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Attaining Arbitrary Load Independent Voltage Gain and Minimizing Inverter VA Rating in S(C)-S(C) Compensated Wireless Power Transfer Links

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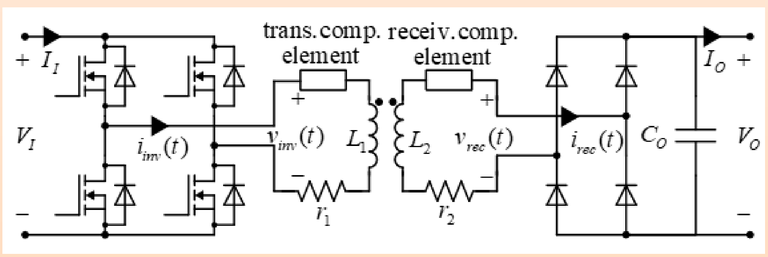
Abstract

It is well known that fixed-frequency constant-coupling series(capacitor)-series(capacitor) (S(C)-S(C)) compensated inductive wireless power transfer links (IWPTL) may be designed to operate with load-independent voltage gain (LIVG) within bounds dictated by parameters of the loosely coupled transformer (LCT). Lately, it has been shown that these bounds may be extended by employing series(inductor)-series(capacitor) (S(L)-S(C)) or series(capacitor)-series(inductor) (S(C)-S(L)) compensation networks, allowing attaining arbitrary LIVG at the expense of utilizing full-rating inductors as compensation elements. This work proposes a design method allowing to simultaneously attain arbitrary LIVG with S(C)-S(C) compensated IWPTL and minimize inverter VA rating. The revealed methodology is validated in PSIM simulation and experiments.

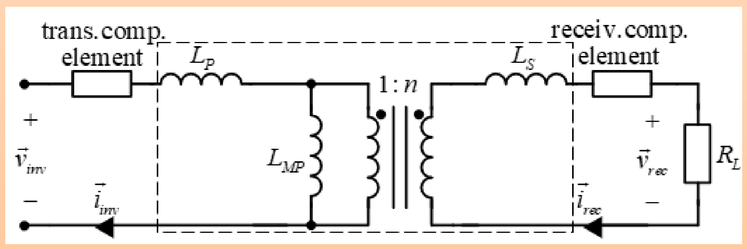
1. FHA Model



Generalized S(X)-S(X) compensated IWPTL.

$$L_P=\left(1-\frac{k}{\alpha}\right)L_1,\ L_S=(1-\alpha k)L_2,\ n=\alpha\sqrt{\frac{L_2}{L_1}},$$

$$L_{MP}=\frac{k}{\alpha}L_1>0\rightarrow\alpha>0.$$



Generalized FHA model of S(X)-S(X) compensated IWPTL.

$$|\vec{v}_{inv}|=\frac{4}{\pi}V_I,\quad |\vec{v}_{rec}|=\frac{4}{\pi}V_O,\quad R_L=\frac{8}{\pi^2}\frac{V_O^2}{P_O}.$$

Desired voltage gain: $G_v=\dfrac{|\vec{v}_{rec}|}{|\vec{v}_{inv}|}=\dfrac{V_O}{V_I}=n=\alpha\sqrt{\dfrac{L_2}{L_1}}$

2. Inductor Compensation for Extended LIVG Range

Generalized compensation capacitors are found as:

$$C_{cP}=\frac{1}{\omega^2 L_P}=\frac{1}{\omega^2\left(1-\frac{k}{\alpha}\right)L_1},\ C_{cS}=\frac{1}{\omega^2 L_S}=\frac{1}{\omega^2(1-\alpha k)L_2}.$$

However, for certain values of G_V, one of the capacitors is negative and may be replaced by an inductor, attaining any arbitrary LIVG according to:

$$\begin{cases} S(L)-S(C), & G_V<k\sqrt{\left(L_2L_1^{-1}\right)^*} \\ N-S(C), & G_V=k\sqrt{\left(L_2L_1^{-1}\right)^*} \\ S(C)-S(C), & k\sqrt{\left(L_2L_1^{-1}\right)^*}\le G_V\le\frac{1}{k}\sqrt{\left(L_2L_1^{-1}\right)^*} \\ S(C)-N, & G_V=\frac{1}{k}\sqrt{\left(L_2L_1^{-1}\right)^*} \\ S(C)-S(L), & G_V>\frac{1}{k}\sqrt{\left(L_2L_1^{-1}\right)^*} \end{cases}.$$

