Optimize Wireless Power Transfer Link Efficiency

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In the first part of this series we measured the inductance of the transmitting and receiving coils, their respective Q's near the resonant frequency, and the coupling coefficient of the two inductors, "k." We showed that the Q, and associated series resistance, RS are significantly impacted by proximity effects of the two coils. In this article, we compare the benefits of simulating the wireless power linkage using an RF simulator, such as the Agilent's ADS with a typical SPICE simulator. There are many benefits to using ADS for an application such as a resonant converter or resonant link, and, in this article, we'll focus on three benefits in particular.

The three benefits to ADS we focus on in this article are:

- Simulation speed
- Parametric DC sweep simulations
- Post processing functions

A simplified ADS model of the resonant link allows simulation of the link and display of the various waveforms in the link. The ADS platform offers many types of simulators allowing analysis in the frequency, time, modulation, and algorithmic domains. These include Harmonic Balance, Envelope, Momentum and SPICE to name a few. Each of these serves a different purpose and offers a different set of capabilities. In this case, we will use the Harmonic Balance (HB) simulator, which is a Fourier based solver to perform a fast, steady state simulation of the resonant link. The simulation produces a frequency domain solution, while also allowing the results to be transformed into the time domain. This is analogous to the transformation of a transient domain SPICE model to a state space average SPICE model. Since the Harmonic Balance engine is a large signal simulator, the simulation results include non-linear, as well as small signal effects. The Harmonic Balance engine simulates much faster than the transient time domain solver such those found in SPICE.

Harmonic Balance (HB) is a large signal frequency domain analysis primarily used to assess non-linear effects such as distortion and compression in RF systems. The HB engine also includes the transformation of frequency domain to time domain. In this way, the steady state solution of a nonlinear circuit can be solved quickly and the answers can be displayed in the frequency domain (spectrum plots) or in time domain. A major benefit of this simulation engine is that it performs sweeps within an analysis For example, we can look at the output voltage of the rectified resonant link (huh??) while sweeping the coupling of the transmit and receive coils. For more detailed information on HB, visit:http://cp.literature.agilent.com/litweb/pdf/ads2008/cktsimhb/ads2008/Harmonic_Balance_Basics.html

