

# Series-Coupling Test Characterization of High-Leakage Transformers

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Presenter: John G. Hayes



**Power Electronics Research Laboratories**  
University College Cork, Ireland  
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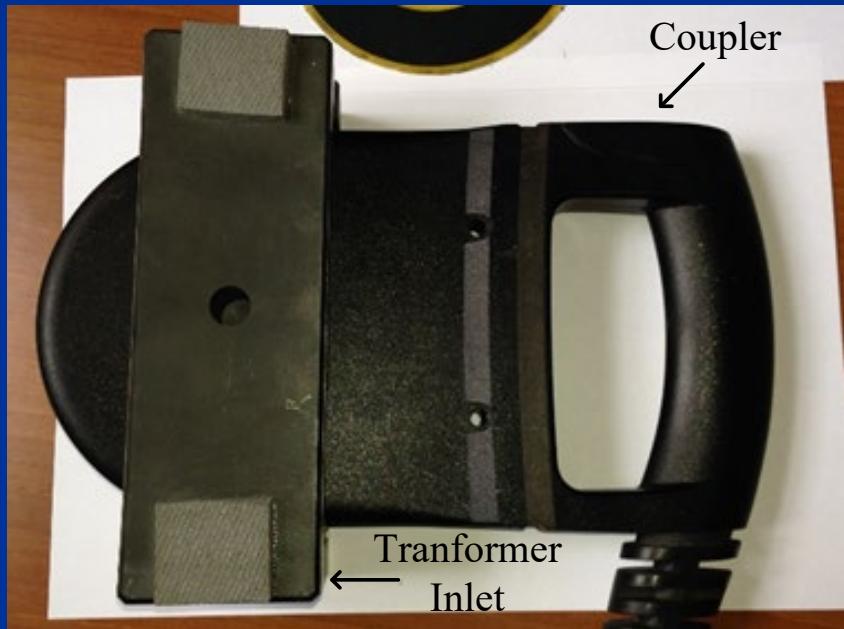


# Objectives

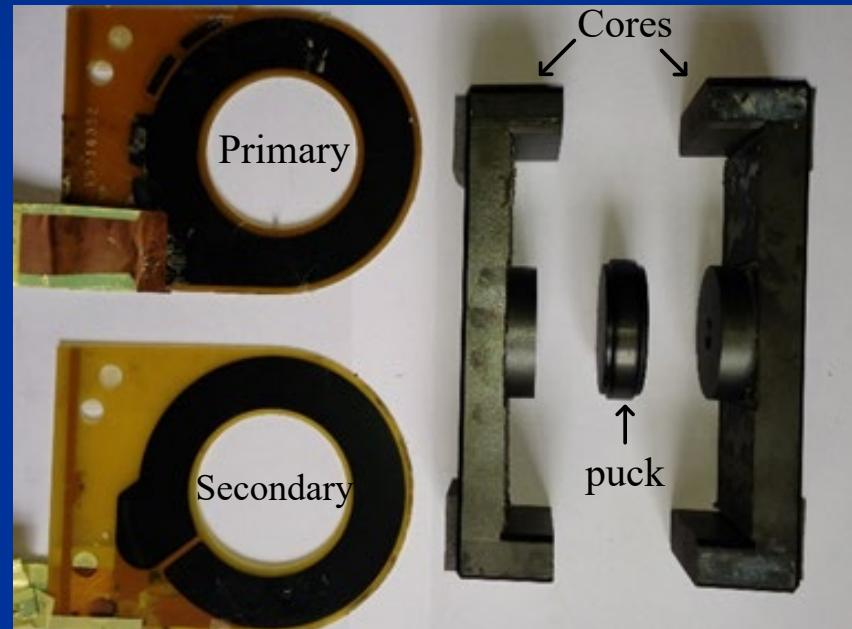
- Present three types of high-leakage transformers.
- Poor performance of open-circuit and short-circuit tests.
- Develop series-coupling tests to accurately extract resistive and inductive elements of transformer.
- Validate with FEA for prototypes.



