A Modular Single-Phase Bidirectional EV Charger with Current Sharing Optimization

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Overview

1. Motivation of Research
2. System Description
3. Simulation and Experimental Work
4. Conclusions

EVGI Problem

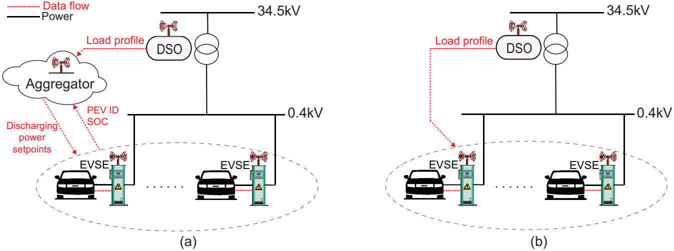
Problems with EV-grid integration (EVGI)

- Mass penetration of EVs will put grid under more stress.
- Users will want to charge as quickly as possible.
  - Increase on peak loading on feeders and transformers
  - Increased distribution level voltage drops
  - Increased unbalanced loading due to single-phase charging
  - New investment requirements (i.e. replacement of the transformers)
- Solution: Unidirectional (G2V) and Bidirectional (V2G) charging

Motivation for Modular Charger Design

Why modular on-board charger design?

- Smart EV charging/discharging:
  - Centralized/distributed control: optimization, voltage-based, or RT price-based control...
  - Fixed charging: uncontrolled, on-off, delay control, charge staggering.
  - *Variable charging: analog control of charging*

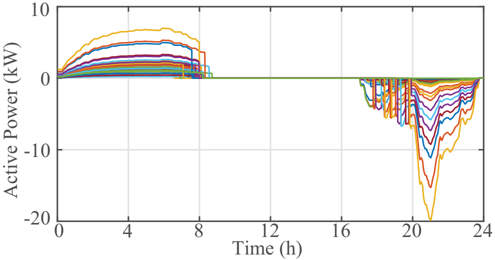


Types of EVGI control: a) Centralized architecture, b) Decentralized architecture.

Motivation for Modular Charger Design

On-board chargers: fixed rated power vs. variable power operation

- Better load management and more flexibility in grid w/variable charging
- Downside: less efficient operation at below rated power levels



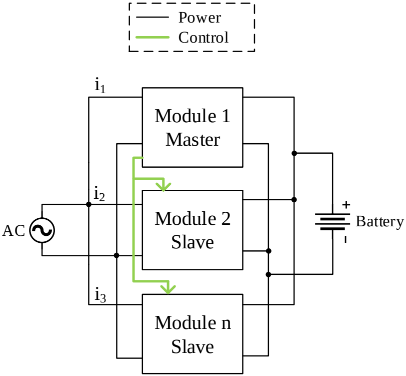
Motivation for Modular Charger Design

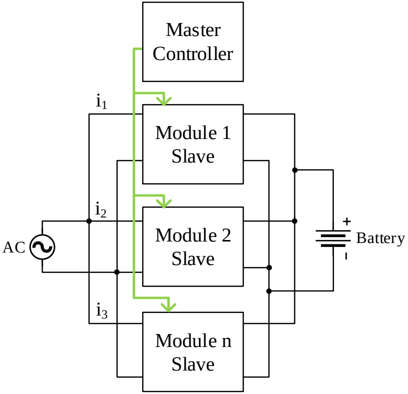
Modular charger design can serve better for variable operation:

- Flatter efficiency curve throughout the power load range
- Increase in light load efficiency brings better utilization of electrical energy.
- Unidirectional and bidirectional solutions are possible.
- Converter design flexbility
- Ease of maintenance

Modular Design

- Two types of architecture for the modular system invesitaged:





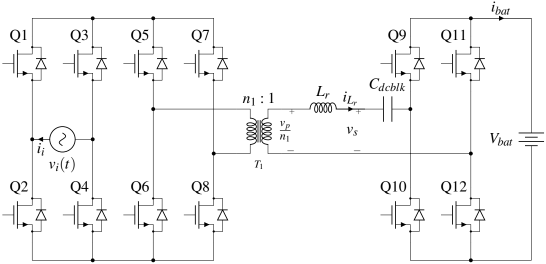
Topology Selection

Advantages:

- Ease of modular configuration
- Bidirectional power flow
- Single-stage for compactness
- Easy power contrallibility thru δ

Disadvantages:

- Fixed power factor operation
- Delivered power reduces with frequency



Instaneous battery current equation:

$$i_{bat}(t) = \frac{\delta \, V_i^2}{8 \, n_1^2 \, L_r \, f_s \, V_{bat}} \{1 - cos(4\pi f_i t)\}$$

N. D. Weise, et. al. “A single-stage dual-active-bridge-based soft switched AC-DC converter with open-loop power factor correction and other advanced features,” IEEE Trans. Power Electron., Aug 2014.