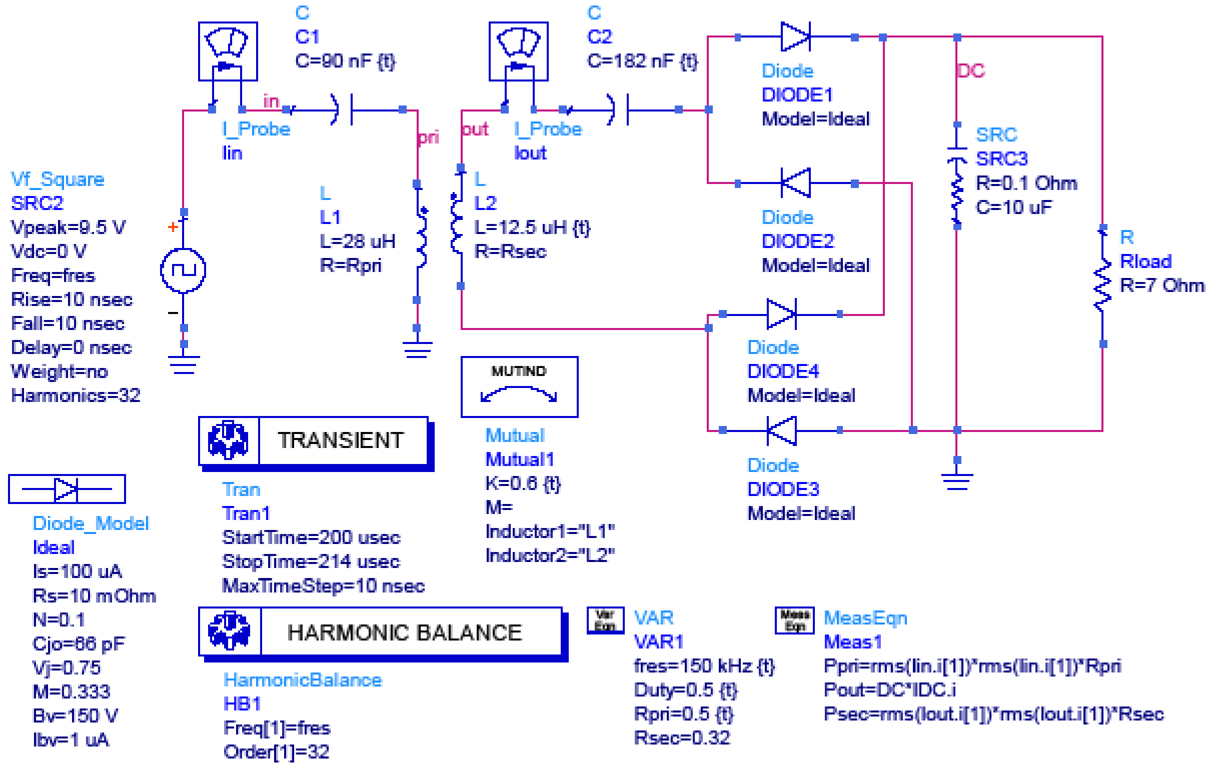


Figure 1 – Simplified ADS schematic of resonant link. Diodes are idealized with very low Vf. Model parameters are shown along with other simulation parameters.

The ADS model is shown in Figure 1 and includes a variable frequency square wave at the input to simulate the “H” Bridge and four ideal diodes to simulate the synchronous output rectifiers. The ideal diodes are much simpler to model than the synchronous rectifiers and, for our purposes, are more than adequate.

The “smoothness” of the HB waveforms is a function of the number of harmonics that are evaluated. The tradeoff is the larger the number of harmonics, the longer the simulation computation time and the more computing power that will be required.

A comparison of the waveform results from Harmonic Balance and transient simulations, along with the simulation times, are shown in Figure 2.

The ADS software allows a selection of the number of harmonics to include in the HB simulation, as well as the maximum timestep for the transient simulation. While we could use any SPICE simulator for the transient simulation, we used the ADS SPICE engine to obtain a fair comparison.

A comparison of the secondary current and output DC voltage are shown in Figure 2.

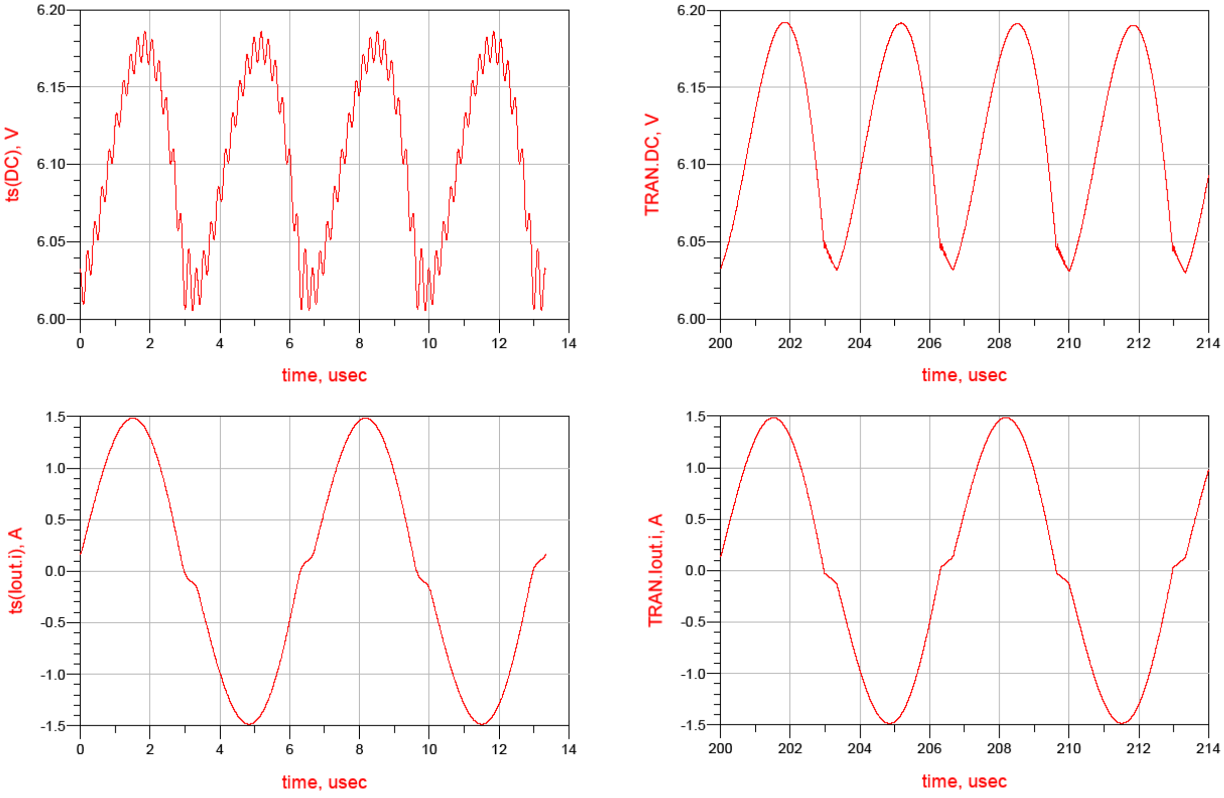
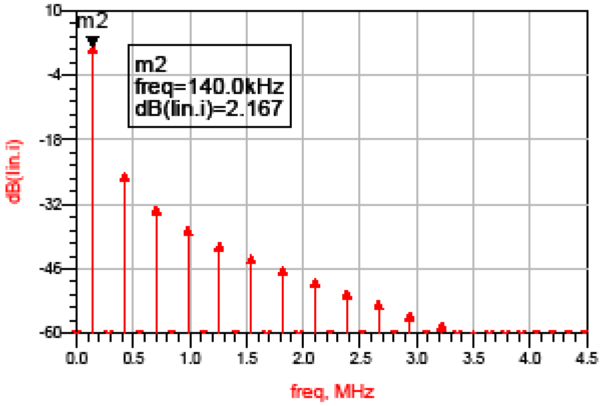


