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RESPONSES IN TRANSFORMERS BUILT WITH PLANAR COILS INNER RING COILS EXCITED BY SQUARE WAVES

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Abstract—This paper presents an analysis about the results of experiments using planar coils inner ring coils to determine a transformer. The excitation of this system was a square wave voltage, where experiments were realized in two ways: considering planar coil as primary and observing responses on secondary being ring coil (direct system) and the inverse (ring coil as primary and planar coil as secondary-inverted system). In this study, a phenomenon not common in literature on system response is analyzed, showing effects of changes on transfer function in both cases when varying turn numbers of each coil and several variations on responses due to changes on resistances, parasitic capacitances, self and mutual inductances of the coils. The uncommon phenomenon appears as modulated response on specific turn ratio. The obtained results can be used to researches in areas as power electronics and pulse transformers.

1. INTRODUCTION

Several works have been developed about transformers [1–3], considering sinusoidal excitation [4–7]. Others studies evaluate effects on transformers when excited with square waves [8–10], generally on power electronics [11], studies about effects on core materials or analysis in high voltage [12, 13], as pulse transformers [14–17].

When analyzing a transformer with an excitation of square wave, some works relate effects by its transfer function, while researches

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about planar coils and transformers built with these types of coils [18–22] is generally made on microcircuits [23–29], where some analysis about electromagnetic fields are realized [30–33], to apply technology in [34, 35]. Considering transformers built with planar coils inner ring coils, basically we find very little in the literature, where important effects are shown as in [36], where some brief similarities are found in problems as in [12, 13].

Considering the effects presented in [36], we observe similar considerations when analyzing systems with pulsed excitation [12–17]. However, although these systems show similarities, analysis about systems defined as planar coil inner ring coil is not found. In the analysis presented in [36], we see the phenomenon of double sine waves in response to an excitation by square wave in primary coil (planar) of the transformer for 200 turns planar coil, which is uncommon in literature. In this case, these effects are shown as presence of parasitic capacitances [37–39]. This phenomenon of double sine wave which appears as amplitude modulation occurs only when the turn ratio between planar coil and ring coil appears between 15 and 25. This phenomenon is very interesting to several research areas such as power electronics, pulse transformers, etc. In this case, an analysis using other planar coils, with different turn numbers, has shown other effects about these responses (with double sine waves), which is a phenomenon that occurs in specific values in terms of the transfer function of the system. Such an analysis is shown in this paper, where these effects open new prospects on researches with planar coils and other areas that use pulse excitation.

This paper is presented as follows: in Section 2 demonstrates the coils data and utilized equipments in realized experiments; Section 3 offers analysis about responses of the defined configurations, transfer function of the equivalent circuit based on Laplace transform and some discussions about found results; Section 4 analyzes the problem of inversion of the system; Section 5 presents the conclusions of this work.

2. DATA OF EXPERIMENTS

In the work that based on this paper, experimental data were obtained on some planar coils inner ring coils. Basic data of the systems are:

- Planar coils used were built with turn number defined by: 10, 20, 50, 200, 500 and 1600;
- Ring coils were built with turn number of: 2, 5, 7, 9, 10, 12, 15, 20, 30 and 50;
- Excitation system was given through a square wave of 5 V peak to peak (2.5 V peak);

- Frequencies ranging from 1 kHz to 300 kHz;
- Coils built on copper wire with diameter 2.02×10^{-4} m (32 AWG) or 1.80×10^{-4} m (36 AWG);
- Planar coils diameter $d = 4.01 \times 10^{-2}$ m, with height from $h = 1.80 \times 10^{-4}$ m (10 to 50 turns) to $h = 5 \times 10^{-4}$ m (≥ 200 turns);
- Ring coils diameter $D = 4.65 \times 10^{-2}$ m arranged such that its height have approximately the same height of the planar coil;
- Digital storage oscilloscope Agilent Technologies DSO3202A with passive probe N2862A (input resistance $= 10M\,\Omega$ and input capacitance $\simeq 12$ pF);
- Function generator Rigol DG2021A;
- Digital multimeter Agilent Technologies U1252A.

