Запропоновано експертну систему автоматизованого проектування конструкції жолобкового хвилеводу. Електродинамічне моделювання виконане за використанням модифікованого МЧО, який верифіковано експериментально.

Ключові слова: експертна система, жолобковий хвилевод, CAD

A knowledge based CAD system of groove guide design has been developed. Modified mode matching method of electrodynamics modeling was used, which was proved by an experimental data.

Key words: knowledge based CAD system, groove guide design

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THE METHOD OF REDUCING THE INTENSITY OF MAGNETIC FIELD OUTSIDE HIGH VOLTAGE POWER SUBSTATIONS

В данной работе рассматриваются теоретические методы уменьшения магнитного поля за пределами подстанций высокого напряжения. Было показано, что чередование фаз проводов соседних ошиновок влияет на снижение интенсивности магнитного поля за пределами подстанций высокого напряжения, и эти меры могут быть реализованы на стадии проектных работ, не требуя дополнительных затрат для их реализации.

Ключевые слова: электромагнитные процессы, воздействие на людей и окружающую среду, системы защиты, шины электропитания, подстанции высокого напряжения, последовательность фаз.

Introduction. It is known [1] that 50-Hz frequency magnetic fields produced inside (for personal) and outside (for population) the territory of high voltage (HV) power substations located in city areas do not reach the exposure limits specified by Ukrainian regulations (1750 μT) [2], the International Commission on Non-Ionizing Radiation Protection guidelines (200 μT and 1000 μT) [3], and the proposed European Union Directive (1000 μT) [4].

The newly proposed limit will be 0,5 μT [5], and as such, some power objects may not comply with this limit value. This fact indicates a possible exceedance of the new regulations outside HV substations located in city areas. Therefore, investigation of measures to reduce the values of MFs at the design stage of power objects is an important task.

Problem statement. Typical power substations have multilayer and multicell arrangement of busbar wires; thus, it is certainly incorrect to consider a single cell or a single horizontal layer. However, for the purpose of identifying patterns, it is acceptable to introduce simplifications that allow an investigator to separately consider a layer, a cell, or several cells in a two dimensional form. Thus, the essence is not lost.

Theoretical studies of MF were performed for common types of 110/10 kV substations in Ukraine. Dimensions of the busbar wires of this substation are taken based on typical projects. This study, adopted the following dimensions:

- the distance between cells of the HV switchgear was 9 m;
- the distance between the wires of the HV busbars was 2,5 m;
- the average suspension height of the upper layer HV busbars was 11,2 m;
- the average suspension height of the lower layer HV busbars was 3,6 m;
- the distance between the wires of the low voltage (LV) busbars was1 m;
- the average suspension height of the LV busbars was 3 m.

Currents in the busbar wires are specified in accordance with [6] for one of the three variants of the setting, i.e., the currents in HV wires are adopted as $I_C = 210$ *A*, $I_B = -105$ *A*, $I_A = -105$ *A,* and $I_C = 2300$ A, $I_B = -1150$ A, $I_A = -1150$ A for the LV wires. Arrangement of phases is from the left to right («C-B-A»). The height *h* of the observation points is 2 m. A busbar wire is considered as a system of parallel linear currents over a flat earth. Each phase is calculated separately, and finally, the total field *B* is summed as a square root of the sum of the horizontal and vertical components squared.

Main results of the research. Table 1 shows the results of calculation of MF produced by HV busbar wires, given in Figure 1, under the different suspension heights *H* and the distance between the wires *d*.

Table 1 – Comparison of variants of reducing MFs by changing suspension height and phase-to-phase distance of HV switchgear busbar wires

Parameters of busbar wires (Figure 1)	*B*, µT at distance *x* from projection of middle phase wire («B»), m			
	0	20	40	60
d = 2,5 m, *H* = 11,2 m	1,74	0,34	0,10	0,04
d = 1 m, *H* = 11,2 m	0,99	0,19	0,05	0,02
d = 5 m, *H* = 11,2 m	1,82	0,40	0,11	0,05
d = 2,5 m, *H* = 8 m	1,47	0,34	0,09	0,04
d = 2,5 m, *H* = 13 m	1,29	0,29	0,08	0,04
d = 2,5 m, *H* = 3,6 m	1,74	0,34	0,10	0,04

Table 2 shows the results of MF calculations produced by HV and LV busbar wire configurations, given in Figure 2, under the different wire dimensions (*a*, *b*, *d*).

Table 3 shows the results of MF calculations produced by LV busbar wire configurations, given in Figure 1, under the different suspension heights H and the distance between the wires d.

