A Search for a Better Primary – Part 2

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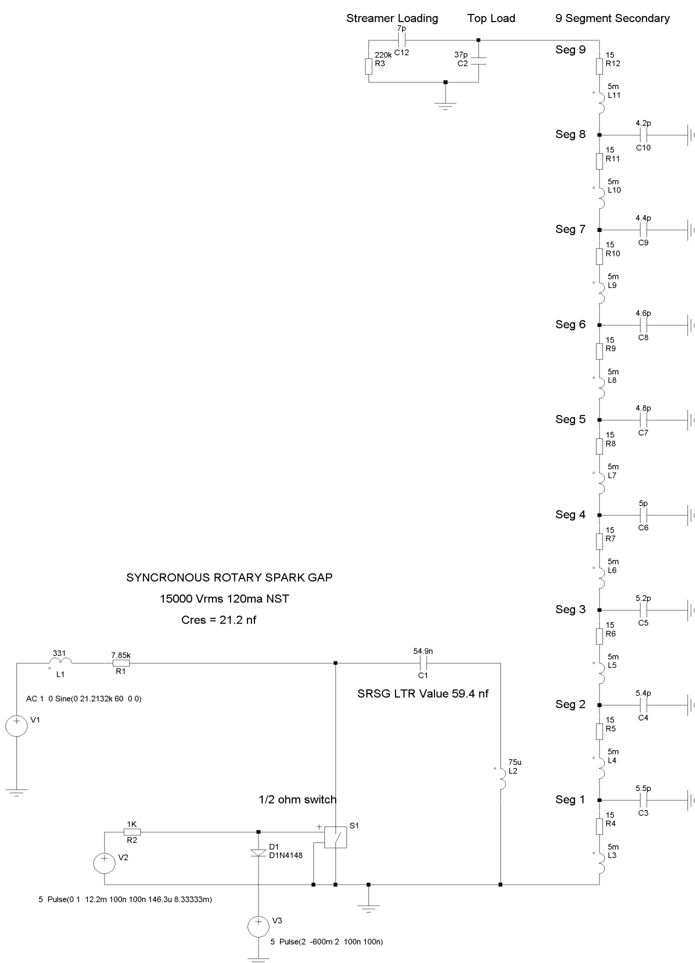
In Part 1, a search was made for a primary that could give greater overall coupling to achieve a faster energy rise time at the toroid, and potentially avoid racing arcs induced by over coupling. To determine the truth in the theory that a more uniform coupling distribution from such a primary may help avoid racing arcs, it was necessary to study the mechanisms that result in racing arcs. To this end, I created a spice model for a segmented secondary that modeled both the distributed coupling from the primary to the secondary segments as well as the coupling between each of the segments. I used my 8x36 inch coil with its primary one inch below the bottom turn of the secondary for the model as this coil has shown a propensity for racing arcs.



C:\Program Files\SIMetrix\Work\SRSG_15kv_120ma_NST.sxsch - Wednesday, August 23, 2006

