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Future of Electric Vehicle Charging

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***Abstract*— Charging infrastructure for electric vehicles (EV) will be the key factor for ensuring a smooth transition to e-mobility. This paper focuses on five technologies that will play a fundamental role in this regard: smart charging, vehicle-to-grid (V2G), charging of EVs from photovoltaic panels (PV), contactless charging and on-road charging of EVs. Smart charging of EVs is expected to enable larger penetration of EVs and renewable energy, lower the charging cost and offer better utilization of the grid infrastructure. Bidirectional EV chargers will pave the way for V2G technology where the EV can be used for energy arbitrage and demand-side management. Solar charging of EV will result in sustainable transportation and use of the EV battery as PV storage. On the other hand, stationary contactless charging and on-road inductive charging of EV will remove the necessity for any cables, eliminate range anxiety issues and pave the way for automated driving. The electromagnetic and power converter design for contactless power transfer systems for future highways is reviewed in this paper.**

Keywords*— *Charging, contactless power transfer, electric vehicles, solar energy, smart charging, vehicle-to-grid

I. INTRODUCTION

It is expected that 500 million electric vehicles (EVs) will be on the roads by 2030 [1]. The technology and infrastructure for charging of electric vehicles will be the key enabler for this mobility transition. EV charging facilities will be required at homes, workplaces, shops, recreational locations and along highways. The EV charging power has to be provided by the distribution network at low cost, with minimal reinforcement and at maximum reliability.

Large penetration of EV can lead to increase in the peak demand on the grid and possible overloading of distribution network assets [2], [3]. Secondly, the current electricity grid is mostly powered by fossil fuels like coal and natural gas [4]. When EVs are charged from such a grid, a large part of the emissions are merely moved from the vehicle to the power plant. This makes EVs not truly green as one would expect. Hence it is important for the future that EVs are charged from sustainable sources of electricity like solar or wind [5]–[8]. At the same time, EV can play a decisive role with their ability to act as controllable load and as a storage for the grid with fast response.

Charging infrastructure for electric vehicles will be the key factor for ensuring a smooth transition to e-mobility. It is here that five technologies will play a vital role in the EV charging infrastructure: smart charging, vehicle-to-grid (V2G) technology, charging of EVs from photovoltaic panels (PV) contactless charging and on-road charging of EVs. The goal of this paper is to review these five technologies, provide examples of their implementation and recommendations for the future.

II. CONDUCTIVE CHARGING OF EVS – CURRENT STATUS

Charging of EVs using a cable can be done today with AC or DC charging [9]. Table I gives an overview of the currently existing AC and DC charging plugs, communication standards and power levels. What is immediately clear is that there is no single standard used across the world and there is a significant variation in the charging power levels. The simplest way to charge EVs is to use the onboard AC charger, which is an AC/DC converter with isolation [10]–[13]. Currently, there exist three types of AC charging systems – Type 1 SAE J1772-2009 used in the US, Type 2 Mennekes charger used in Europe and the Tesla US charger [10], [12]. The main difference is that the European Type 2 plug provides for much higher charging powers of up to 43kW (up to 63A) through the use of three phase 400V grid connection. The control pilot (CP) and proximity pilot (PP) is used for communication between charger and EV. The Type 3 EV charger of the EV plug alliance has been abandoned in favor of Type 2 by nearly all EV manufacturers.

Due to space and weight restrictions on the EV, the onboard AC charger is usually limited to charging power levels of up to 20kW in commercial EVs. The only exception to this is when the drivetrain propulsion power electronics, which are typically of a much higher power rating (80-500kW), are

TABLE I
AC, DC CHARGING PLUGS, POWER LEVELS IN EUROPE AND USA [10]–[13]

