COP26).

Studies show that the combination of electric vehicles (EVs) and RESs, especially solar power, contributes to promoting the development of both fields and, at the same time, mitigating adverse impacts of high penetration of distributed sources (such as rooftop photovoltaic (PV) systems) and charging load on the existing distribution grid [2], [3]. Smart grid development, on the one hand, further enhances the flexibility in grid operating, power dispatching, load balancing etc. and, on the other hand, contributes to the development of electricity market with numerous participants.

In the Vietnamese context, recent research such as [4], [5], elucidated the potential of EVs, particularly electric two-wheelers (E2Ws), in urban traffic. To be specific, from 0.9 million E2Ws in circulation by 2017, the number of E2Ws grew to five million units by 2019. Annually, the growth rate of the E2W market is up to 30-40 %. The continuing growth of these emerging vehicles has been projected to result in an accelerated burden on the distribution grid, which propels research on charging infrastructure and charging solutions in the context of Vietnam.

With modest battery capacity and charging power compared to electric cars, E2Ws charging might utilize portable chargers plugging in standard socket outlets. These chargers are designed to optimally supply electricity to E2Ws without caring about the electricity price, impacts on grid as well as on other loads.

However, in locations like offices, supermarket, campuses, apartment buildings, transport terminals or public parking, a high number of E2Ws charging simultaneously would introduce an extremely high load demand which might impact on the grid, power quality and other components. In such cases, it is required dedicated charging stations which could coordinate charging loads, decide charging patterns based on vehicle owners' settings, technical constraints and/or economic/technical objectives.

Currently, there are very few studies on E2Ws charging stations. In [6], the authors developed a PV-powered electric bicycle charging station. The station had a built-in energy storage device and allowed both grid-connected and standalone operation. Research [7] introduced a charging station powered by grid, fuel cell and PV to unburden the grid from charging while the work [2] aimed at sustainable charging solutions and evaluating the feasibility of PV-integrated charging stations in Vietnam. Charging algorithms for E2Ws aiming at load leveling were mentioned in [8], [9] in which the algorithm outputted long-term charging schedule in the form of charging power over timeslots of 15 or 30 minutes.

However, the works [8], [9] didn't investigate the real-time charging responses following the optimal long-term charging patterns. Thus, in this study, a testing workbench is developed to verify the feasibility of long-term charging algorithm in real-world conditions.

The contributions of this work include:

- 1) Developing a test bench for electric two-wheeler charging stations.
- 2) Empirical testing implementation of real-time charging/discharging responses.
- 3) Verifying the feasibility of optimal long-term charging algorithm in practical conditions.

2. Testing workbench development

2.1. The technical scope of the test bench

The investigated specifications in [5] indicated that the majority of electric bicycles in Vietnam use batteries with a voltage of 36-48 V and a capacity of 12 Ah. E-bikes adopt motor

power below 250 W and have a design speed not exceeding 25 km/h (according to QCVN 75:2019/BGTVT, QCVN 68:2013/BGTVT). E-bikes can travel a maximum distance of approximately 50-60 km. On the other hand, electric motorcycles use larger batteries (48-60 V; 20 Ah) with higher motor power (800-1200 W), enabling them to travel a maximum distance of around 70-80 km.

Generally, most chargers for E2Ws work with single-phase AC power from the residential grid. The charging power of these chargers is typically around 400 W, and the charging time ranges from 3 to 5 hours. On the other hand, the discharge power can be up to 1200 W.

Since the test bench is designed to investigate the real-time charging/discharging responses, in the experimental model, the range of charging/discharging power is from 0 W to 400 W, and the chosen batteries are 12.8 V, 30 Ah. The battery type is LiFePO₄. It has a continuous discharge current of up to 30 A (maximum continuous discharging power of 380 W), instantaneous discharge current up to 100 A, and maximum charging current of 10 A. It's also worth noting that to optimize the lifetime of cells, the battery pack is integrated with an active voltage balancing circuit.

