Research of TVR Electromagnetic Field

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Abstract – Thyristor voltage regulator (TVR) is a 6 kV electrical installation which is being developed by NNSTU. The article is devoted to the study of the electromagnetic field (EMF), created by the TVR operation. The features and the principle of the TVR operation are described. The techniques for estimating the intensity of EMF exposure, developed by the authors, are presented. The dependences of the electric and magnetic field strengths on the voltage and the power of TVR for various calculation points have been obtained. It has been established that the intensity indices of EMF exposure do not exceed permissible norms, and the operation of TTR will not produce a negative impact on the personnel and on the secondary control and protection circuits. The results of the studies will be taken into consideration when choosing a rational arrangement of TVR elements.

Index Terms – Electromagnetic fields, automatic voltage control, thyristor circuits, design methodology

Abbreviation
EMF – electromagnetic field
TVR – thyristor voltage regulation
EMC – electromagnetic compatibility
EIC – electrical installations code
MPL – maximum permissible limit
MV – medium voltage

I. Introduction

The choice of a rational arrangement of elements is an crucial task in the development of new power electrical installations with the voltage of 6-20 kV [1-3]. It is necessary to take into consideration that during the operation of these electromagnetic field (EMF) electrical installations of industrial frequency occurs, which might cause the attendants failure in the operation of the central nervous and cardiovascular systems. This manifests itself in the form of increased fatigue, headache, changes in blood pressure, palpitation and arrhythmia [4-6]. To add to this non-observance of the electromagnetic compatibility conditions in magnetic fields of industrial frequency in 6-20 kV switchgears is a serious cause of disturbances (up to 9%) in the operation of secondary technical devices in distribution substations [7]. However, at the stage of preliminary design there are no data of the experimental studies of a new device, necessary for optimal location analysis of its elements.

The task of layout solutions was faced by the scientists of the NSTU after R.E. Alekseev in the development of a thyristor voltage regulator (TVR) experimental sample [8, 9]. This is a high-speed power semiconductor device of 6 kV. It is intended for voltage regulation and power flows control in medium voltage distribution networks. The main elements of TVR are thyristor switches, transformer equipment, cable lines and a control and protection system. The power elements that make up TVR form an EMF, which can have a negative impact on the person and the TVR control system. The correct arrangement of TVR elements will minimize the impact of EMF.

The analysis of regulatory documents has shown that existing techniques do not take into consideration the features of the TVR being developed, so they cannot be used to estimate the intensity of EMF exposure in the TVR operation.

The authors aim at developing the technique for calculating the intensity of the electromagnetic field effect during the operation of the TVR and to study the dependence of the EMF indices on the voltage and the power of the TVR.

II. Description TVR

The schematic diagram of the developed experimental TVR sample is shown in Fig.1. The electrical installation consists of a three-phase shunt transformer, three single-phase series transformers, a transverse regulation module (thyristor switches TS1-TS4) and a longitudinal control module (thyristor switches TS5-TS8).

Thyristor switches TS1-TS4 allow to regulate the voltage of the network in the phase, and TK5-TK8 regulate the voltage of the network in magnitude. The joint application of the control modules provides longitudinal and transverse control.

The main sources of EMF for TVR operation are shunt and serial transformers, as well as medium voltage (MV) cable lines.