Plug	Number of pins (Communication)	Charging level	Voltage, Current, Power
Type 1 SAE J1772 USA	3 power pins – L1,N,E 2 control pins – CP, PP (PWM over CP)	AC Level 1	1Φ 120V, ≤ 16A, 1.9 kW
		AC Level 2	1Φ 240V, ≤ 80A, 19.2kW
Type 2 Mennekes Europe	4 power pins – L1,L2,L3,N,E 2 control pins – CP, PP (PWM over CP)	AC Level 1	1Φ 230V, ≤ 32A, 7.4kW
		AC Level 2	3Φ 400V, ≤ 63A,43kW
Type 4 Chademo	3 power – DC+,DC-,E 7 control pins (CAN communication)	DC Level 3	200-500V, ≤ 400A, 200kW
SAE CCS Combo	3 power pins – DC+,DC-,E 2 control pins – CP, PP (PLC over CP, PE)	DC Level 3	200-1000V DC, ≤ 350A, 350kW
Tesla US	3 power pins – DC+,DC-,E (or) L1,N,E 2 control pins – CP, PP	DC Level 3	Model S, 400V, ≤ 300A, 120kW

re-used for EV charging as well. These are referred to as 'on-board integrated' chargers [14], [15]. The integrated chargers use a combination of the drivetrain inverter and the windings of the propulsion motor for the EV charging. An example is the integrated 'Chameleon' charger of the Renault Zoe which is rated for 43kW. For high power EV charging beyond 50kW, DC charging is preferred which uses an off-board charger.

DC charging was introduced in order to facilitate faster charging of EVs (up to 350kW) and to overcome the weight and size limitation of an onboard charger [10], [16]. Currently, there exist three types of DC chargers: Type 4 Chademo, CCS/COMBO (Combined Charging System), and Tesla US and Europe chargers.

III. Smart Charging of EVs

EVs have three unique abilities which make them an excellent asset in the grid: the flexibility to vary their charging power, the capability to quickly ramp up/down the charging power and the ability to both charge and discharge. However, this potential is presently unused. Currently, EV charging is an uncontrolled process where the EV charges at a fixed power once connected to a charger and charges till the battery is full.

With the use of smart charging, the EV charging power and direction can be continuously controlled (dynamic charging). Smart charging of EVs can provide several benefits to the EV owner and to the providers of the EV charging infrastructure:

1. Reduce the cost of EV charging based on energy prices [17]
2. Provide new revenue streams like vehicle-to-grid [18]
3. Increase the use of solar energy for charging of EV in the day and wind in the night [19]. EV battery can be a storage for renewables, so an extra storage is not required
4. Reduce distribution system losses [20]
5. Reducing the peak demand on the grid due to EV charging by demand side management. This delays/negates the need for infrastructure upgrade in the distribution network [3], [21], [22]
6. Use the EV's fast ramp up/down potential to provide regulation services to the grid and for ancillary services like reactive power compensation and voltage control [23], [24]
7. Implementing multiplexing of EV chargers and using a single charger for several EVs. This will drastically reduce cost of EV charging infrastructure [17][25]

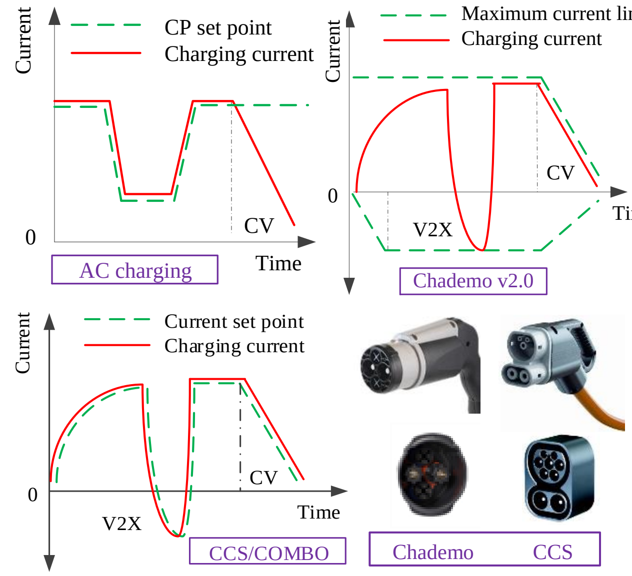

Fig. 1. Dynamic charging using AC, Chademo v1.2 and CCS/COMBO

The traditional approach to smart charging is to consider one or few of these applications in an optimization to reap direct or indirect economic benefits. While this method is simpler, it does not utilize the complete potential of smart charging and makes the benefits economically uninteresting. In the future, integration of several smart charging applications in a single framework will be the key. The benefits will then add up and the net gain will become economically attractive for large-scale implementation [17].

