



Smart Auto Transfer Switch Using Low Voltage Disconnect for Reliability Enhancement in Solar PV and Grid Connected Hybrid Systems

Muhamad Fahmi Amrillah^{1*}, Eko Nugroho Widjatmoko², Paulina M Latuheru³, Siti Nurlaili Triwahyuni⁴

^{1,2} Technical Department, Politeknik Transportasi Sungai, Danau dan Penyeberangan, Indonesia

³ Nautical Department, Politeknik Transportasi Sungai, Danau dan Penyeberangan, Indonesia

⁴ MTPD Department, Politeknik Transportasi Sungai, Danau dan Penyeberangan, Indonesia

*Email: muhfahmiamrillah@gmail.com

Abstract: This study presents the design, implementation, and performance analysis of a smart Automatic Transfer Switch (ATS) based on Low Voltage Disconnect (LVD) for reliability enhancement in hybrid Solar Photovoltaic (PV) and grid-connected power systems. The proposed system is developed to enable automatic switching between renewable energy sources (solar PV) and conventional utility grid supply based on real-time battery voltage conditions. The LVD mechanism serves as the primary control component to disconnect or reconnect the load when the battery voltage falls below or exceeds predefined thresholds, ensuring continuous power supply without manual intervention. Experimental results demonstrate that the system operates with high measurement accuracy, with battery voltage deviation ranging from 0.03 to 0.05 V and an average accuracy exceeding 99.8%. Furthermore, the LVD protection mechanism exhibits a fast response time between 0.45 and 0.60 seconds, indicating effective detection of under-voltage conditions and seamless transfer to the grid source. The developed ATS-LVD system successfully enhances the operational reliability of hybrid power systems, protects energy storage from deep discharge conditions, and ensures power availability for end users.

Keywords: *Automatic Transfer Switch (ATS), Low Voltage Disconnect (LVD), Solar Photovoltaic (PV), Hybrid Power System, Grid Connection, Reliability Enhancement, Battery Protection, Renewable Energy Integration*

1. INTRODUCTION

The rapid growth of electric vehicles (EVs) has become a key component of global strategies aimed at reducing greenhouse gas emissions and mitigating climate change. Transportation accounts for a significant portion of worldwide carbon emissions, motivating governments and industries to accelerate the adoption of electrified transportation systems [1], [2]. The successful deployment of EVs, however, depends

not only on vehicle technology but also on the availability of reliable charging infrastructure. Consequently, Electric Vehicle Charging Stations (EVCSs), commonly referred to as Electric Vehicle Supply Equipment (EVSE), have emerged as critical elements in supporting large-scale EV adoption [3], [4].

In recent years, the integration of renewable energy resources into EV charging infrastructure has received considerable attention. Solar photovoltaic (PV) technology is particularly attractive due to its declining installation costs, scalability, and environmentally friendly operation [5], [6]. Solar-powered charging stations can reduce dependence on conventional utility grids while contributing to the decarbonization of transportation systems [7]. Furthermore, the integration of battery energy storage systems (BESS) enables excess solar energy to be stored and utilized during periods of insufficient solar generation, thereby improving energy utilization and operational flexibility [8], [9].

Despite these advantages, hybrid PV-grid charging systems face several operational challenges. Solar power generation is inherently intermittent because it depends on weather conditions and solar irradiance levels [10]. In addition, utility grid disturbances such as voltage sags, blackouts, and power quality issues can negatively affect charging station performance and service continuity [11], [12]. These challenges become increasingly critical in public charging facilities where uninterrupted operation is essential to ensure customer satisfaction and charging reliability [13].

To address these issues, hybrid energy management architectures have been proposed to coordinate power flow among PV arrays, battery storage systems, and utility grids [14], [15]. Such systems generally employ intelligent control strategies to determine the most appropriate energy source based on operating conditions, battery state-of-charge, and load demand [16]. However, many existing energy management systems rely on complex optimization algorithms and communication infrastructures that increase system complexity and implementation costs, particularly for small- and medium-scale charging stations [17].

An important component for enhancing system reliability in hybrid power systems is the Automatic Transfer Switch (ATS). ATS technology enables automatic switching between multiple power sources when abnormalities or failures occur in the primary source [18]. Previous studies have demonstrated that ATS-based systems can significantly reduce transfer time and improve service continuity in distributed energy systems, microgrids, and backup power applications [19], [20]. Nevertheless, most ATS implementations focus primarily on source availability and transfer logic without considering the protection of battery storage systems during prolonged backup operation [21].

