Sparse Operation of Multi-Winding Transformer in Multiport-Ac-Coupled Converters

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Background & Motivation

- Multiport-Ac-Coupled (MAC) architecture
  - Applications in highly modular systems

Solar Cells | Battery Energy Storage
Data Center Servers | Energy Router

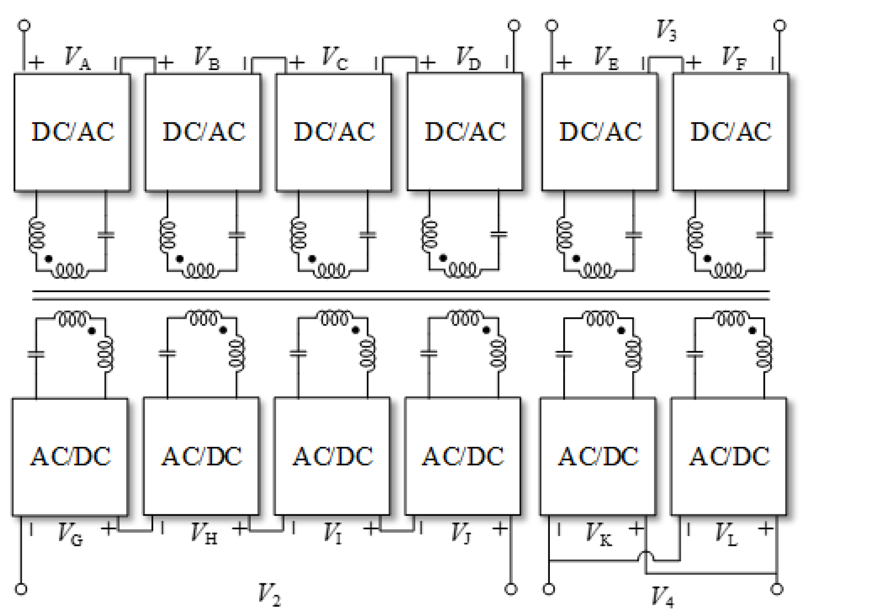


Fig. 1: MAC converter implemented with a single magnetic core.

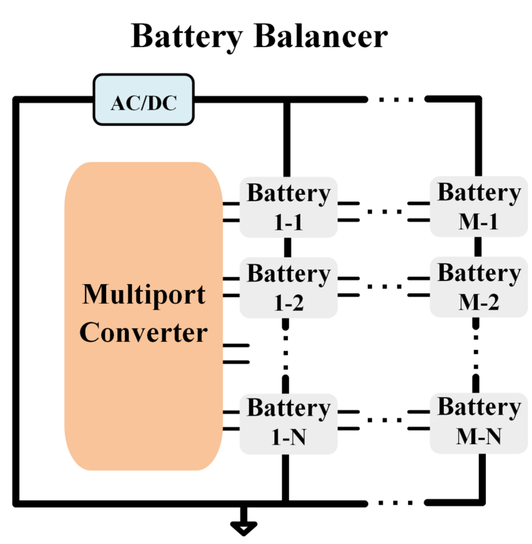


Fig. 2: Multiport converter configured for battery balancing.

- Sparse Operation

When **only** a few **windings deliver power** and a **majority** of the windings **remain open-circuited**