A. AC smart charging

In AC EV charger, the EV and charger operate in a MASTER and SLAVE manner, respectively. A PWM pulse on the control pilot (CP) can be continuously adjusted on the EV charger to control the maximum charging power. Using the PWM limit as a constraint, the EV (master) determines the actual charging current as shown in Fig. 1. It is the duty of the EV charger (Slave) to deliver the requested current. Thus, by controlling the CP, variable power, dynamic, smart charging can be implemented.

For example, a simple implementation is to measure the generation from a PV system and correspondingly adjust the CP so that the EV charging can follow the PV generation [19]. For demand side management, EV charging via the CP can be adjusted based on the loading of distribution network assets. This can help reduce the peak demand and the associated demand charges.

B. DC smart charging via Chademo and CCS/Combo

Chademo and CCS/Combo DC charging standards in their

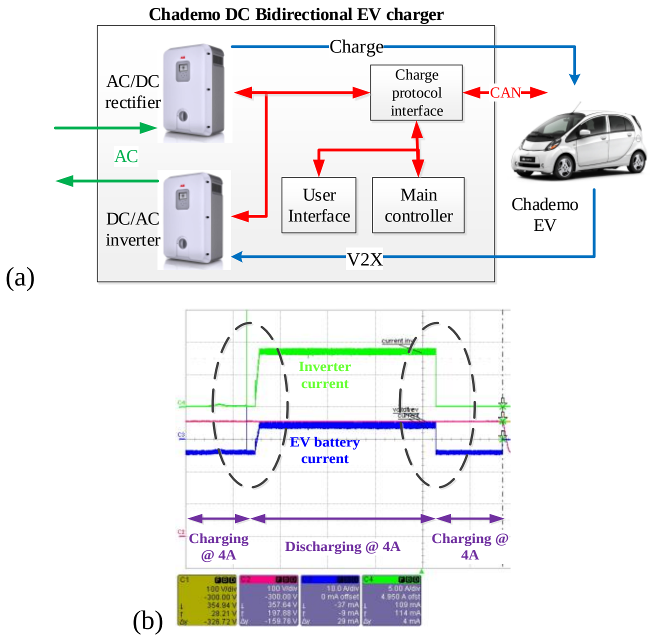

Fig. 2. (a) Experimental setup for dynamic charging and V2G using Chademo v1.2; (b) Experimental waveforms for EV current and voltage. Chademo uses CAN bus communication between charger and EV

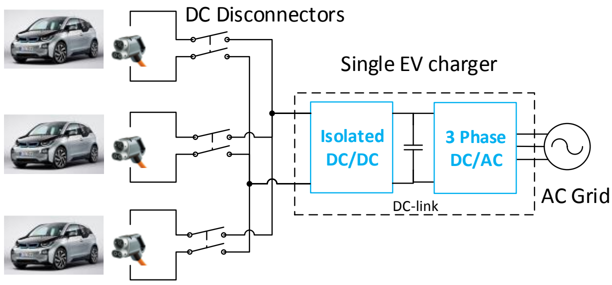

Fig. 3. DC fast charger multiplexed to several EVs

new versions are enabling communication for smart charging and V2G. In Chademo v1.2, the EV continuously sets the maximum current limit for charging and discharging (V2G) every 200ms based on the battery management system (BMS), as seen by the green dotted lines in Fig. 1. The chademo charger can provide any current between the charging and discharging current limits. When the discharge current limit is set at zero by the EV, then V2G is not possible.

In contrast, CCS/COMBO operates in a MASTER (EV)-SLAVE (charger) fashion. ISO 15118 standard is used for higher order communication for smart charging via PLC on CP. For V2G or dynamic charging, the charger can make a request for change of charging current (from I_1 to I_2) and/or direction. EV is the MASTER and can decide the charging current based on this request. The EV charger (slave) must supply the requested charging current, shown in Fig. 1. The important factor is the time lag between the current request from the EV charger and response from the EV. If it takes time t_1 for the EV to respond to the new request and if it changes the set point from I_1 to I_2 over the time t_2, then a buffer capacity E_{buff} is required for the period (t_1+ t_2). This buffer capacity is not necessary with Chademo, where V_{batt} is the battery voltage:

$$E_{buff} = V_{batt}(I_1 - I_2)\left(t_1 + \frac{t_2}{2}\right) \qquad (1)$$

Thus, by continuously changing the set point for current magnitude and direction in Chademo or COMBO, smart dynamic charging can be implemented.

