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OF THE REPUBLIC OF KAZAKHSTAN
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ГЕОЛОГИЯ ЖӘНЕ ТЕХНИКАЛЫҚ ҒЫЛЫМДАР СЕРИЯСЫ

♦

СЕРИЯ ГЕОЛОГИИ И ТЕХНИЧЕСКИХ НАУК

♦

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Қазақстан Республикасы Ұлттық ғылым академиясы "ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы" ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

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CALCULATION AND VISUALIZATION OF THE FIELD OF A COAXIAL CABLE CARRYING A STEADY CURRENT

Abstract. The article presents the calculations and visualization of a magnetic field of the coaxial cable consisting of two concentric conductors carrying a steady current by using the package of MATLAB applied programs. Calculation of a magnetic field induction as a function of distance is performed for both inside and outside of a cable, namely: 1) inside the central conductor from its center to its surface; 2) between two concentric conductors from an external surface of the internal conductor up to an internal surface of the external conductor; 3) inside the external conductor; 4) outside of the external conductor. There are images of a magnetic field lines depending on the specified distances. The lines of the magnetic field are drawn in a projection on the X-Y plane. The density of the magnetic field lines in the picture completely correlates with the calculated values of the magnetic induction within considered area of its variation. It is shown that the magnetic field outside of a cable is equal to zero.

Results of visualization and calculations of the magnetic field of a coaxial cable are used in a theoretical electrical engineering.

Key words: coaxial cable, magnetic induction, magnetic field lines, steady current, electric current density.

Nowadays all educational institutions of Kazakhstan are provided with computer hardware and software, interactive boards and internet. Almost all teachers have completed language and computer courses for professional development. Hence the educational institutions have all conditions for using computer training programs and models for performing computer laboratory works. During several years we have been conducting the work on organization computer laboratory works on physics with use of resources of the Fizikon Company [1, 2] which are developed at Al-Farabi Kazakh National University by V. V. Kashkarov and his group. Some of worksheet templates for computer laboratory works are introduced in educational process of our university and schools of the Southern Kazakhstan [3-31]. Students of the physics specialties 5B060400 and 5B011000 successfully master the discipline “Computer modeling of physical phenomena” which is the logical continuation of the disciplines “Information technologies in teaching physics” and “Use of electronic textbooks in teaching physics”. The aim of this discipline is to study and learn the MATLAB program language [32] system, acquaintance with its huge opportunities for modeling and visualization of physical processes. The present article is devoted to calculation and visualization of the magnetic field of the coaxial cable carrying a steady current by using the package of MATLAB applied programs.

For working out the program for calculation and visualization of the magnetic field of a long coaxial cable consisting of two concentric conductors it is necessary to know the sizes of the cable. We take the sizes to be as followings: the radius of the inner conductor is a = 6 mm, the internal radius of the external conductor is b = 10 mm, the external radius of the latter is c = 11.7 mm. These sizes make both conductors to have identical current densities. The cable carries a steady current of I = 1 A. There is the formulation of the problem: it is necessary to determine

1) The magnetic field induction **B** at the points inside the central conductor ($0 < r < a$);
2) The magnetic field **B** in the space between two conductors ($a < r < b$);
3) The magnetic field **B** at the points inside the external conductor ($b < r < c$);
4) The magnetic field **B** at the points outside the cable ($r > c$).

The cross-section of the cable, consisting of two conductors is shown in the figure 1.

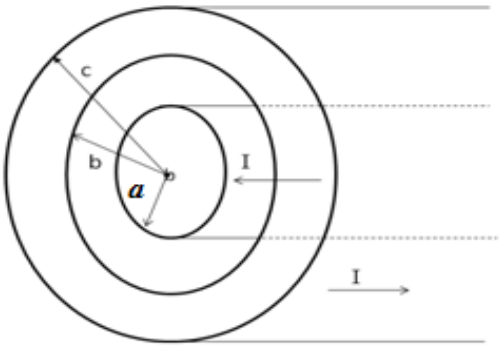

Figure 1 – The cross-section of the coaxial cable, consisting of two concentric conductors carrying a steady current