Considering these data and equipments used in the experiments, initially we excite planar coil and observe the induced *emf* in the ring coil (system response), and later, we invert the system exciting the ring coil and checking the induced *emf* in the planar coil. In the first case, we call direct system and in second case, inverted system. In each planar coil, we realize crossing with all defined ring coil to realize the induced *emf* measurements, which give a total of 60 crosses considering the planar coils as primary of the system (direct system), and the same 60 crossings considering the ring coils as primary (inverted system).

In Fig. 1, we see basic structure of the experimental system, where the results of this paper are found.

The defined configuration generated some information about behavior of its transfer function, showing existence of parasitic capacitances [36–39], as well as important and specific patterns not common in literature, such as double sinusoidal and double exponential drop in response, modulated responses between the two oscillatory frequencies, and variations on frequencies and modulated responses

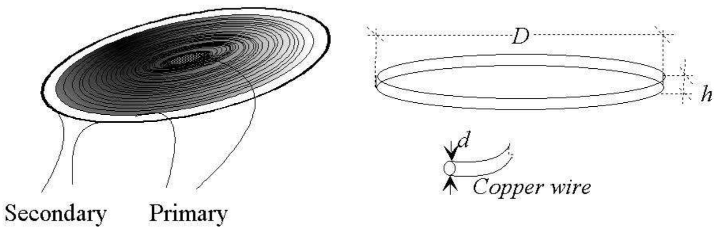


Figure 1. Air core transformer with planar coil inner ring coil.

with changes on turn numbers of coils. The analysis shown in the following sections describes information that open some feasibility of researches and applications in this area.

3. BASIC EXPERIMENTS ON SYSTEM: RESULTS AND INFORMATIONS

As cited in [36], the equivalent circuit of the system is described as shown in Fig. 2 where r_j are the resistances of the coils (measured with digital multimeter), L_j the self inductances, M the mutual inductance, both calculated with results of [40–43], and the parasitic capacitances are C_{gj} (parasitic capacitances in relation to a ground) and C_{cj} (turn to turn parasitic capacitances) where $j = 1, 2$, calculated with results of [37–39], with v_i being the input signal and v_0 the output signal. Initially, we excite the primary of the system by a square wave with frequencies ranging from 1 kHz to 300 kHz. In most cases, the response remained constant as an input step voltage, with signal response following the rise and fall of the square wave. In these primary experimental results, the analyzed systems were considered with planar coils as primary and ring coils as secondary (direct system).

In these experiments, for frequency $f = 1\,\text{kHz}$, the obtained results of some configurations is shown in Fig. 3, where the upper graph is the channel 1 (input signal) and lower graph (channel 2) is the response. In some graphs the input signal (square wave) is presented with exponential drop, because passive probe of the oscilloscope is in parallel with the coil. As the primary coil has a resistance, the signal is seen as response of RL circuit. These responses are similar to input step voltage and equal in most cases until frequencies $f = 300\,\text{kHz}$.

