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RESONANCE BETWEEN PLANAR COILS VS RING COILS EXCITED BY SQUARE WAVES

E. M. M. Costa

Universidade Federal do Vale do São Francisco — UNIVASF
Colegiado de Engenharia Elétrica — CENEL
Av. Antônio Carlos Magalhães, 510, Juazeiro, BA, Brazil

Abstract—This paper presents a basic analysis about experiment results using planar coils inner ring coils, defining a transformer, when this system is excited by square wave voltage. In this study phenomena of response to step voltage due to parasitic capacitances is analyzed, and a sum of responses when the input square wave frequency increases is given too. These phenomena are uncommon in literature, which can be applied to several areas of researches in electrical engineering, pulse transformers and power electronics.

1. INTRODUCTION

Resonance studies have been developed in several aspects. Some works are found in literature [1–4] about coupled circuits (transformers), and on square waves, works are more related to power electronics [5, 6]. Some works are about resonance effects on circuit impedances, where circuit excitation is based on square wave, as we can see in [6, 7]. Also, some of these researches are applied to planar coils in several contexts, as impedances, mutual inductance and self inductances [8, 9, 11, 12], stray capacitances [13–15], and others [16]. However, most works found in literature about planar coils are in microcircuits [17–23].

On the other hand, works about resonance are usually formalized in sinusoidal low frequencies on common transformers or, in some cases, in microcircuits as microstrip disks [24, 25], etc.

When analyzing transformers, analysis about inductors is basic, where parasitic capacitances effect are visible [13–15]. Also, analysis about electromagnetic fields is realized for several cases [26–29], to find relationships between the phenomena and technological applications [30, 31].

Corresponding author: E. M. M. Costa (eduard.montgomery@univasf.edu.br).

Since coils present their capacitive and inductive effects, some responses to step voltage have features of second, or higher order, with sine waves (RLC circuit). One the other hand, when a coupled inductance circuit with air core is excited by a square wave, the response to each step in the rise or fall is always equal, but with inverted signal (the response follows the inverse direction of the rise or fall of square wave by the Faraday's law, repeatedly on each reversal of the input signal) a variation of stored energy in the form of magnetic fields (inductor) as sine wave is presented. Such an effect, a priori, is imperceptible in most cases, specially when inductor is considered ideal (without resistance or capacitance). However, the phenomena which appear with increasing input square wave frequency which excites primary coil will be seen only as the impedance relationship, or effects of active filters. But considering using planar coils as primary of an air core transformer inner to ring coils, ring coil as its secondary, and using time division of oscilloscope in order of nanoseconds, we find as a response to secondary an output voltage which appears as sum of responses of each rise and fall of the input square wave, that comes from stored energy on inductors. In this case, the response in the secondary circuit presents voltages higher than input peak signal, while the turns ratio is not satisfied, in accordance with circuit theory and transformer theory.

Research on these phenomena is of great importance in several aspects of engineering, such as analysis about self and mutual inductances [32–35], stray capacitances [13–16], power electronics [36] and specially, pulse transformers [37, 38].

This paper is arranged as follows: Section 2 shows the basic data of coils and utilized equipments; Section 3 presents discussions about circuit responses and observed phenomena; Section 4 discusses the responses about the inversion of the system; Section 5 presents the conclusions.

2. BASIC INFORMATION ABOUT REALIZED EXPERIMENTS

This paper was based on a system of coils defined by a planar coil inner ring coil. The experiments were realized initially by exciting planar coil and observing the response of the induced *emf* in the ring coil, and later, inverting the input and the output, exciting the ring coil and checking the induced *emf* in the planar coil.

The planar coils used were built with number of turns defined by 20, 50, 200, 500 and 1600, while the ring coils were built with number of turns of 2, 5, 7, 9, 10, 12, 15, 20, 30 and 50. Each planar coil was cross

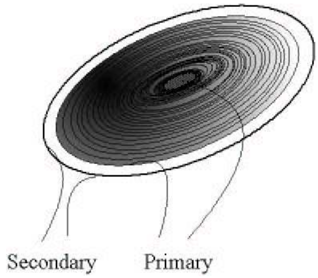


Figure 1. Air core transformer with planar coil of 200 turns as primary and ring coil as secondary.

with each ring coil, where measurements were realized, giving a total of 50 crosses considering the planar coils as primary of the transformer, and the same 50 crosses considering the ring coils as primary.

The excitation of this system was given through a square wave of 5 V peak to peak (2.5 V peak), with frequencies from 300 kHz to 25 MHz.

All coils were built by copper wire with diameter 2.02×10^{-4} m (32 AWG) or 1.80×10^{-4} m (36 AWG), where the planar coils present a diameter $d = 4.01 \times 10^{-2}$ m with the copper wires bunched together on layers with height from $h = 1.80 \times 10^{-4}$ m (20 and 50 turns) to $h = 5 \times 10^{-4}$ m ($\geq$ 200 turns). The diameters of ring coils are the same and equal to $D = 4.65 \times 10^{-2}$ m arranged such that it has approximately the same height of the planar coil in transformer's primary.

The used equipments in these experiments were a digital storage oscilloscope Agilent Technologies DSO3202A with passive probe N2862A (input resistance = 10 MΩ and input capacitance $\simeq$ 12 pF), a function generator Rigol DG2021A and a digital multimeter Agilent Technologies U1252A.

Figure 1 shows the basic structure of the system in analysis, where the experiments were realized.

The experimental data obtained in this configuration, a priori, were sufficient to determine several uncommon effects, as the variation of the output voltage (secondary coil), that presents peaks of voltage, which are increasing with the frequency, although the ratio of turns is reversed (smaller number of turns in secondary coil). These phenomena are described in the next sections.

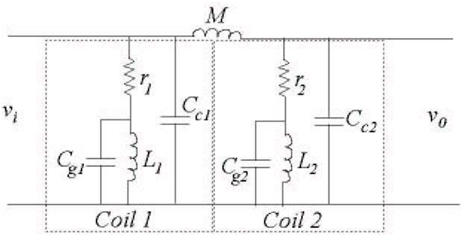


Figure 2. Equivalent circuit of the system, considering coils' resistance and parasitic capacitances.

3. BASIC RESULTS OF THE EXPERIMENTS

As cited in the previous section, the excitation of the system by a square wave, considering initially the planar coil as the primary of the transformer and the ring coil as the secondary, we have the equivalent system as shown in Fig. 2, where the coils' resistance r_i, self inductances L_i, mutual inductances M and parasitic capacitances (C_{gi} the parasitic capacitances in relation to a ground, and C_{ci} turn to turn) for $i = 1, 2$ are considered. In this case, v_i is the input signal, and v_0 is the output signal.