Optimization

- Efficiency stament for individual modules in either mode with operating voltages are fixed

$$\eta_{G2V,n} = f_{G2V,n}(i_n)$$

$$\eta_{V2G,n} = f_{V2G,n}(i_n)$$

- Overall efficiency function of the system in either mode

$$\eta_{G2V} = \frac{f_{G2V,1}(i_1) \cdot i_1 + f_{G2V,2}(i_2) \cdot i_2 + \cdots + f_{G2V,n}(i_n) \cdot i_n}{i_1 + i_2 + \cdots + i_n}$$

$$\eta_{V2G} = \frac{i_1 + i_2 + \cdots + i_n}{\frac{i_1}{f_{V2G,1}(i_1)} + \frac{i_2}{f_{V2G,2}(i_2)} + \cdots + \frac{i_n}{f_{V2G,n}(i_n)}}$$

Optimization Problem Statements

In G2V mode:

$$\min \frac{\sum_{k=1}^{n} i_k}{\sum_{k=1}^{n} f_{G2V,k}(i_k) \cdot i_k}$$

subject to;

$$\sum_{k=1}^{n} i_k = i_{demand}$$

$$\begin{bmatrix} i_1 & i_2 & \cdots & i_n \end{bmatrix} \leq i_{rated}$$

$$\begin{bmatrix} -i_1 & -i_2 & \cdots & -i_n \end{bmatrix} \leq 0$$

In V2G mode:

$$\min \frac{\sum_{k=1}^{n} \frac{i_k}{f_{V2G,k}(i_k)}}{\sum_{k=1}^{n} i_k}$$

subject to;

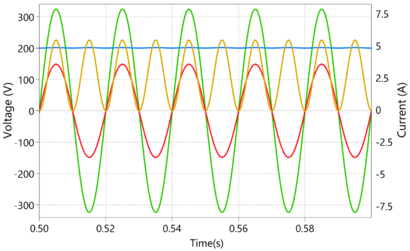
$$\sum_{k=1}^{n} i_k = i_{demand}$$

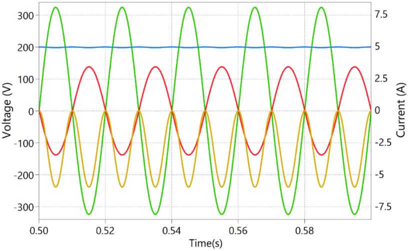
$$\begin{bmatrix} -i_1 & -i_2 & \cdots & -i_n \end{bmatrix} \leq i_{rated}$$

$$\begin{bmatrix} i_1 & i_2 & \cdots & i_n \end{bmatrix} \leq 0$$

Single Module Simulation

- Single module simulation in PLECS using 220V AC grid voltage, 200V DC battery voltage, 600 W operation
- Bidirectional power flow verified
- δ vs. power flow relationship verified

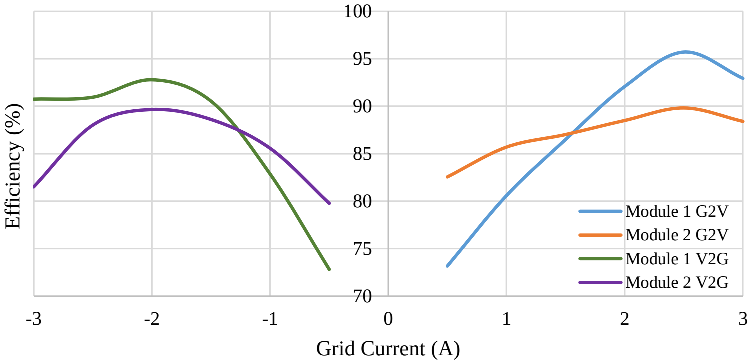




grid voltage, grid current, battery voltage, battery current

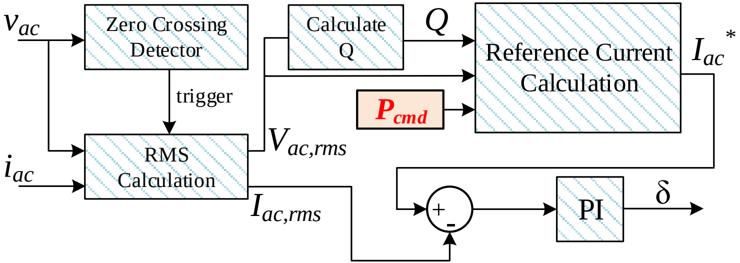
Simulation for Modular Operation

- Two modules operated in parallel
- Hypothetical efficiency curves converted into mathematical functions
- Optimization algortihm verified



