Multi-Constraint Optimization and Co-Design of a 2-MHz All-GaN based 1kW 96% Efficient LLC Converter

Nitish Jolly, Electrical Engineering
Mentor: Ayan Mallik, Assistant Professor
School of Electrical, Computer, and Energy Engineering, Arizona State University

Objective

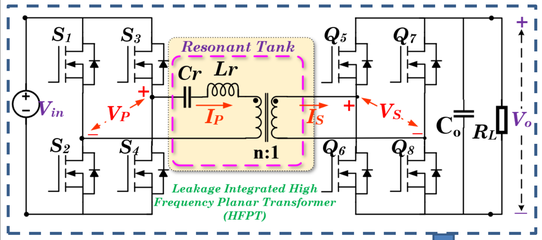
- Minimizing the power losses in a 2MHz LLC resonant converter, a novel multi-variable multi-constraint design optimization algorithm as well as a control system is developed.
- Designing a GaN-based High-density Highly Efficient Power Convertor for Data Centers applications.

Key Contributions of the work

- Comprehensive frequency dependent loss characterization, minimization, and detailed design specific trade-off analysis by developing and solving a multi-variable multi-constraint optimization function
- Intricate quantification of gain gradients corresponding to achievable frequency resolution facilitating MHz level digital implementation
- Accurate parameterization of linearized small signal model using GHA based extended describing function
- Presentation of feasibility and fast transient response of proposed sliding mode control scheme

LLC Resonant Converter Topology

General Harmonic Approximation (GHA) based Modeling



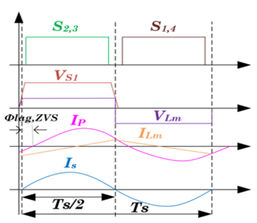


Fig. Timing diagram

Modeling of Converter

$$V_{p,k}(t) = L_r \frac{di_{L,k}(t)}{dt} + v_{c,k}(t) + L_m \frac{d(i_{m,k}(t))}{dt} + i_{L,k}R_p$$

$$\frac{1}{n}V_{m,k}(t) = \frac{1}{n}L_m \frac{d(i_{m,k}(t))}{dt} = V_{s,k}(t)$$

$$i_{L,k}(t) - i_{m,k}(t) = \frac{i_{s,k}(t)}{n}$$

$$i_{L,k}(t) = C_r \frac{dV_{c,k}(t)}{dt}$$

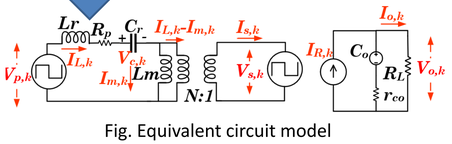


Fig. Equivalent circuit model

Multi-constraint Design Optimization

Objective: $\boldsymbol{Min}\sum P_{loss}\{f_s, n, L_r, P_{load}\} = P_{cond} + P_{sw} + P_{core} + P_{winding} + P_{C_{ESR}}$

Frequency-dependent active loss equation and constraint imposed by ZVS

$$\frac{2C_{oss}\left|\sum_{k=1,3,5\ldots}^{2n+1} Z_{in,k}\{f_s,\ n,\ P_{load}\}\right|^2}{\sin^2\varphi} < L_r < \frac{R_{ac}}{2\pi f_r}\sqrt{\frac{k_L C_m f^2 - 1}{k_L(f^2-1)}} - \frac{(k_L C_m f^2 - 1)^2}{k_L^2 f^2}$$

$$P_{active}\{n, f_s,\ P_{load}\} = P_{sw} + P_{cond} = \frac{K_{1,x}}{\left|\sum_{k=1,3,5\ldots}^{2n+1} Z_{in,k}\{f_s,\ n,\ P_{load}\}\right|^2} + \frac{K_2' f_s \sin\varphi}{\left|\sum_{k=1,3,5\ldots}^{2n+1} Z_{in,k}\{f_s,\ n,\ P_{load}\}\right|} + K_2'' f_s$$

where, $K_{1,x} = \frac{8V_{in}^2}{\pi^2}\sum_{k=1,3,5\ldots}^{2n+1}\frac{1}{k^2}\sin k\omega_s t\, R_{ds_{on},x}$

$$K_2' = \frac{4V_{in}^2}{\pi}(t_3 + t_4)\sum_{k=1,3,5\ldots}^{2n+1}\frac{1}{k}\sin k\omega_s t\ ;\ K_2'' = C_{oss}{V_o}^2$$