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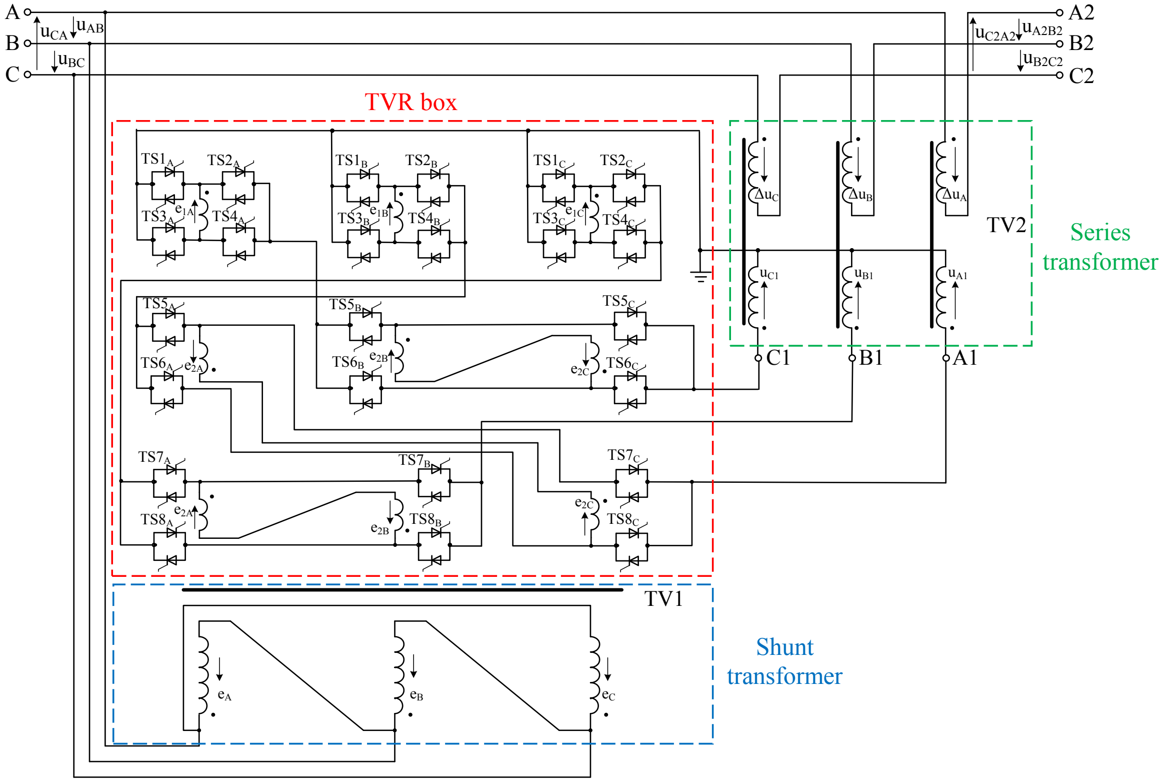

Figure 1. Principal power scheme TVR.

III. Estimation Methodology of the Electromagnetic Field TVR Influence

The intensity of EMF exposure is characterized by the electric (E, kV/m) and magnetic (H, A/m) fields strength. The authors have worked out the technique for estimating the intensity of the EMF exposure to TVR. The initial data are the nominal power, overall dimensions, the distance between the phases of the shunt and series transformers, the TVR box, and the wire cross-section. The calculation procedure is the following:

1) adesign layout of the electrical equipment TVR is compiled;

2) points for calculating the intensity of electric and magnetic fields are marked;

3) the distance to the calculated points and the electrical equipment TVR is measured;

4) the electric field strength is calculated by the formula (1):

$$E=\frac{CU}{2\pi\varepsilon_0 h_p}\left[\frac{1}{h_{sht(st)}^2+x_1^2}-\frac{0.5}{h_{sht(st)}^2+x_2^2}-\frac{0.5}{h_{sht(st)}^2+x_3^2}\right], \quad (1)$$

where C is the capacitance of a unit of cable length, F/m; U – rated voltage, kV; $\varepsilon_0 = 8{,}85\cdot 10^{-12}$ – electrical constant, F/m; h_p – height of the calculated point, m; $h_{sht(st)}$ – height from the calculated point to the point with maximum strength for the shunt/serial transformer, m; x_1 – distance from the first phase to the calculated point, m; x_2 – distance from the second phase to the calculated point, m; x_3 – distance from the third phase to the calculated point, m. Length unit capacity of a conductor is determined by the formula (2):

$$C=\frac{24\cdot 10^{-12}}{\lg\left(\frac{2D_{sht(st)}}{d_w}\right)}, \quad (2)$$

where $D_{sht(st)}$ – distance between phases of shunt/series transformer d_w – diameter of the wire conductor, m [10];

5) the magnetic field strength is calculated from the formula (3):

$$H=\gamma\cdot I, \quad (3)$$

where γ is the coefficient of proportionality between the working conductor current and the magnetic field strength; I – is the operating conductor current, A [11];

6) the strength calculating results of electric and magnetic fields are compared with the requirements of [12] and the electromagnetic compatibility of technical devices levels [13-15]. In case the electric and magnetic field strengths do not meet the regulatory requirements, measures are taken to reduce the negative impact of EMF.