Observing response of the system in low frequencies (from 1 kHz to 300 kHz) when the planar coils have more than 200 turns, the response is uniform, similar to response to a step voltage. In the planar coils with lower number of turns (as 50 and 20 turns), the response presents variations in frequencies from 150 kHz for some configurations (when ring coil presents more turns than planar coil). In these low frequencies, the system's response for some configurations appears as shown in Fig. 3.

Without loss of information, considering the output of the system shown in Fig. 3(d), the transfer function of the system can be obtained. Since the system's response is [16]:

$$v_0 = A\left[\sin(\omega_1 t)\sin(\omega_2 t)\, e^{-bt} + c\right] e^{-dt}, \tag{1}$$

considering parameters $y_1 = (\omega_1 + \omega_2)^2$, $y_2 = (\omega_1 - \omega_2)^2$ and $x = b+d$, we have the transfer function of the system given by:

$$G(s) = \frac{z_5 s^5 + z_4 s^4 + z_3 s^3 + z_2 s^2 + z_1 s}{s^5 + p_4 s^4 + p_3 s^3 + p_2 s^2 + p_1 s + p_0} \tag{2}$$

where $z_5 = c$, $z_4 = 4xc$, $z_3 = (6x^2 + y_2 + y_1)c + 2(y_2 - y_1)a$, $z_2 = (4x^3 + 2x(y_2 + y_1))c + 2(y_2 - y_1)(x + d)a$, $z_1 = (x^4 + x^2(y_2 + y_1) + y_2 y_1)c + 2(y_2 - y_1)xda$, and $p_4 = 4x + d$, $p_3 = 6x^2 + y_2 + y_1 + 4xd$, $p_2 =$

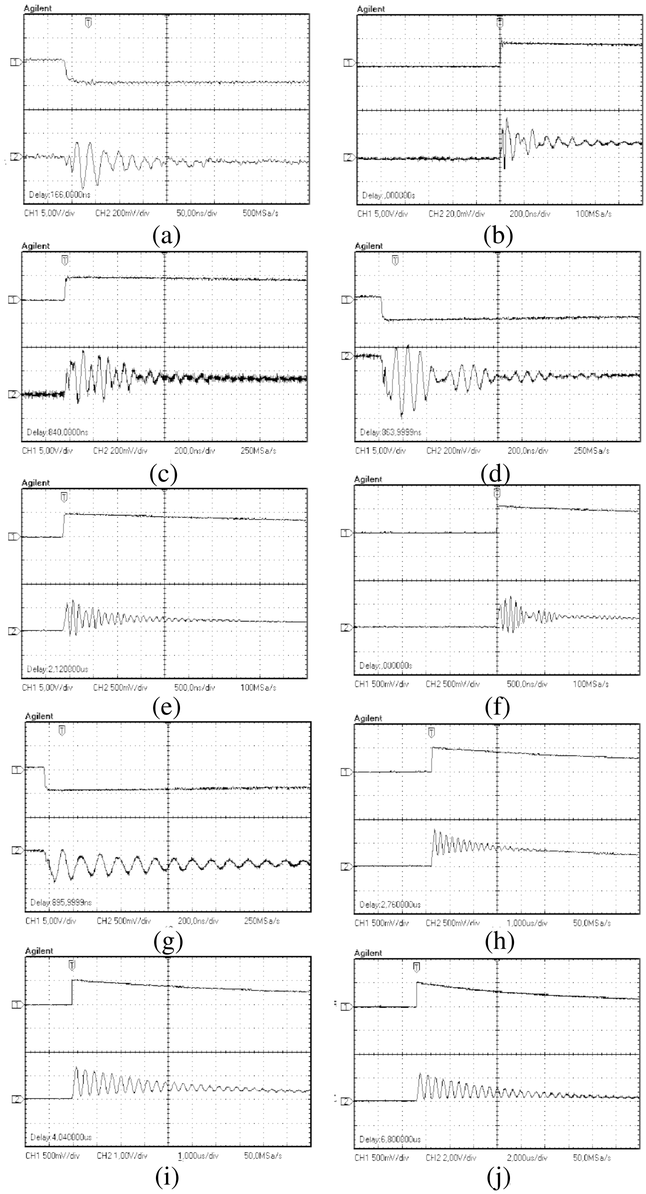
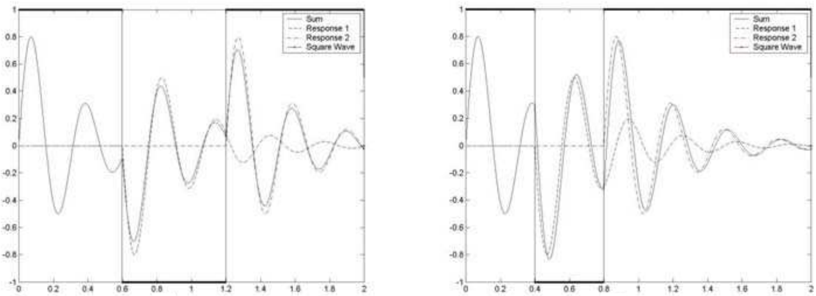
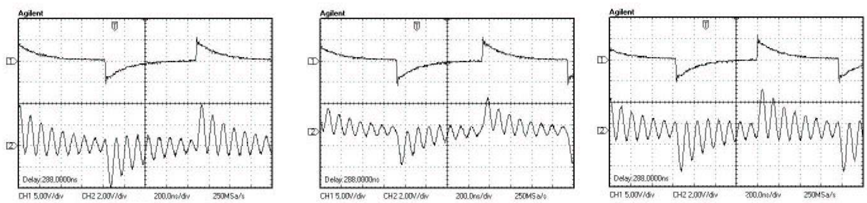


Figure 3. Responses of the system to low frequencies: 200 turns planar coil *vs* (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 7 turns ring coil; (d) 9 turns ring coil; (e) 10 turns ring coil; (f) 12 turns ring coil; (g) 15 turns ring coil; (h) 20 turns ring coil; (i) 30 turns ring coil and (j) 50 turns ring coil.



(a) (b)

Figure 4. Graphics shown sum of atenuated sine wave.



(a) (b) (c)

Figure 5. Experimental data, shown the sum of responses in accordance to frequency of the square wave for: (a) 580 kHz; (b) 620 kHz and (c) 650 kHz.

$4x^3+6x^2d+(2x+d)(y_2+y_1)$, $p_1 = x^4+4x^3d+(2xd+x^2)(y_2+y_1)+y_2y_1$ and $p_0 = (x^4 + x^2(y_2 + y_1) + y_2y_1)d$.

