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# Power Electronics Converter Technology Integrated Energy Storage Management in Electric Vehicles: Emerging Trends, Analytical Assessment and Future Research Opportunities

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**Abstract:** Globally, the research on electric vehicles (EVs) has become increasingly popular due to their capacity to reduce carbon emissions and global warming impacts. The effectiveness of EVs depends on appropriate functionality and management of battery energy storage. Nevertheless, the battery energy storage in EVs provides an unregulated, unstable power supply and has significant voltage drops. To address these concerns, power electronics converter technology in EVs is necessary to achieve a stable and reliable power transmission. Although various EV converters provide significant contributions, they have limitations with regard to high components, high switching loss, high current stress, computational complexity, and slow dynamic response. Thus, this paper presents the emerging trends in analytical assessment of power electronics converter technology incorporated energy storage management in EVs. Hundreds (100) of the most significant and highly prominent articles on power converters for EVs are studied and investigated, employing the Scopus database under predetermined factors to explore the emerging trends. The results reveal that 57% of articles emphasize modeling, experimental work, and performance evaluation. In comparison, 13% of papers are based on problem formulation and simulation analysis, and 8% of articles are survey, case studies, and review-based. Besides, four countries, including China, India, the United States, and Canada, are dominant to publish the maximum articles, indicating 33, 17, 14, and 13, respectively. This review adopts the analytical assessment that outlines various power converters, energy storage, controller, optimization, energy efficiency, energy management, and energy transfer, emphasizing various schemes, key contributions, and research gaps. Besides, this paper discusses the drawbacks and issues of the various power converters and highlights future research opportunities to address the existing limitations. This analytical assessment could be useful to EV engineers and automobile companies towards the development of advanced energy storage management interfacing power electronics for sustainable EV applications.

**Keywords:** power electronics; energy storage management; electric vehicles; emerging trends analytical assessment



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## 1. Introduction

In recent years, humankind has faced one of the biggest challenges in terms of climate change, which is to deal with the emission of carbon dioxide due to a need to supply the increasing energy demand to support the industrial growth around the globe [1]. Globally, poor air quality in developing countries such as China is a significant and growing problem. As the economies of developing nations grow, the increased demand for automobiles and freight movement will only make these problems more difficult to address. One of the primary causes of global warming and climate change is the rising usage of fossil fuels in diesel-powered automobiles [2,3]. The increasing demand for energy consumption and dependency on carbon-based energy in the automotive industries in the last decade has become one of the most significant concerns around the globe. It was observed from different surveys that more than 500 million metric tons of carbon-based elements are emitted from the transportation sector only [4]. To tackle this major issue, electric vehicles (EVs) have appeared as a blessing to support building a totally sovereign society of carbon-based energy consumption and usage [5]. Unlike conventional vehicles, which run on gasoline or diesel, fuel cell cars and trucks combine hydrogen and oxygen to produce electricity. As a result, they have low energy densities and high energy efficiencies. Internal-combustion engines, which have hundreds of moving parts, are getting rapidly replaced to EVs with typically less than 20 moving parts, eliminating the need for conventional automobiles. Energy storages (ESs), traction motors, and power electronics are the new focal points of innovation in EVs [6]. The demand for greater vehicle range, safety, lifetime, and, of course, sustainable transportation drives technological developments in these components [7,8].

In EVs, power electronics largely process and control the flow of electrical energy [9]. They also regulate the motor's speed and the torque it generates. Finally, power electronics transform and distribute electrical power to other vehicle systems like heating, ventilation, lighting, and information technology [10]. Inverters, DC-DC converters, and chargers are examples of power electronics components [11,12]. Perfect synchronization between ESs and power electronic converters is key to the efficient performance of EVs [13]. The application and interfacing of ESs and power electronic converters in EVs can be further understood by the basic illustration of an EV shown in Figure 1.

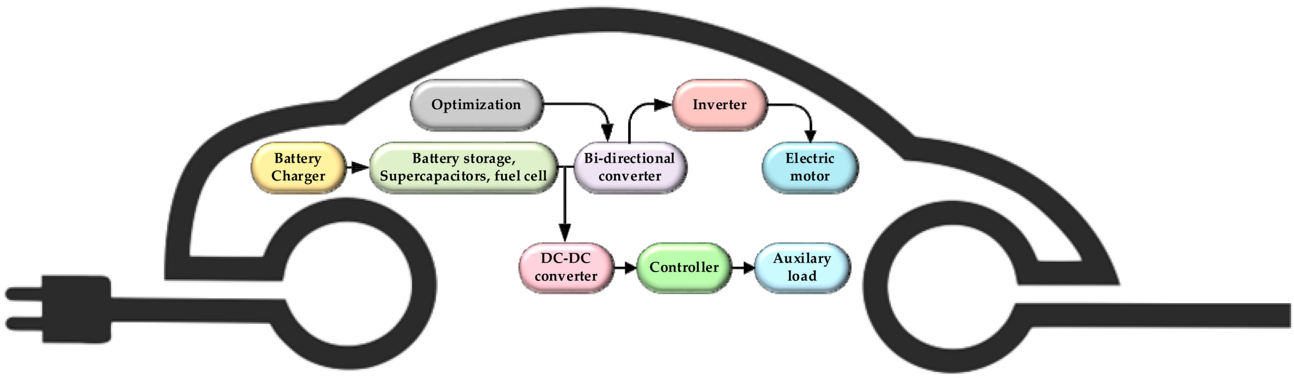


**Figure 1.** Schematic illustration of the application and interfacing of power electronic converters and ESs in EVs.

Various types of ESs, including supercapacitors, batteries, fuel cells, are integrated with power electronic converters/inverters to develop the internal structure of EVs [14–17]. In EVs, an AC-DC inverter is required to convert DC energy from ESs to AC power to drive the motor. An inverter also serves as a motor controller and a filter, protecting the ESs from stray current damage. The electricity delivered by ESs, on the other hand, has unreliable characteristics and significant voltage drops. DC-DC converters effectively tackle this issue. To accommodate the voltage needs of motors of EVs, DC-DC converters are used to improve ESs voltage profile. A boost converter is required if the EV's motor design requires higher voltage, such as an internal permanent magnet motor. As a result, DC-DC converters are critical for regulated power flow in EVs [18–21]. However, the enormous size of the capacitor storage on the DC link is one of the major issues with boost converters. In addition, these converters have the drawback of injecting discontinuous current into the load. Furthermore, the capacitor's ripple current is roughly equivalent to the load current. As a result, the capacitor tank's Externally Supported Roof (ESR) regulation is fairly stringent. This is especially true in new EV power conversion application domains, where the input voltage is generally very low and, equally, a huge voltage boost is required.

The primary goal of utilizing a controller in an EV converter is to achieve performance enhancement characteristics, including better and faster steady-state and dynamic response, reduced settling time, and reduced steady-state faults [22,23]. The better dynamic response eventually leads to reduced electromagnetic interference (EMI), switching losses, and common-mode voltage (CMV). The DC-DC converters in EVs are controlled by various linear and non-linear controllers [24]. Linear controllers have a basic design and are simple to implement. Nevertheless, their performance significantly deteriorates when the design parameters are changed or in the presence of load disturbances [25,26]. Intelligent controllers are being used to overcome these issues, and they have been successful in providing an exceptionally dynamic response with better stability and higher efficiency [27]. Intelligent controllers can also handle systems that are highly non-linear and complicated [28–30].

In EV converters, the primary objective of the optimization technique is to optimize the converter's structure and enhance other characteristics while considering a variety of limitations [31–33]. The converter's design can be improved by reducing the number of power electronic components and making the converter economical. Accordingly, the converter's efficiency can be enhanced by lowering switching and conduction loss, switching angle, and voltage/current ripple [34]. A multi-objective function aids in the achievement of all requirements for developing an optimized converter for EVs [35]. The design of a multi-objective function, on the other hand, is a time-consuming task that necessitates the assignment of numerous parameters, variables, and constraints, such as switching frequency, duty cycle, components count, switching angles, and input voltage/current. Akkaldevi et al. [36] introduces the quantitative validation carried out on a prismatic 20 Ah LiFePO4 battery sandwiched between two mini channel cold plates. Purohit et al. [37] two-layer feed-forward artificial neural-network-based machine learning to design soft sensors. Subsequently, estimate the state of charge (SOC), state of energy (SOE), and power loss (PL) of a formula student electric vehicle (FSEV) battery-pack system. Choudhari et al. [38] discuss the thermal performance of the battery module, which contains $5 \times 5$ li-ion battery arranged in series and parallel. In terms of battery equalization and self-heating, various authors widely utilized different strategies such as Integrated Self-Heater [39], Automotive Battery Equalizers [40], compact resonant switched-capacitor heater [41], and sine-wave heating circuit [42]. Apart from this, various reviewers believe that usage of some interpretable tool will be beneficial for power electronics integrated energy storage management [43,44].

The topological reviews on DC-DC converters and their controls have been carried out in numerous manuscripts, especially on EVs and renewable energy applications. The objectives, focused areas, and research gaps of these articles are summarized in Table 1. Chakraborty et al. [45] investigated different topologies of DC-DC converters used in EVs, giving additional attention to converter topologies and their evaluation. However, they omitted to review the DC-DC converters' controller and optimization approaches and related implementation challenges in EVs. This shortcoming was overcome by the review article of Anbazhagan et al. [31], which provided a detailed review on converters for EVs, emphasizing both isolated and non-isolated converters; nevertheless, control, function, optimization, and modulation were not covered in depth. The review article [46] provided an extensive overview of the multi-input DC-DC converters for EVs. However, it did not include the issues associated with implementing these converters in EV applications. Different DC-DC converters in EV applications were described and compared [47]. However, the converter's description was confined to limited control methods. Furthermore, like [31], the manuscript failed to provide insight into the DC-DC converters' operation, optimization, and modulation. Therefore, it can be stated that the majority of these articles failed to provide an effective review of the control and performance optimization of DC-DC converters for EV applications. Thus, this review provides a detailed analysis and evaluation of various power electronics converters in the relevant 100 papers highlighting research trends, critical analyses, contributions, and research gaps. This review adopts a statistical approach to analyze publication year, authorship, journals, publisher, university, country, and collaboration. In addition, this review covers various key aspects, including comparative analysis among power electronic converters, types of the energy storage system, benefits of artificial intelligence (AI), controllers, and optimization in EV power converters. Furthermore, numerous key issues and challenges are explored, and accordingly, effective suggestions and insightful remarks are outlined.

**Table 1.** The notable studies on EV power electronics converters, focused areas, and research gaps.

| Objectives | Focused Areas | Research Gaps | Ref |
|---|---|---|---|
| Reviewing DC-DC converters for EVs | • Focus on the converter topologies for plugged-in hybrid vehicles.<br>• A thorough review of converters for charging stations. | • No information on the converter's controllers.<br>• Omitted to review the converter's optimization methods. | [45] |
| Reviewing isolated and non-isolated converters for EVs | • Detailed review on the isolated and non-isolated converters for EV applications. | • No emphasis was given on the converters' control, operation, performance, or optimization. | [48,49] |
| Reviewing DC-DC converters for EVs | • A topological comparison of the converters is presented in terms of EV applications.<br>• Some control methods are analyzed. | • Only a few control methods of converters were discussed.<br>• No emphasis was given on the performance and optimization of converters.<br>• Issues and challenges of implementing converters are not discussed. | [47] |
| • Reviewing multi-input DC-DC converters for EVs.<br>• Reviewing energy sources for EVs. | • Detailed review on different multi-input converter topologies for EV and renewable energy applications.<br>• Cost analysis on the energy sources for EV applications. | • Only multi-input converters are considered.<br>• No emphasis was given on the converters' control, operation, performance, or optimization.<br>• Issues and challenges of implementing converters are not discussed. | [50–52] |
| Reviewing multi-input DC-DC converters and their controls for battery charge balancing in EVs. | • A comprehensive review of various converters for EVs.<br>• A comprehensive review of the control methods of converters for EV applications.<br>• Issues and future trends associated with converters'based battery charge balancing in EVs are discussed briefly. | • No discussion is provided on the controller optimization and performance of the converters. | [53,54] |

**Table 1.** *Cont.*

| Objectives | Focused Areas | Research Gaps | Ref |
| --- | --- | --- | --- |
| 1. Reviewing non isolated converters for EVs.<br>2. Reviewing energy sources for EVs. | • Detailed review and comparative analysis on the non-isolated converters for EV applications.<br>• Implementation of various energy sources in practical EVs are discussed extensively. | • No emphasis was given on the converters' control, operation, performance, or optimization.<br>• Issues and challenges of implementing converters are not discussed. | [55] |
| Reviewing DC-DC converters for battery storage systems in EVs and grid applications. | • A comprehensive review on converters for battery storage systems in EVs and grid systems.<br>• Focus on the charge control methods of batteries for EVs and grids.<br>• Issues and future recommendations for implementing converters in EVs are discussed briefly. | • No emphasis was given on the converters' control, operation, performance, or optimization. | [56] |

Analytical assessment is a type of research article that combines the library and information science with statistics and quantitative approaches to provide information and analysis in a variety of formats [57,58]. Emerging trends and analytical evaluation are important areas because they provide historical and extensive information that can be used to address future challenges and provide appropriate recommendations [59,60]. Analytical assessment can be used by researchers, higher education institutions, and their respective students and lecturers to evaluate a journal article's quality utilizing a range of key factors like citations, h-index, impact factors, and quartiles. Gingras [61] looked at the impact of analytical assessment on research objectives and offered a few guidelines and criteria for building an appropriate assessment technique for a certain research plan and analysis size. Andres [62] discussed the procedures, significance and impacts of analytical analysis in real-world applications. This paper performs an analytical analysis to look at the present state of published activity in power electronic DC-DC converters for EV applications.

In literature, some analytical assessment articles can be found that are based on EVs such as reliability of EVs [63], fuzzy optimization control based EVs [64], autonomous vehicles [65], optimization of energy management schemes in EVs [66], advanced and next-generation EVs [67], EV battery industries' expansion in China [68] are just a few of the analytical assessment analyses conducted on EVs and their applications. As of now, no analytical analysis of DC-DC power converters for EV applications has been performed, to our knowledge. Therefore, this study describes the first analytical evaluation of power converters applied in EV applications, which was conducted from the year 2010 until November 2021 to look at the articles, investigation, achievements, and innovation, and recent advances in this field. The key findings and overall contributions of this paper are highlighted below.

- In terms of the number of articles published to date, a brief synopsis of DC-DC converters for EV applications is presented. The analysis is carried out once a year and is followed by a discussion.
- Power converters for EV applications are analyzed using the most cited authors, the universities with the highest number of articles, and the nation with the most published articles on the discussed topic. This is vital for determining author, organization, and country productivity in the discussed topic and enhancing research production and collaboration among authors.
- The keywords and topics used in the content analysis and gap analysis are assessed.
- Original manuscripts, review articles, and book chapters are among the studied document categories. The impact factors of the journals and the reputation of the publishers in the research community are also analyzed.

- The extent of collaboration between researchers is identified. The number of authors in the manuscripts and the links between different universities and countries are utilized to evaluate the team.

The emerging trends and analytical assessment aim to explore the 100 most significant publications in power electronics converter (PEC) for EV applications. Accordingly, complete and detailed information, critical debates, facts, analyses, achievements and shortcomings, issues, and challenges of these publications are presented. This review offers several benefits, including,

- To provide the history, current trends, evolution, applications, and future research opportunities of PEC in EV applications.
- To deliver a comparative study of the most appropriate papers for PEC in EVs that will support the future expansion of present knowledge, experience, and implementation.
- Finally, this analytical assessment provides constructive suggestions for the development and prospects of PEC in EV applications.

This review is structured into six sections. Section 1 describes an outline of the PEC and analytical assessment along with contributions and research gaps; Section 2 highlights the approaches and procedures of the surveying methodology for analytical evaluation; Section 3 covers an in-depth investigation of the selected manuscripts on PEC in EV applications. Section 4 explores the numerous existing issues, limitations, and issues. The future research opportunities and suggestions are depicted in Section 5, while Section 6 delivers the conclusion.

## 2. Survey Methods

This work was conducted in end of November, 2021 using the bibliometric technique, a statistical analysis of the Scopus database (www.scopus.com, accessed on 5 November 2021). The Scopus database was utilized as an article source in this bibliometric study because it has a greater quantity of publications than other platforms and databases, such as Web of Science [69]. Google Scholar is not examined in this study [70] due to a lack of credible results. The analysis was taken place at the end of November 2021. The bibliometric analysis approaches used in the Scopus database are illustrated in Figure 2. The technique is separated into five steps, as shown in the diagram below:

### *2.1. Inclusion and Exclusion Criteria*

The papers were chosen using predetermined conditions from the Scopus database. The fundamental searching keywords code for article search from the Scopus database is shown in Table 2. For the 100 most noteworthy publications in the area of PEC technology integrated energy storage management (ESM) in EV applications, the following criteria for article inclusion and exclusion were used:

- Keywords like converter, energy storage, and electric vehicle were used as the major criterion for paper inclusion. Some articles were excluded manually due to the field's insignificance.
- Manuscripts written in the English language that were published between 2010 and 2021 were analyzed for this bibliometric analysis.

### *2.2. Screening Procedures*

As the number of published papers varies under different databases, the following criteria and procedures were utilized to find the most appropriate publication from the Scopus database.

- A total of 1954 ($n$ = 1954) manuscripts were selected from the fundamental selection process.
- A total of 1704 ($n$ = 1704) research papers were selected after employing year limitation range from 2010 to 2021.
- By defining topic areas, a total of 1688 ($n$ = 1688) articles were chosen.