According to the proposed techniques, the calculation of intensity indices for the EMF of the experimental sample TVR (6 kV voltage and 630 kVA load capacity) has been performed.

The schemes of the electrical equipment location TVR are shown in Fig. 2 and Fig. 3. The calculated points (Fig. 3) are selected with consideration of the possible maintenance personnel location and the placement of secondary control and protection circuits. The distances are chosen in accordance with [16-18]. The dimensions of the electrical equipment of the experimental TVR sample are given in Table 2.

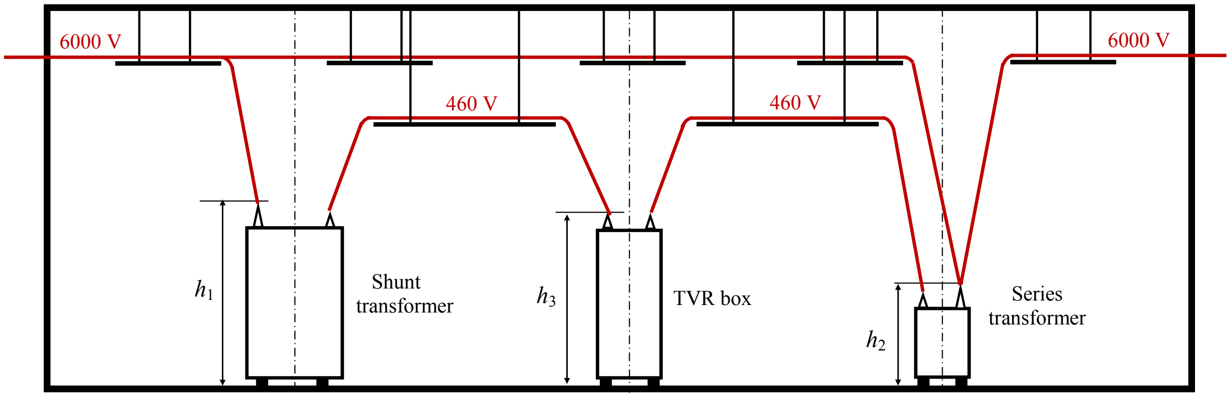

Figure 2. The layout of the electrical equipment TVR (side view).