Figure 2 HB simulation results (left) and SPICE simulation results (right). The HB simulation requires 2.26 seconds to simulate while the transient simulation requires 39.66 seconds. The upper traces are the DC output voltage

The "fuzzy" DC waveform in the HB simulation results is due to the 32 harmonic limit that we arbitrarily set. More harmonics would result in a sharper waveform at the expense of longer simulation times. For comparison purposes, 48 harmonics required 5.96 seconds.

While it is certainly a benefit to simulate large signal steady state solutions quickly, this is only one benefit of the HB simulation engine.



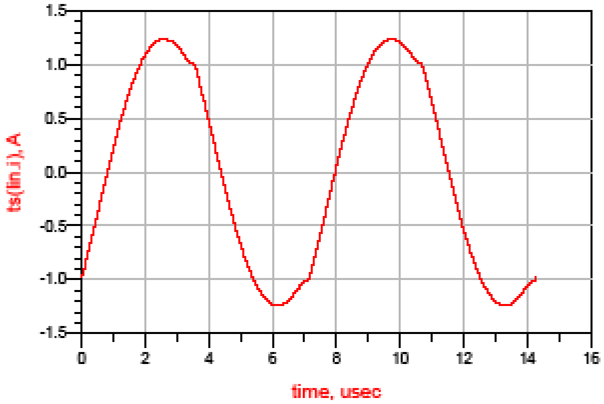


Figure 3 – The HB simulator is a Fourier simulator. Results can be displayed in native Fourier as a spectrum (left) or transformed into time domain (right). These results are for the transmit coil current.

The spectrum nature of the results allows the determination of frequency dependent terms, such as skin effect in the coil wires.

A second and possibly even more significant benefit is the ability to perform DC parametric sweeps within this resonant simulation. This is not easy to perform using a SPICE simulator. For example,

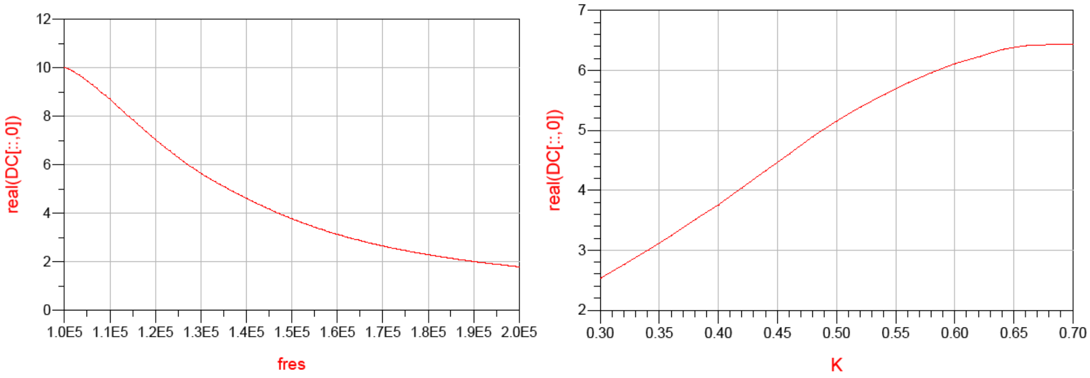


Figure 4 – The sweep capability allows fast simulation of the DC output voltage as a function of the square wave frequency or as a function of coil coupling (K) as two examples.