By applying the Gauss's theorem and the principle of superposition we derive the magnetic field induction **B** at the points inside the central conductor ($0 < r < a$)

$$B = \frac{\mu_0 Ir}{2\pi a^2}; \quad j = \frac{I}{\pi a^2}.$$

Then the MatLab program for calculation of the magnetic field at the points inside the central conductor is the following:

```
>> I=1; % input the electric current
>> m0=4*pi*1e-7; % input the permeability of free space
>> a=6e-3; % input the radius of the central conductor
>> r=0:a/10:a; % input the distance vector
>> B=m0*I.*r./(2*pi*a^2); % calculation of the magnetic induction inside the central conductor
>> plot(r,B,'k') % visualization
>> grid on% drawing the coordinate grid
>> xlabel('r, m') % input the name of the axis x
>> ylabel('B, T') % input the name of the axis y
>> title('B=F(r)') % input the name of the graph
>> B=m0*I.*6e-3./(2*pi*a.^2) % calculation of the magnetic induction at the surface of the central
   conductor
```

The result of calculation is presented in the figure 2. It shows, that the magnetic induction inside the central conductor increases linearly from zero up to $3.33 \cdot 10^{-5}$ T. B =3.3333e-005 is the result of calculation of the magnetic induction at the surface of the central conductor.

Here is the program for visualization of the magnetic field at the points inside the central conductor:

```
>> x=-a:0.001*a:a; % input the coordinate vector
>>y=-a:0.001*a:a; % input the coordinate vector
>> [X,Y]=meshgrid(x,y); % drawing the grid at knots of which x and y coordinates are recorded %
   (arrays X and Y).
>> I=1; m0=4*pi*1e-7; % input the current and permeability of free space
>> r1 = ((X -0.01* a).^ 2 + (Y+0.01*a).^ 2).^0.5; % calculation of the distance
>> r2 = ((X +0.01* a).^ 2 + (Y-0.01*a).^ 2).^0.5; % calculation of the distance
>> r=sqrt(r1.^2+r2.^2); % calculation of the distance
>> B=m0*I.*r./(2*pi*a^2); % calculation of the magnetic induction as a function of the distance r
>> Z=B; % redesignation
```

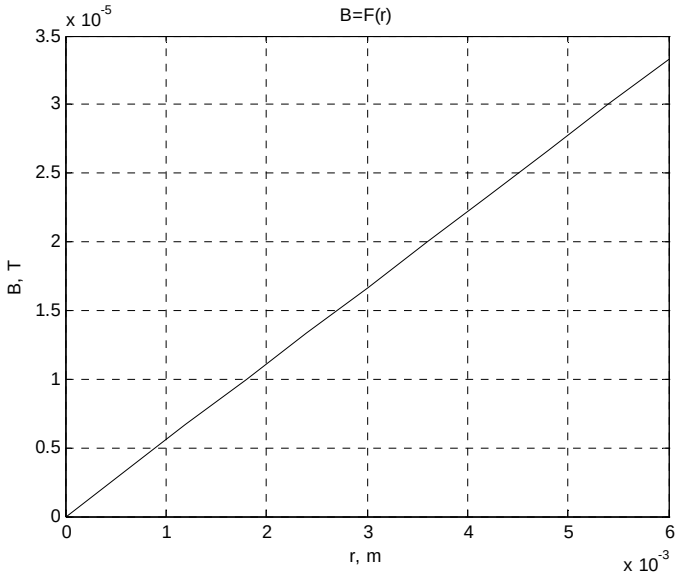

Figure 2 – The induction of the magnetic field of the central conductor versus the distance ($0 < r < a$)

```
>> contour3(X,Y,Z,100); % drawing the lines of the magnetic induction
>> xlabel('X,m') % input the name of the axis x
>> ylabel('Y,m') % input the name of the axis y
>> zlabel('B,T') % input the name of the graph
```

The result of visualization is presented in the figure 3.