C. Multiplexing of EV charger to several EVs

As the penetration of EVs increase, the demand for EV chargers will rise as well. At the same time, at public charging locations or at workplaces, the EVs will not be charging for all the time they are parked. This means that EV charging infrastructure is under-utilized. To overcome this, smart charging can facilitate the multiplexing of a single charger to several EVs [26][27]. As shown in Fig. 3, DC disconnectors can be used to connect different EVs to the same EV fast charger. Based on the EV user energy demand and departure time, the EV charging can be scheduled for the multiplexed EVs [17], [25].

IV. Vehicle to Grid (V2G)

Vehicle to Grid (V2G) is the technology of discharging an EV battery to provide energy to the grid [9], [18], [28]. V2X is a generic name that refers to V2G (grid), V2B (building), V2H (home) or V2L (load). V2G is a special case of smart charging

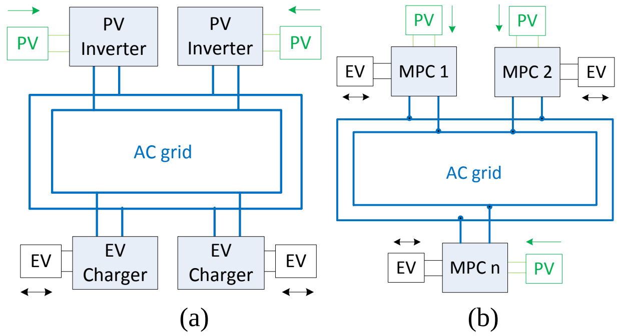

Fig. 4. (a) Charging of EV from PV using separate PV inverter and EV charger. (b) An integrated multiport power converter (MPC) that charges the EV from PV and the AC grid.

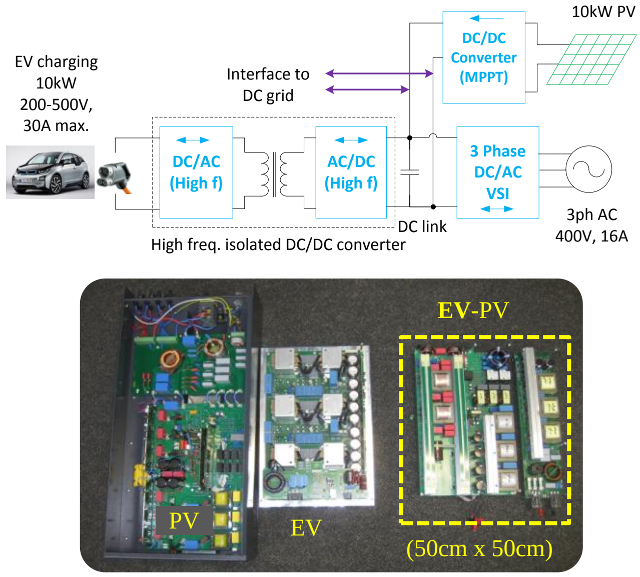

Fig. 5. (Top) Topology of power converter. (Bottom) 10kW prototype of developed converter compared to a conventional PV inverter and EV charger of 10kW

and V2G opens up a plethora of opportunities such as using the EV for storing renewable energy, participation in energy markets and providing ancillary services. Currently, EVs have only unidirectional EV chargers on board. Hence, bidirectional off-board DC chargers are being developed for implementation of V2G and both Chademo and CCS/Combo support V2G.

A. Implementing V2G using Chademo

Chademo v1.2 uses CAN bus signaling where EV continuously sets the maximum current for charging and discharging every 200ms. Fig. 2 shows an experimental setup for implementing V2G using a Chademo compatible EV [29]. Two separate unidirectional converters are used to charge and discharge the EV battery, respectively with Chademo implemented on the charge protocol interface. The scope shows the EV battery being charged and then discharged with a current of 4A. The quick ramp up and ramp down of the EV battery at 20A/s can be observed as well. This exhibits the vast potential of EV battery to provide quick response for spinning reserve and frequency regulation application [18], [30]. With a bidirectional EV charger, even an EV at zero charging power can provide regulation power capacity up for both up and down regulation up to the rated power of the charger.

