ECE Illinois

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

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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2012 IEEE INTERNATIONAL ELECTRIC VEHICLE CONFERENCE

07 March, 2012, Greenville
South Carolina, USA

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Overview

- Introduction
- Charger Power Levels
- Unidirectional and Bidirectional Chargers
- Integrated Chargers
- Conductive and Inductive Charging
- Conclusion

Chevrolet Volt PHEV
http://gm-volt.com

Toyota Prius PHEV
http://en.wikipedia.org

Tesla Roadster EV
http://www.stefanoparis.com

Nissan Leaf EV
http://www.nytimes.com

- 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

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

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

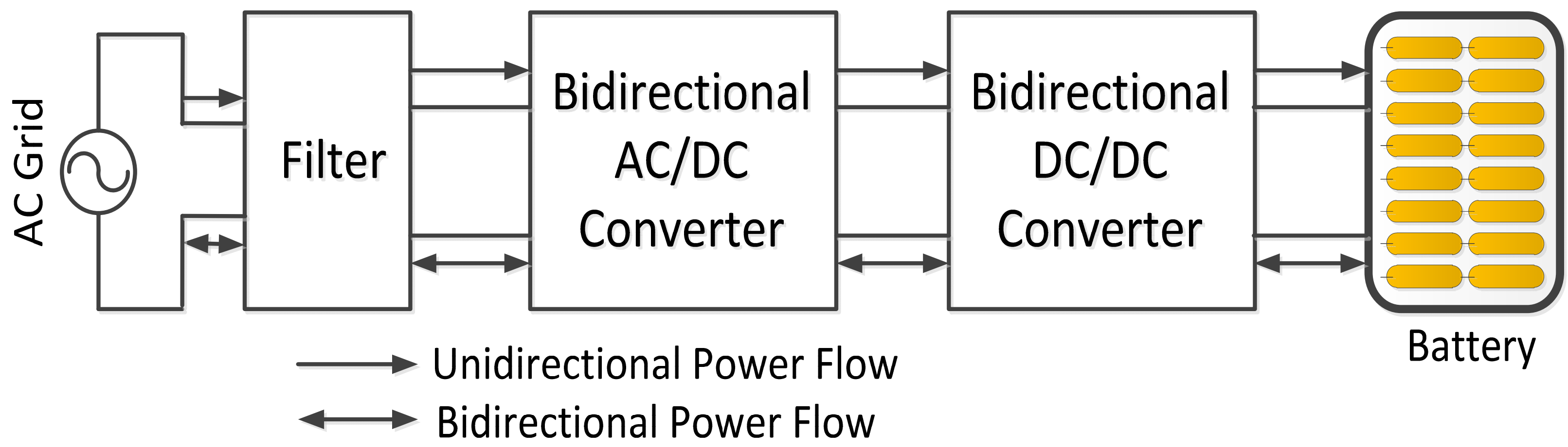
- **Level 1 charging:** cost reported as **$500 - $900** but usually integrated into vehicle.
- **Level 2 charging:** cost reported as **$1000 - $3000**.
- **Level 3 charging:** cost reported as **$30,000 - $160,000**.

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

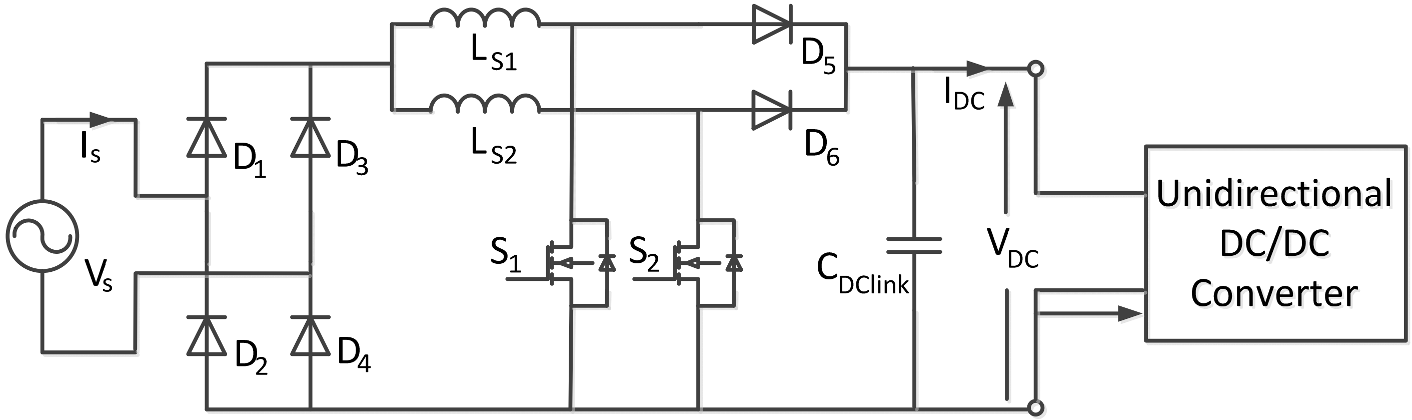
SAE International, "SAE's J1772 'combo connector' for ac and dc charging advances with IEEE's help," retrieved Sept 8, 2011 [Online]. Available: http://ev.sae.org/article/10128

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.

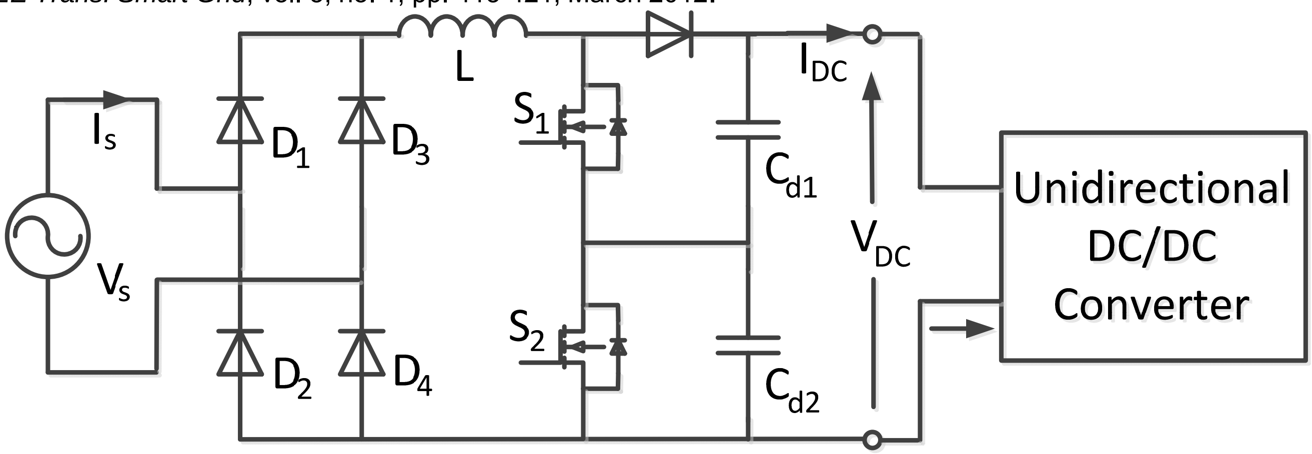


Battery Chargers for Plug-in Vehicles



Interleaved unidirectional charger topology

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 Trans. Smart Grid*, vol. 3, no. 1, pp. 413-421, March 2012.