# Inductive Charging for EVs



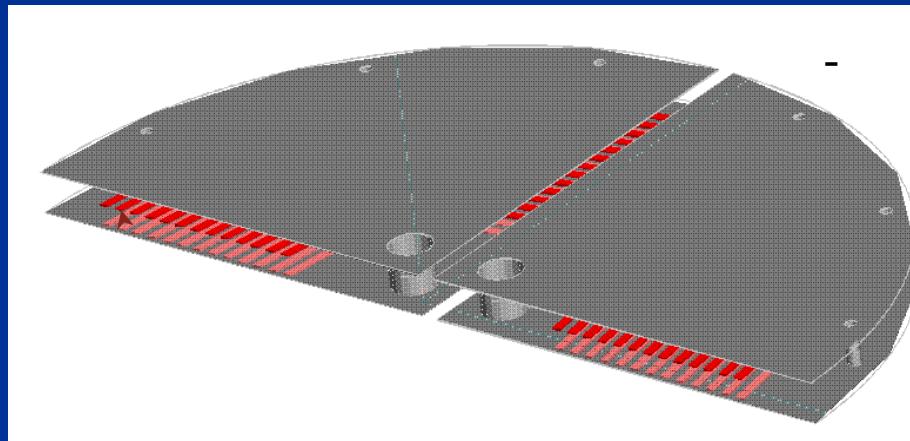
(a)



(b)



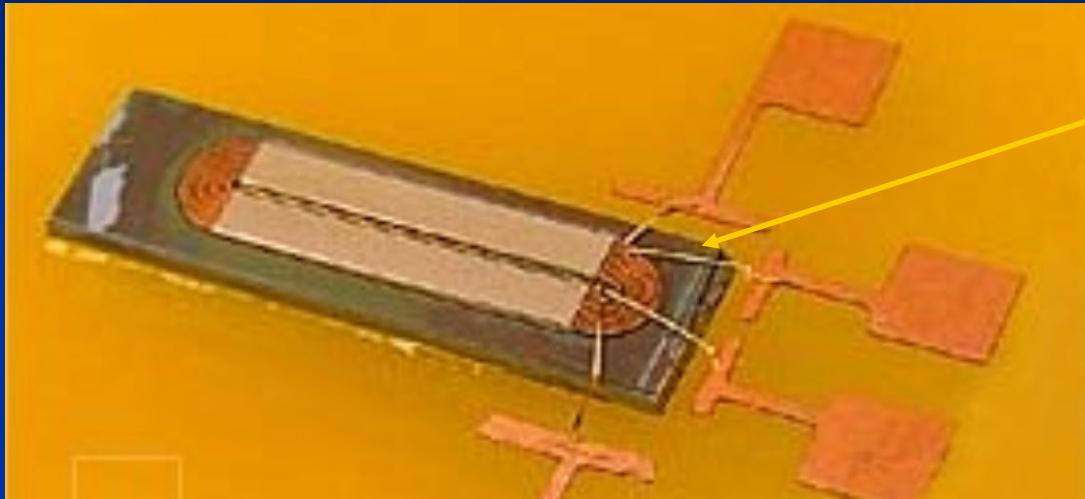
# PWB-Integrated Transformer



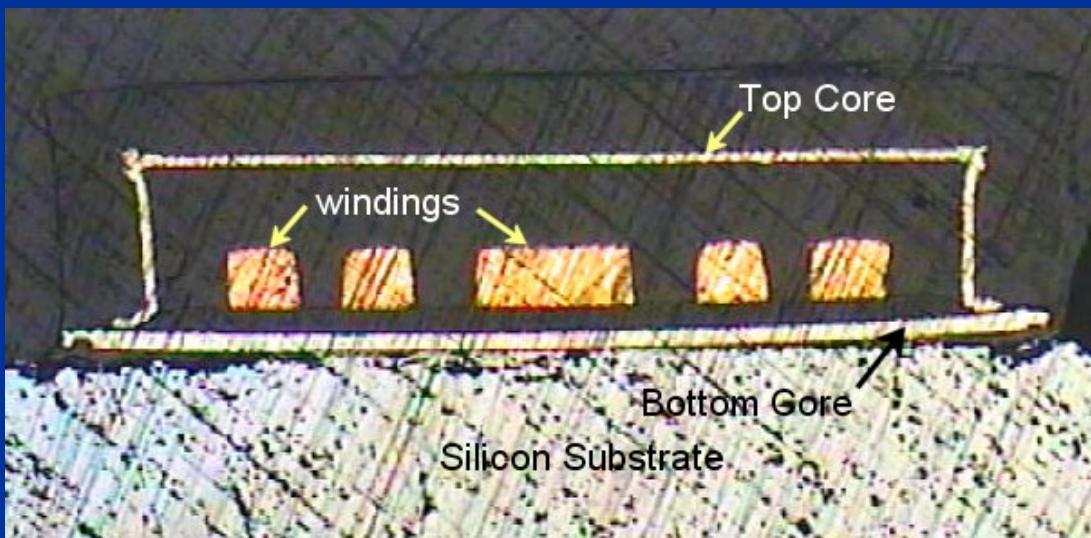
- 6 layer PWB
  - Windings on the four inner layers
  - Permalloy on the two outer layers
- Permalloy (80/20 nickel iron alloy)