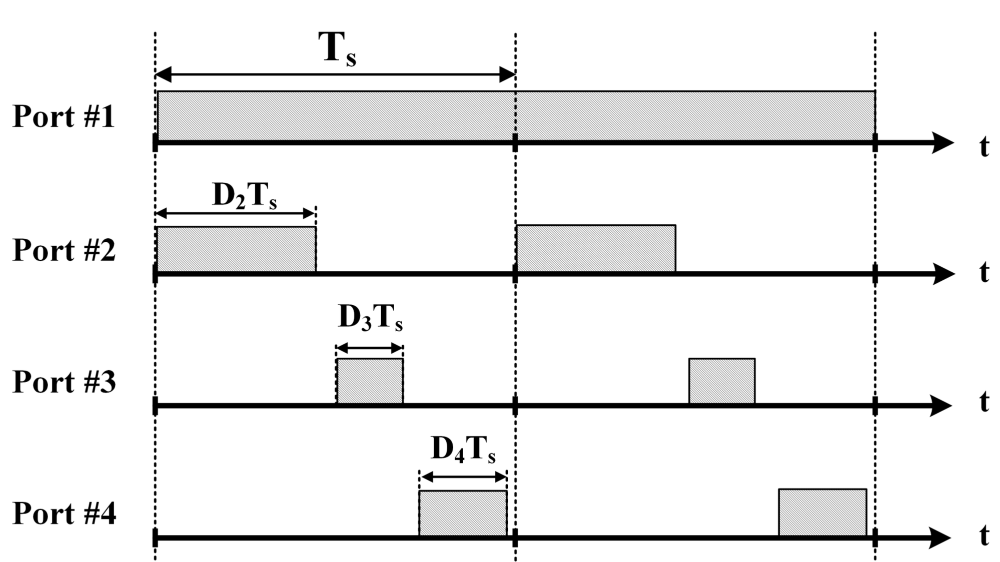


Fig. 3: Time sharing control scheme of a multiport converter, resulting in highly sparse winding stacks.

Modular Layer Model

- Each layer represented as 3-terminal impedance network
- Hypothesis for "sparse operation"
  1. Less power can be transferred between ports that are further away (with many "open" windings in between)
  2. Eddy current will be induced in "open" windings and lead to additional loss

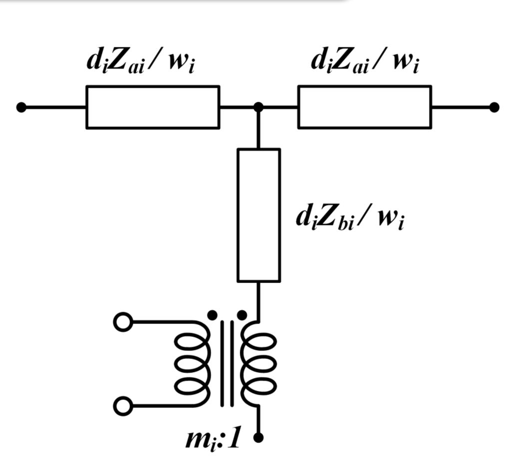


Fig. 4: Modular Layer Model (MLM) of a single layer.

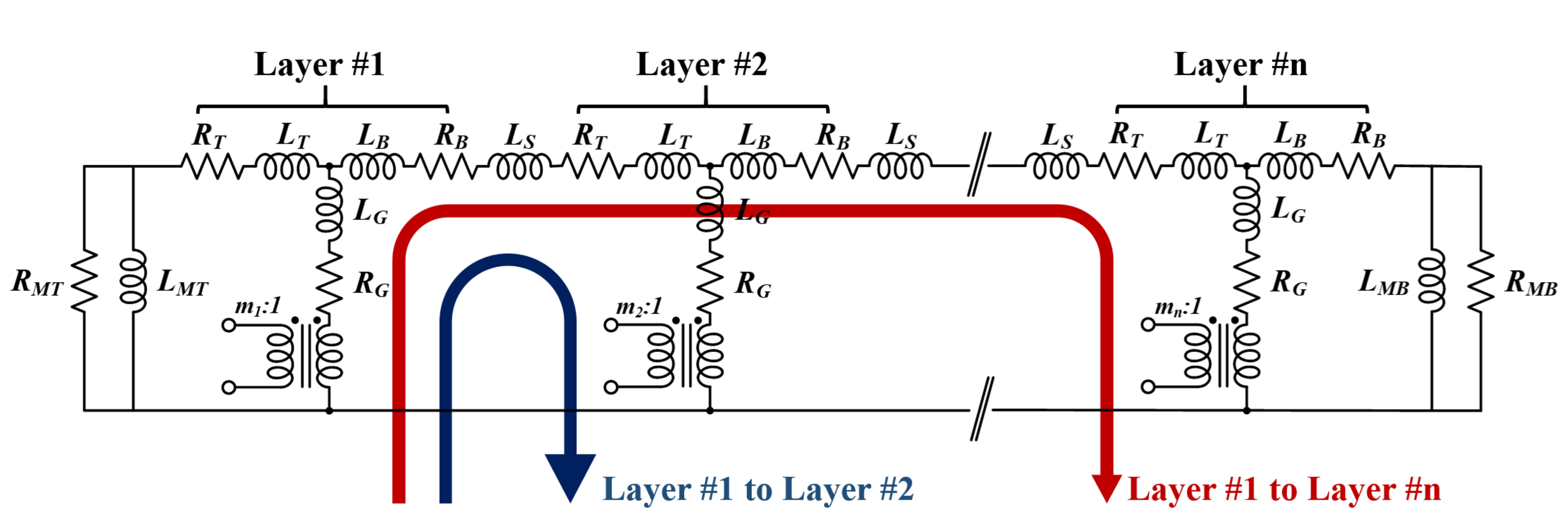


Fig. 5: MLM of an n layer multi-winding transformer.

