Review of Charging Power Levels and Infrastructure for Plug-In Electric and Hybrid Vehicles

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***Abstract*—This paper reviews the current status and implementation of battery chargers, charging power levels and infrastructure for plug-in electric vehicles and hybrids. Battery performance depends both on types and design of the batteries, and on charger characteristics and charging infrastructure. Charger systems are categorized into off-board and on-board types with unidirectional or bidirectional power flow. Unidirectional charging limits hardware requirements and simplifies interconnection issues. Bidirectional charging supports battery energy injection back to the grid. Typical on-board chargers restrict the power because of weight, space and cost constraints. They can be integrated with the electric drive for avoiding these problems. The availability of a charging infrastructure reduces on-board energy storage requirements and costs. On-board charger systems can be conductive or inductive. While conductive chargers use direct contact, inductive chargers transfer power magnetically. An off-board charger can be designed for high charging rates and is less constrained by size and weight. Level 1 (convenience), Level 2 (primary), and Level 3 (fast) power levels are discussed. These system configurations vary from country to country depending on the source and plug capacity standards. Various power level chargers and infrastructure configurations are presented, compared, and evaluated based on amount of power, charging time and location, cost, equipment, effect on the grid, and other factors.**

***Keywords*-plug-in electric vehicles: Level 1, 2, and 3 chargers: charging infrastructure: unidirectional/bidirectional chargers: integrated chargers: conductive and inductive charging.**

I. INTRODUCTION

There is growing interest in electric vehicle (EV) and plug-in hybrid electric vehicle (PHEV) technologies because of their reduced fuel usage and greenhouse emissions [1-3]. PHEVs have the advantage of long driving range since fuel provides a secondary resource. Connection to the electric power grid allows more opportunities such as ancillary services, reactive power support, tracking the output of renewable energy sources and load balance. For purposes of this paper, plug-in vehicles will be lumped together with electric vehicles.

In the US, an official domestic goal of putting one million PHEVs on the road by 2015 has been established, and public policies to encourage electrification have been implemented by governments at all levels [4]. Several organizations, such as IEEE, the Society of Automotive Engineers (SAE) and the Infrastructure Working Council (IWC), are preparing standards and codes with respect to the utility/customer interface. EVs have yet to gain wide acceptance. Three important barriers include the high cost and cycle life of batteries, complications of chargers, and the lack of charging infrastructure. Another drawback is that battery chargers can produce deleterious harmonic effects on the electric utility distribution systems [5, 6], although chargers with an active rectifier front end can mitigate this impact.

Most EV charging can take place at home overnight in a garage where the EV can be plugged in to a convenience outlet for Level 1 (slow) charging. Level 2 charging is typically described as the primary method for a battery EV charger for both private and public facilities and requires a 240V outlet. These charging power levels are summarized in Table I. Future developments focus on Level 2; semi-fast charging provides ample power and can be implemented in most environments [7-10]. Usually single-phase solutions are used for Levels 1 and 2 charging. Level 3 and DC fast charging are intended for commercial and public applications and would operate like a filling station. Three-phase solutions are applied to Level 3 chargers and high power. General public stations are expected to use Level 2 or 3 chargers installed in parking lots, shopping centers, hotels, rest stops, theaters, restaurants, etc. [11-13]. Public charging infrastructure can address range anxiety [14].

EV battery chargers are classified as on-board and off-board with unidirectional or bidirectional power flow. Unidirectional charging is a logical first step because it limits hardware requirements, simplifies interconnection issues, and tends to reduce battery degradation [15, 16]. A bidirectional charging system supports charge from the grid, battery energy injection back to the grid, and power stabilization with adequate power conversion [17-20]. Typical on-board chargers limit the high power because of weight, space and cost constraints [21-22]. They can be integrated with the electric drive to avoid these problems. [23-25]. On-board charger systems can be conductive or inductive. Conductive charging systems use direct contact between the connector and charge inlet [26]. An inductive charger transfers power magnetically. This type of charger has been explored for Levels 1 and 2 [27-29] and may be stationary [30] or moving [31-33]. An off-board battery charger is less constrained by size and weight.