B. *The road ahead for V2G*

The challenges to the large-scale adoption of V2G are the increased battery degradation, higher cost of bidirectional EV chargers compared to unidirectional and the lack of revenue streams to encourage its usage. Chademo has proposed the use of V2G for providing backup power in case of emergencies. It is expected that with large-scale use of smart charging, V2G will play a vital role in the future.

V. SOLAR CHARGING OF EVS

In order to ensure that the use of electric vehicles results in net zero CO_2 emissions, it is important that the charging infrastructure derives all/majority of its power from renewable energy sources. It is here that the falling costs of PV over the years and the ease of integrating into the distribution network play a key role. Workplaces like office buildings and industrial areas are ideal to facilitate solar EV charging where the rooftops and car parks can be installed with PV panels. There are several advantages of charging EVs from photovoltaic panels (PV) besides the net reduction of CO_2 emissions:

1. EV and PV can be installed close to each other
2. EV battery can be used as an energy storage for the PV
3. Reduced energy demand on the grid as the EV charging power is locally generated from PV [31]
4. Reduced cost of EV charging and reduced impact of changes in PV feed-in tariffs [8]

A. *AC charging of EV from PV*

The charging of EV from PV can be done by using a conventional PV inverter and an EV charger which are both connected to the AC grid, as shown in Fig. 4. However, this AC interconnection is less efficient than DC as :

1. PV and EV are fundamentally DC by nature, hence exchanging power over AC leads to additional conversion steps and losses [6], [7].
2. Two inverters would be needed, one each for the PV, EV
3. Communication will be required between the converters if the EV has to be charged based on the PV power

B. *Integrated EV-PV power converter with DC charging*

To overcome the above disadvantages, a better solution is to use a single integrated multi-port converter where EV, PV, grid are connected together as shown in Fig. 4 [6], [7], [32], [26]. It has three sub-converters connected via a DC link: a DC-DC converter for PV, a DC-DC isolated converter for EV and a DC-AC inverter to connect to the AC grid. An isolated converter for EV is required due to safety and is stipulated in the EV charging standards. The PV converter has maximum power point tracking for the solar array and EV charger is controlled based on the charging current.

Fig. 5 shows such an integrated three-port converter for EV charging [33]. A high-frequency, bidirectional, isolated topology based on the flyback converter is used for the EV sub-converter. This helps in reducing the size of the converter and enables implementing V2G. An interleaved boost converter is used for the PV sub-converter [34]. Interleaving,

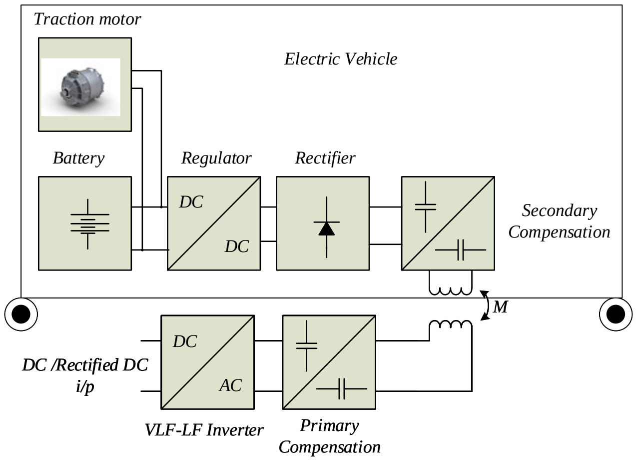

Fig. 6. Block diagram of an EV IPT based system highlighting the various power conversion stages.

