Some observations on impedance and Ferranti effect

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***Abstract*— It could be assumed that there is little or no uncertainty left at all regarding electrical resonance, 150 years after (1865) James Clerk Maxwell wrote a letter to Sir William Grove explaining the whole theory of the condenser in multiple connection with a coil, and 122 years after Arthur Edwin Kennelly presented his paper on impedance to the American Institute of Electrical Engineers. Nevertheless ambiguity has been detected during impedance measurement, which was hard to explain. It is well known, that frequency dependent vector representing impedance of the passive electrical circuit, when depicted on the complex plane, situates on the right side of it, having positive real part, and phase angle between +90° and -90° degrees. Positive real part indicates that passive circuit can only consume energy, and does not generate any. Measurement results should certainly always agree with the above quite fundamental statement, however they do not. Appearance of the negative real part can be observed under certain circumstances. It has been measured with several different instruments, in wide apart geographical locations and at different time points over number of years.**

Keywords— impedance; resonance; real part

I. INTRODUCTION

"The most important aspect of any phenomenon from a mathematical point of view is that of a measurable quantity. I shall therefore consider electrical phenomena chiefly with a view to their measurement, describing the methods of measurement, and defining the standards on which they depend." wrote James Clerk Maxwell, the first Cavendish Professor of Physics at Cambridge, in the preface to his treatise on electricity and magnetism [2]. On 16.th of May 2014 an experiment was conducted in order to evaluate the impedance of the coil with human head inserted into it. Simple ad-hoc wire wound inductor was put around the head of the experimenter, and attached to the Wayne Kerr 6500P precision impedance meter. At first glance everything looked as expected: series resistance of the wire dominated at very low frequencies, and then mostly inductive behavior followed, turning later into capacitive, due to the parasitic capacitance between the turns of the wire, resulting in well-known magnitude curve. Closer look however revealed something peculiar: instead of the phase jump from +90° to the -90° at resonant frequency, the phase rose near resonant frequency sharply to 180° and then jumped to -180°. The instrument was switched to show the real part of the impedance, and indeed it was negative.

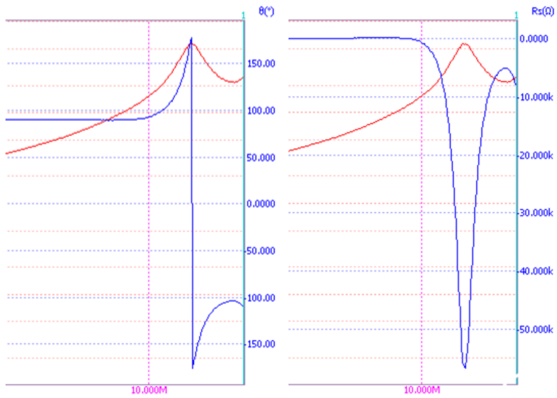

Fig. 1. Phase angle (left picture) and real part (right picture) dependence on frequency (pictures not from the described experiment, but similar). Frequency in MHz on horisontal axis. Magnitude curve in red on both pictures.

In order to investigate possible measurement error the same test was repeated with multiple ordinary signal generators and oscilloscopes with very similar results. (Later also with other impedance measurement devices, such as Hewlett Packard 4194A Impedance/Gain-Phase Analyzer). After discussions and search it became evident that similar behavior has been observed before and by different groups. Results were typically simply rejected as erroneous, without any further analysis, investigation or explanation.

II. EXPERIMENTS AND SOME DISCUSSION

A. *Measurement error*

Simplest, and by far the most favored explanation. The instrument can be blamed, and the experiment conditions as well. First guess was to look towards parasitic coupling. One of the experimenters from different lab explained similar results very easily: generator was leaking energy, and that in turn was picked up by the coil. Several experiments were conceived to prove that explanation. Twisted and shorted transmission line was made. Due to twisting it was believed to be more immune to the outside energy sources. Results can be seen on Fig. 2. On second stage said wire was put into closed, earthed, tinned iron cookie jar, with minimal possible opening for instrument connectors. Faraday cage seemed not have substantial impact on results. Many different coil geometries were tested, and one thing is certain: effect can be observed in different configurations, and at vastly different frequencies.

