Towards the Vision of All Electric Vehicles in a Decade

Effective Charging Options of Electric Vehicles

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The consumers as well as the manufacturers and inventors have been pondering over the idea of electrifying transportation. Despite all these, the wheels on the road are largely fossil fuel based. Alternate technologies like hydrogen fuel cells and biofuels have also been "on the near horizon" for years. Despite the advent of various strong policy incentives, Electric Vehicles (EV) have had limited success in the market till now. However, the recent surge in the advancement of battery technology and the market forces have all combined to pose a serious threat to the centuries-old internal combustion vehicles. In this article, different charging aspects of Battery Electric Vehicle (BEV) are discussed.

1. TYPES OF ELECTRIC VEHICLE

Many different types of EVs in the market are outlined in Figure 1. Battery EVs only use batteries to power the vehicle. Hybrid EVs (HEVs) and plug-in HEVs are powered using both gasoline and electricity. Hybrid-EVs use regenerative braking to re-charge their battery. In contrast, Plug-in HEVs, recharge the battery using regenerative braking or external power source.

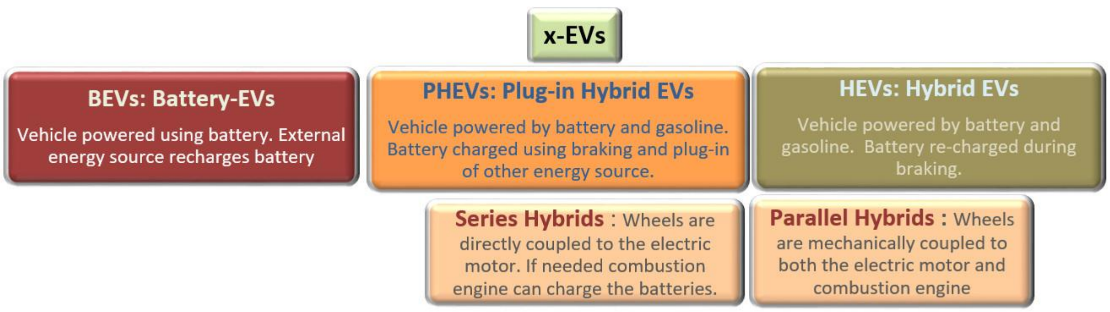


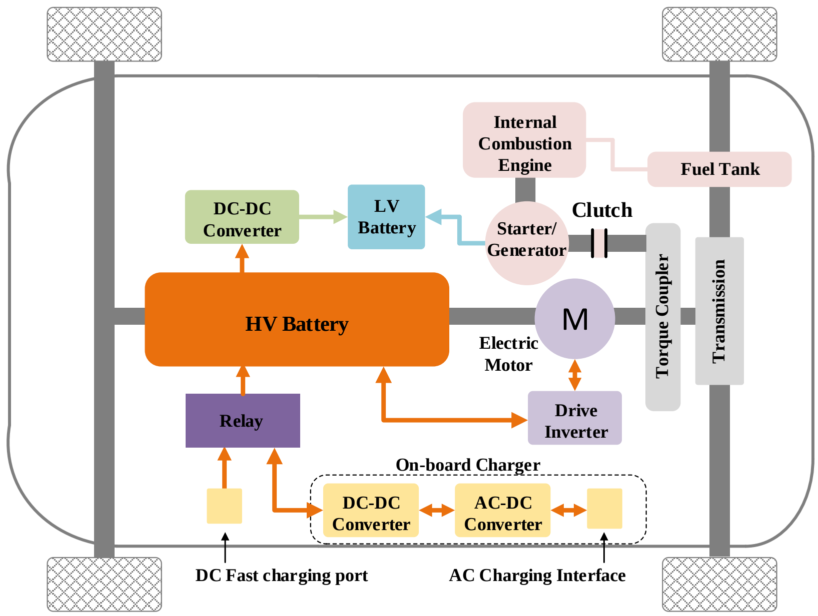
FIGURE 1. A broad classification of different EVs.

