A Three-Phase Synergetically Controlled Buck-Boost Current DC-Link EV Charger

Daifei Zhang
Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
Research Background

- **Transportation**: 25% of World Energy & CO2 Emission
- **Sustained Transportation Electrification**
- **More Compact & Efficient EV Chargers**

- 3-Φ Non-Isolated Bidirectional AC/DC Converter System → Standard Building Block
- Buck-boost Capability: 200V to 1000V

![Diagram of EV Charger Systems](source: Electrichasgoneaudi.net)
**Bidirectional Buck-Boost AC/DC Converter System**

- **Buck-Boost (bB) OR Boost-Buck (Bb) Combination**
- **Shared Current (Inductive) OR Voltage (Capacitive) DC-Link**

- **3-Φ bB Current DC-Link PFC AC/DC Converter System**
- **3-Φ Bb Voltage DC-Link PFC AC/DC Converter System**

- Advanced PWM Schemes Enabling Optimal Clamping Operation w/ Significantly Reduced Losses
- "Synergetic Control" of AC/DC and DC/DC Converter Stage
- Comprehensive Comparison based on Realized Demonstrator Systems
**Buck-Boost | Boost-Buck Demonstrator Systems**

- **Buck-Boost Current DC-Link AC/DC Converter**
  - $10\,kW$ @ $400\ldots1000\,V_{DC} @ 3$-$\Phi$ $400\,V_{rms}$ Mains
  - $U_{out} = 200\ldots1000\,V_{DC}$
  - $\eta = 98.8\%$ @ $6.4\,kW/dm^3$
  - AC/DC $\rightarrow f_{sw} = 100$ kHz
  - DC/DC $\rightarrow f_{sw} = 2 \times 50$ kHz/100 kHz eff.

- **Boost-Buck Voltage DC-Link AC/DC Converter**
  - $10\,kW$ @ $400\ldots800\,V_{DC} @ 3$-$\Phi$ $400\,V_{rms}$ Mains
  - $U_{out} = 200\ldots800\,V_{DC}$
  - $\eta = 98.8\%$ @ $5.4\,kW/dm^3$
  - AC/DC $\rightarrow f_{sw} = 100$ kHz
  - DC/DC $\rightarrow f_{sw} = 2 \times 100$ kHz/200 kHz eff.

- **Min. # of Inductive Components** → AC/DC Buck-Stage Output Inductor Utilized as DC/DC Boost Inductor
- **Reduced Hardware Manufacture Cost & Complexity**
- **Reduced Control/Firmware Implementation Efforts**
3-Φ bB Current DC-link PFC AC/DC Converter System

200...1000 VDC | 10 kW 98.8% | 6.4 kW/L
**Loss-Optimal Operating Principles**

- **Buck-Mode Operation**
- 3/3-PWM w/ Zero State
- Constant DC-Link Current

- **Boost-Mode Operation**
- 2/3-PWM w/o Zero State
- Pulse-shape DC-Link Current

- Min. # of Switching Instants & Reduced Sw. Voltage → App. 77% Reduction of Switching Losses
- Min. DC-Link Current → 8% Reduction of Conduction Losses
Synergetic Control Strategy

- Enable 2/3-PWM with Variable DC-Link Current
- Collaborative Operation of AC/DC & DC/DC Converter Stages

- Ensure Seamless / Democratic Transitions between Proposed Loss-Optimal Modes
**Efficiency Measurement Results**

- Measurements Covering 200V to 1000V & 25% Load to Full Load

- **Peak Efficiency of 98.8%**
- **Flat Efficiency Characteristic -- Above 98% in Most Area**
- **Up to 1% Efficiency Improvement in Boost-Mode Operation**
Two *Independently* Regulated DC Outputs

- Extended Synergetic Control Allows Independent Regulation of $V_{\text{out}}$ or $P_{\text{out}}$
- Heavy-Duty EV Battery Charging

- Loss-Optimal Operation Modes & 2/3-PWM are Still Maintained
Future *RCD-Based Non-Isolated EV Charger*

Source: www.wolfspeed.com
3-Φ AC/DC Converter in EV Chargers

- Galvanic Isolated EV charger
- Multi-Stage Structure
- 50 Hz Or HF Transformer (DAB, LLC, DCX…)
- Small Ground Current → End-User Safety
- Bulky & Low Power Efficiency & High Cost

- Non-Isolated EV charger
- Residual Current Device (RCD) → End-User Safety
- Battery Package Parasitic Cap. up to Several uFs
- Min. Ground Current → Avoid Nuisance Tripping
- Conv. EMI Filter Suppress HF Ground Current
- PV Inverter → 1% More Efficiency w/ Half Volume
- Enable High Power On-Board Charger (OBC)
Virtual Grounding Control (VGC)

- **Current DC-Link Rectifier Stage Generates LF CM Voltage**
- **Use DC/DC to Actively Compensate LF CM of AC/DC**

- **Reduced LF CM Noise Emission** → **Time-Varying (150 Hz) Output Capacitor Voltage**
- **Similar DM Operations** → **Constant Output Voltage & 2/3-PWM**
Ground Current Control (GCC)

- Hard Connection between Output Midpoint & PE
- Direct Measure & Feedback Regulate Ground Current

- Ground Current: < 6 mA, Far Below 30 mA Limit
- Pre-Compliance Test Accord. to UL 2202 & IEC 61851 Considering TT & TN Systems
3-Φ Bb Voltage DC-link PFC AC/DC Converter System

200…800 VDC | 10 kW 98.8% | 5.4 kW/L
Loss-Optimal Operating Principles

- Boost-Mode Operation
- 3/3-PWM
- Constant DC-Link Voltage

- Buck-Mode Operation
- 1/3-PWM
- Pulse-shape DC-Link Voltage

- Min. # of Switching Instants & Min. Amplitude of Switched Current
- App. 70% Reduction of Switching Losses
Conducted EMI Pre-Compliance Tests

● **Buck-Boost Current DC-Link AC/DC Converter**

- Lower EMI Noise Emission Achieved by Advanced PWM Schemes
  - **Current DC-Link**: Output Voltage Independent but Power Dependent
  - **Voltage DC-Link**: DC-Link Voltage and Output Voltage Dependent

- **EMI Filter Redesign is Not Needed When Applying the Advanced PWM Schemes**

● **Boost-Buck Voltage DC-Link AC/DC Converter**

- Buck-Boost Current DC-Link AC/DC Converter
- Boost-Buck Voltage DC-Link AC/DC Converter
Conclusion & Contribution

■ Advanced PWM Schemes
  ● Current DC-Link : 2/3-PWM
  ● Voltage DC-Link : 1/3-PWM & 2/3-PWM-OPT
  ● Enables Optimal Clamping Operation

■ Synergetic Control Strategies
  ● Loss-Optimal Buck-Boost Operation
  ● Seamless & Smooth Transitions Between Different Modes

■ Independent Output Voltage/Power Control
  ● Fully Leverage Hardware Capacity
  ● Allow Loss-optimal Operation for Voltage or Power Asymmetry

■ Ground Current Control Strategy
  ● Target Future RCD-Based Non-Isolated EV Chargers
  ● Closed-Loop Regulation of Ground Current
  ● More Compact & Efficient EV Chargers
Thank you!