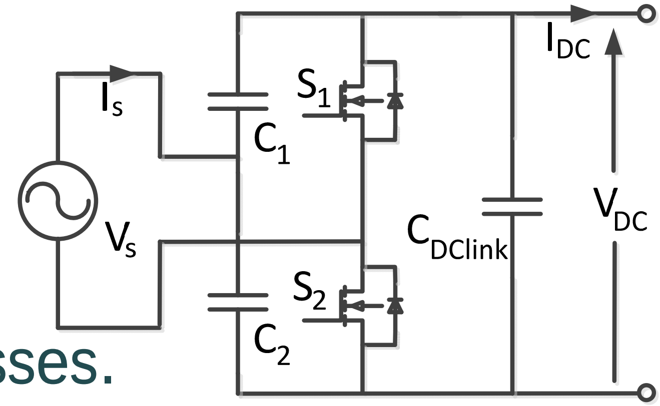


Single-phase unidirectional multilevel charger

B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey and D. P. Kothari, "A Review of Single-Phase Improved Power Quality AC–DC Converters," IEEE Trans. Ind. Electron., vol. 50, no. 5, pp. 962-981, 2003.

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.



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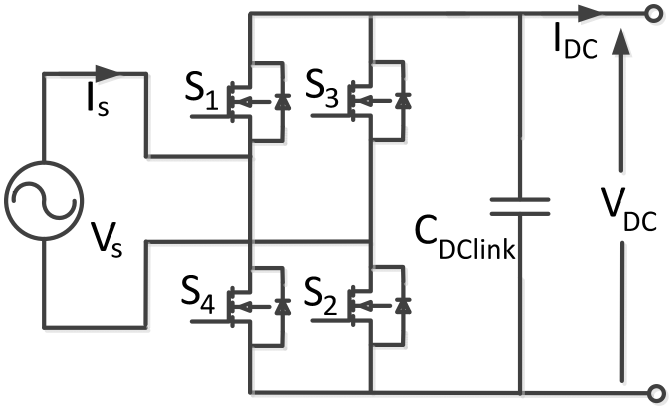

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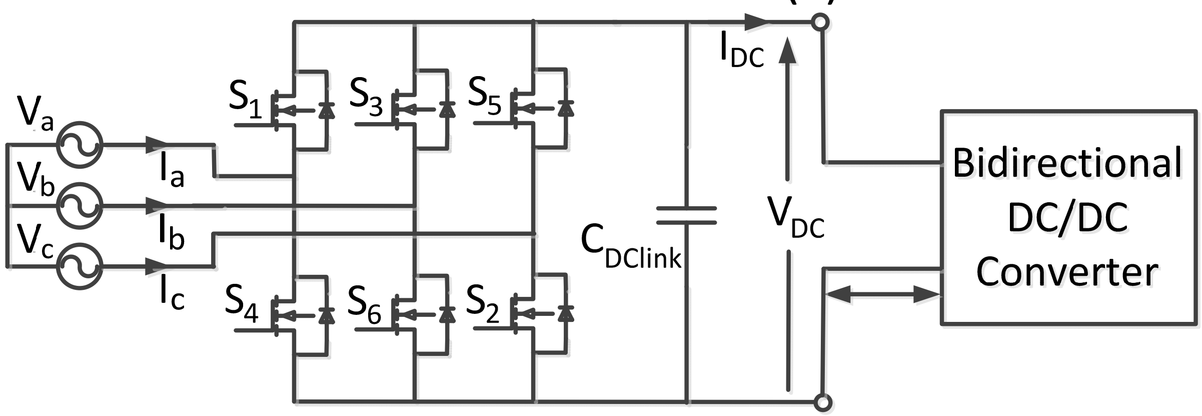
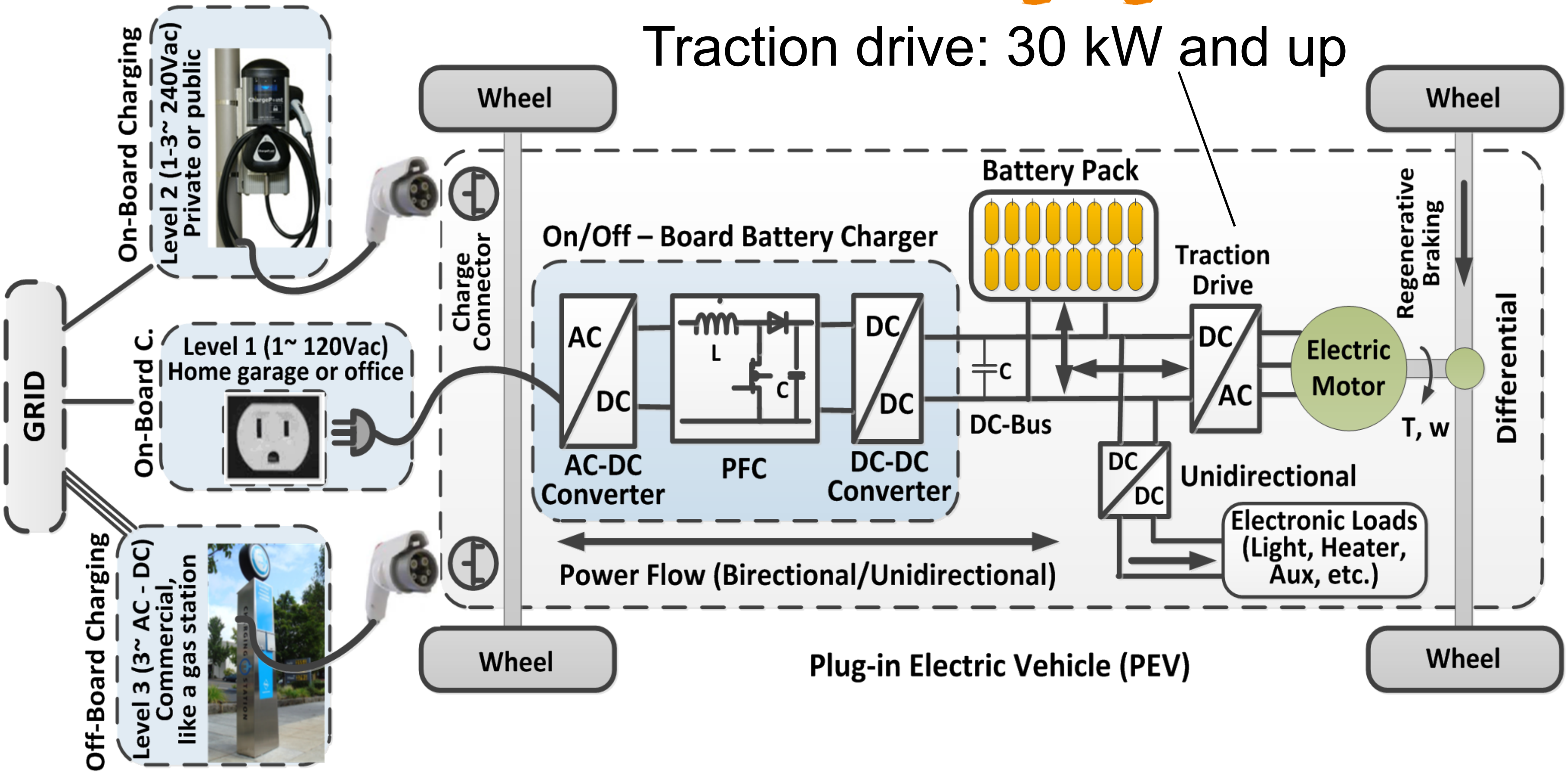


