2022 IEEE 7th International conference for Convergence in Technology (I2CT)
Pune, India. Apr 07-09, 2022

2022 IEEE 7th International conference for Convergence in Technology (I2CT) | 978-1-6654-2168-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/I2CT54291.2022.9824535

Multi-Stage Fast Charging Technique for Lithium Battery in Photovoltaic systems

Syakirin O. Yong[1], Nasrudin A. Rahim[2], Senior Member, IEEE, Bilal M. Eid[3], *Member, IEEE*, Buray Tankut[4]
[1]UM Power Energy Dedicated Advanced Centre (UMPEDAC), Wisma R & D, University of Malaya, 59990 Kuala Lumpur, Malaysia
[2]Founder and director of UM Power Energy Dedicated Advanced Centre (UMPEDAC), Wisma R & D, University of Malaya,.
[3]Electrical and Electronics department, Hasan Kalyoncu University, Gaziantep, Turkey..
[4]Electrical Engineer, Gaziantep, Turkey.
[1]syakirin@um.edu.my, [2]nasrudin@um.edu.my, [3]bilal.eid@hku.edu.tr, [4]buraytankut@gmail.com

***Abstract*— In renewable energy resources such as photovoltaic (PV) systems, fast charging is an emerging case for the battery charger. In this paper, constant-current (CC) and constant-voltage (CV) charging scheme has been studied since it has the highest possible reliability for lithium based batteries. In this work a new charging technique to expedite charging time is proposed. This is a multi-stage technique which improves the threshold voltage detection during CC-stage. Thus the transition to CV-stage occurs accurately at the knee voltage. The novelty of the proposed technique is in the charging algorithm. An experiment was setup based on PIC18f4520 microcontroller. The performance of the proposed technique and the conventional CC-CV Li-ion battery charger has been compared. The result of the proposed technique shows that there is 20% improvement in charging time compared to the conventional CC-CV Li-ion battery charger.**

***Index Terms*— PV System, Lithium-ion, Charger, Constant Current, Constant Voltage, Renewable Energy.**

I. Introduction

Since many more electrical products such as electrical vehicles (EV), personal gadget and portable appliances have been introduced the demand for energy is increasing day by day, with more concern on clean energy [1-2]. Therefore, the integration of more renewable energy sources (RESs) is the target for electrical network operators. The sun is a source of unlimited energy. In fact, in one-hour the sun radiates more than enough energy to be consumed by the entire world in one year. Moreover, the energy offered by the sun is sustainable and clean [3].

Photovoltaic (PV) systems are used to harvest sun energy [4-6]. PV cells convert light radiated by the sun to electrical energy. In a PV system, an energy storage device must be used to ensure continuity of energy supply. The energy storage device must be very efficient to ensure maximum energy supply. Long life cycle with minimum self-discharging loss is an important advantage as well. Lithium-based batteries were used as energy storage devices for a few years now [6, 7]. They have a relatively long lifetime, fast response, high energy and power density, and most attractively, their cost is decreasing dramatically [2, 6-8]. Lithium-ion battery is also immune to memory effect, which is an important feature for a PV charging system. For some battery like Nickel Cadmium, memory effect severely affects battery performance. The lithium-based battery can be charge or discharge at any capacity level without performance decrease as long as the operation still in a safe operating area.

The charging process in Lithium based battery occurs when electrical energy is converted to chemical energy. This process is a controllable process. A fast charging process is critical for many applications. In [9], fast charging technique is proposed for a solar powered telemetric station. The station needs a fast charger due to the narrow time window when solar energy is available. In [7], a fast charging technique gives an additional advantage for a charging station especially when the load is at the peak.

Most of the PV systems use constant-current and constant-voltage (CC-CV) as charging schemes [10-12]. This scheme injects maximum current to charge the battery during CC-stage until the voltage of the battery reaches the maximum level. Then the charger transit to CV-stage. At this stage, instead of current, the charger maintains the constant-voltage (CV-stage). Current reading drops at this stage until a minimum level set by the charger. The battery is considered fully charged when the current reading reaches the minimum level. Many efforts have been made to expedite the charging process of CC-CV scheme. All the efforts can be divided into three categories; (i) improve the constant-current stage [13-18]; (ii) improve the constant-voltage stage [19, 20]; (iii) improve the transition from CC-stage to CV-stage [21-26].