Simulation Results

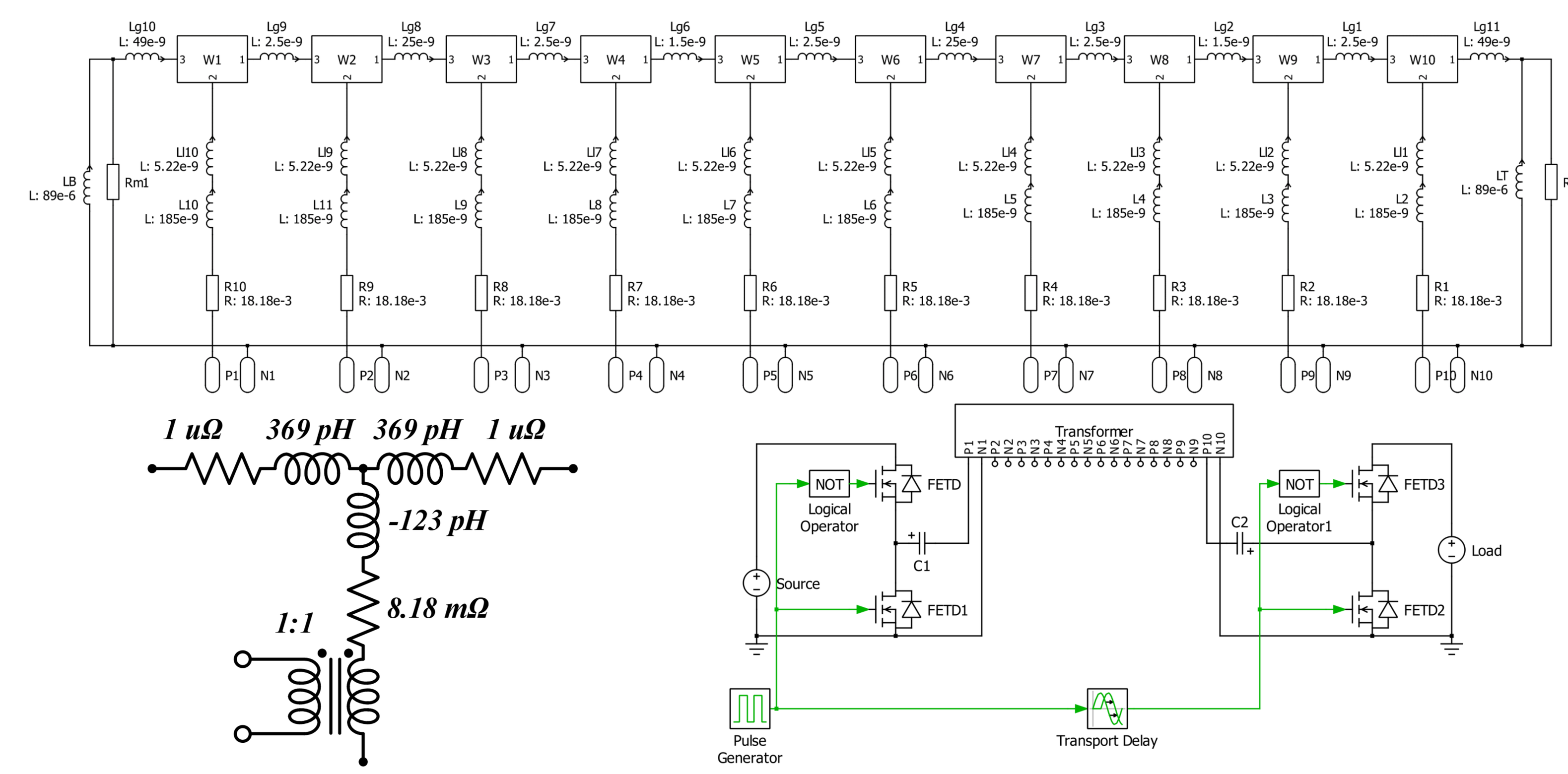


Fig. 5: M2SPICE generated 10-layer multi-winding transformer MLM, the single layer MLM schematic, and a dual-active-bridge simulation testbench