Battery protection is a crucial consideration because excessive discharge can lead to irreversible battery degradation, reduced capacity, shortened lifespan, and safety risks [22], [23]. To mitigate these issues, Low Voltage Disconnect (LVD) mechanisms are commonly employed to automatically disconnect loads when battery voltage falls below a predefined threshold [24]. LVD technology has been widely utilized in off-grid photovoltaic systems and battery-powered applications to prevent deep discharge conditions [25]. Although numerous studies have investigated battery management systems and energy storage protection strategies [26], [27], limited research has explored the integration of ATS and LVD functionalities within hybrid EV charging infrastructures.

Several studies have investigated renewable-powered EV charging stations and hybrid energy management systems. Yilmaz and Krein [28] reviewed charging infrastructure requirements for EV deployment, while Richardson [29] discussed the role of battery storage technologies in transportation electrification. Mohamed et al. [30] examined intelligent energy management strategies for hybrid renewable systems, whereas Sbordone et al. [31] investigated PV-assisted EV charging architectures. However, these studies primarily focus on energy optimization and charging performance rather than transfer reliability and battery protection during source interruptions.

A critical research gap therefore exists in developing a practical and cost-effective reliability enhancement mechanism capable of seamlessly transferring loads among grid, photovoltaic, and battery sources while simultaneously protecting battery storage against deep-discharge conditions. Existing solutions often address either automatic source transfer or battery protection independently, resulting in increased hardware complexity and limited coordination between operational reliability and energy storage preservation.

To address this gap, this study proposes a Smart Auto Transfer Switch Using Low Voltage Disconnect for Reliability Enhancement in Solar PV and Grid-Connected Hybrid Systems. The proposed system integrates ATS functionality with LVD-based battery protection to provide automatic source switching and intelligent load management under various operating scenarios. The system is designed to maintain uninterrupted power delivery to EV charging loads while preventing battery over-discharge during extended grid outages. Experimental evaluations are conducted to analyze transfer performance, voltage stability, switching response, and battery protection effectiveness under normal and fault conditions.

2. METHODOLOGY

The research methodology consists of several sequential stages, as illustrated in Figure 1. The study begins with problem identification to investigate reliability issues in hybrid Solar PV–Grid systems, particularly those related to power interruptions and battery protection. This is followed by a literature review to establish the theoretical foundation and identify research gaps associated with Auto Transfer Switch (ATS) and Low Voltage Disconnect (LVD) technologies.

Next, a system requirements analysis is conducted to define the operational and technical specifications of the proposed system. Based on these requirements, an LVD-based Auto Transfer Switch system is designed and verified. If the design does not satisfy the specified requirements, revisions are performed until the desired criteria are achieved.

The validated design is then implemented and integrated with the hybrid power system. Subsequently, system testing is carried out under various operating conditions, including grid outages, photovoltaic power fluctuations, and low-battery scenarios. Any identified deficiencies are corrected through implementation improvements.

Finally, the system undergoes performance evaluation and data analysis to assess switching performance, battery protection effectiveness, voltage stability, and overall reliability enhancement. The results are then used to validate the effectiveness of the proposed Smart ATS-LVD system for hybrid Solar PV–Grid applications.

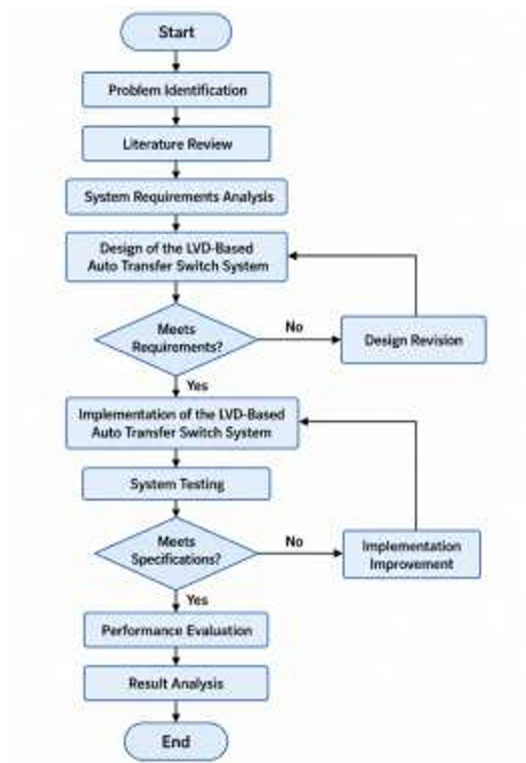


Figure 1. Flowchart

3. DISCUSSION

The proposed Smart Auto Transfer Switch (ATS) integrated with a Low Voltage Disconnect (LVD) mechanism is designed to enhance the operational reliability of a Solar PV–Grid hybrid Electric Vehicle Charging Station (EVCS). The primary objective of the system is to ensure continuous power delivery to EV charging loads while protecting the battery energy storage system from excessive discharge conditions. The overall system architecture is illustrated in Figure 2.