This work attempts to improve the transition from CC-stage to CV-stage. The main problem in this category is to solve the internal resistance error effect. This error would prolong CV-stage because CC-stage ended before the true threshold voltage [21-26]. Many previous works have used a built-in resistance compensator to tackle this problem [21-23, 26]; this method shifts the threshold voltage to the front. [25] used fuzzy logic control, searching for the optimal charging current during CV-stage. The new charging current is greater than the normal CV-stage charging current. These methods include some calculation or circuit modification.

The goal of this paper is to propose the development and implementation of a new technique to improve charging time in CC-CV li-Ion battery charger. The rest of paper is structured as follows. In section II, we review the standard CC-CV charging method and potential areas of improvement. Section III presents fast charging demand for PV application. Section IV presents the theory utilized in this study together with the in-depth discussion about the proposed method Section V presents hardware development as well as the software development. Section VI discusses the results and findings and finally, Section VII concludes the paper.

II. CC-CV Analysis

Figure 1 illustrates the standard CC-CV charging characteristics. In normal operation, the CC-CV method has two charging stages. In the first stage, the battery charged by Constant Current (CC-stage). The current is usually half the battery's rated capacity (or 0.5C). At this stage, the voltage of the battery increased. This stage continues until the battery voltage reaches the threshold voltage level (4.2V V_{max}). At this point, the CC-stage will transit to the CV-stage. During the CV-stage the current will decrease until it reached 0.05C (0.045A I_{min}). The battery is then considered fully charged.

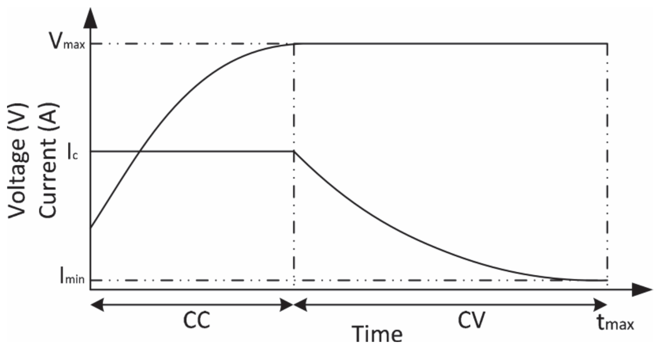


Fig. 1. Standard CC-CV charging characteristics [27]

There are three main settings in the CC-CV methods, and all of these settings are very critical and they cannot be changed. They are 1) the charging current during CC-stage; 2) the voltage point where the CC-stage will transit to CV-stage; 3) the charging voltage during CV-stage.

In the CC-stage, the current is set to 0.5C as per manufacturer recommendation. If the current value of CC-stage increased, certainly the charging time will be short. But, this may expose the battery to the risk of overheating due to the large current value. The same concept applies when we increase the threshold voltage value of the CC-stage to CV-stage transition. Then the charging time will be short, but this may expose the battery to the risk of over-voltage. If the voltage value of CV-stage increased, then the charging process will be accelerated, but the risk of over-charge and over-heating will occur. Another simple technique to shorten charging time is to eliminate the time-consuming CV-stage. But the problem is that battery would not be fully charged yet. Thus, there is no risk but no optimum performance occurs either.

Hence, the safest way to improve the charging process of the li-ion battery is to let the CC-CV run at optimum settings. Any possibilities of loss must be eliminated, so that the charging process is optimum. Thus, the issue of loss must thus be addressed first.

The key to CC-CV charging is the smooth and accurate transition from the CC stage to the CV stage [28]. During charging the battery voltage has to be read to determine whether the voltage has reached threshold voltage. Three possible cases exist: (1) the voltage read being higher than the actual battery terminal voltage (the CC-stage then prematurely transitions into CV-stage, i.e., before the real battery voltage equals the reference voltage, prolong duration of charging would occur); (2) the voltage read being lower than the real battery terminal voltage (the CC-stage then transitions into CV-stage, which is critical because the battery voltage has already exceeded the reference voltage, causing the battery to overcharge); (3) the voltage read being equal with the real battery terminal voltage (which is the most desired but ideal case). The first case often occurs. This is due to the existence of internal and parasitic resistance. The value cannot be ignored because it affects the length of charging time.

III. Fast charging for PV application

In the future, in Malaysia many more PV applications will appear such as solar parking systems, mobile charging stations, solar generation stations and many more. As it can be seen in Fig 2, solar generation in Malaysia is increasing year by year. This means that solar energy application is also becoming more popular and important. Thus, a fast charger will benefit the entire energy system either directly or indirectly.