(c)

(a) Single-phase half-bridge bidirectional charger
(b) Single-phase full-bridge bidirectional charger
(c) Three-phase full-bridge bidirectional charger

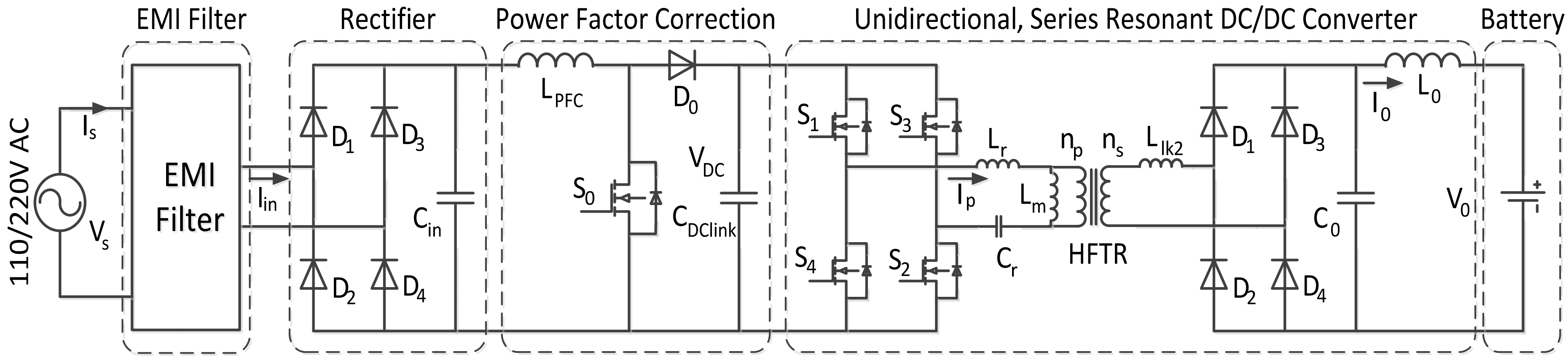
On/off-board charging

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

G. Y. Choe, J.S. Kim, B. K. Lee, C. Y. Won, and T.W. Lee, “A Bi-directional Battery Charger for Electric Vehicles Using Photovoltaic PCS Systems,” in *Proc. IEEE VPPC*, 2010.

Unidirectional charging:

Simplifies interconnection issues

Avoids extra battery degradation

Simple control – may make feeder management easy

Reactive power support

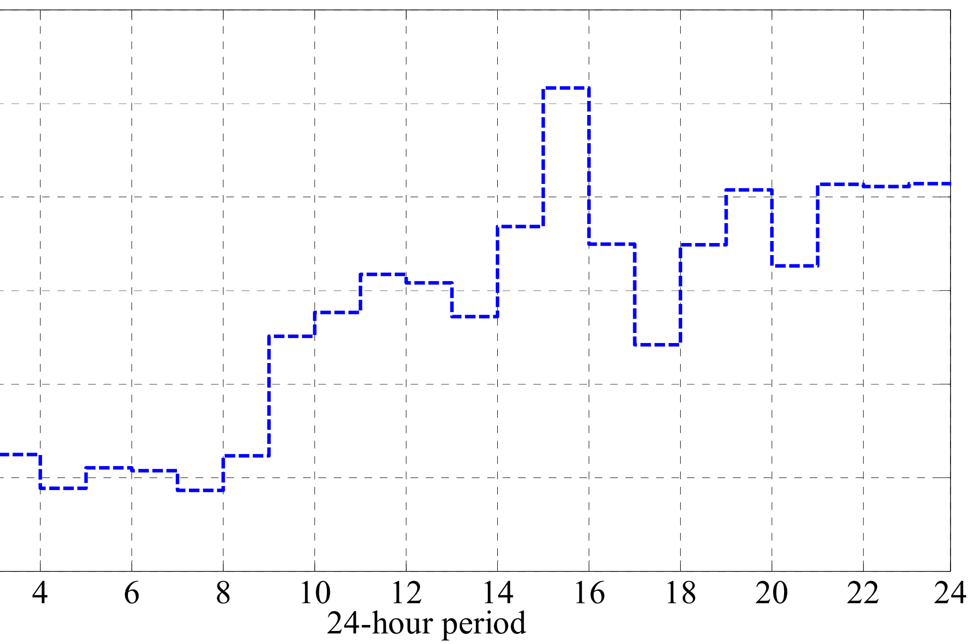
With high penetration of EVs: meets most utility objectives

The "energy load" concept

- A load whose energy needs have no flexibility in *quantity*
  - 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 stand point
  - 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.

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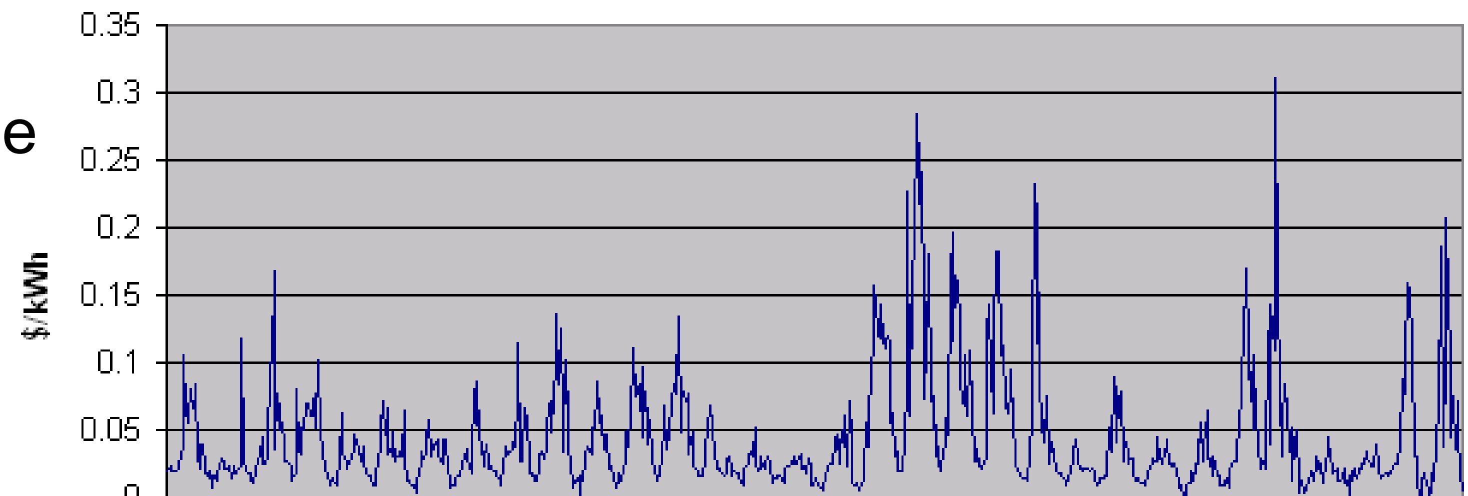


