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E.I. Sokol, M.M. Rezinkina, O.G. Gryb, V.I. Vasilchenko, A.A. Zuev, A.V. Bortnikov, E.V. Sosina

A METHOD OF COMPLEX AUTOMATED MONITORING OF UKRAINIAN POWER ENERGY SYSTEM OBJECTS TO INCREASE ITS OPERATION SAFETY

The paper describes an algorithm of the complex automated monitoring of Ukraine's power energy system, aimed at ensuring safety of its personnel and equipment. This monitoring involves usage of unmanned aerial vehicles (UAVs) for planned and unplanned registration status of power transmission lines (PTL) and high-voltage substations (HVS). It is assumed that unscheduled overflights will be made in emergency situations on power lines. With the help of the UAV, pictures of transmission and HVS will be recorded from the air in the optical and infrared ranges, as well as strength of electric (EF) and magnetic (MF) fields will be measured along the route of flight. Usage specially developed software allows to compare the recorded pictures with pre-UAV etalon patterns corresponding to normal operation of investigated transmission lines and the HVSs. Such reference pattern together with the experimentally obtained maps of HVS's protective grounding will be summarized in a single document – a passport of HVS and PTL. This passport must also contain the measured and calculated values of strength levels of EF and MF in the places where staff of power facilities stay as well as layout of equipment, the most vulnerable to the effects of electromagnetic interference. If necessary, as part of ongoing monitoring, recommendations will be given on the design and location of electromagnetic screens, reducing the levels of electromagnetic interference as well as on location of lightning rods, reducing probability lightning attachment to the objects. The paper presents analytic expressions, which formed the basis of the developed software for calculation of the EF strength in the vicinity of power lines. This software will be used as a base at UAV navigation along the transmission lines, as well as to detect violations in the transmission lines operation. Comparison of distributions of EF strength calculated with the help of the elaborated software with the known literature data has been presented also. The difference between the proposed method of monitoring and the existing methods is full automation of the complex control of a number of parameters characterizing the state of the external power grid facilities, as well as its basic electrical parameters. This will be possible due to usage of specially developed software for recognition of optical and infrared images, as well as pictures of lines of equal EF and MF strength. References 12, figures 4.
Key words: **power line, electric and magnetic fields, automated monitoring, unmanned aerial vehicles.**

Статья посвящена описанию алгоритма комплексного автоматизированного мониторинга объектов энергетической системы Украины, направленного на обеспечение безопасности функционирования ее оборудования и персонала. Данный мониторинг предполагает использование беспилотных летательных аппаратов (БПЛА) для плановой и внеплановой регистрации состояния линий электропередачи (ЛЭП) и высоковольтных подстанций (ВП). Предполагается, что внеплановые облеты будут производиться при аварийных ситуациях на ЛЭП. С помощью БПЛА будут записываться с воздуха картины ЛЭП и ВП в оптическом и инфракрасном диапазонах, а также измеряться напряженности их электрического (ЭП) и магнитного (МП) полей вдоль трассы пролета. Использование специально разработанного программного обеспечения позволит сравнить регистрируемые БПЛА картины с предварительно созданными эталонными картинами, соответствующих штатным режимам работы контролируемых ЛЭП и ВП. Такие эталонные картины в совокупности с экспериментально полученными картами защитных заземлений ВП будут сведены в единый документ – паспорт ВП и ЛЭП. Данный паспорт должен содержать также измеренные и рассчитанные значения уровней напряженностей ЭП и МП в местах пребывания персонала энергетических объектов и расположения оборудования, наиболее уязвимого к воздействию электромагнитных помех. При необходимости в рамках выполнения проводимого мониторинга будут даны рекомендации по конструкции и расположению электромагнитных экранов, снижающих уровни электромагнитных воздействий, и молниеотводов, уменьшающих вероятность поражения молнией исследуемых объектов. В работе приводятся аналитические выражения, которые легли в основу разработанного программного обеспечения для расчета напряженности ЭП в окрестности ЛЭП. Данное программное обеспечение будет использовано в качестве базового при навигации БПЛА вдоль ЛЭП, а также для распознавания нарушений в работе ЛЭП. Приведено также сравнение зависимостей напряженности ЭП, рассчитанных с помощью данного программного обеспечения, с данными, известными из литературы. Отличие предлагаемой методики мониторинга от существующих состоит в том, что комплексный контроль ряда параметров, характеризующих внешнее состояние объектов энергосистемы, а также ее основных электрических параметров будут полностью автоматизированы. Это станет возможным в результате использования специально разработанного программного обеспечения по распознаванию оптических и инфракрасных изображений, а также картин линий равной напряженности ЭП и МП. Библ. 12, рис. 4.
Ключевые слова: **линии электропередачи, электрическое и магнитное поле, автоматизированный мониторинг, беспилотные летательные аппараты.**