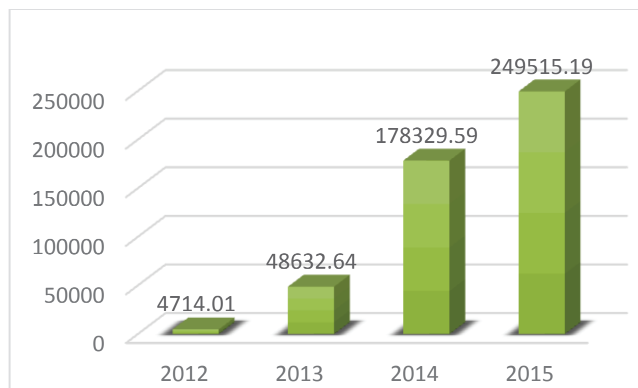


Fig. 2. Solar Generation (MWh) by Year in Malaysia [29].

There are many applications that benefit from fast chargers. However, for some applications a fast charger is a must due to particular reasons such as; (1) narrow time window for solar energy availability; (2) Emergency; (3) limited space for PV-panels; (4) peak usage and many more. In [9], a fast charging technique is proposed for a solar powered telemetric station. The station needs a fast charger due to the narrow time window when solar energy is available. In [7], a fast charging technique gives an additional advantage for EV charging station especially when the load is at the peak. Therefore, fast charger will provide added advantages to PV system either directly or indirectly.

IV. Multi-stage Charger

Figure 3 illustrates the typical circuit of a battery charger. The real battery contains an ideal battery as a voltage source and an internal resistance (R_i). In the charger circuit there are also various resistances (R_m) such as long wire and a bad contact surface. To read battery voltage (V_b), the point available for the battery charger are points ‘2’ and ‘3’. If the charger reads V_b at point ‘3’, the error component will appear bigger due to the existence of R_m. When V_b is read at ‘1’ then the component of R_m can be removed, but R_i remains as a reading error.

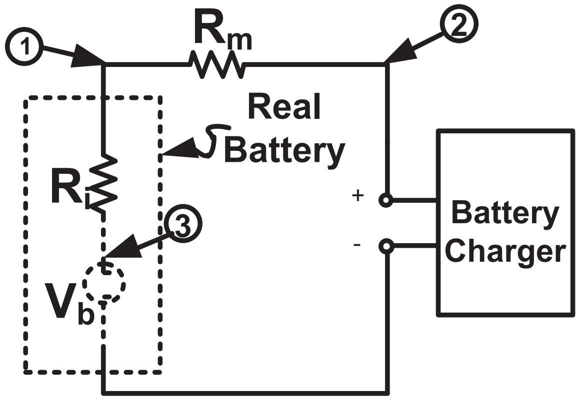


Fig. 3. Typical battery charger circuit

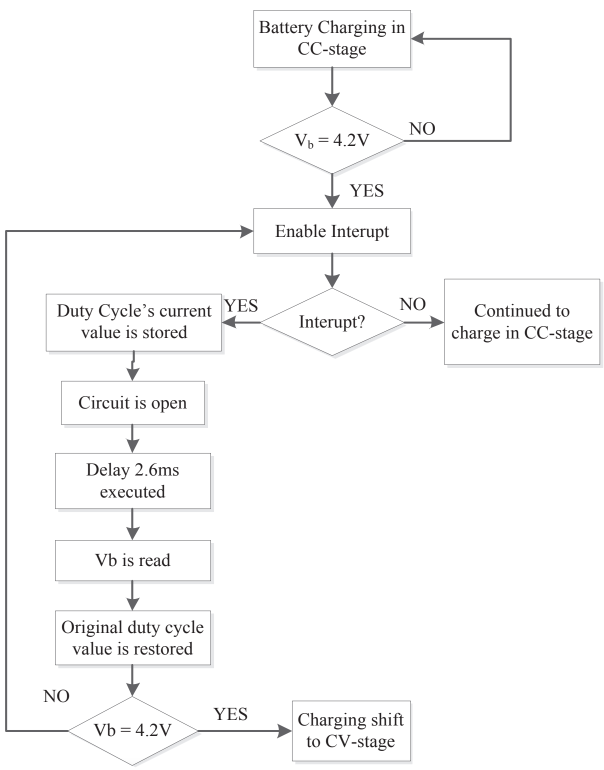


Fig. 4. Flowchart of proposed method implementation.