Price-based charging

oblem formulation

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

$$\sum_{h} P_k\times\Delta t = E_{des}$$

$$\leq P_k \leq P_{\max}$$

$$C(P_k)=C_k{}^0+\alpha_k\times P_k$$

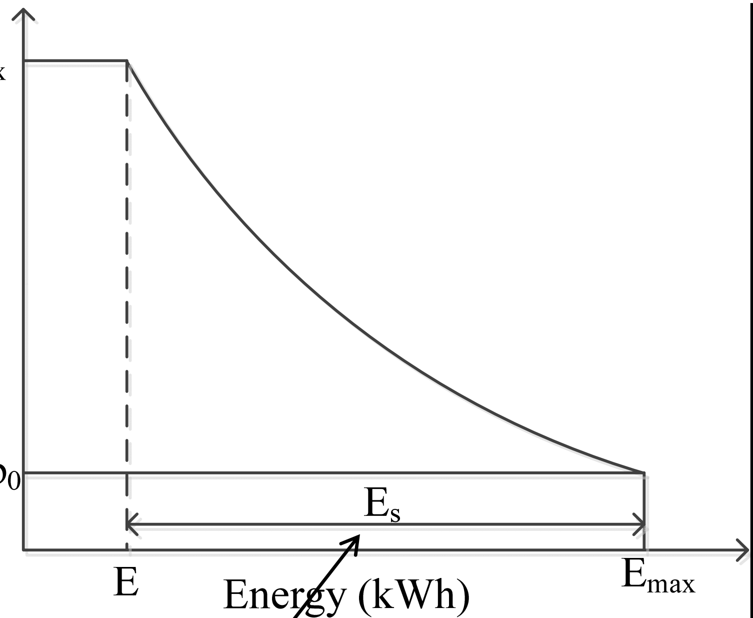
ith retail rate function

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

he utility sets the rate
ructure but decisions are
ade by the EV owner

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

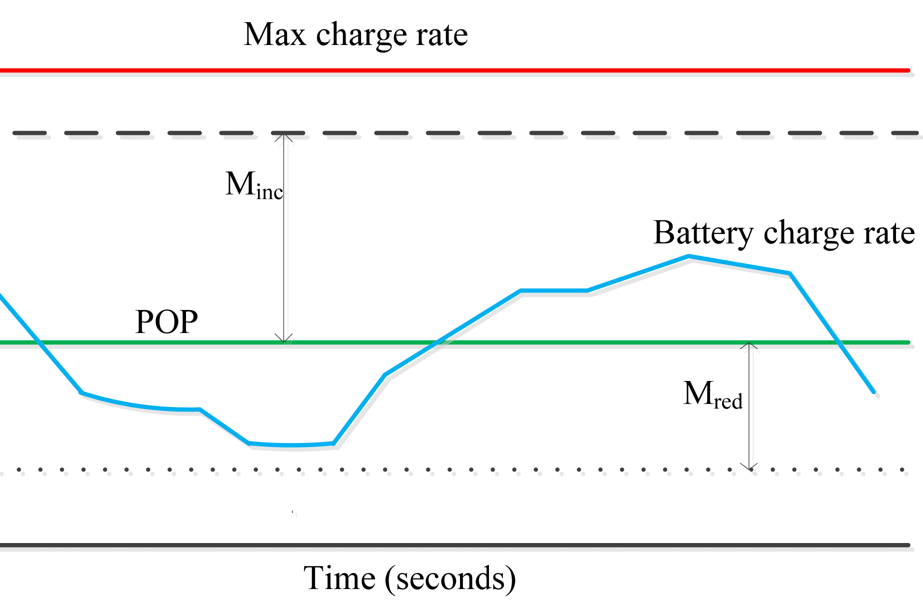
Price-sensitive energy bidding



Energy shortfall
when electricity price
quals ρ_{max}

- 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

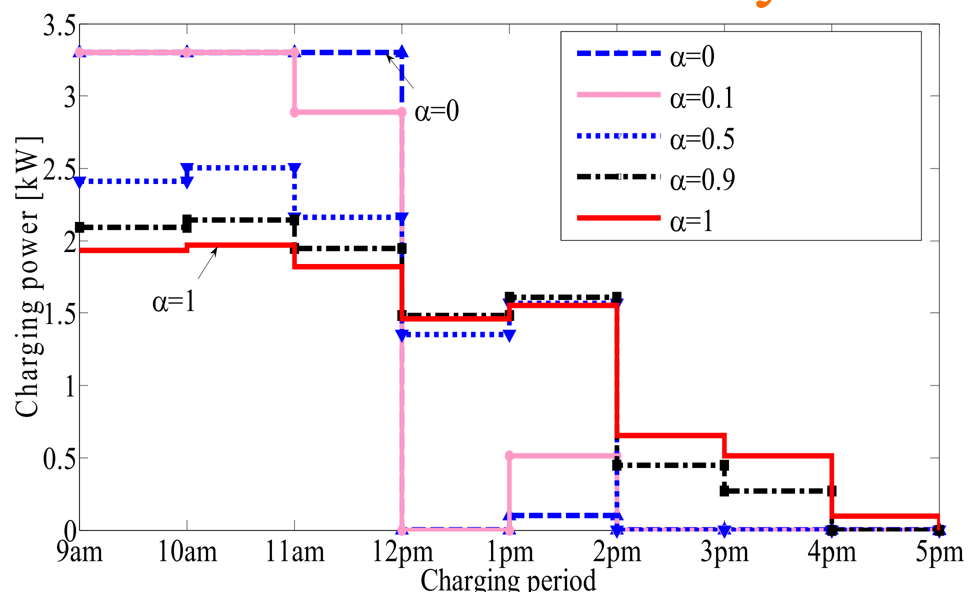
V2G benefit: active power regulation



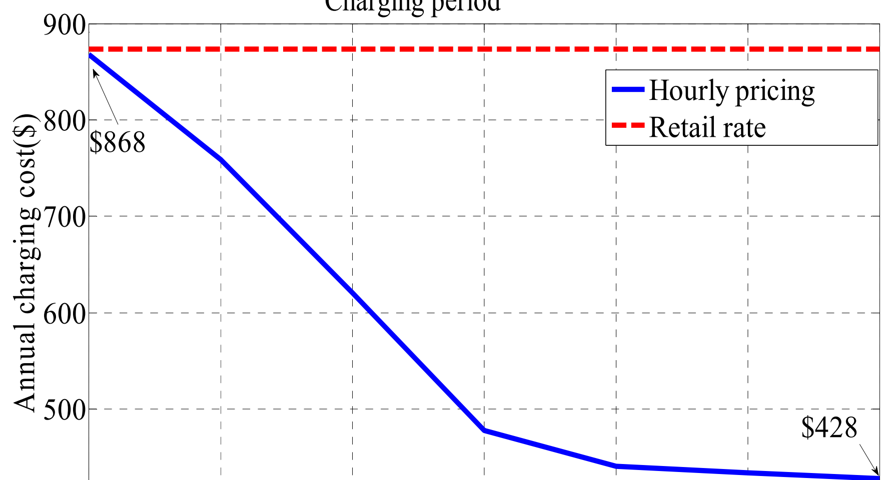
- Dynamic charging control