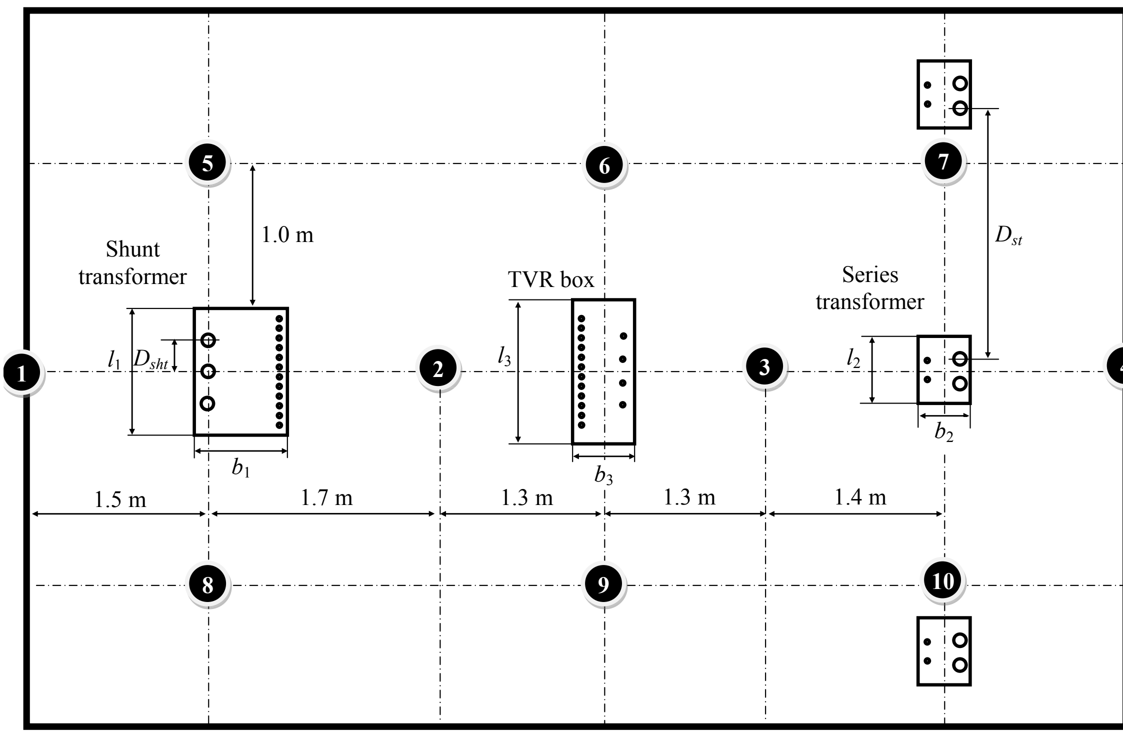

Figure 3. The layout of the electrical equipment TVR (top view).

TABLE I. CHARACTERISTICS OF THE EXPERIMENTAL TVR SAMPLE ELECTRICAL EQUIPMENT

Equipment	Power, kVA	Dimensions			*D*, m (primary winding)	*D*, m (secondary winding)	d_w, mm²	
		l, mm	*b*, mm	*h*, mm			primary winding	secondary winding
Shunt transformer	106	1020	750	1180	0.25	0.05	3.57	13.63
TVR box	106	1160	500	1160	0.05	0.2	13.63	3.57
Serial transformer	3x28	540	420	560	0.2	0.2	3.57	3.57

The electric field strength of the shunt transformer E_{sht} is calculated from the expressions (4-10):

Point 1

$$E_{sht} = \frac{CUh_{sht}}{2\pi\varepsilon_0}\left[\frac{1}{h_{sht}^2+1.5^2}-\frac{0.5}{h_{sht}^2+1.5^2+D_{sht}^2}-\frac{0.5}{h_{sht}^2+1.5^2+D_{sht}^2}\right]. \quad (4)$$

Point 2

$$E_{sht} = \frac{CUh_{sht}}{2\pi\varepsilon_0}\left[\frac{1}{h_{sht}^2+1.7^2}-\frac{0.5}{h_{sht}^2+1.7^2+D_{sht}^2}-\frac{0.5}{h_{sht}^2+1.7^2+D_{sht}^2}\right]. \quad (5)$$

Point 3

$$E_{sht} = \frac{CUh_{sht}}{2\pi\varepsilon_0}\left[\frac{1}{h_{sht}^2+4.3^2}-\frac{0.5}{h_{sht}^2+4.3^2+D_{sht}^2}-\frac{0.5}{h_{sht}^2+4.3^2+D_{sht}^2}\right]. \quad (6)$$

Point 4

$$E_{sht}=\frac{CUh_{sht}}{2\pi\varepsilon_0}\left[\frac{1}{h_{sht}^2+7.2^2}-\frac{0.5}{h_{sht}^2+7.2^2+D_{sht}^2}-\frac{0.5}{h_{sht}^2+7.2^2+D_{sht}^2}\right]. \quad (7)$$

Points 5, 8

$$E_{sht}=\frac{CUh_{sht}}{2\pi\varepsilon_0}\left[\frac{1}{h_{sht}^2+(\frac{l_1}{2}-D_{sht}+1)^2}-\frac{0.5}{h_{sht}^2+(\frac{l_1}{2}+1)^2}-\frac{0,5}{h_{sht}^2+(\frac{l_1}{2}+D_{sht}+1)^2}\right]. \quad (8)$$

Points 6, 9

$$E_{sht}=\frac{CUh_{sht}}{2\pi\varepsilon_0}\left[\frac{1}{h_{sht}^2+(\frac{l_1}{2}-D_{sht}+1)^2+3^2}-\frac{0.5}{h_{sht}^2+(\frac{l_1}{2}+1)^2+3^2}-\frac{0.5}{h_{sht}^2+(\frac{l_1}{2}+D_{sht}+1)^2+3^2}\right]. \quad (9)$$

