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# Study on Transformer JED Cap Actuation Systems in the Field of Very Strong Electromagnetic Disturbances

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**Abstract.** This work presents the results of research on the influence of strong external electromagnetic fields on the operation of JED spark caps activated by transformer systems. The tests were carried out in order to determine the conditions of safe use of JED caps installed in control systems of generators producing electric current pulses using the principle of an explosive magnetic field cumulation [1]. For this purpose, the measurements of the voltages induced in the transformer JED spark cap actuation system were performed using sinusoidal external current with an amplitude of 10 kA for a period of 15 microseconds.

This current flowed at a distance from $d$ = 10 mm to $d$ = 40 mm from the axis of the ferrite cores of the applied transformers: a closed core with an outer diameter of 20 mm, an inner diameter of 10 mm and a height of 10 mm and an open core with a diameter of 6 mm and a length of 25 mm. The transformers used in Air Force Institute of Technology (AFIT) were placed alternately parallel and perpendicular to the axis of the current conductor. In the case of a transformer with a cylindrical open core perpendicular to the current axis, the induced voltages significantly exceeded the values at which the caps were activated (about 2 kV) and became lower than these values at $d$ of about 40 mm. Toroidal closed cores provided induced voltages of up to 200 V (10 times lower) for all configurations tested. The measurements were performed using a system and methods developed at AFIT.
**Keywords:** explosion physics, spark cap, induced voltage

## 1. INTRODUCTION

Explosive devices, such as: single and two-stage cumulative charges [2], explosive electric current pulse generators [3], systems of super-strong shock wave generators [4] and others, require the initiation of detonation at multiple points, in a set time sequence and with the initiation time accuracy from several to a few dozen nanoseconds. For this purpose, high-voltage JED type spark caps are used (the commonly adopted name probably comes from the Russian “Iskrovyi Elektro-Detonator”; the letter “J” was adopted instead of “I” for convenience and for distinguishing from the definition of improvised explosives).

JED spark caps are pyrotechnic elements that enable detonation to be initiated with short delay (~ 1.5 μs) and high time precision (~ 50 ns) [5]. This precision (due to the principle of operation – initiation as a result of an electric discharge along the surface of the pyrotechnic substance moulding) is related to the high sensitivity of these caps to static electricity and electromagnetic fields in their environment.

JED caps react to the supply of even small amounts of electricity (0.16-0.81 mJ, average energy of approx. 0.5 mJ) [5] from a source with a voltage above approx. 2 kV (average voltage from tests 2.57 kV, standard deviation 0.37 kV, minimum measured response voltage 1.48 kV), which requires the operators to be particularly careful when handling them (danger of static triboelectrization). In some technical solutions, transformer circuits [5], in which the inputs to the fuse are statically short-circuited, seem to be safer when actuating these caps, as compared to the direct application of high voltage pulses. Such systems are advantageous in the cap property testing phase because they allow for the simultaneous determination of voltage and time delay in a single shot. However, in this case, accidental actuation may be triggered by electromotive forces induced by rapidly changing currents flowing nearby. This work deals with investigating the influence of such currents.

## 2. MEASURING SYSTEM

The schemes of two versions of the measuring system are shown in Figures 1 and 2. The disturbance was induced by a circuit in which an electric current pulse $i(t)$ was generated in the shape of a damped sinusoid with an amplitude of $I_{max}$ = 10 kA, period of $T$ = 15 μs and a maximum increase rate of $4.2\times10^9$ A/s. The circuit, designed to actuate primers (firing circuit), constituted a ferrite transformer with a primary winding (which was energized with a pulser voltage) with a shorted resistor $R$ = 50 Ohm, the secondary winding of which, "operationally" sending the actuating voltage to the cap, was connected to a high-voltage capacitive divider with a division of 805:1. In this system of target cap actuation, they could potentially be located, together with the isolating transformer, in the vicinity of single long power cables. Treating the interfering DC cable with current ($I$) as rectilinear and infinitely long, it can be stated that the magnetic field strength it produces changes as a function of the distance ($d$) from it using the following equation:

$$H = I / (2\pi d),$$

therefore, the electromotive strength of the disturbance is

$$\mathrm{SEM} = \mu_0\mu\, S_E\, \mathrm{d}H/\mathrm{d}t = \mu_0\mu\, S_E\, (\mathrm{d}I/\mathrm{d}t) / (2\pi d) \sim 1 / d. \tag{1}$$

$\mu_0$ is the magnetic permeability of the vacuum, $\mu$ - the relative permeability of ferrite, $S_E$ is the effective active surface area of the winding. In the general case of winding consisting of $n$ turns, each of which has a surface area $S$, where the normal to their respective surfaces forms an angle $\varphi_i$ with vector $\underline{\mathbf{H}}$, we obtain the sum:

$$S_E = {}_{i=1}\Sigma^n\, S \cos \varphi_i\,, \tag{2}$$

where $\varphi_i = 0$ for winding of area $\perp \underline{\mathbf{H}}$ , $\varphi_i = \pi/2$ for winding of area $\parallel \underline{\mathbf{H}}$.
For $d$, which is much larger than the transformer dimensions, it can be assumed that each of the angles $\varphi_i$ is the same. However, in the measurements presented below it is not true and for the convenience of further description we will introduce the averaged angle $\varphi_{av}$ such that:

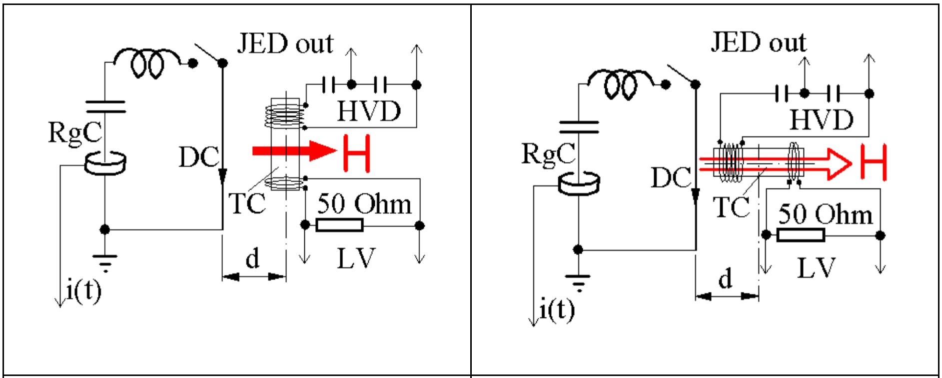
$$\cos \varphi_{av} = ({}_{i=1}\Sigma^n \cos \varphi_i) / n \tag{3}$$

and yet, when we talk about the inclination of the entire winding with respect to $\underline{\mathbf{H}}$ (in particular perpendicular or parallel), we mean this angle.

The induced voltage waveforms were recorded using a digital oscilloscope: $U_0$ – from a 50 Ohm resistor and $U_{WN}$ – from a capacitive divider (5 pF/4025 pF), and the waveform of the disturbing current, measured using Rogowski coil with a passive integrator circuit with a time constant of 1.94 ms and sensitivity of the measuring channel of 27 kA/V. Two cases were examined:

A) – a firing system with a transformer with an open cylindrical ferrite core with a diameter of 6 mm and a length of 25 mm;

B) – a firing system with a transformer with a closed toroidal ferrite core with the following diameters: outer 22 mm and inner 10 mm, and a height of 10 mm.




| a) | b) |
|---|---|

Fig. 1. Scheme of the measuring system; a) – measurement in the case of (A-α), b) – in the case of (A-β); designations: RgC – Rogowski coil; *i*(*t*) – measured current signal output to the oscilloscope; DC – cable of the system generating the current inducing noxious voltage; TC – transformer core (in Figs. c and d – core cross-section); LV – voltage induced in the primary winding of the transformer output to the oscilloscope; JED out – output from the secondary winding to the actuated cap; HVD – high-voltage capacitive divider output to the oscilloscope; H – vector of the DC current magnetic field (in c) and d) – perpendicular to the plane of the drawing).

The axes of the firing system transformers were placed at three distances from the rectilinear section of the cable with the disturbing current flow. In each case, the effect was tested by the plane of the core coils approximately

- parallel (α)
- and perpendicular (β) in the sense of formula (3) to the vector of magnetic field strength **H** generated by the cable conducting the current.

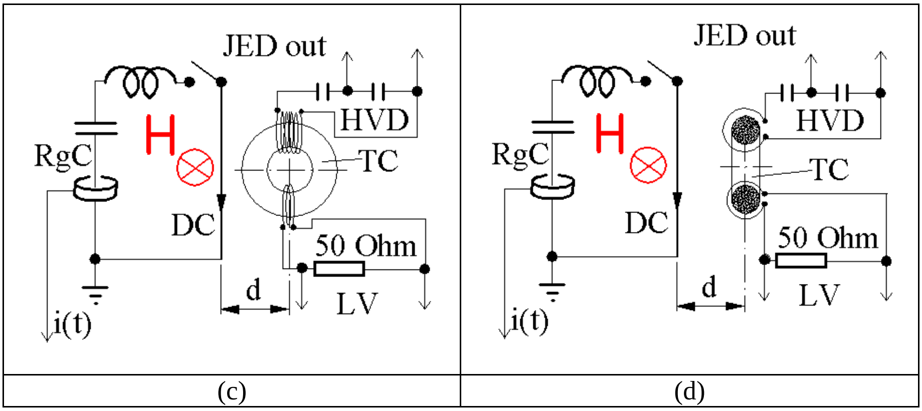



Fig. 2. Scheme of the measuring system; c) – measurement in the case of (B-α), d) – in the case of (B-β); designations – as in Fig. 1; H – vector of the DC current magnetic field in c) and d) – perpendicular to the plane of the drawing.

## 3. TEST MEASUREMENT RESULTS

### 3.1 Measurements in a system with an open core transformer

Examples of the disturbing current and voltage $U_0$ and $U_{WN}$ waveforms induced by the disturbing current in the transformer windings in various configurations are shown in Figs. 3-8. The summary of the measured maximum induced voltages is presented in Table 1.

