# Wide Voltage Range High-Efficiency Sigma Converter 48V VRM With Fast Transient Response

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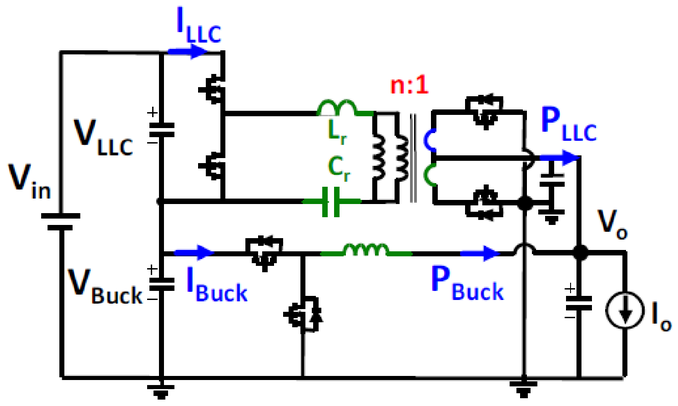
## Sigma Converter Structure




$$I_{LLC} = I_{Buck}$$

$$\frac{P_{LLC}}{P_{Buck}} = \frac{V_{LLC}}{V_{Buck}}$$

- Power Shared between two-converters
- Majority of Power through efficient LLC-DCX
- Small Buck converter for regulating output voltage

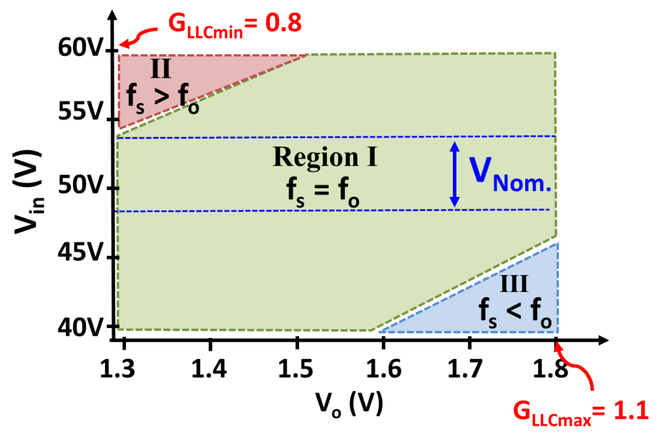
**More Efficient Power Conversion Comparing to Two-Stage Approaches**

## Sigma Converter Design with Integrated Matrix Transformer and Inductor

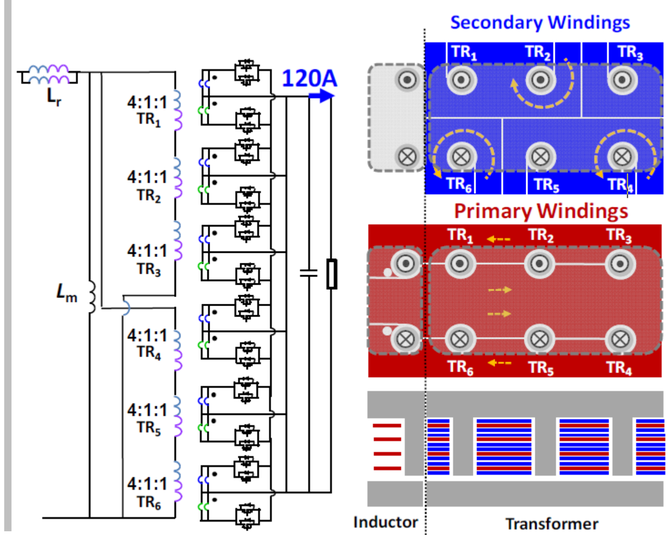
Sigma Converter Operation Regions

Const. 1: $n_{max} \le \left(\frac{V_{inmin}}{V_{omax}} - D_{max}\right) G_{LLCmax}$

Const. 2: $n_{min} \ge \left(\frac{V_{inmax} - V_{Buckmax}}{V_{omin}}\right) G_{LLCmin}$