In order to eliminate the R_i component, this work proposes that the charger has to read V_b during the time the current is zero. This is possible when the circuit is open. Hence, a second stage was introduced in the charging process to measure V_b during the open circuit. Notes that, charging process will be interrupted if the circuit is open. To ensure that the proposed method does not delay the charging process, it started when the reading of V_b equals 4.2V in close circuit operation. Optimizations of the proposed method were achieved by two steps; (1) the circuit's open time is minimized, and (2) the process to read V_b is minimized. If the proposed method starts at the early stage of charging, it will retard the charging process. This process is illustrated in Figure 4.

V. Experimental Set-Up

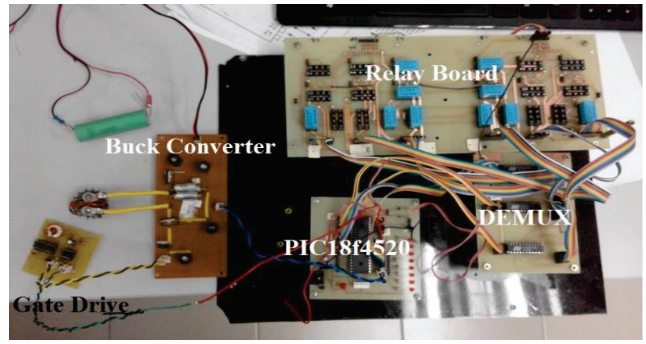


Fig. 5. Experimental Setup

The proposed technique was validated by a custom-built microcontroller-based Li-ion battery charger. The charger unit contains one microcontroller circuit (PIC18f4520), two latching relays, one current sensor (CS), and one basic buck converter; see Figure 5. The buck converter steps down the supply voltage (V_s) to get constant current or constant voltage. The microprocessor generates and controls the pulse signal to be sent to the N-Type MOSFET (S). The power diode (D2) located after the converter ensures single-direction current flow from the charger to the battery, to prevent power from leaving the battery and going into the converter during a possible mishap. Relay 1 switches the battery to charging mode when the battery voltage falls to the lowest threshold (3.3V) and isolates the battery from the charger when the battery is full. Relay 2 connects the battery to the load and vice versa. Table 1 lists the specifications of the battery used in the experiment.

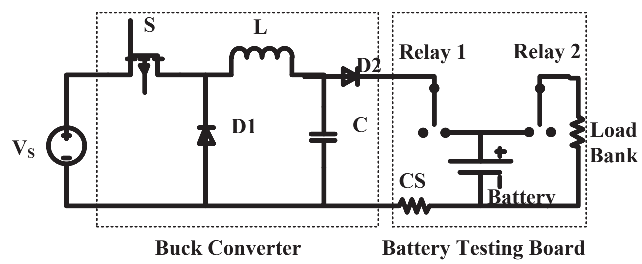


Fig. 6. Battery charger circuit schematic

TABLE I. Specifications of the Lithium-Ion Battery

Model	Cylindrical
Type	ICR18f4520 22F
Nominal Capacity (mAh)	2,250
Nominal Voltage (V)	3.60
Charge Method	CC-CV
Charge Voltage (V)	4.20
Charge Current(C)	0.5
Discharge Voltage (V)	2.75
Discharge Current (C)	0.2
Dimension (mm)Thickness / Width / Length	18.0 / - / 65.0
Max Weight (g)	44.2

TABLE II. SPECIFICATION OF THE SENSORS USED

Equipment	Type	Range	Accuracy
Current sensor	Resistor	5W	0.045A
Voltage sensor	Direct Sensing	5V	0.00488V

In this work, only a current sensor is needed. The voltage sensor can be eliminated because the battery voltage can be read directly from the microcontroller. This is the advantage of the 5V rating of the controller unit. All the sensor data of this experiment are as listed in Table 2. The primary objectives in selecting the sensors are accuracy, efficiency, and simplicity.