Introduction. Currently, the problem of guaranteeing the energetic security of Ukraine is very important. Here, the monitoring of the state of electrical energy transmission systems from producer to electrical customer is extremely important. Such a monitoring should be directed to prevent emergency switching of power transmission lines (PTL) as well as to recover as soon as possible their working capacity if such a switching takes place.

One of more perspective modern methods of the PTL state diagnosing is monitoring by using unmanned aerial vehicles (UAVs). Such a monitoring is developed in Russian Federation (RF) [1], as well as in Europe [2], China [3], Brazil [4] and other countries. Here, the PTL state check is carried out by the way of its optical registration, registration by using infrared imagers, as well as registration of partial discharges taking place in insulation.

As analysis of reasons of PTL faults in RF which power network is rather like Ukrainian one shows they take place mainly on PTL 110 kV – 86 %, 11 % – PTL 220 kV, and 3 % – PTL 330-750 kV [1]. Such a distribution of fault numbers is proportionate to the corresponding PTL length. Most number of PTL faults in RF is resulted by damage of wires and lighting guard ropes – 56 %. Other reasons of PTL faults are such damages as insulator breakdowns – 19 %, tower damage – 15 %, and damage of other PTL elements – 10 %. In the correspondence with present statistics sharp increase of PTL faults takes place in spring and summer because of bridging of insulation gaps by green plantations. There are a lot of PTL faults because of vandalism such as insulator chain damage, theft of wires and PTL tower elements, throwing over on PTL wires, etc. [1].

Problem definition. From above-stated it is following that on-line testing of the state of PTL as well as high-voltage substations which represent an integral part of the power-supply system and removal of the fault sources can be very effective. The aim of this paper is to develop an algorithm of the complex automated monitoring of objects of the power network of Ukraine directed to guarantee its safety operation.

Materials of investigations. An algorithm to carry out monitoring of objects of the power network of Ukraine. Patented engineering solutions are known which aim is to guarantee the traffic control of UAVs by using electric field (EF) strength or magnetic field (MF) strength [5, 6]. These solutions can be used to develop a method of monitoring of objects of the power network of Ukraine safety. Such a method envisages creation of passports – etalon patterns describing PTL and substations operation in normal mode. Passport data – etalons should include optical images of investigated objects and their images in infrared band obtained by infrared imagers. Besides, such passports should include distributions of electric and magnetic fields strength obtained by using calculations and measurements in determined distances over the PTL as well as in determined distances under high-voltage substations. It is supposed that UAVs with given periodicity will carry out aerophotography of investigated objects in optical and infrared bands as well as to measure their EF and MF strength. It is supposed that extraordinary flies will be carried out at PTL faults to determine place and character of damage. Comparison by the developed software of data collected during UAVs' flies with passport data as investigated object's etalon will permit to take operative decisions on its current state: to remote arose failures which presence can result in faults, or to find places of faults if it was impossible to avoid them.

Utilization of an unmanned system to compare most important parameters describing normal operation of investigated objects (PTL and high-voltage substations) will also prevent illegal power takeoff from the power network. Analysis of such parameters can be used for optimization of operation modes as well as structure of investigated energetic objects.

Besides, such passports should include maps of placement of high-voltage substations' systems of protective grounding which play a key role to guarantee safety operation of personnel and equipment. Here, such maps should be obtained as a result of MF strength measurements during the current flow by protective grounding. To obtain reliable information on actual state of the protective grounding system (PGS) it is proposed to connect a current generator to it and measure the MF density over the earth surface. The map obtained in such a way will reflect real placement of the protective grounding system's elements. It will give a possibility to assess the reliability of protection of the investigated object by the protective grounding system at various short-circuit failures and, if necessary, to develop recommendations on restoration of damaged parts of the PGS as well as on its development and modernization. Obtained in such a way data on placement of elements of the protective grounding system are used as initial data for the developed software which permits to build distributions of equipotential lines and EF strength on the earth surface, to determine levels of step voltages and touch voltages as well as impedance of the grounding system. By these distributions conclusions on the reliability of the existing protective grounding systems are done. If necessary, in the frame of the carried out monitoring recommendations on the design and placement of electromagnetic shields utilization of which permits to decrease electromagnetic exposures level will be made [7].