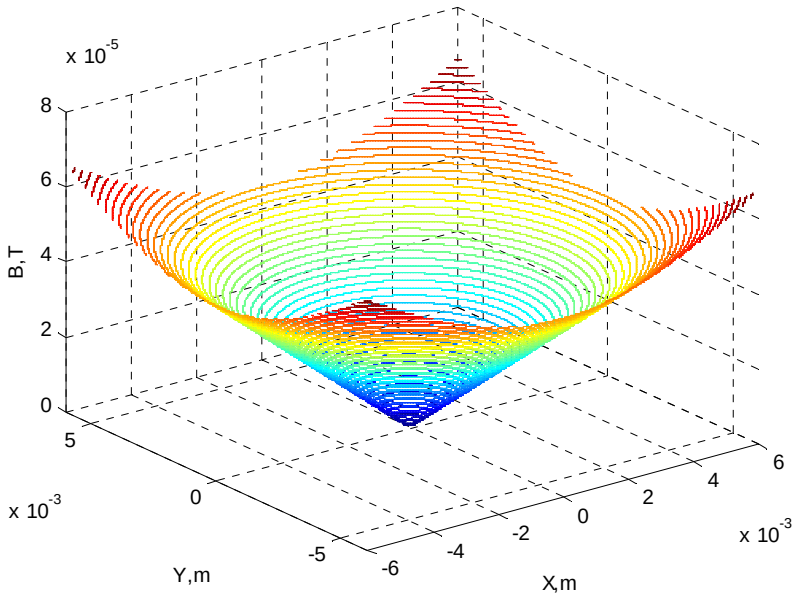

Figure 3 – The lines of magnetic induction inside the central conductor in three-dimensional space

```
>> view([0 0 50]) % visualization in the projection on the plane XY
```

The result is presented in the figure 4.

The graph in figure 2 demonstrating that the magnetic induction linearly increases with the distance from the center of the central conductor towards its surface is confirmed by the picture in figure 4, where the density of the magnetic field lines increases with a distance from the center of the conductor to its surface.

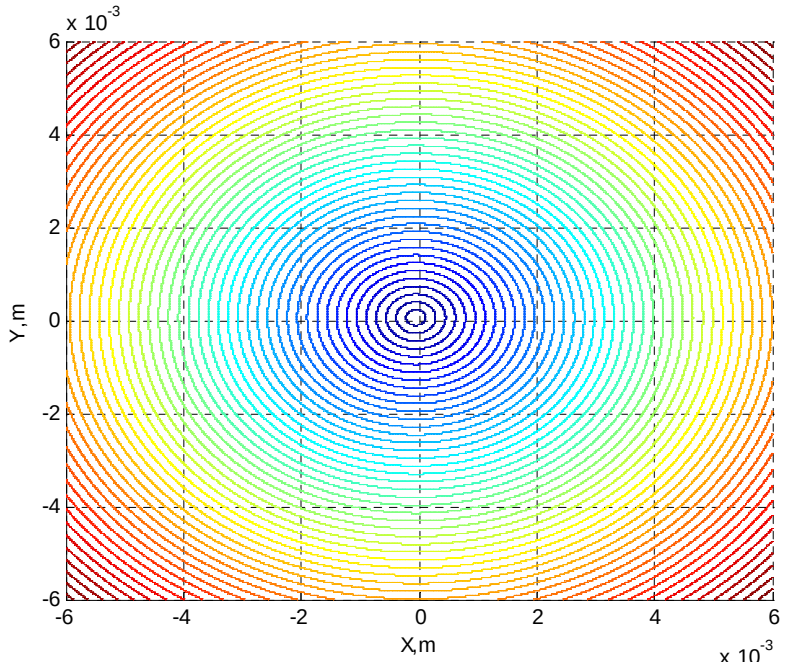

Figure 4 – The lines of magnetic induction inside the central conductor in the projection on the X-Y plane