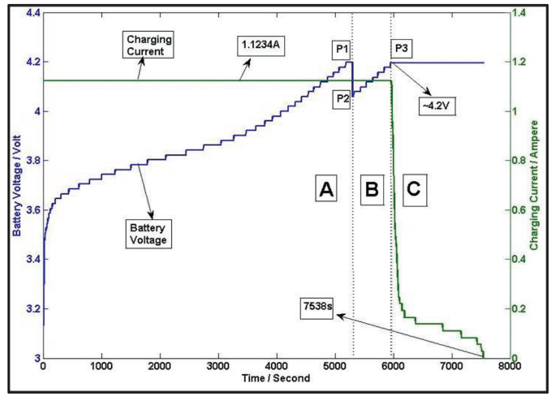
All the experiment data were collected on a PC through parallel communication via standard RS232 cable between the PC and the microcontroller. For data processing and display, data acquisition was developed in Microsoft Visual Basic 2010 Express. The program was set to obtain two data sets: current and voltage.

VI. RESULTS AND DISCUSSION

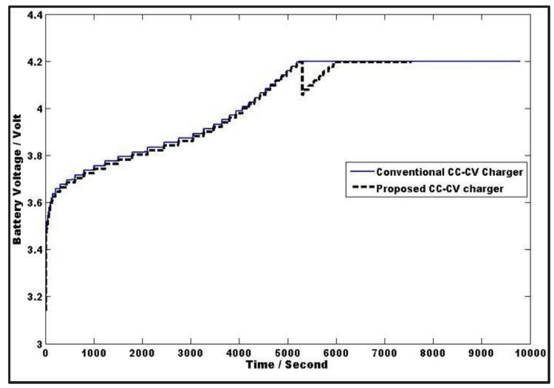
The results of the proposed technique are shown in Figure 7(a). The charging process starts with the regular CC-stage, marked section ‘A'. During this stage, the current is kept constant by the microcontroller and the battery voltage is read while the circuit is closed. So far this stage is not different from that of a conventional CC-CV charger. This stage continued until the battery voltage reading is at 4.2V in a closed circuit. At this threshold voltage (marked point ‘P1'), in a conventional charger, the CC-stage transitions directly into the CV-stage but here the proposed technique is implemented right after the point ‘P1' before transitioning to the CV stage (marked as section ‘B'). In this section, the battery voltage is read while the circuit is open, and this removes error reading from the conventional CC-stage, thus improving the reading before passing it on to the CV stage. The actual and error-free battery voltage (point ‘P2') is lower than 4.2V. The charging current can remain constant because the CC stage is unable to transition to the CV stage for as long as the battery voltage does not equal the threshold voltage. When the real battery voltage achieves 4.2V (point ‘P3'), the charger enters section ‘C’, where the CV stage is applied. Upon entering the CV stage the value of the charging current drops tremendously from its value in the preceding CC stage (unlike in a conventional CC-CV charger). Charging ends when the current reads zero on the microcontroller (i.e., 0.045A or 0.05C).

Figure 7(b) compares the battery voltages. The proposed CC-CV charger shows a shorter CV-stage. Figure 7(c) compares the charging currents. The proposed charger shows that the charging current drops slowly but tremendously (down to 0.05C) when the charger transitions into CV stage (unlike in a conventional charger). Figure 5(d) shows the battery capacity in CC stage to be higher in the proposed charger than in a conventional charger.

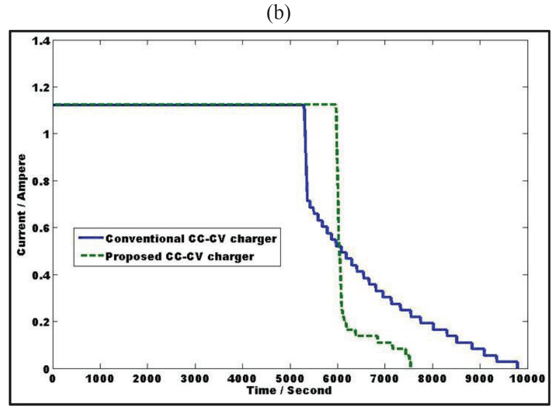
Table 3 compares the charging times and charging capacities of a normal CC-CV charger with those of the proposed charger. The proposed charging technique charges at least 20% faster and at least 10% higher during CC charging.