Further, the hybrid vehicles including both HEVs and PHEVs can have series or parallel drive-trains. In case of series hybrids, the wheels are coupled to only the electric motor. It draws power from the battery

Table 1. Existing Battery EVs and their specifications

Make	Battery		Range (miles)	On-Board Charger Capacity (kW)	Miles added per Hour
	kWh	V			
Nissan Leaf-2017	30	360	107	6.6	23.54
Ford Focus Electric	33.5	320	115	6.6	22.65
Chevy Bolt	60	350	238	7.2	26.18
Kia Soul Electric	30	375	111	6.6	24.42
Fiat 500e	24	364	84	6.6	23
Mitsubishi i MiEV	16	330	62	3.3	12.79
BMWi3	33	350	114	7.4	25.56
Tesla Model S	100	400	315	17.3	54.5
Tesla Model 3	75	350	220	7.7	22.59

pack, which is recharged using the Gasoline engine/generator. In the case of parallel hybrids, the wheels are coupled to both the electric motor and the internal combustion engine, and the vehicle optimises their usage based on the driver's requirement to achieve the best performance. Fig. 2 shows the power train architecture of different types of parallel HEVs. The figure is color coded to show the difference between different power trains of parallel HEVs [1].



Vehicle Classification	Color coding of components
Internal Combustion Engine Vehicle	+ +
Plug in Hybrid EV	+ + + + + + +
Battery EV	+ + + + + +

FIGURE 2. Block level architecture of a parallel hybrid vehicle.

Table 1 lists some of the existing BEVs and their battery specifications. The on-board charger rating of each of the BEVs is also shown. If on-board charger is used, miles added per an hour of charging is specified. The range of EVs is around 100 miles, which is much less than their counterpart gasoline vehicles with a range of about 400 miles. In comparison to the gasoline vehicles, the EVs take significantly more time to recharge. The charging rate of the battery is also limited by its battery chemistry [2].

2. Types of EV Charging

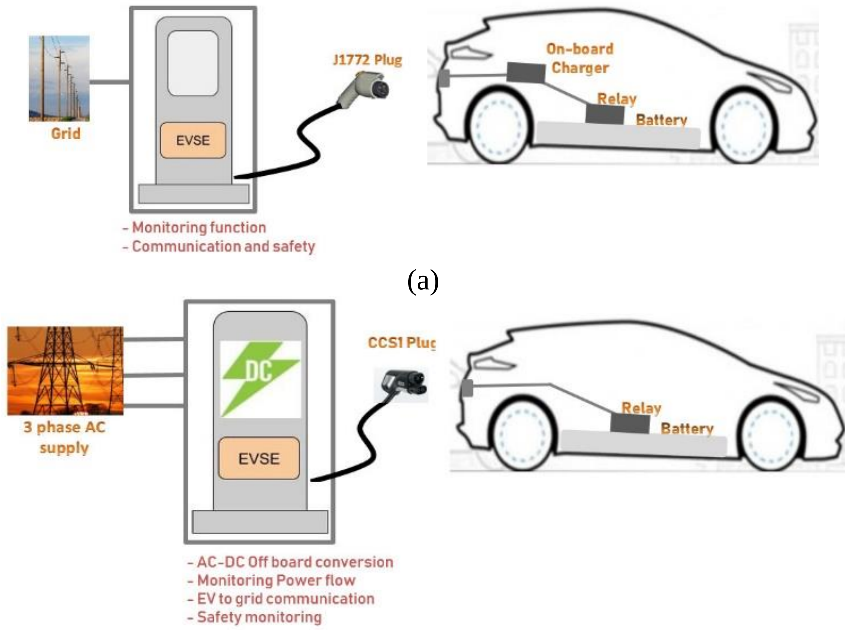
The EV battery can be charged using a DC or AC source. In both the cases, the final objective is to charge the battery with specific voltage and current that can be safely accepted by the battery. In case of AC charging, an on-board charger is required to convert AC to DC. Since the on-board charger is located in the vehicle, its size and weight are limited. This puts a limitation on the charger's power capacity, and therefore AC charging of an EV is relatively slow. In contrast, a DC charger directly provides the DC power to the battery by bypassing the on-board charger. Figure 3 depicts the two different types of charging. As the DC charger by-passes the on-board charger, it is inherently of higher power rating. An Electric Vehicle Supply Equipment (EVSE) is used to seamlessly interface a power source to the car.

AC and DC Charging Standards:

In order to regulate EV charging, various standards are formulated based on, whether the source is AC or DC. The charging standards for AC chargings are shown in Table 2. For DC charging, the roadmap is provided based on data provided by various regulators. All DC chargers take 3 phase AC input, as the power level is high. Currently, 60 kW DC chargers are available in the market for most EVs. However, Tesla Supercharger with capacity of 120 kW (DC Level 2) are also available for Tesla EVs. DC chargers are meant for fast charging of EV batteries and also referred to as Quick Chargers.