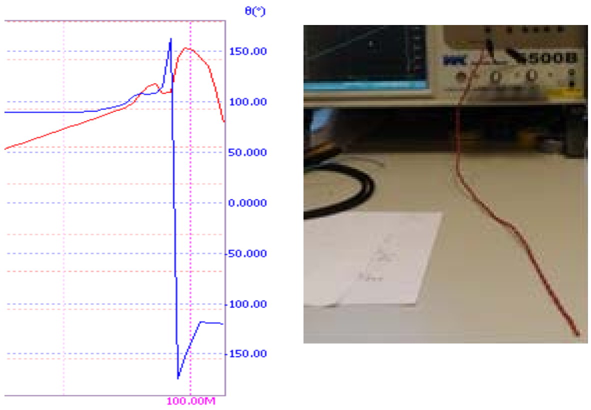

Fig. 2. Phase angle (left picture) of the twisted wire (right picture). Frequency in MHz on horisontal axis.

Very subtle change in the positioning of the connecting wires was enough to turn the real part from positive to negative in some borderline cases (Fig. 3). That suggests that precision impedance meter is not to be blamed, since the same device measures both the correct behavior of the resonant circuit, and soon after (presumably) incorrect.

Fig. 3. Borderline coil, which can exibit both positive and negative real part of the impedance, depending on the position of (blue) connecting wires.

B. *"Life detection"*

Change in the sign of the real part of the impedance of the coil can be observed also by placing different objects into it. Pot of three wool flowers (Celosia) was used during one set of experiments. Normally (positive real part) behaving coil was placed over one of them at a time. Change in the sign of the real part of the impedance was observed. After first flowers started drying out the experiment was repeated. Clearly only the healthy plants contributed to the change of the sign. Experiment was repeated by placing different amounts of water with different salinity in different plastic reservoirs inside coil with no apparent effect during that experiment.

Later it was cleared that one of the first guesses was true: capacitive coupling was the culprit instead of inductive coupling. Both measurements and simulations finally agreed. Instead of getting energy through inductive coupling the coil is leaking some energy to the ground through parasitic capacitance. The effect has been described and analyzed by Doctor Ramon Pallas-Areny group in several papers [3-5].

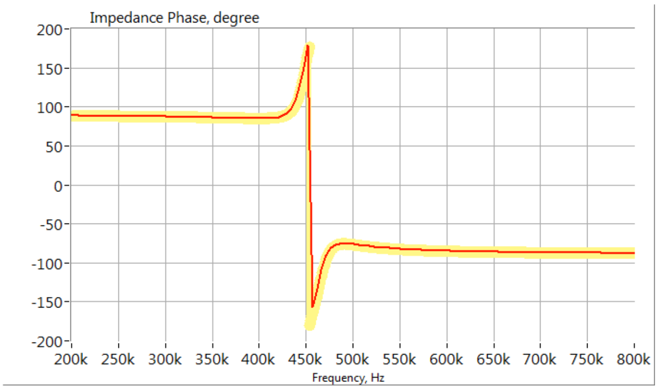

Fig. 4. Two coils connected in series L = 4.3mH, parasitic parallel C = 26pF, parasitic Cpar = 6.2pF from the center of coils to ground. Narrow red line: simulation, wide yellow line: measured value.

C. *Historical note on*

Blaming the results simply on measurement error, without proper explanation, resembles in many ways the situation with "Ferranti effect" during the discussion of the presentation of the famous paper by Arthur Edwin Kennelly [1].

"…Mr. Kennelly referred to the "well-known Ferranti effect... which did not exist." - W. J. Hammer the chairman

"… The next point which I wish to discuss very briefly is the so called Ferranti effect… Well, the statement then that was given to our Chairman makes me hesitate. I also rushed into print about something like the Ferranti effect… The Ferranti effect is only a special case of the more general effect which I call the resonance. It could have been foreseen twenty five years ago from Maxwell's equations deduced at about that period." - Dr. Mihajlo Idvorski Pupin

Acknowledgment

The research was supported by the European Union through the European Regional Development Fund in frames of the research center CEBE and the competence center ELIKO.

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