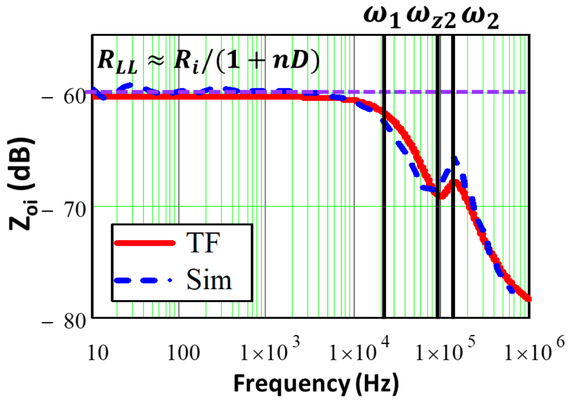



LLC-DCX with 6 x 4:1 matrix transformer and integrated inductor

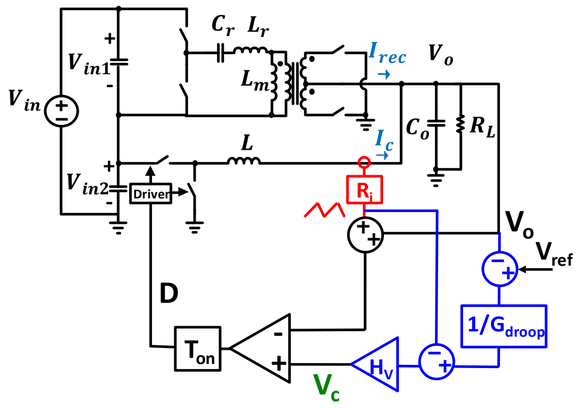



## Adaptive Voltage Positioning (AVP) Design and Load Transient Performance

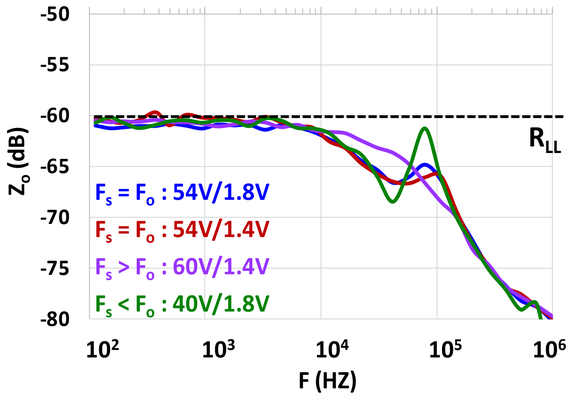
Output Impedance with Enhanced V² Control



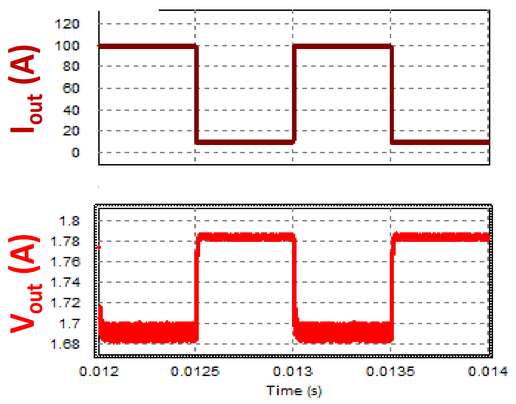

Proposed Enhanced V² Control and Active Droop Control Scheme




Constant $Z_o$ with Different Operating Points

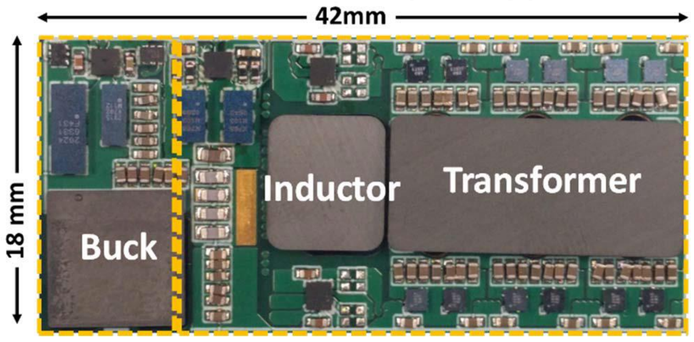



Load Transient Simulation with $V_{in}$=54V and $V_o$=1.8V

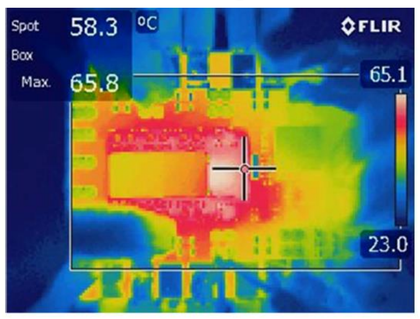



## Experimental Results

Hardware prototype



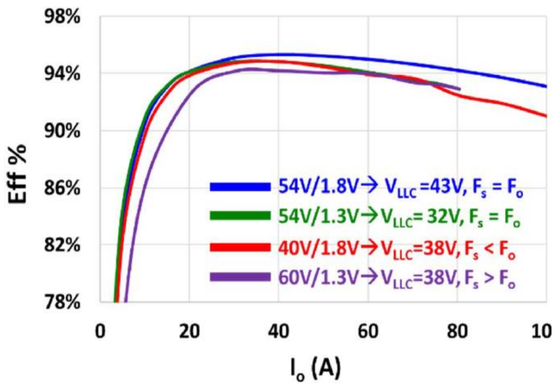

Thermal Image @120A



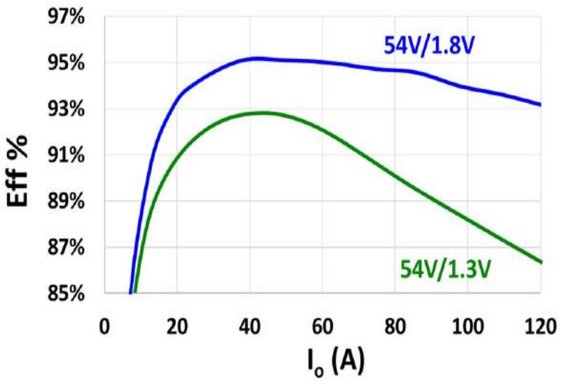

200 LFM Air Cooling

| Solution | This Work | Two-Stage DCX+Buck | PSFB | Hyberid DC/DC |
|---|---|---|---|---|
| Max. Eff. | 95.3% | 94% | 93% | 94.6% |
| Full Load Eff. | 93% | 89% | 91.4% | 87.2% |
| Power Density | 700W/in3 | N/A | N/A | 420W/in3 |
| | 200W/in2 | N/A | 66W/in2 | N/A |

LLC-DCX measured efficiency




Sigma measured efficiency




**LLC-DCX:**
- **Maintain Maximum Efficiency > 94%**
- **Small Efficiency Variation With D2D Operation**

**Sigma Converter:**
- **Peak Efficiency: 95.3%**
- **Higher peak and full load efficiency**
- **Higher power-density**