Electric Vehicle Supply Equipment (EVSE):

In order to make the charging infrastructure safe for operation by users, a charging interface is introduced between the power source (e.g., grid) and the electric vehicle (EV). It is called Electrical Vehicle Supply Equipment (EVSE) [3]. This device communicates with the EV and the grid to control the power flow and ensures that recommended safety standards are met. In case of AC charging its function is mainly to monitor the AC power flow to the on-board charger. In case of DC charging, the EVSE provide off-board AC-DC conversion along with power flow control and safety monitoring. These functions are depicted in Fig. 3 (a) and (b).



(a)

(b)

FIGURE 3. Different types of charging technology: (a) Components of AC charging station: uses on-board charger inside an EV (b) Components of DC charging station: directly charges the EV battery.

Table 2 Different Levels of AC and DC Charging

AC Level 1	AC Level 2	AC Level 3
120V single phase AC up to **16A** for up to **1.9kW.** Typically, this is limited to 12A. It takes **8 to 12 hours to charge a battery completel**y	**240V** single phase AC up to **80A** for up to **19.2kW.** Typically, this is limited to 32A. It takes **4 to 6 hours to charge a battery completel**y	**More than Level 2**. A couple of car makers make cars supporting three-phase AC charging at rates **up to 43kW.** Generally, these provide almost **80% charge in 30 minutes**

Roadmap for DC Charging:

2016	2018	2020
CHAdeMO:500V DC up to **62.5kW (125A)** **CCS: 400V** DC up to **50kW**	**CHAdeMO:500V** DC up to **150kW (350A)** **CCS: 400V** DC for at least **150kW**	**CHAdeMO:1000V** DC up to **350kW (350A)** **CCS: 400V** DC for at least **350kW**

The key protective functions performed by EVSE as per standards are presented in Fig. 4. In case of AC charging, EVSE acts as a smart controller between grid and EV and facilitates safe and controlled power flow using a pilot wire communication signal. The charging station communicates the available output parameters to EV on-board charger controller via pilot wire pulse width modulated (PWM) signals. The use of pilot wire communication ensures safe power delivery to vehicle with limited user interaction [1].

Table 3: Various charging standards

Standard/Plug connectors	**Charging Specs for corresponding standards (as of 2016 installations)**	**Communication Protocol**	**Compatible Manufactures**
CHAdeMo (Charge de Move)	62.5 kW DC Fast Charging	CAN	Nissan, Mitsubishi, Toyota
SAE-J1772-2009 (SAE: Society of Automotive Engineers)	Level 1 and Level 2 Supports AC charging: 110 V/240 V @ 19.2 kW	Power Line Communication (PLC)	GM, Ford, Nissan, Tesla
SAE-Combined Charging System **(CCS)**	AC Level 1 or Level 2+ DC Fast Charging: AC: up to 19.2 kW DC: up to 90 kW	Power Line Communication (PLC)	Volkswagen, GM, BMW
GB/T	AC: Level 1 and Level 2 250 V / 16 A or 32 A DC: 220-470 V, 125 A	CAN	Chinese EV manufacturers

There are several charging standards, connectors, and communication protocols. EV manufacturers use one of the standards given in Table 3.

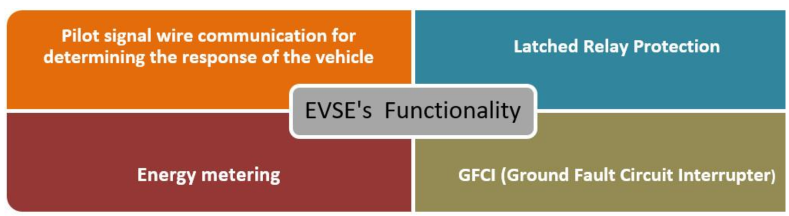


FIGURE 4. Functions of EVSE.

3. EV Battery Technology

EVs use various types of Lithium-Ion batteries. The battery of EVs needs replacement with aging. This is one of the major issues posed before a new EV buyer. At low state of charge (SOC), a battery is charged at constant current and once the SOC reaches near 90 % it is charged with a constant voltage. This cycle of charging and discharging thereafter leads to aging of the battery. As depicted in Figure 5, various companies handle the aging of EV batteries differently for a consumer.