# On-Chip Silicon-Integrated Transformer



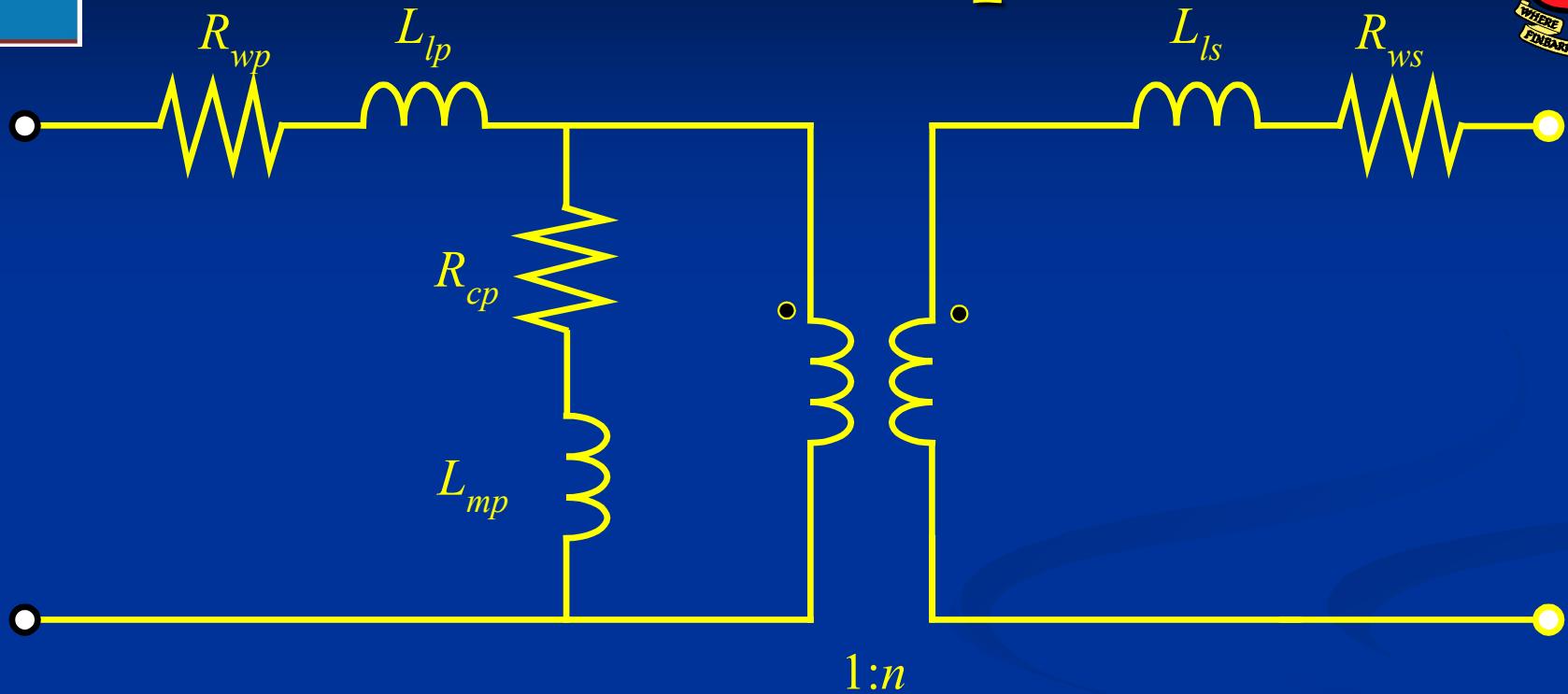
Very high-impedance  
wirebonds



- Transformer deposited onto silicon wafer
- 10  $\mu\text{m}$  thick nickel-iron alloy
- Race-track shaped copper winding
- Electroplated copper
- 4 or 6 turn primary
  - 45  $\mu\text{m}$  wide
- 1 turn secondary
  - 105  $\mu\text{m}$  wide



# Transformer Equiv. Cct



- Low magnetizing inductance
- High leakage inductances
- High copper and core resistances



$$Z_{p(SS)} = R_{p(SS)} + j\omega L_{p(SS)}$$

# Characterization Tests: Short Circuit



Short-circuit Impedance :  $Z_{p(SS)} = R_{p(SS)} + j\omega L_{p(SS)}$

$$R_{cp}^2 \frac{R_{ws}}{n^2} + R_{cp} \frac{R_{ws}^2}{n^4} + \omega^2 \left( L_{mp}^2 \frac{R_{ws}}{n^2} + R_{cp} \frac{L_{ls}^2}{n^4} \right)$$