- Then, a total of 659 articles were selected by limiting document type (Article and Review).
- By applying the "English Language" filter, a total of 612 ($n$ = 612) articles were chosen.
- Finally, on the basis of relevancy, a total of 100 ($n$ = 100) manuscripts were selected for the final evaluation from the Scopus database.

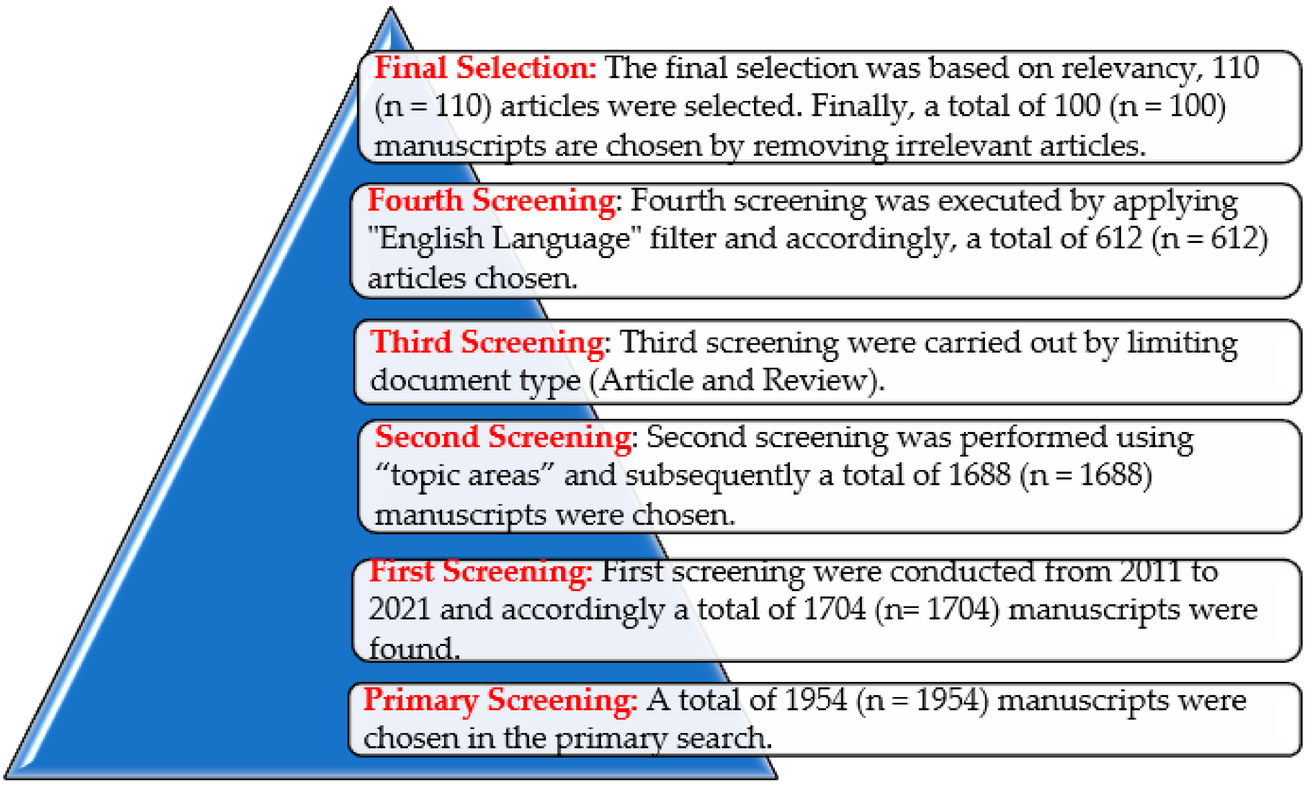


**Figure 2.** Manuscript's selection stages from Scopus database.

**Table 2.** Searching codes to find the most relevant 100 manuscripts from the Scopus database.

| Step | Types of Filtering | Search Code | Number of Manuscripts |
|---|---|---|---|
| Primary | By keyword: Converter Energy Storage Electric Vehicle | TITLE-ABS-KEY (converter AND energy AND storage AND electric AND vehicle) | 1954 |
| 2nd | Year (2010–2022) | TITLE-ABS-KEY (converter AND energy AND storage AND electric AND vehicle) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010)) | 1704 |

**Table 2.** *Cont.*

| Step | Types of Filtering | Search Code | Number of Manuscripts |
| --- | --- | --- | --- |
| 3rd | Subject area | TITLE-ABS-KEY (converter AND energy AND storage AND electric AND vehicle) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010)) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "CENG") OR LIMIT-TO (SUBJAREA, "CHEM")) | 1688 |
| 4th | Document Type (Article and Review) | TITLE-ABS-KEY (converter AND energy AND storage AND electric AND vehicle) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010)) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "CENG") OR LIMIT-TO (SUBJAREA, "CHEM")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) | 659 |
| 5th | Language (English) | TITLE-ABS-KEY (converter AND energy AND storage AND electric AND vehicle) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018) OR LIMIT-TO (PUBYEAR, 2017) OR LIMIT-TO (PUBYEAR, 2016) OR LIMIT-TO (PUBYEAR, 2015) OR LIMIT-TO (PUBYEAR, 2014) OR LIMIT-TO (PUBYEAR, 2013) OR LIMIT-TO (PUBYEAR, 2012) OR LIMIT-TO (PUBYEAR, 2011) OR LIMIT-TO (PUBYEAR, 2010)) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "ENER") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "MATH") OR LIMIT-TO (SUBJAREA, "PHYS") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "MATE") OR LIMIT-TO (SUBJAREA, "CENG") OR LIMIT-TO (SUBJAREA, "CHEM")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re")) AND (LIMIT-TO (LANGUAGE, "English")) | 612 |

### *2.3. Research Trend*

To develop more efficient ESM for EV applications, researchers are currently doing lots of research on PEC [71–80]. The researchers use different power electronics converters to provide more effective energy storage management. Figure 3 shows the research trend from 2010 to 2021, showing an upward trend. The number of published articles rises along with time, which means researchers are more focused on the field of PEC, as seen in Figure 3. A total of 1954 articles were published between 2010 and 2021. The figure shows a constant growth in terms of the number of publications. Apart from this, the figure illustrates a different trend after 2012, and the figure was 78 in 2013, which was lower than the previous year's total publication. According to Figure 3, the research articles in the area of PEC integrated ESM in EV applications have increased linearly along with time.

### *2.4. Data Extraction*

The following criteria were used to extract information from the selected most relevant 100 manuscripts: name of the authors, types of converters, abbreviated keywords, types of manuscripts (original research work and review paper), name of the journal, publisher name, publication year, name of the corresponding authors affiliated country, and the number of total citations. Following the study of the data from the selected manuscript, a conclusion is drawn to offer a complete picture of energy storage strategies for EV applications.

### *2.5. Study Characteristics and Findings*

The Scopus database yielded a total of 1954 papers from the elementary search. The highly appropriate 100 manuscripts were selected and depicted in Table 2 with the name of the authors, types of converters, abbreviated keywords, types of manuscripts (original research work and review paper), name of the journal, publisher name, publication year, name of the corresponding authors' affiliated country, and the number of total citations, respectively. The selected manuscripts have a total of 4014 citations (mean 40.14; median 18.5; and citation range 0 to 809). In addition, 11 of the 100 articles received over 100 citations. With 809 citations and an impact factor (IF) of 6.153, Cao et al. [81] authored the most cited manuscripts in the "IEEE Transactions on Power Electronics" journal in 2012.

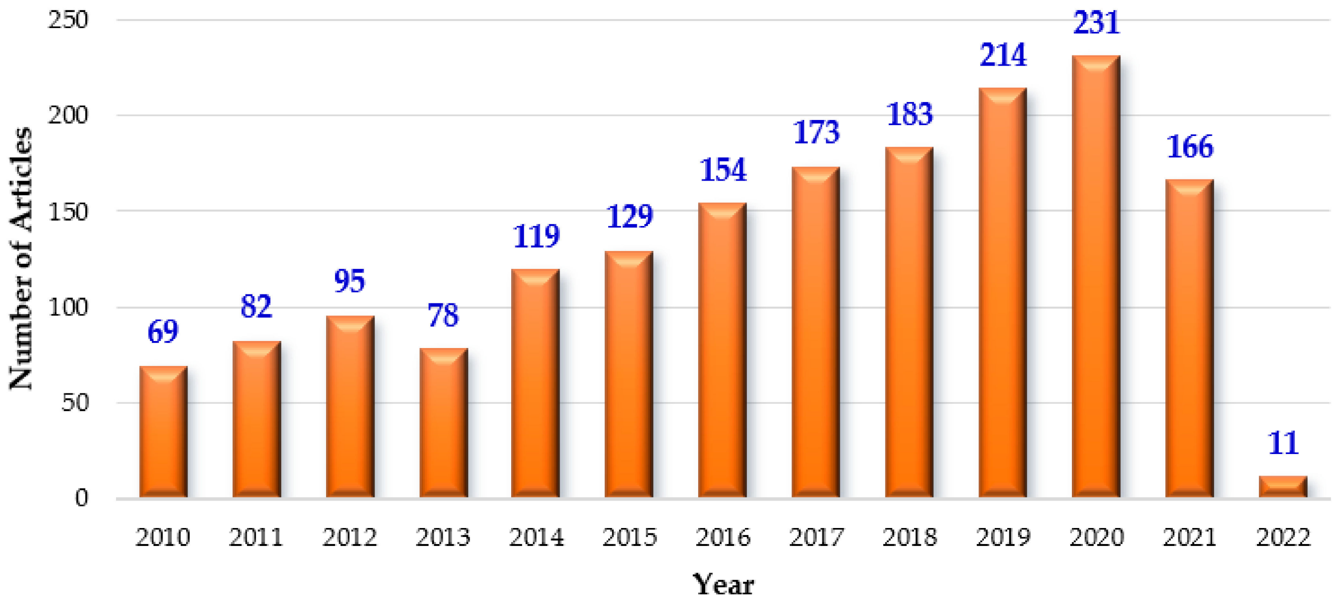


**Figure 3.** Conducted research works on the field of PEC integrated ESM for EV applications between 2010 and 2022.

## 3. Analytical Discussion

The most relevant article analysis in a certain field is important for categorizing and understanding current research trends and providing a solid indication of the influence of a journal. This analytical discussion aims to provide a clear indication about the most valuable articles, recent research trends, outcomes, critical discussion in PEC integrated ESM in EVs.

### *3.1. Citation Evaluation of the Highly Influential Publications*

The 100 most influential publications in the area of PEC integrated ESM in EV application, as collected from the Scopus database, are depicted in Table 3. It is noticed from Table 3 that the number of citations for the 100 selected relevant manuscripts ranged from 0 to 809; the first three manuscripts each had above 150 citations, and the initial 11 papers each contained 100 citations. Cao et al. published the paper with the greatest number of citations in 2012, while Fang et al. produced the manuscript with the lowest number of citations in 2021.

**Table 3.** The most relevant 100 articles in the field of PEC integrated ESM in EV applications.

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | [81] | Cao et al. | a larger DC-DC converter | Hybrid Energy Storage System | Battery; Control; DC/DC converters; EV; ES; HEV; PHEV; PE; propulsion systems; UC | Article | ITPEE | IEEE | 2012 | United States | 809 |
| 2 | [82] | Song et al. | Unidirectional DC-DC converter | Hybrid Energy Storage System | EV; HESS; LiFePO4 battery degradation; multi-objective optimization | Article | APEND | Elsevier Ltd. | 2014 | China | 193 |
| 3 | [83] | Zheng et al. | a hybrid cascaded multilevel converter | Battery Storage | BC; charging and discharging; EV; hybrid cascaded multilevel converter; voltage balance | Article | ITPEE | IEEE | 2014 | China | 168 |
| 4 | [84] | Nahavandi et al. | a new non isolated multi-input multioutput DC-DC boost converter | Hybrid Energy Storage System | DC-DC converters; EV; hybrid power system; MIMO; small-signal modeling; state-space averaging | Article | ITPEE | IEEE | 2015 | Iran | 148 |
| 5 | [85] | Laldin et al. | DC-DCDC-DC converter | Hybrid Energy Storage System | BMS; DC-DC converters; DC; EVs; EM; HESS; UC | Article | ITPEE | IEEE | 2013 | United States | 144 |
| 6 | [86] | Samosir et al. | a bidirectional DC-DCDC-DC converter | Hybrid Energy Storage System | BDC; dynamic evolution control; FC; UC; ES | Article | ITIED | IEEE | 2010 | Indonesia | 133 |
| 7 | [87] | El Fadil et al. | a boost-buck converter | Hybrid Energy Storage System | DC-DC power converters; EV; FC; nonlinear control; SC | Article | ITVTA | IEEE | 2014 | Morocco | 132 |
| 8 | [88] | Blanes et al. | interleaved bidirectional buck-boost converter | Hybrid Energy Storage System | Battery; EV; EM; field-programmable gate array; interleaved DC-DC converter; UC | Article | ITPEE | IEEE | 2013 | Spain | 128 |
| 9 | [89] | Song et al. | two bi-directional DC-DC converters | Hybrid Energy Storage System | EV; HESS; Lyapunov function-based controller; sliding-mode controller; SC | Article | ENEYD | Elsevier Ltd. | 2017 | China | 109 |
| 10 | [90] | Akar et al. | a novel bidirectional non isolated multi-input converter | Hybrid Energy Storage System | Batteries; bidirectional; HESSs; multi-input converter; UC | Article | ITVTA | IEEE | 2016 | Turkey | 109 |
| 11 | [91] | Rubino et al. | - | Battery Storage | ESS; PEV charging infrastructure; PEV; PEC; SG | Article | APEND | Elsevier Ltd. | 2017 | Italy | 104 |
| 12 | [92] | Wang et al. | DC-DC converter | Hybrid Energy Storage System | Direct current to direct current converter; EV; EMS; HESS | Article | JPSOD | Elsevier B.V. | 2015 | China | 90 |
| 13 | [93] | Ahrabi et al. | a multi-input dc-dc converter | Fuel Cell Storage | HEV; multi-input converter; PM | Article | ITPEE | IEEE | 2017 | Iran | 81 |

**Table 3.** *Cont.*

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | [94] | Rivera et al. | a grid-tied neutral-point-clamped converter | Battery Storage | Bipolar DC bus; EVs; ESS; FC; power balance management; three-level dc-dc converter | Article | ITPEE | IEEE | 2017 | Canada | 76 |
| 15 | [95] | Wang et al. | boost converter | Hybrid Energy Storage System | Adaptive sliding-mode control; boost converter; EVs; HESS; mode switch strategy | Article | ITIED | IEEE | 2017 | China | 75 |
| 16 | [96] | Varajao et al. | high-frequency link matrix converter | Battery Storage | AC-DC power conversion; BC; ES; matrix converters; silicon carbide; soft switching; space vector pulse width modulation | Article | ITIED | IEEE | 2018 | Portugal | 68 |
| 17 | [97] | Capasso et al. | AC-DC converter | Battery Storage | CS; EV; ES; HEV; V2G | Article | APEND | Elsevier Ltd. | 2015 | Italy | 64 |
| 18 | [98] | Amjadi et al. | a hybrid switched-capacitor bidirectional DC-DCDC-DC converter | Supercapacitor Storage | BS; capacitors; CS; efficiency; EVs; PE | Article | ITIED | IEEE | 2010 | Canada | 64 |
| 19 | [99] | Lai et al. | bidirectional DC-DC converter | Battery Storage | BDC; dual battery storage; HEV | Article | ITVTA | IEEE | 2018 | Taiwan | 59 |
| 20 | [100] | Sun et al. | a flywheel energy storage system converter | Flywheel energy storage | distributed control; fast charging stations; flywheels; PEV | Article | ITPEE | IEEE | 2016 | Denmark | 59 |
| 21 | [101] | Jyotheeswara et al. | multi-input DC-DC converter | Hybrid Energy Storage System | Battery; flywheel; FC; HEV; multi-input DC-DC converter; UC | Review | IJHED | Elsevier Ltd. | 2018 | India | 55 |
| 22 | [102] | Geetha et al. | power electronic converters | Hybrid Energy Storage System | Battery; EV; EMS; HESS; UC | Review | IJERD | John Wiley and Sons Ltd. | 2017 | India | 55 |
| 23 | [103] | Amjadi et al. | a hybrid switched-capacitor bidirectional DC-DC converter | Hybrid Energy Storage System | BS; control; DC-DC power conversion; efficiency; EV; ES; PE | Article | ITSG | IEEE | 2012 | Canada | 50 |
| 24 | [104] | Kasimalla et al. | - | Hybrid Energy Storage System | Battery; BDC; EM; FC; regeneration energy; UC | Review | IJERD | John Wiley and Sons Ltd. | 2018 | India | 48 |
| 25 | [105] | Gan et al. | a modular multilevel converter | Battery Storage | Battery fault tolerance; charging and discharging; flexible DC-bus voltage; HEV; MMC; SRM | Article | ITPEE | IEEE | 2019 | China | 47 |