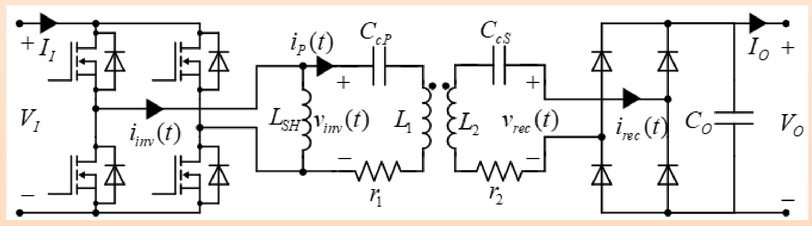
In the S(L)-S(C) case, the resulting inductor is sized as

$$L_{cP}=-\left(1-\frac{k}{\alpha}\right)L_1,$$

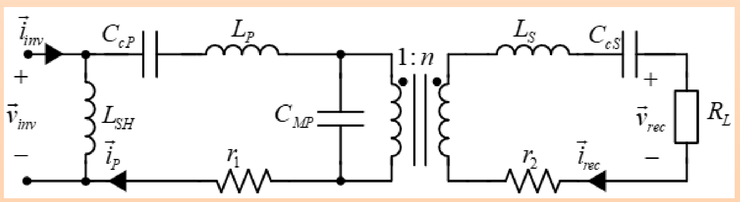
while S(C)-S(L) case requires

$$L_{cS}=-(1-\alpha k)L_2.$$

3. Proposed S(C)-S(C) Design for Arbitrary LIVG



Proposed S(C)-S(C) compensated topology.



FHA model of proposed S(C)-S(C) compensated topology.

Allowing for negative α, L_{MP} turns negative, replaced by equivalent capacitance:

$$C_{MP}=-\frac{1}{\omega^2 L_{MP}}=-\frac{\alpha}{\omega^2 k L_1}.$$

Consequentially, any arbitrary LIVG can be attained by capacitive compensation alone such that

$$G_V=\frac{|\vec{v}_{inv}|}{|\vec{v}_{rec}|}=\frac{V_O}{V_I}=\left|\alpha\sqrt{\frac{L_2}{L_1}}\right|.$$

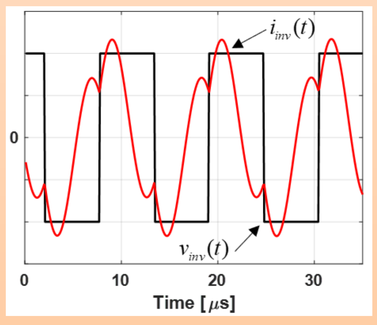
Note that if the circuit is operated L_{SH}, the inverter operates in capacitive region which leads to large reactive currents and lack of ZVS!

4. Reducing Inverter Current and Achieving ZVS

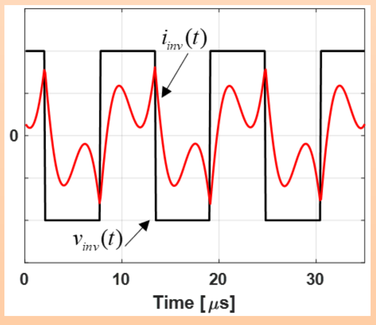
In order to reduce reactive currents, inductor L_{SH} value resulting in zero phase angle may be calculated as

$$L_{SH}=-\frac{k}{\alpha}L_1.$$

In practice, a slightly lower value is chosen, in order to operate in lightly inductive region, imposing ZVS. The difference in behavior (inductive vs capacitive) and inverter current amplitude are demonstrated schematically below.



Without L_{SH} – capacitive.



With L_{SH} – slightly inductive.