$$\text{where } R_{p(SS)} = R_{wp} + \frac{\left( R_{cp} + \frac{R_{ws}}{n^2} \right)^2 + \omega^2 \left( L_{mp} + \frac{L_{ls}}{n^2} \right)^2}{\left( R_{cp}^2 \frac{R_{ws}}{n^2} + R_{cp} \frac{R_{ws}^2}{n^4} \right)}$$

- Complex equations, dependent on flux level.
- Can be simplified for well-coupled transformers.
- Distorted results due to parasitics and wirebonds.



# Open & Short Cct Tests Results for Silicon-Integrated Transformer:



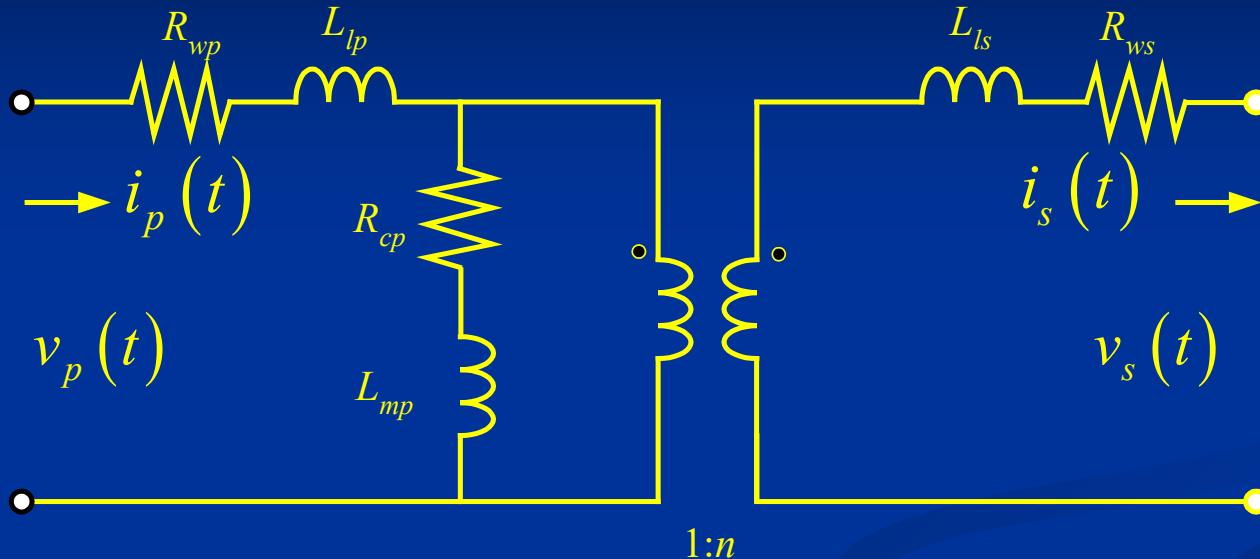
	$R_{wp}$	$L_{lp}$	$R_{cp}$	$L_{mp}$	$R_{ws}$	$L_{ls}$
	(Ω)	(nH)	(Ω)	(nH)	(Ω)	(nH)
FEA Average	0.560	13	0.297	418	0.057	6
Exp Std(2 test)	0.461	134	0.333	266	-0.135*	-4*

Poor performance by open and short-circuit tests.