**Table 3.** *Cont.*

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 26 | [106] | Veneri et al. | a bidirectional DC-DC converter | Hybrid Energy Storage System | Dynamic test bench; SC; EV; EMS; HESS; ZEBRA batteries | Article | APEND | Elsevier Ltd. | 2018 | Italy | 47 |
| 27 | [107] | Pires et al. | two new non-isolated DC-DC converters | Fuel Cell Storage | FCEV; low-voltage stress; non-isolated converter; Quadratic Boost and Cuk converters; single-switch; wide voltage-gain | Article | ITVTA | IEEE | 2019 | Portugal | 41 |
| 28 | [108] | Zhang et al. | DC-DC converter | Hybrid Energy Storage System | Battery life; EV; EM; HESS | Article | ITPEE | IEEE | 2020 | China | 40 |
| 29 | [109] | Jiang et al. | bidirectional converter | Battery Storage | BDC; dynamic characteristic; harmonic analysis; single-stage; V2G | Article | Energies | MDPI AG | 2014 | China | 39 |
| 30 | [110] | Wang et al. | a bidirectional (Bi) DC-DC converter | Hybrid Energy Storage System | DC-DC; efficiency model; EV; energy loss; power dissipation; topology | Article | APEND | Elsevier Ltd. | 2016 | China | 38 |
| 31 | [111] | Muttaqi et al. | power-electronic converters | Hybrid Energy Storage System | EV; ES; future power grids; magnetic bus; RES; SC | Article | ITASE | IEEE | 2019 | Australia | 32 |
| 32 | [112] | Wen et al. | a hybrid-mode two-phase interleaved boost converter | Fuel Cell Storage | Continuous conduction mode; discontinuous conduction mode; efficiency; FCEV; input current ripple; interleaved boost converter; output voltage ripple | Article | ECMAD | Elsevier Ltd. | 2016 | China | 32 |
| 33 | [113] | Kandasamy et al. | cascaded H-bridge (CHB) converter | Battery Storage | Amphibious vehicles; BMS; bridge circuits; charging (batteries); EB; EV; fault tolerance | Article | IETPE | IET | 2015 | Singapore | 32 |
| 34 | [114] | Mukherjee et al. | dc-side modular multilevel converter | Hybrid Energy Storage System | Boost-multilevel buck converter; comparison; HESS; multiple battery types; second-life battery energy storage systems | Article | IJESTP | IEEE | 2016 | United King-dom | 30 |
| 35 | [115] | Wang et al. | boost converter | Hybrid Energy Storage System | Adaptive sliding-mode control; boost converter; EV; EM; HESS; SC | Article | ECMAD | Elsevier Ltd. | 2017 | China | 27 |
| 36 | [116] | Amjadi et al. | a hybrid switched-capacitor bidirectional DC-DC converter | Hybrid Energy Storage System | BS; CS; efficiency; EV; PE; UC | Article | ITSG | IEEE | 2014 | Canada | 27 |
| 37 | [117] | Zhang et al. | bidirectional DC-DC converter | Hybrid Energy Storage System | Coupled inductor; DC-DC converter; HESS; soft-switching; ZVS | Article | ITIED | IEEE | 2018 | China | 26 |

**Table 3.** *Cont.*

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 38 | [118] | Badawy et al. | an interfacing DC-DC converter | Hybrid Energy Storage System | Battery; DC-DC converter; EV; HESS; interior permanent magnet; inverter; motor control; permanent magnet motor; UC | Article | ITIAC | IEEE | 2017 | United States | 26 |
| 39 | [119] | Michalczuk et al. | two DC-DC interleaved converters | Hybrid Energy Storage System | EV; FL; HESS; UC | Article | CODUD | Emerald Group Publishing Ltd. | 2015 | Poland | 26 |
| 40 | [120] | Lipu et al. | - | Battery Storage | BMS; lithium-ion batteries; EV; thermal management; fault diagnosis; battery equalization | Review | JCLP | Elsevier Ltd. | 2021 | Malaysia | 25 |
| 41 | [121] | Yang et al. | two bidirectional DC-DC converters | Hybrid Energy Storage System | Battery/supercapacitor HESS; EV; perturbation observer; robust fractional-order sliding-mode control | Article | JPSOD | Elsevier B.V. | 2020 | China | 25 |
| 42 | [122] | Amjadi et al. | a hybrid switched-capacitor bidirectional DC-DC converter | Hybrid Energy Storage System | BS; CS; efficiency; EV; PE; UC | Article | ITVTA | IEEE | 2011 | Canada | 24 |
| 43 | [123] | İnci et al. | Power converters | Fuel Cell Storage | Converters; EM; FCEV; future aspects; marketing; system topologies | Review | RSERF | Elsevier Ltd. | 2021 | Turkey | 23 |
| 44 | [73] | Sorlei et al. | DC-DC converters | Fuel Cell Storage | DC-DC converter topologies; EMS; FCEV; global optimization; real-time optimization; rule-based | Review | Energies | MDPI AG | 2021 | Romania | 22 |
| 45 | [124] | Khan et al. | an isolated hybrid multi-port converter | Battery Storage | BC; clean energy; EV; isolation; micro-grid; multi-port converter | Article | ITASE | IEEE | 2019 | Australia | 22 |
| 46 | [125] | Capasso et al. | a DC-DC bidirectional power converter | Hybrid Energy Storage System | Dynamic test bench; EMS; HESS; modelling of electric double layer capacitors | Article | APEND | Elsevier Ltd. | 2018 | Italy | 22 |
| 47 | [126] | Zhang et al. | DC-DC converter | Hybrid Energy Storage System | Controllers; cost-benefit analysis; cost effectiveness; DC-DC converters; EB; EE; EM; ES; HESS | Article | JCSE | Hindawi Publishing Corporation | 2016 | China | 22 |

**Table 3.** *Cont.*

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 48 | [127] | Wang et al. | two isolated soft-switching symmetrical half-bridge bidirectional converters | Hybrid Energy Storage System | Energy allocation; HESS; SC | Article | Energies | MDPI AG | 2020 | China | 21 |
| 49 | [128] | Li et al. | DC-DC converters | Hybrid Energy Storage System | EV; Energy distribution; four-wheel independent drive; HESS | Article | JCROE | Elsevier Ltd. | 2019 | China | 21 |
| 50 | [129] | Wang et al. | - | Hybrid Energy Storage System | DC-DC converter; EV; HESS; mode control strategy; SC | Article | JPE | Korean Institute of Power Electronics | 2015 | China | 20 |
| 51 | [130] | Malik et al. | high-power level DC-DC converters | Supercapacitor Storage | Charge pump capacitor; DC-DC converter; dynamic modeling; EV | Article | Energies | MDPI AG | 2020 | China | 19 |
| 52 | [131] | Mumtaz et al. | AC-DC-AC converter | Battery Storage | Adaptive PID; CS; hybrid power system; PHEVs; RES | Article | Energies | MDPI AG | 2017 | Pakistan | 18 |
| 53 | [132] | Kumar et al. | DC-DC converter | Hybrid Energy Storage System | batteries; EV; FC; HEV; motors; power converters; UC | Review | IJERD | John Wiley and Sons Ltd. | 2020 | India | 15 |
| 54 | [133] | Omran et al. | DC-DC and AC-DC converters | Hybrid Energy Storage System | DC-DC converters; EI; FC; HEV; HESS; superconducting magnetic energy storages | Article | IETEST | IET | 2018 | Iran | 15 |
| 55 | [134] | Chung et al. | modular multiphase dc-dc converter | Hybrid Energy Storage System | BS; current control; DC-DC power conversion; EM; ES; frequency control; PE | Article | ITTE | IEEE | 2017 | Canada | 15 |
| 56 | [135] | Trovão et al. | DC-DC converter | Hybrid Energy Storage System | Batteries; EV; EMS; HESS; motor drive DC input stability; SC | Article | APEND | Elsevier Ltd. | 2017 | Canada | 15 |
| 57 | [136] | Jha et al. | a multiport converter | Battery Storage | EV; ES; grid-connected photovoltaic systems; EMS; multiport converter | Article | Energies | MDPI AG | 2019 | India | 14 |
| 58 | [137] | Xia et al. | DC-DC converter | Hybrid Energy Storage System | DC-DC converter; EV; HESS; integrated magnetic structure; power dynamic limitation | Article | CJEE | IEEE | 2018 | China | 14 |

**Table 3.** *Cont.*

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 59 | [76] | Zhang et al. | DC-DC converter | Hybrid Energy Storage System | Case study; DC-DC converter; EV; EM; HESS; optimal sizing; smart grid | Review | RSERF | Elsevier Ltd. | 2021 | China | 13 |
| 60 | [138] | Becker et al. | two individual DC-DC converters | Battery Storage | BMS; EV; EMS; Li-ion battery system | Article | JEET | Korea Science | 2013 | Germany | 11 |
| 61 | [139] | Wang et al. | a new bidirectional three-level cascaded (BTLC) converter | Hybrid Energy Storage System | Deadbeat control; EV; HESS; three-level cascaded converter | Article | ITTE | IEEE | 2019 | China | 10 |
| 62 | [140] | Liu et al. | a switching bi-directional buck-boost converter | Hybrid Energy Storage System | HESS; Li-battery; SC; switching bi-directional buck-boost converter; V2G | Article | IEEE Access | IEEE | 2020 | China | 9 |
| 63 | [141] | Wang et al. | two associated DC-DC converters | Hybrid Energy Storage System | EM; HESS; PHEV; temperature uncertainty; Wavelet transform | Article | APEND | Elsevier Ltd. | 2019 | China | 9 |
| 64 | [142] | Liu et al. | bidirectional DC-DC converter | Battery Storage | BS; EV; energy internet; energy router; microgrid; PV | Article | Energies | MDPI AG | 2019 | China | 8 |
| 65 | [143] | Cheng et al. | a family of non-isolated DC-DC three-port converters | Hybrid Energy Storage System | Bi-directional loads; dual-input single-output; ES; RES; single-input dual-output; single-input single-output; three-port converter | Article | JPE | Korean Institute of Power Electronics | 2017 | Australia | 8 |
| 66 | [144] | Moradisizkoohi et al. | a double-input three-level converter | Hybrid Energy Storage System | Double-input converter; multilevel converter; RES; wide bandgap semiconductors | Article | ITIAC | IEEE | 2019 | United States | 6 |
| 67 | [145] | Bae et al. | a bidirectional DC-DC converter | Hybrid Energy Storage System | HESS; lead-acid battery; lithium-ion battery; HEV; state-of-charge | Article | JEET | Korean Institute of Electrical Engineers | 2018 | South Korea | 5 |
| 68 | [74] | Moradisizkoohi et al. | a voltage-quadrupler interleaved bidirectional dc-dc converter | Hybrid Energy Storage System | Bidirectional DC-DC converter; EV; interleaved converter; non-isolated converter; wide-bandgap devices | Article | ITIED | IEEE | 2021 | United States | 4 |
| 69 | [146] | Bindu et al. | - | Supercapacitor Storage | EV; induction motor; LFP battery; multi-input BDC; power flow; three phase inverter; UC | Article | IJR | Taylor and Francis Ltd. | 2020 | India | 4 |
| 70 | [147] | Wang et al. | a bidirectional non-isolated DC-DC converter | Hybrid Energy Storage System | BDC; HESS; low-voltage stress; wide-voltage gain range | Article | JPE | Springer | 2020 | China | 4 |

**Table 3.** *Cont.*

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 71 | [148] | Bai et al. | - | Hybrid Energy Storage System | EV; H∞controller; HESS; regenerative braking; SC | Article | IJAT | Korean Society of Automotive Engineers | 2019 | China | 4 |
| 72 | [149] | Vidhya et al. | an efficient bi-directional converter | Hybrid Energy Storage System | BDC; EMS; HESS; Indian driving cycle; light electric vehicle | Article | MEACB | SAGE Publications Ltd. | 2019 | India | 4 |
| 73 | [75] | Daya et al. | a novel non-isolated multi-input DC-DC boost converter | Battery Storage | charging; controller; DC-DC boost converter; discharging; EV; small signal model | Article | IJEEPS | De Gruyter Open Ltd. | 2021 | India | 3 |
| 74 | [150] | de Melo et al. | an interleaved bidirectional DC-DC converter | Supercapacitor Storage | Bidirectional power flow; DC-DC converters; EV; interleaving; SC | Article | EENGF | Springer | 2020 | Brazil | 3 |
| 75 | [151] | Veerendra et al. | 4-level converter | Hybrid Energy Storage System | fuel cell and battery; HEV; multilevel converter; switched reluctance motor | Article | IJAED | Taylor and Francis Ltd. | 2020 | Malaysia | 3 |
| 76 | [152] | Joseph et al. | a hybrid forward-boost converter | Hybrid Energy Storage System | Charging (batteries); ES; RES; charging efficiency; electric vehicle charging; ESS; DC-DC converters | Article | IETPE | IET | 2019 | India | 3 |
| 77 | [153] | Zhang et al. | a soft switching DC-DC converter | Hybrid Energy Storage System | DC-DC converter; EV; HESS; sliding mode control; soft switching | Article | EPCS | Taylor and Francis Inc. | 2017 | China | 3 |
| 78 | [154] | Jiang et al. | a bidirectional DC-DC converter | Hybrid Energy Storage System | Bidirectional; DC-DC converter; HESS; maximum efficiency; peak-valley control; variable frequency control; zero voltage switching | Article | IJPE | Inderscience Publishers | 2014 | China | 3 |
| 79 | [155] | Rahman et al. | DC-DC converters | Hybrid Energy Storage System | Fuzzy based EM; HESS; hydrogen fuel consumption; super twisting sliding mode control | Article | JES | Elsevier Ltd. | 2021 | Pakistan | 2 |
| 80 | [156] | Suresh et al. | four-port converter | Battery Storage | BS; BDC; EV; multi-port converter; regenerative charging | Article | IEEE Access | IEEE | 2021 | India | 2 |
| 81 | [157] | Tseng et al. | a full-bridge DC-DC converter | Hybrid Energy Storage System | CS; DC-DC converters; LVP; light rail transit; SC; charging current; HESS | Article | IETPE | IET | 2020 | Taiwan | 2 |
| 82 | [158] | Lai et al. | a patented bidirectional power converter | Hybrid Energy Storage System | Battery/ultracapacitor; BDC; dual-energy; EV | Article | Energies | MDPI AG | 2020 | Taiwan | 2 |

**Table 3.** *Cont.*

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 83 | [159] | Deng et al. | a novel multiphase bidirectional DC-DC converter | Fuel Cell Storage | BDC; EM; FCEV; real-time digital simulator | Article | JPE | Korean Institute of Power Electronics | 2011 | United States | 2 |
| 84 | [78] | Chelladurai et al. | an interval type-2 fuzzy logic-controlled shunt converter | Battery Storage | Battery charger; EVs; FLC; power quality; total harmonic distortion | Article | ITII | IEEE | 2021 | India | 1 |
| 85 | [160] | Lipu et al. | power electronics converters | Battery Storage | BSS; DC-DC converter; EV; intelligent controller; meta-heuristic optimization; modulation techniques | Review | Electronics | MDPI AG | 2021 | Malaysia | 1 |
| 86 | [161] | Eroğlu et al. | Multilevel converters | Battery Storage | Automotive batteries; BMS; charging (batteries); EPTN; PC; RES; V2G; EVs | Article | IETRPG | John Wiley and Sons Inc | 2021 | Turkey | 1 |
| 87 | [162] | Tirpude et al. | a bidirectional DC-DC converter | Hybrid Energy Storage System | CS; EV; EMS; HESS; lithium-ion battery; neural network; Proportional-Integral (PI) controller; SC | Article | IJETER | World Academy of Research in Science and Engineering | 2020 | India | 1 |
| 88 | [163] | Devi et al. | a modular multilevel capacitor clamped converter | Hybrid Energy Storage System | CS; EV; failure (mechanical); LVP; MATLAB; outages; regenerative braking; SB; SC; BDC | Article | IETPE | IET | 2019 | India | 1 |
| 89 | [164] | Kolbasov et al. | photovoltaic (PHV) converters | Hybrid Energy Storage System | Charging infrastructure; CS; EV; photoelectric converters; solar battery | Article | Energies | MDPI AG | 2019 | Russian Federation | 1 |
| 90 | [165] | Amjadi et al. | a 4-quadrant (4-Q) switched-capacitor (SC) Luo bidirectional DC-DC converter | Hybrid Energy Storage System | BS; CS; EVs; PE; UC | Article | IJPE | Inderscience Publishers | 2011 | Canada | 1 |
| 91 | [166] | Amjadi et al. | a two-quadrant hybrid switched capacitor (SC) converter | Hybrid Energy Storage System | BS; Capacitors; CS; DC-DC converters; EV; ES; PE | Article | IJEHV | Inderscience Publishers | 2011 | Canada | 1 |
| 92 | [167] | Ebrahimi et al. | DC-DC converters | Hybrid Energy Storage System | DC-AC converters; EVs; HESS; multisource inverters; SVM | Article | ITPEE | IEEE | 2022 | Canada | 0 |

**Table 3.** *Cont.*

| Rank | Ref. | Authors | Converter Type | Energy Storage Type | Author Keywords | Article Type | Journal Abbreviation | Publisher | Year | Country | Citation |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 93 | [168] | Suresh et al. | a modular multi-input bidirectional DC-DC buck-boost converter | Hybrid Energy Storage System | BESS; DC-DC multi-port converter; UC | Article | JASE | Tamkang University | 2022 | India | 0 |
| 94 | [169] | de Oliveira-Assis et al. | integrates Z-source converters | Hybrid Energy Storage System | EV; EMS; hydrogen system; microgrid; PC | Article | ECMAD | Elsevier Ltd. | 2021 | Spain | 0 |
| 95 | [80] | Shi et al. | an additional cascaded DC-DC converter | Hybrid Energy Storage System | Dual-inverter; EV; EM; HESS; open-winding machine | Article | ITIED | IEEE | 2021 | Canada | 0 |
| 96 | [79] | Raman et al. | interleaved bi-directional converter | Hybrid Energy Storage System | Configurable EV; distributed ES; EV; HESS; interleaved converter; SC | Article | Energies | MDPI | 2021 | Hong Kong | 0 |
| 97 | [77] | Fang et al. | interleaved quasi-resonant converters | Battery Storage | High conversion ratio; onboard ESS; resonant converter; small characteristic impedance; zero current switching | Article | ITVTA | IEEE | 2021 | China | 0 |
| 98 | [170] | Shen et al. | a multi-port DC-DC converter | Hybrid Energy Storage System | battery life; EMS; FLC; HESS | Article | ITEEE | John Wiley and Sons Inc | 2021 | China | 0 |
| 99 | [71] | Katnapally et al. | multiple-input bidirectional DC-DC converter | Hybrid Energy Storage System | BDC; EV; HESS; model predictive control | Article | ICTAC | John Wiley and Sons Ltd. | 2021 | India | 0 |
| 100 | [72] | Fang et al. | grid-tied converters | Battery Storage | Active filters; ancillary services; batteries; capacitors; droop control; grid forming; phase locked loops; PC | Article | IJESTP | IEEE | 2021 | United States | 0 |

ES = Energy Storage, EV = Electric Vehicles, SB = Secondary Batteries, HV = Hybrid Vehicles, HESS = Hybrid Energy Storage Systems, EM = Energy Management, SC = Supercapacitor, PC = Power Converters, EMS = Energy Management Systems, EI = Electric Inverters, LVP = Land Vehicle Propulsion, FC = Fuel Cells, EB = Electric Batteries, FS = Fuel Storage, SM=Storage Management, BMS = Battery Management Systems, CS = Capacitor Storage, ELF = Electric Load Flow, EPTN = Electric Power Transmission Networks, UC = Ultracapacitors, EMC = Electric Machine Control, HVDCPT = HVDC Power Transmission, VA = Vehicle Applications, BS = Battery Storage, RES = Renewable Energy Resources, BDC = Bidirectional Converter, EES = Electric Energy Storage, EPSC = Electric Power System Control, EE = Energy Efficiency, PE = Power Electronics, PEC = Power Electronics Converter, HEV = Hybrid Electric Vehicle, RB = Regenerative Braking, SC = Solar Cells, V2G = Vehicle-to-grid, FL = Fuzzy Logic, PHEV = Plug-in Hybrid Vehicles, TM = Traction Motors, VC = Voltage Control, BP = Battery Pack, MIMO = Multiple-input-multiple-output, MMC = modular multilevel converter, SRM = switched reluctance motor.