The next important system which secures safety operation of energetic systems is their lightning protection system. By the developed software using the method [8] distributions of probability of lightning hit on the high-voltage substations' territory will be built and, if necessary, recommendations on development and modernization of existing lightning protection system will be given.

By using maps of EF and MF strength distributions at PTL and high-voltage substations operation obtained as a result of measurements and calculations of the EF and MF strength as well as by using reliable maps of the protective grounding systems, plans of the safety movement of the high-voltage substations' technical personnel and placement of equipment especially sensitive for possible electromagnetic exposures will be prepared.

To develop the monitoring system of the energetic system objects' safety, methods for EF and MF strength calculation are necessary. Here, at the absence of the personnel in the EF exposure zone analytical methods can be used.

The main parameter which characterizes the PTL electromagnetic field and does not depend on the kind of the PTL load is the EF strength. Let’s describe in detail principles of the developing the software used to realize the proposed method of the complex monitoring of energetic system’s objects.

Analytical methods of PTL EF calculation.

To use analytical methods for the PTL electrical field strength calculation the following assumptions should be taken:

- it is supposed that PTL wires are parallel infinite long cylinders which charge is uniformly distributed along their axes;
- voltage in the PTL wires changes by the sinusoidal low with frequency of 50 Hz;
- phase displacement in time between PTL wires’ voltages equals 120°;
- the earth surface is supposed flat, and earth proper is supposed absolutely conductive in the comparison with air and having zero potential;
- presence of towers, buildings, technical and biological objects in the PTL zone is not taken into account;
- presence of additional strands (lightning protective, compensative, etc.) is not taken into account;
- it is supposed that the PTL wires are in the air with relative dielectric capacitivity equals $\varepsilon_e = 1$;
- root-mean-square values of the electric field strength are determined near a plain which is perpendicular to the PTL wires’ direction in the area of the maximal wires approaching to the earth.

At the mentioned assumptions values of potentials, specific charges and EF strength can be written in the symbolic form for complex quantities, and the electric field can be presented as a sum of the PTL wires’ electric fields and their mirror images relatively the earth surface [9, p. 84, 93].

Typical cases of the PTL wires placements are shown in Fig. 1.

If PTL wires are bundle the equivalent wire’s radius is calculated by the formula [9, p. 42]:

$$r = \left(M \cdot r_{ph} \cdot a^{M-1}\right)^{\frac{1}{M}},$$

where M – number of bundle wires of the PTL phases; r_{ph} – radius of the PTL phases wires’ section [m]; a – radius of the circle on which PTL bundle phases are placed [m].

In the general case of the arbitrary placement of the PTL wires the capacity value per the unit of length is calculated by the formula [10, p. 96]:

$$C_S = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\left[2\frac{\sqrt[3]{h_1 \cdot h_2 \cdot h_3}}{r} \cdot \frac{\sqrt[3]{r_{12} \cdot r_{23} \cdot r_{31}}}{\sqrt[3]{r_{12'} \cdot r_{23'} \cdot r_{31'}}}\right]},$$

where h_1, h_2, h_3 – distances from the earth surface to each PTL wire; r_{12}, r_{23}, r_{31} – distances between PTL wires; $r_{12'}$, $r_{23'}$, $r_{31'}$ – distances between PTL wires and their mirror images.