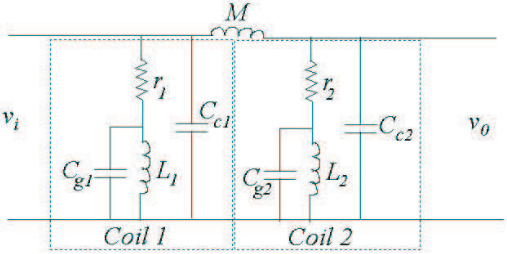
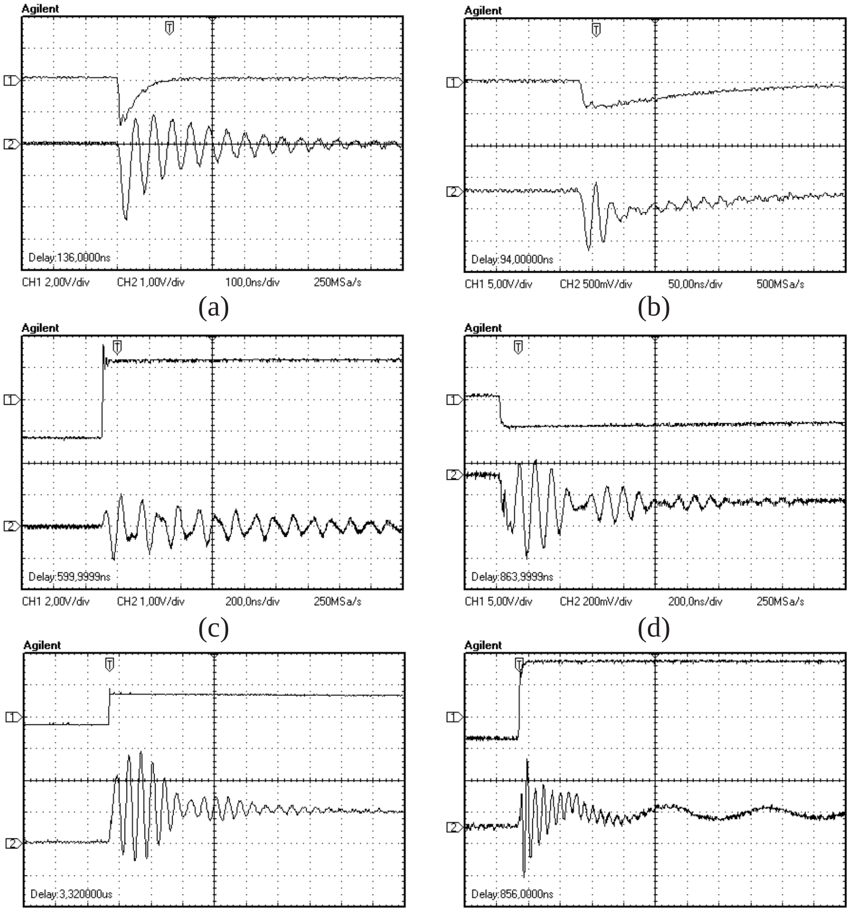


Figure 2. Equivalent circuit of the system, considering resistance of the coils, self and mutual inductances and parasitic capacitances.

In Fig. 4, we see responses of the system in the same frequency $f = 1\,\text{kHz}$ as other configurations. In this case, excluding Fig. 4(f), the



(a) (b)

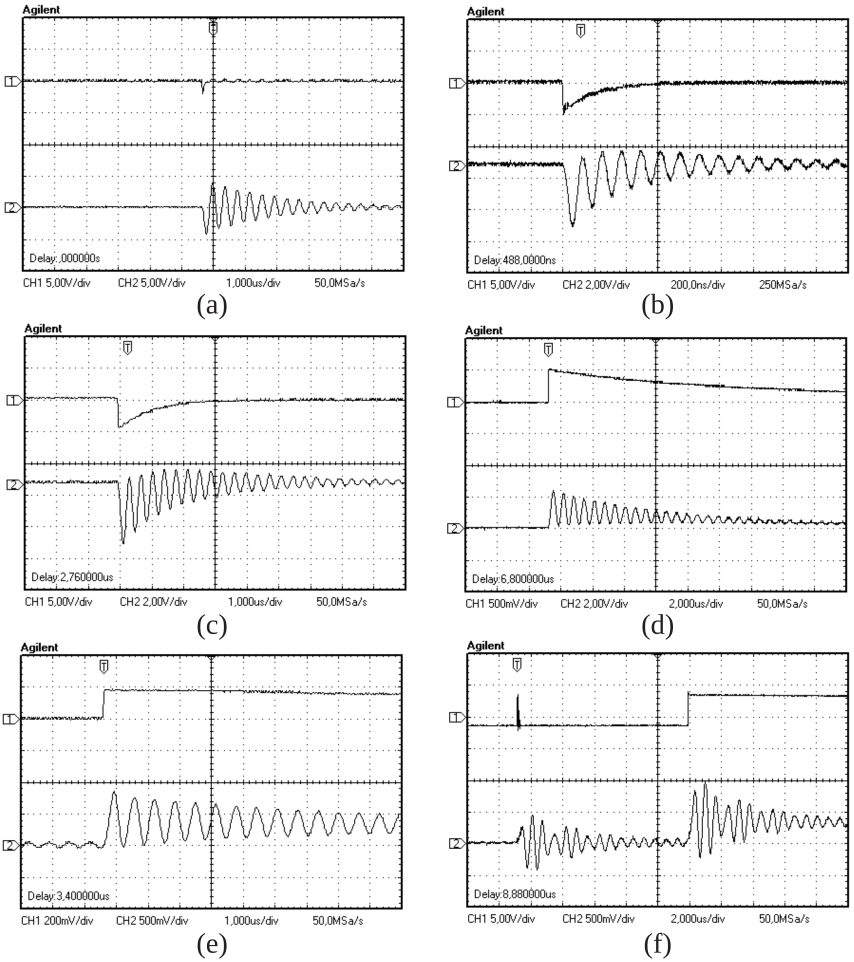
(c) (d)