The magnetic field **B** in the space between two conductors (a < r < b):

$$B = \frac{\mu_0 I}{2\pi r}$$

The MatLab program for calculation of this magnetic field is given below:

```
>> b=10e-3; % input the inner radius of the external conductor
>> r=a:a/50:b; % input the distance vector
>> B=m0*I./(2*pi.*r) % calculation of the magnetic induction magnitude
>> plot(r,B1,'k-') % visualization
>> grid on% drawing the coordinate grid
>> xlabel('r, m') % input the name of the axis x
>> ylabel('B, T') % input the name of the axis y
>> title('B=F(r)') % input the name of the graph
>> B=m0*I./(2*pi.*a) % calculation of the magnetic induction at the surface of the central conductor
   B = 3.3333e-005% the answer
>> B=m0*I./(2*pi.*b) % calculation of the magnetic induction at the inner surface of the external
   conductor
   B = 2.0000e-005% the answer
```

The result is presented in the figure 5.

The figure 5 shows that the magnetic induction is inversely proportional to the distance r between the external radius of the central conductor and the inner radius of the external conductor, i.e. it decreases from B = $3.33 \cdot 10^{-5}$ T till $2 \cdot 10^{-4}$ T within distances r from a up to b.

The program for visualization of the lines of the magnetic induction between the central and external conductors (a< r < b) is the following:

```
>> b=10e-3; % input the inner radius of the external conductor
>> x=a:0.001*a:b; % input the coordinate vector
>> y=a:0.001*a:b; % input the coordinate vector
>> [X,Y]=meshgrid(x,y); % drawing the grid at knots of which the coordinates x and y are recorded
   % (arrays X and Y).
>> I=1; m0=4*pi*1e-7; ; % input the current and magnetic induction
>> r1 = ((X -0.01* a).^ 2 + (Y+0.01*a).^ 2).^0.5; % calculation of the distance
```

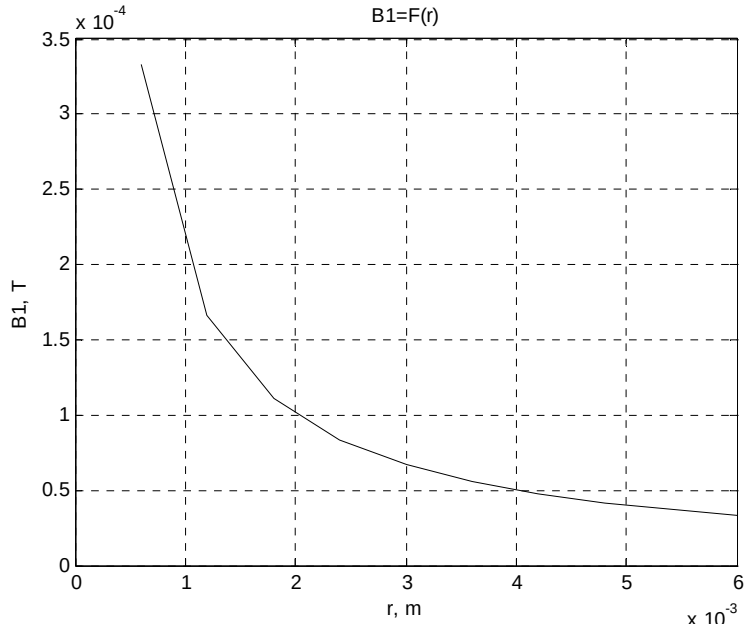

Figure 5 – The dependence of the magnetic induction on the distance r between the external radius of the central conductor and the inner radius of the external conductor

>> r2 = ((X +0.01* *a*).^ 2 + (Y-0.01**a*).^ 2).^0.5; % calculation of the distance
>> r=sqrt(r1.^2+r2.^2); % calculation of the distance
>> B=m0*I./(2*pi.*r) % calculation of the magnetic induction magnitude
>> Z=B; % redesignation
>> B=m0*I./(2*pi.**a*) % calculation of the magnetic induction at the surface of the central conductor
B = 3.3333e-005% the answer
>> B=m0*I./(2*pi.*b) % calculation of the magnetic induction at the inner surface of the external \ conductor
B = 2.0000e-005 % the answer
>> contour3(X, Y, Z, 100); % drawing the lines of the magnetic induction
The result is presented in the figure 6.