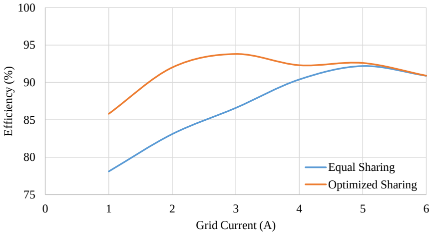
Simulation for Modular Operation, cnt'd

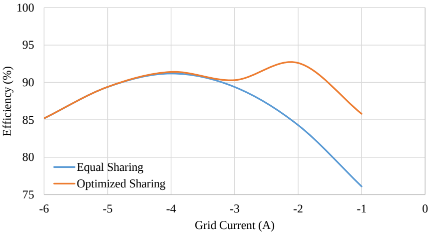
Closed loop controller block diagram



Simulation for Modular Operation, cnt'd

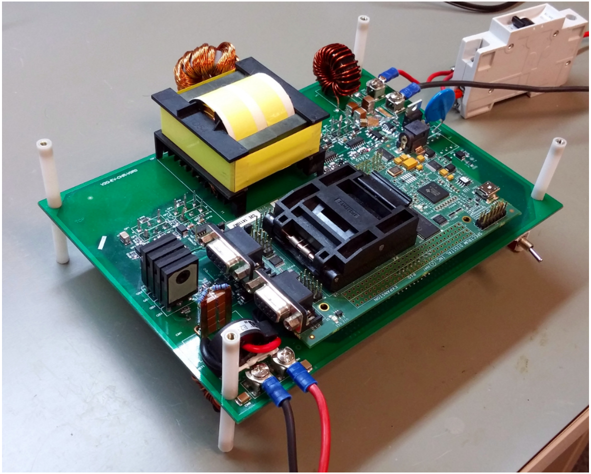
- Equal sharing operation
  - Modules are operated with equal references for each operating point
- Optimized sharing operation
  - Individual references of the modules are generated by the master controller after running optimization algorithm





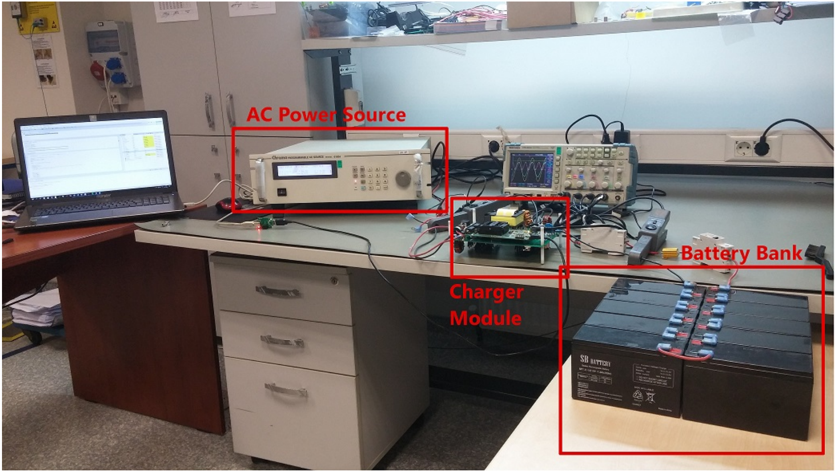
Experimental Verification

Single 600W charger module



Experimental Verification, cnt'd

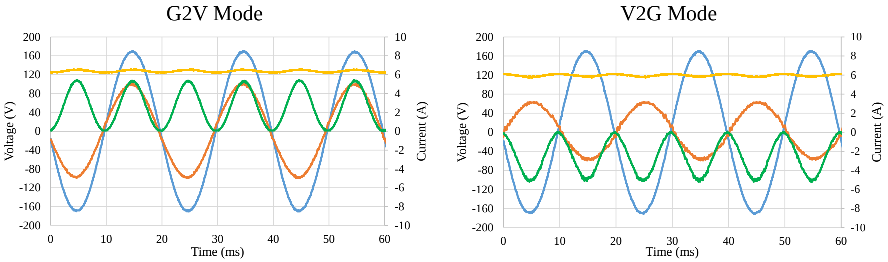
Experimental system set-up for single module



Experimental Verification, cnt'd

Results for single module operation

- Bidirectional operation is verified using a single module.
- In G2V mode: 0.99 PF and 1.19% THD
- In V2G mode: 0.98 PF and 2.77% THD



grid voltage, grid current, battery voltage, battery current

Conclusions and Future Work

Conclusions

- Proposed a modular charger design with optimized current sharing.
- Simulation results show efficiency increase of up to 13%.
- Results for the single-module experimental data is presented.
- Two-module bidirectional operation (600W+600W) initial experimental data showed 10-13% increase in efficiency.
- A good fit for smart grid integration of EVs.

Future Work

- System operation will be further developed with two hardware prototype charger modules.
- Operation can be extended to three-phase with balanced current sharing.

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