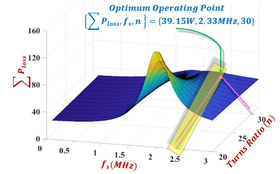


Fig. $\sum P_{loss}\{f_s, n, L_r, P_{load}\}$ vs P_{load}

GHA-based small signal modeling

$$\frac{d\tilde{x}}{dt} = A_k.\tilde{x} + B_k.\tilde{u}$$

$$\tilde{y} = C_k.\tilde{x}$$

where,

$$[A_k] = \begin{bmatrix} -M_1 & \frac{-R_p}{L_{sN}} & M_2 + k\Omega_s & 0 & 0 & 0 & -\frac{1}{L_{sN}} & 0 & M_3 \\ -M_4 & 0 & M_7 & -\frac{R_p}{L_{sN}} & 0 & 0 & \frac{1}{L_{sN}} & 0 & -M_8 \\ -M_2 & -k\Omega_s & M_1 & 0 & 0 & 0 & 0 & -\frac{1}{L_{sN}} & -M_{13} \\ M_6 & -k\Omega_s & -M_7 & 0 & 0 & 0 & \frac{1}{C_R} & -M_{14} & \\ 0 & 0 & 0 & 0 & 0 & k\Omega_s & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{C_R} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{C_R} & 0 & 0 & -k\Omega_s & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -M_{19} \\ M_{17} & 0 & M_{18} & 0 & 0 & 0 & 0 & 0 & \end{bmatrix}$$

$$\tilde{x} = [\widetilde{i_{ss,k}}\ \ \widetilde{i_{Ls,k}}\ \ \widetilde{i_{sc,k}}\ \ \widetilde{i_{Lc,k}}\ \ \widetilde{i_{ms,k}}\ \ \widetilde{i_{mc,k}}\ \ \widetilde{V_{cs,k}}\ \ \widetilde{V_{cc,k}}\ \ \widetilde{V_{Co,k}}]$$

$$\tilde{u} = [\widetilde{\omega_n}\ \ \widetilde{V_{in}}\ \ \tilde{d}]$$

$$\tilde{y} = \widetilde{V_o}$$

$$[B_k] = \begin{bmatrix} Q_3 & M_4 & M_5 \\ Q_1 & M_9 & M_{10} \\ Q_4 & 0 & 0 \\ Q_2 & 0 & 0 \\ Q_8 & M_{11} & M_{12} \\ Q_7 & M_{11} & M_{12} \\ Q_5 & 0 & 0 \\ Q_6 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$[C_k] = [M_{20}\ \ 0\ \ M_{21}\ \ 0\ \ 0\ \ 0\ \ 0\ \ M_{22}]$$

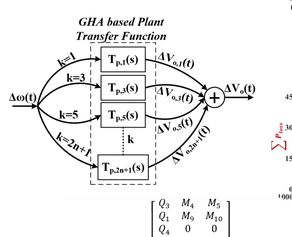


Fig. $\sum P_{loss}\{f_s, n, L_r, P_{load}\}$ vs f_s

Sliding Mode Control Scheme

Sliding surface definition

$$S = \lambda_1 E^* + \lambda_2 \int_0^t E^* dt$$

Settling time constraint

$$\frac{\lambda_2}{\lambda_1} > \frac{\ln(10)}{\tau_s}$$

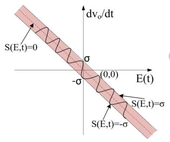


Fig. Sliding-surface

Overshoot/Undershoot constraint

$$\Delta V_{o,k} < \frac{-\frac{\lambda_2 M_{20} T_{on}}{M_{22}}\widetilde{i_{ss,k}} - \frac{\lambda_2 M_{21} T_{on}}{M_{22}}\widetilde{i_{sc,k}} + \frac{\sigma}{\pi}\omega_s - \lambda_2 V_o^* \frac{\pi}{\omega_s}}{-\lambda_1 - \frac{\lambda_2 T_{on}}{M_{22}}}$$

$$T_{CL}(s) = \frac{\left(\lambda_1 + \frac{\lambda_2}{s}\right)T_p(s)}{1 + \left(\lambda_1 + \frac{\lambda_2}{s}\right)T_p(s)}$$