Points 7, 10

$$E_{sht}=\frac{CUh_{sht}}{2\pi\varepsilon_0}\left[\frac{1}{h_{sht}^2+(\frac{l_1}{2}-D_{sht}+1)^2+5.7^2}-\frac{0.5}{h_{sht}^2+(\frac{l_1}{2}+1)^2+5.7^2}-\frac{0.5}{h_{sht}^2+(\frac{l_1}{2}+D_{sht}+1)^2+5.7^2}\right]. \quad (10)$$

The electric field strength of the series transformer E_{st} is calculated from the expressions (11-17):

Point 1

$$E_{st}=\frac{CUh_{st}}{2\pi\varepsilon_0}\left[\frac{1}{h_{st}^2+7.2^2}-\frac{0.5}{h_{st}^2+7.2^2+D_{st}^2}-\frac{0.5}{h_{st}^2+7.2^2+D_{st}^2}\right]. \quad (11)$$

Point 2

$$E_{st}=\frac{CUh_{st}}{2\pi\varepsilon_0}\left[\frac{1}{h_{st}^2+4.0^2}-\frac{0.5}{h_{st}^2+4.0^2+D_{st}^2}-\frac{0.5}{h_{st}^2+4.0^2+D_{st}^2}\right]. \quad (12)$$

Point 3

$$E_{st}=\frac{CUh_{st}}{2\pi\varepsilon_0}\left[\frac{1}{h_{st}^2+1.4^2}-\frac{0.5}{h_{st}^2+1.4^2+D_{st}^2}-\frac{0.5}{h_{st}^2+1.4^2+D_{st}^2}\right]. \quad (13)$$

Point 4

$$E_{st}=\frac{CUh_{st}}{2\pi\varepsilon_0}\left[\frac{1}{h_{st}^2+1.5^2}-\frac{0.5}{h_{st}^2+1.5^2+D_{st}^2}-\frac{0.5}{h_{st}+1.5^2+D_{st}^2}\right]. \quad (14)$$

Points 5, 8

$$E_{st}=\frac{CUh_{st}}{2\pi\varepsilon_0}\left[\frac{1}{h_{st}^2+(D_{st}-\frac{l_2}{2}-1)^2+5.7^2}-\frac{0.5}{h_{st}^2+(\frac{l_2}{2}+1)^2+5.7^2}-\frac{0.5}{h_{st}^2+(D_{st}+\frac{l_2}{2}+1)^2+5.7^2}\right]. \quad (15)$$

Points 6, 9

$$E_{st}=\frac{CUh_{st}}{2\pi\varepsilon_0}\left[\frac{1}{h_{st}^2+(D_{st}-\frac{l_2}{2}-1)^2+2.7^2}-\frac{0.5}{h_{st}^2+(\frac{l_2}{2}+1)^2+2.7^2}-\frac{0.5}{h_{st}^2+(D_{st}+\frac{l_2}{2}+1)^2+2.7^2}\right]. \quad (16)$$

Points 7, 10

$$E_{st}=\frac{CUh_{st}}{2\pi\varepsilon_0}\left[\frac{1}{h_{st}^2+(D_{st}-\frac{l_2}{2}-1)^2}-\frac{0.5}{h_{st}^2+(\frac{l_2}{2}+1)^2}-\frac{0.5}{h_{st}^2+(D_{st}+\frac{l_2}{2}+1)^2}\right]. \quad (17)$$

The height from the calculated point to the point with maximum intensity for the shunt and series transformers is calculated by the formulas (17, 18):

$$h_{sht}=h_p-h_1, \quad (17)$$

$$h_{st}=h_p-h_2. \quad (18)$$

where h_1, h_2 – is the height of the shunt and serial transformer, m.

When calculating the magnetic field strength, the coefficient γ is equal to 0.0893.

The electric and magnetic fields level control with a frequency of 50 Hz is carried out at an altitude of 1.7 m.