The most referenced publication in the field of energy storage management in electric vehicles is "A New Battery/Ultracapacitor Hybrid Energy Storage System for Electric, Hybrid, and Plug-In Hybrid Electric Vehicles," along with 809 citations, which is generated by Cao et al. and published in the IEEE Transactions on Power Electronics journal in 2012 [81]. In this manuscript, the authors presented a novel battery and supercapacitor-based hybrid energy storage system (HESS) for electric drive cars, such as plug-in hybrid electric vehicles and hybrid electric vehicles. Experimental and simulation outcomes also validate the proposed HESS in EV applications. According to the citation, "Multi-Objective Optimization of a Semi-Active Battery/Supercapacitor Energy Storage System for Electric Vehicles" is an original article by Song et al. that evaluates a semi-active battery and ultracapacitor-based hybrid energy storage system for EV applications. To incorporate the supercapacitors and batteries in the proposed HESS, a considerably smaller unidirectional dc-dc converter was used, resulting in increased HESS efficiency and lower system costs [82]. In 2014, the manuscript was published in the "Applied Energy" journal, and it received 193 citations. "A Hybrid Cascaded Multilevel Converter for Battery Energy Management Applied in Electric Vehicles" [83] was the third most referenced paper published in the "IEEE Transactions on Power Electronics", publication in 2014. Zheng et al. produced the manuscripts, which obtained 164 citations. This research work suggests a hybrid cascaded multilayer converter for EV, which includes both battery energy management and motor drives. Each battery cell in the proposed topology may be connected to the circuit or bypassed by a half-bridge converter. According to Table 3, the first ten articles are the original research work.

### 3.2. Distribution of the 100 Manuscripts Chosen from 2010 to 2021

The allocation of the selected 100 most relevant manuscripts in PEC integrated ESM in EV applications from 2010 to 2021 is illustrated in Figure 4. The number of articles produced between the years 2010 and 2013 was around four. According to Figure 4, the article publication is highest in 2021 (17 research articles), while 2012 delivers the lowest research publication (two research articles) rate, respectively. With 13 manuscripts each, the number of articles published in 2017 and 2020 was the same. Generally, the manuscripts publication trend from 2012 to 2021 indicates an upward trend along with several fluctuations. The years 2014 demonstrate the same number of articles, indicating six.

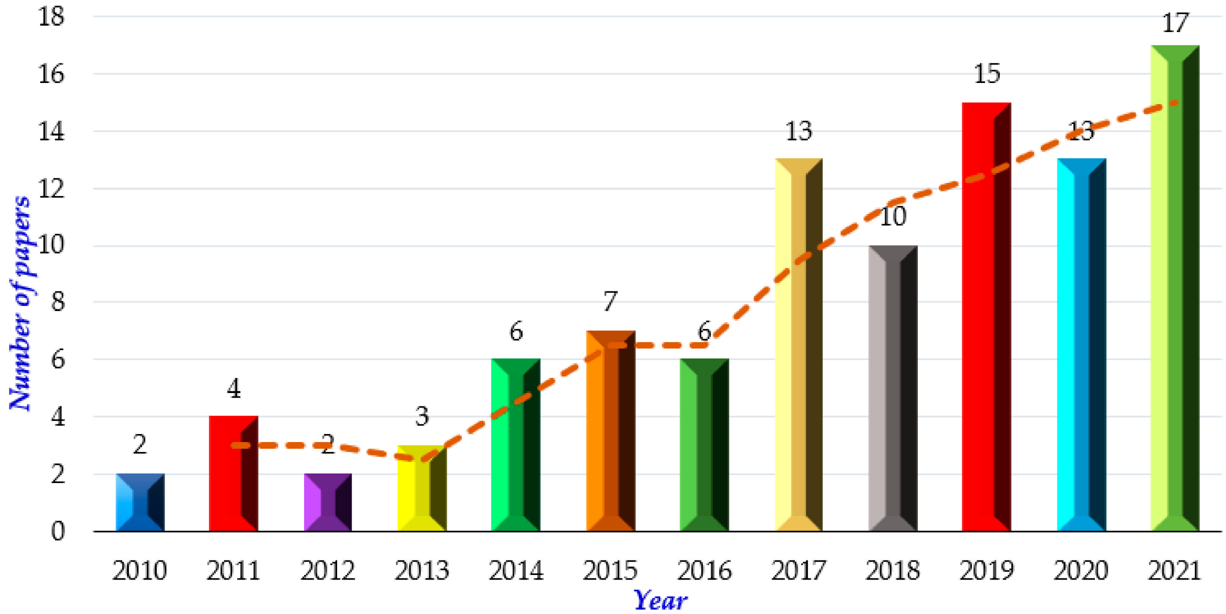


**Figure 4.** Distribution of selected research articles from 2010 to 2021.

### 3.3. Co-Occurrence Keyword Analysis

Table 4 and Figure 5 denote the co-occurrence keyword analysis obtained from the 100 most relevant publications using the Scopus database. Figure 5 depicts the connective network of highly frequent keywords produced in the VOSviewer program. The impact of appropriate keywords determines the volume of the circle and label, but the connecting line between the keywords is portrayed as a conjunctive connection. Various colors are used to distinguish different clusters depending on the area of expertise. The power converters, plug-in electric vehicle, electric machine control, electric power transmission network, HVDC power control, voltage control, vehicle to grid, electric load flow, cascaded multilevel converter, and matrix converter are in the red cluster that represents the power converter-related factors. The blue cluster represents the optimization techniques and powers electronics converters such as fuzzy logic control, DC-DC converter, supercapacitor, interleaved converter, multilevel converter, multiport converter, automotive batteries, optimization, and multi-objective optimization for smooth power transition. Energy efficiency, energy management, voltage regulations, fuel cells, hybrid energy storage management, electric batteries are clustered by green color. Finally, electric vehicles, capacitor storage, ultracapacitors, controllers, control strategies, buck converter, switched capacitors, and power electronics, are directly connected to electric vehicles and presented by a yellow cluster.

Table 4 shows the top 15 general keywords from the selected database that were used in multiple papers between 2010 and 2021. Based on Table 4, the existing literature gaps may be identified, and insight into the current study area in the subject can be gained. “DC-DC Converters”, “Energy Storage”, and “Electric Vehicles” are the three most prevalent terms in Table 4. The values for “DC-DC Converters” and “Energy Storage” are 71 and 60, respectively, while “Electric Vehicles” has a figure of 45. “DC-DC Converters”, “Energy Storage”, and “Energy Management” have also been the most popular terms in the recent two years, reflecting the growing interest in energy storage management in EV application. The exact distribution of keywords and the graphical depiction of Table 4 are depicted in Figure 6. As a result of examining the data from the co-occurrence keywords in Figure 6 and Table 4, it can be concluded that:

- Researchers are now concerned not just with energy storage efficiency but also a focus on smooth energy transition.
- There has been a considerable rise in power electronics converter integrated energy storage management in EV applications.
- Scholars are emphasizing power electronic converter controllers and optimizations to achieve stable power transfer between energy storage and motor.
- Nowadays, researchers are also moving towards renewable energy integration with EV applications.
- There has been a tremendous increase in employing bidirectional energy management systems in the vehicle to grid (V2G) and grid to vehicle (G2V) applications.
- Researchers are focusing on the applications of power electronic converters to develop fast-charging stations in EV applications.

### 3.4. Analysis of Power Electronic Converter in EVs in Relevant 100 Cited Papers

Based on the information on Table 3, the prominent power electronics converters employed in 100 top cited articles have been identified including cascaded multilevel converter [80,83,139], buck-boost converter [140,168], neutral point clamp converter [94], matrix converter [96], modular multilevel converter [105,134,163], interleaved boost converter [88,112,119], H-bridge converter [113], switched capacitor bidirectional converter [86,90,98], soft-switching DC-DC converter [117,127], z-source converter [169], quasi-resonant converter [77], and multi-phase DC-DC converter [134,159]. The objectives, advantages, and disadvantages of the aforesaid converters are highlighted in Table 5.

**Table 4.** Top-most 15 keywords from the selected 100 manuscripts between 2010 and 2021.

| Top Keywords | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | Frequency |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DC-DC Converters | [86,98] | [122,165,166,171] | [81,103] | [85,88,138] | [82,87,109,116,154] | [84,92,97,113,119,129] | [90,100,110,112,114,126] | [89,93–95,102,115,118,131,134,135,143,153] | [99,101,106,117,125,133] | [107,128,139,141,142,144,148,152,163] | [108,121,130,132,140,147,157] | [71,73–76,78,80,156,170] | 71 |
| Energy Storage | [86] | [159,165,166] | [81,103] | [85] | [82,87,116,154] | [92,97,119,129] | [90,100,110,114,126] | [89,91,94,95,102,115,134,135,143,153] | [96,99,104,106,117,145] | [105,111,128,139,141,148,152] | [108,121,127,132,140,147,150] | [71–80] | 60 |
| Electric Vehicles | [86] | [122,165,166] | [81,103] | [85,88,138] | [83,87,116,154] | [84,92,97,113,119,129] | [100,110] | [94,102,115,118,135,153] | [106,137] | [111,124,128,142,148,163,164] | [108,121,132,146,150,158] | [78,156,169] | 45 |
| Secondary Batteries | 0 | [122,159] | [81,103] | 0 | [82] | [92,113,119,129] | [100,114,126] | [89,95,102,131,135] | [96,99,104,106,117,133,145] | [105,128,139,141,142,148,163,164] | [127,140,151,158] | [71,76,80,155] | 42 |
| Energy Management | 0 | [159] | 0 | [85,88] | 0 | [92,119] | [126] | [89,93,102,115,131,134,135] | [104,106,125] | [136,141,148] | [108,121] | [73,76,80,123,169] | 26 |
| Charging (batteries) | 0 | 0 | 0 | 0 | [83] | [97,113] | [100] | [91,94,131,134,135] | [145] | [105,124,128,136,148,152,164] | [127,140,146] | [78,155,161,170] | 24 |
| Controllers | [98] | [122,165,166] | 0 | 0 | [87,116] | 0 | [126] | [89] | 0 | [148] | [121,140] | [78,155] | 13 |
| Electric Power Transmission Networks | 0 | 0 | 0 | 0 | [109] | [97] | [114] | [91,131] | [96] | [111,124,136] | 0 | [72,76,161] | 12 |
| Renewable Energy Resources | 0 | 0 | 0 | 0 | 0 | [97] | 0 | [91,131,143] | 0 | [124,144,152] | [130] | [161] | 10 |
| Energy Efficiency | 0 | 0 | 0 | 0 | 0 | 0 | [110,126] | [89,153] | 0 | [111,128,136] | [150] | [73] | 9 |
| Power Electronics | [98] | [122,165,166] | [81,103] | 0 | [116] | 0 | 0 | [134] | 0 | 0 | 0 | [156] | 9 |

**Table 4.** *Cont.*

| Top Keywords | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | Frequency |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuzzy Logic | 0 | 0 | 0 | 0 | 0 | [119] | 0 | 0 | 0 | [141] | [108,146] | [78,155,170] | 7 |
| Voltage Control | 0 | 0 | 0 | 0 | [109] | [113] | 0 | 0 | [96,99] | [142] | [158] | [72] | 7 |
| Sliding Mode Control | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [89,95,115,153] | 0 | 0 | [121] | [155] | 6 |
| Energy Transfer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | [153] | [99] | [152] | [150] | 0 | 4 |