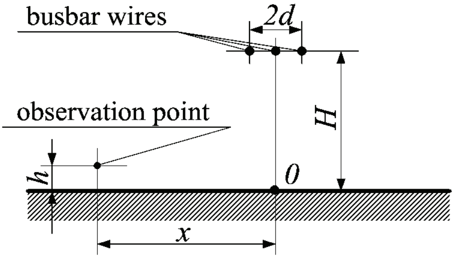

Figure 1 – Scheme of HV and LV busbar wire locations (H is the suspension height; h is the height, and x is the distance from the point of observation; d is the distance between the busbar wires)

Table 2 – Comparison of variants of reducing MFs by changing horizontal phase arrangement of HV and LV busbar wires into triangular construction

Parameters of busbar wires (Figure 2)	B, µT at distance x from projection of middle phase wire («B»), m			
	0	20	40	60
horizontal: $d = 2{,}5$ m, $H = 11{,}2$ m	1,74	0,34	0,10	0,04
equilateral triangular: $d = 2{,}5$ m, $H = 11{,}2$ m, $a = \sqrt{3}/2 \cdot d$, $b = 1{,}25$ m	0,99	0,19	0,05	0,02
equilateral triangular: $d = 5$ m, $H = 11{,}2$ m, $a = \sqrt{3}/2 \cdot d$, $b = 2{,}5$ m	1,82	0,40	0,11	0,05
triangular: $d = 3{,}5$ m, $H = 11{,}2$ m, $a = 2{,}5$ m, $b = 0{,}5$ m	1,47	0,34	0,09	0,04
triangular: $d = 3$ m, $H = 11{,}2$ m, $a = 2{,}45$ m, $b = 0{,}5$ m	1,29	0,29	0,08	0,04

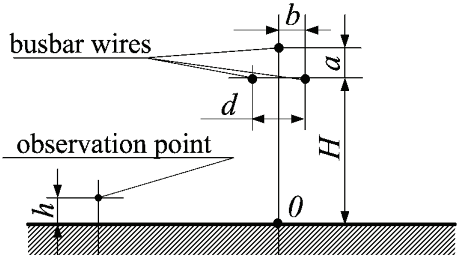

Figure 2 – Scheme of HV and LV triangular busbar wire locations (H is the suspension height; h is the height, and x is the distance from the point of observation; a, b, and d are the parameters of busbar wires)

Table 3 – Comparison of variants of reducing MFs by changing suspension height and phase-to-phase distance of LV switchgear busbar wires

Parameters of busbar wires (Figure 1)	B, µT at distance x from projection of middle phase wire («B»), m			
	0	20	40	60
$d = 1$ m, $H = 3$ m	363,66	1,75	0,43	0,19
$d = 0{,}6$ m, $H = 3$ m	310,44	1,04	0,26	0,11
$d = 1{,}4$ m, $H = 3$ m	360,14	2,48	0,61	0,27
$d = 1$ m, $H = 2{,}5$ m	663,42	1,76	0,43	0,19
$d = 1$ m, $H = 3{,}5$ m	217,49	1,75	0,43	0,19

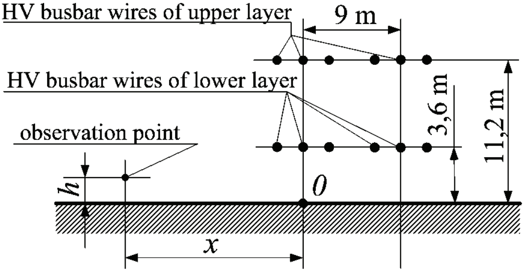

Figure 3 – Scheme of HV busbar wire locations of two neighboring cells (3.6 m is the height of the lower layer HV busbars; 11.2 m is the height of the upper layer HV busbars; 9 m is the distance between neighboring cells; h is the height, and x is the distance from the point of observation)

From Table 1-3, it can be concluded that decreasing the distance between phases, increasing the suspension height, and alternating the arrangement of the HV and LV busbar conductors comprise one of effective measures that allows us to reduce the intensity of MFs (as well as electric fields) generated inside and outside the territory of a substation. However, the possibility of an effective application of these solutions is limited by some requirements associated with providing safety and the convenience of repair works. Additionally, there is an additional barrier to implementation concerning the complication of tower construction and consequently, an increase in cost. Based on these facts, the measures that are related to the phase sequence alternation of HV and LV busbars are especially important.

Table 4 shows the results of MF calculations produced by HV busbar wire configurations of one cell given in Figure 3, under the different phase sequence and current directions.