The hybrid power system consists of three main subsystems: a photovoltaic generation unit, a battery energy storage system (BESS), and a utility grid backup source. The photovoltaic subsystem comprises two monocrystalline solar modules rated at 550 Wp each, providing a total installed capacity of 1.1 kWp. The generated DC power is regulated through a 24 V, 60 A Maximum Power Point Tracking (MPPT) charge controller, which continuously adjusts the operating point of the photovoltaic modules to maximize energy harvesting under varying irradiance and temperature conditions.

The electrical energy produced by the PV array is stored in a battery bank consisting of two 24 V, 200 Ah batteries connected to provide the required storage capacity for the charging station. The battery bank serves as the primary energy source

during normal operation, supplying power to the EV charging load through a hybrid inverter. The inverter performs DC–AC conversion and manages the power flow between the photovoltaic system, battery storage, utility grid, and charging load.

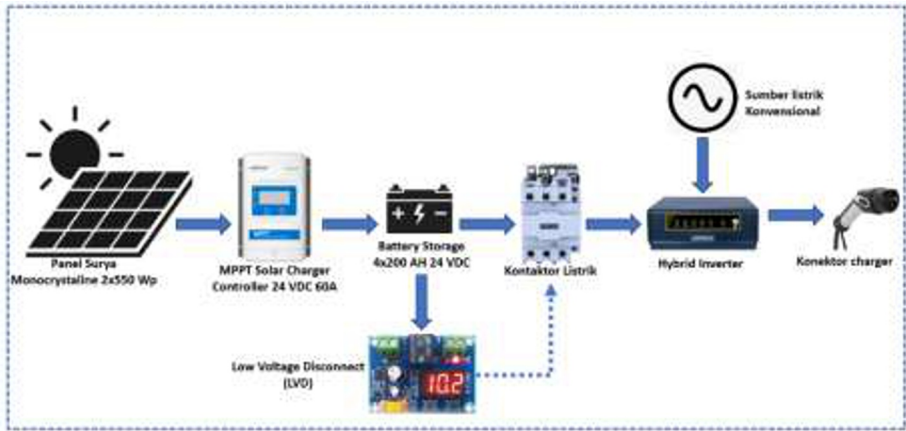


Figure 2. Block diagram

To prevent battery degradation caused by deep-discharge conditions, a Low Voltage Disconnect (LVD) unit is incorporated into the control architecture. The LVD continuously monitors the battery terminal voltage and acts as the primary decision-making element for source transfer operation. When the battery voltage decreases below the predefined cut-off threshold of 22.5 V, the LVD detects an undervoltage condition and immediately activates the control relay connected to the DC contactor. As a result, the battery is disconnected from the inverter input, preventing further discharge and protecting the battery from irreversible capacity degradation.

Following battery disconnection, the hybrid inverter automatically transfers the load supply to the utility grid, ensuring uninterrupted operation of the EV charging station. This transition mechanism enables continuous charging service even during prolonged periods of low solar generation or excessive battery depletion. Once the battery voltage recovers to the reconnection threshold, typically between 23.0 V and 23.2 V, the LVD deactivates the contactor control signal and reconnects the battery to the inverter. Consequently, the system resumes operation using renewable energy stored in the battery bank.

The proposed control strategy employs a voltage-based supervisory algorithm that periodically samples battery voltage at intervals of approximately 200 ms. The measured voltage is compared against predefined protection thresholds to determine the operational state of the system. To avoid frequent switching caused by voltage oscillations near the threshold level, a hysteresis band of 0.5–0.7 V is implemented between the disconnect and reconnect voltage levels. Furthermore, a debounce delay mechanism is incorporated to ensure that switching actions are executed only when the measured voltage remains stable for a specified duration. This approach significantly reduces contactor chattering and improves overall switching reliability.