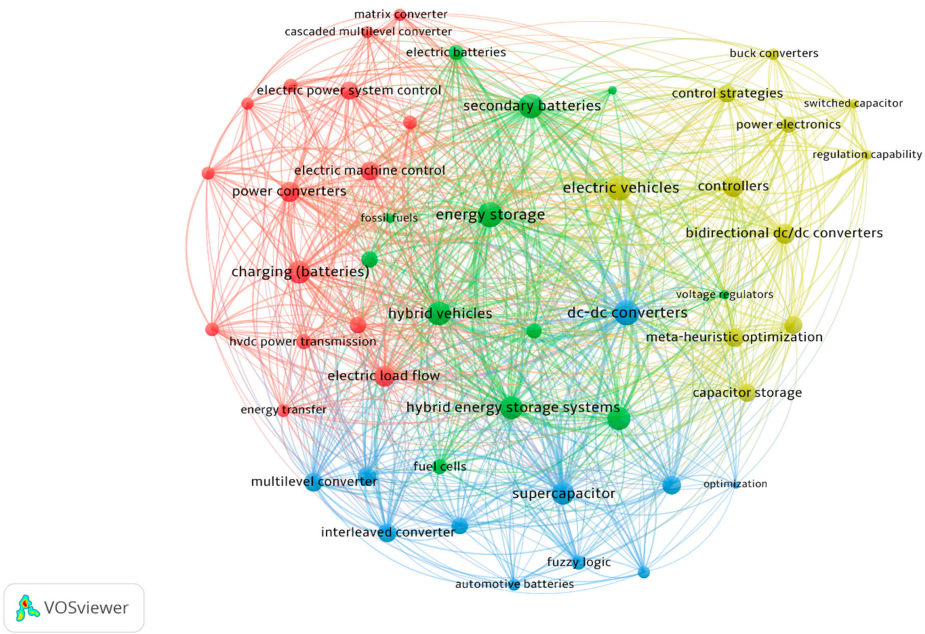


**Figure 5.** VOSviewer visualization for the analysis of co-occurrence keywords based on the Scopus database.

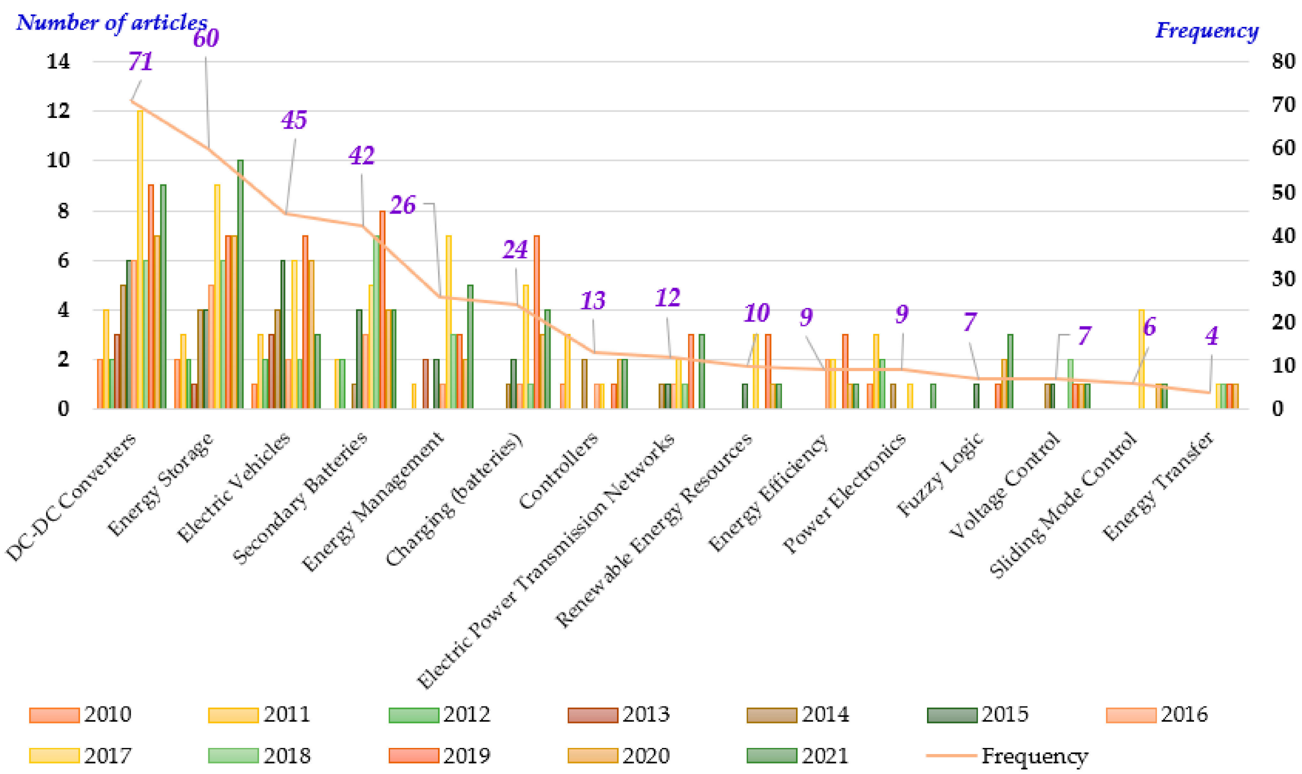


**Figure 6.** Distribution of topmost 15 keywords over the year 2010 to 2021.

**Table 5.** Comparative study of different power electronics converters used in EVs.

| Ref. | Type of Converter | Target | Advantages | Disadvantages |
| --- | --- | --- | --- | --- |
| [80,83,139] | Cascaded multilevel converter | • Achieve high-quality output voltages and input currents. | • Ability to synthesize more voltage levels.<br>• Less harmonic distortion due to the stepped level voltage output.<br>• Less noise generation.<br>• Ease of operation at lower switching frequencies. | • Higher number of power semiconductor switches required. |
| [140,168] | Buck-boost converter | • Deliver a range of output voltages, ranging from much larger than the input voltage down to almost zero. | • Provides efficient solutions.<br>• Smaller external components. | • Input current and charging current of the output capacitor is discontinuous, hence, large filter size and more EMI issues.<br>• Output is inverted, which results in complex sensing and feedback circuit. |
| [94] | Neutral point clamp converter | • Obtain multilevel voltage waveform through a split DC-link, using multiple sources and storage through a single converter. | • Superior waveform quality.<br>• Leading to reduced filtering requirements.<br>• Superior blocking voltage capability. | • Requires a greater number of diodes for increased levels.<br>• Capacitor voltage cannot be maintained as per the selected switching pattern. |
| [96] | Matrix converter | • Achieve automatic conversion of power from AC to AC without a DC-link capacitor. | • A steady AC input source can be converted directly into a variable voltage and variable frequency output with nine bidirectional switches. | • Limited capacity to maximize the output voltage.<br>• Input filter is needed to reduce the high switching frequency harmonics.<br>• Complex, less reliable, and costly. |
| [105,134,163] | Modular multilevel converter | • A wide range of medium and high-voltage applications. | • Smaller output harmonic content.<br>• Adjustable power factor.<br>• Flexible control operation.<br>• Weaker the voltage stress of semiconductor switch and electromagnetic disturbances. | • Requires a bulky and costly isolated transformer for each cell.<br>• Requires voltage sensor for each cell. |

**Table 5.** *Cont.*

| Ref. | Type of Converter | Target | Advantages | Disadvantages |
|---|---|---|---|---|
| [88,112,119] | Interleaved boost converter | • To increase the efficiency and reliability. | • Low input current ripple.<br>• High efficiency.<br>• Faster transient response.<br>• Reduced electromagnetic emission.<br>• Simple control. | • High components count.<br>• High switching losses.<br>• Sensitive to the duty cycle variation. |
| [113] | H-bridge converter | • Allow DC motors to run forwards or backward. | • Lower winding costs.<br>• Proximity effect losses. | • The half-bridge converter is used in the application of a high voltage requirement.<br>• It offers slightly more voltage ripple than the half-bridge. |
| [86,90,98] | Switched capacitor bidirectional converter | • A high step-up/step-down voltage gain. | • A wide voltage-gain range.<br>• Low-current ripple on the low-voltage side.<br>• Low voltage stresses across power switches. | • Fails to maintain better efficiency for a broad range of output voltages.<br>• Complex control and structure limit its application. |
| [117,127] | Soft-switching DC-DC converter | • To minimize the intersection of their waveforms. | • Lower losses.<br>• Low EMI.<br>• Allows high-frequency operation.<br>• Additional clamping circuit<br>• is not required. | • Low fault tolerance capability.<br>• High current rating of gates.<br>• Large capacitor is required. |
| [169] | z-source converter | • Use the shoot-through (ST) state to boost the input voltage to higher. voltages to achieve high efficiency and high gain. | • Reduced cost and volume.<br>• High switching frequency.<br>• Low voltage stress on the devices.<br>• Good harmonic performance. | • Behave in a boost or buck operation only.<br>• The combined system of the DC-DC boost converter and the inverter has lower reliability.<br>• The main switching device of VSI and CSI are not interchangeable. |
| [77] | Quasi-resonant converter | • Minimizing converter loss while optimizing multi targets. | • Lower switching losses, especially when switching on the lowest valley point.<br>• Partial resonance with better EMI.<br>• High conversion ratio and efficiency.<br>• Low cost. | • The frequency increases as the load decreases.<br>• Complex integrated transformer.<br>• Expensive controller. |

**Table 5.** *Cont.*

| Ref. | Type of Converter | Target | Advantages | Disadvantages |
|---|---|---|---|---|
| [134,159] | Multi-phase DC-DC converter | • Delivers continuous input/output current compared to traditional converters. | • Higher efficiency from lower transitional losses.<br>• Lower output ripple voltage.<br>• Better transient performance.<br>• Lower ripple-current-rating requirements for the input capacitor. | • Large number of components.<br>• Switching converters are prone to noise.<br>• Complex analysis under steady-state and transient conditions.<br>• Difficult to achieve proper synchronization. |

In [80,83,139], the cascaded multilevel converter is used to achieve high-quality output voltages and input currents. It has ease of operation at lower switching frequencies, less noise generation, and less harmonic distortion. However, this converter has a weakness of a higher number of power semiconductor switches. In [140,168], the buck-boost converter is employed to deliver a range of output voltages varying from much larger than the input voltage. It offers efficient solutions with smaller external components. Nevertheless, it needs a large filter size leading to electromagnetic interference (EMI) issues due to the discontinuous operation of the input current and charging current of the output capacitor. In [94], the neutral point clamp converter is used to achieve multilevel voltage waveform through a split DC-link, using multiple sources and storage through a single converter. Although this converter has improved waveform quality leading to reduced filtering requirements, it requires a greater number of diodes for increased levels. In [96], the matrix converter is utilized to achieve automatic conversion of power from AC to AC without DC-link capacitor. It provides a steady AC input source that can be converted directly into a variable voltage and variable frequency output. However, this converter is complex, less reliable, costly, and has limited capacity to produce the output voltage. In [105,134,163], the modular multilevel converter is used for a wide range of medium and high-voltage applications. It has an adjustable power factor, flexible control operation, and smaller output harmonic content. Nonetheless, this converter requires a bulky and costly isolated transformer. In [88,112,119], the interleaved boost converter is employed to achieve high efficiency and reliability. It offers numerous benefits, including faster transient response, high efficiency, low input current ripple, and reduced electromagnetic emission. Nonetheless, it possesses several disadvantages, such as high components count, high switching losses, and sensitivity to the duty cycle variation. In [113], the H-bridge converter allows DC motors to run forwards or backward. Although it has lower winding costs and proximity effect losses, it offers slightly more voltage ripple than the half-bridge. In [86,90,98], the switched capacitor bidirectional converter is applied to attain a high step-up/step-down voltage gain. It has a wide voltage-gain range, low-current ripple on the low-voltage side, and low voltage stresses across power switches. However, it has some limitations, such as complex structure, control operation, and failure to maintain better efficiency for a broad range of output voltages. In [117,127], the soft-switching DC-DC converter is used to minimize the intersection of their waveforms. It has lower losses, low EMI, and allows high-frequency operation. Nevertheless, it experiences a high current rating of gates and low fault tolerance capability. In [169], the z-source converter utilizes a shoot-through (ST) state to boost the input voltage to higher voltages to achieve high efficiency and high gain. This converter offers high switching frequency, good harmonic performance, low voltage stress, reduced cost, and volume. However, it has the drawbacks of lower reliability, vulnerability to EMI noises, and non-interchangeable voltage source inverter (VSI) and current source inverter (CSI) switching devices. In [77], a quasi-resonant converter is used to resemble a resonance action partially. This converter has a high conversion ratio, efficiency, and lower switching losses with better EMI. Nonetheless, it has shortcomings in terms of a complex integrated transformer and an expensive controller. In [134,159], a multi-phase DC-DC converter exhibits lower output ripple voltage, better transient performance, and lower ripple-current-rating requirements. Nevertheless, this converter suffers from higher components, synchronization, and sensitivity to duty cycle.

Table 6 presents the comparison of the technical features among various power electronics converters which are most frequently utilized in EV applications.

**Table 6.** Comparison of technical features of power electronics converters in EV applications.

| Type of Converter | Current/Voltage Ripple | Switching Frequency | Complexity of Control Circuit | High Power Conversion | EMI Suppression | Cost |
|---|---|---|---|---|---|---|
| Cascaded multilevel converter | Complex | High | Moderate | Appropriate | Reduced | Low |
| Buck-boost converter | Simple | High | Complex | Appropriate | Reduced | Medium |
| Neutral point clamp converter | Moderate | Low | Moderate | Appropriate | Reduced | Low |
| Matrix converter | Complex | High | Complex | Appropriate | Reduced | High |
| Modular multilevel converter | Simple | High | Moderate | Appropriate | Needed | High |
| Interleaved boost converter | Complex | Low | Complex | Appropriate | Reduced | Low |
| H-bridge converter | Complex | High | Moderate | Appropriate | Needed | Low |
| Switched capacitor bidirectional converter | Moderate | High | Moderate | Appropriate | Needed | Medium |
| Soft-switching DC-DC converter | Complex | Low | Complex | Appropriate | Reduced | Medium |
| Z-source converter | Simple | High | Complex | Appropriate | Needed | Medium |
| Quasi-resonant converter | Simple | High | Moderate | Appropriate | Reduced | Low |
| Multi-phase DC-DC converter | Complex | Low | Complex | Appropriate | Needed | High |

### *3.5. Analysis of Energy Storage Connected Power Electronic Converter for EVs in Most Relevant 100 Papers*

The selection of proper energy storage type or the combination of different storage devices plays a crucial role in EV applications. Figure 7 represents the different types of energy storage utilized in this most relevant selected 100 manuscripts. It is found that hybrid energy storage system (HESS) is the most widely used storage type in the selected database, with the figure of 66% followed by conventional battery storage type (23%). Fuel cell storage and supercapacitor storage are the less utilized energy storage type in this selected database with the figure of 6% and 4%, respectively. Flywheel energy storage is the lowest significant storage type with 1%. According to selected papers, most of the researchers prefer hybrid energy storage in EV applications to ensure greater performance.

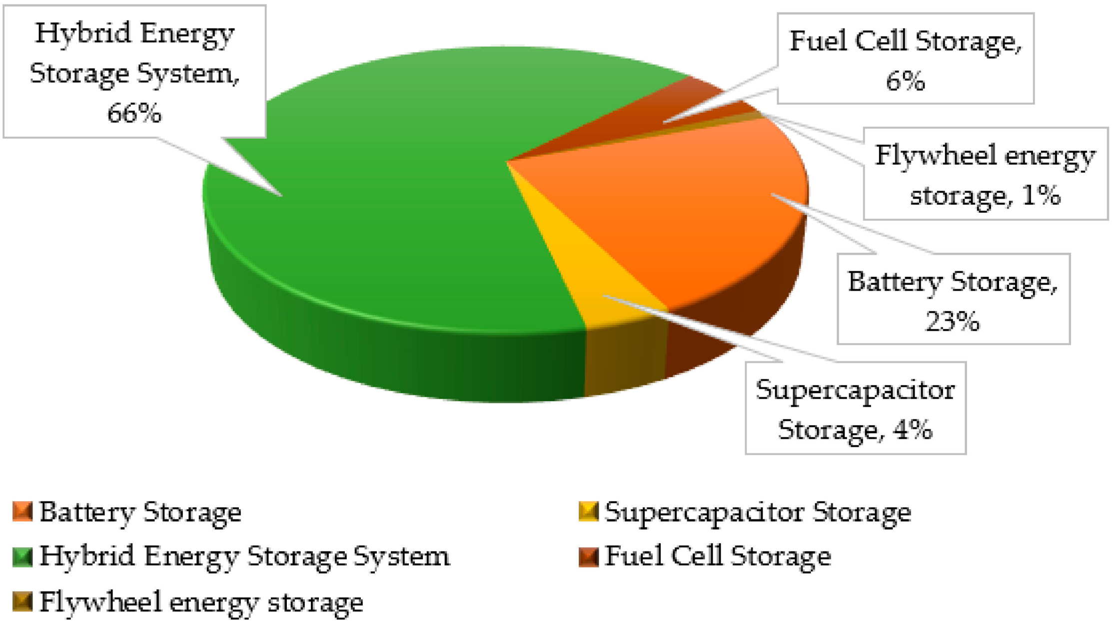


**Figure 7.** Classification of energy storage types from the selected database.

*3.6. Role of AI to Power Electronics Converter Technology Integrated Energy Storage Management*

Some recent works based on artificial neural network (ANN), fuzzy logic control, adaptive neuro-fuzzy inference system (ANFIS), and optimization techniques based on genetic algorithm (GA) and particle swarm optimization (PSO) are used in power electronics converter technology integrated energy storage management. Table 7 represents the various types of AI algorithms that are widely utilized in EVs along with their key findings and challenges. The following bullet points represent the benefit of the AI method in different EV applications:

- Yilmaz et al. [172] proposed an ANN-based half-bridge LLC resonant converter for EV technology. The presented technology delivered satisfactory outcomes with regard to long battery life and high efficiency resulting in better mileage for EVs. Mean square error (MSE) was considered to evaluate the performance of the ANN-based converter technology. The delivered results indicate that ANN-based technique achieved high efficiency with 96.2% with ripple voltage being 0.5 V and a total harmonic distortion (THD) of 5%, respectively. While Teja et al. [173] presented A-based framework towards executing better power flow under two operational processes: the energy regeneration stage and the dual-source powering stage. The outcomes suggested high accuracy of the ANN model compared with the proportional-integral (PI) control technique with regards to fast response time and low harmonics.
- Ferreira et al. [174] introduced an integrated fuzzy logic control and power electronics converter circuits towards achieving high-performance efficiency in EV technology. Several energy storage systems such as battery storage, supercapacitor, and fuel cell were utilized where battery storage controls the input current while supercapacitor regulates DC-link voltage. The power flow control between the input sources and load was controlled with fuzzy interface. In other work, Adam et al. [175] presented a fuzzy logic control with converter topology towards achieving control for battery operation based on charging and discharging. The presented technique delivered adequate results regarding high battery capacity and long lifespan. Furthermore, the simulation outcome delivered high stability with output voltage parallel to high efficiency.
- The adaptive neuro-fuzzy inference system (ANFIS) is regarded as the integration of fuzzy systems and neural networks. The ANFIS depicts fast response and delivers results with high accuracy compared with traditional fuzzy based technique. Reddy and Sudhakar [176] developed a ANFIS controller for EV technology comprising of

Fuel Cells, boost converter, three-phase inverter and motor respectively. The ANFIS technology was employed towards extracting maximum energy from the fuel cells. Additionally, the ANFIS operation demonstrated high superiority compared with conventional fuzzy logic control in terms of increased DC-link power and low average time to attain maximum power point.

- Some of the optimization techniques employed with power converters for EV technology relate to GA and PSO, respectively. For instance, Nguyen et al. [177] presented optimized GA-based dual active bridge (DAB) bidirectional converters for EV application. The main aim of the optimization framework was to maximize efficiency and minimize converter loss with low harmonics. The optimization framework varies several key parameters of transformer such as leakage inductance, peak flux density, voltage conversion ratio, and switching frequency. While Prithivi and Sathyapriya [178] developed improved the performance efficiency of fuzzy control technique with PSO. The achievement of the optimal value of switching angle was completed by eliminating current harmonics.

**Table 7.** AI methods in EV converters highlighting objectives, key findings, benefits, and shortcomings.

| AI Methods | Objectives | Key Findings | Benefits | Shortcomings | Refs. |
|---|---|---|---|---|---|
| ANN | Maximize power factor, reduce current harmonics. | Achieved high efficiency, low harmonics, and THD. | Demonstrates high robustness and accuracy. | Requires high computational processor and expensive processor devices. | Yilmaz et al. [172] |
| Fuzzy | Maximize efficiency and develops interfacing among battery system, generator, and voltage DC-link bus. | Depicts appropriate synchronization between various battery sources and load. | Presents high robustness, flexibility, and fast response. | Requires appropriate expertise towards designing the controller. | Ferreira et al. [174] |
| ANFIS | Maximize power point tracking. | Increase in DC link power and reduction in time required to achieve maximum power point. | Highly effective towards tracking. | High computational cost with complex structure and gradient learning. | Reddy and Sudhakar [176] |
| GA | Maximization of system efficiency. | No requirement of external inductors. | Requires less information and fast computational ability. | Time consuming and unguided mutation. | Nguyen et al. [177] |
| PSO | Optimize energy consumption. | Reduction of effect of control strategy. | High robustness, effectiveness, and simple implementation. | Easy to fall into local optimum and low convergence rate. | Prithivi and Sathyapriya [178] |

### *3.7. Analysis of Average Citation Per Year, Contributions, and Research Gaps*

Table 8 shows the top ten manuscripts with the average citation per year (ACY) in the recent five years. The manuscript by Cao et al. [81] has the highest ACY of 95.6 and is ranked 1st in total citations, followed by the second paper by Song et al., which has an ACY of 31.6. As the researchers' fields of interest change over time, the average citation per year (ACY) rank differs from the overall citation rank. With the ACY of 16, Kasimalla et al. [104] produce the last article in the table, whose citation rank is 24th. According to Table 4, the most frequent limitations are cost and relatively short lifetime for LiFePO4 battery, and the key weak point of FCs is their dynamic limitation. The fundamental disadvantage of the traditional technique is that non-linear properties are ignored, resulting in poor controller performance. The main limitation of the mentioned strategy is the use of a single DC bus and dynamic charging power limitation through G2V services; the inductive charging is the valid solution only for a short period, the mentioned control strategy cannot analyze the average positive and negative needs, and the hydrogen infrastructure, performance, reliability, and robustness are the future difficulties for FC systems. To overcome the issues mentioned above, further in-depth investigation is required. The future recommendations will be discussed in the following sections.