100-Layer Simulation | 10-Layer Simulation

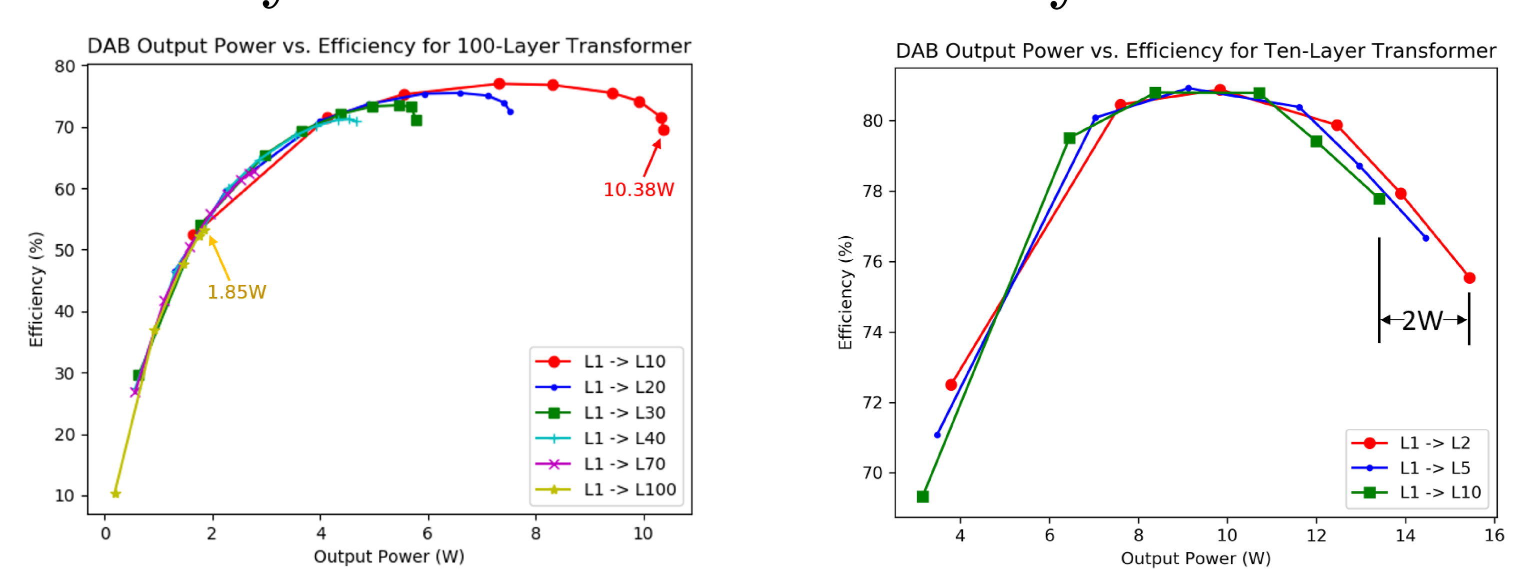


Fig. 6: Simulation results for 100-layer and 10-layer multi-winding transformer

Distance between layers ↑ | **Max. Transferrable Power ↓**
Port-to-Port Efficiency ↓

Finite Element Analysis

- Increased eddy current as:
  1. Layers get further apart
  2. Switching frequency increases
- Contributes to lower efficiency as layers are further with increased "open" windings in between