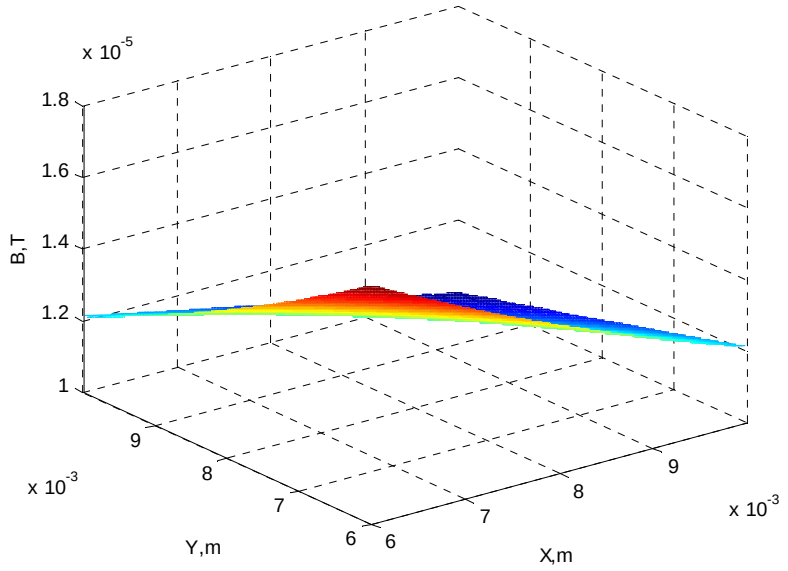

Figure 6 – The lines of the magnetic induction between the external radius of the central conductor and inner radius of the external conductor in three-dimensional space

The picture of the magnetic field lines is not so much informative, for this reason we present it in the projection on X-Y plane. The program for this task is:

>> view([0 0 100]) % visualization of the magnetic field lines in the projection on X-Y plane

The result is presented in the figure 7.

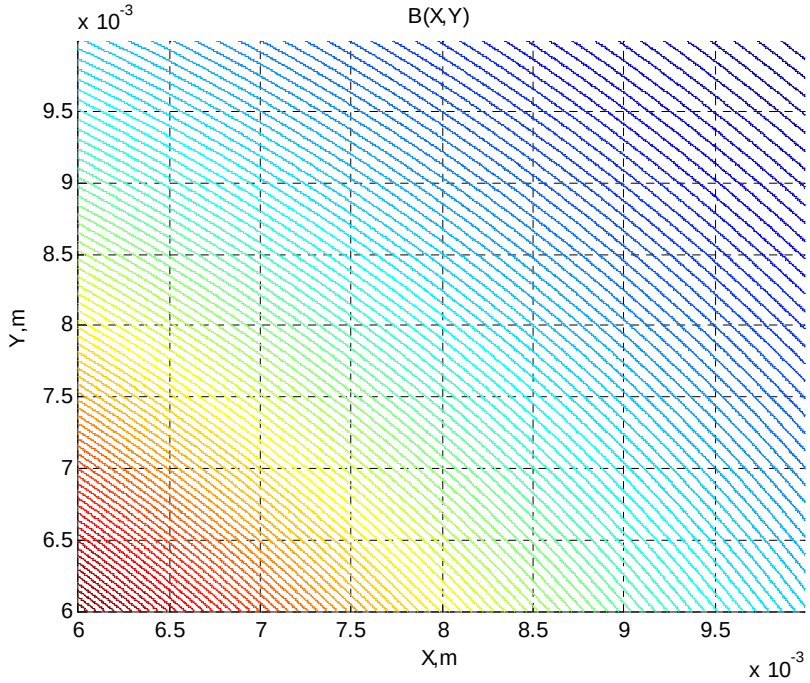

Figure 7 – The lines of the magnetic induction between the external radius of the central conductor and inner radius of the external conductor in the projection on X-Y plane

The figures 5-7 show that the magnetic induction between the external radius of the central conductor and inner radius of the external conductor decreases inversely proportionally to the given distance and the density of magnetic field lines decreases with approaching the inner surface of the external conductor.