Cao et al. [81] applied a DC-DC converter connected with battery and supercapacitor-based hybrid energy storage system (HESS) in plug-in hybrid EVs and hybrid EVs. This scheme can utilize up to 75% of the ultracapacitor energy and generate a relatively constant battery load profile, leading to improved battery lifespan. However, the sizing of the DC-DC converter and the choice of the supercapacitor needs further exploration to reduce the system cost. Song et al. [82] employed a unidirectional DC-DC converter integrating a semi-active battery and ultracapacitor-based hybrid energy storage system in EV applications. This topology can minimize the battery capacity loss and system cost simultaneously. Although this approach is applicable for wide working temperatures, it has issues regarding cost and the short lifetime of LiFePO4 battery. Zheng et al. [83] used a hybrid cascaded multilevel converter for battery energy management and motor drives. This converter has lower harmonics and DV-DT, can efficiently utilize battery energy, and avoids the imbalance of SOC and voltage. Nahavandi et al. [84] designed a non-isolated multi-input multi-output DC-DC boost converter for EV applications using hybridized alternative energy sources. This converter has lower voltage harmonics leading to decrease torque ripple of the electric motor in EVs. El Fadil et al. [87] employed hybrid energy storage, including fuel cell and super-capacitor integrated with boost converter and boost–buck converter. A nonlinear control system is developed to track the supercapacitor current to its reference and regulate voltage regulation. Song et al. [89] introduced a fifth-order averaged model-based sliding-mode controller for a fully active hybrid energy storage system that employs two bi-directional DC-DC converters to decouple supercapacitor and battery pack from the DC bus. This converter can track DC bus voltage and the reference current of battery/SC under various load conditions. Akar et al. [90] proposed a new bidirectional non-isolated multi-input converter consisting of energy storage systems with various electrical properties in EVs. The proposed configuration has reduced components count, allowing a single switch connected with the converter's inductors. Experimental investigation indicates the prototype converter efficiency is above 93%. Rubino et al. [91] emphasized the significance of charging infrastructure in large-scale diffusion of EV, highlighting inductive and conductive charging methods, innovative power electronics architectures, battery management, and integration of EV with distributed energy sources. The authors outlined several limitations such as slow charging, high dimension, oversizing, and complex hardware. Varajao et al. [96] proposed an improved control scheme for the high-frequency link matrix converter to achieve a controllable power factor for EV applications. This converter can generate high power quality grid currents as well as perform voltage and current regulation efficiently. Besides, this topology has lower weight and circuit volume and ensures a longer service life battery storage system. Kasimalla et al. [104] conducted a thorough investigation on the effectiveness of fuel cell EV (FCEV) based energy management systems connected with batteries and ultracapacitors. The various braking control schemes together with energy allocation, energy recovery regeneration, and experimental investigation are carried out to examine the hydrogen energy utilization. However, further attention is necessary on hydrogen infrastructure, performance, reliability, and robustness along with the FC system concerning size, cost weight, durability, and thermal management.

**Table 8.** "Average citation per year (ACY)" of top 10 articles and their schemes, contributions, and research gaps.

| Rank | Ref. | Authors | ACY | Rank (Based on Citation) | Author Keywords | Converter Type | Topology/Scheme | Contributions | Research Gaps/Future Directions |
|---|---|---|---|---|---|---|---|---|---|
| 1 | [81] | Cao et al. | 95.6 | 1 | Battery; Control; DC-DC converters; EV; ES; HEV; PHEV; PE; propulsion systems; UC | DC-DC converter | A novel battery and SC-based hybrid energy storage system (HESS) for electric drive cars, such as plug-in hybrid electric vehicles and hybrid electric vehicles. | • Smaller size DC-DC converter can transfer energy utilizing up to 75% of the ultracapacitor energy.<br>• A relatively constant load profile is generated that improves the battery life. | • System efficiency in the high voltage condition was not analyzed.<br>• The sizing of the DC-DC converter and the selection of the SC needs to figure out to reduce the system cost. |
| 2 | [82] | Song et al. | 31.6 | 2 | EV; HESS; LiFePO4 battery degradation; multi-objective optimization | Unidirectional DC-DC converter | A semi-active battery and ultracapacitor based hybrid energy storage system for electric vehicle applications. | • The battery capacity loss and system cost are reduced.<br>• The battery degradation is decreased quickly with the initial rise in supercapacitor use. | • Cost and relatively short lifetime are the main issue of $LiFePO_4$ battery.<br>• As the outcome of this hybrid approach is satisfactory for wide working temperature, hence, this model can be utilized in future real time applications. |
| 3 | [83] | Zheng et al. | 27.6 | 3 | BC; charging and discharging; EV; hybrid cascaded multilevel converter; voltage balance | Hybrid cascaded multilevel converter | A hybrid cascaded multilevel converter is proposed, including battery energy management and motor drives. | • The type of converter has lower harmonics and dv/dt. Efficient utilization of battery energy.<br>• SOC and voltage imbalance can be avoided. | • As the cascaded model has better fault-tolerant ability and no drawback on the number of cascaded cells, it can be utilized in the real-time application. |
| 4 | [84] | Nahavandi et al. | 26.8 | 4 | DC-DC converters; EV; hybrid power system; MIMO; small-signal modeling; state-space averaging | Non-isolated multi-input multioutput DC-DC boost converter | A new non-isolated multi-input multi-output DC-DC boost converter for EV applications by hybridizing alternative energy sources. | • This converter can produce several outputs with different voltage levels.<br>• Multilevel inverter reduces the voltage harmonics leading to decrease torque ripple of electric motor in EVs. | • As the proposed converter was experimentally verified, this strategy can be utilized in practical EV applications. |

**Table 8.** *Cont.*

| Rank | Ref. | Authors | ACY | Rank (Based on Citation) | Author Keywords | Converter Type | Topology/Scheme | Contributions | Research Gaps/Future Directions |
|---|---|---|---|---|---|---|---|---|---|
| 5 | [87] | El Fadil et al. | 22.4 | 7 | DC-DC power converters; EV; FC; nonlinear control; SC | Bidirectional DC-DC converter | A boost converter and a boost–buck converter connected with fuel cell and SC serving as main power sources and auxiliary power source, respectively. | • A nonlinear control system can track the SC current accurately.<br>• Can control DC voltage regulation. | • One of the key weak points of FCs is their dynamic limitation.<br>• As the outcome of this manuscript is batter, hence, this strategy can be utilized in practical application. |
| 6 | [89] | Song et al. | 21.6 | 9 | EV; HESS; Lyapunov function-based controller; sliding-mode controller; SC | Two bi-directional DC-DC converters | A sliding-mode controller connected with two bi-directional DC-DC converters to decouple SC and battery pack from the DC bus. | • This converter can track DC bus voltage and the reference current of battery/SC under various load conditions. | • The fundamental disadvantage of the traditional technique is that non-linear properties are ignored, resulting in poor controller performance. |
| 7 | [90] | Akar et al. | 21.6 | 10 | Batteries; bidirectional; HESSs; multi-input converter; UC | Bidirectional non-isolated multi-input converter | A new bidirectional non-isolated multi-input converter consisting of energy storage systems with various electrical properties. | • The converter requires a single switch connected with inductors of the converter leading to reduced components count.<br>• The prototype converter efficiency is greater than 93% in both operation modes. | • For future work, a full-scale battery/UC hybrid system can be built using proposed converter. |

**Table 8.** *Cont.*

| Rank | Ref. | Authors | ACY | Rank (Based on Citation) | Author Keywords | Converter Type | Topology/Scheme | Contributions | Research Gaps/Future Directions |
|---|---|---|---|---|---|---|---|---|---|
| 8 | [91] | Rubino et al. | 20.8 | 11 | ESS; PEV charging infrastructure; PEV; PEC; SG | - | A complete outlook for innovative charging infrastructures in EV applications. | • Comparative analysis of inductive and conductive charging methods, including scalability, efficiency, and charging time/power, are presented.<br>• The off-board DC fast-charging architectures integrated and renewable energy sources and energy storage systems with the main grid are discussed. | • The main limitation of the mentioned strategy is the use of a single DC bus.<br>• Dynamic charging power limitation through G2V services.<br>• The inductive charging is the valid solution only for a short period. |
| 9 | [96] | Varajao et al. | 16.75 | 16 | AC-DC power conversion; BC; ES; matrix converters; silicon carbide; soft switching; space vector pulse width modulation | High-frequency link matrix converter | A novel modulation and control algorithms have been developed for the high-frequency link matrix converter. | • This converter can generate grid currents with high power quality.<br>• The converter can perform voltage and current regulation efficiently.<br>• The total harmonic distortion (THD) is 3.44% and 2.58% in inverter mode and charger mode, respectively. | • As the outcome of this manuscript is excellent hence, this strategy can be utilized in real-world applications. |
| 10 | [104] | Kasimalla et al. | 16 | 24 | battery; BDC; EM; FC; regeneration energy; UC | - | This survey focuses on several energy management schemes based on FCEV in conjunction with two secondary energy storage systems, such as batteries and SCs to create a high-performance energy storage system. | • The various braking control strategies to improve hydrogen utilization in FCEV connected with batteries and ultracapacitors are explored.<br>• The experimental investigation, energy utilization, allocation plans, recovery of regeneration for FCEV are presented. | • The hydrogen infrastructure, performance, reliability, and robustness are the future difficulties for FC systems.<br>• Need further studies of FC system with regard to size, cost weight, durability, thermal management. |

### 3.8. Research Category in the Most Relevant 100 Papers

Table 9 and Figure 8 demonstrate the research classification of the selected most relevant manuscripts. The relation among study type, year ranges, and citation ranges is also demonstrated. The category of modeling, simulation, and performance evaluation has the most papers (57%), followed by problem formulation (13%) and state-of-the-art and technical overview (9%). With eight manuscripts each, review (systematic and nonsystematic) and survey, meta-analysis, and case study are in the fourth place together, where the citation range is 1–55 and 0–133, respectively. The observational overview has the lowest number of papers (5%) with a citation range (15–81). The majority of papers from 2010 to 2021 are original research work (modeling, simulation, and performance evaluation) and problem formulation categories. In recent times, researchers are mostly focusing on the power electronics converter for the smooth power transition from energy storage to electric vehicle applications.

**Table 9.** Research types and citation range of the most relevant 100 publications based on the Scopus database.

| Types of Study | Year Range | Citation Range |
|---|---|---|
| Original research work (modeling, experimental work, and performance evaluation) | 2010–2021 | 0–809 |
| Problem formulation and simulation analysis | 2014–2021 | 3–193 |
| State of art and technical overview | 2012–2020 | 0–109 |
| Review (Systematic and Nonsystematic) | 2011–2021 | 1–55 |
| Survey, Meta-analysis, and Case study | 2011–2021 | 0–133 |
| Observational overview | 2013–2019 | 15–81 |

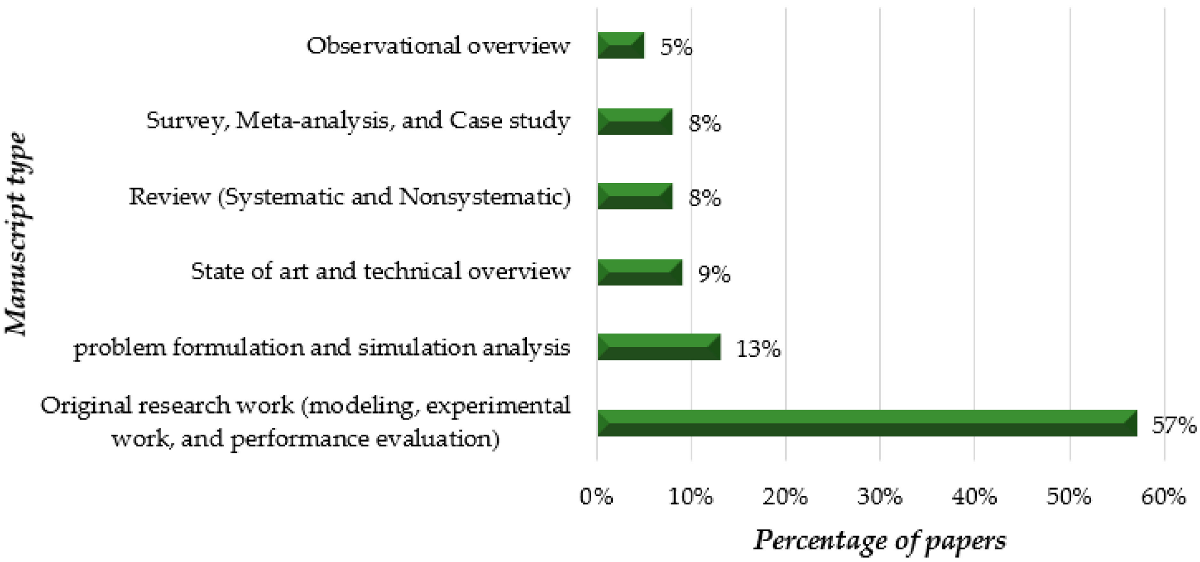


**Figure 8.** The percentage of manuscript types in the relevant top 100 cited papers.

### 3.9. Analytical Evaluation of Journals and Publishers

According to Figure 9, the selected most relevant 100 manuscripts were published under 17 different publishers. From Figure 9, future researchers will obtain a clear idea about the publisher, who frequently publishes the manuscripts related to energy storage management in EV applications. With 38 articles, the Institute of Electrical and Electronics Engineers published the highest number of publications from the selected 100 articles, where the maximum of them are original research work. Elsevier takes the second place with 19% of publications, MDPI AG with 10% and IET (5%). The rest of the publishers published less than 5% of the selected manuscripts. The rest of the publishers are John Wiley & Sons, Inc. (4%), Korean Institute of Power Electronics (3%), Inderscience Publishers (3%), Korea Science (2%), Taylor and Francis Inc. (2%), Springer (2%), Emerald Group Publishing Ltd. (1%), Hindawi Publishing Corporation (1%), SAGE Publications Ltd. (1%), De Gruyter Open Ltd. (1%), World Academy of Research in Science and Engineering (1%), Research India Publications (1%), and Tamkang University (1%). Currently, scholars are focusing on the development of new energy storage management strategies and models in EV applications to reduce carbon emission, which has a lower environmental impact. Models based on EMSs for EV applications are investigated in Refs. [89,93,102,115,131,134,135].

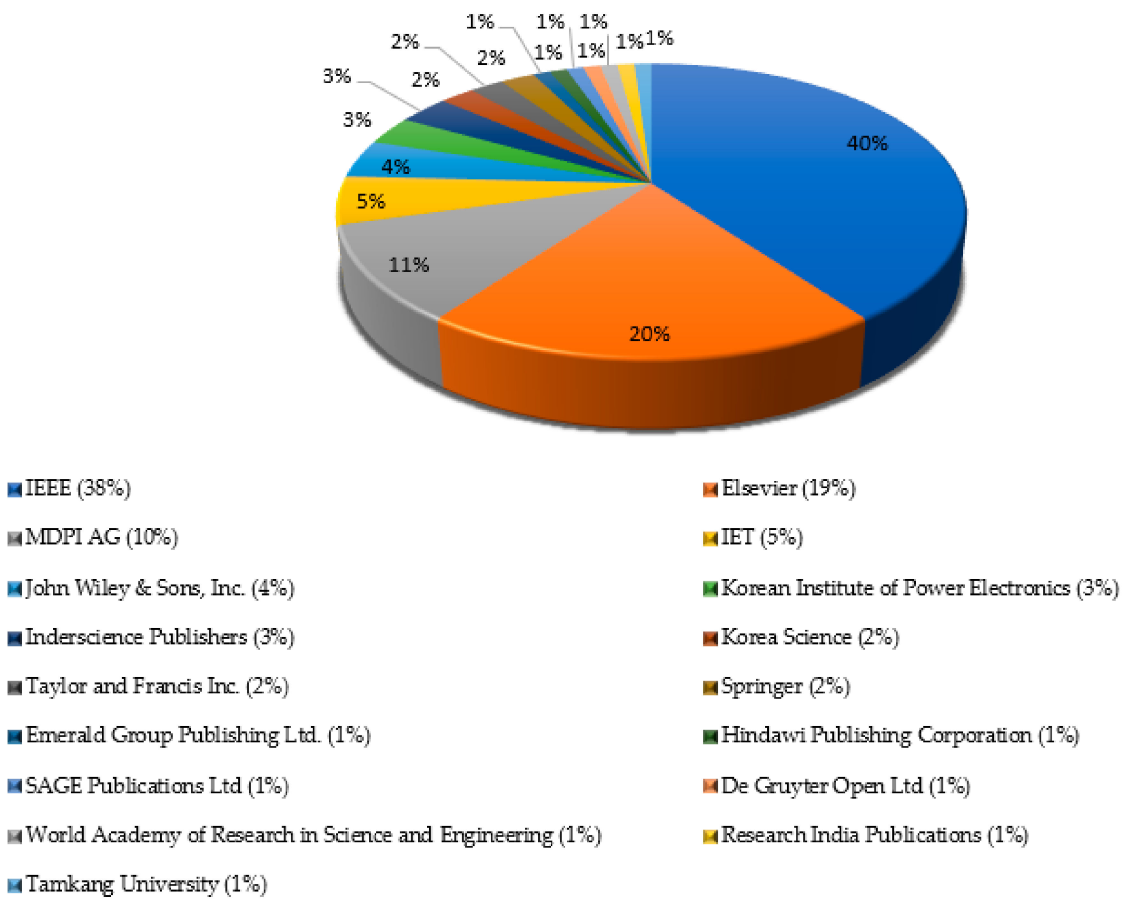


**Figure 9.** Distribution of 100 manuscripts over the different publishers.

The number of papers published in various journals, as well as their impact factor, is shown in Figure 10. The selected most relevant 100 manuscripts were published in 43 different journals. The top five journals with the highest number of publications have published 42% of the 100 most relevant manuscripts, with impact factors ranging from 1.069 to 14.982. The "IEEE Transactions on Power Electronics" journal published the highest number of papers (11), followed by "Energies" with ten manuscripts. "Applied Energy" and "IEEE Transactions on Industrial Electronics" both published eight and seven papers, respectively. Followed by "IEEE Transactions on Vehicular Technology" journal with the figure of six. "IET Power Electronics" and "Journal of Power Electronics" both published four articles each. "Energy Conversion and Management" and "International Journal of Energy Research" taken seventh place by publishing three articles each. The rest of the journals published less than three manuscripts from the selected database, and few of them are IEEE Access, IEEE Journal Of Emerging and Selected Topics In Power Electronics, IEEE

Transactions On Applied Superconductivity, IEEE Transactions On Industry Applications, IEEE Transactions On Smart Grid, IEEE Transactions On Transportation Electrification, International Journal Of Power Electronics, Journal Of Electrical Engineering And Technology, Journal Of Power Sources, and Renewable and Sustainable Energy Reviews. Based on the journal citations report 2020, the selected 100 manuscripts published in the journal impact factor ranges from 1.069 to 14.982. "Renewable and Sustainable Energy Reviews" journal contain the highest IF of 14.982, while the number of manuscripts is only 2%. On the other hand, the "Journal of Electrical Engineering and Technology" journal with the same frequency of publication contains the lowest IF of 1.069.