It is clearly seen from Table 4 that the worst configuration of the cells, in respect to MFs generated far away from sources of the field, is that in which upper and lower layer currents have the same direction.

Table 5 shows the results of MF calculations produced by HV busbar wire configurations of two cells given in Figure 3, under the different phase sequence and current directions.

Table 4 – Comparison of variants of reducing MFs by alternating HV busbar wire phase of one cell («CBA» means positive direction of currents; «cba» is opposite direction)

Phase sequence in busbar wires (Figure 3)	*B*, μT at distance *x* from projection of middle phase wire («B»), m			
	0	20	40	60
C B A C B A	21,78	0,70	0,19	0,09
C B A c b a	18,56	0,27	0,04	0,01
C B A -----	1,74	0,34	0,10	0,04
----- C B A	20,16	0,41	0,10	0,04
C B A A B C	18,72	0,26	0,04	0,01
C B A a b c	21,64	0,67	0,19	0,09

Table 5 – Comparison of variants of reducing MFs by alternating HV busbar wire phase of two cells («CBA» means positive current direction; «cba» is opposite direction)

Phase sequence in busbar wires (Figure 3)	*B*, μT at distance *x* from projection of middle phase wire («B»), m			
	0	20	40	60
C B A C B A ------- -------	2,01	0,51	0,16	0,08
C B A C B A C B A C B A	19,25	1,06	0,32	0,15
C B A C B A C B A -------	21,46	0,88	0,26	0,12
------- ------- C B A C B A	17,96	0,61	0,17	0,08
C B A C B A c b a c b a	24,33	0,35	0,06	0,02
C B A A B C ----- -----	2,02	0,18	0,03	0,01
----- ----- C B A A B C	21,99	0,23	0,04	0,01
C B A A B C C B A A B C	24,01	0,37	0,07	0,02
C B A A B C c b a a b c	19,97	0,19	0,02	0,01

Table 6 presents the results of MF calculations produced by LV busbar wire configurations of two cells given in Figure 4, under the different phase sequence and current directions.

A substation during normal operation mode is usually characterized by 2, 3, 4 variants that are favorable for environmental conditions outside the territory of substations. Variant 1 is possible only for a small number of substations and only in specific operation modes.

Thus, the location of phase conductors and current directions in a single cell in normal operation mode of the substation provides the lowest MF values. For this reason, alternating the phase of one cell is not effective. However, when designing substations, one should pay attention to the MF created by the currents of outer cells, and if it is possible, avoid the same direction of the currents (power) in any section of a cell, especially in the outer cells.

From Table 5, it is seen that when we have the same direction of currents in neighboring cells (standard phasing), the MF produced by a single cell is strengthened due to an additional field produced by currents with the same direction in busbar conductors of neighboring cells that are located at a distance of 9 m. When we have the opposite direction, the effect of reducing the resulting MF is achieved through partial compensation of the field produced by a single cell, using the field produced by the currents flowing in opposite directions in the phase conductors of neighboring cells.

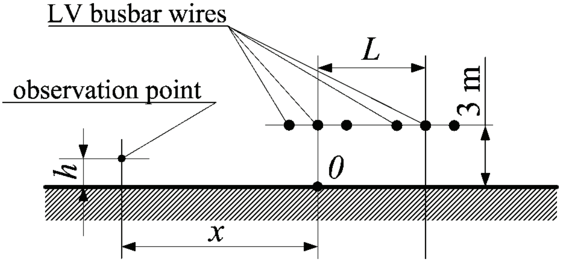

Figure 4 – Scheme of two neighboring LV busbar wire locations (3 m is the suspension height of the LV busbars; *L* is the distance between neighboring cells; *h* is the height, and *x* is the distance from the point of observation)

Thus, in changing the current phase values of the neighboring cells at the edges of the next cell, i.e., at the limit distance from each other («C-B-A»–»A-B-C»), it is possible to obtain a significant (3–5 times) reduction of MF at the distances of 40–60 m from the projection of the wire of the middle phase of the first cell in comparison with the standard phasing.

As it can be noticed from Table 6, *5* variant that means a mirrored arrangement of the phases, and *3* variant with the opposite flowing currents in the phases of the busbar conductors leads to a significant reduction of MFs in comparison with the same direction of the currents. The field reducing multiplicity at the distances of 40–60 meters is 3–4 times. It is important to note that the variant with opposite currents is difficult to put into practice because it requires the installation of additional equipment.