One the other hand, when the frequency is increased, the system's response to a step voltage appears in each rise (in positive signal) and in each fall (in negative signal) of the square wave. Consequently, the effect of increased square wave frequency determines that these responses are overlapped, such that the higher is the square wave frequency, the greater is the amount of overlapping responses. Consequently, the overlapped sine waves (system's responses), depending on the square wave frequency, may be lagged, which determines low values of voltage and high voltages in some frequencies. This effect can be seen in Fig. 4 for two attenuated sine waves (similar to responses of the system in analysis), where we can see the variation of the overlapping, as the square wave frequency is increased.

The proof of this fact is shown in Fig. 5, which is the experimental

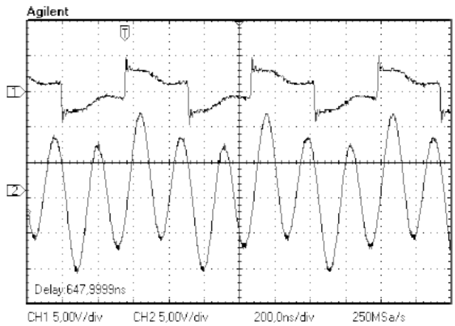


Figure 6. Experimental data: sum of responses in phase in accordance to frequency of the square wave $f = 1.4\,\mathrm{MHz}$ for configuration 20 turns planar coil *vs* 20 turns ring coil. Input channel (upper graph) and output channel (lower graph) with $5\,\mathrm{V/div}$, and time division of $200\,\mathrm{ns/div}$.

data of the analyzed system.

Also, when the frequency of the square wave (f_s) is in phase with the sine wave of the higher frequency in the system's response

$$f_r = 7.1428 \times 10^7 \times k/n_s \tag{3}$$

with

$$k = \begin{cases} 1, & \text{to configuration planar coil vs ring coil} \\ 4.39, & \text{to configuration ring coil vs planar coil} \end{cases} \tag{4}$$

and n_s being the turn number of secondary's transformer (being these equations extension results of [16]), we can see that,

$$f_s = f_r/n, \tag{5}$$

where n is the cycles number of sine wave between one rise and one fall of the square wave; the values of responses of the system (their peak voltages) are added, reaching maximum values, as we can see in Fig. 6, which are experimental data, and in Fig. 7 as simulation.

Based on this information and without loss of information, eliminating the lower frequency of the response (ω_2), we find that the response of the system appears as:

$$v_0 = \sum_{p=0}^{n} (-1)^p \left(\alpha \sin\left(\omega_1 \left(t - p\right)\right) e^{-b(t-p)} + a\right) \tag{6}$$

for $t - p > 0$, where p is the square wave period. This equation was obtained through analysis of the sum of responses on each rise and

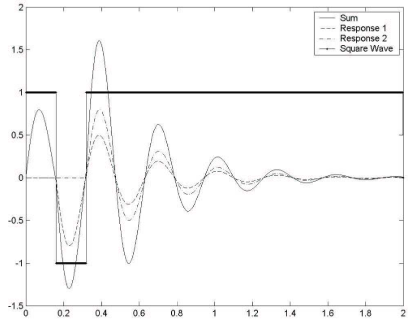


Figure 7. Simulation shown the sum of responses when square wave is in phase with the senoidal response.

fall of the input square wave. We observe that, in a semi period $p/2$ (rise square wave) the system responds with a sine wave of amplitude α, frequency ω_1, exponential drop and DC response a. In the second semi period $p/2$ (fall square wave) the system yet presents its initial response, but it is added with the response of inverted step voltage. In resonance, the periods of the input and output are equal, and the maximum value on output is obtained.

Based on these observations, realized measurements between 1 kHz and 25 MHz, define graphs shown in Figs. 8, 9, 10, 11 and 12, for primary coils as being planar coil of 20, 50, 200, 500 and 1600 turns, respectively, crossed with some ring coils, since the other graphs are similar.

Some of these graphs, specially the graphs of the system in configurations with 2 turns ring coil, the errors are more perceptible, because obtained data are in the same range of the other set (same frequencies where responses of the system are obtained when considering the crossing of planar coil with ring coils with more than 2 turns). Also, comparing these graphs with the others and observing that this resonance frequency is above 30 MHz, we observe their similarity with peaks in low frequencies of the others (ring coils with turn number greater than 5). We see in these graphs that the obtained voltage, defined by Equation (6), determines that the peaks voltage are found such that theirs are almost linear. Also, we observe that when increasing turn number of the ring coil the system resonance frequencies are shifted to lower frequencies and shifted to higher frequencies when increasing the turn number of the planar coil, in accordance to Equation (3). In addition, the peak voltage increases with increasing turn number of the ring coil, and decreases

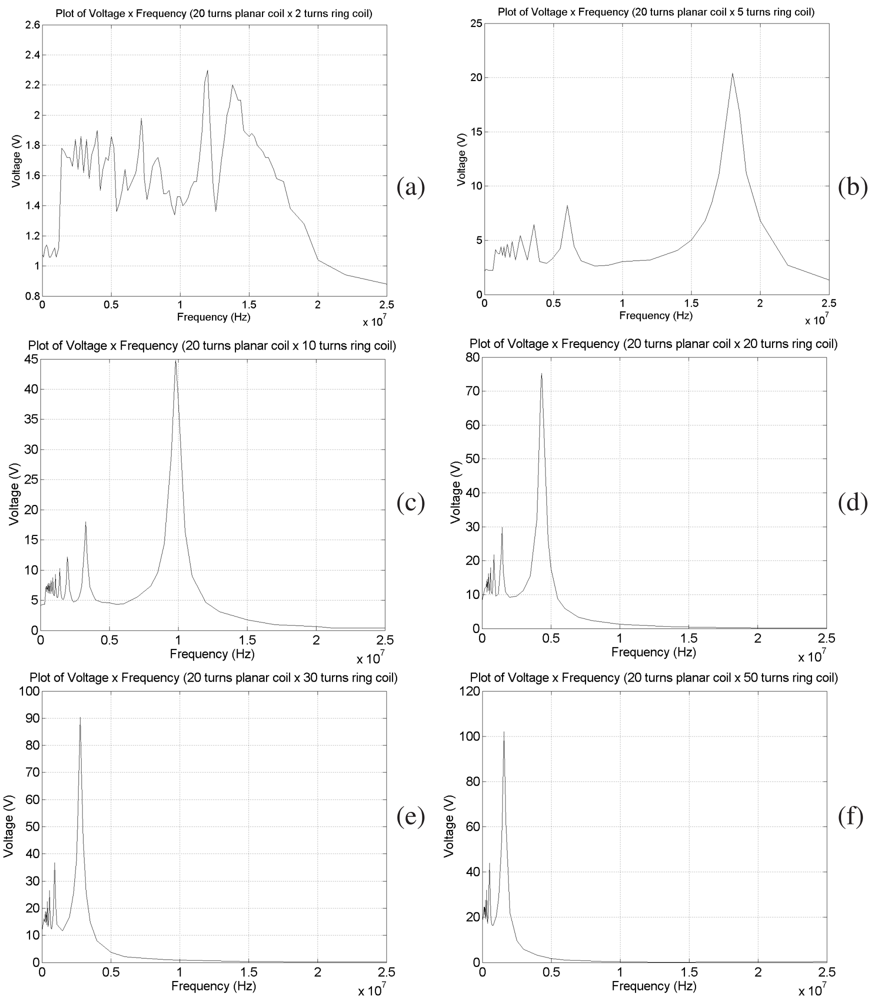


Figure 8. Graphics of crossing of 20 turns planar coil as primary vs: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

with increasing turn number of the planar coil.