\* Negative – distorted results due to secondary wire bond impedances.



# Series Coupling Tests: Back EMFs

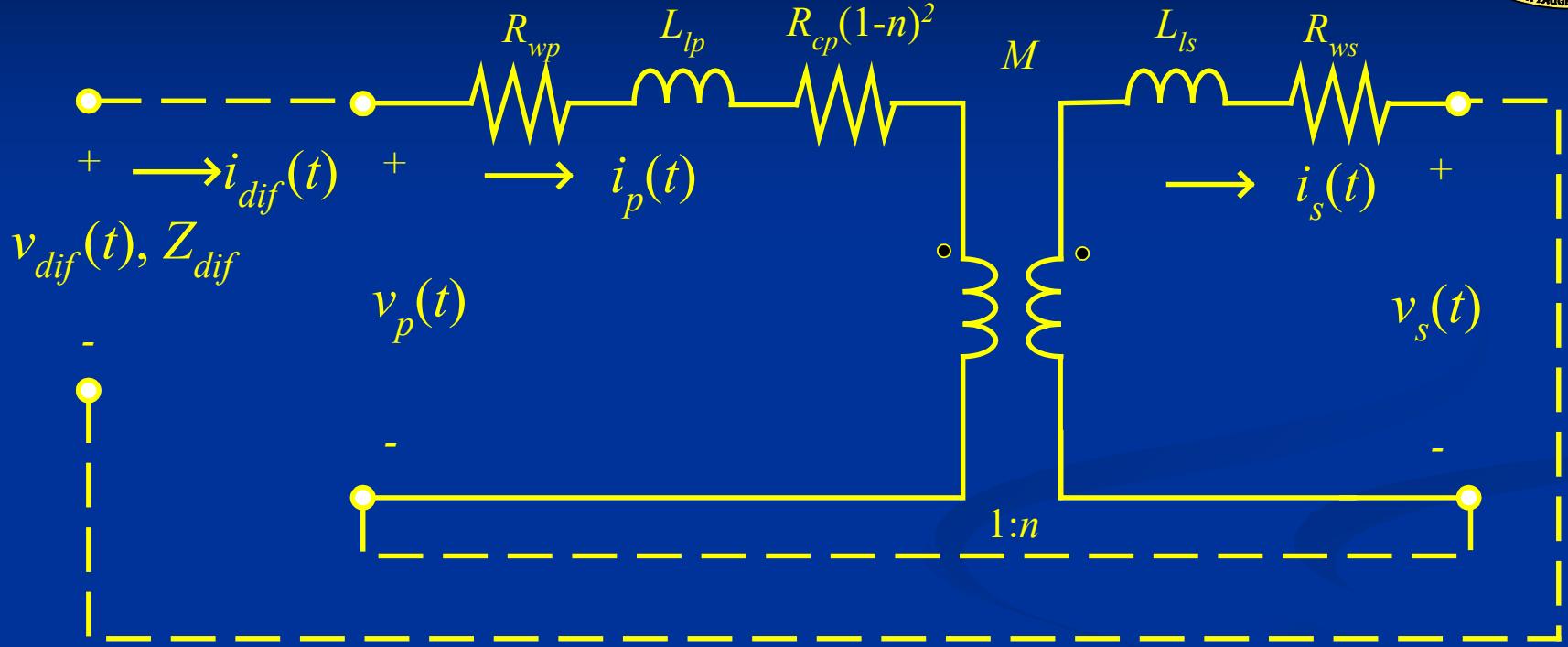


$$v_p(t) = (R_{wp} + R_{cp})i_p(t) - nR_{cp}i_s(t) + (L_{lp} + L_{mp}) \frac{di_p(t)}{dt} - nL_{mp} \frac{di_s(t)}{dt}$$

$$v_s(t) = -(R_{ws} + n^2 R_{cp})i_s(t) + nR_{cp}i_p(t) - (L_{ls} + n^2 L_{mp}) \frac{di_s(t)}{dt} + nL_{mp} \frac{di_p(t)}{dt}$$



