2012 IEEE International Electrical Vehicle Conference
(IEVC’12)

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

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07 March, 2012, Greenville
South Carolina, USA
Overview

- Introduction
- Charger Power Levels
- Unidirectional and Bidirectional Chargers
- Integrated Chargers
- Conductive and Inductive Charging
- Conclusion
- Official U.S. domestic goal **one million PHEVs** by 2015
- **IEEE, SAE** and **the Infrastructure Working Council (IWC)** preparing standards for utility/customer interface.
- **EVSE**: electric vehicle supply equipment
- **Barriers**
  - high cost and limited cycle life of batteries
  - complications of chargers
  - lack of charging infrastructure.
## Charging Power Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Charger Location</th>
<th>Typical Use</th>
<th>Energy Supply Interface</th>
<th>Power Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 (Opportunity)</td>
<td>On-board 1-phase</td>
<td>Home or office</td>
<td>Convenience outlet</td>
<td>Up to 2 kW</td>
</tr>
<tr>
<td>120 V / 230</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Level 2 (Primary)</td>
<td>On-board 1 or 3 phase</td>
<td>Dedicated outlets</td>
<td>Dedicated outlet</td>
<td>4 - 20 kW</td>
</tr>
<tr>
<td>240 V / 400 V</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level 3 (Fast)</td>
<td>Off-board 3-phase</td>
<td>Commercial filling station</td>
<td>Dedicated EVSE</td>
<td>50-100kW</td>
</tr>
<tr>
<td>(480-600 V or direct dc)</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Charging Power Levels and Infrastructure

• **Overnight or at-work charging:** Level 1.
• **Typical charging:** Level 2. Usually single phase
• **Level 3 and DC fast charging** for commercial and public filling stations.
• Public infrastructure discussion emphasizes Level 2.
• Wide availability of chargers can address **range anxiety**.

news.medill.northwestern.edu
Charger cost, location

- **Level 1 charging**: cost reported as $500 - $900 but usually integrated into vehicle.
- **Level 2 charging**: cost reported as $1000 - $3000.
- **Level 3 charging**: cost reported as $30,000 - $160,000.

J1772 “combo connector” for ac or dc Level 1 and Level 2 charging

Basic Requirements

• An EV charger must minimize power quality impact
• Draw current at high power factor to maximize power from an outlet.
• **Boost active PFC** topology is a typical solution.
• **Interleaving** can reduce ripple and inductor size.
• **Multilevel converters**: suitable for Level 3 chargers.
Battery Chargers for Plug-in Vehicles

Interleaved unidirectional charger topology


Single-phase unidirectional multilevel charger

Battery Chargers for Plug-in Vehicles

- **Half-bridge** circuits have fewer components and lower cost, but high component stresses.
- **Full-bridge** circuits cost more in exchange for lower component stresses.

(a) Single-phase half-bridge bidirectional charger  
(b) Single-phase full-bridge bidirectional charger  
(c) Three-phase full-bridge bidirectional charger
On/off-board charging

Traction drive: 30 kW and up

On-board chargers: size and weight constraints limit power.
Off-board disadvantages: cost of redundant power electronics, risk of vandalism, and added clutter in an urban environment.
Power Flow

Level 1 unidirectional full-bridge series resonant charger


Unidirectional charging:

- Simplifies interconnection issues
- Avoids extra battery degradation
- Simple control – may make feeder management easy
- Reactive power support
- With high penetration of EVs: meets most utility objectives
The “energy load” concept

A load whose energy needs have no flexibility

- Energy needs must be met
- Utility: obliged to meet demand

EVs are energy loads

- No flexibility in energy demand (or time of delivery) from utility’s standpoint
- Energy guarantee must be assured
Role of dynamic pricing

- It should be more expensive to charge an EV during high cost periods
- Dynamic pricing offers incentives to use electricity effectively
  - Reflects wholesale market conditions
  - EV charging should reflect prevailing market conditions
Implementing unidirectional V2G

Coordinated charging of EVs is necessary
  – Power-draw management
  – Avoid local feeder overloads

Charging-time flexibility is crucial
  – Inherently tied into the charging rate level of the respective EV
  – But still enforce energy load concept
Charging strategies

Price-based with the objective of minimizing charging cost

Charging based on price-sensitive energy bidding.

Until real-time, one year, during 2007
Price-based charging

Problem formulation

\[
\min \sum_{k=h}^{H} C(P_k) \times (P_k \times \Delta t)
\]

\[
\sum_{k=h}^{H} P_k \times \Delta t = E_{des}
\]

\[
\leq P_k \leq P_{\text{max}}
\]

\[
C(P_k) = C_k^0 + \alpha_k \times P_k
\]

with retail rate function

\[
C_k^0 + \theta(P_k - P_0), \quad \{\theta = 0 \ \forall P_k \leq P_0\}
\]

The utility sets the rate structure but decisions are made by the EV owner.