Let us consider the magnetic field **B** inside the external conductor ($b < r < c$):

$$B = \frac{\mu_0 I}{2\pi r} \frac{c^2 - r^2}{c^2 - b_2}$$

Then the program for calculation of this magnetic induction is the following:

>> *a*=6e-3; % input the radius of the central conductor
>> b=10e-3% input the inner radius of the external conductor
>> c=sqrt(*a***a*+b*b) % calculation of the external radius of the external conductor c =0.0117% the answer
>> I=1; m0=4*pi*1e-7; % input the current and the permeability of free space
>> r2=b:b/50:c; % input the distance vector
>> B2=m0*I.*(c.^2-r2.^2)./(2*pi*(c.^2-b.^2)); % calculation of the magnetic induction inside the external conductor
>> plot(r2,B2,'k-') % visualization
>> grid on% drawing the coordinate grid
>> xlabel('r2, m') % input the name of the axis *x*
>> ylabel('B2, T') % input the name of the axis *y*
>> title('B2=F(r2)') % input the name of the graph

The result is presented in the figure 8.

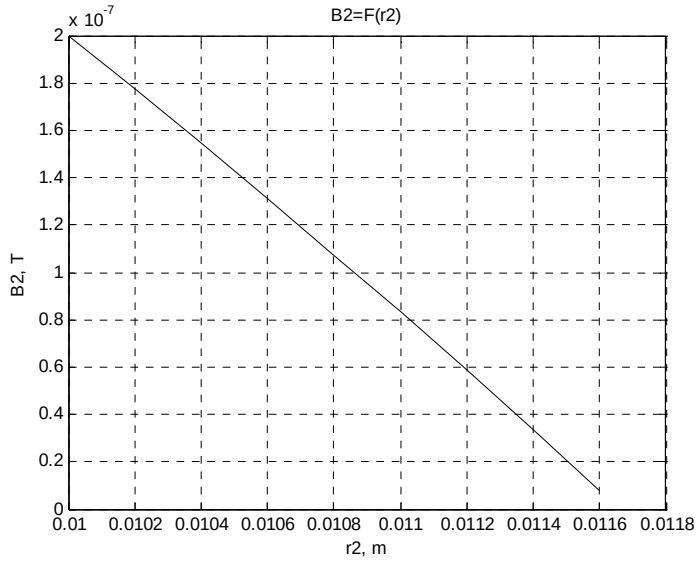

Figure 8 – The magnetic induction versus the distance inside the external conductor

According to the graph in the fig.8 the magnetic induction inside the external conductor monotonically decreases with the distance from the inner surface to the external surface of the external conductor.

The program for visualization of the lines of the magnetic field inside the external conductor ($b < r < c$) is:

```
>> a=6e-3; % input the radius of the central conductor
>> r2=b:b/50:c; % input the distance vector
>> c=sqrt(a*a+b*b) % calculation of the external radius of the external conductor c = 0.0117% the
   answer
>> I=1; m0=4*pi*1e-7; % input the current and the permeability of free space
>> b=10e-3; % input the inner radius of the external conductor
>> x=b:0.001*c:c; % input the coordinate vector
>> y=b:0.001*c:c; % input the coordinate vector
>> [X,Y]=meshgrid(x,y); % drawing the grid at knots of which the coordinates x and y are recorded
   % (arrays X and Y).
```