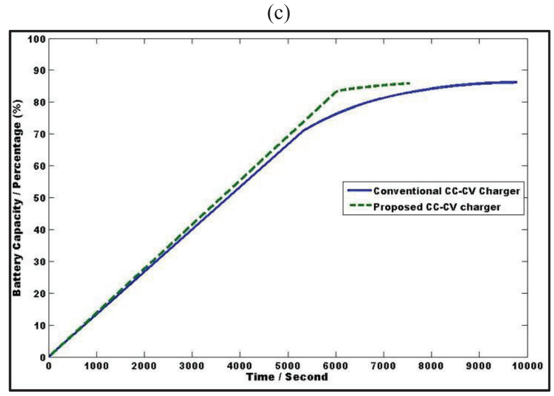
(a)



(b)



(c)



(d)

Fig. 7. (a) Results of the proposed charging method; (b): The comparison of battery voltage; (c): The comparison of charging currents; (d): The comparison of battery capacities

TABLE III. COMPARING THE PROPOSED TECHNIQUE WITH CONVENTIONAL CC-CV SCHEME

	Charging Time (s)	Capacity during CC-stage (Ah)
Normal CC-CV mode	9784	1.589
Proposed charging method	7538	1.865
Percentage of improvement (%)	23	14.7

VII. CONCLUSION

The goal of this study is to develop a fast charger for a PV system that uses lithium-ion based battery as energy storage. The CC-CV charging scheme was selected because of its availability and reliability. Analysis of the CC-CV charging scheme has been done first. From the analysis, it is found that, if the transition from CC-stage to CV-stage can be made as accurate as possible to the threshold voltage, then the charging process will be run at optimum level. There are errors in voltage detection that can cause a premature transition from CC-stage to CV-stage. Hence, we propose a technique which does not need any hardware addition and does not involve any fix calculation. The proposed technique is straightforward to understand and implement. This technique is able to expedite the charging process. The findings show that the CC-CV charging time is improved by at least 20%. While in the CC-stage the charging capacity is improved by at least 10%. The improvement of the proposed method over the conventional is thus proven.

REFERENCES

[1] Jaalam, N., N. A. Rahim, A. H. A. Bakar, and B. M. Eid. "LVRT capability based on PI-scanning for three-phase grid-connected photovoltaic system." In 4th IET Clean Energy and Technology Conference (CEAT 2016), pp. 1-5. IET, 2016.

[2] Alshahr, Shahr A., Bilal M. Eid, and Johnson A. Asumadu. "Reactive Power Dispatching for Microgrid's Voltage Stability with High Penetration of Renewable Energy Resources." In 2018 6th International Conference on Control Engineering & Information Technology (CEIT), pp. 1-6. IEEE, 2018.

[3] Al Bdwawi, A., et al., Modular Photovoltaic Charging Station for UAE University Golf Carts, in Clean, Efficient and Affordable Energy for a Sustainable Future, J. Yan, et al., Editors. 2015. p. 314-318.

[4] Li, W., et al., A Smart and Simple PV Charger for Portable Applications, in 2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition. 2010. p. 2080-2084.

[5] B. Eid and B. E. Tankut, "Voltage Problems Causes and Effects in Grid Connected Photovoltaic systems in Turkey," 2021 International Conference on Electric Power Engineering – Palestine (ICEPE- P), 2021, pp. 1-3, doi: 10.1109/ICEPE-P51568.2021.9423480.

[6] Hussein, A.A. and A.A. Fardoun, Design considerations and performance evaluation of outdoor PV battery chargers. Renewable Energy, 2015. 82: p. 85-91.

[7] Hamidi, A., et al., EV Charging Station Integrating Renewable Energy and Second-Life Battery, in 2013 International Conference on Renewable Energy Research and Applications. 2013. p. 1217-1221.

[8] Rydh, C.J. and B.A. Sanden, Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies. Energy Conversion and Management, 2005. 46(11-12): p. 1980-2000.

[9] Schreiber, M., et al., Practical and commercial issues in the design and manufacture of vanadium flow batteries. Journal of Power Sources, 2012. 206: p. 483-489.

[10] Hsieh, H.I., C.Y. Tsai, and G.C. Hsieh, Photovoltaic Burp Charge System on Energy-Saving Configuration by Smart Charge Management. IEEE Transactions on Power Electronics, 2014. 29(4): p. 1777-1790.

[11] Andrade, A., et al., Design and Implementation of PV Power Zeta Converters for Battery Charger Applications, in 2015 IEEE Energy Conversion Congress and Exposition. 2015. p. 3135-3142.

[12] Tsang, K.M. and W.L. Chan, State of health detection for Lithium ion batteries in photovoltaic system. Energy Conversion and Management, 2013. 65: p. 7-12.