- Regulation services: modulate charging rate about scheduled levels
- The actual EV charge must integrate to the scheduled energy
  - ➢ Energy guarantee must be enforced
- Deviations from the POP provide regulation capacity
  - ➢ Extra revenue based on this capacity

Results: cost benefits to EV owners for flexibility

ulation parameters:
0 kWh requested daily
.6 kW max charge rate
 x 10 h charging periods
Charge above 3.3 kW
enalized up to full retail



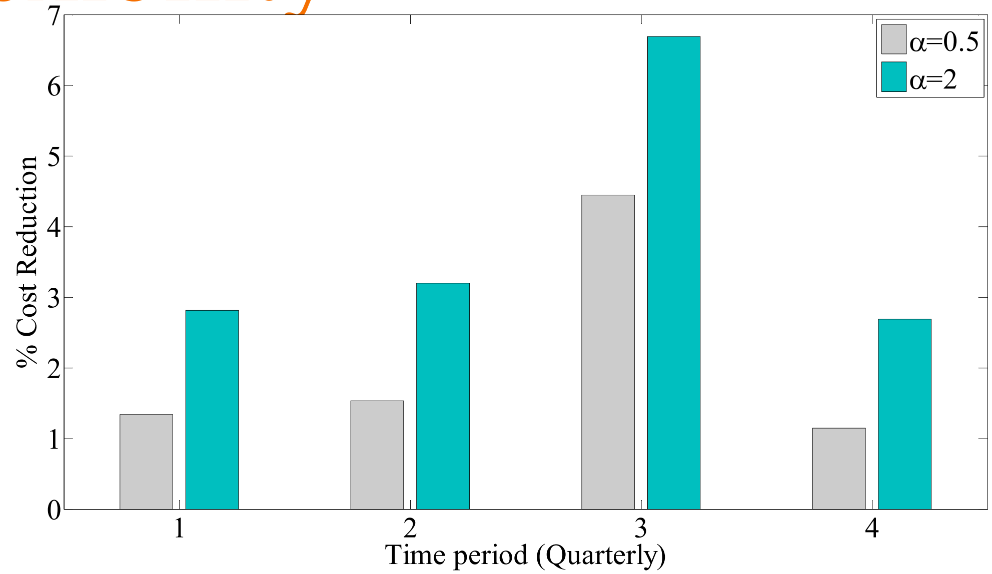
mplements the desired
arging time flexibility
nnual cost savings of $440
courages power-draw flex



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



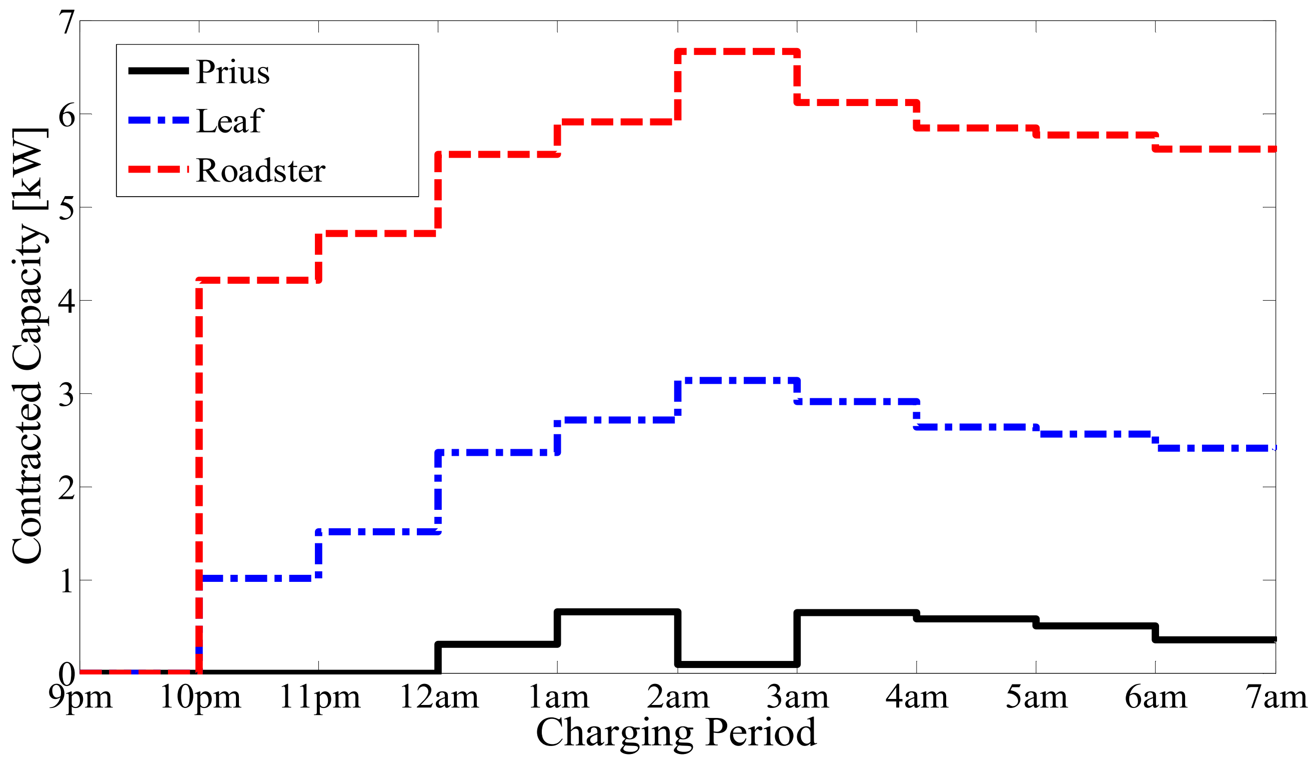
With higher power-draw slackness (α=2), and 20% EV penetration, 7% cost reduction is observed in the third quarter