# Differential Coupling - I

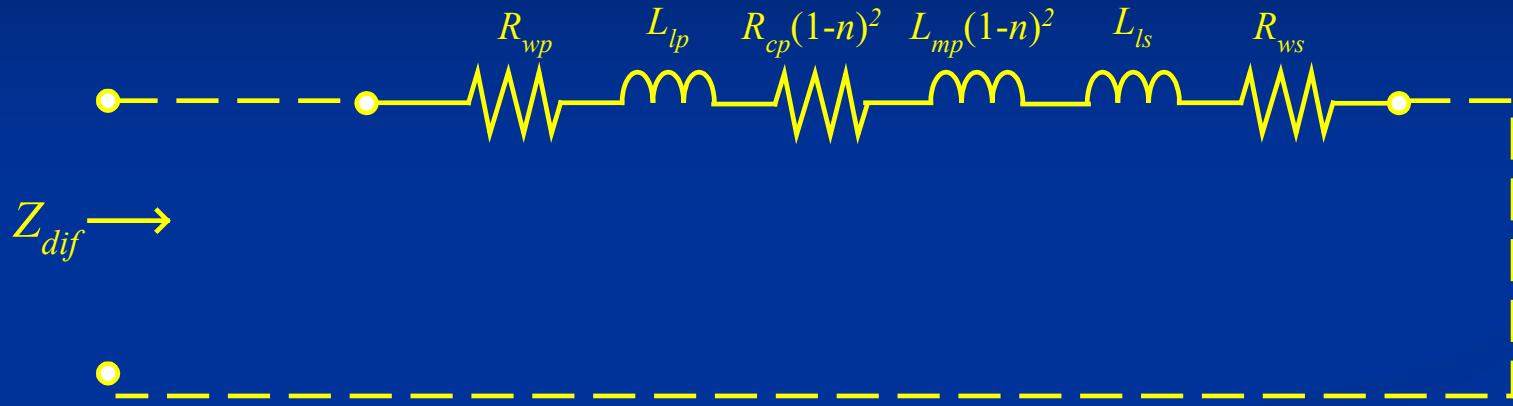


$$v_{dif}(t) = v_p(t) - v_s(t)$$

$$= \left[ R_{wp} + R_{ws} + (1-n)^2 R_{cp} \right] i_{dif}(t) + \left[ L_{lp} + L_{ls} + (1-n)^2 L_{mp} \right] L_{p(OS)} \frac{di_{dif}(t)}{dt}$$



