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Design and Optimization of a High Frequency Power Transformer for Solid State Transformer Application

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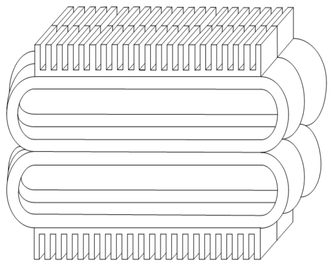
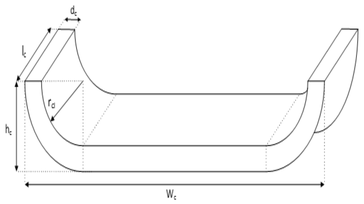
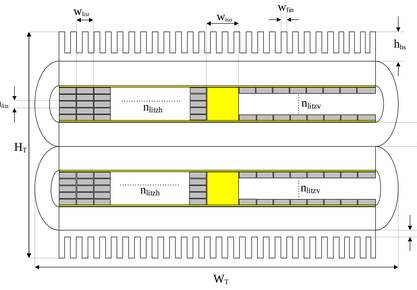
Design Criteria

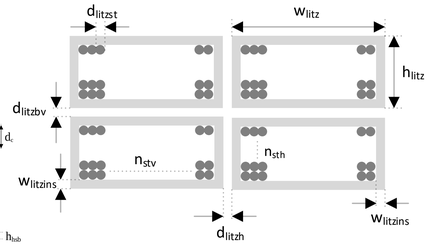
1- Cost
2- Reliability
3- Manufacturability
4- efficiency
5- power density