Ancillary service levels

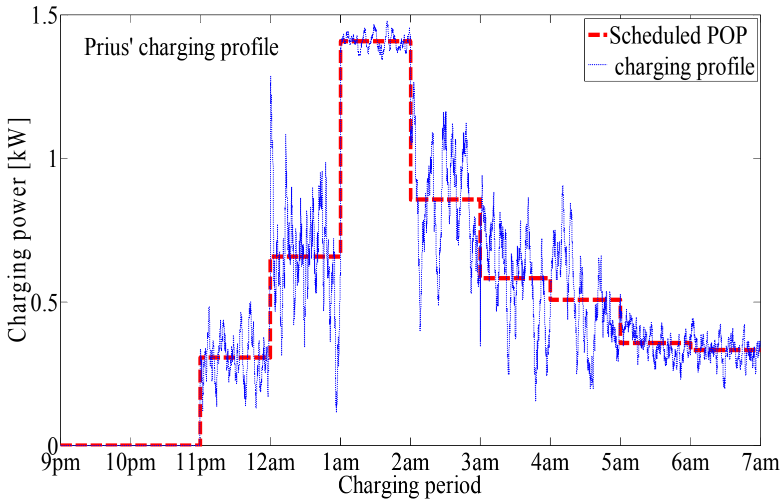
- Ancillary service levels (regulation capacity) of 3 EVs with different battery capacities are investigated
- The EVs are connected from 9 pm to 7 am
- Power draw is scheduled hour by hour throughout the interval
- Timing flexibility is crucial for an EV to perform regulation services
- The capacity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

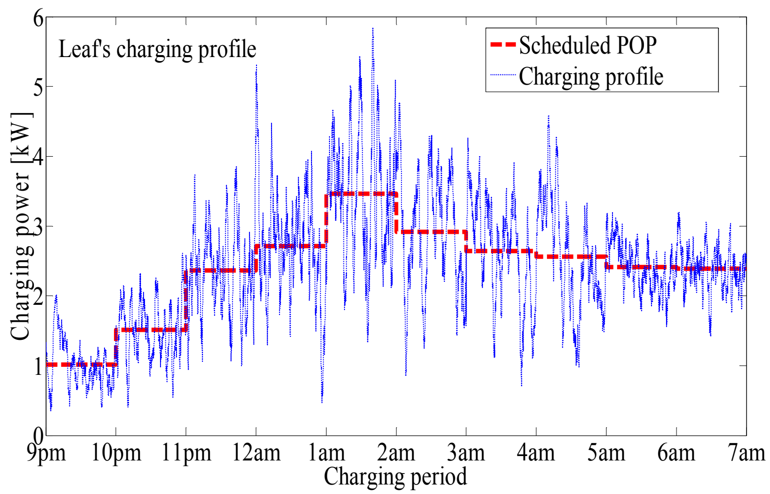
Ancillary service levels

EV model	Toyota Prius [21]	Nissan Leaf [18]	Tesla Roadster [22]
Battery capacity[21]	5kWh	24 kWh	56 kWh
Maximum charge rate	1.5 kW @120Vac	6.6 kW @ 240 Vac	16.8 kW @ 240 Vac
Energy request	5 kWh	20 kWh	56 kWh



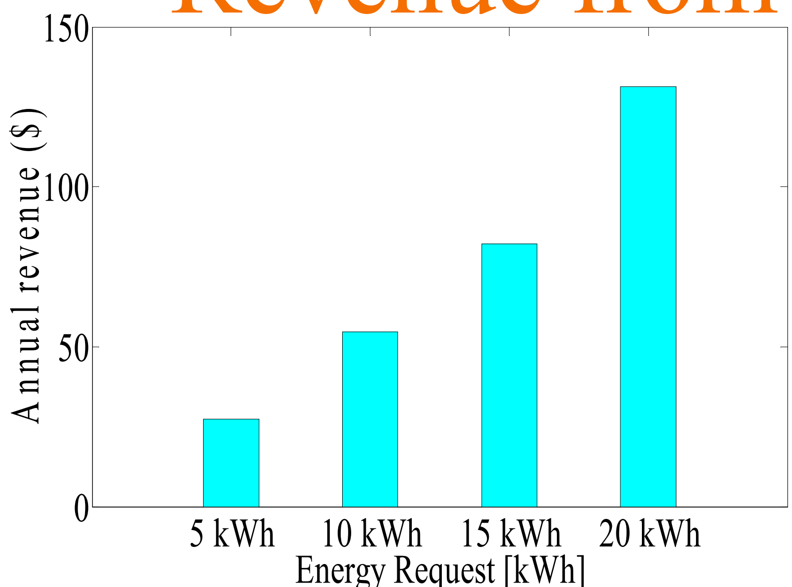
Charging profile of EVs performing regulation





- 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



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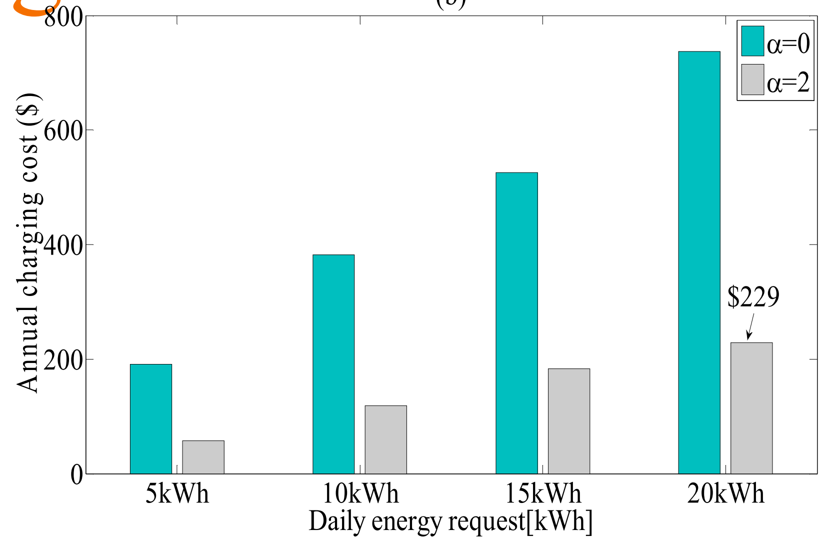
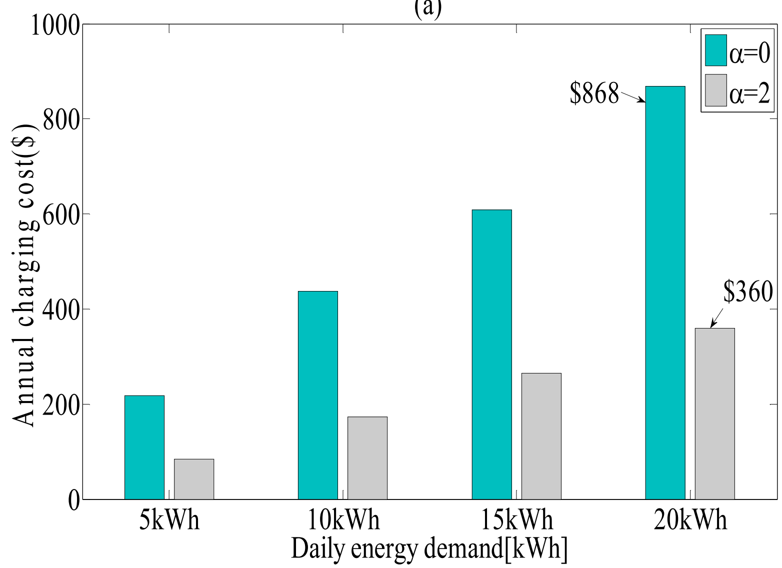