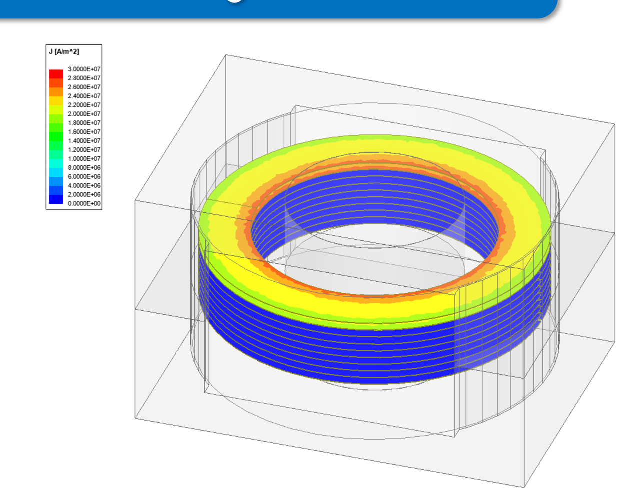
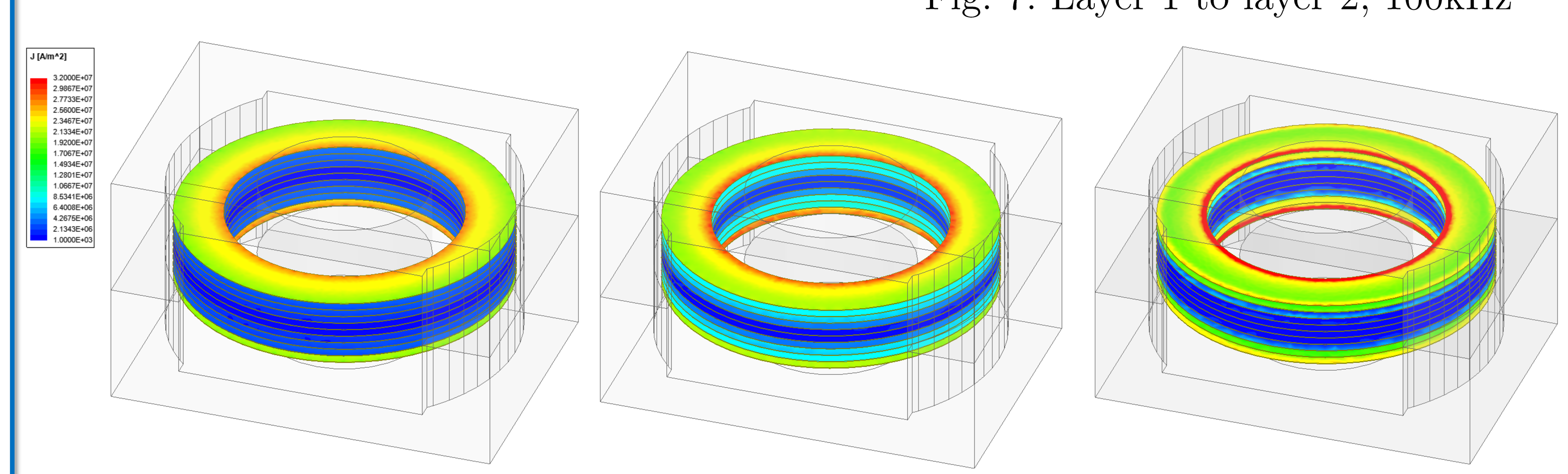


Fig. 7: Layer 1 to layer 2, 100kHz



(a) 25 kHz (b) 100 kHz (c) 1 MHz

Fig. 8: Layer 1 to layer 10 at various frequencies

Experimental Results

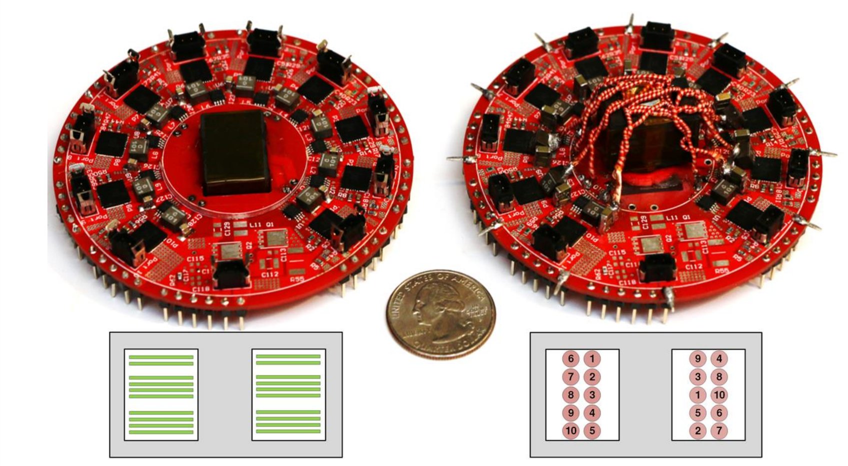


Fig. 9: Prototype MAC converters with planar vs. twisted litz-wire multi-winding transformer.