Although the system presents a different response when inverted for step voltage and low frequencies excitation (due to inversion of the self inductances, parasitic capacitances and resistances of the coils in the transfer function of the system and in equivalent circuit of Fig. 2), similar data are found when frequency increases. This is shown in the next section.

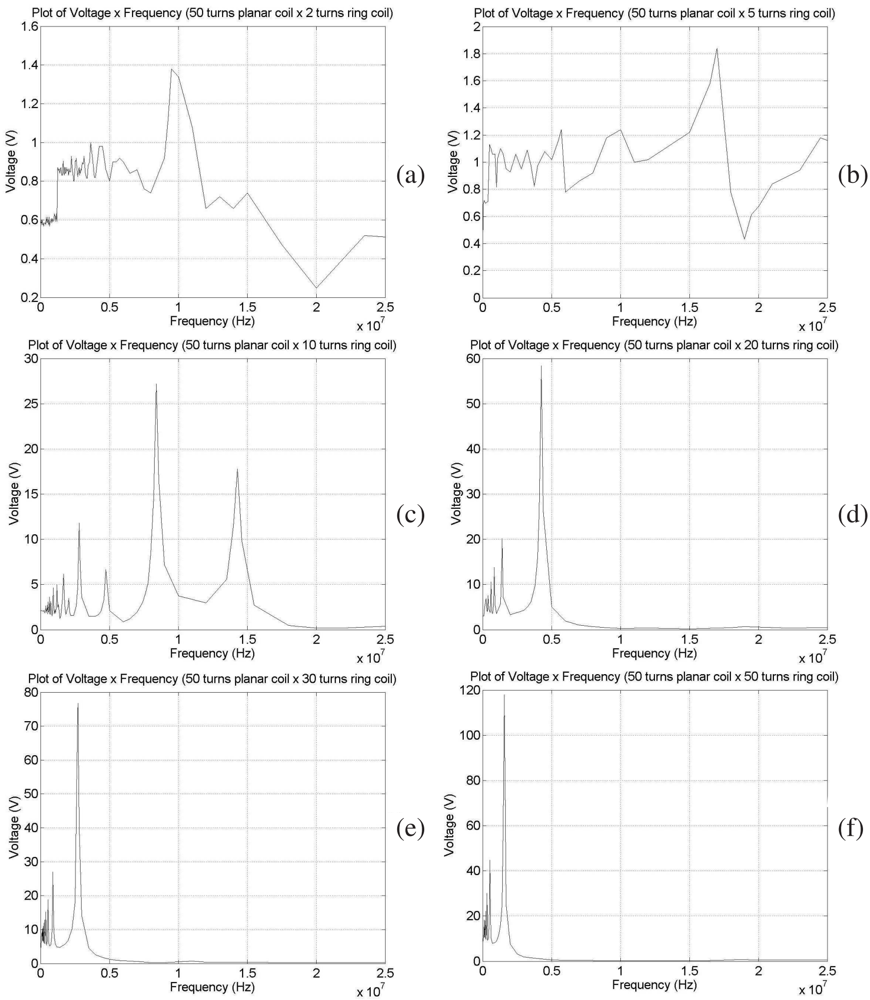


Figure 9. Graphics of crossing of 50 turns planar coil as primary vs: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

4. INVERSION OF THE SYSTEM

The realized experiments about previously described system were developed with inversion, considering planar coil as secondary (output of the signal) and the ring coil as primary (input of the signal). According to experiments, we observe that the response of the inverted

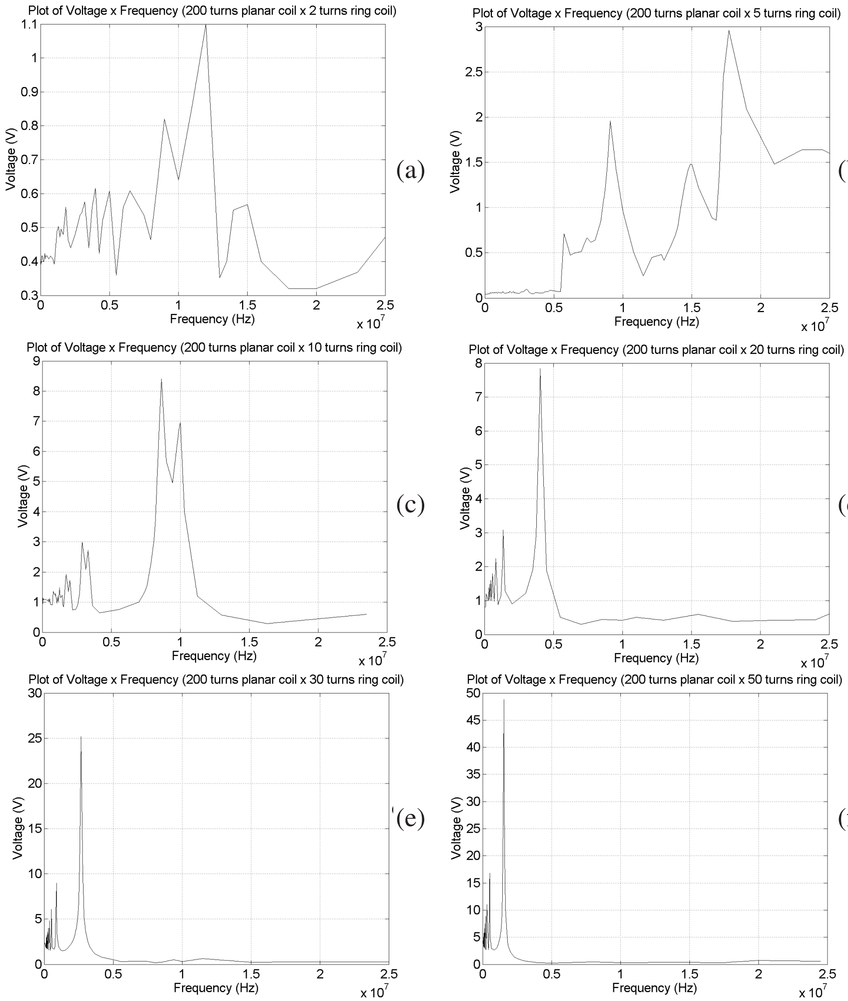


Figure 10. Graphics of crossing of 200 turns planar coil as primary vs: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

system is similar to the cases where the turn ratio between coils in the described system satisfies

$$n_p/n_s > 25,$$

n_p being the turn number in primary and n_s the turn number in secondary. This is verified in the relations in terms of transfer function of the system, as can be seen with the inversion of the parasitic