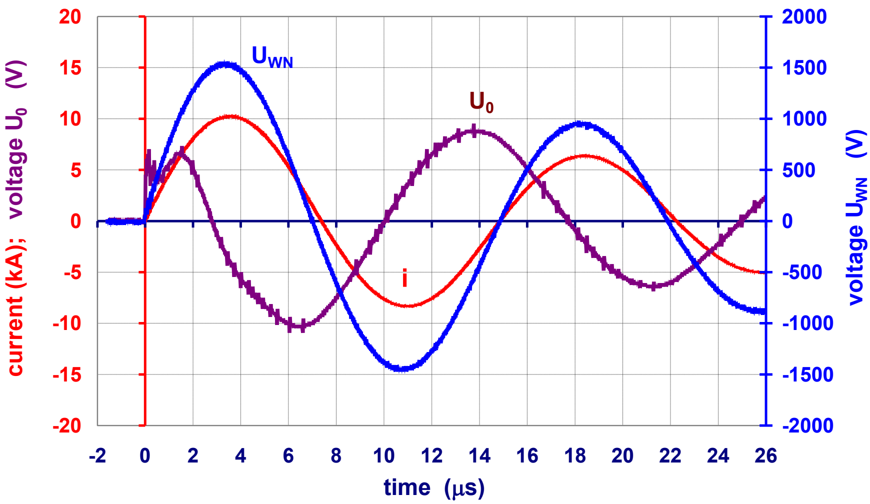



Fig. 3. Operation of the transformer (A) in position (α), *d* = 1 cm (directly by the cable with the disturbing current)

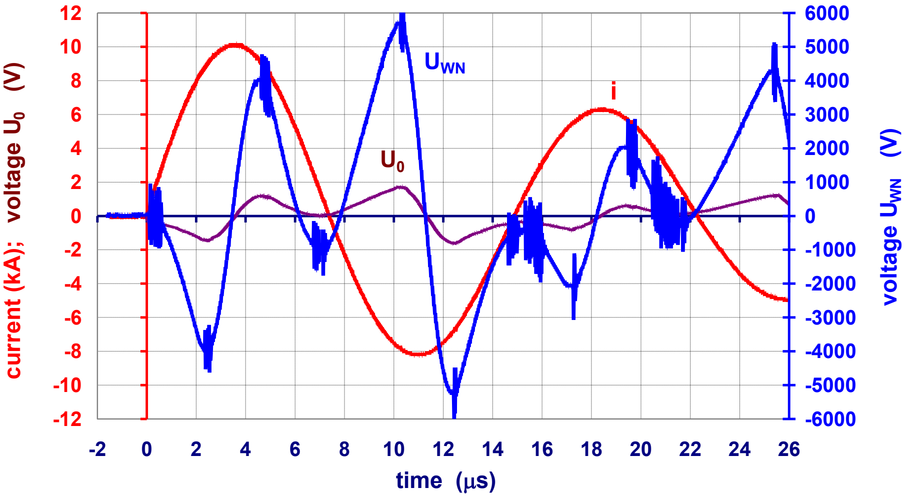



Fig. 4. Operation of the transformer (A) in position (β), *d* = 1 cm (directly by the cable with the disturbing current)