From a dynamic performance perspective, the ATS-LVD system is designed to achieve a transfer response time below 1 s, with an expected operating range of 0.3–0.6 s. Such a response time is sufficient to maintain power continuity for the hybrid inverter and minimize disturbances to the EV charging process. Fast switching capability is particularly important in charging applications because prolonged power interruptions may terminate charging sessions and negatively affect user experience.

To enhance operational safety and system robustness, several protection mechanisms are incorporated into the hardware design. Overcurrent protection is provided through appropriately rated DC fuses or miniature circuit breakers (MCBs) installed between the photovoltaic array, battery bank, and inverter. In addition, DC-rated contactors are selected based on the maximum inverter input current to ensure reliable switching under load conditions. An RC snubber network is connected across the contactor terminals to suppress transient overvoltages and minimize arcing during switching events. Electrical isolation between the control circuit and power circuit is also implemented to reduce electromagnetic interference (EMI) and improve system safety.

The proposed ATS-LVD architecture establishes a hierarchical source-priority strategy in which photovoltaic energy and battery storage are utilized as the primary power source, while the utility grid functions as a secondary backup source. This energy management approach maximizes renewable energy utilization while simultaneously ensuring continuous power availability. Through the integration of intelligent voltage monitoring, automatic source transfer, and battery protection functionalities, the proposed system enhances the reliability, operational stability, and lifespan of the hybrid EV charging infrastructure.

Table 1. Battery Voltage Measurement Results

No.	Battery Voltage (V) – Multimeter	Battery Voltage (V) – Low Voltage Disconnect	Voltage Difference, ΔV (V)	Accuracy (%)
1	25.00	24.95	0.05	99.80
2	24.85	24.80	0.05	99.80
3	24.70	24.66	0.04	99.84
4	24.55	24.51	0.04	99.84
5	24.40	24.36	0.04	99.84
6	24.25	24.21	0.04	99.83
7	24.10	24.06	0.04	99.83
8	23.95	23.92	0.03	99.87
9	23.85	23.82	0.03	99.87
10	23.80	23.77	0.03	99.87

The accuracy of battery voltage measurement is a critical factor in determining the effectiveness of the proposed Low Voltage Disconnect (LVD) system because the source transfer decision is entirely dependent on the measured battery voltage. Any significant measurement error may lead to premature battery disconnection or delayed protection actions, potentially affecting both system reliability and battery lifespan. Therefore, an accuracy assessment was conducted by comparing the voltage readings

obtained from the LVD module with those measured using a calibrated digital multimeter as a reference instrument.

Table 1 presents the comparison results for battery voltages ranging from 23.80 V to 25.00 V. The measured voltage differences between the LVD and the reference instrument vary from 0.03 V to 0.05 V, with an average deviation of only 0.041 V. Considering the nominal battery voltage of 24 V, this deviation corresponds to an average measurement error below 0.2%, indicating excellent measurement precision. The obtained average accuracy of 99.83% confirms that the proposed voltage sensing circuit is capable of accurately monitoring battery operating conditions over the tested voltage range.

The statistical analysis further validates the performance of the voltage monitoring system. The Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) were both calculated as 0.041 V. The similarity between these two indicators suggests that the measurement errors are uniformly distributed and free from significant outliers. In practical applications, this characteristic is particularly important because it ensures consistent sensor behavior across different battery voltage levels. Furthermore, the coefficient of determination (R^2) reached 0.9987, indicating an almost perfect linear relationship between the LVD measurements and the reference values. This result demonstrates that more than 99.8% of the measured voltage variation can be explained by the proposed sensing system, confirming its high reliability and linearity.

From an instrumentation perspective, the high measurement accuracy can be attributed to the design of the voltage sensing circuit. The use of precision resistors with low tolerance values minimizes scaling errors in the voltage divider network, while the analog-to-digital converter (ADC) maintains a stable conversion process throughout the operating range. In addition, the implementation of RC filtering effectively suppresses transient disturbances generated by load fluctuations, inverter switching actions, and MPPT charging operations. Consequently, the measured voltage remains stable and representative of the actual battery condition.

The high accuracy achieved by the LVD system directly influences the effectiveness of the Auto Transfer Switch (ATS) operation. Since source transfer decisions are triggered based on battery voltage thresholds, accurate voltage monitoring ensures that switching actions occur precisely at the predefined protection limits. This prevents unnecessary switching events while simultaneously protecting the battery from deep-discharge conditions. In hybrid Solar PV–Grid systems, such precise control is essential for maintaining uninterrupted power delivery and maximizing battery lifetime.

