Innovative Feature Analysis of Electric Vehicle Technology, Charging Infrastructure, Power management, and Control Methods

A. K. ONAOLAPO, B. T. ABE
Electrical Engineering Department,
Tshwane University of Technology,
Witbank Campus,
SOUTH AFRICA

Abstract: - Lowering the dependence on fossil fuels and reducing pollution from greenhouse gas (GHG) emissions is incredibly achievable through electric vehicle (EVs) technology. EV technology is an innovation that uses electricity, rather than fossil fuels, to power and refuel (recharge) vehicles. The adoption and development of EVs should lead to a decline in future demand for fossil fuels, which are finite in supply and exhaustible. Inherent challenges in EV technology, such as inadequate supply of critical minerals, power grid overload, battery technology constraints, extended charging durations, insufficient charging infrastructures, high initial costs, and limited driving range, must be addressed. The technology of charging infrastructures cannot be over-emphasized in EV technology. EV technology, charging infrastructures, vis-à-vis the impact of their integration into the grid is investigated. Effective control strategies and power management systems (PMSs) are required to optimize energy use to improve EVs' efficiency and lifetime. This research uses comprehensive analysis methods to assess various control strategies, PMSs, and their effects on EV integration into the grid.

Key-Words:- Electric vehicle technology, Charging infrastructure, Battery chargers, Control strategies, Power management systems, Renewable energy resources, Feature analysis.

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1 Introduction

EV technology was born out of the need to combat the increasing environmental concerns arising from the transport sector and contributing significantly to climate change challenges. As of 2022, the transport sector in the USA is said to be the highest contributor of greenhouse gas (GHG) emissions, contributing about 28% of the total GHG emissions, [1]. EV systems use less or no fossil fuels but use more electric grids or renewable energy (RE) for recharging purposes. Fossil fuel consumption has been reduced significantly through the adoption of EVs. The growing demand for conventional vehicles using fossil fuels has applications in EVs. This demand for alternatives to conventional transport systems results from the recognition of the risks fossil fuels pose to the planet and the environment. Various governments have encouraged this shift through incentives, subsidies, and policies. Fossil fuels present significant risks to the earth's ecosystem through GHG emissions, while EVs are environmentally sustainable. EVs offer many more societal benefits, such as economic viability, a safer and cleaner environment, and improved public health. A clean and safe environment is vital for human beings' existence. Besides, fossil fuel deposits are finite and depleting rapidly. The adoption of EVs is projected to increase significantly as governments adopt measures to facilitate investments and reduce carbon dioxide (CO_2) emissions.