For Lithium battery charging, the most popular method is the Constant Current-Constant Voltage (CCCV) because of its simplicity and easy implementation [10], [11]. Research [12] shows that more than 80% of the battery capacity is filled during CC stage. However, about 50% of the total charging time is taken during CV stage [12], [13]. To address the long charging time of CCCV method, solutions (such as multistage constant current (MCC) method; pulse charging; boost charging; variable current profiles) manage to regulate the charging current in the CC phase. Higher current levels are usually chosen for the earlier CC stages.

It is obvious that the charging rate increases with charging power. The control of charging rate or charging power is primarily performed during the CC stage. Therefore, in the test bench, tests are conducted to observe different charging responses within the CC stage.

2.2. Test bench design and operation

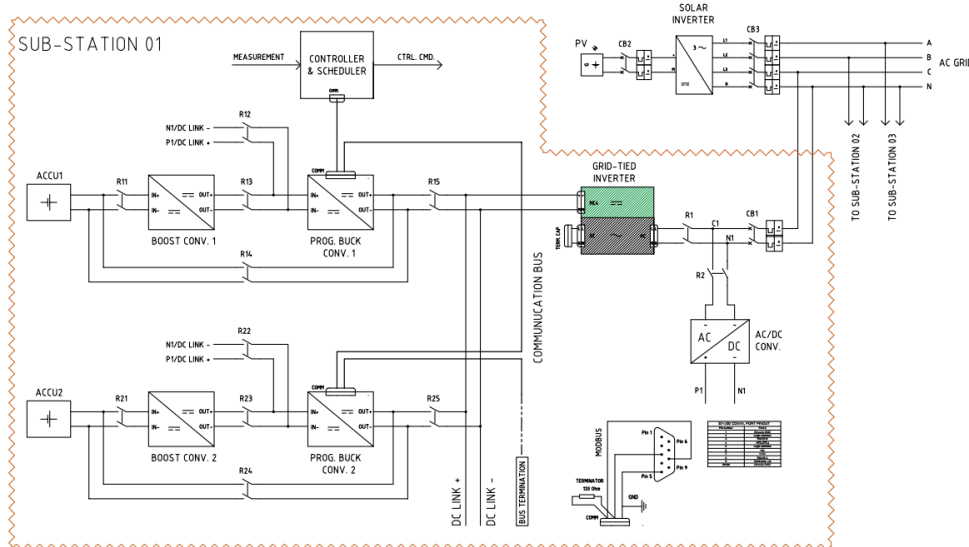


Figure 1. Testing workbench design

Figure 1 illustrates the design of the test bench. It employs separate buck/boost converters and utilizes two inverters: a grid-tie solar inverter, and a single-phase grid-tie inverter converting DC link voltage into AC voltage.

In case of battery discharging, because the input voltage of the inverter must be greater than a minimum value specified by the inverter's specifications, the test bench should have proper buck/boost converters to convert the battery voltage to the suitable input voltage level of the

inverter. When charging, these converters are responsible for converting the DC voltage (from the DC link or AC/DC converter) to the appropriate level for the battery.

For a small-scale E2W charging station, because of modest permitted charging power and battery capacity, a single-phase grid-tie inverter is a suitable option. However, in the case of larger scale, it is possible to add multiple sub-stations being connected to different phases. By this way, the charging station can be easily expanded in terms of power and scale. However, the addition of new sub-stations to the three-phase grid should consider phase load balancing and cooperation between sub-controllers.

In the experimental setup, because of the small-scale pilot prototype and available equipment limitations, the single-phase grid-tie inverter is unidirectional. Thus, an AC/DC converter is adopted to convert AC electricity from the grid for DC charging. Besides, an additional path of charging can be realized from the DC link as in Figure 1. If charging is executed from the DC link, the total charging power must be lower than the total discharging power of the remaining batteries. Besides, in the case of using bidirectional grid-tie inverters, the employment of AD/DC converter is not necessary.