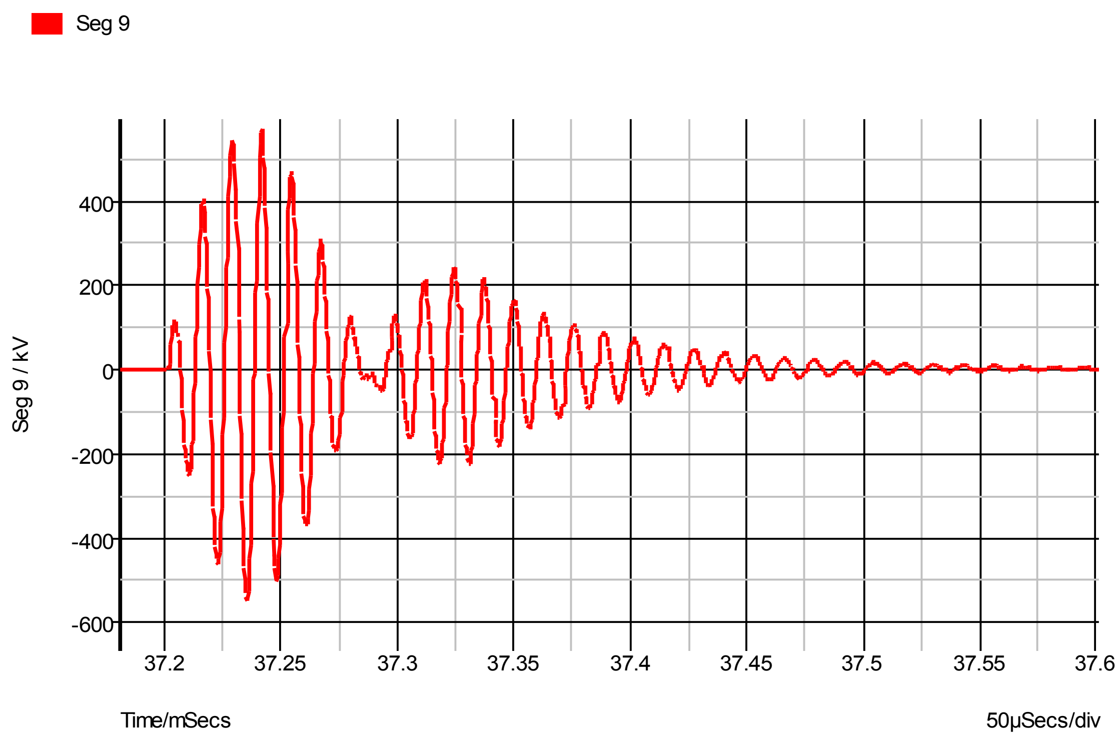
In the schematic, the power source (V1) models a 15KV 120ma NST farm that is operated at 120Vac input. The source resister (R1) reflects the measured primary resistance transferred to the secondary and added to the measured secondary resistance. V2 and switch S1 model a SRSG and the timing of the firing is set to maximize the firing voltage on the TC primary cap C1 and to provide for 2^{nd} notch quenching. Source V3 for these simulations is not used and can be ignored. L2 represents the TC primary and the nine segment TC secondary is modeled by L3 thru L11. The fraga resistance is evenly distributed across the segments (R4-R12). The distributed C along the secondary is modeled by C3-C10. JavaTC was used to determine the L and C of each secondary segment without the presence of the other segments. Each pair of segments was modeled in JavaTC (one as a primary and the other as a secondary) with the appropriate geometry and spacing to determine the coupling between them. The following are the coupling coefficients that were added by editing the spice deck.

K23 L2 L3 .264	K34 L3 L4 .309	K35 L3 L5 .077	K36 L3 L6 .028
K24 L2 L4 .121	K45 L4 L5 .309	K46 L4 L6 .077	K47 L4 L7 .028
K25 L2 L5 .058	K56 L5 L6 .309	K57 L5 L7 .077	K58 L5 L8 .028
K26 L2 L6 .030	K67 L6 L7 .309	K68 L6 L8 .077	K69 L6 L9 .028
K27 L2 L7 .017	K78 L7 L8 .309	K79 L7 L9 .077	K710 L7 L10 .028
K28 L2 L8 .011	K89 L8 L9 .309	K810 L8 L10 .077	K811 L8 L11 .028
K29 L2 L9 .007	K910 L9 L10 .309	K911 L9 L11 .077	
K210 L2 L10 .005	K1011 L10 L11 .309		
K211 L2 L11 .003			

K37 L3 L7 .013	K38 L3 L8 .007	K39 L3 L9 .004	K310 L3 L10 .003
K48 L4 L8 .013	K49 L4 L9 .007	K410 L4 L10 .004	K411 L4 L11 .003
K59 L5 L9 .013	K510 L5 L10 .007	K511 L5 L11 .004	
K610 L6 L10 .013	K611 L6 L11 .007		
K711 L7 L11 .013			K311 L3 L11 .002