Some measures that will encourage EV adoption are developing proportional electric generation systems and charging infrastructures. The availability of renewable energy resources (RERs), such as fuel cells, hydroenergy, wind, and solar photovoltaic (PV), in urban and rural areas makes them viable alternatives for EV charging, [2]. EV accessibility relies on the development of vital charging infrastructures. Suitable and effective charging infrastructures must be considered appropriately to realize EVs' full potential. EV technology is crucial to modern transportation systems because it involves different emerging technologies, such as charging infrastructures, battery systems, and electric motor systems. However, problems such as range anxiety, high initial costs, and extended charging durations make the transition to EVs slower than anticipated. The growing demand for EVs and charging infrastructures has necessitated research into mitigating the strain on electrical grids, exploring suitable control strategies, and using appropriate power management systems. Authors in [3] explored the plugin hybrid electric vehicles (PHEV) nonlinear control strategy for power flow of grid-to-vehicle and vehicle-to-grid systems using adaptive super-twisting sliding mode controller (AST-SMC) for voltage regulation. In [4], the authors delved into the grid impacts of electric vehicles' highway fast charging (HFC) to support decarbonization and address range anxiety concerns, analyzing the potential adverse effects of spatial concentration, high power requirements, and relative inflexibility features of HFC systems. In [5] a method to reduce voltage variations and losses from EV charging stations connected to electricity grids using distributed generators' weak bus placement (WBP) strategy was proposed. In [6], an in-depth review of control and charging techniques of recent research on EV grid integration was done. An in-depth assessment of the complex interactions between the smart grid infrastructures and EVs was provided. The [7] explored the technologies of vehicle-to-vehicle (V2V), grid-to-vehicle (G2V), and vehicle-to-grid (V2G) concerning grid integration of EVs. They posited the use of EVs as alternative sources of energy for different network systems, such as virtual power plants, microgrids, and smart grids. Vehicle-to-Grid (V2G) technology was comprehensively discussed in autonomous EVs in [8] and was posited to have enormous potential to optimize the use of EVs and revolutionize energy management. V2G-enabled autonomous EVs were analyzed to be capable of relieving the grid of strain during peak demand, optimizing EV charging operations to off-peak hours, engaging in demand response programs, harmonizing high electricity demand, enhancing grid stabilization, and functioning as mobile energy storage units. Researchers in [9] exhausted the possibility of dealing with the challenges of voltage fluctuations, power losses, and transformer overloads using a machine learning charging management strategy whilst considering vehicle-to-grid (V2G) technology, fast charging, and conventional charging scenarios and the results were validated by the long short-term memory (LSTM) machine learning model which successfully minimized voltage fluctuations and power losses. They flattened the load curve, thereby achieving peak shaving. Authors in [10] provided the architectures of the battery management systems (BMS), their impacts on vehicle performance, and a comprehensive review of BMS subsystems, analyzing its thermal management, cell balancing, state estimation, battery modeling, and control strategies. In [11] an in-depth review of solar photovoltaic (PV)-based EVs Power Converter Topologies integrated into the grid was done, devoting attention to the analysis of V2G operation bi-directional power ability, efficiency, voltage and power ranges, isolation, and topologies. Much research has been conducted to explore EV technologies, but more research is needed to address the persisting challenges. Some of the contributions of this study to the body of knowledge are as follows:

i). outlining EV's technologies and their associated challenges.
ii). innovative analysis of EV charging infrastructures
iii). in-depth investigation of EV charger types, and
iv). assessments of EV power management strategies and control methods.

2 Electric Vehicle Technology Analysis

There are different types of EV technologies with their peculiar features. Such technologies include fuel cell electric vehicles (FCEV), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEVs). Table 1 (Appendix) shows a comprehensive analysis of the different features of these EV technologies.

3 Electric Vehicle Charging Technology

The two critical components of EV technology are the power source and the charging system. Charging systems can be broadly categorized based on power flow and installation designs. The power flow design can be unidirectional or bidirectional, while the installation design can be on-board or off-board. A unidirectional charger is a one-way charger sending alternating current (AC) to the EV, where it is converted to direct current (DC), while a bidirectional charger allows the EV to convert the battery's DC back to AC for different uses such as vehicle to home (V2H) or vehicle to building (V2B), vehicle to grid (V2G), vehicle to load (V2L), vehicle to vehicle (V2V), and vehicle to everything (V2X). Also, an on-board charger is built into the EV while the off-board charger is located at a particular location where the EV can go and refuel or recharge, [12]. Feature analysis of power flow and installation design chargers are presented in Table 2 and Table 3 in Appendix.

4 EV Charging Infrastructures

Charging infrastructure comprises different equipment, such as charging stations, outlets, charge controllers, monitors, etc. The availability of this infrastructure is vital for charging, reliability, safety, enhancing extensive usage, and facilitating long-distance EV driving. Charging infrastructure could be categorized as grid-connected, off-grid, hybrid-microgrid, and renewable energy-based. Table 4 (Appendix) shows a feature analysis of these charging infrastructures.