# Differential Coupling - II

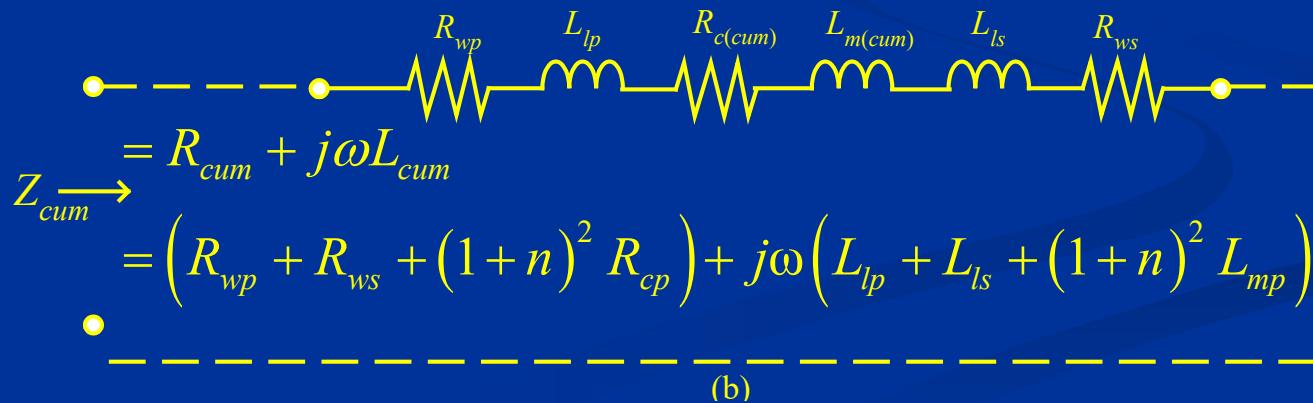
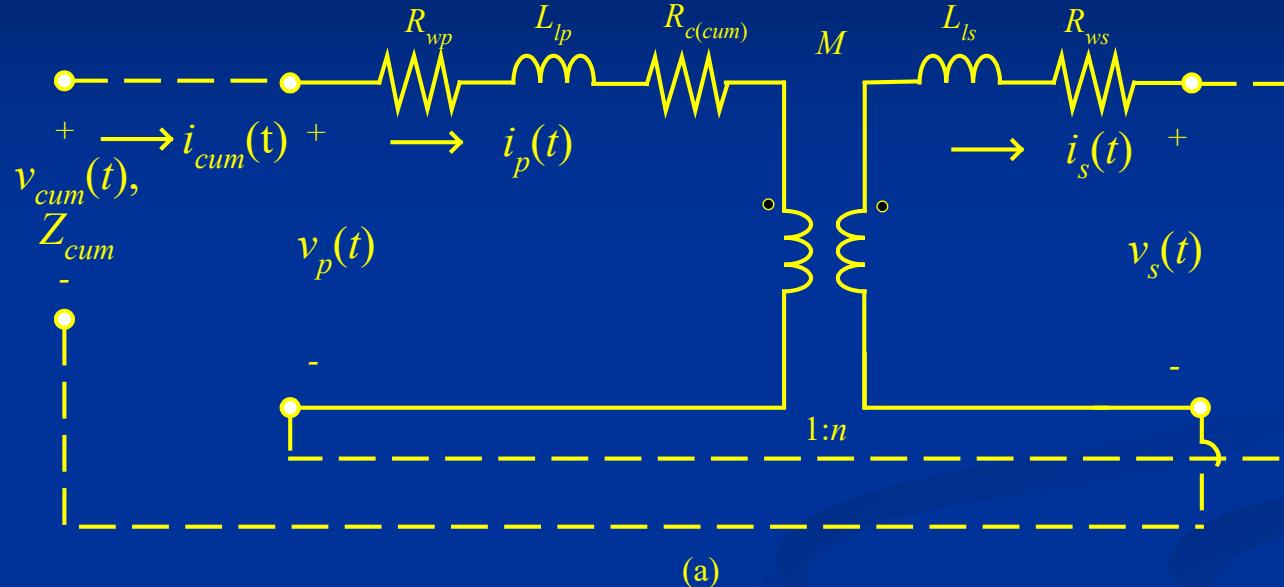


$$\begin{aligned}Z_{dif} &= R_{dif} + j\omega L_{dif} \\&= \left( R_{wp} + R_{ws} + (1-n)^2 R_{cp} \right) + j\omega \left( L_{lp} + L_{ls} + (1-n)^2 L_{mp} \right)\end{aligned}$$

Series elements only – addresses wire bond problem



# Cummulative Coupling





# Series-coupling Test Currents



- Uniform magnetizing flux and resultant core loss

$$B_m = \frac{L_{mp} I_{p(OS)}}{N_p A_c} = \frac{L_{ms} I_{s(OP)}}{N_s A_c} = \frac{L_{m(dif)} I_{dif}}{(N_p - N_s) A_c} = \frac{L_{m(cum)} I_{cum}}{(N_p + N_s) A_c}$$