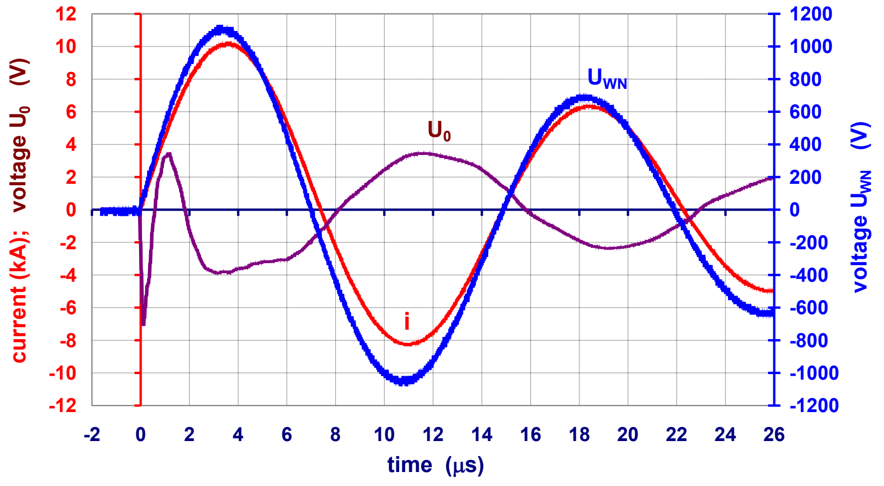



Fig. 5. Operation of the transformer (A) in position (α), *d* = 20mm

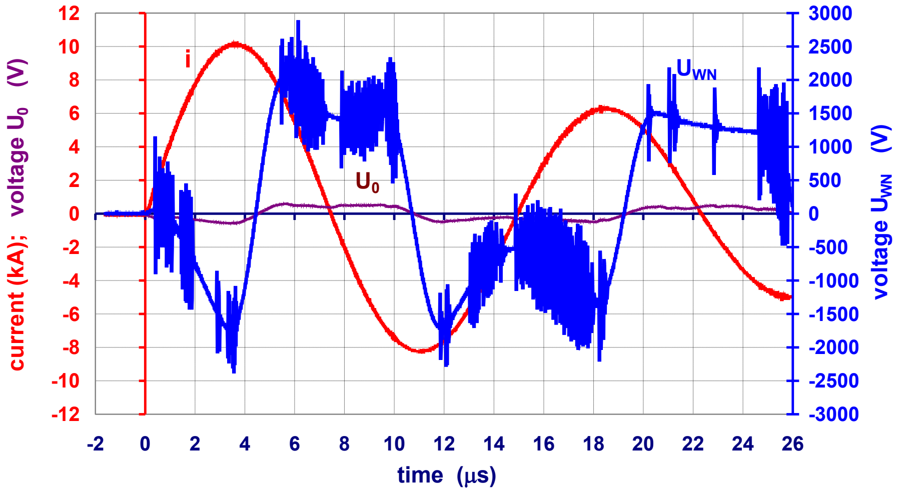



Fig. 6. Operation of the transformer (A) in position (β), *d* = 20mm

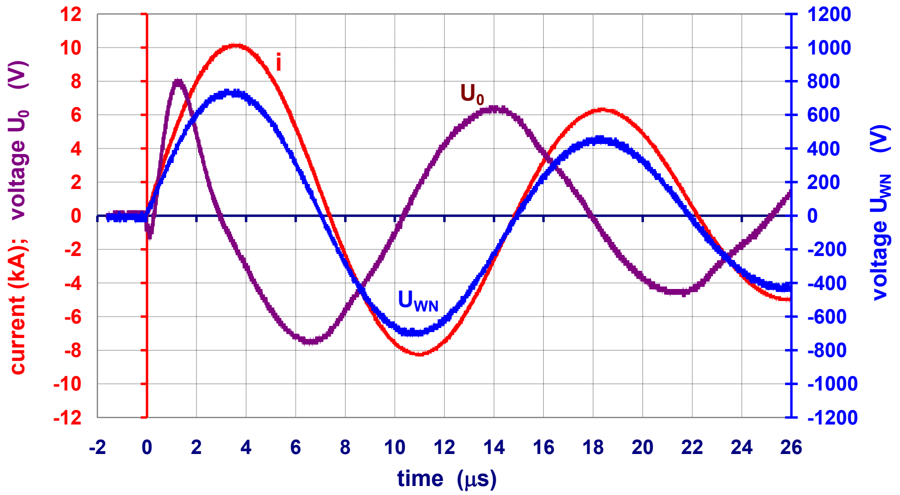



Fig. 7. Operation of the transformer (A) in position (α), *d* = 40mm

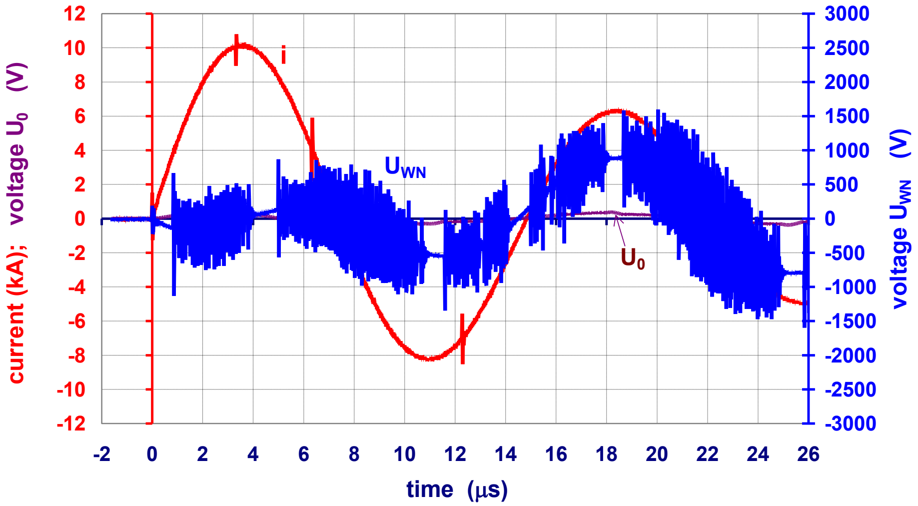



Fig. 8. Operation of the transformer (A) in position (β), *d* = 40mm

Table 1. Results of measurements for the firing system with transformer (A) with open core

| Distance from the cable with current *d* [cm] | Voltage amplitude at the output (on JED) $U_{WN}$ [V] | Position of windings in relation to current cable magnetic field |
|---|---|---|
| 1 | 6,000 | perpendicular (β) |
| 1 | 1,550 | parallel (α) |
| 2 | 2,890 | perpendicular (β) |
| 2 | 1,110 | parallel (α) |
| 4 | 1,600 | perpendicular (β) |
| 4 | 750 | parallels (α) |

Descriptions: 1) column – as in Fig.1 and 2; 2) column – output to JED voltage; 3) column – transformer winding location in relation to the disturbing current wire.

The waveform of the same quantities as a function of the distance from the cable with the disturbing current is shown in Fig. 9. High-frequency vibrations overlapping the $U_{WN}$ waveforms in the zones of high inclination *i*(*t*) come from the Barkhausen effect in the transformer core (shift of the domain walls in the ferromagnetic with changes in the magnetic field intensity).