5 EV Energy Management Systems

The Energy Management System (EMS) is responsible for controlling multiple energy sources and delivering the required energy to EVs. This management affects EVs' lifespan and efficiency. EMS performs crucial roles in EVs, such as enhancing seamless integration into the grid, conducting effective charging operations, coordinating supply from different resources, and optimizing EVs' use. Table 5 (Appendix) shows a list of available EMSs that have been designed and executed by different researchers.

6 EV Control Strategies

An increase in load demand due to the adoption of EVs can increase power losses, overload transformers, reduce transformers' lifespan, and reduce grid voltage; hence, the necessity for implementing appropriate control strategies. Control strategies perform crucial roles in EVs, such as improving the reliability of EVs, optimizing drive range and efficiency, and ensuring effective operations of charging infrastructures and EVs. The dynamics of the state of charge (SOC) are expressed as [27]:

$$E_i = E_{i-1} - P_{b,i}\Delta t \tag{1}$$

where Δt and $P_{b,i}$ are the discretized time interval and battery power respectively. Also,

$$SOC_i = \frac{E_i}{E_{full}} \tag{2}$$

with E_{full} representing the battery's full capacity. During motion, retarding the vehicle requires forces such as air drag, gradient resistance, and rolling resistance. The vehicle torque needed for acceleration is expressed as:

$$T_{o,i} = \frac{r}{k_f}\left[m\dot{v}_i + mg(\sin\alpha_i + f\cos\alpha_i) + \frac{1}{2}c_D A_f \rho v_i^2\right] \tag{3}$$

where v_i, α_i, g, m, k_f, and r represent the current vehicle velocity, road slope, gravity acceleration, vehicle mass, final reduction ratio, and wheel radius, respectively. Also, ρ, A_f, C_D, and f represent the air density, vehicle frontal area, aerodynamic drag coefficient, and rolling friction, respectively.

At maximum speed, the associated maximum engine torque is expressed as:

$$\overline{T}_e = T_e^{\max}(\omega_e^{\max}.\omega_i) \tag{4}$$

where T_e and ω_e represent engine torque and engine speed, respectively. Losses in the battery are derived as:

$$P_{b,i} = \frac{U_{oc,i}(U_{oc,i} - \sqrt{U_{oc,i}^2 - 4P_{end,i}R_{b,i}})}{2R_{b,i}} \tag{5}$$

where the battery current $I_{b,i}$ is negative while charging and positive while discharging; $P_{end,i}$ represents power at the battery terminals, $U_{oc,i}$ represents the open-circuit voltage of the battery and $R_{b,i}$ represents the equivalent internal resistance of the battery. Both $R_{b,i}$ and $U_{oc,i}$ depend on the battery's SOC.

Table 6 (Appendix) lists available control strategies designed and executed by different researchers.

7 International Standards and the EU Directives about Electric Vehicles

Currently, many international organizations are working on different EV charging codes and standards. Some of the standards are shown in Table 7 (Appendix).

8 Conclusions

Different EV charging infrastructures, architectures, and grid-integrated systems have emerged due to the developments in EV technology. Efficient and effective management of its charging operations requires suitable power management approaches and control methods. This study provides an innovative analysis of EV technologies, charging infrastructures, control strategies, and power management approaches. This study helps make decisions to alleviate strains from EV integration into the grid. Engineers and researchers working on similar research focus will find this study helpful in advancing their research. Future research should focus on finding solutions to different challenges experienced in the development of EV technologies and charging infrastructures, such as easy, fast, and rapid charging mechanisms, improving the efficiency and lifespan of EV batteries, developing appropriate and highly efficient power management systems, and the development of advanced V2H or V2B, V2G, V2L, V2V, and V2X systems.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used Grammarly for language editing. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

References:

[1] EPA, Transportation, Air Pollution, and Climate Change, [Online]. https://www.epa.gov/transportation-air-pollution-and-climate-change/carbon-pollution-transportation#:~:text=Transportation%20and%20Climate%20Change,-Burning%20fossil%20fuels&text=%E2%80%8BGreenhouse%20gas%20(GHG)%20emissions,contributor%20of%20U.S.%20GHG%20emissions (Accessed Date: July 4, 2024).