To charge Battery 1, the grid voltage is converted into DC voltage through the AC/DC converter. It then goes through R12 and a programmable buck converter to regulate the voltage and current before passing through R14 to Battery 1.

To discharge Battery 1, DC voltage from Battery 1 goes through R11 and then it is boosted by a boost converter. Boosted DC voltage runs through R13 and the programmable buck converter which is responsible for creating the appropriate voltage level for the inverter. The inverter converts the DC voltage to the AC.

The charging station can be expanded by adding additional buck/boost converters connected to the DC link. If only one single-phase inverter is used, the maximum number of E2Ws in the station depends on the power rating of the inverter. However, it is possible to increase the number and/or rating of inverters if expansion is needed.

The station utilizes a centralized controller to deliver charging and discharging commands. These commands are sent to relay switches and programmable buck converters through a communication network.

In the test bench, Modbus RTU communication standard is leveraged because of its high reliability and low cost. Additionally, Modbus RTU is a simple communication protocol, easy to implement, and supports relatively long communication distances. Each master can manage multiple slaves. With up to 255 slaves, the chosen protocol meets the requirements of the test bench.

2.3. Test bench set up

Table 1. Battery pack specifications

| No. | Item | Value |
|-----|-----------------------------------|-------------------------|
| 1 | Cell type | LifePO4 |
| 2 | Battery nominal capacity | 30 Ah |
| 3 | Voltage | 12.8 V |
| 4 | Continuous discharging current | 30 A |
| 5 | Instantaneous discharging current | 100 A |
| 6 | Maximum charging current | 10 A |
| 7 | Fully charged voltage | 14.6 V |
| 8 | Cut-off discharge voltage | 10 V |
| 9 | Short-circuit protection | Yes |
| 10 | Overtemperature protection | Yes (65 ⁰ C) |
| 11 | Cell voltage balancing | Yes, active balancing |



The selection of equipment for the test bench is carefully considered based on the available market equipment and datasheets. Additionally, the chosen devices need to be compatible with the specified ranges of current, voltage, and power, as described in Section 2.1.

The selected battery type is LiFePO₄ with battery pack specifications as in Table 1.

In the test bench, a single-phase micro inverter is adopted with specifications as in Table 2.

Table 2. Micro grid-tie inverter specifications

| Input data (DC)/Output data (AC) | | Other specs | |
|-------------------------------------|---------------|-------------------------|-------------|
| Input voltage range | 16÷60 V | Peak efficiency | 96.7 % |
| Maximum input current | 11.5 A | Nominal frequency/range | 50/45÷55 Hz |
| Rated output power | 600 W | Power factor | >0.99 |
| Nominal output voltage/range | 230/180÷275 V | Operating temperature | -40÷85 (°C) |
| Rated output current | 2.61 A | | |



Boost converters are employed to step up the battery voltage to suitable voltage levels. A programmable buck converter which can be controlled and communicated with the controller via the Modbus RTU, is used to regulate the voltage supplied to the DC link (when battery discharges) and to control the charging current and voltage (when battery charges). The specifications of Boost/Buck converters are as in Table 3.

Table 3. Boost/Buck converters specifications

| Boost converter | | Buck converter | |
|------------------------------|----------|--------------------|----------|
| Input voltage | 10÷60 V | Input voltage | 20÷110 V |
| Maximum input current | 20 A | Output voltage | 0÷96 V |
| Output voltage | 12÷84 V | Output current | 0÷20 A |
| Idle current | 15 mA | Output power | 0÷1920 W |
| Maximum output power | 1200 W | Voltage resolution | 10 mV |
| Operating temperature | -40÷85°C | Current resolution | 10 mA |
| Efficiency | 92÷97 % | Output ripple | <50 mVpp |
| | | Efficiency | 92 % |



In the test bench, a controller is utilized for sending charging/discharging commands to batteries via Modbus RTU communication protocol.