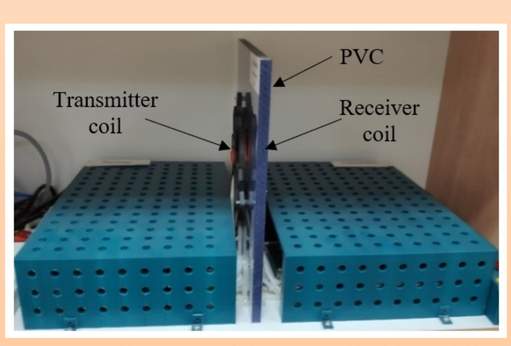
$$|\vec{i}_{inv}|\approx\sqrt{\left(\frac{\pi}{2}\frac{P_O}{V_I}\right)^2+\left(\frac{4}{\pi}\omega C_{MP}V_O\right)^2}\quad>\quad\frac{\pi}{2}\frac{P_O}{V_I}\approx|\vec{i}_{inv}|$$

From the two figures it is evident that the shunt inductor imposes ZVS while reducing reactive currents (and therefore, current RMS values).

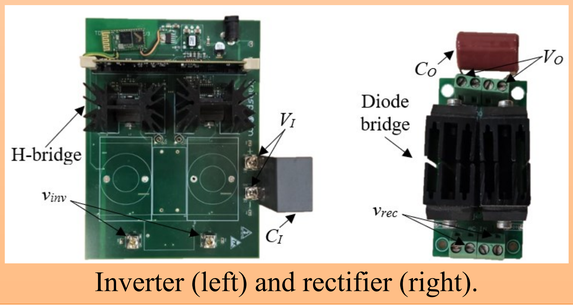
5. Example System

SYSTEM PARAMETERS

Parameter	Value	Units
V_I	200	V
V_O	48	V
L_1, L_2	180	µH
ω	2π·88	krad/s
C_{cP}	8	nF
C_{cS}	17	nF
L_{SH}	210	µH
k	0.3	--

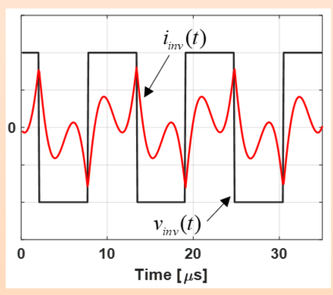


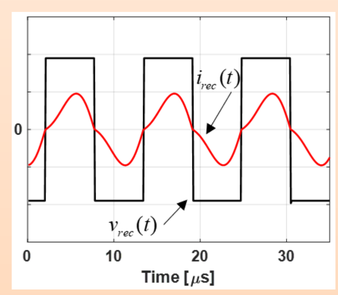
Example IWPT coil setup – k is controlled by adding spacers.



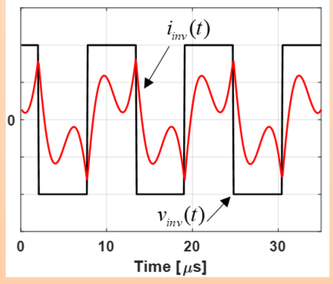
Inverter (left) and rectifier (right).

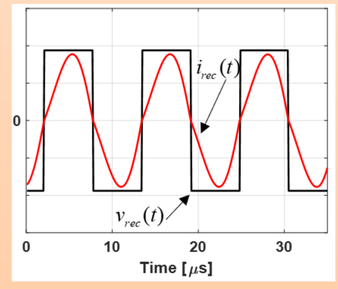
6. Results



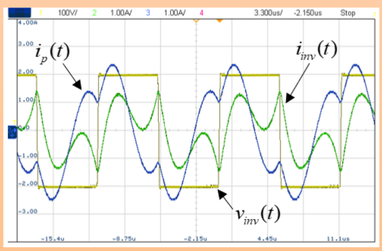


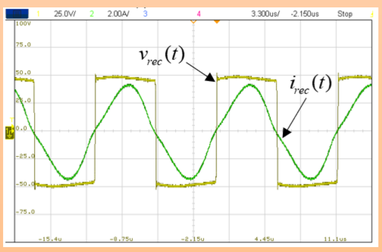
Simulated inverter and rectifier side waveforms for P_o=50W.





Simulated inverter and rectifier side waveforms for P_o=100W.





Experimental inverter and rectifier side waveforms for P_o=100W.

(Simulated A/div and V/div are identical to the experiment)