$$\Rightarrow I_{p(OS)} = I_{s(OP)} n - I_{dif} (1 - n) = I_{cum} (1 + n)$$



# Test Currents and Measurements

<i>Test</i>	<i>Resistance</i>	<i>Inductance</i>	<i>Current</i>
$Z_{p(OS)}$	$R_{p(OS)} = R_{wp} + R_{cp}$	$L_{p(OS)} = L_{lp} + L_{mp}$	$I$
$Z_{s(OP)}$	$R_{s(OP)} = R_{ws} + R_{cp} \cdot n^2$	$L_{s(OP)} = L_{ls} + L_{mp} \cdot n^2$	$\frac{I}{n}$
$Z_{dif}$	$R_{dif} = R_{wp} + R_{ws} + (1 - n)^2 R_{cp}$	$L_{dif} = L_{lp} + L_{ls} + (1 - n)^2 L_{mp}$	$\frac{I}{(1 - n)}$
$Z_{cum}$	$R_{cum} = R_{wp} + R_{ws} + (1 + n)^2 R_{cp}$	$L_{cum} = L_{lp} + L_{ls} + (1 + n)^2 L_{mp}$	$\frac{I}{(1 + n)}$



# Core-loss Resistance and Magnetizing Inductance Formulae



<i>Test</i>	<i>Resistance</i>	<i>Inductance</i>
<i>Differential</i>	$R_{cp} = \frac{R_{p(OS)} + R_{s(OP)} - R_{dif}}{2n}$	$L_{mp} = \frac{L_{p(OS)} + L_{s(OP)} - L_{dif}}{2n}$
<i>Cumulative</i>	$R_{cp} = \frac{R_{cum} - R_{p(OS)} - R_{s(OP)}}{2n}$	$L_{mp} = \frac{L_{cum} - L_{p(OS)} - L_{s(OP)}}{2n}$
<i>Average</i>	$R_{cp} = \frac{R_{cum} - R_{dif}}{4n}$	$L_{mp} = \frac{L_{cum} - L_{dif}}{4n}$



# Test measurements for silicon-integrated transformer at 1 MHz

*including wire bonds.*



	$Z_{p(OS)}$	$Z_{p(SS)}$	$Z_{s(OP)}$	$Z_{s(SP)}$	$Z_{cum}$	$Z_{dif}$
$I$ (mA)	5.03	20.5	20	19.9	4.01	6.6
$R$ ( $\Omega$ )	0.970	1.273	0.215	0.242	1.318	1.088
$L$ (nH)	413	294	48	26	658	283



# Simulation results and hysteresis loss calculation *excluding* wire bonds.



	$Z_{p(OS)}$	$Z_{s(OP)}$	$Z_{cum}$	$Z_{dif}$
$I$ (mA)	5.03	20	4.01	6.6
$L$ (nH) - FEA	431	32	675	257
$R$ ( $\Omega$ ) - FEA	0.604	0.060	0.684	0.644
$R$ ( $\Omega$ ) - hysteresis	0.253	0.016	0.396	0.143
$R$ ( $\Omega$ ) - total	0.857	0.076	1.080	0.787



# Parameter values for silicon-integrated transformer.



	$R_{wp}$	$L_{lp}$	$R_{cp}$	$L_{mp}$	$R_{ws}$	$L_{ls}$
	(Ω)	(nH)	(Ω)	(nH)	(Ω)	(nH)
FEA Cumulative	0.562	7	0.295	424	0.057	6
FEA Differential	0.558	19	0.299	412	0.057	6
FEA Average	0.560	13	0.297	418	0.057	6
<i>Exp Std(2 test)</i>	0.461	134	0.333	266	-0.135*	-4*
<b>Exp-SC Cumulative</b>	<b>0.529</b>	<b>6</b>	<b>0.266</b>	<b>394</b>	<b>0.023</b>	<b>10</b>
<b>Exp-SC Differential</b>	<b>0.601</b>	<b>44</b>	<b>0.194</b>	<b>356</b>	<b>0.028</b>	<b>13</b>
<b>Exp-SC Average</b>	<b>0.565</b>	<b>25</b>	<b>0.230</b>	<b>375</b>	<b>0.026</b>	<b>12</b>



# Summary/Conclusions

- Developed series-coupling tests to characterize high-leakage transformers.
- Series-coupling tests performed well for characterizing loosely-coupled devices.
- Far better performance of series-coupling tests compared to standard open and short-cct tests.
- *Caveats: Pay attention to flux levels and external cabling.*