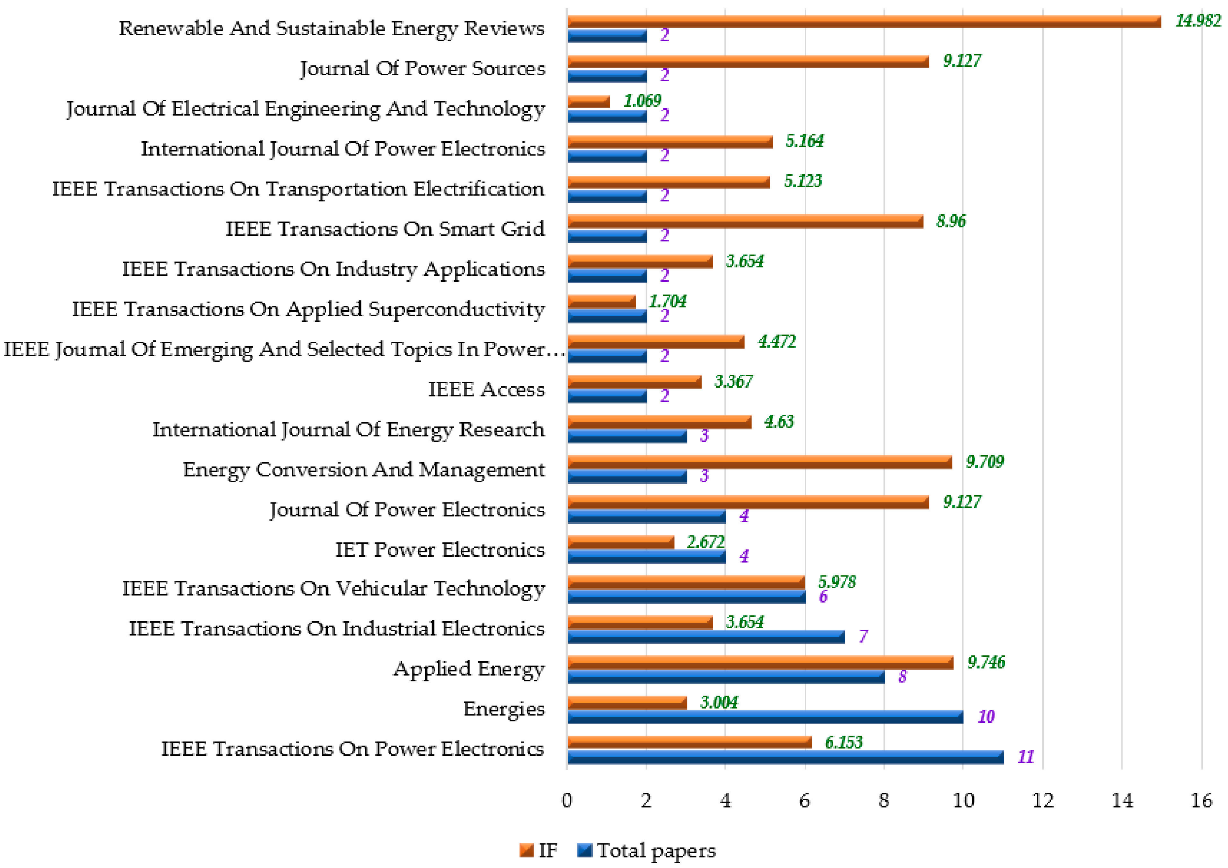


**Figure 10.** Distribution of manuscripts for Journal evaluation and Journal of impact factor.

### *3.10. Document Authorship and Collaboration Analysis*

Table 10 depicts the research profiles of the prominent authors who have contributed three or more articles in the selected 100 manuscripts. From the most relevant 100 articles, ten authors produced more than three articles. Amjadi, Zahra of the Florida Polytechnic University, United States, is the leading author with six publications as a first author. Williamson, Sheldon S., and Xu, Jun published five manuscripts each from the Ontario Tech University, Canada and State Key Laboratory for Manufacturing Systems Engineering, China, respectively. This is followed by Binggang Cao, Clemente Capasso, Ottorino Veneri, and Bin Wang, who each published four articles from the Xi'an Jiaotong University, China and Istituto Motori, Italy, respectively. The rest of the authors published three articles each. In terms of citations, Josep M. Guerrero from the Aalborg University, Denmark takes the first place with 55862 citations and an h-index of 104. This is followed by Williamson, Sheldon S., and Cao, Binggang, with citations of 5635 and 3374, respectively. Among the topmost ten authors, four of them are from China. Figure 11 presents the co-authorship and collaboration analysis using the VOSviewer software tool. It is observed that the highest number of authors participated from China, followed by India.

**Table 10.** Topmost 10 prominent authors profiles based on most relevant 100 manuscripts.

| Rank | Author Name | Present Affiliation | Country Name | Number of Articles | Total Number of Citations | h-Index | Authors Position |
|---|---|---|---|---|---|---|---|
| 1 | Amjadi, Zahra | Florida Polytechnic University | United States | 6 | 457 | 7 | First author = 6 |
| 2 | Williamson, Sheldon S. | Ontario Tech University | Canada | 5 | 5635 | 36 | Senior author = 5 |
| 3 | Xu, Jun | State Key Laboratory for Manufacturing Systems Engineering | China | 5 | 1945 | 21 | Co-author = 5 |
| 4 | Cao, Binggang | Xi'an Jiaotong University | China | 4 | 3374 | 28 | Senior author = 2<br>Co-author = 2 |
| 5 | Capasso, Clemente | Istituto Motori | Italy | 4 | 619 | 12 | First author = 2<br>Co-author = 2 |
| 6 | Veneri, Ottorino | Istituto Motori | Italy | 4 | 1233 | 21 | First author = 1<br>Senior author = 3 |
| 7 | Wang, Bin | State Key Laboratory for Manufacturing linebreak Systems Engineering | China | 4 | 571 | 11 | First author = 4 |
| 8 | Guerrero, Josep M. | Aalborg University | Denmark | 3 | 55862 | 104 | Co-author = 1<br>Senior author = 2 |
| 9 | Song, Ziyou | University of Michigan | United States | 3 | 1970 | 22 | First author = 2<br>Co-author = 1 |
| 10 | Yin, Chengliang | Shanghai Jiao Tong University | China | 3 | 1821 | 20 | Co-author = 2<br>Senior author = 1 |

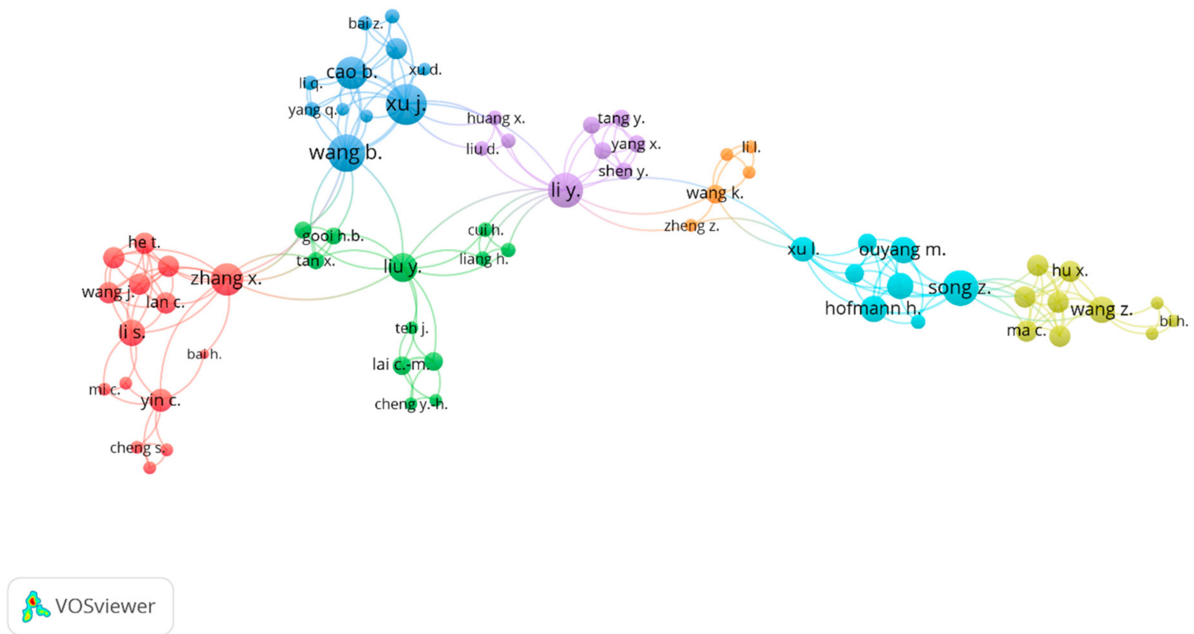


**Figure 11.** VOSviewer illustration for co-authorship analysis using Scopus database.

Research interests vary from author to author. Zahra Amjadi from Florida Polytechnic University, Lakeland, United States, primarily focuses on power electronics, electric vehicles, hybrid electric vehicles, transportation electrification, and electric energy storage systems. She recently published couple of research papers on energy storage management in EV applications [98,103,116,122,165,166]. Her most recent two journals are "Digital Control of a Bidirectional DC-DC Switched-Capacitor Converter for Hybrid Electric Vehicle Energy Storage System Applications" [116] and "Prototype Design and Controller Implementation for a Battery-Ultracapacitor Hybrid Electric Vehicle Energy Storage System" [122]. Sheldon S. Williamson from Ontario Tech University, Oshawa, Canada, is currently working on the following fields: batteries and charging, electric machines, electric vehicles, energy harvesting, energy storage systems, motor drives, power electronics, renewable energy, and transportation electrification [98,103,116,122,165,166]. His most recent two articles are "Modeling of Average Current in Non-Ideal Buck and Synchronous Buck Converters for Low Power Application" [122] and "Technological Perspective of Cyber-Secure Smart Inverters Used in the Power Distribution System: State of the Art Review" [179]. Jun Xu from State Key Laboratory for Manufacturing Systems Engineering, Xi'an, China, takes third place in selected most relevant 100 manuscripts. His primary research interests are inductive power transmission, charging (batteries), electric vehicles, high voltage direct current systems, converters, static synchronous compensators, space vector modulation, and inverter [92,95,115,180,181]. "A Relative State of Health Estimation Method Based on Wavelet Analysis for Lithium-Ion Battery Cells" [182] and "A Hybrid Self-Heating Method for Batteries Used at Low Temperature" [183] are the articles recently generated by Jun Xu.

### 3.11. Country Analysis in the Most Relevant 100 Papers

Figures 12 and 13 present the graphical representation of the top ten countries and co-occurrence countries using VOSviewer that dominate the power converter integrated ESM in EV applications, respectively. China has taken first place by publishing 33 manuscripts followed by India, with 17 manuscripts. The United States is in the third position with 14 articles. With one publication, South Korea is placed in the last position based on our selected database. Figure 13 represents the co-occurrence network among all the countries, who published the selected 100 articles. Moreover, Figure 13 illustrates that China has the highest number of links with other countries, followed by Malaysia and the United States. Portugal and Germany have the lowest number of collaboration networks from the selected database. "National Natural Science Foundation of China" is the sponsor of the highest number of manuscripts from the selected most relevant 100 articles followed by "European Regional Development Fund" and "European Regional Development Fund" that is placed at second position with three manuscripts each.

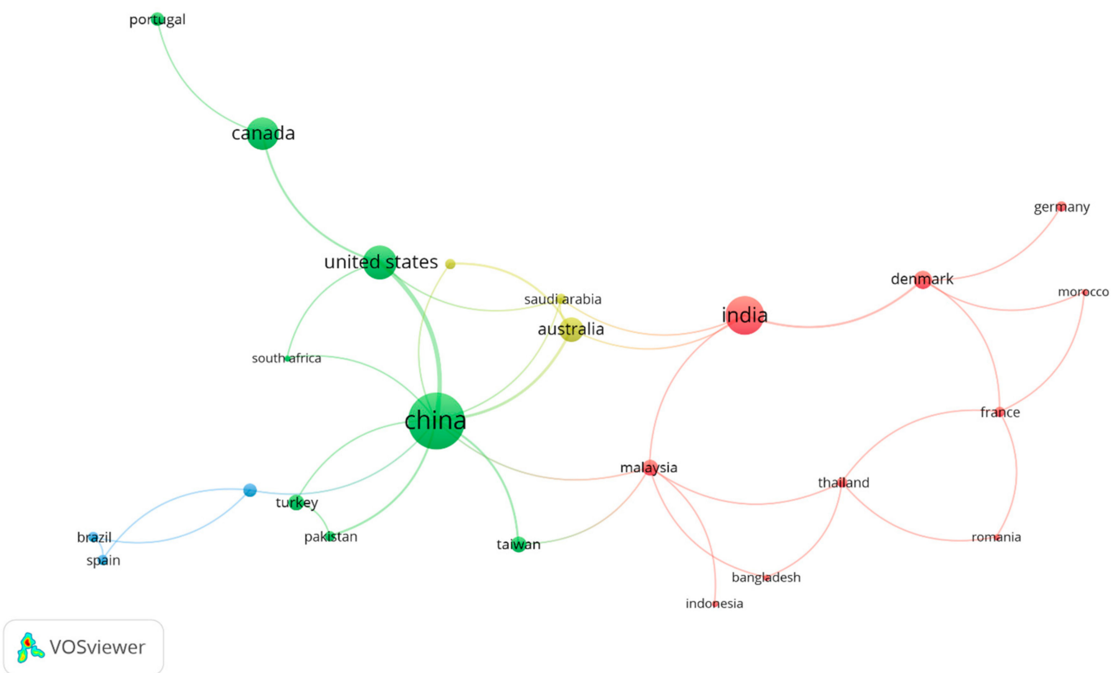


**Figure 12.** Graphical representation of top ten countries that dominate the EMSs for EV application.

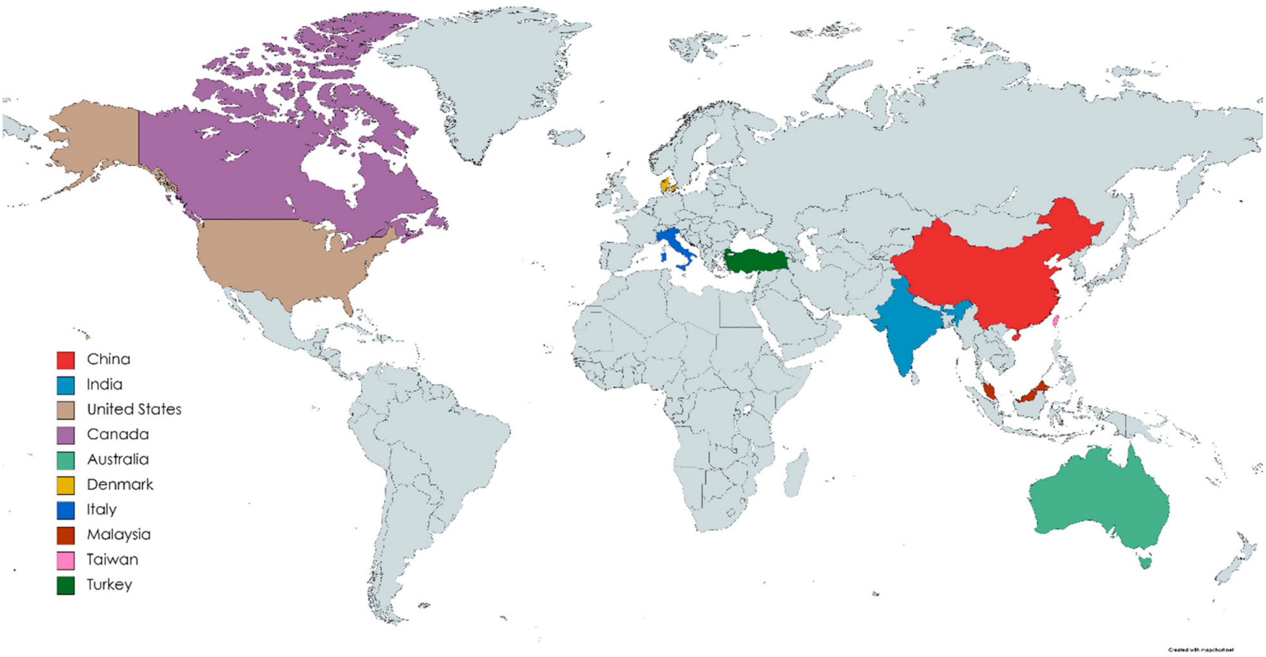


**Figure 13.** Co-occurrence country analysis by VOSviewer from the Scopus database.

## 4. Issues and Challenges of EV Converters

Even though various efforts have been initiated to develop state-of-the-art converter technologies with regards to design, operation control, and optimization, numerous key issues should be addressed towards enhancing the converter performance accuracy. Table 11 represents the key challenges with different EV application converters along with their impacts and possible suggestions/solutions. To address this, the key issues and challenges have been proposed as:

**Table 11.** Key challenges and possible solutions of EV converter technology.

| No. | Issues and Challenges | Causes | Impacts | Remedies/Suggestions |
|---|---|---|---|---|
| 1 | EV Converter Topology and Design Criteria | -Lack of an appropriate design and configuration. -Application of filter circuits increases the converter cost. | Presence of unwanted harmonics, voltage stress, improper synchronization, and switching loss. | GA /PSO optimization-based bidirectional converters for EVs can be employed to enhance efficiency with low output current ripple and converter loss. |
| 2 | Traditional Controller Implementation Issues | Slow response rate to sudden disturbances and highly sensitive to controller gains. | Delivers unsatisfactory outcomes for highly non-linear and time-varying systems. | Various AI controller schemes can be employed towards controlling DC-link voltage and load current and achieving better power management. |
| 3 | Intelligent EV Controller Complexities Issues | Requirement of large volume of data and human expertise. | Presents inadequate stability control and dynamic response. | -Appropriate selection of suitable hyperparameters. -Utilization of high computational processors. |

**Table 11.** *Cont.*

| No. | Issues and Challenges | Causes | Impacts | Remedies/Suggestions |
|---|---|---|---|---|
| 4 | Optimization Framework Issues | Suitable parameters selection and proper optimization technique. | Increase system complexity and computational cost. | Application of advanced optimization framework with low complexity and high effectiveness is required. |
| 5 | Development of Multi-Objective Function | Quite tedious and challenging to formulate multi-objective function | Less possibility to achieve optimal results with ripple current and number of components simultaneously. | More realistic parameters, including design, cost, energy loss, and related constraints need to be considered. |
| 6 | Application of Metaheuristic Techniques | Complex mathematical computations with several hyperparameter adjustments. | Acquisition of unsatisfactory outcomes with regard to convertor loss and components cost respectively. | The computational complexity can be reduced with suitable selection of hyperparameters. |
| 7 | Execution of Intelligent Controller Schemes | Requirement of suitable input features, network configuration and hyperparameter tuning. | Loss of time and human energy. | Further studies are required to reduce the data training operation and hyperparameter settings of intelligent controllers. |
| 8 | Battery Storage Integration Issues | Improper converter operation, complex control, and modulation. | Heat dissipation, battery over-charging/ over-discharging issues. | Appropriate selection of components and converter levels. |

### *4.1. EV Converter Topology and Design Criteria*

In Refs. [73,81,95,96,107,117,139,160], numerous authors have demonstrated various converter topologies and their operational features for EV application. The performance of EVs can be enhanced by employing an appropriate converter design. Undesirable outcomes can occur during the inappropriate selection of converter topology for the desired requirement. The inclusion of a large number of switching components may result in more weight to the converter. Furthermore, the application of filter circuits could increase the converter cost. Additional to this, various other converter operational issues such as the presence of unwanted harmonics, voltage stress, improper synchronization, and switching loss may deteriorate the performance and accuracy. Henceforth, an effective converter topology for EV application needs further investigation.

### *4.2. Traditional Controller Implementation Issues*

In Ref. [131], the author explored the characteristics features of the conventional controller in EV applications. The traditional controller such as PI controller and PID controller has been utilized in EV applications. The PI controller depicts simple topology and execution, delivers satisfactory outcomes but shows some disadvantages such as slow response rate to sudden disturbances and highly sensitive to controller gains. While PID controller demonstrates better feasibility and easy implementation, it delivers unsatisfactory outcomes for highly non-linear and time-varying systems. Furthermore, the transient response of the PID controller with time-delayed circuits is sluggish.

### *4.3. Intelligent EV Controller Complexities Issues*

In Refs. [75,89,126,148,160], the authors discussed various aspects of the intelligent EV controller design and operational features. Various controllers in EV application such as fuzzy controller, ANN controller, SM controller, etc. With regards to a fuzzy controller and ANN controller, satisfactory results have been achieved with efficient and better control of converters. The fuzzy controller is effective, robust, flexible, and delivers a better transient response, and is therefore utilized in the EV control application. However, fuzzy controllers have various weaknesses, such as the requirement of a large volume of data, regular upgradation of rules, and human expertise. On the other hand, the ANN controller delivers effective results, requires no mathematical model, and operates satisfactorily under various loading conditions. Nonetheless, ANN requires a large volume of training datasets to train the ANN model and high computational processors. The sliding mode (SM) control technique delivers stability, reliability, and robustness but suffers from fluctuations in switching frequency and requires appropriate suitable parameter selection.

### *4.4. Optimization Framework Issues*

In Refs. [73,82,160], various authors discussed the application of optimization algorithms for optimal outcomes in terms of performance enhancement and design optimization. The applicability of various optimization frameworks in EV applications significantly contributes to achieving optimized design, performance, and accuracy. Nonetheless, the inclusion of the optimization techniques has resulted in some negative impacts in terms of suitable parameter selection. For instance, genetic algorithm (GA) is easy to implement and performs satisfactorily with parallel searching ability, but requires large computational time due to slow convergence, whereas particle swarm optimization (PSO) presents easy implementation, requires few hyperparameter adjustments, and shows fast convergence to achieve optimal results. Nevertheless, the premature convergence and assigning appropriate values for the design parameters in PSO delivers undesirable outcomes. Henceforth, satisfactory results with optimization techniques in EV application can be achieved with proper metaheuristic optimization techniques.

### *4.5. Development of Multi-Objective Function*

The development of MOF in EV application is a critical step for designing the optimization technique due to the formulation of the objective function with several variables and constraints. In a converter circuit, the optimal performance can be achieved with the optimization of various parameters such as the number of components, switching losses, current, and voltage. To accomplish the task, the construction of MOF is required. However, the acquisition of two optimal solutions simultaneously is quite tricky and could result in delivering unsatisfactory outcomes. Henceforth, further studies need to be conducted for exploring the construction of MOF and its related constraints.

### *4.6. Application of Metaheuristic Techniques*

The implementation of metaheuristic techniques to control EV converters may deliver undesirable outcomes due to complex mathematical computations with several hyperparameter adjustments. The training time in metaheuristic optimization techniques is long and requires complex mathematical expressions. Furthermore, the performance accuracy among various optimization schemes by utilizing a single convergence curve is difficult. Additionally, the hybridization of optimization may lead to unsatisfactory outcomes in a case when insufficient data is provided along with other procedures such as data preprocessing, suitable selection of hyperparameters not performed appropriately. Therefore, further investigation is required to address the complexity of optimization techniques.

### *4.7. Execution of Intelligent Controller Schemes*

The performance accuracy of intelligent controllers depends on various factors such as appropriate selection of input data, model configuration, and selection of suitable hyperparameters. The performance accuracy of the converter is increased by accurately optimizing the hyperparameters. In some work, the membership function and hyperparameter adjustment were not performed with fuzzy and ANN controllers [98,119]. Additionally, the implementation of the hit and trial method for selecting the hyperparameters for intelligent controllers requires significant time and human energy. Henceforth, the issues related to intelligent controller schemes' design and execution need further exploration.

### 4.8. Battery Storage Integration Issues

The energy storage system comprises several battery technologies such as the lithium-ion battery, supercapacitor, and fuel cell, respectively [184]. Even though the lithium-ion battery has been extensively utilized in several applications, nevertheless, the battery displays low robustness and suffers from aging [185]. While supercapacitor technology presents benefits such as fast charging time and long life cycle, however, the supercapacitor is not suitable for long-term usage [186]. On the other hand, fuel cell technology shows zero carbon emission but demonstrates complexity to store at ambient room temperature and pressure [187]. Commonly, energy storage technologies suffer from issues such as aging, charging/discharging, uncertainties, limited availability, and high costs [188]. Furthermore, the integration of energy storage system with power convertor circuitry indicates some critical issues. For instance, when the energy storage system is integrated with two-level full-bridge converters topology, it may distort output waveform due to the operation of converter topology as a buck converter. Additionally, when energy storage technology is integrated with a three-level neutral-point clamped (NPC) converter, it may suffer from complex control. However, the battery integration issue with power converters can be suitably resolved with appropriate selection of components and converter levels, respectively [189].

## 5. Future Research Opportunities for EV Converters

The manuscript provides several effective and fruitful suggestions for improving PEC in EV applications which are mentioned below.

- Usually, the converter circuits present a high magnitude of switching and power loss in passive components. At present, various wide bandgap (WBG) material compositions such as silicon carbide (SiC) and gallium nitride (GaN) are utilized in EV converter development due to their capability for handling high voltage and current and delivering high power density while dissipating low heat. Nonetheless, the material is non-reliable and expensive. Thus, the implementation of these sophisticated materials for EV applications should be given more priority in future research.
- Apart from the usage of wide bandgap (WBG) materials such as SiC and GaN, a significant amount of emphasis is currently given on the ultra-wide bandgap (UWBG) materials like Al(Ga)N and $Ga_2O_3$ since they have even higher power density and can be applied in high power applications. Although fabrication of UWBG materials is still in its early stage, they have the potential to be applied as switches of DC-DC converters that can bring many advantageous aspects for EV applications. Therefore, further research study should be carried out towards selecting appropriate material composition for developing suitable converter for EV application with better reliability, low cost, and high switching frequency.
- The schemes of the various converter topologies face various issues related to high harmonics in output current, low current and voltage stress, and low impedance, respectively. Henceforth, further investigation is needed for improving the electrical design features to achieve high frequency and low converter loss. Furthermore, studies related to mechanical design optimization should be conducted to obtain better reliability and accuracy.
- The importance of external design schemes is as important as the internal design features of converters. Improving the internal electric design features are not alone enough to bring expected results and improvement. Besides, changing the internal electric design is often brings unwanted complexity and is extremely time-consuming and expensive. In this regard, significant numbers of studies are conducted to develop various passive and active power filters that can improve the performance of converters externally. The major advantage of these power filters is that they can be easily built with cheap power electronic components and can drastically reduce high harmonics, disturbances, and noises in the output signals of the converters. Thus,

similar importance should be offered in researching the developments of power filters for converters in EV applications.

- The employment of multilevel multi-phase bidirectional converters in EV technology has seen a significant rise due to their various aspects such as low current stress, easy control mechanism, and high-performance efficiency. However, further research work should be performed to investigate the requirements of additional components and complex analysis under steady-state and transient conditions. Furthermore, the converters present high sensitivity in the duty cycle towards variable loading conditions. Therefore, it is suggested to concentrate on developing an integrated design framework to achieve better scalability and fidelity, respectively.
- The application of an intelligent control mechanism is utilized in controlling DC link voltage with better power management, fast-tracking capability, and high-performance efficiency. Nevertheless, they suffer from various shortcomings, such as a complex training process, which requires large training time and an appropriate selection of hyperparameters. Henceforth, future study is needed to address various issues with intelligent control schemes.
- Even though various metaheuristic optimization techniques are benefitted by minimizing the components, converter loss, and cost, their implementation in EV application is limited. To date, two optimization techniques, i.e., GA and PSO, have been utilized for optimizing design and cost. Therefore, it is recommended to implement other advanced and hybridized optimization techniques in EV applications.
- Parameter specification of the electric power components applied in the converters is one of the most effective ways of ensuring optimized performance. Selecting and deciding these parameters manually is both difficult and time-consuming. Besides, they often do not bring expected results in terms of performance. For this purpose, advanced optimization techniques and machine learning techniques can be applied to select the parameters of the power electronic components in converters and accurately predict the performances of the converters. Hence, future research needs to be more focused on developing such techniques for converters in EV applications.
- Machine learning techniques are currently under vast study for predicting and analyzing various types of faults in power converters, such as short circuit and open circuit faults. Accurate prediction of these faults is highly important since it can protect the converters from physical damage and prevent other hazardous incidences. As a result, the development of machine learning techniques is of high importance in terms of the implementation of power converters in EV applications.

The aforementioned suggestions could pave the way to develop and execute state-of-the-art converters in EV applications. Furthermore, this review work will encourage the researchers and automotive industries to conduct future research work on developing intelligent converters in the automotive field with better design configuration and operational capabilities. Overall, this review helps to achieve a pathway for future sustainable EV expansions.

## 6. Conclusions

The integration of energy storage management and power electronic converter improves the overall performance of EVs technology regarding EVs internal structure development, motor speed and torque regulation, voltage compensation, voltage boost, and power flow control. The focal point of this study is to come up with an academic research culture overview and highlight the characteristics and development of power electronic converter integrated energy storage management technology in EV applications through top-notch research articles. The key findings of this review are summarized below.

- This work explores the most related 100 research works published in the last ten years on ESSs integrated converter technology in EV applications from the database of Scopus by assessing the current trends, operation, applications, and problems.

- Several exclusive sections are created based on the most popular keywords, top highly cited research works, and top contributed authors. Additional insights are provided on the research articles by allocating them in terms of the year, citation, publishers, journal impact factor, and nations.
- It was investigated that the highest cited paper belongs to Cao et al. published in IEEE Transactions on Power Electronics 2012 from the USA with 809 citations.
- The most prominent author was Zahra Amjadi, with a total of six publications as the first author and constituting 457 citations with 7 h-index. While the second position was secured by Sheldon S. Williamson with 5635 citations in five publications
- China secured the first position in terms of country analysis with 33 publications followed by India with 17 and USA with 14 respectively.
- An in-depth investigation is carried out to examine the emerging power electronic converter topologies, targets, advantages, disadvantages, schemes, contributions, and research gaps. Several key challenges and feasible solutions are discussed, focusing on the converter design, controller operation, intelligent controllers design, and metaheuristic techniques.
- Comprehensive and insightful remarks for future research opportunities are delivered towards the advancement of EVs.

Finally, it is desired that the shared research works concepts, deliberations, and invaluable statistics on converter and energy storage management technology in EV applications will facilitate magnifying EV implementation and contribute to the automobile industry on the road to achieving sustainable development goals (SDGs) and decarbonization.

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## Abbreviations

| | |
|---|---|
| ACY | Average citation per year |
| AI | Artificial Intelligence |
| ANN | Artificial neural network |
| ANFIS | Adaptive neuro-fuzzy inference system |
| BDC | Bidirectional Converter |
| BMS | Battery Management Systems |
| BP | Battery Pack |
| BS | Battery Storage |
| CMV | Common-mode voltage |
| CS | Capacitor Storage |
| CSI | Current source inverter |
| EB | Electric Batteries |
| EE | Energy Efficiency |
| EES | Electric Energy Storage |
| EI | Electric Inverters |
| ELF | Electric Load Flow |
| EM | Energy Management |
| EMC | Electric Machine Control |
| EMI | Electromagnetic interference |
| EMS | Energy Management Systems |
| EPSC | Electric Power System Control |

| | |
|---|---|
| EPTN | Electric Power Transmission Networks |
| ES | Energy Storage |
| ESM | Energy storage management |
| ESR | Externally Supported Roof |
| EV | Electric Vehicles |
| FC | Fuel Cells |
| FCEV | Fuel cell EV |
| FL | Fuzzy Logic |
| FS | Fuel Storage |
| FSEV | Formula student electric vehicle |
| GA | Genetic algorithm |
| GaN | Gallium nitride |
| G2V | Grid to vehicle |
| HESS | Hybrid Energy Storage Systems |
| HEV | Hybrid Electric Vehicle |
| HV | Hybrid Vehicles |
| HVDCPT | HVDC Power Transmission |
| IF | Impact factor |
| LVP | Land Vehicle Propulsion |
| MIMO | Multiple-input-multiple-output |
| MMC | modular multilevel converter |
| PC | Power Converters |
| PE | Power Electronics |
| PEC | Power Electronics Converter |
| PHEV | Plug-in Hybrid Vehicles |
| PI | Proportional-Integral |
| PL | Power loss |
| PSO | Particle swarm optimization |
| RB | Regenerative Braking |
| RES | Renewable Energy Resources |
| SB | Secondary Batteries |
| SC | Supercapacitor |
| SiC | Silicon carbide |
| SM | Storage Management |
| SOC | State of charge |
| SOE | State of energy |
| SRM | switched reluctance motor |
| ST | Shoot-through |
| THD | Total harmonic distortion |
| TM | Traction Motors |
| UC | Ultracapacitors |
| UWBG | Ultra-wide bandgap |
| VA | Vehicle Applications |
| VC | Voltage Control |
| VSI | Voltage source inverter |
| V2G | Vehicle-to-grid |
| WBG | Wide bandgap |

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