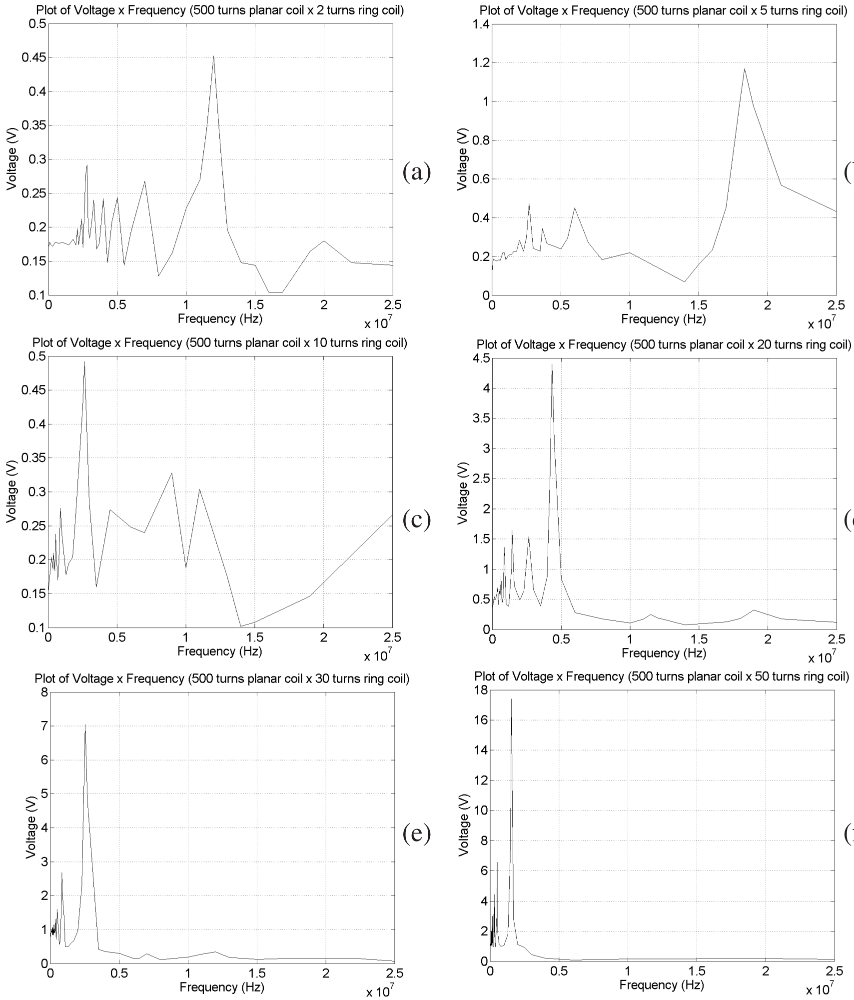


Figure 11. Graphics of crossing of 500 turns planar coil as primary vs: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

capacitances, resistances and self inductances in equivalent circuit shown in Fig. 2. In this way, these changes in terms of transfer function cause variation on system's response (reduces the higher frequency response and increases values of α and a of the Equation (6)) and consequently reduction on resonance frequencies and higher gain.

Considering the inversion of the system, the responses commonly

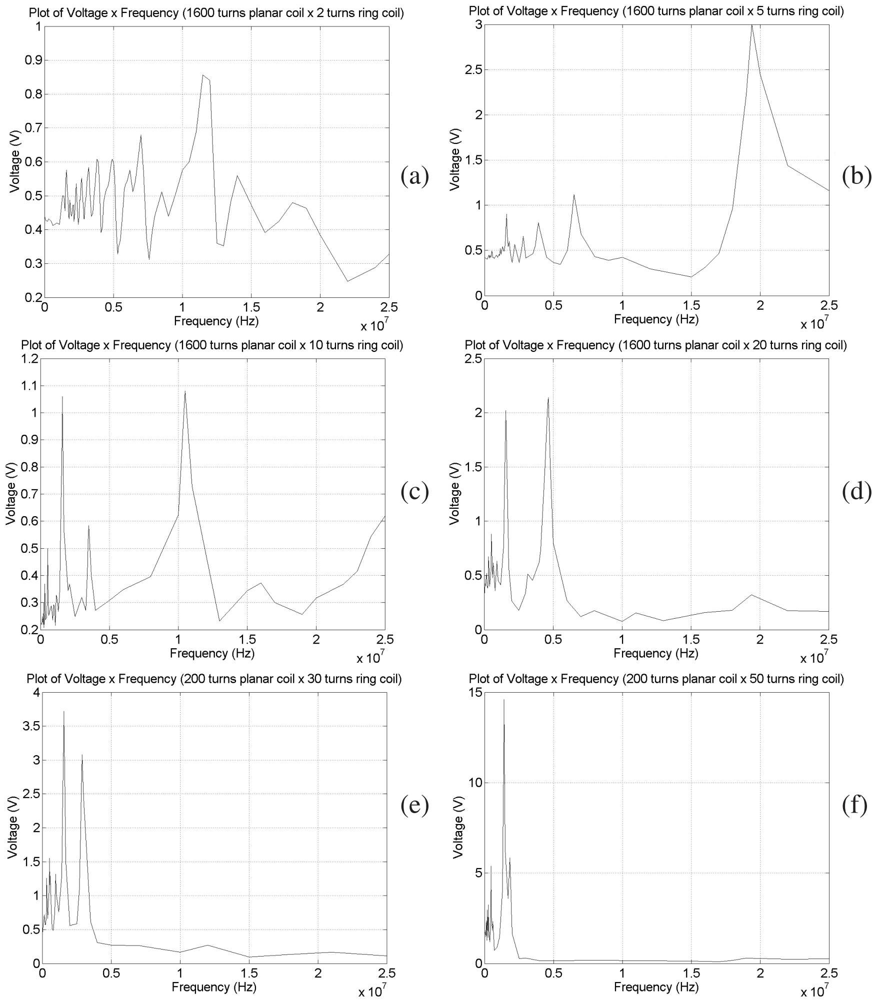


Figure 12. Graphics of crossing of 1600 turns planar coil as primary vs: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

found for described cases of coils crossing appear as shown in Fig. 13, that is the system's responses for primary being a 10 turns ring coil and secondary being the planar coils used in the experiments, for low frequencies.