[2] A. K. Onaolapo and B. T. Abe, An extensive assessment of the energy management and design of battery energy storage in renewable energy systems, *WSEAS Transactions on Power Systems,* 2024, vol. 19, issue 17, pp. 146-170, https://doi.org/10.37394/232016.2024.19.17.

[3] U. Masood, M. K. Azeem, I. Ahmad, and A. ul Jabbar, Robust adaptive nonlinear control of plugin hybrid electric vehicles for vehicle to grid and grid to vehicle power flow with hybrid energy storage system, *ISA Transactions,* 2023, vol. 139, issue 1, pp. 406–424, https://doi.org/10.1016/j.isatra.2023.03.035.

[4] A. M. Mowry and D. S. Mallapragada, Grid impacts of highway electric vehicle charging and role for mitigation via energy storage, *Energy Policy,* 2021, 157, 112508, https://doi.org/10.1016/j.enpol.2021.112508.

[5] S. Aggarwal, A. K. Singh, R. S. Rathore, M. Bajaj, and D. Gupta, Revolutionizing load management: A novel technique to diminish the impact of electric vehicle charging stations on the electricity grid, *Sustainable Energy Technologies and Assessments,* 2024, vol. 65, issue 1, pp. 103784, https://doi.org/10.1016/j.seta.2024.103784.

[6] P. H. Femy and J. Jayakumar, A comprehensive review on electric vehicles: charging and control techniques, electric vehicle-grid integration, *Energy Harvesting and Systems*, 2023; 10(1): 1–14, https://doi.org/10.1515/ehs-2021-0083.

[7] M. Inci, O. Celik, A. Lashab, K. C. Bayındır, J. C. Vasquez, J. M. Guerrero, Power system integration of electric vehicles: A review on impacts and contributions to the smart grid, *Applied Sciences*, 2024, vol. 14, issue 1, pp. 2246. https://doi.org/10.3390/app14062246.

[8] P. Seo-yeon, and C. Sung-hoon, Integrating Vehicle-to-Grid Technologies in Autonomous Electric Vehicle Systems, *Applied Research in Artificial Intelligence and Cloud Computing,* 2022, 5(1), 105-120.

[9] M. Shibl, L. Ismail, and A. Massoud, Electric vehicles charging management using machine learning considering fast charging and vehicle-to-grid operation, *Energies,* 2021, vol. 14, issue

1, pp. 6199. https://doi.org/10.3390/en14196199.

[10] B. Ashok, C. Kannan, B. Mason, S. D. Ashok, V. Indragandhi, D. Patel, A. S. Wagh, A. Jain, and C. Kavitha, Towards safer and smarter design for lithium-ion-battery-powered electric vehicles: A comprehensive review on control strategy architecture of battery management system, *Energies*, 2022, vol. 15, issue 1, pp. 4227, https://doi.org/10.3390/en15124227.

[11] F. N. Esfahani, A. Darwish, and B. W. Williams, Power converter topologies for grid-tied solar photovoltaic (PV) powered electric vehicles (EVs)-A comprehensive review, *Energies,* 2022, vol. 15, issue 1, pp. 4648. https://doi.org/10.3390/en15134648.

[12] M. Kumar, K. P. Panda, R. T. Naayagi, R. Thakur, and G. Panda, Comprehensive Review of Electric Vehicle Technology and Its Impacts: Detailed Investigation of Charging Infrastructure, *Power Management, and Control Techniques. Appl. Sc*., 13, 8919 (2023). https://doi.org/10.3390/app13158919.

[13] L. Zhang, C. Sun, G. Cai, and L. H. Koh, Charging and discharging optimization strategy for electric vehicles considering elasticity demand response, *ETransportation,* 2023, vol. 18, issue 1, pp. 100262, https://doi.org/10.1016/j.etran.2023.100262.