This paper reviews the current status and implementation of EV battery chargers, power levels, and charging infrastructure. It begins with an overview of battery charger systems. This is followed by an overview and evaluation of battery infrastructure and charging power levels. Various power level chargers and infrastructure configurations are

TABLE I
CHARGING POWER LEVELS (BASED IN PART ON [26])

Power Level Types	Charger Location	Typical Use	Energy Supply Interface	Expected Power Level	Charging Time	Vehicle Technology
Level 1 (Opportunity) 120 Vac (US) 230 Vac (EU)	On-board 1-phase	Charging at home or office	Convenience outlet	1.4kW (12A) 1.9kW (20A)	4–11 hours 11–36 hours	PHEVs (5-15kWh) EVs (16-50kWh)
Level 2 (Primary) 240 Vac (US) 400 Vac (EU)	On-board 1 or 3 phase	Charging at private or public outlets	Dedicated EVSE	4kW (17A) 8kW (32 A) 19.2kW (80A)	1–4 hours 2–6 hours 2–3 hours	PHEVs (5-15 kWh) EVs (16–30kWh) EVs (3 –50kWh)
Level 3 (Fast) (208-600 Vac)	Off-board 3-phase	Commercial, analogous to a filling station	Dedicated EVSE	50kW 100kW	0.4–1 hour 0.2–0.5 hour	EVs(20–50kWh)

presented, compared, and evaluated based on the amount of power required, charging time and location, cost, component ratings, equipment, effect on the grid, and other factors.

II. BATTERY CHARGERS

Battery chargers play a critical role in the development of EVs. Charging time and lifetime of the battery are linked to the characteristics of the battery charger. A battery charger must be efficient and reliable, with high power density, low cost, and low volume and weight. An EV charger must ensure that the utility current is drawn with low distortion to minimize power quality impacts and at high power factor to maximize the real power available from a utility outlet. IEEE1547 [34], IEC1000-3-2 [35] and the US National Electric Code (NEC) 690 [36] standards limit the allowable harmonic and dc current injection into the grid, and PEV chargers are usually designed to comply with these standards. Conventional EV battery chargers contain a boost converter for power factor correction (PFC) for this purpose [37-38]. Interleaving has been proposed to reduce battery charging current ripple and inductor size [39]. Various topologies and schemes have been reported for both single-phase and three-phase chargers [15, 40].

A. Charger Power Levels and Infrastructure

Charger power levels reflect power, charging time and location, cost, equipment, and effect on the grid. Deploying charging infrastructure and electric vehicle supply equipment (EVSE) is an important consideration because of the many issues that need to be addressed: charging time, distribution, extent, demand policies standardization of charging stations and regulatory procedures. Charging infrastructure availability can be used to reduce on-board energy storage requirements and costs.

EV charge cords, charge stands (residential or public), attachment plugs, power outlets, vehicle connectors, and protection are major components of the EVSE [41]. They generally found in two configurations: a specialized cord set and a wall or pedestal mounted box. The specific configurations vary from country to country depending on frequency, voltage, electrical grid connection and transmission standards. According to the Electric Power Research Institute (EPRI) [42], most electric vehicle owners are expected charge overnight at home. For this reason, Level 1 and Level 2 charging equipment will be the primary options [10].

1) Level 1 Charging

Level 1 charging is the slowest method. In the US, Level 1 uses a standard120V/15A single-phase grounded outlet, such as NEMA 5-15R. The connection may use a standard J1772 connector into the EV ac port [43]. For home or business sites, no additional infrastructure is necessary. Low off-peak rates are likely to be available at night. The total cost of a residential Level 1 charger infrastructure has been reported as approximately $500 - $880 [44-45].

2) Level 2 Charging

Level 2 charging is the primary method for dedicated private and public facilities. Existing Level 2 equipment offers charging through 208V or 240V (at up to 80A, 19.2 kW). It may require dedicated equipment and a connection installation for home or public charging [7], although vehicles such as the Tesla have the power electronics on board. Most homes have 240 V service available, and Level 2 devices can charge a typical EV battery overnight. Owners seem likely to prefer Level 2 technology owing to its faster charging time and standardized vehicle-to-charger connection. A separate billing meter is typical. A residential Level 2 infrastructure installation reportedly costs approximately $2,150 [45]. The Tesla Roadster charging system, for example, is reported to impose an additional cost of $3,000 [46].

