Quality factor measurements of air-cored solenoids at overtone frequencies

R.M. Craven, I.R. Smith and B.M. Novac

Although Tesla transformers and helical cavity filters are employed in quite different technical areas, a previous contribution demonstrated that applying the techniques used in designing these filters to the secondary winding configurations of a Tesla transformer improved the spectral purity of the output. In the present reported work, measurements of the quality factors of the original and a number of modified secondary windings are shown to provide results at the fundamental and overtone frequencies, thereby illustrating the scale of the possible benefits that can be achieved.

Introduction: This Letter considers quality factor (Q) measurements made on the original and a number of modified secondary windings of a typical Tesla transformer and discusses ways in which the Q-factor can be significantly altered at overtone frequencies while imparting little change at the fundamental resonant frequency. Specifically, the secondary winding of the transformer is a wound helical coil along which standing waves are established at the fundamental resonant wavelength λ of the coil, and a series of shorter wavelengths which are given by [1]

$$1\frac{\lambda}{4},\ 3\frac{\lambda}{4},\ 5\frac{\lambda}{4},\ \ldots,\ \frac{(2n+1)\lambda}{4},\ n=1,\ 2,\ \ldots \tag{1}$$

These correspond to a series of odd harmonic frequencies given by

$$f,\ 3f,\ 5f,\ \ldots,\ (2n+1)f,\ n=1,\ 2,\ \ldots \tag{2}$$

with the frequency of the mode whose electrical length is $(((2n+1)\lambda)/4)$ being $(2n+1)f$, where f is the fundamental frequency.

Reversing the winding sense of a portion of the secondary winding turns has been shown theoretically [2] and confirmed experimentally by the present authors to leave the fundamental resonant frequency (f_1) substantially unchanged. However, the reversal both raises the frequencies and reduces the Q of the higher-order harmonics, by amounts that are sensitive to the proportion of turns that were reversed. Since the simple circuit theory applied to a lumped representation of the coil by a series resistor and inductor together in parallel with a capacitor demonstrates that the current in the (unloaded) winding is directly proportional to the Q of the winding, the possibility arises of using this technique to control the higher-order harmonic currents present in the secondary winding.

Experimental investigation: During an experimental investigation [3] into novel Tesla transformer winding configurations that improve the spectral purity of the output, a number of single-layer solenoidal air cored coils were produced, typical of those found in many medium-sized Tesla transformers. All were 563 mm long with an outside diameter of 114 mm and contained 1600 turns. The coil with all its turns wound in the same direction was considered as a benchmark and termed the '0%' coil, with the others having 10, 22.5, 33 and 50% of the turns from one end of the coil counterwound [3].

The resonant frequencies of each of the coils were calculated approximately and confirmed by frequency domain measurements when a constant amplitude radio-frequency (RF) current was swept over a range covering the fundamental resonant frequency and the first few overtone modes. The complex impedances of the coils were then measured over the same frequency range using a vector network analyser, and the results displayed on a Smith chart. The data provided by the two sets of experimental results enabled the Q at any mode frequency f_m to be identified for all the coils from [4, 5]

$$Q=\frac{f_m}{f_u-f_l} \tag{3}$$

where f_u and f_l are, respectively, the upper and the lower frequencies at which the input power is half of that at the resonant frequency. Additionally, the change in the current flowing in the coil ΔI_L when a change in Q of ΔQ is brought about by the winding alteration is

$$\Delta I_L = I_s \Delta Q_s \tag{4}$$

where I_s is the constant RF current at which the frequency domain measurements were made. It is evident from (3) and (4) that, since the two changes are linearly related, they are much less pronounced at the fundamental frequency (~250 kHz) than at the high-order modes (600 kHz and above).

Typical results: As an entirely arbitrary example of the effect of the part-winding reversal, Table 1 compares the Q factors of the coils with different proportions of counterwound turns with those of the benchmark coil. Table 2 shows the percentage changes from the benchmark figure at the lower mode frequencies f_3 and f_5. All the experimental coils show minor increases in the resonant mode frequencies but it is significant that the coil with 10% of the turns reversed exhibits both the largest reduction in Q at the fundamental frequency and the smallest changes at the higher-order mode frequencies.

Table 1: Q measurements of experimental coils at different mode frequencies

Coil	f_o (kHz)	Q_l
0% f_1	233	199
0% f_3	566	255
0% f_5	811	194
10% f_1	259	202
10% f_3	648	234
10% f_5	942	172
22.5% f_1	248	203
22.5% f_3	649	220
22.5% f_5	883	187
33% f_1	258	201
33% f_3	659	225
33% f_5	821	231
50% f_1	281	191
50% f_3	622	272
50% f_5	972	158

Table 2: Coil responses as percentage changes from the benchmark figures. The significant Q_l reductions for the f_3 mode are emphasised in bold

Mode	f_1		f_3		f_5	
Coil	kHz	Q_l	ΔkHz (%)	ΔQ_l (%)	ΔkHz (%)	ΔQ_l (%)
0%	233	199	567	255	811	194
10%	+11.2	+1.5	+14.2	**−8.2**	+16.2	**−11.4**
22.5%	+6.4	+2.0	+14.5	−13.7	+8.9	−3.6
33%	+10.7	+1.1	+16.2	−11.8	+1.2	+19
50%	+20.6	−4.0	+9.7	+6.7	+19.9	−18.6

Conclusion: This Letter has confirmed that reversal of a selected proportion of turns of a solenoidal coil can undoubtedly produce a beneficial effect, and ongoing work aims to establish the proportion that produces the greatest effect. Other areas under investigation include the effects of varying the location of one or more counterwound sections along the coil.

18 June 2014
doi: 10.1049/el.2014.2241

R.M. Craven, I.R. Smith and B.M. Novac (*School of Electronic, Electrical and Systems Engineering, Loughborough University, Leicestershire LE11 3TU, United Kingdom*)

E-mail: I.R.Smith@lboro.ac.uk

References

1 Macalpine, W.W., and Schildknecht, R.O.: 'Coaxial resonators with helical inner conductor'. In Proc. IRE, New York, NY, USA, December 1959, pp. 2099–2105
2 Vizmuller, P.: 'Filters with helical and folded helical resonators' (Artech House, Norwood, MA, USA, 1987)
3 Craven, R.M.: 'A study of secondary winding designs for the two-coil Tesla transformer'. PhD thesis, Loughborough University, 2014
4 Chang, K.: 'Encyclopedia of RF and microwave engineering', 6-Volume Set (Wiley-Interscience, Hoboken, NJ, USA, 2005)
5 Terman, F.E.: 'Radio engineer's handbook' (McGraw-Hill Handbooks. McGraw-Hill Book Company Inc., New York, NY, USA, 1943)