Similar to initial system, the inverted system presents a sum of responses to step voltage, when the frequency is increased. However, these sum and resonance are observed at lower frequencies. This is due to inversion of data and changes in values of transfer function of the system, where the oscillatory frequency (system's response) is smaller than the initial system. Thus, peak voltage is found in the same way as Equation (6), following same results of graphs and comments about shift of resonance frequencies. These cases are shown in Figs. 14, 15, 16, 17 and 18, for the same set of Fig. 8, 9, 10, 11 and 12, respectively.

Naturally we observe that the graphs follow the same pattern in

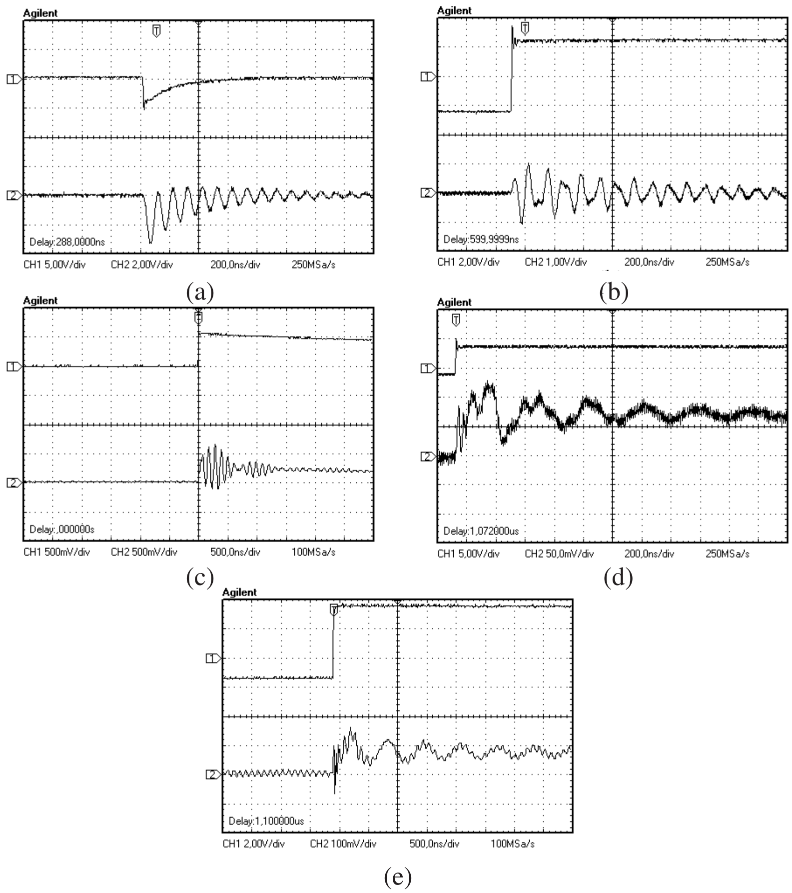


Figure 13. Responses of inverted system for case of 10 turns ring coil vs: (a) 20 turns planar coil; (b) 50 turns planar coil; (c) 200 turns planar coil; (d) 500 turns planar coil and (e) 1600 turns planar coil.

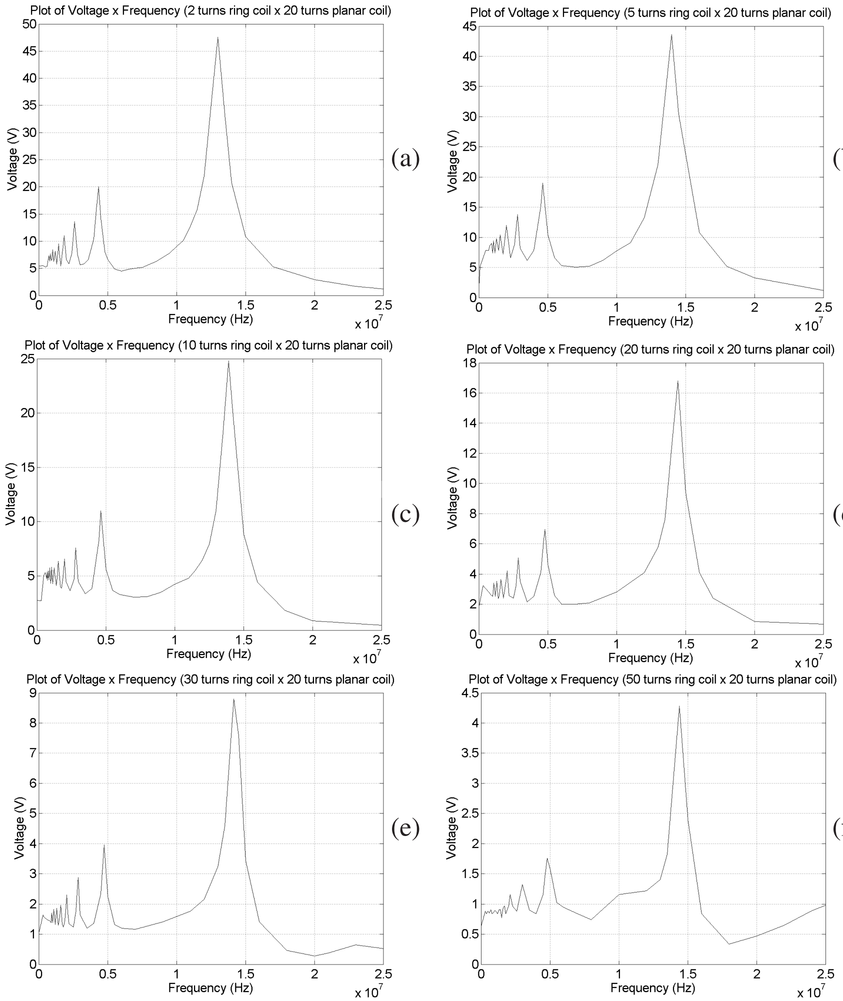


Figure 14. Graphics of inverted system for 20 turns planar coil: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

both cases (initial system and inverted system), since system's response follows the same transfer function. With inversion, only the values of the transfer function are changed, which varies the frequency of oscillatory response and the sum of the sine wave (as see in response where the turn ratio does not satisfy $15 < n_p/n_s < 25$).