3) Level 3 Charging

Level 3 commercial fast charging can be installed in highway rest areas and city refueling points, analogous to gas stations. It typically operates with a 480 V or higher three-phase circuit [14] and requires an off-board charger to provide regulated ac-dc conversion. Level 3 charging is rarely feasible for residential areas. Standards for dc plugs and hardware are in progress. A Japanese protocol known as CHAdeMO is gaining international recognition [47]. Cost of installation is a potential issue. Level 3 charging infrastructure costs between $30,000 and $160,000 have been reported [48]. Maintaining the charging stations is another cost factor [49].

The SAE J1772 standard [26] prescribes that Level 1 and Level 2 electric vehicle supply equipment should be located on the vehicle, while Level 3 is located outside the vehicle [50-52]. General public stations are expected to use Levels 2 or 3 to enable fast charging in parking lots, shopping centers, at hotels, rest stops, theaters, restaurants, etc. A lower charge power is an advantage for utilities seeking to minimize on-

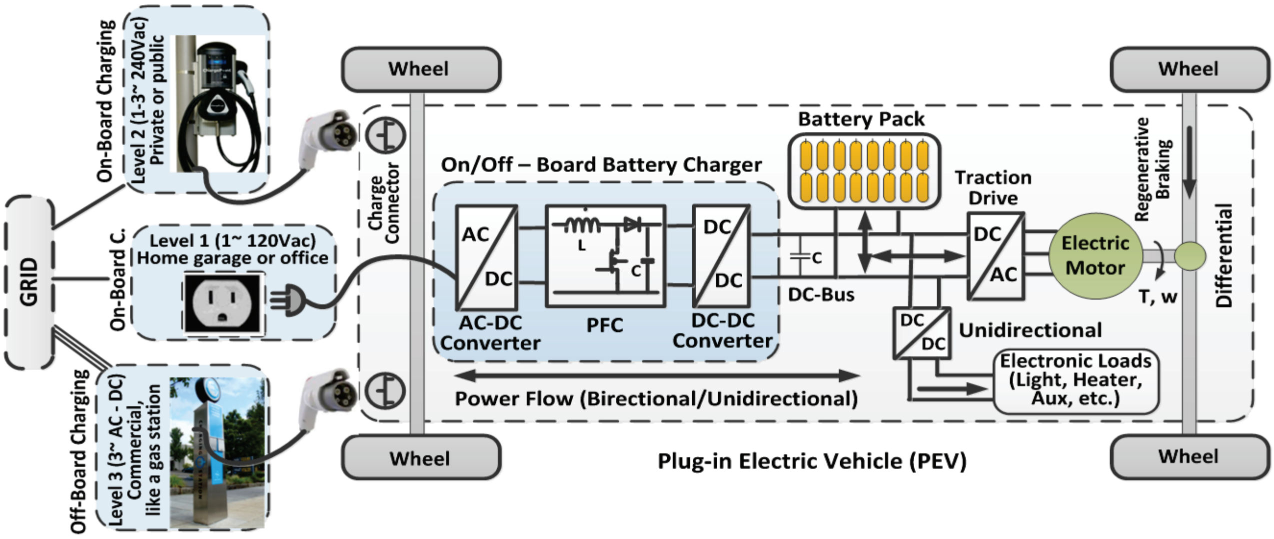

Fig. 1. On/off board plug-in electric vehicle charging system and power levels.

TABLE II
CHARGING CHARACTERISTICS AND INFRASTRUCTURES OF SOME MANUFACTURED PHEVS AND EVS

	Battery Type Energy	All-Electric Range	Connector Type	Level 1 Charging		Level 2 Charging		DC Fast Charging	
				Demand	Charge Time	Demand	Charge Time	Demand	Charge Time
Toyota Prius PHEV(2012)	Li-Ion 4.4kWh	14 miles	SAE J1772	1.4kW (120V)	3 Hours	3.8kW (240V)	2.5 hours	N/A	N/A
Chevrolet Volt PHEV	Li-Ion 16kWh	40 miles	SAE J1772	0.96–1.4 kW	5–8 Hours	3.8kW	2–3 hours	N/A	N/A
Mitsubishi i-MiEV EV	Li-Ion 16kWh	96 miles	SAE J1772 JARI/TEPCO	1.5kW	7 Hours	3kW	14 hours	50kW	30 Minutes
Nissan Leaf EV	Li-Ion 24kWh	100 miles	SAE J1772 JARI/TEPCO	1.8kW	12–16 Hours	3.3kW	6–8 hours	50 + kW	15-30 Minutes
Tesla Roadster EV	Li-Ion 53kWh	245 miles	SAE J1772	1.8kW	30 + Hours	9.6–16.8 kW	4–12 hours	N/A	N/A