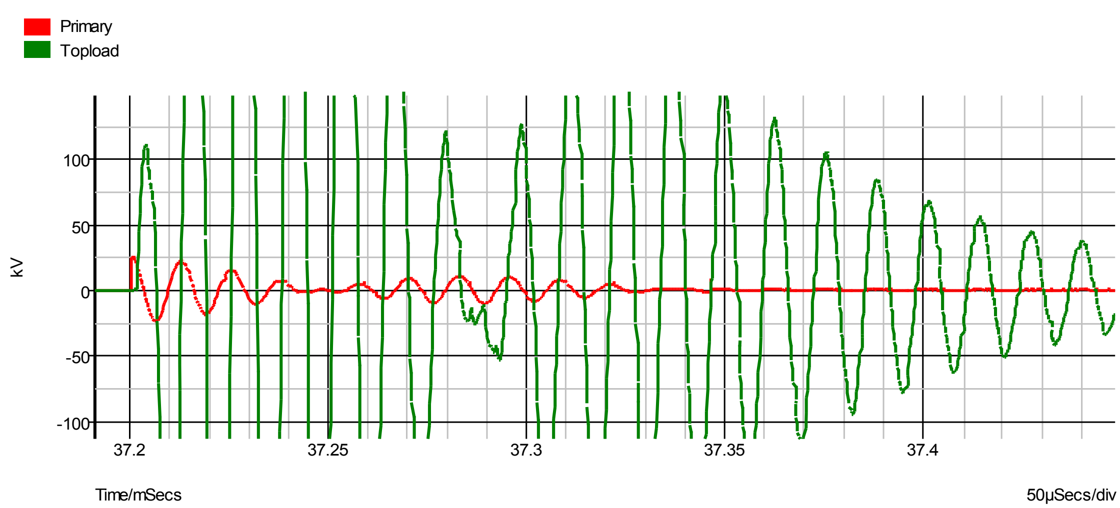
Note, the number of coupling coefficients is n(n+1)/2 where n is the number of secondary segments used in the modeling.

I had to alter the capacitive values somewhat to achieve proper tuning before measurements were taken. The distributed C was lowered a little to reflect a lower capacitance at the top then at the bottom where the segment is closer to the ground plane (I'm not sure my interpretation of the capacitor values from JavaTC is correct). To achieve final tuning, the inductance of the primary was increased from the value that JavaTC indicated was needed to achieve tuning in a full blown simulation. This probably compensated for streamer loading that is present in the schematic model. In any case, the topology wasn't altered and the changes to achieve tuning were kept minor. The following shows the secondary voltage with 2^{nd} notch quenching:

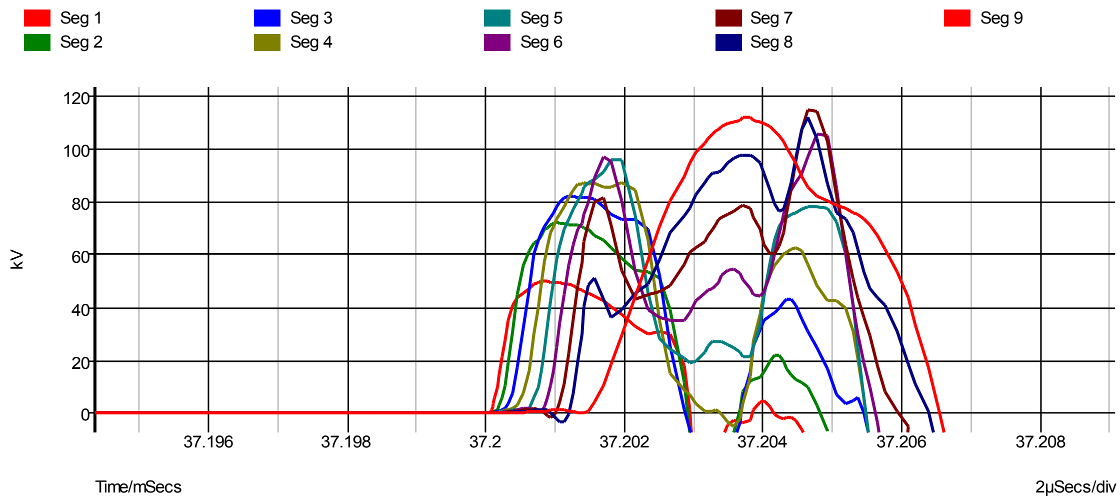


The decay after quenching reflects the damping caused by the streamer loading and the fraga resistance.