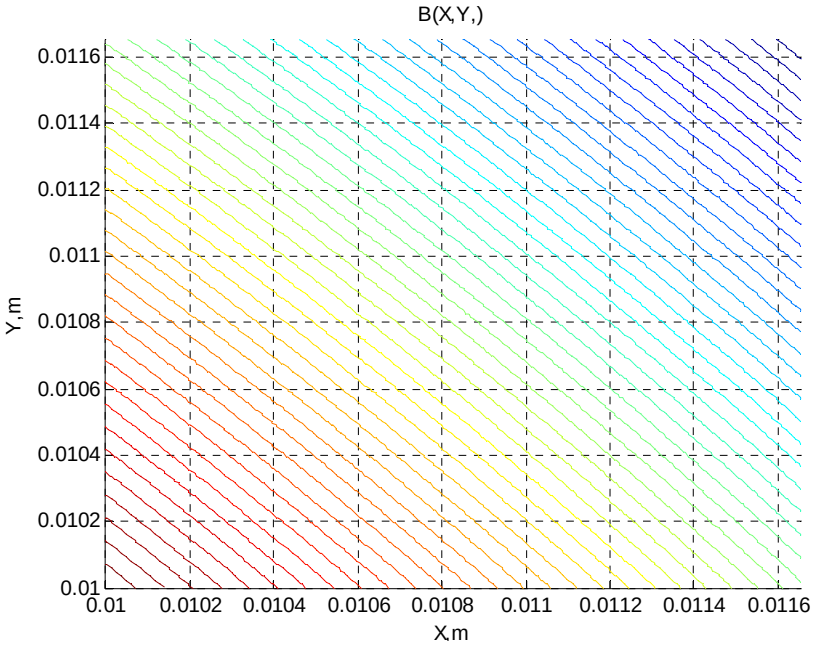

Figure 9 – The lines of the magnetic induction inside the external conductor in the projection on the X-Y plane

```
>> r1 = ((X -0.01* b).^ 2 + (Y+0.01*b).^ 2).^0.5; % calculation of the distance
>> r2 = ((X +0.01* b).^ 2 + (Y-0.01*b).^ 2).^0.5; % calculation of the distance
>> r=sqrt(r1.^2+r2.^2); % calculation of the distance
>> B=m0*I.*(c.^2-r2.^2)./(2*pi*(c.^2-b.^2)); % calculation of the magnetic induction inside the
   external conductor
>> Z=B; % redesignation
>> view([0 0 50]) % visualization of the magnetic field lines in the projection on the the X-Y plane
```

The result is presented in the figure 9.

The figures 8, 9 tell us that the magnetic induction magnitude inside the external conductor also decreases with the distance, but more slowly than in the space between two conductors. This is because the resultant field is produced due to superposition of fields of two currents flowing in opposite directions.

The magnetic field **B** outside the external conductor (r > c) is zero. Since the current densities in the central and external conductors are identical the resultant field outside the external conductor is equal to the sum of two magnetic inductions with the same magnitude but opposite directions, i.e. B = 0. (It is supposed that cable consists of two concentric infinitely long conductors)

Conclusion. The package of MatLab applied programs is used for calculation and visualization of the magnetic field of the coaxial cable consisting of two concentric conductors carrying a steady current. The four regions of the magnetic field are studied: 1) the magnetic field inside the central conductor as a function of the distance from its center to its surface; 2) the magnetic field in the space between two conductors; 3) the magnetic field inside the external conductor; 4) the magnetic field outside the external field. The following results are obtained:

1) Inside the central conductor the magnetic induction linearly increases with the distance from the center to its surface. This is confirmed by the density of visualized magnetic field lines which increases towards the surface of the central conductor.

2) The magnetic field in the space between two concentric conductors decreases inversely proportionally to the distance from the external surface of the central conductor to the inner surface of the external conductor.

3) The magnetic field inside the external conductor also decreases with distance from the inner to the external surfaces of the conductor but more slowly than between two conductors. This is explained by the fact that the resultant field is due to superposition of magnetic fields of two currents flowing in opposite directions.

4) The magnetic field outside the external conductor is zero, because it is assumed that the current densities in the central and external conductors are identical. It means that the magnetic inductions due to currents through conductors are of equal magnitudes but have opposite directions. So the resultant magnetic field taken as the sum of these magnetic inductions is equal to zero.