- Cost function weight \(\gamma_k\) penalizes hourly power draw
  - It should be more expensive to charge at a higher rate (encourages slackness)
  - Limited to retail price
- When \(\alpha_k = 0\), an EV can charge at its maximum without cost penalty
- V2G benefits are obtained with the resulting power-draw schedule
Price-sensitive energy bidding

- EV owner bids for energy in the day-ahead market
  - A price-energy (P-E) schedule is submitted
  - An energy bid function is built from the P-E schedule
- An opportunity to purchase from the real time market is possible
- Inherent delivery risk: EV owner must be capable of short-fall
- Complicated to implement for an individual owner
  - Aggregator opportunity
  - Bidding process could be
V2G benefit: active power regulation

- Dynamic charging control
- Regulation services: modulate charging rate about scheduled levels
- The actual EV charge must integrate to the scheduled energy
  - Energy guarantee must be enforced
- Deviations from the POP provide regulation capacity
  - Extra revenue based on this capacity
Results: cost benefits to EV owners for flexibility

Simulation parameters:
- 0 kWh requested daily
- 6 kW max charge rate
- x 10 h charging periods
- Charge above 3.3 kW penalized up to full retail

Implement the desired charging time flexibility

Annual cost savings of $440 encourages power-draw flex

<table>
<thead>
<tr>
<th>Hourly pricing</th>
<th>Retail rate</th>
</tr>
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<tbody>
<tr>
<td>$868</td>
<td>$428</td>
</tr>
</tbody>
</table>
Results: cost benefits to utilities due to flexibility

Simulation setup:
- IEEE 118-bus system test bed
- 2009 historical data from New England ISO
- EV penetration levels of 20% relative to the load energy at each node
- Each EV requests 20 kWh in two intervals
- The OPF problem is solved to determine the MCP

With higher power-draw slackness (α=2), and 20% EV penetration, 7% cost reduction is observed in the third quarter.
Ancillary service levels

- Ancillary service levels (regulation capacity) of 3 EVs with different battery capacities are investigated.
- The EVs are connected from 9 pm to 7 am.
- Power draw is scheduled hour by hour throughout the interval.
- Timing flexibility is crucial for an EV to perform regulation services.
- The capacity of a unidirectional charging EV to perform regulation services depends on the magnitude of the energy request and power limits.
## Ancillary service levels

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td><strong>Battery capacity[21]</strong></td>
<td>5 kWh</td>
<td>24 kWh</td>
<td>56 kWh</td>
</tr>
<tr>
<td><strong>Maximum charge rate</strong></td>
<td>1.5 kW @120 Vac</td>
<td>6.6 kW @240 Vac</td>
<td>16.8 kW @240 Vac</td>
</tr>
<tr>
<td><strong>Energy request</strong></td>
<td>5 kWh</td>
<td>20 kWh</td>
<td>56 kWh</td>
</tr>
</tbody>
</table>

![Graph showing contracted capacity over time for Prius, Leaf, and Roadster.](image)
Charging profile of EVs performing regulation

- A suitable charge profile ensures regulation capacity is available over the charging interval
- Notice that the profile needs no negative values -- reverse current not required
- A unidirectional charger can reap the full benefits of regulation
Revenue from regulation services

- Revenue from regulation services yields 21% in cost reduction
- A higher energy request will reap more revenue: more capacity
- Slackness has a more profound cost impact on an EV owner with higher energy demand
Unidirectional vs. bidirectional: battery degradation cost

- Assuming a 10 h interval and 20 kWh demand, a max charge and discharge rate of 6.6 kW, and an RMCP of $0.02/kWh, annual regulation revenue is $480.

- For bidirectional, a conservative battery cost estimate leads to battery degradation cost of about $0.014/kWh/year.
  - This yields $335/year in degradation cost

- A bidirectional charger might provide up to 12% higher revenue than a unidirectional charger ($130 annual revenue).
**Power Flow**

**Bidirectional chargers** support full vehicle-to-grid (V2G) operation, and power stabilization.

- How to pay for extra battery degradation, the charger, metering, etc.?
- Communications, anti-islanding.
- Not expected for Level 1 or Level 3.
Integrated Chargers

• Integration of the charging function with the electric drive and motor was developed by 1985 and patented by Rippel and Cocconi.
• Use motor windings for inductors. The motor drive inverter serves as a bidirectional ac-dc converter.
• The main disadvantage is control complexity.
Integrated battery charger: the traction drive is transformed into a boost PFC battery charger.

Conductive and Inductive Chargers

**Conductive chargers** use metal-to-metal contact. Conductive chargers on the Chevrolet Volt, Tesla Roadster, and Toyota Prius plug-in use Level 1 and 2 chargers with basic infrastructure.

Conductive chargers on the Nissan Leaf and Mitsubishi i-MiEV use either basic infrastructure or dedicated off-board chargers.

The main drawback of this solution is that the driver needs to plug in the cord, but this is conventional.
Conductive and Inductive Chargers

Inductive power transfer (IPT) of EVs is based on magnetic contactless power transfer. As been tested for Level 1 and 2, stationary or moving.ords are eliminated. A recommended practice for EV ductive charging was published by the SAE in 1995.

advantages include relatively low efficiency and power, gh complexity and cost.

PT principles follow transformers, though most have low magnetic oupling and high leakage flux.
Stationary Inductive Chargers

Inductively coupled stationary charger and GM EV1 system

Stationary inductive charging:
- Primary and secondary transducers
  - L1 version:
    - Primary transducer is a paddle
    - Secondary transducer is vehicle charge port.
Contactless Roadbed EV Charging

IPT in roadbed is an old concept.
Maximum power with perfect alignment and resonant tuning.
Challenges of contactless roadbed charging include:

- low coupling
- loop losses
- high reactive current
- misalignment effects
- large air gap
- stray field coupling

Conductix-Wampfler
Contactless Roadbed EV Charging

Primary Side DC/AC Resonant Circuit

Pickup Compensation

Secondary Side AC/DC Conversion

Battery Pack

DC/AC Conversion

AC

DC

AC

Track Compensation

Pickup Inductance

L2

Mutual Inductance M

Track Inductance, L1

Track Distance

High Frequency AC Source (20kHz)