- Revenue from regulation services yields 21% in cost reduction
- A higher energy request will reap more revenue: more capacity
- Slackness has a more profound cost impact on an EV owner with higher energy demand

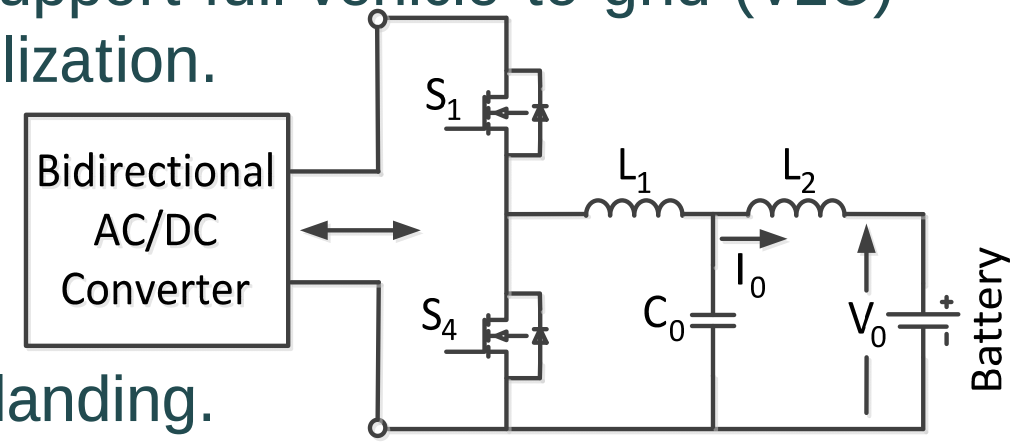
Unidirectional vs. bidirectional: battery degradation cost

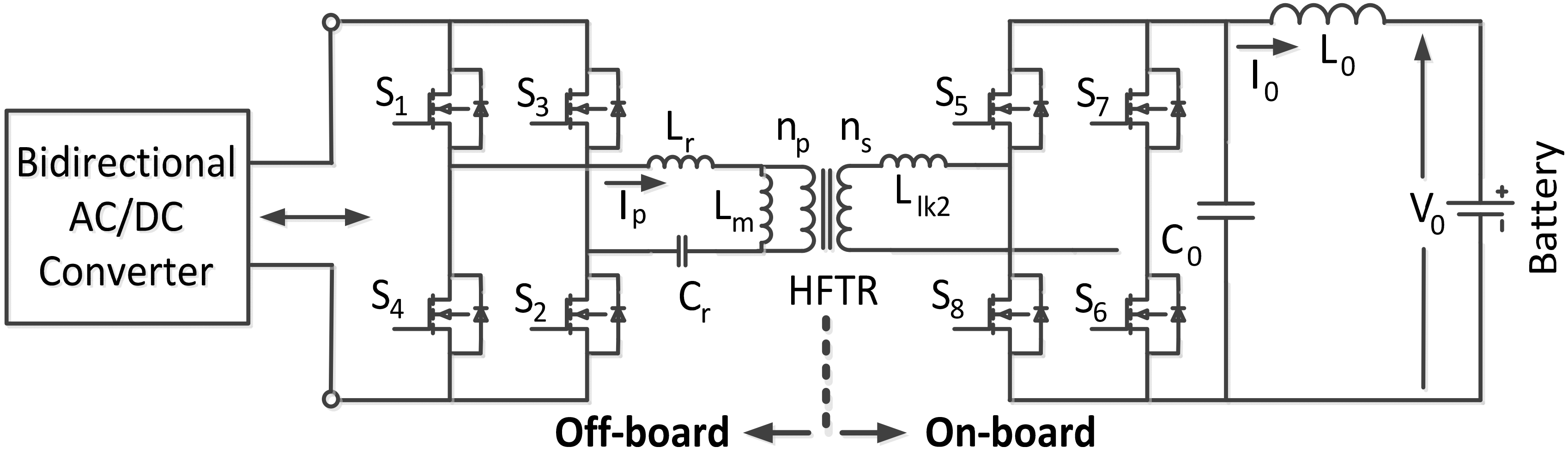
- Assuming a 10 h interval and 20 kWh demand, a max charge and discharge rate of 6.6 kW, and an RMCP of $0.02/kWh, annual regulation revenue is $480.
- For bidirectional, a conservative battery cost estimate leads to battery degradation cost of about $0.014/kWh/year.
  - This yields $335/year in degradation 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.

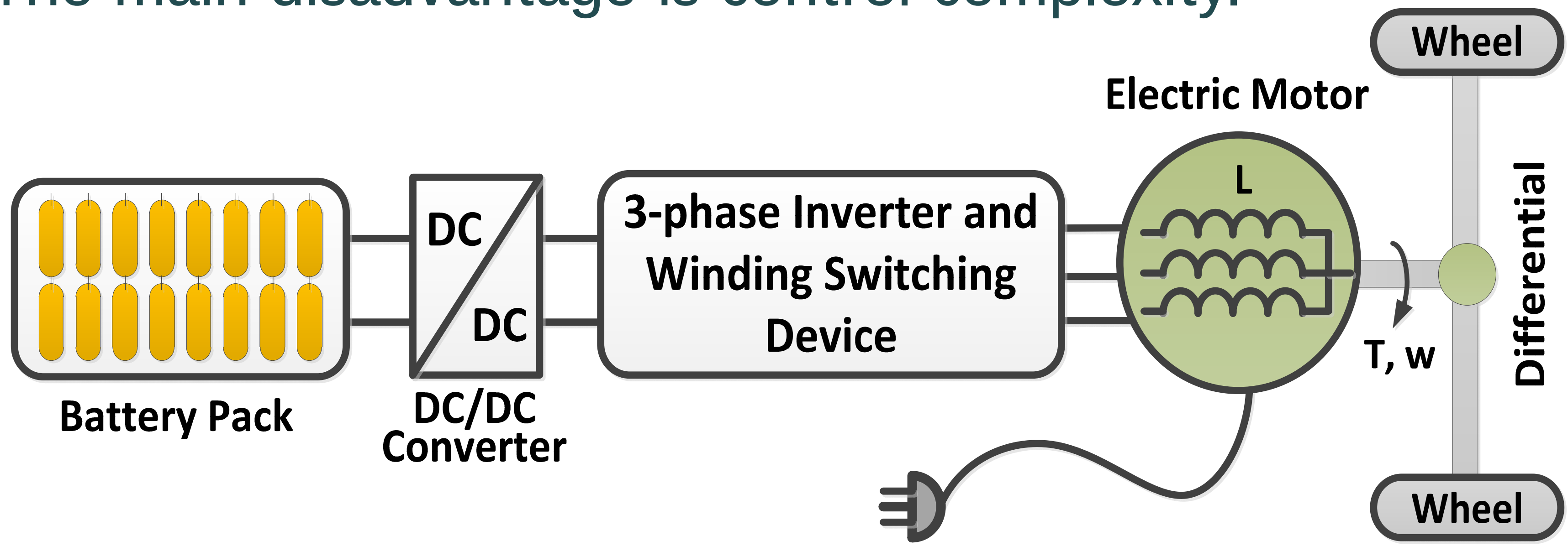
- How to pay for extra battery degradation, the charger, metering, etc.?
- Communications, anti-islanding.
- Not expected for Level 1 or Level 3.