Because charging schedule can be interpreted into charging power at specific timeslots [8], [9], the controller must store these power values as charging currents and charging voltages in the controller's memory as in Figure 2.

```
// Scheduling Table for Batt 1
// Timeslot 1
VW110 1460 // 14.6 V
VW112 1000 // 1.000 A
// Timeslot 2
VW114 1460 // 14.6 V
VW116 2000 // 2.000 A
// Timeslot ...
```

Figure 2. Scheduling commands

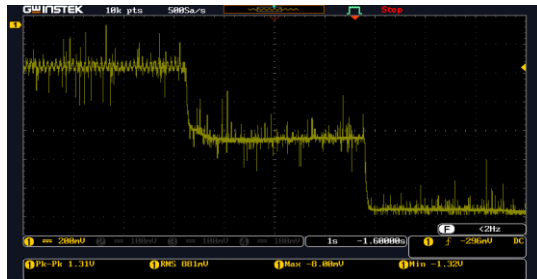
After designing and installation, the completed test bench is set up as in Figure 3.



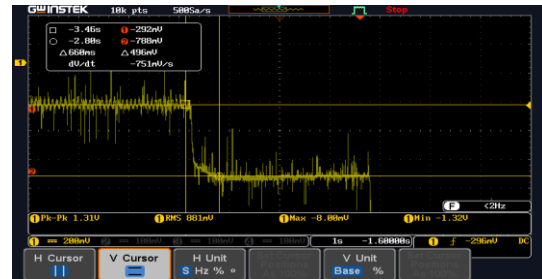
- | | | |
|--------------------------------|---------------------------------|--------------------|
| 1. Controller | 4. Boost converter | 7. AC/DC converter |
| 2. Relay switches | 5. Battery measuring instrument | 8. Inverter |
| 3. Programmable buck converter | 6. Battery | 9. Oscilloscope |

Figure 3. Test bench set up

3. Testing results



a) Three charging commands



b) Charging response when the charging power changes from 19.2 W to 51.2 W



c) Charging response when charging power changes from 51.2 W to 76.8 W



d) Charging response transition 1



e) Charging response transition 2

Figure 4. Real-time charging response

Since charging/discharging power can be expressed through battery voltage and battery current and because battery voltage does not change dramatically, it is understandable that real-time charging response can be observed through observing real-time charging current. In the test bench, the observation of charging current is conducted through a voltage drop across a resistor.

Figure 4 shows the charging response of a battery when charging power changes from 19.2 W to 51.2 W and 76.8 W. It can be seen that battery can quickly adapt to the change in charging command, being around 660 ms in Figure 4b and 230 ms in Figure 4c.

Figure 5 depicts the discharging response when three discharging commands are sent to the converter. Battery shows a quick adaptation to the discharging commands with setting times being 487ms in Figure 5b and 842 ms in Figure 5c.