The following shows the phase relationship between primary and secondary:

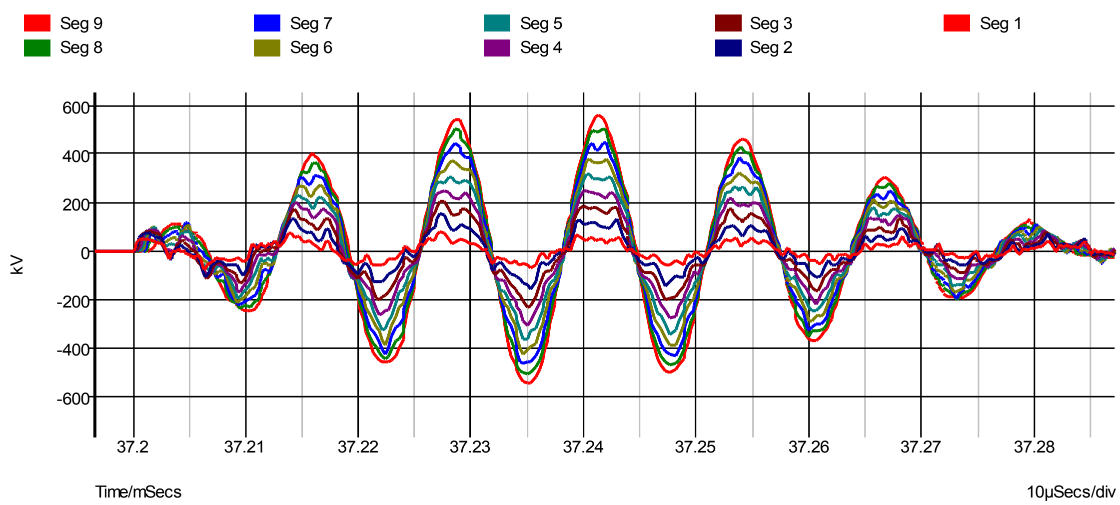


The important factor here is that the voltage on the topload does not instantly jump to its initial value at the instant the spark gap fires. In fact, there is a delay between firing and when the topload even begins to change. There are some in the TCML group that suspected that the initial voltage profile would be the cause for racing arcs. This initial profile is represented by the first peak of the secondary that is around 110KV. The following focuses on this initial profile by measuring the voltage at top of each of the 9 segments:

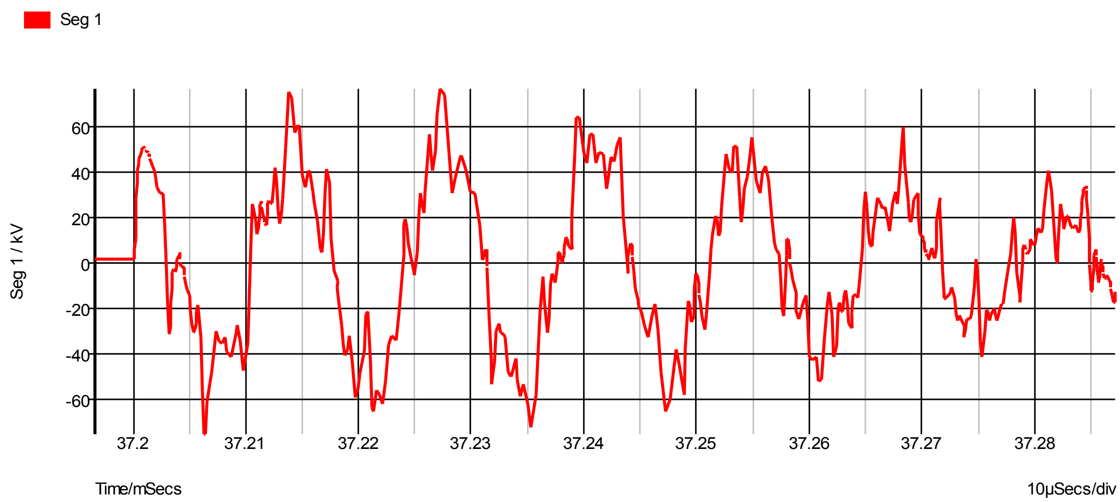


It can be seen that the bottom segment (seg1) ramps up first and that a wave action occurs before the energy reaches the top (seg9). The leading wave front propagating toward the top takes ~6us before reaching the top and has a rise time of ~2us. For my 36 inch coil, this rise in voltage would be spread over 12 inches. The stress of the coil would therefore be 100Kv/12inches and not enough to overstress.