In accordance with [17], when inspecting power electro-installations with a voltage of 1-35 kV, people are allowed to approach protected current-carrying parts under voltage at a distance of 0.6 m.

IV. EXPERIMENTAL RESULTS

The TVR EMF effect of various nominal power and voltage was evaluated (in accordance with Table 2) in a similar way.

TABLE II. TVR TRANSFORMER EQUIPMENT OF VARIOUS POWER AND VOLTAGE SUPPLY

Equipment	Rated voltage, kV	Rated power, kVA	Adjustable power S_{adj}, kVA	Power load in the network S_{load}, kVA
Shunt transformer	6, 10, 20/0.46	106, 168, 270, 420	106, 168, 270, 420	630, 1000, 1600, 2500
TVR box	0.46	106, 168, 270, 420		
Serial transformer	0.46/0.46	3x28, 3x44, 3x70, 3x110		

Table 3 shows the values of EMF indicators for a 6-20 kV network and the load capacity of 2500 kVA. The ratios between the values of the electric field strength for the other variants are similar.

TABLE III. CALCULATION RESULTS OF EMF IMPURITY INDICATORS (FOR THE CASE OF 6-20 KV NETWORK AND LOAD CAPACITY 2500 KVA)

Parameter	**Calculation points**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
6 кV										
E, kV/m	0.006	0.013	0.198	0.171	0.076	0.037	0.457	0.076	0.037	0.457
H, A/m	23.164									
10 кV										
E, kV/m	0.008	0.020	0.311	0.268	0.094	0.057	0.806	0.094	0.057	0.806
H, A/m	13.895									
20 кV										
E, kV/m	0.009	0.031	0.519	0.446	0.073	0.081	1.204	0.073	0.081	1.204
H, A/m	7.055									

Table 3 shows that the electric and magnetic field strengths are maximum at points 7 and 10. For these points, the dependencies of the EMF parameters on the power and voltage of the TVR electrical equipment have been obtained (Fig. 5, 6).

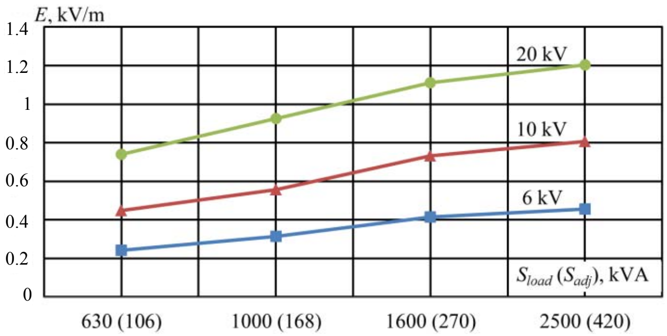

Figure 5. Dependence of electric field strength on power and voltage TVR.

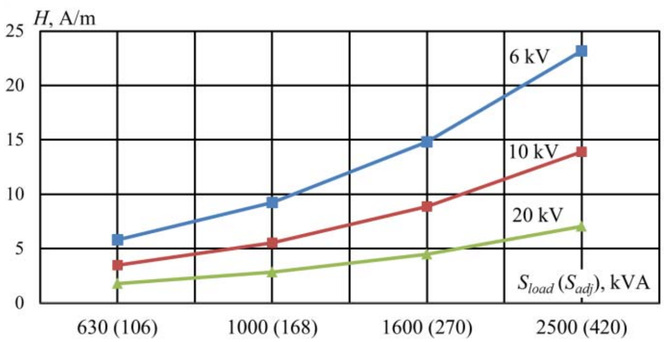

Figure 6. Dependence of magnetic field strength on power and voltage TVR.

Fig. 7, 8 show the dependences of the maximum values of the electric and magnetic field strengths for different calculation points.

The obtained dependences are given in comparison with the maximum permissible norms (MPL) [15-18].