[14] A. Ghasemi-Marzbali, Electric vehicle fast charging station design by considering probabilistic model of renewable energy source and demand response, *Energy,* 2023, vol. 267, issue 1, pp. 126545, https://doi.org/10.1016/j.energy.2022.126545.

[15] S. Khan, K. Sudhakar, and M. H. bin Yusof, Building integrated photovoltaics powered electric vehicle charging with energy storage for residential building: Design, simulation, and assessment, *Journal of Energy Storage,* 2023, vol. 63, issue 1, pp. 107050, https://doi.org/10.1016/j.est.2023.107050.

[16] V. Powar, and R. Singh, End-to-End direct-current-based extreme fast electric vehicle charging infrastructure using lithium-ion battery storage, *Batteries*, 2023, vol. 9, issue 3, pp. 169, https://doi.org/10.3390/batteries9030169.

[17] M. A. Nazari, V. Blazek, L. Prokop, S. Misak, and N. Prabaharan, Electric vehicle charging by use of renewable energy technologies: A comprehensive and updated review, *Computers and Electrical Engineering*, 2024, vol. 118, issue 1, pp. 109401, https://doi.org/10.1016/j.compeleceng.2024.109401.

[18] P. Barman, L. Dutta, S. Bordoloi, and A. Kalita, Renewable energy integration with electric vehicle technology: A review of the existing smart charging approaches, *Renewable and Sustainable Energy Reviews*, 2023, vol. 183, issue 1, pp. 113518, https://doi.org/10.1016/j.rser.2023.113518.

[19] T. Mazhar, R. N. Asif, M. A. Malik, M. A. Nadeem, I. Haq, M. Iqbal, M. Kamran, and S. Ashraf, Electric vehicle charging system in the smart grid using different machine learning methods, *Sustainability,* 2023, vol. 15, issue 3, pp. 2603, https://doi.org/10.3390/su15032603.

[20] A. Parlikar, M. Schott, K. Godse, D. Kucevic, A. Jossen, and H. Hesse, High-power electric vehicle charging: Low-carbon grid integration pathways with stationary lithium-ion battery systems and renewable generation, *Applied Energy*, 2023, vol. 333, issue 1, pp. 120541, https://doi.org/10.1016/j.apenergy.2022.120541.

[21] K. S. Arikumar, S. B. Prathiba, R. S. Moorthy, G. Srivastava, and T. R. Gadekallu, Software defined networking assisted electric vehicle charging: Towards smart charge scheduling and management, *IEEE Transactions on Network Science and Engineering*, 2024, vol. 11, issue 1, pp. 163-173, https://doi.org/10.1109/tnse.2023.3293053.

[22] S. J. Sultanuddin, R. Vibin, A. R. Kumar, N. R. Behera, M. J. Pasha, and K. K. Baseer, Development of improved reinforcement learning smart charging strategy for electric vehicle fleet, *Journal of Energy Storage*, 2023, vol. 64, issue 1, pp. 106987, https://doi.org/10.1016/j.est.2023.106987.

[23] M. Secchi, G. Barchi, D. Macii, and D. Petri, Smart electric vehicles charging with centralised vehicle-to-grid capability for net-load variance minimisation under increasing EV and PV penetration levels, *Sustainable Energy, Grids and Networks*,

2023, vol. 35, issue 1, pp. 101120, https://doi.org/10.1016/j.segan.2023.101120.

[24] M. S. Mastoi, S. Zhuang, H. M. Munir, M. Haris, M. Hassan, M. Alqarnid, and B. Alamrie, A study of charging-dispatch strategies and vehicle-to-grid technologies for electric vehicles in distribution networks, *Energy Reports*, 2023, vol. 9, issue 1, pp. 1777–1806, https://doi.org/10.1016/j.egyr.2022.12.139.