peak impact. High-power charging can increase demand and has the potential to quickly overload local distribution equipment at the peak times [53-54]. The charging power levels are summarized in Table I and shown in Fig. 1. Charging characteristics and infrastructure aspects are detailed in Table II for a few vehicles.

The successful deployment of EVs over the next decade is linked to the introduction of international standards and codes, a universal infrastructure, and associated peripherals and user-friendly software on public and private property. Costs associated with the charging infrastructure correlate with hardware standards [55-57].

B. *On-Board and Off-Board Chargers*

A charger located inside the vehicle allows EV owners to charge their vehicles everywhere a suitable power source is available. Typical on-board chargers limit the power because of weight, space, and cost constraints and are dedicated to charge the battery for a long period of time [21-22]. An off-board (stand-alone) battery charger is less constrained by size and weight.

EVs in the future can benefit from fast and frequent to extend the effective all-electric drive range. Charging time can be less than one hour with Level 3 units. Off-board charging disadvantages include the extra cost of redundant power electronics, risk of vandalism, and added clutter in an urban environment [58]. Typical structure of an onboard or off-board EV charging system and power levels can be represented as given in Fig. 1.

1) *Integrated Chargers*

To minimize weight, volume and cost of the battery charger, the idea of integrating the charging function into the electrical drive system has been proposed [58-60]. Integration of the charging function into the electric drive system and electric motor was first developed to minimize battery charger costs and weight in 1985 [23] and patented by Rippel and Cocconi in 1990, 1992 and 1994 [24, 61-62].

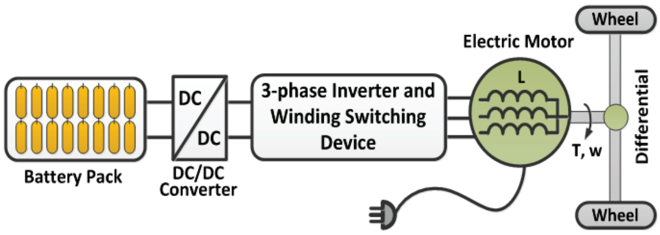

Fig. 2. Typical structure of integrated EV charger.

The charging function can be integrated if charging and traction are not simultaneous. Integrated chargers can use motor windings for the inductors. The motor drive inverter serves as a bidirectional ac-dc converter. A typical integrated charger is shown in Fig. 2. Integrated charger topologies may be categorized on the basis of number of motors (one or two) and inverters (one or two) [21, 24, 63-64]. They are also subdivided based on motor type (induction motor [61, 65], permanent magnet motor [44, 64, 66] and switched reluctance motor [25, 67]) with isolated or non-isolated circuit topology. The main disadvantage of integrated chargers is the control complexity.

C. *Unidirectional Chargers*

Unidirectional charging is the traditional method. EVs with unidirectional chargers can charge but not inject energy into the power grid. These chargers are realized using a diode bridge in conjunction with a filter and dc-dc converters. Today, these converters are implemented in a single stage to limit cost, weight, volume, and losses [15]. High-frequency isolation transformers can be employed when isolation is desired [40].

Simplicity in the control of unidirectional chargers makes it relatively easy for a utility to manage heavily loaded feeders due to multiple EVs [16]. They can provide local reactive power support by means of current phase angle control, without having to discharge a battery. Research on unidirectional charging seeks optimal charging strategies that maximize benefits, and explore impact on distribution networks [16, 68]. With high penetration of EVs, and active control of charging current, unidirectional chargers can meet most utility objectives while avoiding cost, performance and safety concerns associated with bidirectional chargers [16, 18, 69].