Impact on the Electric Utility Grid:

An electric vehicle typically sources its power from the utility grid to recharge the battery. If overnight charging is used by all the vehicles at home, it will increase the night-time power demand on the grid.

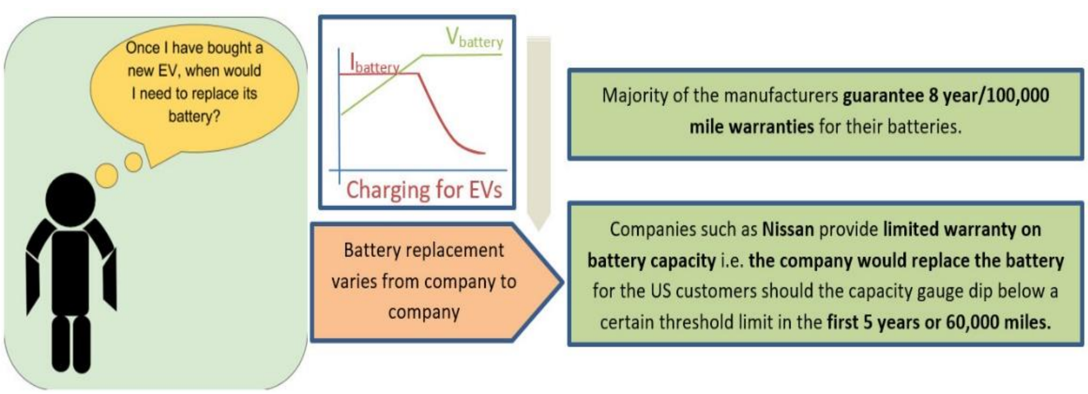


FIGURE 5. User concerns over batteries is a major factor for EV adaptation.

Therefore, it is important to map the energy demand on the grid over a 24-hour period and, ideally, charge the EV when the energy demand on the grid is low. However, practically, this is difficult to implement. Smart charging is also explored as an option where a third party monitors the charging of EVs in a more intelligent way [4]. In this case, pre-used or aged batteries can be used to source power to the EV and reduce peak power demand on the grid.

Mix-energy source can also be used to provide energy for EV charging, as shown in Figure 6(a). This essentially means that apart from the grid, other sources of energy, such as, Solar PV, Diesel generator, Wind energy, can also be used to charge the EV. This strategy not only reduces the power demand on the grid, but also provides a reliable energy source for EV charging, where grid is unhealthy (intermittent power outages are common). It is a promising concept to help EV penetration for developing countries like India.

4. **Power Electronics in EV Charging**

Power electronics converter ensure galvanic isolation between the source and the EV. It also ensures that EVs with wide battery voltage rating can be charged from the same charger. Typical Level 2 onboard charger structure for an x-EV is shown in Figure 6(b) [5-7].

Conventionally bridgeless totem pole power factor correction (PFC) circuit is used as the input AC-DC conversion stage for Level 1&2 chargers due to their high efficiency and good EMI characteristics. Traditionally, PWM converters, e.g., dual active bridge or phase shifted full bridge converters are common choice for secondary isolated DC-DC conversion stage due to their wide gain capability. The growing demand for highly efficient and power dense solutions have led to the use of resonant converters such as LLC, CLLC as viable alternative for secondary stage due to their soft switching characteristics aiding in high frequency efficient operation of circuit.

Long-term vision:
Bidirectional power flow: With smart grid becoming popular, the aim is to aid the economics of the electric service by building a two-way relationship between the EVs and the grid. Since all the EVs have batteries, the idea is to use it as temporary storage as efficiently as possible. This means, charging the battery during the off-peak hours and pumping energy back to the grid during the peak demand hours. This will help in relieving the stress on the electricity generation sources and can also act as a revenue source for customers to alleviate rising electricity cost [8].