[25] J. Li, G. Wang, X. Wang, and Y. Du, Smart charging strategy for electric vehicles based on marginal carbon emission factors and time-of-use price, *Sustainable Cities and Society*, 2023, vol. 96, issue 1, pp. 104708, https://doi.org/10.1016/j.scs.2023.104708.

[26] A. Almutairi, and T. M. Aljohani, Reliability-driven time-of-use tariffs for efficient plug-in electric vehicle integration, *Sustainable Cities and Society*, 2024, vol. 107, issue 1, pp. 105463, https://doi.org/10.1016/j.scs.2024.105463.

[27] F. Ju, N. Murgovski, W. Zhuang, X. Hu, Z. Song, and L. Wang, Predictive energy management with engine switching control for hybrid electric vehicle via ADMM, *Energy*, 2023, vol. 263, no 1, pp. 125971, https://doi.org/10.1016/j.energy.2022.125971.

[28] F. Barrero-González, M. I. Milanés-Montero, E. González-Romera, E. Romero-Cadaval, and C. Roncero-Clemente, Control strategy for electric vehicle charging station power converters with active functions, *Energies,* 2019, vol. 12, issue 20, pp. 3971, https://doi.org/10.3390/en12203971.

[29] M. Jha, F. Blaabjerg, M. A. Khan, V. S. B. Kurukuru, and A. Haque, Intelligent control of converter for electric vehicles charging station, *Energies,* 2019, vol. 12, issue 12, pp. 2334, https://doi.org/10.3390/en12122334.

[30] Z. Zhang, H. Min, Y. Yu, Q. Cao, M. Li, and K. Yan, An optimal thermal management system heating control strategy for electric vehicles under low-temperature fast charging conditions, *Applied Thermal Engineering*, 2022, vol. 207, issue 1, pp. 118123, https://doi.org/10.1016/j.applthermaleng.2022.118123.

[31] J. Guo, F. Jiang, A. novel electric vehicle thermal management system based on cooling and heating of batteries by refrigerant, *Energy Conversion and Management*, 2021, vol. 237, issue 1, pp. 114145, https://doi.org/10.1016/j.enconman.2021.114145.

[32] A. Singh, K. Pal, and C. B. Vishwakarma, State of charge estimation techniques of Li-ion battery of electric vehicles, *e-Prime- Advances in Electrical Engineering, Electronics and Energy*, 2023, vol. 6, issue 1, pp. 100328, https://doi.org/10.1016/j.prime.2023.100328.

[33] M. El Marghichi, S. Dangoury, Y. Zahrou, A. Loulijat, H. Chojaa , F. A. Banakhr, and M. I. Mosaad, Improving accuracy in state of health estimation for lithium batteries using gradient-based optimization: Case study in electric vehicle applications, *PLoS One*, 2023, vol. 18, issue 11, pp. e0293753, https://doi.org/10.1371/journal.pone.0293753.

[34] J. Chen, A. Behal, Z. Li, and C. Li, Active Battery Cell Balancing by Real-Time Model Predictive Control for Extending Electric Vehicle Driving Range, *IEEE Transactions on Automation Science and Engineering*, 2023, pp. 1–13, https://doi.org/10.1109/tase.2023.3291679.

[35] M. H. Uddin, S. Dhar, and A. M. Siddiqee, Analysis of a field-oriented control based variable direct current link drive for electric vehicles, *Indonesian Journal of Electrical Engineering and Computer Science*, 2023, vol. 32, no. 1, pp. 52-60, DOI: 10.11591/ijeecs.v32i1.pp52-60.

[36] H. Tiwari, A. Ghosh, C. Sain, F. Ahmad, and L. Al-Fagih, Modified direct torque control algorithm for regeneration capability of IM driven electric vehicle by using hybrid energy storage system, *Renewable Energy Focus*, 2024, vol. 48, no 1, pp. 100534, https://doi.org/10.1016/j.ref.2023.100534.