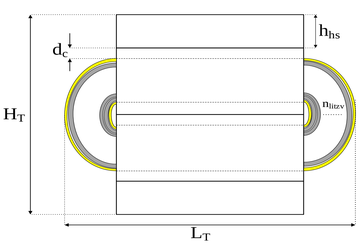
Proposed Structure

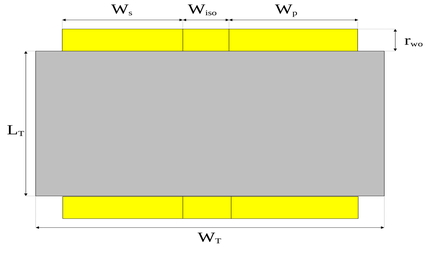




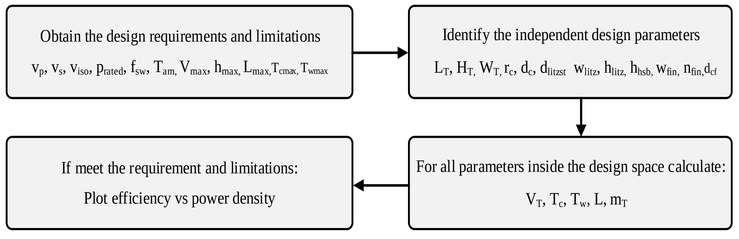








Design Algorithm

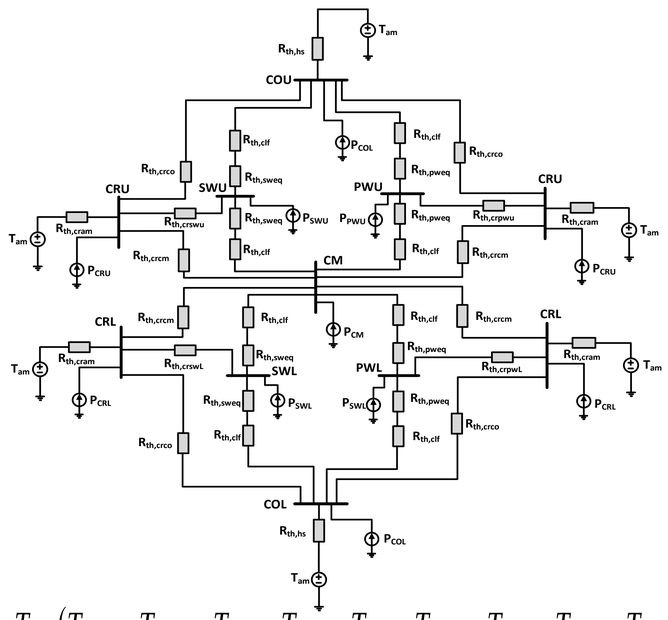


Leakage inductance

$$E_{cw}=\frac{1}{4}\mu w_w l_w\left(\frac{I}{w_w}\right)^2\sum_{i=1}^{m_w}\{\int_0^{d_{cu}}\left|i\frac{\sinh(\alpha z)}{\sinh(\alpha d_{cu})}\right|^2 dz+\int_0^{d_{cu}}\left|(i-1)^2\frac{\sinh(\alpha(z-d_{cu}))}{\sinh(\alpha d_{cu})}\right|^2 dz+\int_0^{d_{cu}}\left|i(i-1)\frac{\sinh(\alpha z)}{\sinh(\alpha d_{cu})}\frac{\sinh(\alpha(z-d_{cu}))}{\sinh(\alpha d_{cu})}\right|dz\}$$

$$L=\mu\frac{l_{litz}}{n_{litzh}w_{litz}}\left[\frac{n_{st}d_{st}}{3\Delta^2}\left(\left(4{n_{litzv}}^2-1\right)\frac{\sinh(2\Delta)-\sin(2\Delta)}{\cosh(2\Delta)-\cos(2\Delta)}-2\left({n_{litzv}}^2-1\right)\frac{\sinh(\Delta)-\sin(\Delta)}{\cosh(\Delta)-\cos(\Delta)}\right)+w_{iso}+w_{litzins}\frac{n_{litzv}-1}{n_{litzv}}\right]$$

Thermal Model



$$T=\left(T_{SWU}\quad T_{PWU}\quad T_{SWL}\quad T_{PWL}\quad T_{CM}\quad T_{COU}\quad T_{COL}\quad T_{CRU}\quad T_{CRL}\right)^T$$

$$AT+BU=0 \qquad T=-A^{-1}BU$$

$$A=\begin{pmatrix}
R_{SWU} & 0 & 0 & 0 & \frac{1}{R_{th,pweq}+R_{th,clf}} & \frac{1}{R_{th,sweq}+R_{th,clf}} & 0 & \frac{1}{R_{th,crswu}} & 0\\
0 & R_{PWU} & 0 & 0 & \frac{1}{R_{th,pweq}+R_{th,clf}} & \frac{1}{R_{th,pweq}+R_{th,clf}} & 0 & \frac{1}{R_{th,crpwu}} & 0\\
0 & 0 & R_{SWL} & 0 & \frac{1}{R_{th,sweq}+R_{th,clf}} & 0 & \frac{1}{R_{th,sweq}+R_{th,clf}} & 0 & 0\\
0 & 0 & 0 & R_{PWL} & \frac{1}{R_{th,pweq}+R_{th,clf}} & 0 & \frac{1}{R_{th,pweq}+R_{th,clf}} & 0 & \frac{1}{R_{th,crpwL}}\\
\frac{1}{R_{th,clf}+R_{th,sweq}} & \frac{1}{R_{th,clf}+R_{th,pweq}} & \frac{1}{R_{th,clf}+R_{th,sweq}} & \frac{1}{R_{th,clf}+R_{th,pweq}} & R_{CM} & 0 & 0 & \frac{2}{R_{th,crcm}} & \frac{2}{R_{th,crcm}}\\
\frac{1}{R_{th,clf}+R_{th,sweq}} & \frac{1}{R_{th,clf}+R_{th,pweq}} & 0 & 0 & 0 & R_{COU} & 0 & \frac{2}{R_{th,crco}} & 0\\
0 & 0 & \frac{1}{R_{th,clf}+R_{th,sweq}} & \frac{1}{R_{th,clf}+R_{th,pweq}} & 0 & 0 & R_{COL} & 0 & \frac{2}{R_{th,crco}}\\
\frac{1}{R_{th,crswu}} & 0 & 0 & 0 & \frac{1}{R_{th,crcm}} & \frac{1}{R_{th,crco}} & 0 & R_{CRU} & 0\\
0 & 0 & \frac{1}{R_{th,crco}} & 0 & \frac{1}{R_{th,crcm}} & 0 & \frac{1}{R_{th,crswu}} & 0 & R_{CRL}
\end{pmatrix}$$

Optimization

$$\vec{x}=(x_1,x_2,\dots,x_n) \qquad x_i\in[x_{imin},x_{imax}]\ ,\ i\in[1,n]$$

$$\vec{f}(\vec{x})=(f_1(\vec{x}),f_2(\vec{x}),\dots,f_m(\vec{x})) \qquad \Omega^*\equiv\arg\min f(x)=\left\{x^*\in\Omega: f(x^*)<f(x),\forall x\in\Omega\right\}$$