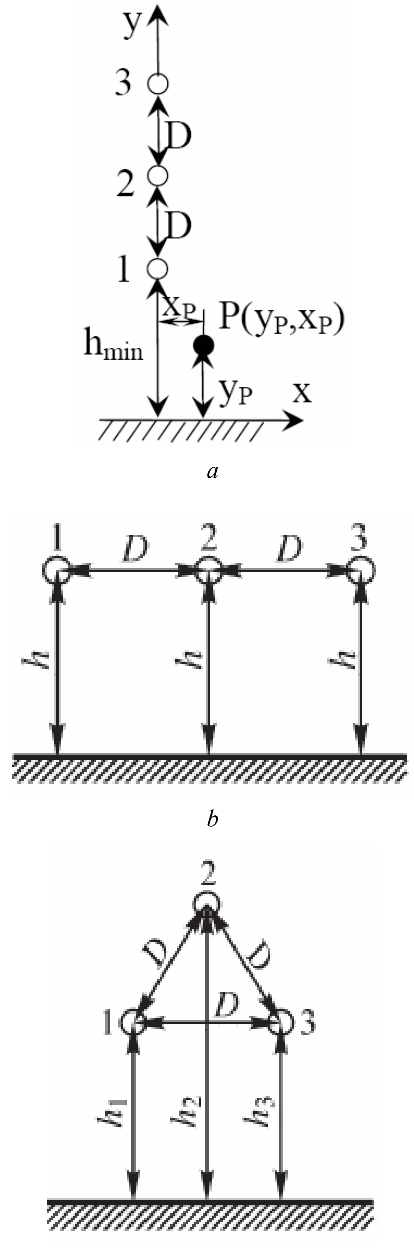


Fig. 1. Typical cases of the PTL wires placements

In the case of the vertical placement of PTL wires as it is shown in Fig. 1,*a* the PTL capacity per the unit of length is calculated by the formula:

$$C_S = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\left[\frac{2D\sqrt[3]{2}}{r} \cdot \sqrt[3]{\frac{h_{\min} \cdot (h_{\min} + D) \cdot (h_{\min} + 2D)}{(2h_{\min} + D) \cdot (2h_{\min} + 2D) \cdot (2h_{\min} + 3D)}}\right]}$$

where D – distance between PTL wires [m]; $h_{\min}$ – minimal distance between PTL wires and earth ($h_{\min} = \min\{h_1, h_2, h_3\}$) [м]; ε_r – relative dielectric permeability of the medium (air) in which the PTL wires are; $\varepsilon_0 = 0.885 \cdot 10^{-9}$ F/m – electrical constant.

In the case of the horizontal placement of PTL wires as it is shown in Fig. 1,*b* the PTL capacity per the unit of length is calculated by the formula [10, p. 96]:

$$C_S = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\left[\dfrac{2h_{\min}\cdot D}{r\cdot\sqrt[3]{(4h_{\min}^2+D^2)\cdot\sqrt{h_{\min}^2+D^2}}}\right]}.$$

In the case of the PTL wires placement in the apexes of the equilateral triangle as it is shown in Fig. 1,*c* the PTL capacity per the unit of length is calculated by the formula:

$$C_S = \frac{2\pi\varepsilon_r\varepsilon_0}{\ln\left[\dfrac{2D}{r}\cdot\sqrt[3]{\dfrac{h_{\min}^2\cdot(h_{\min}+D\sqrt{3}/2)}{\sqrt{(4h_{\min}^2+D^2)}\cdot[(2h_{\min}+D\sqrt{3}/2)^2+D^2/4]}}\right]}.$$

Complex values of the azimuthal and axial components of the PTL EF strength in the point $P(x_p, y_p)$ (see Fig. 1,*a*) are calculated by formulae [9, p. 68]:

$$\dot{E}_x(x_P,y_P) = \frac{U_{ph}\cdot C_S}{2\pi\varepsilon_r\varepsilon_0}\times$$
$$\times\left[\begin{aligned}&-\left[\frac{x_1-x_P}{(x_1-x_P)^2+(h_1+y_P)^2}-\frac{x_1-x_P}{(x_1-x_P)^2+(h_1-y_P)^2}\right]+\\&+\left(\frac{1}{2}+j\frac{\sqrt{3}}{2}\right)\cdot\left[\frac{x_2-x_P}{(x_2-x_P)^2+(h_2+y_P)^2}-\frac{x_2-x_P}{(x_2-x_P)^2+(h_2-y_P)^2}\right]+\\&+\left(\frac{1}{2}-j\frac{\sqrt{3}}{2}\right)\cdot\left[\frac{x_3-x_P}{(x_3-x_P)^2+(h_3+y_P)^2}-\frac{x_3-x_P}{(x_3-x_P)^2+(h_3-y_P)^2}\right]\end{aligned}\right];$$

$$\dot{E}_y(x_P,y_P) = \frac{U_{ph}\cdot C_S}{2\pi\varepsilon_r\varepsilon_0}\times$$
$$\times\left[\begin{aligned}&-\left[\frac{h_1+y_P}{(x_1-x_P)^2+(h_1+y_P)^2}+\frac{h_1-y_P}{(x_1-x_P)^2+(h_1-y_P)^2}\right]+\\&+\left(\frac{1}{2}+j\frac{\sqrt{3}}{2}\right)\cdot\left[\frac{h_2+y_P}{(x_2-x_P)^2+(h_2+y_P)^2}+\frac{h_2-y_P}{(x_2-x_P)^2+(h_2-y_P)^2}\right]+\\&+\left(\frac{1}{2}-j\frac{\sqrt{3}}{2}\right)\cdot\left[\frac{h_3+y_P}{(x_3-x_P)^2+(h_3+y_P)^2}+\frac{h_3-y_P}{(x_3-x_P)^2+(h_3-y_P)^2}\right]\end{aligned}\right].$$