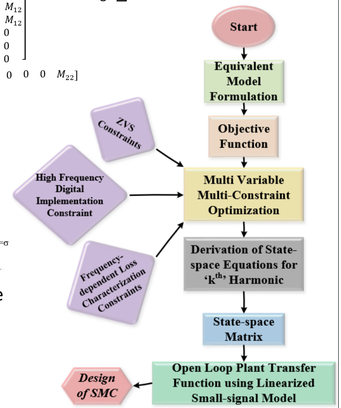


Fig. Flowchart for design optimization

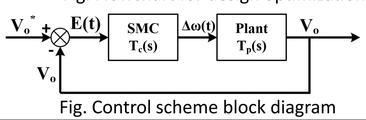
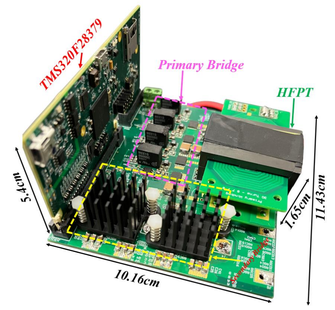


Fig. Control scheme block diagram

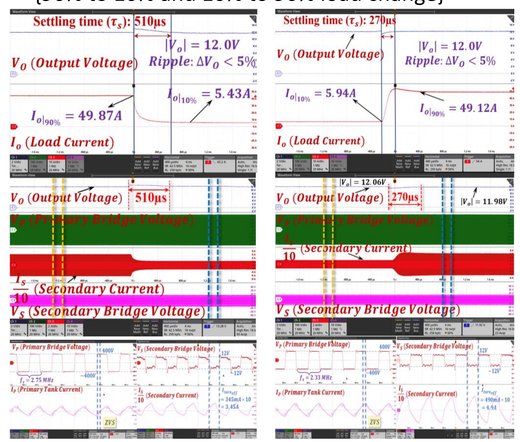
Experimental Verification and Benchmarking

Design Specifications

Parameters	Values
Rated Power (P_o)	1kW
Primary input voltage (V_{in})	380-420V
Secondary output voltage range (V_o)	12V
Transformer Turns Ratio (n)	30:1
Resonant Inductance (L_r)	11.22µH
Magnetizing Inductance (L_m)	95.99µH
Resonant Capacitance (C_r)	0.56497nF
Resonant frequency (f_s)	2MHz



Experimental Waveforms
{90% to 10% and 10% to 90% load change}



Converter Specifications

Parameters	Values
Peak Efficiency (η)	96.08%
Power Density (W/cm^3)	>6.2W/cm^3
Specific Power (kW/kg)	>2kW/kg

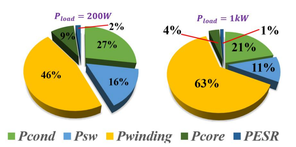


Fig. Loss distribution at light loading and heavy loading operations

Controller response results

Load power variation	Dynamic Behavior	SMC
from 90% to 10%	Settling time	510µs
	Voltage ripple	0.8V
from 10% to 90%	Settling time	270 µs
	Voltage ripple	0.6V

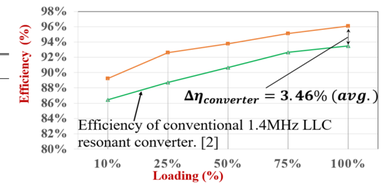


Fig. Efficiency at different loading conditions

Acknowledgement

This research has been supported by ASU, MORE program and Arizona New Economic Initiative, which are gratefully acknowledged. The research project was co-sponsored by W. L. Gore & Associates. Special thanks to Prof. Ayan Mallik (Mentor) for his expert guidance and support.

MORE
Masters Opportunity for Research in Engineering

Ira A. Fulton Schools of Engineering
Arizona State University