Other information obtained with inversion of the system is that

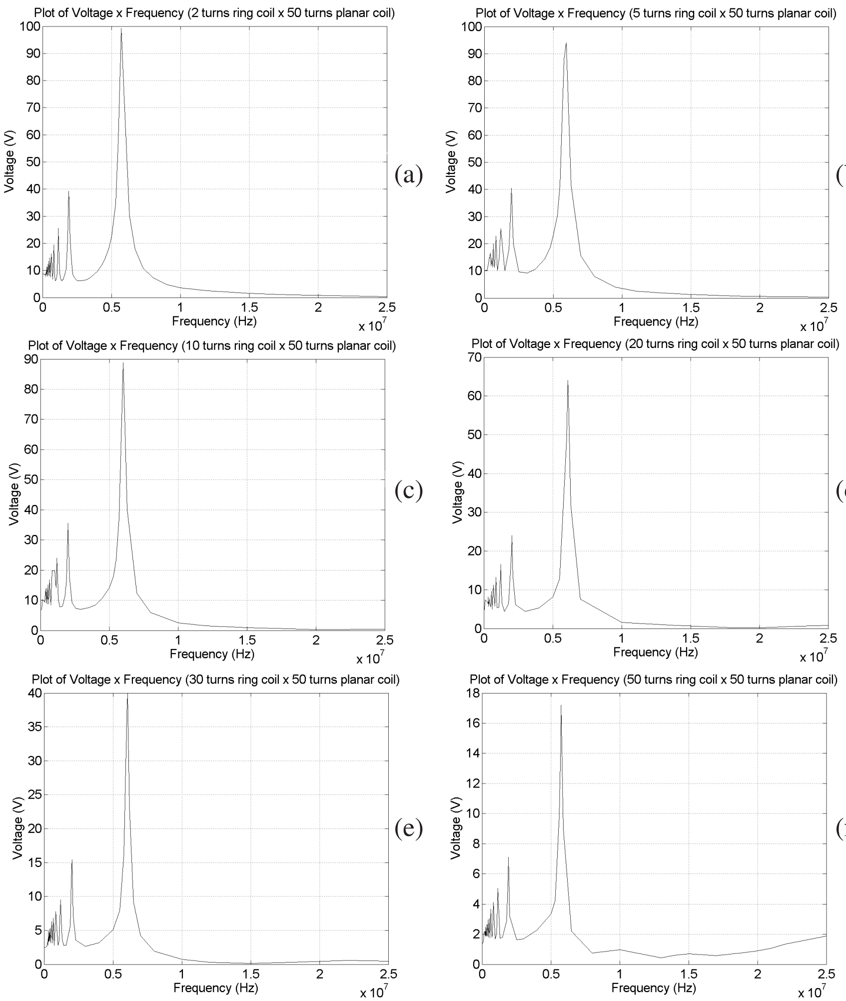


Figure 15. Graphics of inverted system for 50 turns planar coil: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

the gain is not the same when turn number is equal, as the cases of 20 and 50 turns (planar coil vs ring coil and ring coil vs planar coil with the same turn number). In these cases, we can explain this phenomenon in terms of the self inductance and parasitic capacitance of each coil. For each configuration these values change terms of the transfer function, such that the responses present variations in the elements of Equation

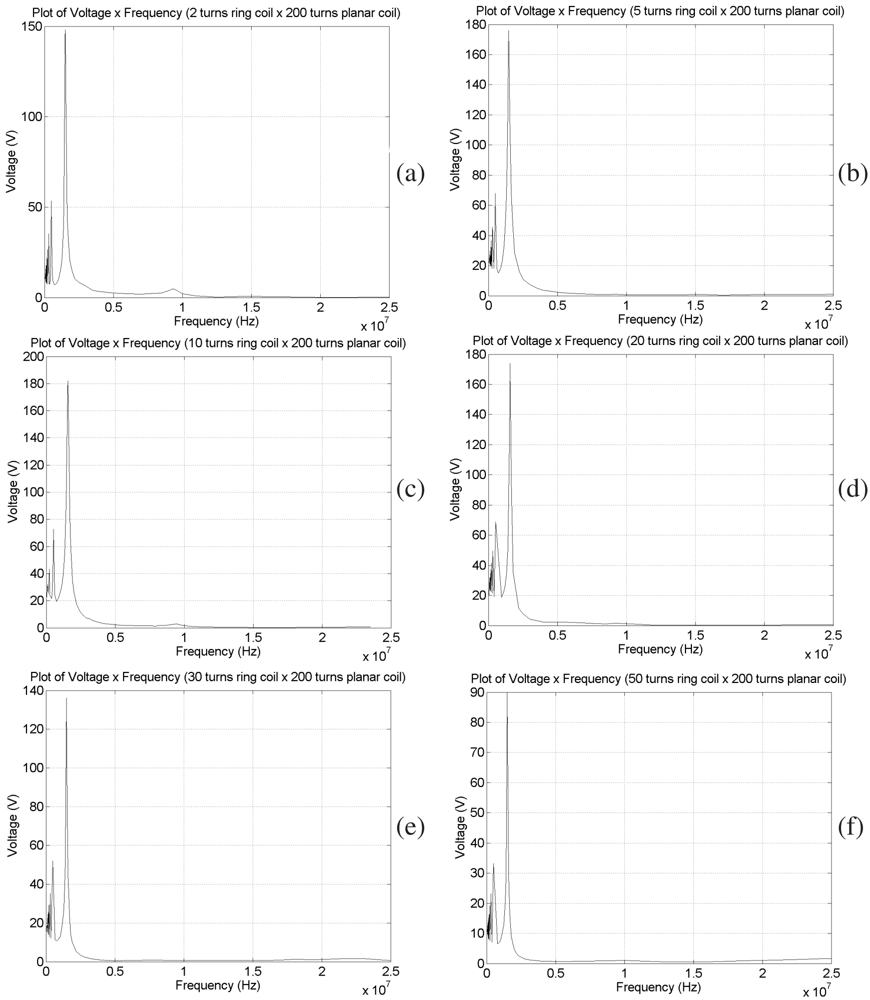


Figure 16. Graphics of inverted system for 200 turns planar coil: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

(1) varying step voltage responses. Consequently, other effects are observed, such as variation on gain and resonance frequencies, due changes on elements of Equation (6).