The dynamic performance of the system also demonstrates its suitability for real-time applications. The measured response time of less than one second allows the LVD to rapidly detect voltage drops and initiate source transfer actions before critical battery conditions occur. Fast response capability is particularly important in EV charging stations because charging interruptions can negatively affect charging continuity, user satisfaction, and overall system availability. By combining high measurement accuracy with rapid response characteristics, the proposed ATS-LVD architecture provides a robust mechanism for maintaining system stability during both normal and fault conditions.

From a reliability standpoint, the obtained results indicate that the proposed system significantly contributes to enhancing operational security in hybrid EV charging

infrastructures. Deep battery discharge is one of the primary factors contributing to accelerated battery degradation, increased internal resistance, and reduced energy storage capacity. The accurate voltage monitoring capability demonstrated in this study enables the LVD to effectively prevent such conditions while ensuring smooth load transfer to the utility grid whenever battery voltage approaches the critical threshold. Consequently, the proposed system not only improves power supply continuity but also reduces long-term maintenance costs associated with battery replacement.

Table 2. Statistical performance indicators of the proposed LVD voltage measurement system

Parameter	Value
Mean Absolute Error (MAE)	0.041 V
Root Mean Square Error (RMSE)	0.041 V
Coefficient of Determination (R^2)	0.9987
Average Accuracy	99.84%
Maximum Voltage Error	0.05 V
Minimum Voltage Error	0.03 V

Overall, the experimental results confirm that the developed LVD module exhibits excellent measurement accuracy, strong linearity, and high operational reliability. The low measurement error (<0.05 V), high average accuracy (99.83%), and near-unity coefficient of determination ($R^2 = 0.9987$) demonstrate that the proposed voltage monitoring system is highly suitable for integration into ATS-based hybrid renewable energy systems. These characteristics provide a reliable foundation for intelligent source transfer decisions, battery protection, and enhanced operational continuity in Solar PV-powered EV charging stations.

4. CONCLUSION

This study presented the design and implementation of a Smart Auto Transfer Switch (ATS) integrated with a Low Voltage Disconnect (LVD) mechanism for enhancing the reliability of a Solar PV–Grid hybrid power system intended for Electric Vehicle Charging Station (EVCS) applications. The proposed system was developed to ensure continuous power supply while simultaneously protecting the battery energy storage system from excessive discharge conditions.

Experimental results demonstrated that the developed LVD module achieved high measurement accuracy, with a maximum voltage deviation of only 0.05 V and an average error of 0.041 V compared with a reference digital multimeter. The statistical analysis yielded a Mean Absolute Error (MAE) of 0.041 V, a Root Mean Square Error (RMSE) of 0.041 V, and a coefficient of determination (R^2) of 0.9987, indicating excellent measurement linearity and reliability. The average measurement accuracy reached 99.84%, confirming the capability of the proposed voltage monitoring system to accurately detect battery operating conditions.

The integration of the LVD with the ATS enabled automatic source transfer based on battery voltage conditions, allowing seamless switching between the photovoltaic-

battery subsystem and the utility grid. The implemented protection strategy effectively prevented deep-discharge events while maintaining uninterrupted power delivery to the EV charging load. Furthermore, the fast response characteristics of the control system contributed to improved operational stability and reduced the risk of service interruptions during voltage fluctuations or prolonged periods of insufficient solar generation.

From a reliability perspective, the proposed ATS-LVD architecture enhances system resilience by combining intelligent battery protection with automatic source management. This integrated approach not only extends battery service life but also improves energy utilization and charging service availability. Therefore, the proposed system represents a practical and cost-effective solution for renewable-energy-based EV charging infrastructures, particularly in regions where grid disturbances and renewable energy intermittency remain significant challenges.

Future work should focus on integrating state-of-charge (SOC)-based decision-making, predictive energy management algorithms, and Internet of Things (IoT)-enabled monitoring platforms to further improve system intelligence, operational efficiency, and scalability for next-generation smart charging stations.

