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Professional paper

ANN (Artificial Neural Network) Controlled Virtual Laboratory Design for NdFeB Magnet Production

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Abstract: Magnets have an important place in electrical and electronic systems and applications nowadays. The developments in the field of magnets have also greatly expanded their usage areas. NdFeB magnets play active and important role in this development. In this study, design of virtual laboratory to be used for the production of nanocomposite NdFeB magnets has been realized. Maximum energy product (BH_{max}) is an important value for permanent magnets. The high BH_{max} value in small volume for the magnets is a desired criterion. In the study, mathematical functions were created from the data related to B_r (permanent magnetism), H_c (magnetic coercivity), BH_{max}, T_c (Curie temperature) and density obtained in the researches on different NdFeB alloys in the laboratory. Additionally, B_r functions were obtained by adding different additives (Co,Ti, Zr, Hf, V, Ta, Nb, Cr, W, Mo, Mn, Ni, Sb, Sn, Ge, Al, Bi) to the NdFeB magnets. A virtual laboratory is prepared with the created functions. The obtained results from the operation of the virtual laboratory system and the results obtained from Matlab Simulink and ANN (Artificial Neural Network) systems are compared. The designed and performed virtual laboratory system can be used both for industrial purposes and for educational purposes.

Keywords: ANN (Artificial Neural Network); BH_{max}; nanocomposite; NdFeB; permanent magnet; virtual laboratory

1 INTRODUCTION

Permanent magnets have the ability to consistently release magnetic flux to the air gap of a magnetic circuit. The flux density may be regular, irregular, stable or variable in the time. The most important property for a permanent magnet is the maximum energy product (BH_{max}). At the beginning of the century, BH_{max} values of natural magnets were 10 kJ/m^3, while NdFeB magnets with a value of 400 kJ/m^3 BH_{max} are made today. Recently, the energy products of nanocomposite NdFeB hard magnets under laboratory conditions have increased to 1090 kJ/m^3[1-4]. A remarkable effort has been made to enhance the magnetic and physical properties of NdFeB magnets. Ferromagnetic elements such as iron and cobalt are widely used. Sm-Co and Nd-Fe-B rare earth magnets have a technologically important place because they give a high BH_{max} value [1, 5]. Sintered NdFeB magnets can be added with small amounts of resistant elements (Ti, Zr, Hf, V, Ta, Nb, Cr, W, Mo, Mn, Ni, Sb, Sn, Ge, Al, Bi) to increase their coercivity [6-8]. In addition, the enhanced magnetic and physical properties make these magnets' thermal stability very good [9]. Ferromagnetic metals such as Co and Ni from the transition elements increase the magnetization and T_C, Curie temperature. Elements such as Mo, Nb, Ti, V, W which have higher melting temperature than non-magnetic metals and elements such as Sn, Ga, Al, Cu and Sn with low melting temperature inhibit the growth of grains with the phases that occur at the grain boundaries. They decrease the magnetic interaction between the grains and increase the strength. At the same time, permanent magnetization can be reduced by these non-magnetic phases [10-15]. As a result of many researches, the coercivity values of Nd-Fe-B permanent magnets have been increased by additive elements with high melting temperatures such as Nb, Mo, W, Ti [16, 17]. In order to obtain optimum magnetic and physical properties of the magnets, it is necessary to sinter and cool immediately between 650 °C and 1160 °C [18]. Sintering is a high temperature process by which material powders combine to one another by diffusion through the effect of temperature and gradually reduce the pore volume between the powders [19]. In multicomponent systems, sintering temperature is set to the lower values of metal with low melting temperature. As the sintering temperature increases, sintering time decreases [20].

Composite materials are composed of two or more of the same or different types of materials combined at a macro level to collect the best properties of the materials in a new and single material. [21]. The nanocomposites are a new type of composite material containing mineral and an amount of nanosized mineral smaller than 10%.

Due to the wide surface area of the nano-sized particles used, mechanical, thermal and magnetic properties show improvements in positive direction. Due to these properties of composite materials, they play active and important role in the production of NdFeB magnets. NdFeB magnets have many properties when they are produced as composites. The high magnetism properties in small volume are at the top of these properties. Significant studies on NdFeB magnets still continue. It is tried to get higher values of magnetism properties by adding various additives.

The obtained data in the production of these magnets have been used for the system we have simulated. In different alloy magnets, the mathematical functions of the magnetic properties which are important for the magnets have been obtained. These functions are BH_{max}, H_c and B_r functions. The virtual laboratory system was designed and performed using the obtained function, MATLAB Simulink and ANN (Artificial Neural Network). There are studies using ANN on MATLAB/Simulink platform in many fields of engineering [22-26]. In this study, ANN controlled virtual laboratory on MATLAB/Simulink platform is presented at the intersection of electrical electronics engineering, material engineering, and software engineering.

The data we used to obtain mathematical functions was taken from the work of United States patent number 5-183-516. [27, 28].