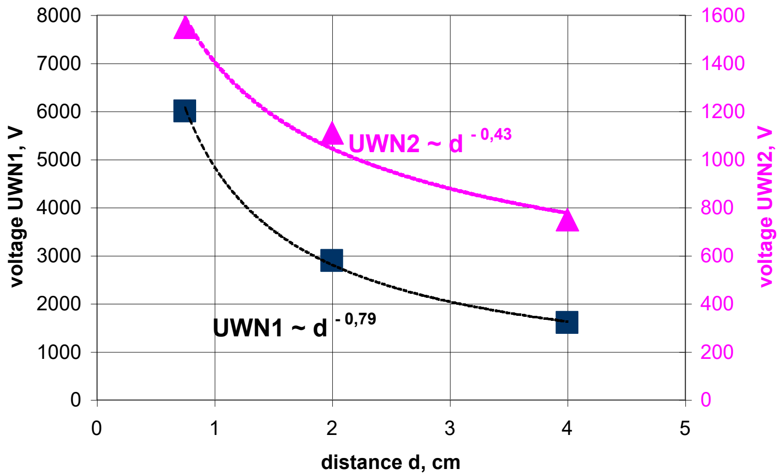



Fig. 9. Maximum values of induced voltage at the transformer output (open core) to the cap asa function of the distance from the disturbing cable UWN1 – perpendicular surface of the coils turns (parallel axis of the core), UWN2 – surface parallel to the magnetic field vector (perpendicular axis); triangle and square – measurement points; added trend lines.

### 3.2. Measurements in a system with a toroidal ferrite transformer

Examples of the disturbing current and voltage $U_0$ and $U_{WN}$ waveforms induced by the disturbing current in the transformer windings in various configurations are shown in Figs. 10-15.

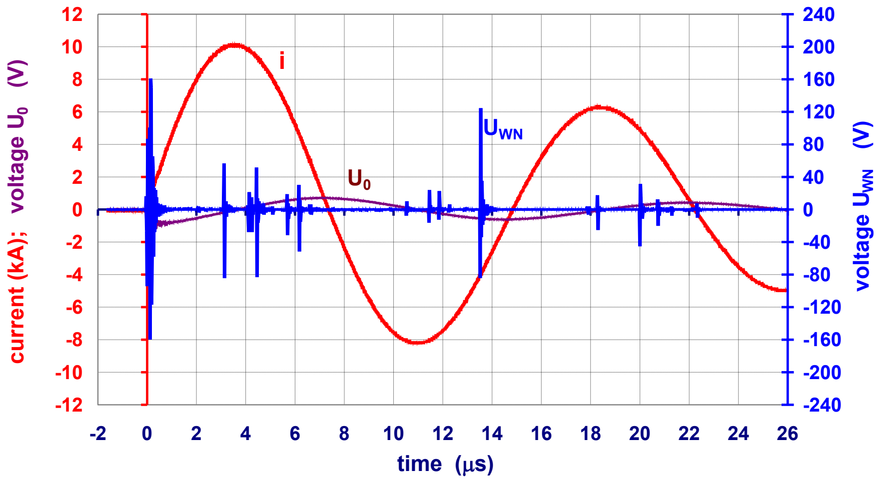



Fig. 10. Operation of the transformer (B) in position (β), $d \approx 1.3$ cm (directly by the cable with the disturbing current)

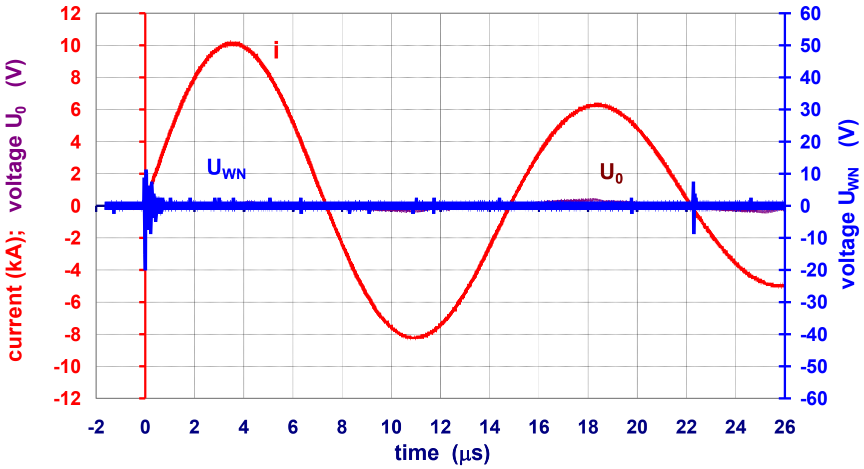



Fig. 11. Operation of the transformer (B) in position (α), *d* ≈ 13 mm (directly by the cable with the disturbing current)