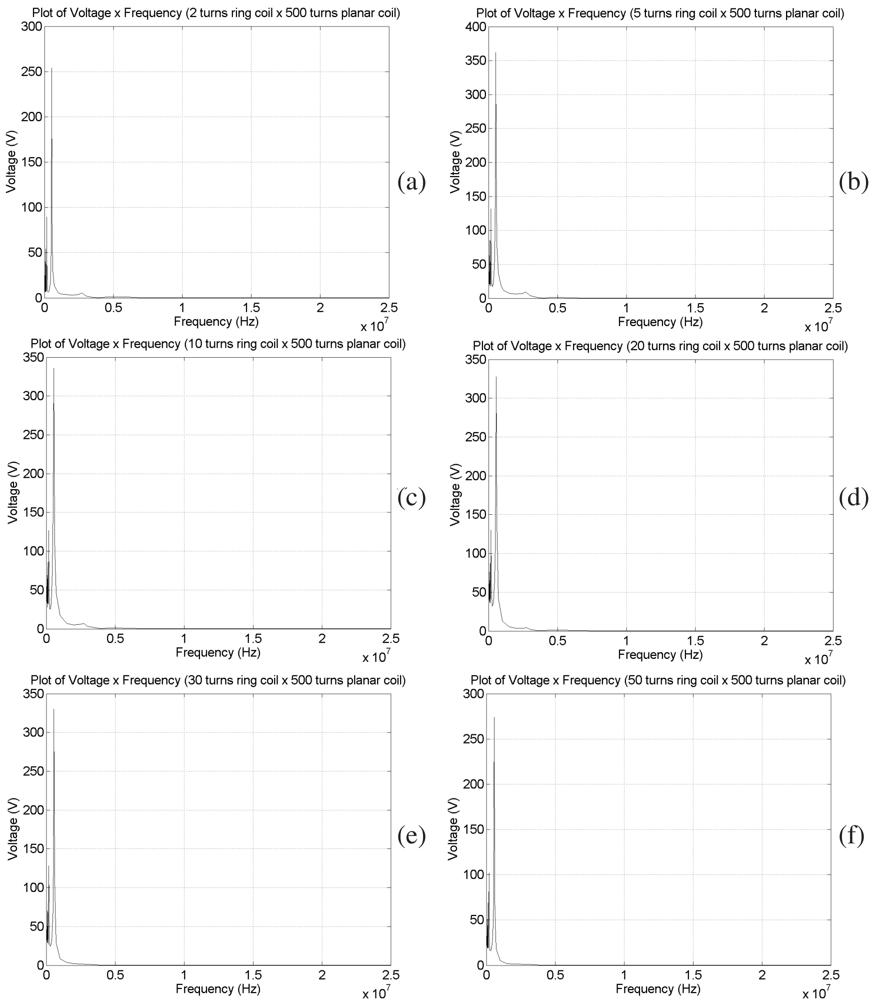


Figure 17. Graphics of inverted system for 500 turns planar coil: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

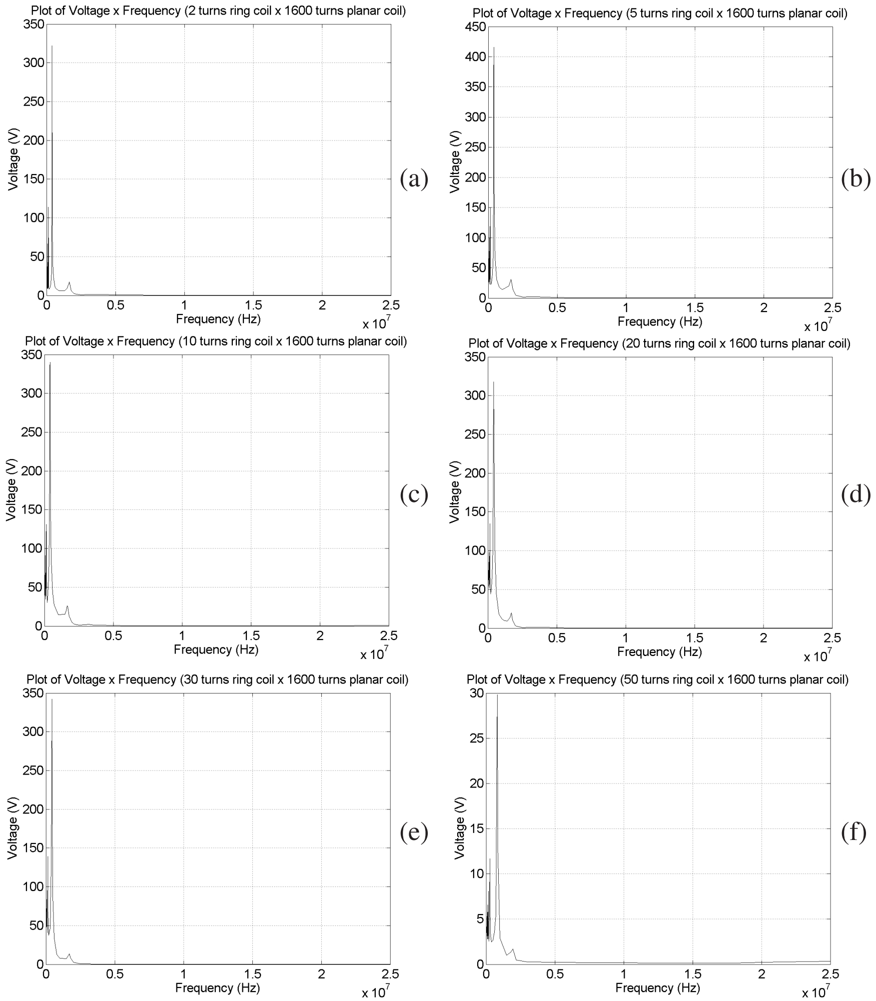


Figure 18. Graphics of inverted system for 1600 turns planar coil: (a) 2 turns ring coil; (b) 5 turns ring coil; (c) 10 turns ring coil; (d) 20 turns ring coil; (e) 30 turns ring coil and (f) 50 turns ring coil.

5. CONCLUSION

This paper presents results of an experimental work, whose aim is to analyze phenomena generated by parasitic capacitance in coupled circuits formalized by a planar coil and a ring coil, as well as the effects of excitations by high frequencies square wave, which can be applied to researches of resonance and pulse transformers, etc.

The experiments were realized by exciting the primary with a square wave and observing the response in secondary, where the theoretical analysis and comparisons with experimental results are explained through equivalent circuit shown in Fig. 2. Initially, the system with the primary as a planar coil was analyzed and later made the planar coil as secondary. The range of frequencies utilized in the experiment is between 1 kHz and 25 MHz.

The observed phenomena show the existence of parasitic capacitance effect on their responses, as well as a feature over the sum of the sinusoidal responses on rise and fall of the square wave that excites the system. The sum of responses is seen with peak voltage that increases as the frequency increases. It was observed that the resonance frequency is shifted to high frequency with the increase of turn number in planar coil, and is shifted to lower frequency with the increase of turn number in ring coil. Relationship of these peak voltages in all cases follows an almost linear pattern, which have higher voltages when the turn number of the ring coil is increased, and these output voltages decrease with increasing turn number of the planar coil. Also we observe that the peak voltages are found exactly when the relation between square wave frequency (f_s) and sine wave frequency (f_r — response of the system) satisfies $f_s = f_r/n$. In all cases, after reaching frequencies such that $f_s > f_r$, the voltage decreases quickly, which is visible in the sum of sine waves. These results are important for study of effects of square waves in circuits as power electronics, circuit theory (parasitic capacitances, self and mutual inductances, resonance and transfer function of transformers) and pulse transformers. The main results of this paper is the application to pulse transformer, which is being analyzed to appear in a future work.

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