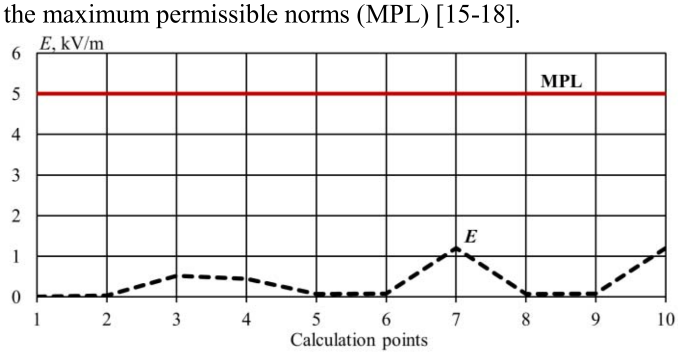

Figure 7. Dependence of the electric field strength on the location (voltage 20 kV, load 2500 kVA)

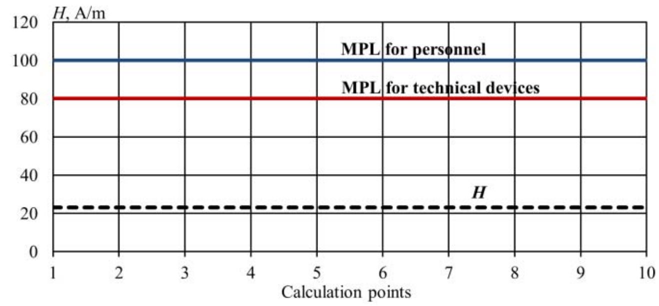

Figure 8. Dependence of the magnetic field strength on the location (voltage 6 kV, load 2500 kVA)

V. DISCUSSION

The dependence of the electric field strength (Fig. 5) has an increasing sigmoidal character of the change. As the voltage and power of the transformer equipment TVR are increasing, the same happens to the electric field strength. This is due to the fact that as the power increases, the capacity of MV cable lines of three single-phase series transformers goes up. In addition, the electric field strength is linearly dependent on the voltage. This explains the increase in the electric field strength at a power from 630 to 2500 kVA and voltage from 6 to 20 kV. The maximum value of *E* is being observed at the voltage of 20 kV and a load of 2500 kVA.

The dependence of the magnetic field strength (Fig. 6) possesses an increasing exponential nature of the change. The strength of the magnetic field depends on the power of the transformer equipment TVR and rises approximately 4 times with increasing power from 630 to 2500 kVA.

This is due to the increase in the current flowing in the circuit, directly proportional to the strength of the magnetic field. For TVR with the voltage of 20 kV in comparison with TVR 10 kV, the intensity of the magnetic field is lower approximately by two times, since at the same nominal power of the transformer equipment the current flowing in the circuit is twice less.

An analysis of the investigation results has shown that the electric and magnetic fields do not exceed the permissible norms (Fig. 7, 8) [12]. The maximum permissible level (MPL) of the electric field strength at the workplace during the whole shift is set at 5 kV/m, and the magnetic field at 80 A/m. For a continuous magnetic field of industrial frequency, the level of H_{norm}=100 A/m is acceptable for technical devices [13-15]. Thus, the maximum calculated values of the EMF intensity indices exposure are lower than the normative values by about 4 times.

VI. Conclusion

When developing the design of new electrical devices, it is necessary to take into consideration at a design stage all possible hazardous and harmful factors that may arise during operation by the maintenance personnel.

For the implementation of TVR into the power supply systems of consumers it is necessary that the amount of harmful influence of the equipment per person should comply with the current sanitary norms and rules.

For this purpose, the layout of the electrical equipment in the TVR was developed considering the minimum permissible distances in accordance with the Electrical installations code (EIC) [16], as well as the techniques for calculating the electric and magnetic field strengths while operating the device.

With the use of the developed technique, studies of the EMF intensity for TVR at 6, 10, 20 kV and load power from 630 to 2500 kVA have been carried out.

The maximum value of the electric field strength is observed at the voltage of 20 kV, and a magnetic field at the voltage of 6 kV with the load power of 2500 kVA.

The results obtained made it possible to conclude that the effect of the EMF intensity indices is much lower than the permissible values [15-18]. EMF, created during the operation of TVR, does not have a significant impact on human and control system.

Conducted evaluation studies of EMF allowed to rationalize the design of the device being developed and to choose the optimal location of its elements, taking into consideration the electromagnetic situation.

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