Objective function
Minimize $f(\vec{x})=V_T(\vec{x})$ where:

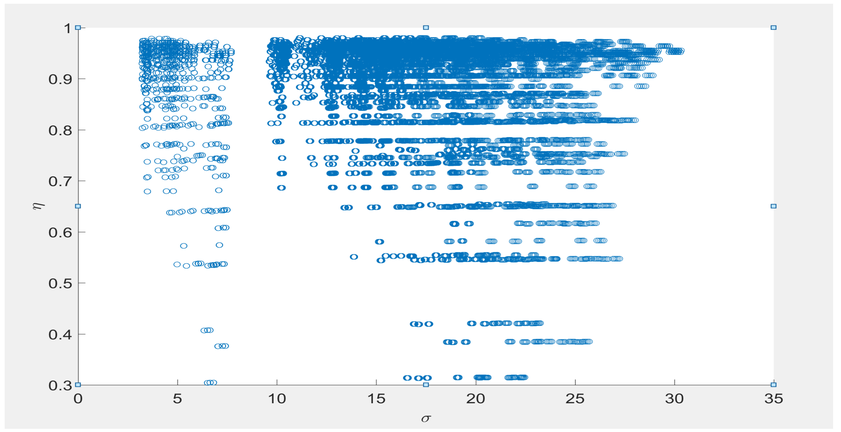
$$f(\vec{x})=\left((x_1x_3+x_4+x_6)(2x_7)+x_{13}+2(x_{11}+x_{10})\right)\left(\left(x_4x_2+x_4+x_5\right)(2x_8)+4x_{14}+4x_{10}+2x_{16}+2x_{15}\right)\left(x_{12}+2x_{14}+\left(x_1x_2+x_4+x_5\right)(x_7)+x_9\right)$$

Such that:

$$g_1(\vec{x})<L_{\max} \qquad g_2(\vec{x})<T_{\max}$$

$$g_1(\vec{x})=\mu\frac{2x_7x_8\left(x_{12}+\pi x_9+(x_8-1)(x_5+x_2x_1+x_4)\right)}{x_7(x_1x_3+x_4)}\left[\frac{x_1x_2x_3}{\frac{3}{2}\left(x_1x_2+x_4\right)^2\omega\mu\sigma}\left(\left(4x_8^2-1\right)\frac{\sinh(2(x_1x_2+x_4)\psi)-\sin(2(x_1x_2+x_4)\psi)}{\cosh(2(x_1x_2+x_4)\psi)-\cos(2(x_1x_2+x_4)\psi)}-2\left(x_8^2-1\right)\frac{\sinh((x_1x_2+x_4)\psi)-\sin((x_1x_2+x_4)\psi)}{\cosh((x_1x_2+x_4)\psi)-\cos((x_1x_2+x_4)\psi)}\right)+x_{13}+x_4\frac{x_8-1}{x_8}\right] \qquad \psi=\sqrt{\frac{\omega\mu\sigma}{2}}$$

$$g_2(\vec{x})=\left(T_{SWU}\quad T_{PWU}\quad T_{SWL}\quad T_{PWL}\quad T_{CM}\quad T_{COU}\quad T_{COL}\quad T_{CRU}\quad T_{CRL}\right)^T$$



Variable	Description	Optimal Value based on GA	Unit
x_1	Diameter of the copper strand inside the litz bundle	0.00015	m
x_2	Number of copper strands placed in a litz bundle vertically	13.0000	-
x_3	Number of copper strands placed in a litz bundle horizontally	27.0000	-
x_4	Width of the insulation layer of litz wire	0.00021	m
x_5	Vertical distance between litz bundles	0.00001	m
x_6	Horizontal distance between litz bundles	0.00001	m
x_7	Number of litz bundles placed horizontally in a core window	7.00000	-
x_8	Number of litz bundles placed vertically in a core window	4.00000	-
x_9	Inner radius of the windings	0.01500	m
x_{10}	Thickness of the core	0.00130	m
x_{11}	Inner radius of the core	0.03750	m
x_{12}	Length of the magnetic core	0.12500	m
x_{13}	Width of the insulation layer	0.00500	m
x_{14}	Thickness of the insulation layer between the core and the winding	0.00100	m
x_{15}	Height of the heatsink	0.01500	m
x_{16}	Height of the base part of the heatsink	0.00200	m
x_{17}	Width of the fin	0.00300	m