The following shows the voltages at each segment over a full ring-up and ring-down cycle:



With this waveform it is important to note that the voltage at the top segment looks very smooth and as expected. However, voltages at intermediate points look very much distorted not unlike distorted waveforms in a transmission line when reflections are occurring. The most distorted waveform is the bottom segment where the greatest coupling occurs:



With this waveform, it can be seen there are many wave fronts propagating up and down the secondary making it hard to make sense of the waveform. Instead, I used the differential voltage probe of the simulator to measure directly the stress on the coil. I found the maximum voltage and noted which peak this maximum occurred in. The following table shows the voltage across various segments in all combinations:

Reference for Differential Voltage Measurement

V@Seg	Gnd	Seg1	Seg2	Seg3	Seg4	Seg5	Seg6	Seg7	Seg8
9	563kv +4	515kv +4	460kv +3	397kv +3	331kv +3	266kv +3	205kv +4	144kv +4	71kv +4
8	513kv -3	468kv +3	422kv +3	359kv +3	290kv +3	224kv +3	151kv +3	73kv +4	_
7	467kv -3	418kv +4	362kv +3	300kv +3	230kv +4	161kv +3	80kv +3	_	
6	428kv -3	374kv -3	295kv -3	231kv +3	158kv +4	82kv +4	_		
5	369kv -3	315kv -3	236kv -3	162kv +3	85kv +3	_			
4	313kv -3	250kv -3	170kv -3	80kv -3	_				
3	237kv -3	174kv -3	93kv -3	_					
2	157kv -3	84kv -3	_						
1	76kv +3	_							

To convert these voltage differences to a voltage stress, the voltage is divided by the distance between measurement points. For example, the top of coil voltage at seg 9, when measured with respect to ground, has its 563kv divided by the 36 inch length of the coil winding giving a stress of 15.6kv per inch. The segment 3 voltage with respect to segment 2 is 93kv and the distance spans 4 inches. Its stress is therefore 23.3kv per inch and is considerably higher. The following table restates the above information in terms of stress.

Reference for Stress (V/inch) Calculation

Stress @Seg	**Gnd**	**Seg1**	**Seg2**	**Seg3**	**Seg4**	**Seg5**	**Seg6**	**Seg7**	**Seg8**
9	15.6kv	16.1kv	16.4kv	16.5kv	16.6kv	16.6kv	17.1kv	18.0kv	17.8kv
8	14.6kv	16.7kv	17.6kv	18.0kv	18.1kv	18.7kv	18.9kv	18.3kv	-
7	16.7kv	17.4kv	18.1kv	18.8kv	19.2kv	20.1kv	20.0kv	-	
6	17.8kv	18.7kv	18.4kv	19.3kv	19.8kv	20.5kv	-		
5	18.5kv	19.7kv	19.7kv	20.3kv	21.3kv	-			
4	19.6kv	20.8kv	21.3kv	20.0kv	-				
3	19.8kv	21.8kv	**23.3kv**	-					
2	19.6kv	21.0kv	-						
1	19.0kv	-							

From these results, it seems likely that any racing arc would breakout at the top of segment 3 as this has the highest stress (23.3kv per inch). This stress occurred with an input voltage of 120Vac. At 140Vac (assuming things scale), the stress would be 27.2kv per inch and seems very likely to result in a racing arc. My coil broke out in this vicinity and arc'd to the top of the coil. However, the stress at the top of coil with respect to segment 3 is only 16.5kv. My guess is when segment 3 arc'd to segment 2, the voltage of segment 3 was pulled down. This in turn increased the stress between segment 4 and segment 3 resulting in that portion of the coil to breakdown and so on. This avalanching effect continued until the top of the coil broke down.

In conclusion, it does seem that a simulation can be used to predict racing arcs. The locality and stress levels seem very close to what was observed and what would be needed. It also seems likely that simulation can be used to compare different primary geometries for their tendency for having racing arcs.