D. *Bidirectional Chargers*

A typical bidirectional charger has two stages: an active grid-connected bidirectional ac-dc converter that enforces power factor, and a bidirectional dc-dc converter to regulate the battery charge or discharge current [70-71]. When operating in charge mode, a bidirectional charger should draw sinusoidal current with a defined phase angle to control power and reactive power. In discharge mode, the charger should return current in a similar sinusoidal form [17-18, 72]. A bidirectional charger supports charge from the grid, battery energy injection back to the grid, referred to as vehicle-to-grid (V2G) operation mode, and power stabilization [19-20, 40]. It is likely to have active PFC.

While most studies have focused on bidirectional power flow, there are serious challenges for adoption [73]. Bidirectional power flow must overcome battery degradation due to frequent cycling, the premium cost of a charger with bidirectional power flow capability, metering issues, and necessary hardware upgrades [68, 74]. Customers are likely to require an energy guarantee to ensure that vehicle state of charge is predictable (and high) when it is time to drive. A successful implementation of bidirectional power flow will require extensive safety measures [74-75]. Anti-islanding protection and other interconnection issues must also be addressed. Level 1 and 2 chargers can be unidirectional or bidirectional, although it is not expected that Level 3 chargers will be used this way.

III. Conductive and Inductive Charging

Conductive chargers use metal-to-metal contact as in most appliances and electronic devices. Inductive charging of EVs is based on magnetic contactless power transfer [76-77].

A. *Conductive Charging*

Conductive charging systems use direct contact between the EV connector and charge inlet [26]. The cable can be fed from a standard electrical outlet (Level 1) or a charging station (Level 2 or 3). There are already several charging posts on the market. This type of charging is applied on the Chevrolet Volt, Tesla Roadster, and Toyota Prius; they use Level 1 and 2 chargers with basic infrastructure. Conductive charging is also employed on the Nissan Leaf and Mitsubishi i-MiEV, which use either basic infrastructure or dedicated off-board chargers [46, 78-80]. The main drawback of this solution is that the driver needs to plug in the cable, but of course this is a conventional issue.

B. *Inductive Charging*

An inductive charger transfers power magnetically. This type of charger has been explored for Level 1 and 2 devices. Cables and cords are eliminated. A recommended practice for EV inductive charging was been published by the SAE in 1995 [43]. Advantages include convenience and possible galvanic isolation [81-83]. Disadvantages include relatively low efficiency and power, manufacturing complexity, size, and cost of the new infrastructure [84-86].

Basic principles of inductive power transfer (IPT) are similar to transformers, although most versions have poor magnetic coupling and high leakage flux. The secondary side may be stationary [28, 30] or moving (roadway charging) [31-33, 87]. Typical stationary and roadbed inductively coupling EV charging system can be represented as given in Fig. 3 and 4.

1) *Stationary Inductive Charging*

Stationary inductive charging employs a primary transducer and secondary transducer. In the version originally developed for the EV1 (Fig. 3) [89], the primary transducer is a paddle and the secondary transducer is the

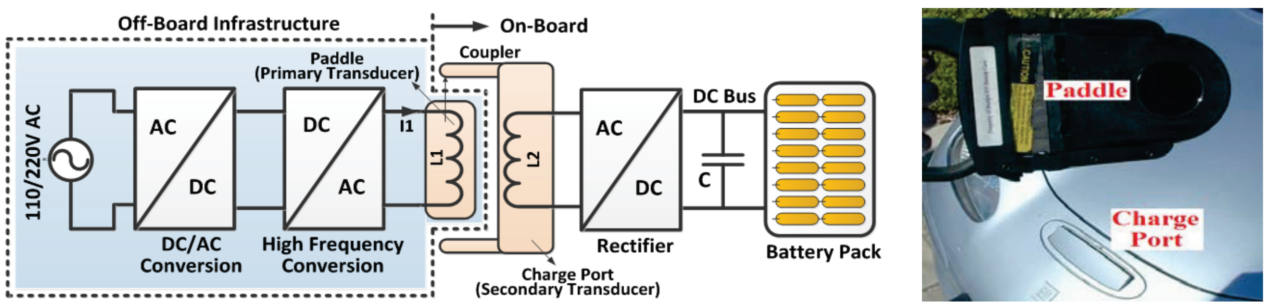

Fig. 3. Typical inductively coupling stationary EV battery charging and GM EV1 system.