Each magnetic field is visualized with the help of magnetic field lines. The results of calculation and visualization of the magnetic field are used in theoretical electric engineering. Students can be suggested to work out the program for calculation and visualization of a magnetic field of two conductors carrying currents in the same direction or for two conductors with different current densities flowing in the same direction and in opposite directions.

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ТҰРАҚТЫ ТОГЫ БАР КОАКСИАЛДЫ КАБЕЛДІҢ ӨРІСІН ЕСЕПТЕУ ЖӘНЕ БЕЙНЕЛЕУ

Аннотация. Екі концентрлі өткізгіштерден тұратын тұрақты тогы бар концентрлі кабелдің магнит өрісін MATLAB программалық ортасында есептеу мен бейнелеу ұсынылған:

1) орталық өткізгіштің центрі мен оның ішкі бетіне дейінгі қашықтыққа байланысты магнит өрісінің индукциясы есептелген және күш сызықтары бейнелген; магнит өрісі индуециясының шамасы центрден орталық өткізгіштің бетіне дейін сызықты ұлғаятыны анықталған, индукцияның мұндай өзгерісін күш сызықтарының тығыздығынан да байқауға болатыны суретте көрсетілген.

2) концентрлі өткізгіштердің арасындағы магнит өрісінің индукциясы есептелген және оның күш сызықтары бейнеленген; магнит өрісі индукциясының шамасы ішкі өткізгіштің сыртқы бетінен бастап сыртқы өткізгіштің ішкі бетінен дейінгі ара қашықтыққа байланысты пропорционал өсетіні көрсетілген.

3) сыртқы өткізгіштің ішкі беті мен сыртқы бетіне дейінгі қашықтыққа байланысты магнит өрісі индукциясының Х-У жазықтығына проекциясы бейнеленген. Сыртқы өткізгіштің магнит индукциясының шамасы ара қашықтыққа байланысты өседі, бірақ 2)-ші жағдайға салыстырғанда азырақ өседі, үйткені қорытынды өріске қарама-қарсы жүрген екі токтың өрістері әсер етеді.

4) Сыртқы өткізгіштің сыртында магнит өрісі болмайды, себебі орталық өткізгіш пен сыртқы өткізгіш бойындағы ток тығыздықтары, есеп шарты бойынша бірдей боғандықтан, суперпозиция принципі бойынша қорытынды өріс қарама-қарсы жүрген токтардың бірдей магнит индукцияларының қосындысынан құралады да, өрістер жойылады.

Есептеулерді бейнелеу нәтижелері теоретикалық электротехникада қолданылады.

Түйін сөздер: таралу, коаксиалды кабель, магнит өрісінің индукциясы, сызықтар, тұрақты ток, ток тығыздығы.

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РАСЧЕТ И ВИЗУАЛИЗАЦИЯ ПОЛЯ КОАКСИАЛЬНОГО КАБЕЛЯ ПО КОТОРОМУ ТЕЧЕТ ПОСТОЯННЫЙ ТОК

Аннотация. В статье приведены расчеты и визуализация магнитного поля коаксиального кабеля, состоящего из двух концентрических проводников, по которым течет постоянный ток, с использованием пакета прикладных программ MATLAB. Вычисление зависимости индукции магнитного поля от расстояния выполнено как внутри так и снаружи кабеля, а именно: 1) внутри центрального проводника от его центра до его поверхности и приведено изображение соответсвующих линий магнитного поля; 2) между концентрическими проводниками от внешней поверности внутреннего проводника до внутренней поверхности внешнего проводника 3) внутри внешнего проводника 4) снаружи внешнего проводника. Даны изображения линии магнитной индукции в зависимости от указанных расстояний. Линии магнитной поля изображены в проекции на плоскость Х-У. Плотность изображенных линий магнитного поля полностью согласуется с вычисленными значениями магнитной индукции в рассматриваемой области ее изменения. Показано, что магнитное поле снаружи кабеля равно нулю.

Результаты визуализации и расчетов магитного поля коаксиального кабеля можно использовать в теоретической электротехнике.

Ключевые слова: коаксиальный кабель, магнитная индукция, линии магнитного поля, постоянный ток, плотность тока.

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