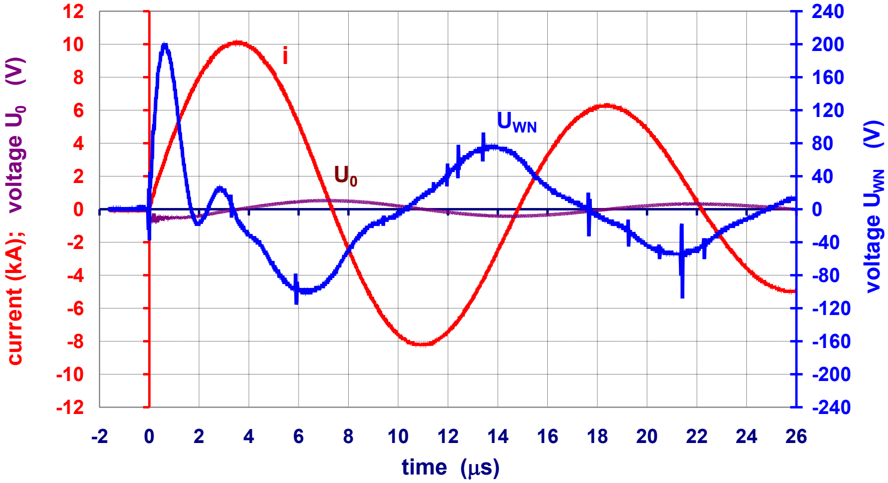



Fig. 12. Operation of the transformer (B) in position (β), *d* = 20 mm

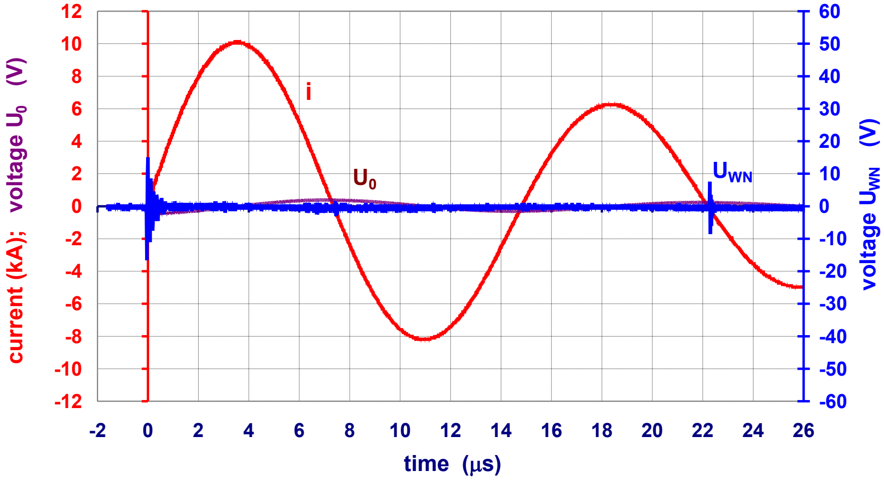



Fig.13. Operation of the transformer (B) in position (α), *d* = 20 mm

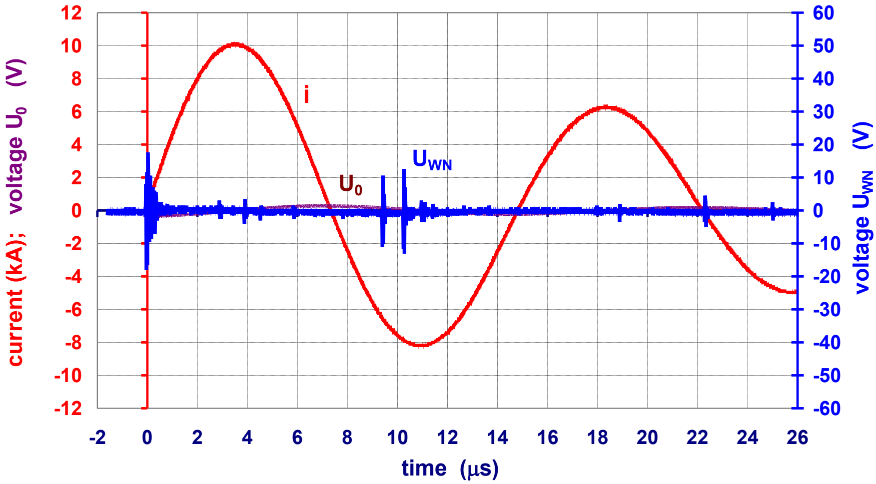



Fig. 14. Operation of the transformer (B) in position (β), *d* = 40 mm

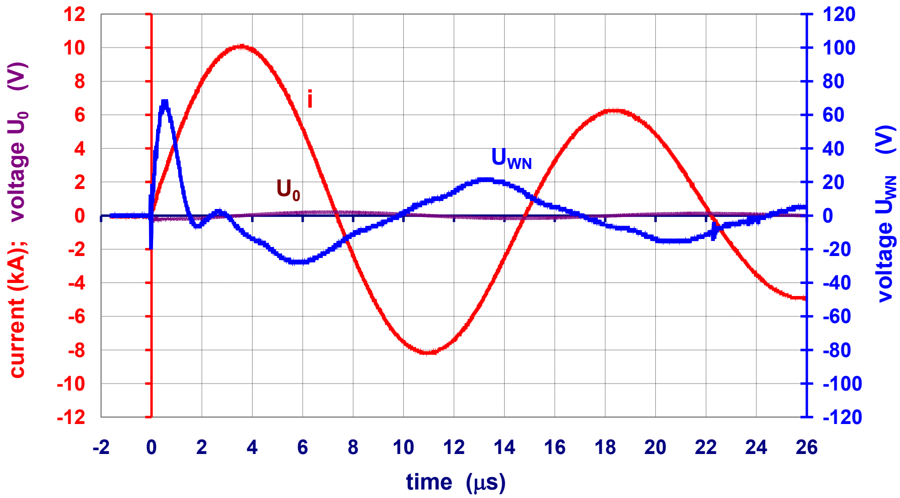



Fig. 15. Operation of the transformer (B) in position (α), $d$ = 40 mm

The summary of the measured maximum $U_{WN}$ values is presented in Table 2. The waveform of the same quantities as a function of the distance from the cable with the disturbing current is shown in Fig. 16. The minimum distance $d \approx 13$ mm was determined by the dimensions of the toroidal core with windings and insulation.

Table 2. Measurement results for the firing system with toroidal transformer (B).

| Distance from the cable with current $d$ [cm] | Voltage amplitude at the output (on JED) $U_{WN}$ [V] | Position of windings in relation to current cable magnetic field |
|---|---|---|
| 1.3 | 160 | Perpendicular (β) |
| 1.3 | 11 | Parallel (α) |
| 2 | 200 | Perpendicular (β) |
| 2 | 15 | Parallel (α) |
| 4 | 68 | Perpendicular (β) |
| 4 | 18 | Parallel (α) |

Designations: as in Table 1.

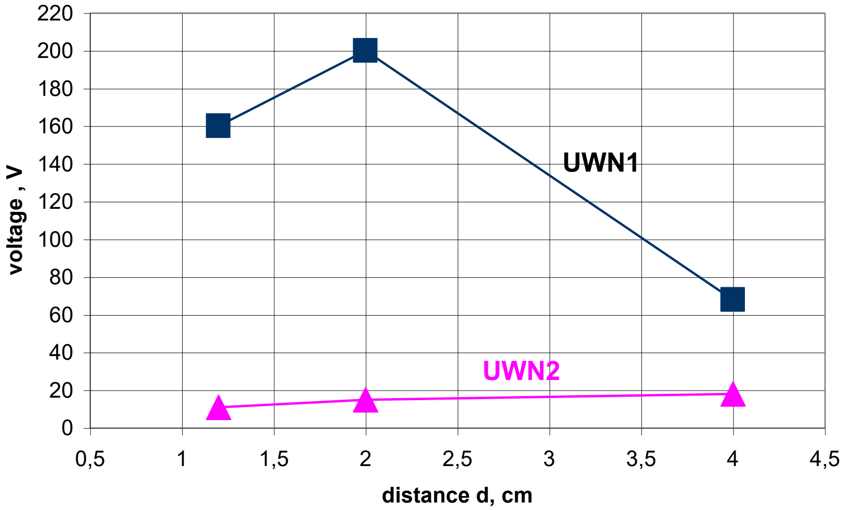



Fig. 16. Maximum values of voltage induced at the toroidal transformer output to the cap as the function of the distance from the disturbing cable; designations – as in Fig. 9

## 4. CONCLUSIONS

The primary purpose of this work was to determine the safe conditions of use for the tested type of caps in the designed system used for other experiments. Therefore, the conclusions from the conducted research can be divided into those regarding the measurement results themselves and those concerning recommendations for potential users. Regarding the first group:

- As predicted, the induced voltages decrease with the distance from the cable conducting the disturbing current, with the highest values in the system (A-β) almost exactly as in formula (1) (~ $1 / d^{0.95}$);