Specification	Description
Power Density	100 W/in^3
Switches	FDMF6833C DrMOS (50A)
Transformer Core	TDK EEQ 20-N97 $\mu_r = 1430$
Inductors	100 nH
Capacitors	141 µF

Table I: Prototype specifications.

Planar Transformer | Litz Wire Transformer

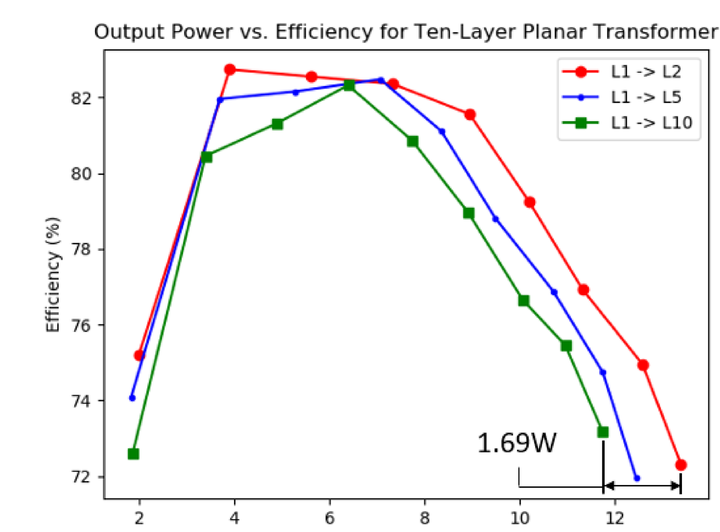


Fig. 10: Output power vs. efficiency curves for planar transformer.

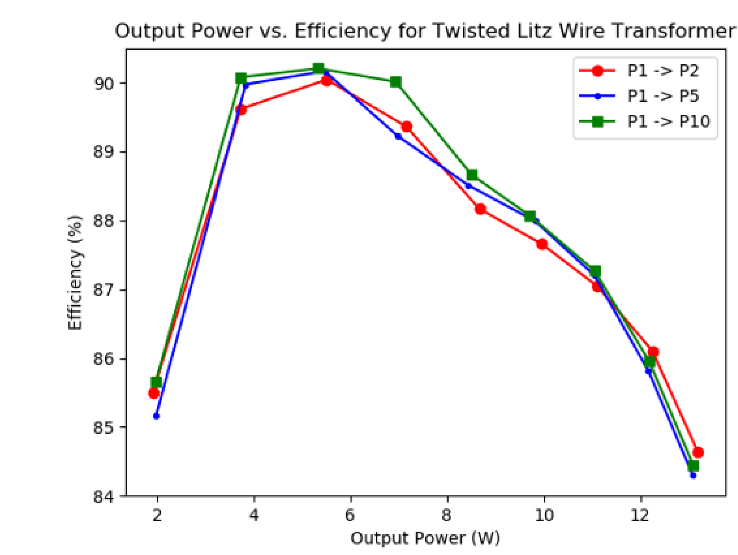


Fig. 11: Output power vs. efficiency curves for planar transformer.