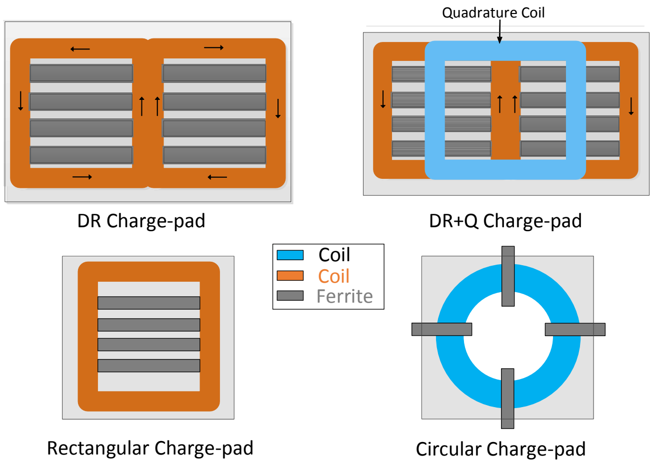

Fig. 7. Different options for multi-coil and single-coil charge-pads. The Quadrature (Q) coil is wound such that it captures the vertical flux whilst the DR receives the horizontal flux [38]

silicon carbide devices and powdered alloy core inductors are used in the design to effectively increase the switching frequency and power density of the converter. The converter has a stable closed-loop control which is capable of executing four power flows and its combinations: PV→EV, PV→ Grid, Grid→ EV, EV→Grid. Fig. 5 shows a 10kW prototype of the EV-PV charger and its compared to a conventional 10kW PV inverter and unidirectional EV charger based on IGBT and ferrite technology. The much smaller size of the integrated converter is clearly seen while it still maintains a peak efficiency of 96.4% and much higher partial load efficiency.

VI. CONTACTLESS CHARGING OF EV

Contactless charging of EVs using Inductive Power Transfer (IPT) is a technology that is increasingly becoming accepted as an important feature of autonomous charging of EVs. This technology uses electromagnetic energy transfer between loosely coupled charge-pads which are placed with an air-gap in between. A block diagram of such a system is shown in Fig. 6. The essential components that make up this technology are:

- Base power electronics – The AC power from the grid (3/1Φ) is rectified and DC power is supplied to an inverter which produces the AC power for IPT.
- Charge pads – Several magnetic structures with maximization of magnetic coupling and power transfer efficiency are being investigated.
- Compensation Circuitry – Resonant capacitors for reactive compensation of the inductive leakages of both the primary and secondary are in investigation. Different combinations including series-series (SS), series-parallel (SP), parallel-series (PS), parallel-parallel (PP), LCL etc. are being investigated.
- Vehicle electronics- Here onboard rectifier and dc voltage regulation stages are present before the energy is stored in the EV battery.

IPT systems are advantageous for the comfort of charging without plugging in a cable, thereby eliminating the risk of electrocution particularly in adverse weather conditions [35]. It is also inherently safe, reliable and requires reduced maintenance. Also, developments in autonomous vehicles can be complemented by autonomous inductive charging.

The magnetics of charge-pads are typically categorized in terms of the shapes of the couplers. Several single-coil configurations including circular pads, rectangular pads, triangular pads etc. are present in literature [36], [37]. A primary requirement for EV charging is the resilience of pads to movements of pads, referred to misalignment. Misalignment-tolerant pads led to developments in multi-coil charge-pads such as double rectangular (DR) pads, double circular (DC) pads etc. Such pads also referred to as polarized pads have currents that are fed by currents that are shifted by 180°[36]. This creates a horizontal flux profile unlike the vertical flux profile of single-coil pads. Some common charge-pad options are represented in Fig. 7 [38].

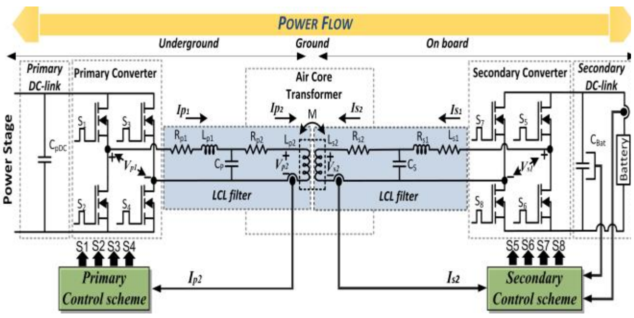

Fig. 8 Schematic representation of a bidirectional IPT system with a dual active bridge. The active rectification stage enables operation of plug-in vehicles and can be useful for V2G operation [41]