vehicle charge port. When the paddle is inserted into the charge port, a magnetic circuit forms and power is transferred through a high-frequency link converter. Power transfer levels of typical systems vary from 0.5 W to 50 kW with air gaps of 1-150 mm [27-29]. One of the first commercially available inductive couplers was developed by Delco Electronics [88]. The main advantage of this approach is the fact that a higher number of turns can be used to maximize the magnetizing inductance of the transformer and hence minimize the requirements on the medium power converter to supply magnetizing current.

A single-stage high power factor converter can be used for inductive Level 1 charging. An alternative is to use a two-stage power converter that can be any one of a number of different types of resonant and PWM converters [90-92]. Due to high peak currents, two-stage approaches dominate for inductive Level 2 charging. Other topologies with a high frequency resonant current link have been used for both the power transmitter and receiver to compensate coils and support efficient power transmission [30]. To meet distortion standards, an active front end is likely for Levels 2 and 3 inductive charging [93-95].

2) *Contactless Roadway EV Charging*

Inductive charging systems have also been considered for roadway contactless power transfer [31]. The vehicle can be moving or stationary in this charging system. Constraints on vehicle storage can be relaxed with roadbed charging systems since a portion of the operational power is delivered from the roadway [96-97]. This can be used for battery weight and size reduction. This type of system transfers power from a stationary primary source (track or loop) embedded below the pavement surface to one or more secondary loops (pickup) installed in a moving vehicle as shown in Fig. 4. Refs. [98-99] propose powering electric vehicles while in motion to address the inherent compromise that on-board energy storage imposes on EV range and availability.

Maximum power can be transferred with perfect alignment and tuning. There have been several proposed methods for increasing the tolerance of this arrangement to lateral movement [100-104] or other position errors, as well as to the inherent large air gap. Configurations, including a long wire loop [96-97, 105-106] and sectional loops [87] have been presented in the literature. Challenges of contactless roadway charging include power ratings, poor coupling [107-108], high supply voltage requirements [85], loop losses, high magnetization current due to loose coupling [32, 97], lateral misalignment [109-110], the large air gap [111], and stray field coupling.

A 1.5 kW H-shaped-core transformer suited for EVs is proposed in [112]. Methods have used a bogie on a track or inductive devices installed in the pavement [110, 113]. By using slim primary ferrite core bars, efficiency can be improved, but cost must be taken into consideration when magnetic components are built into the primary track [114]. A sectional track inductive power transfer system for moving vehicles is proposed and studied in [87] for increasing power efficiency between the primary track and pickup. Much higher efficiencies have been reported for inductive chargers in stationary applications [107-111]. J. Sallan et al. [115] described a design process to select the parameters of a coreless inductively coupled power transfer (ICPT) device with a large air gap that delivers high power efficiently. A polarized coupler called a double-D-quadrature (DDQ) device is introduced and optimized in [27]. The DDQ produces a flux path height twice that of a circular pad along a single-sided flux path. It has the potential to support cost-effective ICPT designs.

3) *Resonant and Compensation Circuit Topologies*

Resonant circuits are normally employed in inductive charging networks to further boost the power transfer capability, while minimizing power supply voltage and current ratings. Conventional compensation circuit topology is not suitable for application to EVs since this involves high power, a long air gap, and low sensitivity to misalignment [30]. For inductive charging, among the most critical parameters are the frequency range, the low magnetizing inductance, the high leakage inductance, and any capacitance needed to set up resonance and support reactive power requirements [28-29].