[37] S. Habib, M. M. Khan, F. Abbas, L. Sang, M. U. Shahid, and H. Tang, A Comprehensive Study of Implemented International Standards, Technical Challenges, Impacts and Prospects for Electric Vehicles, *IEEE Access*, 2018, vol. 6, pp. 13866-13890, https://doi.org/10.1109/access.2018.2812303.

APPENDIX

Table 1. Feature analysis of different electric vehicle technologies

	FCEV	**HEV**	**PHEV**	**BEV**
Resource	Powered by hydrogen fuel or fuel cell.	Combination of fossil fuel and battery.	Combination of fossil fuel, battery, and a plug-in charger for off-board charging.	Powered by battery.
Efficiency	Excellent efficiency but with a limitation of hydrogen fuel availability.	The overall best efficiency of all EV technologies.	Very good efficiency.	Excellent efficiency.
Affordability	Costlier than BEV	Cheapest among all EV technologies.	Costlier than HEV	Costliest among all EV technologies.
Drive range	Longer drive range than BEV.	Moderate drive range.	Longer drive range.	Limited drive range.
Emission	Zero emissions.	Low emissions.	Low emissions.	Zero emissions.

Table 2. Feature analysis of power flow design chargers

	Unidirectional charger	**Bidirectional charger**
Flow direction	One-way power flow (battery charging).	Two-way power flow (plus communication flow).
Affordability	Low cost.	High cost.
Benefit	-Battery life is high. -Highly reliable. -Circuit is less complex. -Charger volume is compact.	-V2H, V2G), V2L, V2V, and V2X are possible. -Input supplies have low harmonics.
Challenge	-V2H, V2G), V2L, V2V, and V2X are not possible. -Power factor correction converter experiences power loss in the diode bridge rectifier.	-Battery life is low (due to charging and recharging frequency). -Less reliable. -Circuit is more complex. -Charger volume is complex.

Table 3. Feature analysis of installation design chargers

	On-board charger	**Off-board charger**
Implementation	Easy	Complex
Affordability	Low cost	High cost
Performance	Low	High
Maintenance	Less	More
Space	Less	More
Benefit	-It is within the vehicle and more secure. -More cost-effective. -Needs no external cord, hence convenient.	-It can charge multiple batteries concurrently. -It is mobile and usable anywhere. -It is faster and more powerful than an on-board charger.
Challenge	-Replacing the charger becomes difficult when faulty. -Its operation is limited to charging one battery per time.	-It is not within the vehicle and is less secure. -Costlier than an on-board charger. -Needs external cords, and may be inconvenient.

Table 4. Feature analysis of EV charging infrastructures

	Feature benefit	Feature challenge
Grid-connected	-Longer drive range. -Accessible everywhere. -Faster charging speed.	-Cost more than off-grid chargers. -Where grid supply is inconsistent, may be unreliable. -Most grids use fossil fuel sources, hence unsustainable.
Off-grid	-Cost less than grid-connected. -Does not depend on the grid, hence more reliable. -Uses renewable energy sources (RES), hence more sustainable. -More cost-effective than grid-connected.	-Limited charging speed. -Limited drive range. -Not accessible everywhere.
Hybrid-microgrid	-It enables charging for both AC and DC sources, hence flexible. -It generates and stores energy locally, hence enhancing grid stability. -It integrates both fossil fuel and renewable sources, hence more efficient.	-Complex setup. -More expensive to implement. -New and not yet available everywhere.
Renewable energy-based	-Clean energy source, zero emission. -Abundant sources of renewable energy resources (RERs) and independence of fossil fuel sources. -Cost-effective. -Reduces strain on the grid.	-High investment or expansion cost. -Intermittency challenge. -Not available everywhere. -Grid integration hurdles.