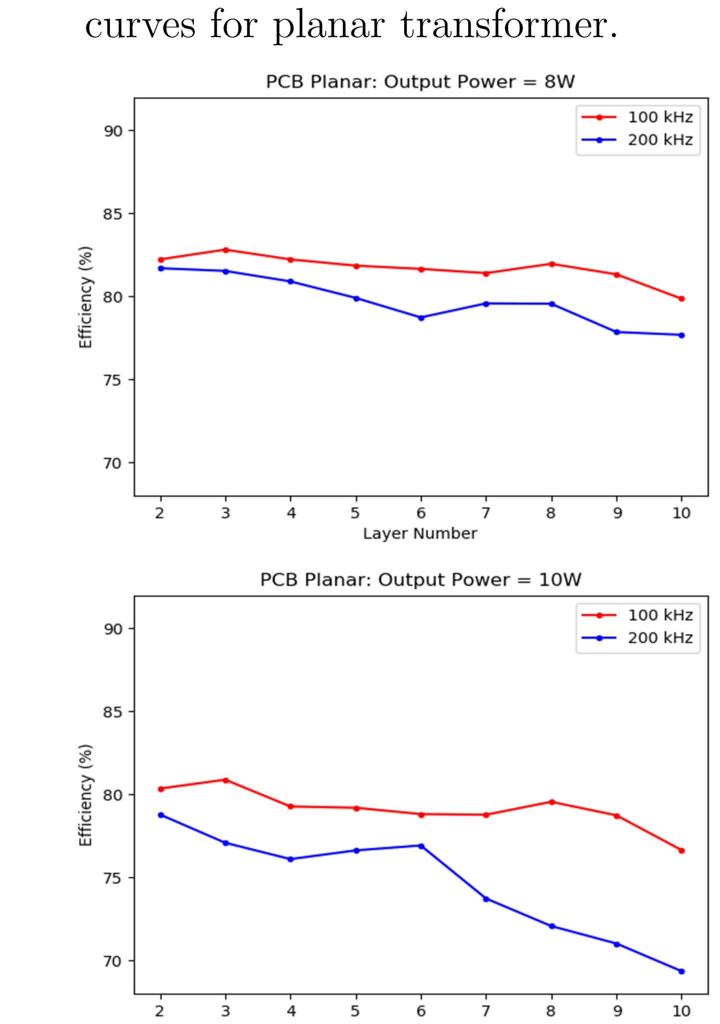


Fig. 12: Layer number vs. efficiency for planar transformer (input: L1).

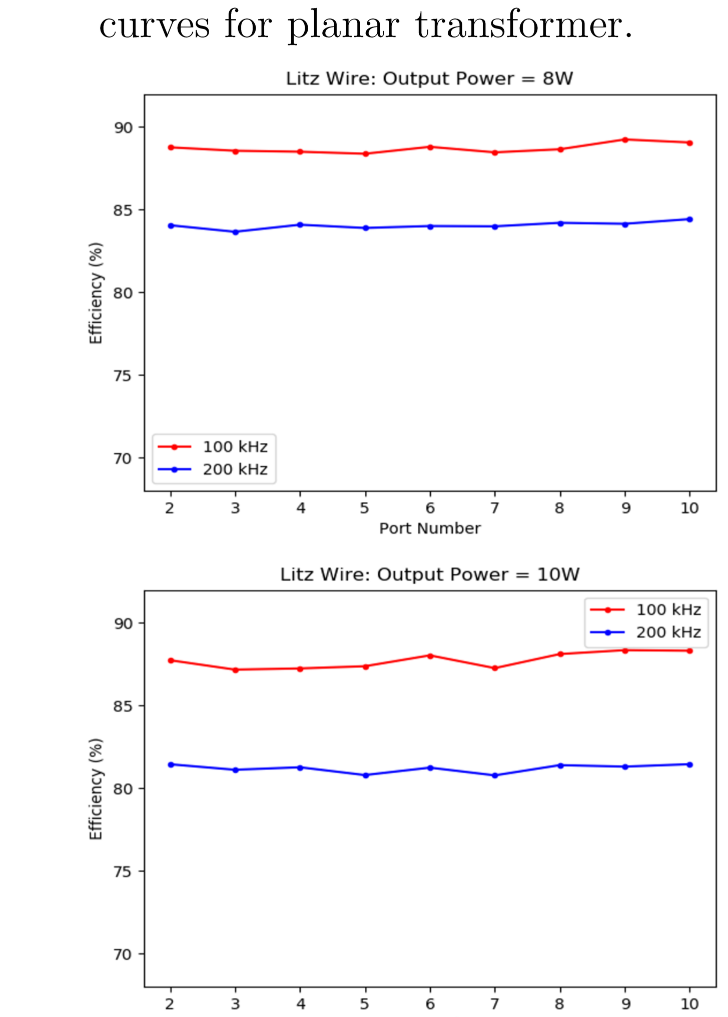


Fig. 13: Port number vs. efficiency for litz wire transformer (input: P1).

Design Guidelines

- **Sparse operation exists**, can be predicted and observed
- MLM can model multi-winding transformers to **predict its impact on loss**, assist in **optimizing design geometry**
- **Threshold on number of ports** exists for particular design
- Twisted litz wire operates better under sparse operation
  - Tradeoffs: **lower modularity/repeatability**
- **Reducing the switching frequency** offers benefits