[13] Liu, Y.H., C.H. Hsieh, and Y.F. Luo, Search for an Optimal Five-Step Charging Pattern for Li-Ion Batteries Using Consecutive Orthogonal Arrays. IEEE Transactions on Energy Conversion, 2011. 26(2): p. 654-661.

[14] Liu, Y.H. and Y.F. Luo, Search for an Optimal Rapid-Charging Pattern for Li-Ion Batteries Using the Taguchi Approach. IEEE Transactions on Industrial Electronics, 2010. 57(12): p. 3963-3971.

[15] Yi-Hwa, L., T. Jen-Hao, and L. Yu-Chung, Search for an optimal rapid charging pattern for lithium-ion batteries using ant colony system algorithm. IEEE Transactions on Industrial Electronics, 2005. 52(5): p. 1328-1336.

[16] Park, D., et al., Fast battery charger MCU with adaptive PWM controller using runtime tracking of polarization curve. IEICE Electronics Express, 2016. 13(8).

[17] Tsang, K.M. and W.L. Chan, A simple and low-cost charger for lithium-ion batteries. Journal of Power Sources, 2009. 191(2): p. 633-635.

[18] Tsang, K.M. and W.L. Chan, Current sensorless quick charger for lithium-ion batteries. Energy Conversion and Management, 2011. 52(3): p. 1593-1595.

[19] Lee, Y.D., S.Y. Park, and Ieee, Rapid Charging Strategy in the Constant Voltage Mode for a High Power Li-Ion Battery, in 2013 IEEE Energy Conversion Congress and Exposition. 2013. p. 4725-4731.

[20] Chao, P.C.-P., W.-D. Chen, and C.-W. Cheng, A fast battery charging algorithm for an intelligent PV system with capability of on-line temperature compensation. Microsystem Technologies, 2013. 19(9): p. 1289-1306.

[21] Huang, T.C., et al., Fast Charging and High Efficiency Switching-Based Charger With Continuous Built-In Resistance Detection and Automatic Energy Deliver Control for Portable Electronics. IEEE Journal of Solid-State Circuits, 2014. 49(7): p. 1580-1594.

[22] Liang-Rui, C., L. Chuan-Sheng, and C. Jin-Jia, Improving Phase-Locked Battery Charger Speed by Using Resistance-Compensated Technique. Industrial Electronics, IEEE Transactions on, 2009. 56(4): p. 1205-1211.

[23] Chia-Hsiang, L., H. Chun-Yu, and C. Ke-Horng, A Li-Ion Battery Charger With Smooth Control Circuit and Built-In Resistance Compensator for Achieving Stable and Fast Charging. Circuits and Systems I: Regular Papers, IEEE Transactions on, 2010. 57(2): p. 506-517.

[24] Yang, S.H., J.W. Liu, and C.C. Wang, A Single-Chip 60-V Bulk Charger for Series Li-Ion Batteries With Smooth Charge-Mode Transition. IEEE Transactions on Circuits and Systems I-Regular Papers, 2012. 59(7): p. 1588-1597.

[25] Liu, C.-L., et al., Optimization of a Fuzzy-Logic-Control-Based Five-Stage Battery Charger Using a Fuzzy-Based Taguchi Method. Energies, 2013. 6(7): p. 3528-3547.

[26] Phu Ho Van, Q., H. Thanh Tien, and J.-W. Lee, A Fully Integrated Multimode Wireless Power Charger IC With Adaptive Supply Control and Built-In Resistance Compensation. IEEE Transactions on Industrial Electronics, 2015. 62(2): p. 1251-1261.

[27] Weixiang Shen, Thanh Tu Vo and A. Kapoor, "Charging algorithms of lithium-ion batteries: An overview," 2012 7th IEEE Conference on Industrial Electronics and Applications (ICIEA), 2012, pp. 1567-1572, doi: 10.1109/ICIEA.2012.6360973.

[28] Yong, Syakirin Othman, and Nasrudin Abd Rahim. "Development of on-off duty cycle control with zero computational algorithm for CC-CV Li ion battery charger." In 2013 IEEE Conference on Clean Energy and Technology (CEAT), pp. 422-426. IEEE, 2013.

[29] Malaysia, S.E.D.A.o., Annual Power Generation (MWh) of Commissioned RE Installations. 2016.