- It should be kept in mind that in formula (1), apart from the distance *d*, the relative permittivity, $\mu$ which depends on the H-field and thus on the distance, plays an important role; it is evidenced by the fact that with the increase of d and therefore the decrease of H, there is a growing share of Barkhausen vibrations, corresponding to the reorientation of domains in the ferromagnet, which appear at the transient phases of the current oscillation (apart from the maxima) and that this happens mainly in the case of the axis of the open transformer core parallel to the disturbing current vector H (A-β).
- Accordingly, the magnetisation conditions are different in the cases of (A-α), where **H** ⊥ core axis and (A-β); at $d \approx 10$ mm there may occur saturation and decrease of $\mu$ – in the case of (A-β), the ends of the core may be in the area of the weaker field and larger $\mu$, which results in

a relatively higher voltage value than at (A-α), where the entire core is located in a strong field zone; it may be one of the flattening factors ($\sim 1 / d^{0.52}$) of the UWN2 curve in Fig. 9 in relation to formula (1).

- Another factor influencing the value of the measured $U_{WN}$ amplitude is the coupling with the primary circuit of the transformer, short circuited with the resistance of 50 Ω
- In the case of a toroidal core, the process of its magnetization by the external field is more complicated and its supersaturation (significant decrease of $\mu$) in the same field is much sharper than for the open cylindrical core, which may explain the lower $U_{WN}$ value at (B-β) for $d$ = 13 mm, than for $d$ = 20 mm in Table 2 and Fig. 16; it should be kept in mind that in this case the plane of each of the winding turns quasi-perpendicular to H forms a different angle with it – formula (2) applies here; for $d$ > 2 cm in the case of (B-β) with an increase in d there is a regular decrease in $U_{WN}$ amplitude.
- In the case of (B-α), very small $U_{WN}$ values, practically independent of $d$, resulted from the fact that at fixed oscilloscope settings the corresponding recorded curves were close to the margin of error of the recordings; this had no effect on establishing safe values.