(e) (f)

Figure 3. Responses of the system on configurations: (a) 10 turns planar coil *vs* 5 turns ring coil; (b) 20 turns planar coil *vs* 2 turns ring coil; (c) 50 turns planar coil *vs* 10 turns ring coil; (d) 200 turns planar coil *vs* 9 turns ring coil; (e) 500 turns planar coil *vs* 30 turns ring coil; (f) 1600 turns planar coil *vs* 5 turns ring coil.

responses are different from that in Fig. 3, because turn ratio described in [36] is not satisfied.

Based on main results found in [36], we see that the output signal



(a) (b) (c) (d) (e) (f)

Figure 4. Responses of the system to configurations: (a) 10 turns planar coil *vs* 30 turns ring coil; (b) 20 turns planar coil *vs* 12 turns ring coil; (c) 50 turns planar coil *vs* 30 turns ring coil; (d) 200 turns planar coil *vs* 50 turns ring coil; (e) 500 turns planar coil *vs* 50 turns ring coil; (f) 1600 turns planar coil *vs* 50 turns ring coil.

response v_0 is given by:

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

which is found based on configuration 200 turns planar coil *vs* 10 turns ring coil. In this way, since

$$\sin(\omega t) = \frac{e^{j\omega t} - e^{-j\omega t}}{2j}$$

then, we have that

$$v_0 = A\left[\left(\frac{e^{j\omega_1 t} - e^{-j\omega_1 t}}{2j} \times \frac{e^{j\omega_2 t} - e^{-j\omega_2 t}}{2j}\right)e^{-bt} + c\right]e^{-dt} \tag{2}$$

$$v_0 = -\frac{A}{4}\left[e^{-tZ_1} - e^{-tZ_2} - e^{-tZ_3} + e^{-tZ_4} + ce^{-dt}\right] \tag{3}$$

where $Z_1 = b + d - j(\omega_1 + \omega_2)$; $Z_2 = b + d - j(\omega_1 - \omega_2)$; $Z_3 = b + d - j(\omega_2 - \omega_1)$ and $Z_4 = b + d + j(\omega_1 + \omega_2)$.

Using Laplace transform, we obtain:

$$V_0(s) = \frac{z_5 s^4 + z_4 s^3 + z_3 s^2 + z_2 s + z_1}{s^5 + p_4 s^4 + p_3 s^3 + p_2 s^2 + p_1 s + p_0} \tag{4}$$

which is the system response to step voltage, being

- $z_5 = c$;
- $z_4 = 4xc$;
- $z_3 = ((6x^2 + y_2 + y_1)c + 2(y_2 - y_1)a)$;
- $z_2 = ((4x^3 + 2x(y_1 + y_2))c + (2(y_2 - y_1)(x + d)a))$;
- $z_1 = ((x^4 + x^2(y_1 + y_2) + y_1 y_2)c + (2(y_2 - y_1)dx)a)$;
- $p_4 = 4x + d$;
- $p_3 = (6x^2 + y_2 + y_1 + 4xd)$;
- $p_2 = 4x^3 + 6dx^2 + (2x + d)(y_1 + y_2)$;
- $p_1 = x^4 + 4dx^3 + (y_1 + y_2)(x^2 + 2dx) + y_1 y_2$;
- $p_0 = (x^4 + x^2(y_1 + y_2) + y_1 y_2)d$