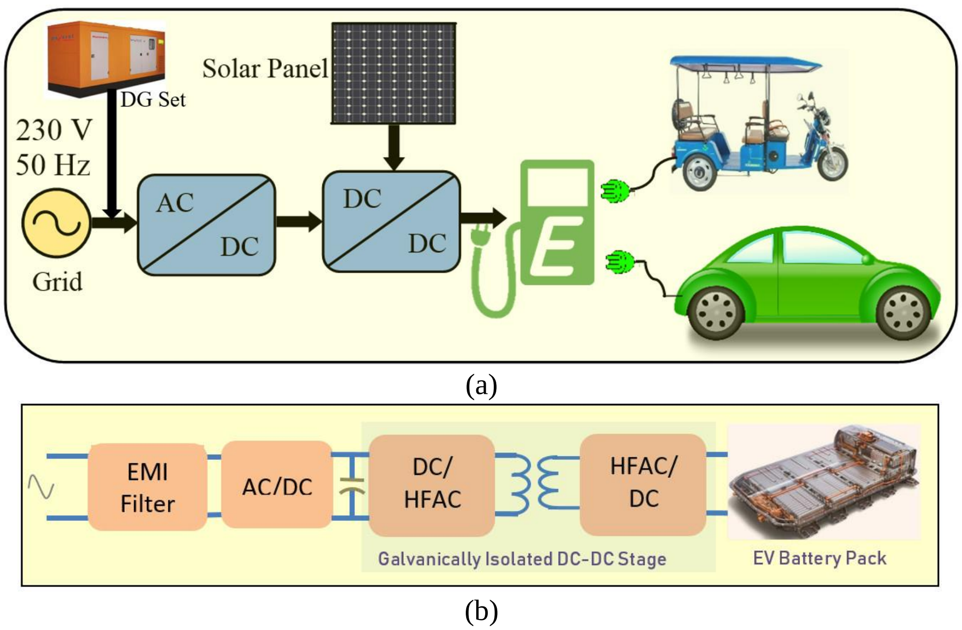


FIGURE 6. (a) Mix-energy source EV charging and (b) Typical on-board EV charger architecture.

Wireless charging: Wireless charging systems capable of transferring power with the help of electric field or magnetic field can act as a viable solution to support full autonomy. Future roads can be built with embedded charging pads enabling charging on transit [9].

Vehicle to Vehicle power transfer: Increase in EV energy demand, leads to mobile charging sources capable of vehicle to vehicle power transfer. These mobile sources can also function as scheduled distributed sinks and sources helping in peak saving features to improve grid stability.

5. Conclusions

This article presents an overview of EVs from a charging infrastructure point of view. The basic architecture of a DC and AC charger are explained. Various types of charging standards are outlined. Impact of significant EV penetration on the utility grid is outlined. The article concludes with some futuristic possibilities for the charging infrastructure.

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Acknowledgement

The work was supported by Department of Science and Technology, India, under Mission Innovation Program with grant no. DST/CERI/MI/SG/2017/086.

References

[1] A. Emadi, Y. J. Lee, and K. Rajashekara, "Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-in Hybrid Electric Vehicles," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 6, pp. 2237-2245, June 2008.

[2] N. Kularatna, "Dynamics and Modeling of Rechargeable Batteries: What electrochemists? work tells the electronic engineers," *IEEE Power Electronics Magazine*, Volume: 1, Issue: 4 , Dec. 2014.

[3] Design Notes by Texas Instruments, "Electric Vehicle Service Architecture" Available Online : https://training.ti.com/level-1-and-2-ac-charging-pile-station-design-considerations?cu=1128055.

[4] L. Dickerman; Jessica Harrison, "A New Car, a New Grid," *IEEE Power and Energy Magazine*, Volume: 8, Issue: 2, March-April 2010.

[5] F. Musavi, M. Edington, W. Eberle and W. G. Dunford, "Evaluation and Efficiency Comparison of Front End AC-DC Plug-in Hybrid Charger Topologies," *IEEE Transactions on Smart Grid*, vol. 3, no. 1, pp. 413-421, March 2012.

[6] M. Yilmaz , and P. T. Krein, "Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles," *IEEE Transactions on Power Electronics*, Volume: 28 , Issue: 5, pp. 2151 – 2169, 2013.

[7] BMW i ChargeForward: PG&E's Electric Vehicle Smart Charging Pilot.

[8] S. Zeff, "My Electric Journey with a Nissan Leaf: A classic early-adopter experience," *IEEE Consumer Electronics Magazine*, Vol. 5, pp.79-80, 2016.

[9] A. Khaligh and S. Dusmez, "Comprehensive Topological Analysis of Conductive and Inductive Charging Solutions for Plug-In Electric Vehicles," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3475-3489, Oct. 2012.