When determining the safe range of parameters, it should be taken into account that in practical applications the isolating transformer (with TC core in Fig. 1 and 2) will be located as close as possible to the actuated cap and the entire transformer-cap system (TR-D) – as close to the disturbing cable as possible (DC in Figures 1 and 2). Also that in the target system it may not be possible to determine the optimal angle between the TC axes and the DC axis and further that the described tests used parameters and elements corresponding to the target system. Therefore, the recommendations for the potential user correspond to the least favourable conditions, in which:

- The transformer JED cap firing system, designed with a miniature open core ferrite transformer shows high sensitivity to strong electromagnetic disturbances; under the given measurement conditions, the maximum induced voltage at the output was approx. 6 kV, which significantly exceeds the JED cap actuation voltage; therefore, such systems should not be used in practice.
- The transformer JED cap firing system, designed with a small-size toroidal ferrite core, shows high resistance to very strong electromagnetic disturbances; under the given measurement conditions, the maximum induced voltage at the output was approx. 200 V, which is only approx. 14% of the JED initiation voltage.

The results of the tests should generally be treated as model ones, showing the scale of threats and in the case of specific structures (also with a different system of disturbing currents and the relative TR-D distribution) such tests should be repeated.

Moreover, in the era of saturation of space with transmitters of electromagnetic radiation of various frequencies (radars, VHF, cellular telephony), it would be desirable to study its impact on the generated parasitic voltages and the methods of shielding against it.

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## REFERENCES

[1] Knoepfel Heinz. 1970. *Pulsed High Magnetic Fields*. Amsterdam-London: North-Holland Publ.Comp.

[2] Wolski J. 2018. „Czołgowa amunicja kierowana". *Nowa Technika Wojskowa*, nr 4, also „Penetratory formowane wybuchowo (EFP)". *Nowa Technika Wojskowa*, nr 5.

[3] Demidov V.A., A.S. Boriskin, S.A. Kazakov et al. 2015. „Disk Magnetocumulative Generator with an Explosive Opening Switch". *Journal of Applied Mechanics and Technical Physics* 56(1) : 16-21.

[4] Derentowicz Henryk, Sylwester Kaliski. 1979. „An Experimental Biconical System for Explosion Microfusion of Plasma". *Bull. Acad. Pol. Sci., Ser. Tech*. XXVII(2), also Derentowicz Henryk, Leon Grygoruk, Karol Jach, Jerzy Wróbel, Zbigniew Ziółkowski. 1981. „Badania doświadczalne bistożkowego układu wybuchowego mikrosyntezy termojądrowej". *Biuletyn WAT* XXX(3).

[5] Faryński Andrzej, Andrzej Długołęcki, Tomasz Klemba, Tomasz Kwaśniak, Zbigniew Ziółkowski, Piotr Krzemiński. 2019. „Wyznaczanie parametrów roboczych spłonek typu JED pobudzanych alternatywnymi metodami". *Problemy Techniki Uzbrojenia* 150 (2): 31-43.

# Badania transformatorowych układów pobudzania spłonek JED w polu bardzo silnych zaburzeń elektromagnetycznych

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**Streszczenie.** W ramach prezentowanej pracy przedstawiono wyniki badań wpływu silnych zewnętrznych pól elektromagnetycznych na działanie spłonek JED pobudzanych za pomocą układów transformatorowych. Badania te prowadzono w celu określenia warunków bezpiecznego użycia spłonek JED montowanych w układach sterowania generatorów wytwarzających impulsy prądowe na zasadzie wybuchowej kumulacji pola magnetycznego [1]. W tym celu wykonywano pomiary napięć indukowanych w transformatorowym układzie pobudzania spłonek elektroiskrowych JED przez sinusoidalny prąd zewnętrzny o amplitudzie 10 kA i okresie 15 mikrosekund. Prąd ten płynął w odległości od d = 1 cm do d = 4 cm od osi ferrytowych rdzeni stosowanych transformatorów: zamkniętego rdzenia o zewnętrznej średnicy 2 cm, wewnętrznej średnicy 1 cm i wysokości 1 cm lub otwartego rdzenia transformatora o średnicy 6 mm i długości 25 mm. Stosowane w ITWL transformatory umieszczano na przemian równolegle i prostopadle do osi przewodu z prądem. W przypadku transformatora o cylindrycznym rdzeniu otwartym prostopadłym do osi prądu napięcia indukowane przekraczały znacznie wartości, przy których następowało inicjowanie spłonek (ok.2 kV) i stawały się mniejsze od nich przy d ok. 4 cm. Toroidalne rdzenie zamknięte zapewniały napięcia indukowane do 200V (10 razy mniejsze) przy wszystkich badanych konfiguracjach. Pomiary prowadzono za pomocą układu i metod opracowanych w ITWL.

**Słowa kluczowe:** fizyka wybuchu, spłonka elektroiskrowa, napięcie indukowane