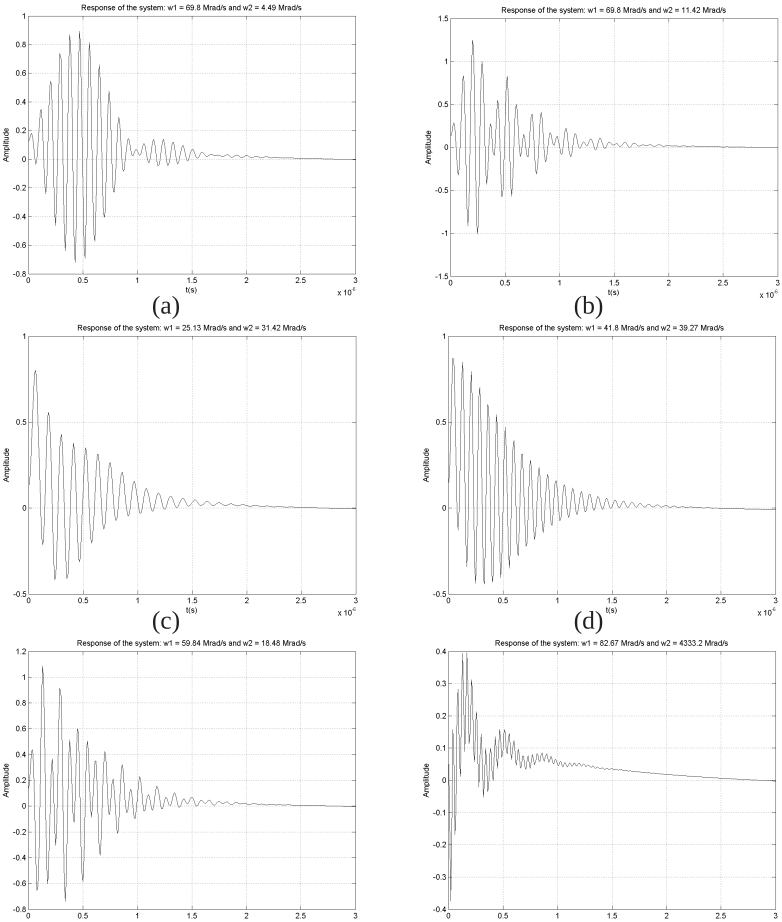
with

- $x = b + d$;
- $y_1 = (\omega_1 + \omega_2)^2$;
- $y_2 = (\omega_1 - \omega_2)^2$;

Since that Eq. (4) is the response to step voltage, whose Laplace transform is given by $1/s$, then multiplying this equation by s, we obtain the transfer function of the system given by:

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

Although this equation is the transfer function of cited configuration (200 turns planar coil *vs* 10 turns ring coil), which was obtained through its response; it is valid for all others, since the system is the same (varying only turn numbers). Using this transfer function in simulation using a input step voltage and varying the values of ω_1 and ω_2, we find the results of other configurations. This is because the same



(a) (b) (c) (d) (e) (f)

Figure 5. Simulations of output voltage of the system by application of step voltage on its transfer function for: (a) $\omega_1 = 69.8 \times 10^6$ rad/s and $\omega_2 = 4.49 \times 10^6$ rad/s; (b) $\omega_1 = 69.8 \times 10^6$ rad/s and $\omega_2 = 11.42 \times 10^6$ rad/s; (c) $\omega_1 = 25.13 \times 10^6$ rad/s and $\omega_2 = 31.42 \times 10^6$ rad/s; (d) $\omega_1 = 41.8 \times 10^6$ rad/s and $\omega_2 = 39.27 \times 10^6$ rad/s; (e) $\omega_1 = 59.84 \times 10^6$ rad/s and $\omega_2 = 18.48 \times 10^6$ rad/s and (f) $\omega_1 = 82.67 \times 10^6$ rad/s and $\omega_2 = 4333.2 \times 10^6$ rad/s.

response can be seen in all configurations, such as double sine wave and double exponential drop, which in some cases, the relationship between the frequencies is great enough to eliminate visibility of the modulation.