Root-mean-square value of the electric field strength in the point $P(x_p, y_p)$ is calculated by the formula:

$$E(x_P,y_P) = \sqrt{\left|\dot{E}_x(x_P,y_P)\right|^2+\left|\dot{E}_y(x_P,y_P)\right|^2},$$

where $\left|\dot{E}_x(x_P,y_P)\right|$, $\left|\dot{E}_y(x_P,y_P)\right|$ – modules of the complex values of the azimuthal and axial components of the PTL EF strength in the point $P(x_p, y_p)$.

On the base of these formulae a software permitting to calculate EF strength in the PTL vicinity is developed. Comparison of root-mean-square values obtained by using this software with data from [11] are presented in Fig. 2,*a*, 3,*a* and Fig. 2,*b*, 3,*b*, respectively. In Fig. 4,*a*, 4,*b* the same comparison with data from [12] is presented.

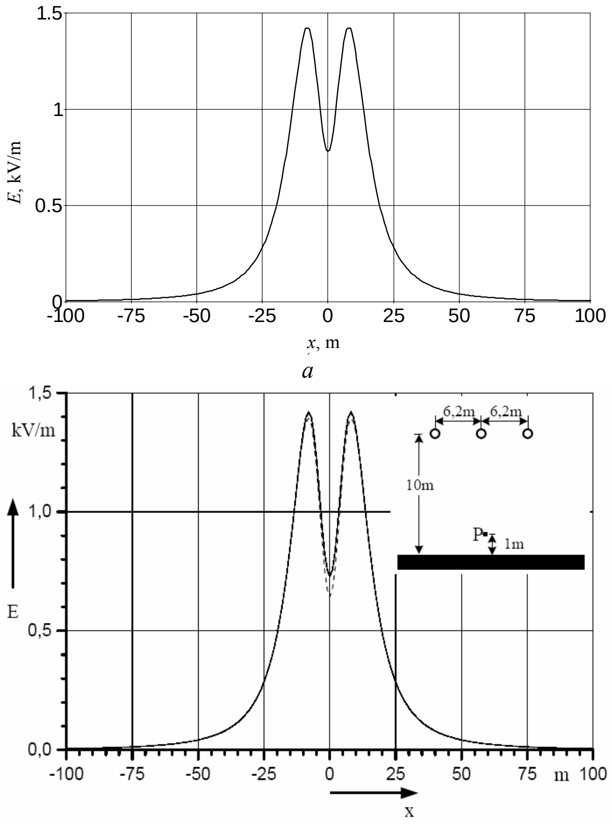


Fig. 2. Calculated dependences of the EF strength in the section perpendicular to the wires of the PTL 150 kV on the distance of 1 m from the earth surface