To deliver the required power with small devices, it is necessary to operate at high frequency [27-29]. To supply the necessary real power efficiently, series or parallel reactive compensation is required for both the primary and secondary

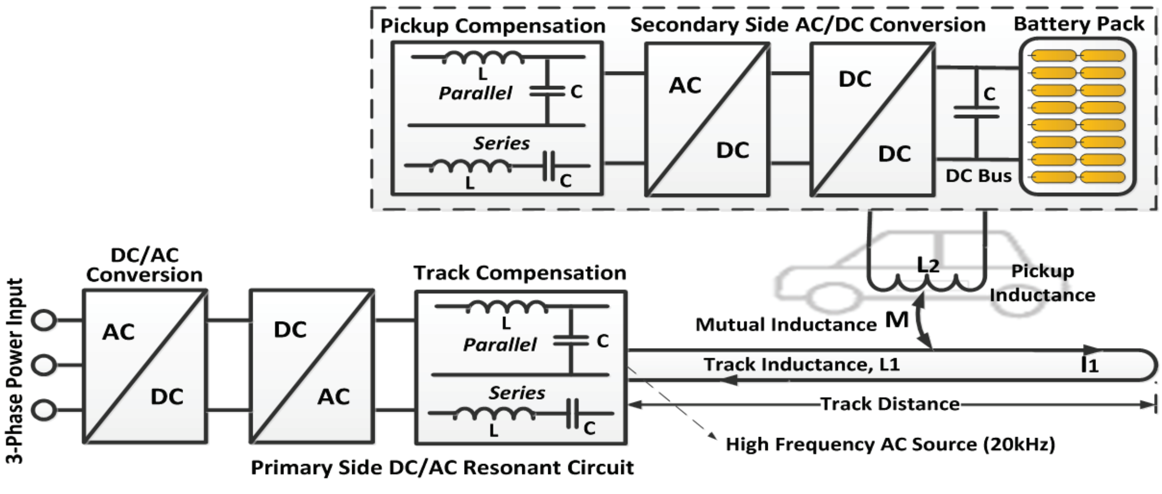

Fig. 4. Inductively coupling roadbed EV battery charging system

sides of an inductive charger [115-117] as suggested in Fig. 4. The series-series (SS) high frequency resonant topology has been established as a good solution because its resonant circuit can be designed independently of the coupling [30]. Parallel-parallel (PP) topologies for both the transmitter and receiver have higher impedance and can be driven more easily [30, 76]. A novel receiver circuit topology for a cordless battery charger for EVs is proposed in [30]. Compared with a PP circuit, the parallel-parallel-series (PPS) circuit there improves the power factor. A PPS circuit allows a larger gap between the transmitter and receiver coils [76]. C.S. Wang et al. [116] proposed a design of the primary resonant circuit that mitigates effects of phase or frequency shifts. N. Kutkut [118] proposed a full bridge LCL resonant battery charger that uses circuit parasitics to achieve soft switching. The EMI performance is improved and the size of the output filter is reduced. A half-bridge LLC resonant converter is proposed in [119] for Level 3 off-board charging. It has advantages such as high efficiency, ability to operate with zero voltage switching over a wide load range, no reverse recovery losses, and low voltage stress. The drawback is that the desired output voltage is adjusted by the switching frequency, complicating filter and transformer designs. H. Sakamato et al. [120] proposed an inductive coupler which has sufficient exciting inductance and low leakage inductance at large air gap length for Level 1 and 2 charging.

IV. Conclusion

This paper reviewed the current status and implementation of battery chargers, charging power levels and infrastructure for EVs. Battery performance depends not only on types and design of the batteries, but also on charger characteristics and charging infrastructure. Charger systems are categorized into off-board and on-board types with unidirectional and bidirectional power flow. Unidirectional charging limits hardware requirements, simplifies interconnection issues, and tends to reduce battery degradation. Bidirectional charging supports battery energy injection back to the grid. Typical on-board chargers restrict power to meet weight, space and cost constraints. There is a possibility of avoiding these problems by using the electric drive system as an integrated charger. The availability of charging infrastructure reduces on-board energy storage requirements and costs.

On-board charger systems can be conductive or inductive. While conductive chargers use direct contact for power transfer, inductive chargers transfer power magnetically. An off-board charger can be designed for high charging rates and is less constrained by size and weight. Battery infrastructure and charging power levels are categorized into three types: Level 1, Level 2, and Level 3. These system configurations vary to some degree from country to country. Various charger power levels and infrastructure configurations were presented and compared based on the amount of power, charging time and location, cost, suitability, equipment necessary, and other factors. Success of EVs depends on standardization of requirements and infrastructure decisions, efficient and smart chargers, and enhanced battery technologies.

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