Table 5. EV energy management systems

S/N	EMS	Description	References
1	Demand response	Charging is managed using methods such as regulating charging patterns in accordance with received signals from the grid operator or arranging scheduled charges to off-peak hours.	[13], [14]
2	Integrating energy storage	During off-peak periods, energy storage stores excess energy, which is released for use during peak periods, thereby reducing strain on the system.	[15], [16]
3	Integrating renewable energy	Effective optimization of RERs can help reduce dependence on the electricity grid, minimize reliance on fossil fuel sources, and maximize the benefits of RES.	[17], [18]
4	Integrating grid management systems	While this method has the tendency to put a strain on the grid, it enables EV charging demand to be monitored and controlled. Measures are put in place to adhere to the grid's capacity limitation.	[19, [20]
5	Smart charging algorithms	Algorithms are designed on factors such as users' preferences, electricity cost, and demand on the grid, to optimize charging operations. Such algorithms can prioritize charging for EVs, initiate charging delay, and vary the charge rate.	[21], [22]
6	Vehicle-to-grid (V-2-G) technology	The stored energy in EV batteries could be harnessed to supply power to commercial outfits, residential buildings, or directly to the grid during peak periods.	[23], [24]
7	Time-of-use (T-O-U) pricing	TOU provides different costs of energy at off-peak and peak periods. This is done to encourage charging during off-peak periods and reduce strain on the grid.	[25], [26]

Table 6. EV control strategies

S/N	Control strategy	Description	References
1	Charging station control	EV charging facilities adhere to strict standards to ensure safety, connectivity, precision, and optimal performance.	[28], [29]
2	Thermal management control	Thermal management of EV charging operation performs crucial roles of safety, optimal operation, and lifespan improvement of EVs. This control keeps the electric motors, power electronic devices, and battery banks at their optimal operating temperatures.	[30], [31]
3	Battery management control	Battery management control, such as cell balancing, state-of-health (SOH) control, and state-of-charge (SOC) control, exerts over the battery bank or individual battery and the associated electronic devices to prevent overcharging and ensure the safety of users.	[32], [33], [34]
4	Motor control	Motor control strategies such as pulse-width modulation (PWM), direct torque control (DTC), and field-oriented control (FOC), regulate the motor's speed, provide fast and accurate response, and improve motor efficiency.	[35], [36]

Table 7. Charging standards [37]

S/N	Charging category	Charger type and phase	Common base	Supply interface	Anticipated output
SAE charging standard					
1.	Convenient charging - 230V, AC (EU) - 120V, AC (US)	On-board/single-phase	Charging in the residence or office.	Any accessible outlet	-1.4kW/12A -1.9kW/20A
2.	Main charging -400V, AC (EU) -240V, AC (US)	On-board/single or three-phase	Charging in the private or public station.	Supply interface for EV	-4kW/17A -8kW/32A -19.2kW/80A
3.	Fast charging -208V-600V, AC	Off-board/ three-phase	Commercial charging station.	Supply interface for EV	-50kW -100kW
4.	-200V-450V, DC	Off-board	Specific charging station.	Supply interface for EV	-40kW/80A
5	-200V-450V, DC		Specific charging station.	Supply interface for EV	-90kW/200A
6	-200V-600V, DC		Specific charging station.	Supply interface for EV	-240kW/400A
IEC charging standard					
7	AC	On-board/single-phase	Charging in the residence or office.	Any accessible outlet	-4kW-7.5kW/16A
8	AC	On-board/single or three-phase	Charging in the private or public station.	Supply interface for EV	-8kW-15kW/32A
9	AC	On-board/ three-phase	Commercial charging station.	Supply interface for EV	-60kW-120kW/250A
10	Rapid charging, DC	Off-board	Specific charging station.	Supply interface for EV	-1000kW-2000kW/400A
CHAdeMo charging standard					
11	Rapid charging, DC	Off-board	Specific charging station.	Supply interface for EV	62.5kW/125A

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research at all stages, from the problem formulation to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare relevant to this article's content.

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