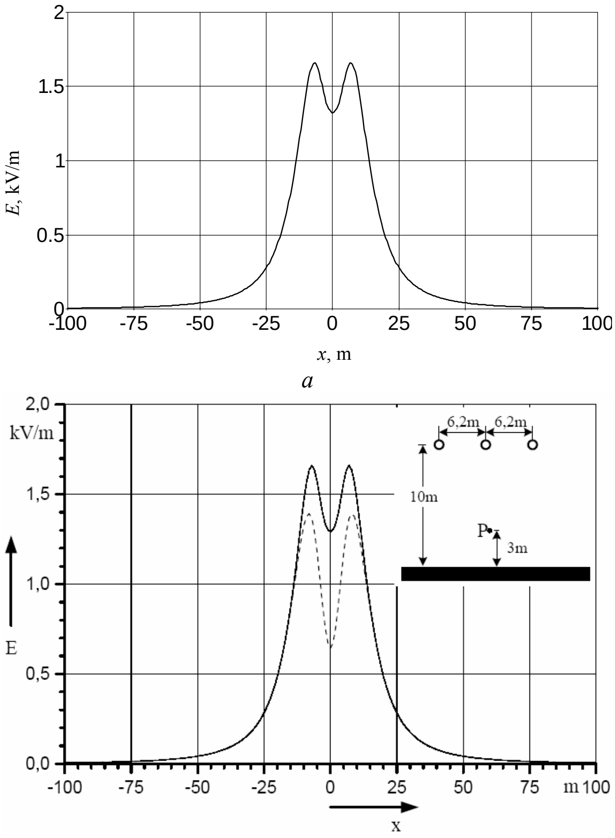
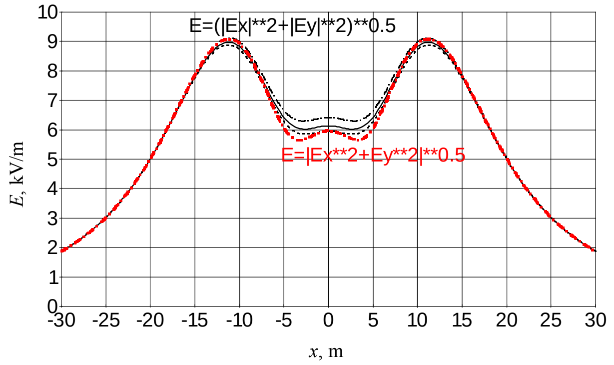
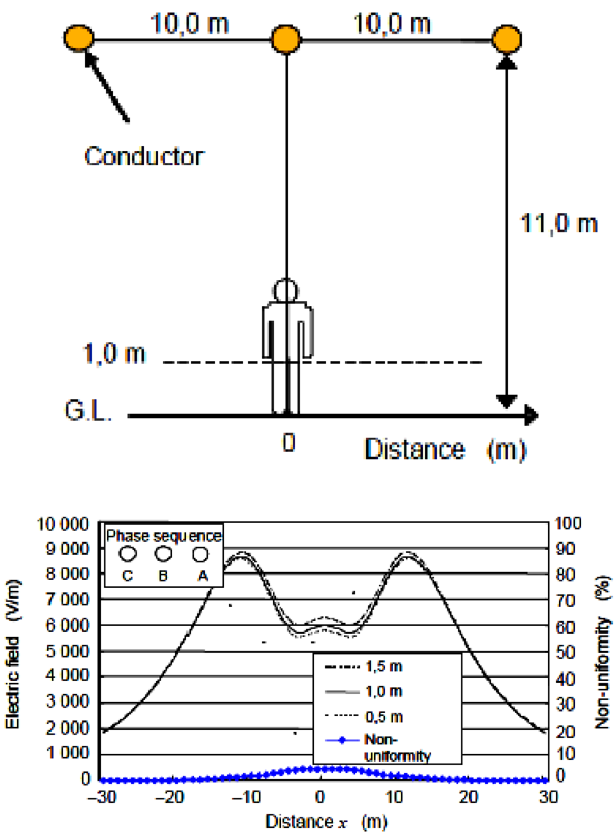


Fig. 3. Calculated dependences of the EF strength in the section perpendicular to the wires of the PTL on the distance of 3 m from the earth surface



a



b

Fig. 4. Calculated dependences of the EF strength in the section perpendicular to the wires of the PTL 500 kV on the distances of 0.5 m, 1 m, 1.5 m from the earth surface

Conclusions.

1. A method of complex automated monitoring of PTL and high-voltage substations representing key elements of power supply system of Ukraine is developed.

2. A software for calculation of the EF in PTL vicinity is developed and tested. This software is necessary for the navigation of UAVs – the main element of the described monitoring system as well as for assessment of electrical parameters of investigated energetic objects.

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E.I. Sokol[1], *Doctor of Technical Science, Professor,*
Corresponding Member of the National Academy of Science of Ukraine,
M.M. Rezinkina[2], *Doctor of Technical Science,*
O.G. Gryb[1], *Doctor of Technical Science, Professor,*
V.I. Vasilchenko[3],
A.A. Zuev[1], *Candidate of Technical Science, Associate Professor,*
A.V. Bortnikov[1], *Engineer,*
E.V. Sosina[1], *Postgraduate Student,*
[1] National Technical University «Kharkiv Polytechnic Institute»,
21, Frunze Str., Kharkiv, 61002, Ukraine,
e-mail: elenasosina09@gmail.com.
[2] State Institution «Institute of Technical Problems of Magnetism of the NAS of Ukraine»,
19, Industrialna Str., Kharkiv, 61106, Ukraine,
e-mail: marinar2@mail.ru.
[3] NPC «Ukrenergo»,
25, Symona Petliury Str, Kyiv, 01032, Ukraine,
phone +380 44 2383015, e-mail: kanc@nec.energy.gov.ua

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