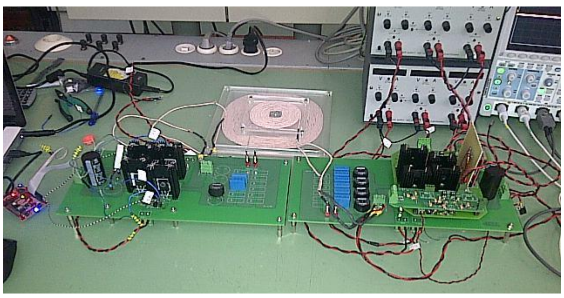

Fig. 9 Constructed laboratory scale bidirectional IPT system [42]

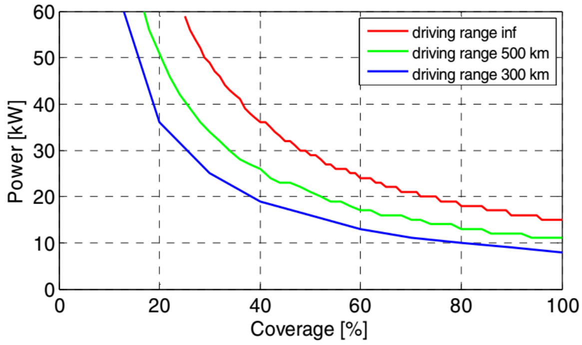

Fig. 10 IPT system power transferred for different coverage of IPT on the roads and range

A recent standard in the making from SAE – J2594 is trying to normalize a small range of frequencies around a center frequency of 85 kHz for light EV charging. Frequency limits also exist for maximum permissible leakage fields – B and H for the safety related to EM emissions [39]. Different standardizing bodies including IEEE and ICNIRP impose these limits [39]. Controlling IPT systems is achieved by using different strategies – variable frequency, variable duty cycle control and using combinational/ dual control [40]. Variable frequency and duty cycle control can be achieved using a voltage cancellation inverter.

A bidirectional LCL IPT system is constructed in [41]. Here, magnitude cancellation technique is applied to both the inverter bridge as well as the active rectifier bridge. Fig. 8 shows the block diagram of such a system. To improve the efficiency at high switching speeds, SiC wide bandgap devices are used. SiC MOSFET (C2M0080120D) is used in the experimental analysis with coupling coefficient k and the mutual inductance M of the IPT coupler measured as 0.25 and 12.7 μH respectively [42]. At a resonant frequency close to 110 kHz, the maximum efficiency measured is 92.6%, designed for 1kW operation. The constructed system is represented in Fig. 9 [42].

VII. On-Road Charging of EV

A. *On-road charging - Powering while driving*

On-road/dynamic powering of EVs is the state-of-art development in future EV charging. The limited range of EVs can be offset by transferring power to vehicles at stop lights (semi-dynamic charging) / while in motion. In such a scenario, charge-pads are repeated over large coverage of the roadways and energy is transferred for the duration for which the vehicles are above the charge-pad. Alternatively, distributed IPT systems propose having tracks on the road which are energized by an inverter and such systems have traditionally found applications in automatic guided vehicles (AGV) and material handling system based on distributed IPT systems are also present [35].

Another advantage of on-road charging is the ability to charge EVs from green energy sources in the neighborhood. Extensive research has been performed in the simulations of highway driving cycle with IPT system with power levels varying from 10–60 kW and coverage from 10–100% [43]. A significant result obtained being that driving range can be achieved with 20kW power and 50% of road coverage or 50kW and 20% coverage, as seen in Fig. 10 [43]. In addition, for coverage greater than 50%, a very high driving range can be achieved for power greater than 20 kW [43].

B. Green energy highway

Some recent developments in highway based IPT systems include the integration of green energy sources, with self-healing roads with IPT enabled [44]. Roadways that will carry EVs will become energy generating with several technologies such as micro-wind generators and solar roadways. This coupled with IPT for charging EVs is the vision for future highways. Also, a complementary development in this field is the development of multi-frequency IPT systems. Multi-frequency power transfer can result in multiplexing power between several harmonics thereby spreading out emissions and processing lower power per frequency bridge [45].

VIII. CONCLUSION

Smart charging, vehicle-to-grid, solar charging of EV, contactless charging and on-road charging will be five key technologies that will enable the transition to electric mobility. These technologies will not only disrupt the transportation industry but will affect the entire energy landscape with their potential to support the grid and to increase the penetration of renewables. The right business models and standardization will play a vital role in the fast acceleration and large-scale implementation of the technologies.

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