The system presents parasitic capacitances, self inductances, mutual inductance and resistances; the values of the frequencies ω_1 and ω_2 are dependent on these parameters. In this way, we observe that when the turn number of the planar coil in relation to turn number of the ring coil (turn ratio increases much above 25) increases, frequency ω_2 decreases. This effect can be seen in some configurations using 1600 turns planar coil, where we observe a sine wave with frequency ω_1 (higher frequency) on exponential drop following the sine wave on second exponential drop with frequency ω_2 (lower frequency). When turn ratio is between 15 and 25, as cited in [36], the modulation of double sine wave is found. In other cases, the frequency ω_2 is such that we do not observe modulation effect.

In Fig. 5, we see some simulations for these cases, which show the found results.

When considering the inverted system, that is, ring coil as primary and planar coil as secondary, we see that the modulation is not observed, as cited in [36] for analyzed configurations. This is discussed in the next section.

4. RESULTS FOR INVERTED SYSTEM

Inversion of the system, exciting ring coil with square wave and observing the response in planar coil were realized to verify effects and relationships with the transfer function described in the previous section. Thus, in all described configurations, considering their inversions, the responses of the system were measured and analyzed, to be compared with described transfer function. In this case of inverted system, since the turn ratio does not satisfies $15 < n_p/n_s < 25$, being n_p the turn number of the primary coil and n_s the turn number of the secondary coil, as may be seen in [36], the responses appear without described modulation, as shown in Fig. 6. But in this case, an effect of antisymmetry is observed when turn number of the ring coil increases. This phenomenon is shown in Fig. 7, in case of primary with 50 turns ring coil and secondary with 1600 turns planar coil, in comparison with Fig. 6(f), where the primary has 2 turns ring coil.

For this case, using the results about transfer function shown in the previous section, we observe that although the transfer function does not change, the inverted turn number generates variations in the elements p_i and z_j of the transfer function. These results are obvious, because the elements in the system are the same. But inversion between primary and secondary generates the inversion in their positions on equivalent circuit shown in Fig. 2. However, inversion of these elements between primary and secondary causes the inversion of the turn ratio which causes changes on the oscillatory frequencies of the response. Consequently, these variations increase periods of oscillatory responses (the two sine waves), such that the lower frequency response becomes not visible in final response.