Any parameter can be swept in the HB simulation, including component parameters, such a resistance, inductance and coupling or simulation variables, such as frequency or input voltage.

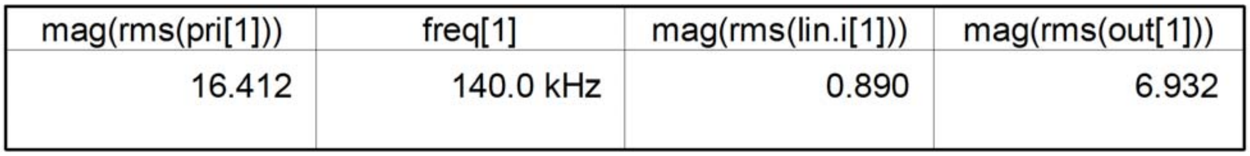
The third major benefit of simulating in ADS is the post processing power, which exceeds the capabilities of those found in general SPICE simulators.

Since the HB simulator is Fourier based, any waveform can be evaluated at any harmonic, including DC (harmonic 0) and mathematical functions can easily be represented. For example, Figure 5 shows the ratio of the receive coil to the transmit coil at the fundamental frequency.

mag(Iout.i[1]/Iin.i[1])
1.24554

Figure 5 – ratio of receive to transmit fundamental current

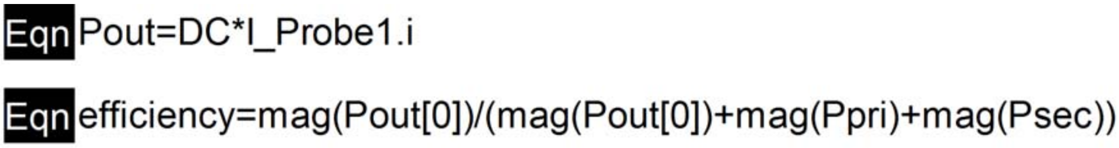
These results can also easily be tabulated. Figure 6 shows the transmit coil voltage, the fundamental frequency, fundamental transmit RMS current and RMS receive coil voltage.



mag(rms(pri[1]))	freq[1]	mag(rms(lin.i[1]))	mag(rms(out[1]))
16.412	140.0 kHz	0.890	6.932

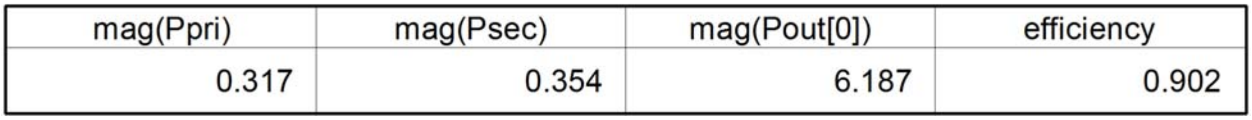
Figure 6 – Ratio transmit fundamental voltage, fundamental frequency, fundamental transmit current and fundamental receive coil voltage.

The transmit and receive coil losses can be calculated as can the overall efficiency, which you will note is very close to the value predicted in the prior article.



Eqn Pout=DC*I_Probe1.i

Eqn efficiency=mag(Pout[0])/(mag(Pout[0])+mag(Ppri)+mag(Psec))



mag(Ppri)	mag(Psec)	mag(Pout[0])	efficiency
0.317	0.354	6.187	0.902

Figure 7 – calculating efficiency from the coil losses.

Using the values of 28.3uH and 12.8uH with the respective Q and k for a 4mm separation results in a calculated efficiency of

$$k := .6 \quad Q := \sqrt{55 \cdot 28} \qquad \eta opt := \frac{(k \cdot Q)^2}{\left[1 + \sqrt{1 + (k \cdot Q)^2}\right]^2}$$

$$\eta opt = 0.919$$

These are just a few of the benefits of simulating wireless power using the harmonic balance simulation. There are many additional benefits, such as the Optimizer Cockpit, which allows the automatic adjustment of parameters in order to optimize a particular result, such as efficiency.

Our simulation model was purposely kept simple, for the purpose of clearly showing the simplicity of the HB engine. It is possible to add additional characteristics, such as the Q's of the coils and coupling as a function of the distance between the coils. This can be accomplished using a 3D EM simulator, such as Agilent EMPro. The results from the EM simulator can then be imported into and simulated within ADS.