In Search for a Better Primary – Part 1

Gerry Reynolds
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Background:

I have an 8x36 inch coil that has worked very well until recently. Last fall I was able to get 86 inch arcs from it using a 15KV 120ma power source and a thumb tack on the 8x32 inch toroid. This summer, I lowered the toroid an inch and re-surfaced and gapped the SRSG electrodes. Much to my surprise, I was only able to get 72 inch arcs and when the thumb tack on the toroid was removed, racing arcs occurred. The toroid size seems appropriate for a coil this size and power, and the TC tuning was checked at both low and full power settings. I suspect when the electrodes on the SRSG were gapped closer, more power went into the secondary pushing it over the edge with regard to racing arcs. It has also been recommended for a coil of my size and power that the clearance between the primary and secondary be 1.5 inches and the bottom turn of the secondary should be 2 inches above the primary plane. My current setup has only 1 inch of clearance and the secondary is only 1 inch above the primary plane so over coupling seems to be a reasonable suspect.

There has been much said within the TCML group about over coupled Tesla Coils having problems with racing arcs up and down the secondary coil. Various procedures have been proposed to adjust the coupling between the primary and secondary coils for optimum performance by raising or lowering the secondary with respect to the primary. Some advocate lowering the secondary (to increase the coupling) until maximum spark length occurs. Others advocate increasing the coupling until racing arcs occur and then back off on the coupling. Within the group, there has also been discussion about faster energy rise time (ERT) at the toroid being more conducive for streamer formation. It seems like a higher ERT requires a higher overall coupling and may be at odds with the need to prevent racing arcs. Consequently, the search began for ways to increase the overall coupling without inducing racing arcs.

Method:

I used JavaTC located at http://www.classictesla.com/java/javatc.html to experiment with various primary geometries since the coupling calculations are reported to be very accurate. On geometries that looked promising, the distributed coupling was also calculated using a procedure described below and compared to the distributed coupling on my current 8 inch coil. I assumed that one could get a higher overall coupling without racing arcs if the coupling was distributed more evenly across the secondary. This *assumption* was the result of a thought experiment regarding initial voltage profiles across the secondary resulting from a contrived case of coupling distribution. More details on this later. This *assumption* certainly needs verification (hopefully by some in the group willing to try). I will attempt verification on my next coil and try to determine if over coupling is the culprit on my existing coil.

The Experiments:

First, I wanted to find a geometry that would give the best overall coupling, yet keep the primary below the bottom turn of the secondary. Using a flat primary geometry kept in the same plane as my 8 inch coil (1 inch below the secondary bottom turn), I clumped all the turns together tightly packed (150 mil centers) and varied the inner diameter clearance from the coil. I was looking for a sweet spot where as the diameter was increased, the coupling to the upper turns would increase as the coupling to the lower turns decreased. Unfortunately, the coupling to the lower turns decreased faster than the coupling to the upper turns increased so the overall coupling monotonically decreased as the inner diameter increased.

I tried this packed geometry with a helical primary as well. Again the overall coupling monotonically decreased as the inner diameter increased. A helical primary at or below the plane of the bottom turn of the secondary also had worst overall coupling than a flat primary at the same position. The only way I could make a helical primary have better coupling than a flat primary was to raise it to where part of the helix was above the bottom turn of the secondary.

The next experiment was to see what effect primary winding pitch had on the overall coupling. Again, I used a flat primary positioned 1 inch below the bottom of the secondary. In all cases, as the pitch was varied, JavaTC was rerun with AUTO TUNE so the number of turns represented a correctly tuned primary. The results were interesting and showed there IS a sweet spot where a certain pitch will yield the best overall coupling:

5 Inch Inner Radius:

Outer Radius	Number of Turns	K
6.7	11.5	0.117
7.4	11.8	0.122
8.6	12.0	0.127
9.8	12.0	0.129
11.0	12.0	0.130
12.1	11.9	0.130
13.2	11.8	0.129
14.3	11.6	0.128

5.5 Inch Inner Radius:

Outer Radius	Number of Turns	K
7.1	10.8	0.113
8.3	11.3	0.120
9.5	11.4	0.124
10.7	11.5	0.125
11.8	11.4	0.126
12.9	11.4	0.126
14.0	11.3	0.125

With the pitch too small, the coupling is mostly into the lower turns and with the pitch too large, the coupling into the lower turns drops faster than the coupling into the upper turns increases.

The next set of experiments seems to get to the heart of a possible improvement. I did two cases both using ¼ inch primary tubing and ½ inch winding pitch (this turned out to be an optimum pitch from the above pitch experiment). One case was with the flat primary at the same position as my 8 inch coil so I would have something to compare to. The other was with the primary ½ inch above the bottom secondary turn. I chose ½ inch above the secondary base so I wouldn't have to move my strike rail. For each set of conditions, I modeled the entire coil in JavaTC and did an AUTO TUNE to get the correct number of primary turns and the overall coupling. Next, I removed the top load, corona ring, and strike rail from the geometry, subdivided the secondary into nine 4 inch segments, and modeled one of the segments. I then ran JavaTC *without* auto tuning so the primary would stay the same and I could extract the coupling into that segment of the secondary. This was done for each of the nine segments making up the coil. The following are the results:

Primary located 1 inch below the secondary base:

Inner R	5.0	5.5	6.0	6.5	7.0
Outer R	**11.0**	**11.2**	**11.5**	**11.8**	**12.1**
# Turns	**12.0**	**11.5**	**11.0**	**10.6**	**10.1**
Ktotal	0.130	0.126	0.121	0.117	0.113
K1	0.264	0.247	0.230	0.215	0.200
K2	0.121	0.119	0.117	0.114	0.111
K3	0.058	0.058	0.058	0.058	0.058
K4	0.030	0.031	0.031	0.032	0.032
K5	0.017	0.018	0.018	0.019	0.019
K6	0.011	0.011	0.011	0.012	0.012
K7	0.007	0.007	0.007	0.008	0.008
K8	0.005	0.005	0.005	0.005	0.006
K9	0.003	0.004	0.004	0.004	0.004

Primary located ½ inch above the secondary base:

Inner R	5.0	5.5	6.0	6.5	7.0
Outer R	**11.0**	**11.2**	**11.5**	**11.8**	**12.1**
# Turns	**12.0**	**11.5**	**11.0**	**10.6**	**10.2**
Ktotal	0.216	0.158	0.150	0.143	0.137
K1	0.332	0.301	0.275	0.251	0.230
K2	0.163	0.158	0.152	0.147	0.141
K3	0.076	0.075	0.075	0.075	0.074
K4	0.038	0.039	0.039	0.040	0.040
K5	0.021	0.022	0.022	0.023	0.023
K6	0.013	0.013	0.013	0.014	0.014
K7	0.008	0.008	0.009	0.009	0.009
K8	0.006	0.006	0.006	0.006	0.006
K9	0.004	0.004	0.004	0.004	0.004

Note: in the two tables above, Ktotal is the overall coupling and K1 is the coupling into the bottom 4 inches of the secondary. Likewise, K9 is the coupling into the upper 4 inches of the secondary. The number of turns is what is required for a tuned primary and the pitch of the primary windings is a constant ½ inch through out.

In both cases, the overall coupling and the coupling into the lower turns is decreased as the inner turn radius is increased. Likewise, the coupling into the upper turns is increased as the inner turn radius is increased. The overall coupling is also increased as one raises the primary as expected.

If we take my 8 inch coil with its present geometry (primary is 1 inch below the secondary base and the inner radius at 5 inches), the overall coupling is 0.130 and the coupling into the bottom 4 inches of the coil is 0.264. This coil seems to be on the edge of producing racing arcs (yet to be proven of course) so the coupling of 0.264 will be used for comparison. Many often reduce the coupling to fix such problems by raising the secondary which lowers the coupling into the lower turns but also lowers the overall coupling. If one raises the primary to the ½ inch above the secondary base (for example) and increases the radius of the inner turn, one can get to the same 0.264 coupling to the bottom turns with a higher overall coupling. For this example, this would occur with an inner radius between 6 and 6.5 inches giving an overall coupling between 0.143 and 0.150. If the above *assumption* is correct, one may be able to eliminate coupling induced racing arcs and still increase the overall coupling.

The Assumption:

First, the maximum $d\Phi/dt$ occurs at the moment of the spark gap firing when the maximum voltage per turn in the primary occurs. If we have the per turn distribution of K and assume that the distributed capacitance per turn is zero, one can easily compute the volts induced on each turn ($Vp/Np * kn$, where kn is the k for that secondary turn) at the moment of firing. The voltage at the top (with no capacitance at the top) will be the sum of all the induced voltages of each secondary turn. As one moves from the secondary base to the top, the voltage monotonically increases. But what if we add the distributed capacitances back in?? The voltage on each little capacitance can't change instantaneously. Current need to flow into the capacitance to get the voltage charged up. If we contrive a coupling distribution profile where say the bottom 4 inches of the coil has its normal coupling and all the other portions of the coil have zero coupling, one can see that at the moment of SG firing (before any current flows in the secondary) all the voltages on each turn will be zero and the top voltage will be zero. Since there is some coupling into the bottom turns there is some current generated slightly after firing to charge up its distributed capacitance. There is no current generated shortly after firing to charge up the distributed capacitance in the region where the coupling is zero. This results in a non monotonic distribution of voltages across the coil. There is a voltage *bump* generated in the lower portion of the secondary that propagates to the top over time (sorta like a transmission line). If this thought experiment is correct, the greater the gradient of coupling is across the length of the secondary, the greater the voltage gradient could be.

Possible Conclusions:

1. There is a limit on how high the overall coupling can be if the primary is constrained to be below the bottom turn of the secondary.
2. Given the above constraint, a flat primary is superior to a helical primary for overall coupling.
3. A flat primary with a larger outer diameter will give better coupling into the upper regions of the secondary.
4. There seems to be an optimum spacing between primary turns on a flat primary to give the best overall coupling.
5. Raising the secondary may not be the only way to fix coupling induced racing arcs. Increasing the inner turn radius of the primary may be an alternative that allows better overall coupling.
6. A slightly larger H/D ratio of the secondary may be good compensation for raising the primary above the bottom turn of the secondary to avoid primary hits.