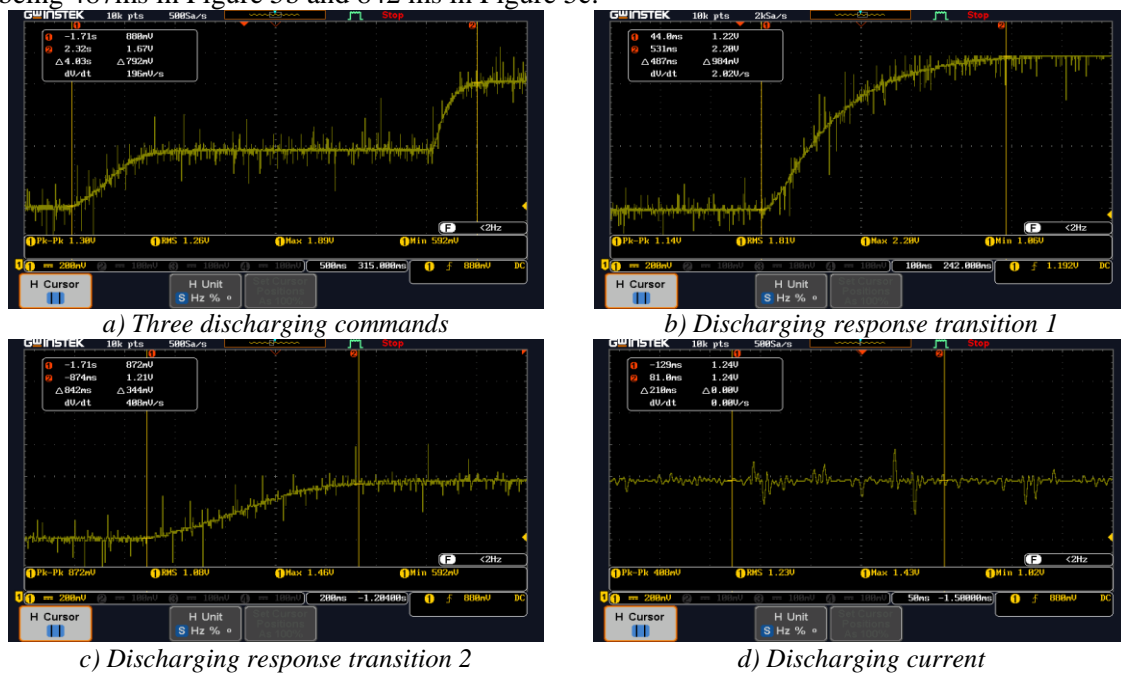


Figure 5. Real-time discharging response

It could be realized that in both cases of charging and discharging, charging power changes with charging command and the transition time is quite short compared to scheduling timeslot duration (from 15 to 30 minutes). Moreover, the charging and discharging current at steady state are not flat (Figure 5d). This is because of output ripple of the selected converter (output ripple <math><50\text{ mVpp}</math>). The output voltage of the programmable buck converter might be improved by adding additional filters or by a higher quality converter replacement. However, this problem is out of the scope of this test.



Figure 6. Real-time charge to discharge response

Figure 6 illustrates charging current response when the battery changes from charging to discharging. During the charging process, a sudden discharge command is sent to the converter. The figure reveals that the transition in the charging current finishes after about 22.5 ms and the battery current experiences an overshoot. However, this overshoot is negligible compared to the variation of battery current in the steady state (positions 1 and 2).

Regarding battery voltage profile and SOC profile, the test bench measuring system currently cannot record these profiles over a long duration. This is one of the limitations of the test bench and will be addressed in the future.

4. Conclusions

In this paper, real-time charging/discharging response research is conducted to test the operation of the charging station with charging/discharging commands obtained from the long-term scheduling algorithm. Experimental results retrieved from the test bench demonstrate that the optimized charging algorithms for E2Ws over a scheduling horizon are feasible under real conditions. The response time for charging/discharging commands is negligible compared to the duration of one timeslot.

The charging/discharging voltage and current setpoints are represented in the form of data tables in the controller's memory and sent to the programmable power converters via Modbus RTU communication. This solution leverages the advantages of Modbus communication and the reliability of industrial control systems while still providing scalability. The setup and operation of the test bench have demonstrated the feasibility of the proposed solution in real-world conditions.

However, the test bench still has some limitations that need to be further developed and investigated in the future, such as: 1) a bidirectional grid-connected inverter should be considered; 2) adoption of monitoring devices for charging voltage, SOC, and State of Health (SOH), which would enable recording and observation of data over a long period of time; 3) Further research and evaluation of the CV charging stage; 4) Further addressing the coordination of battery power control, PV power, and grid power.

However, because the test bench is set up as a pilot prototype to verify the feasibility of optimal charging algorithms in practical conditions, it meets the goal of the research. Other limitations mentioned above will be further investigated in the future test bench development.

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