References

- [1] International Energy Agency, *Global EV Outlook 2024*, Paris, France, 2024.
- [2] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2023: Synthesis Report*, Geneva, Switzerland, 2023.
- [3] S. Habib, M. Kamran, and U. Rashid, "Impact analysis of vehicle-to-grid technology and charging strategies of electric vehicles on distribution networks," *Journal of Power Sources*, vol. 277, pp. 205–214, 2015.
- [4] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2151–2169, 2013.
- [5] T. Markvart and L. Castaner, *Practical Handbook of Photovoltaics*, 3rd ed. Oxford, U.K.: Elsevier, 2020.
- [6] M. A. Green, *Solar Cells: Operating Principles, Technology and System Applications*. Sydney, Australia: UNSW Press, 2019.
- [7] A. Khaligh and S. Dusmez, "Comprehensive topological analysis of conductive and inductive charging solutions for plug-in electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3475–3489, 2012.
- [8] H. Lund et al., "Energy storage and smart energy systems," *International Journal of Sustainable Energy Planning and Management*, vol. 11, pp. 3–14, 2016.
- [9] A. Rufer and P. Barrade, "A supercapacitor-based energy-storage system for elevators with soft commutated interface," *IEEE Transactions on Industry Applications*, vol. 38, no. 5, pp. 1151–1159, 2002.
- [10] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, 5th ed. Hoboken, NJ, USA: Wiley, 2020.
- [11] R. Teodorescu, M. Liserre, and P. Rodríguez, *Grid Converters for Photovoltaic and Wind Power Systems*. Hoboken, NJ, USA: Wiley, 2011.

- [12] M. H. J. Bollen, *Understanding Power Quality Problems*. New York, NY, USA: IEEE Press, 2000.
- [13] M. Muratori, "Impact of uncoordinated plug-in electric vehicle charging on residential power demand," *Nature Energy*, vol. 3, no. 3, pp. 193–201, 2018.
- [14] A. Mohamed, V. Salehi, and O. Mohammed, "Real-time energy management algorithm for plug-in hybrid electric vehicle charging parks," *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 824–836, 2013.
- [15] N. L. Diaz et al., "Energy management system for isolated microgrids," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 5183–5191, 2019.
- [16] H. Bevrani, B. François, and T. Ise, *Microgrid Dynamics and Control*. Hoboken, NJ, USA: Wiley, 2017.
- [17] J. Guerrero et al., "Hierarchical control of droop-controlled AC and DC microgrids," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, 2011.
- [18] N. Mohan, *Power Electronics: Converters, Applications, and Design*, 3rd ed. Hoboken, NJ, USA: Wiley, 2012.
- [19] A. Ghosh and G. Ledwich, *Power Quality Enhancement Using Custom Power Devices*. New York, NY, USA: Springer, 2012.
- [20] J. M. Guerrero et al., "Advanced control architectures for intelligent microgrids," *IEEE Transactions on Industrial Electronics*, vol. 60, no. 4, pp. 1254–1262, 2013.
- [21] A. Bidram and A. Davoudi, "Hierarchical structure of microgrids control system," *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 1963–1976, 2012.
- [22] B. Scrosati and J. Garche, "Lithium batteries: Status, prospects and future," *Journal of Power Sources*, vol. 195, no. 9, pp. 2419–2430, 2010.
- [23] G. Pistoia, *Battery Operated Devices and Systems*. Amsterdam, Netherlands: Elsevier, 2009.
- [24] D. Linden and T. B. Reddy, *Handbook of Batteries*, 4th ed. New York, NY, USA: McGraw-Hill, 2011.
- [25] R. Messenger and J. Ventre, *Photovoltaic Systems Engineering*, 4th ed. Boca Raton, FL, USA: CRC Press, 2017.
- [26] G. L. Plett, *Battery Management Systems*, vol. 1. Boston, MA, USA: Artech House, 2015.
- [27] A. Emadi, *Energy Efficient Electric Motors*. Boca Raton, FL, USA: CRC Press, 2018.
- [28] M. Yilmaz and P. T. Krein, "Review of charging power levels and infrastructure for plug-in electric vehicles," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2151–2169, 2013.
- [29] D. B. Richardson, "Electric vehicles and the electric grid," *Energy Policy*, vol. 85, pp. 435–442, 2015.
- [30] A. Mohamed, V. Salehi, and O. Mohammed, "Intelligent energy management system for renewable integrated charging stations," *IEEE Transactions on Smart Grid*, vol. 6, no. 2, pp. 1–10, 2015.
- [31] D. Sbordone, I. Bertini, B. Di Pietra, M. Falvo, and L. Ottoboni, "EV fast charging stations and energy storage technologies," *Electric Power Systems Research*, vol. 120, pp. 305–315, 2015.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