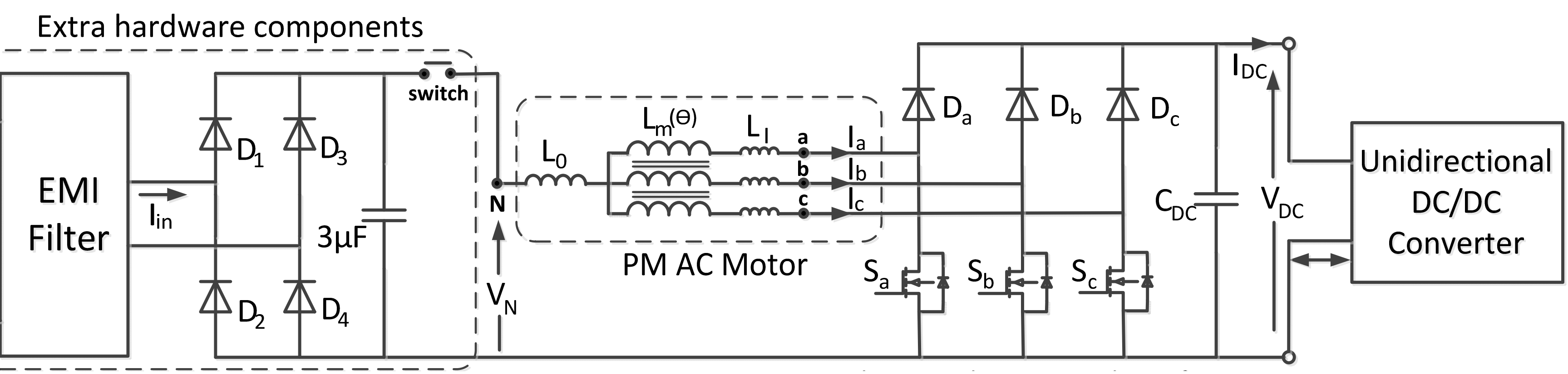


Integrated Chargers

- 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 Chargers



Integrated battery charger: the traction drive is transformed into a boost PFC battery charger

. Pellegrino, E. Armando, and P. Guglielmi, “An Integral Battery Charger with Power Factor Correction for Electric cooter,” *IEEE Trans. Power Electron.*, vol. 25, no. 3, pp. 751-759, 2010.

Conductive and Inductive Chargers

Conductive chargers use metal-to-metal contact.

onductive chargers on the Chevrolet Volt, Tesla Roadster, nd Toyota Prius plug-in use use Level 1 and 2 chargers with asic infrastructure.

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

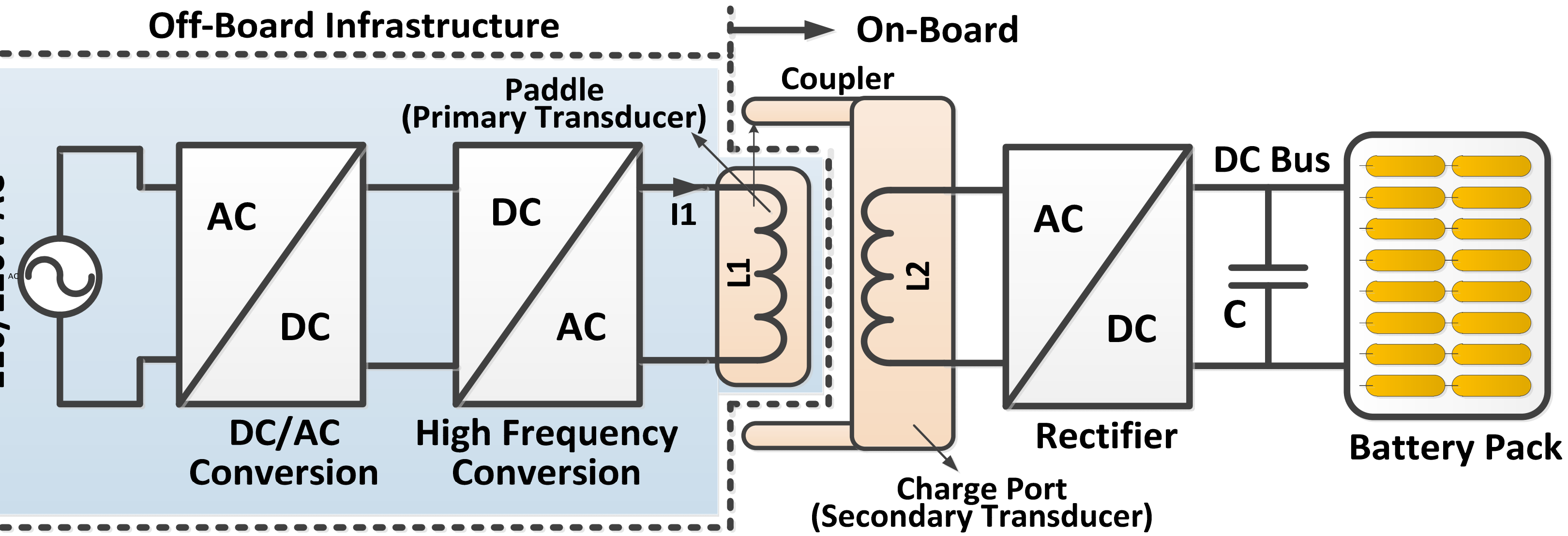
he main drawback of this solution s that the driver needs to plug in the ord, but this is conventional.

Conductive and Inductive Chargers

- **nductive power transfer (IPT)** of EVs is based on agnetic 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.
- isadvantages include relatively low efficiency and power, gh complexity and cost.
- PT principles follow transformers, though most have low magnetic oupling and high leakage flux.

engadget.com

Stationary Inductive Chargers



Inductively coupled stationary charger and GM EV1 system

tionary inductive charging:

rimary and secondary transducers

1 version:

rimary transducer is a paddle

econdary 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