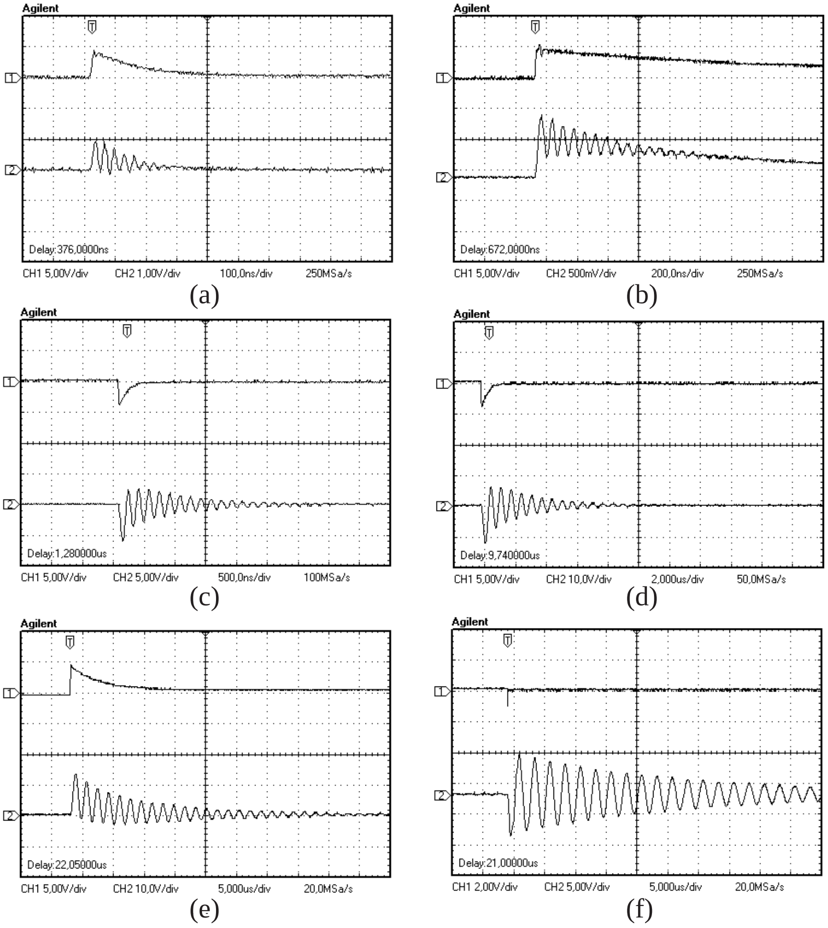


Figure 6. Responses of the inverted system in configurations: (a) 9 turns ring coil *vs* 10 turns planar coil; (b) 30 turns ring coil *vs* 20 turns planar coil; (c) 7 turns ring coil *vs* 50 turns planar coil; (d) 12 turns ring coil *vs* 200 turns planar coil; (e) 50 turns ring coil *vs* 500 turns planar coil and (f) 2 turns ring coil *vs* 1600 turns planar coil.

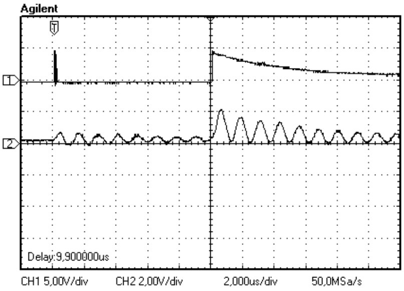


Figure 7. Responses of the inverted system in configurations 50 turns ring coil *vs* 1600 turns planar coil.

When analyzing the inverted system, based on described transfer function, the responses are presented as shown in Fig. 5, since the parameters of the coils meet the conditions of turn ratio. In the analyzed cases, this turn ratio presents results with similarities to cases of Figs. 5(c) and (d) and, in some configurations, as 10 to 50 turns ring coil *vs* 10 turns planar coil, the results appear as the cases shown in Figs. 5(b) and (e).

Through these results, we see that the relationship between the frequencies (which depend on parasitic capacitances, self and mutual inductances and resistances) defines the behavior of system response, proving that the transfer function is the same in both cases: direct and inverted systems. In the other way, we see in both cases that the behavior of the system depends on parasitic capacitances, resistances and self inductances of the coils and mutual inductance, where these parameters change the frequencies of the two sine waves and two exponential drops on response. Consequently, these changes cause the variations in the elements p_i and z_j of the transfer function, determining these observed responses.

Also, in the obtained results we see that the higher frequency presented in response of the inverted system, which is always less than observed frequency in initial case (direct system). However, in the inverted system, the range of frequencies of the input square wave should be lower than 300 kHz, for the system has the same response to input step voltage.

5. CONCLUSION

This paper presents some results about induced *emf* in systems described as transformer built with planar coil inner ring coil, excited by square wave. In the presented results, we observe the behavior of the induced *emf* based on transfer function, showing that the response cited in [36] is common in all cases worked. This behavior is observed as a double sine wave with a double exponential drop, where the two frequencies maintain a relationship between turn numbers of the coils and their parasitic capacitances, self inductances, resistances and mutual inductance, which is an uncommon phenomenon in literature. Considering the inverted system, we observe that the response maintains the same relationship, but due to inverted values of these parameters, the oscillatory frequencies vary so that the effect of the modulation is not available. Also, due to this effect, the response presents a lower frequency. Consequently, the range of the square wave frequency, which excites in the system and maintains the response similar to system response on input step voltage, is lower than the initial analyzed system (planar coil as primary, or direct system), reducing the range of frequencies. Above these frequencies, other phenomena as sum of responses and resonance are verified. These results are of great importance to researches on power electronics and pulse transformers, which are currently applied. From applications perspective, the results of simulations and measurements were formalized in different forms, focusing especially on the frequencies of the system responses.

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