Table 6 – Comparison of variants of reducing MFs by alternating LV busbar wire phase («CBA» means positive current direction; «cba» is opposite direction)

Phase sequence in busbar wires (Figure 4)	B, μT at distance x from projection of middle phase wire («B»), m			
	0	20	40	60
L = 9 m C B A C B A	354,87	2,58	0,72	0,34
L = 5 m C B A C B A	334,54	2,87	0,78	0,36
L = 9 m C B A c b a	372,45	0,92	0,15	0,05
C B A	363,66	1,75	0,43	0,19
L = 9 m C B A A B C	371,82	0,94	0,15	0,05

Therefore, since the measures related to changing the phase and suspension height spacing are also hard to implement, the only rational measures to reduce MFs produced by LV busbar is changing the phase sequence by removing current values of the neighboring cells at the edges in the next LV busbar wires, i.e., at the limit distance from each other («C-B-A»–«A-B-C»).

A comparison of different possible measures to limit the MF outside HV power substations allowed us to identify and choose measures that do not require a significant cost for implementation. They are as follows:

1) the phase sequence alternation («C-B-A»–«A-B-C») of HV busbar wires of two neighboring cells;

2) the phase sequence alternation («C-B-A»–«A-B-C») of two neighboring LV busbar wires at the sector from power transformers to the close type switchgear;

3) the combined application of the first and second measures, i.e., the phase sequence alternation («C-B-A»–«A-B-C») of HV busbar wires in two neighboring cells and two neighboring LV busbar wires.

The listed measures were used to demonstrate the possibility of MF reduction in the example of a 110/10 kV power substation made according to the «two blocks of line-transformer» scheme. A process development of a three-dimensional simulation model and studies of MFs at this power substation have been extensively discussed and presented in [1,6].

The results of applying measures to reduce the field at the considered power substation are summarized in Table 7.

As it can be seen from Table 7, implementation of the proposed measures allows us to significantly reduce values of magnetic flux density outside the territory of the power substation (for example, field value at the distance of 30 m from the substation's fence was lower in 4,4 times under the phase alternation of the HV and LV busbar wires together) and to restrict the area to 0.1–1 μT values in comparison with standard phasing adopted in normal operation mode.

Table 7 – Magnetic flux density values under different measures applied to the «two blocks of line-transformer» substation of 110/10 kV

Measure	B, μT (at 20 m distance from the substation's fence)	B, μT (at 30 m distance from the substation's fence)
without applying any measures (normal operation mode)	0,20	0,15
phase alternation of HV busbar wires	0,16	0,11
phase alternation of LV busbar wires	0,11	0,08
phase alternation of HV and LV busbar wires together	0,07	0,03

Conclusion. Comparison of different possible measures of reducing MFs generated outside HV power substations has shown that decreasing the distance between phases, increasing the suspension height, and alternating the arrangement of the HV and LV busbar conductors comprise one of the effective measures that reduces the intensity of EMFs generated inside and outside the territory of a substation; but, the possibility of an effective application of these solutions is limited due to an increase in cost to its practical implementation.

The most effective measures that can be implemented at the design stage and do not require an additional cost for implementation are the phase sequence alternation of HV busbar wires of two neighboring cells, the phase sequence alternation of two neighboring LV busbar wires at the sector from power transformers to the close type switchgear, the combined application of the phase sequence alternation of HV busbar wires in two neighboring cells and two neighboring LV busbar wires. Implementation of the proposed measures for limiting MF generated outside the 110/10 kV power substation significantly reduces values of magnetic flux density in comparison with standard phasing adopted in normal operation mode.

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This work looks at theoretical methods for reducing the magnetic field generated outside the area of high voltage power substations. It has been shown that changing the construction of busbar wires is an effective measure that facilitates a reduction in the intensity of electromagnetic fields generated inside and outside the area of a substation. The measures connected with the phase sequence alternating of busbar wires can be implemented at the design stage and do not require an additional cost for implementation.

Keywords: electromagnetic processes, impact on humans and environment, systems of protection, busbar, high voltage power substation, phase sequence.

В даній роботі розглядаються теоретичні методи зменшення магнітного поля за межами підстанцій високої напруги. Було показано, що чергування фаз проводів сусідніх шин впливає на зниження інтенсивності магнітного поля за межами підстанцій високої напруги, і ці заходи можуть бути реалізовані на стадії проектних робіт, не вимагаючи додаткових витрат для їхньої реалізації.

Ключові слова: електромагнітні процеси, вплив на людей і навколишнє середовище, системи захисту, шини електроживлення, підстанції високої напруги, послідовність фаз.