2 MATHEMATICAL FUNCTIONS OF NANOCOMPOSITE NdFeB ALLOYS

2.1 Data of Mathematical Functions

Mathematical functions are needed to be used when preparing a virtual laboratory. BH_{max}, H_c and B_r functions must be obtained using the following data for alloy 15Nd-(85-x)Fe-xB. These functions form the basis of the virtual laboratory.

The effect of B (Boron) element on the magnetic properties of NdFeB magnets is shown in Tab. 1.

Table 1 The Data of 15Nd-(85-x)Fe-xB alloy [27]

Alloy Name: 15Nd-(85-x)Fe-xB			
% B	B_r / kG	H_c / kOe	BH_{max} / MGOe
0	0,0	0,00	0
2	7,5	1,3	4,1
3	10,4	1,8	7,0
4	10,8	2,8	13,4
6	13,0	8,0	36,5
7	12,9	8,2	36,0
8	12,1	7,3	32,1
10	11,9	8,0	31,9
12	10,5	8,2	25,2
17	8,7	7,6	17,6
23	6,8	11,3	10,9
30	4,2	10,7	4,0
32	3,0	10,2	1,8

The effect of Nd (neodymium) element on the magnetic properties of NdFeB magnets is shown in Tab. 2.

Table 2 The Data of xNd-(92-x)Fe-8B alloy [27]

Alloy Name: xNd-(92-x)Fe-8B			
% Nd	B_r / kG	H_c / kOe	BH_{max} / kGOe
6	0	0	0
13	13,1	4,8	29,3
14	12,8	7,8	36,5
17	11,6	9,2	31,1
19	10,9	11,4	28,0
25	5,8	12,6	8,8
35	1,9	14,6	≤ 1

Table 3 The Data of 15Nd-(77-x)Fe-8B-zM alloy [27]

Alloy Name: 15Nd-(77-x)Fe-8B-xM								
B_r values when added additives, M = Added material								
% M	Ti / kG	Zr / kG	Hf / kG	V / kG	Ta / kG	Nb / kG	Cr / kG	W / kG
0	12,0	12,0	12,0	12,0	12,0	12,0	12,0	12,0
0,5	12,3	11,9	11,9		11,6		11,6	11,6
1	12,0	11,7	11,7	11,5	11,6	11,9	11,4	11,4
1,5	11,8	11,4	11,4					
2	11,2	10,7	10,7	11,0	11,4	11,7	10,9	11,0
3	8,7	9,2	9,2	10,3				
4	6,0	7,5	7,5	9,8	10,5	11,0	9,5	9,8
5	2,4	5,3	5,3					
6		2,2	2,2	8,5	9,5	10,2	7,6	8,0
7								
8				7,0	8,4	9,4	5,2	5,9
9				5,7	7,5	9,0		
10				3,5	6,0	8,2	2,3	3,5
11					3,7			
12						5,4		

When additives are added to an alloy, the resulting residual magnetism in the alloy (B_r) the data used to obtain the required functions in order to observe the changes are given in Tab. 3 and Tab. 4.

Table 4 The Data of 15Nd-(77-x)Fe8B-zM alloy [27]

Alloy Name: 15Nd-(77-x)Fe-8B-xM							
B_r values when added additives M = Added material							
% M	Mn	Ni	Sb	Sn	Ge	Al	Bi
0,0	12,0	12,0	12,0	12,0	12,0	12,0	12,0
0,5	11,3	11,8			11,4	12,1	
1,0	10,7	11,9	9,2	10,0	11,0	11,4	11,7
1,5							
2,0	9,9	11,6	6,1	7,8	10,3	10,9	11,4
3,0				5,5			
4,0	9,1	11,1	2,9	3,5	8,4	9,6	10,4
5,0							10,0
6,0	8,7	10,2			6,5	8,4	
7,0							
8,0	8,2	9,2			3,5	6,4	
9,0							
10,0	7,3	8,0				3,4	

2.2 B_r Functions

B_r functions are directly effective as a multiplier in determining BH_{max} for alloys. It is a common value for different alloy structures. It is also used for magnet characterization for different magnet alloys. These are functions of residual magnetism when % M additives (M = Ti, Zr, Hf, V, Ta, Nb, Cr, W, Mo, Mn, Ni, Sb, Sn, Ge, Al, Bi) are added to the 15Nd-Fe-8B-xM alloy from the obtained alloys and they are pressed in 10 kOe magnetic field. The obtained B_r functions for the different additives are given in Eqs. (1) to (15).

Alloy Formula: 15 Nd-(77-x)Fe-8B-xM
(M = Ti, Zr, Hf, V, Ta, Nb, Cr, W, Mo, Mn, Ni, Sb, Sn, Ge, Al, Bi).

$$FB_r(\mathrm{Ti}) = -0,02969 \cdot x^6 + 0,4061 \cdot x^5 - 2,03 \cdot x^4 + \\ +4,555 \cdot x^3 - 5,048 \cdot x^2 + 2,181 \cdot x + 12 \quad (1)$$

$$FB_r(\mathrm{Zr}) = 0,002656 \cdot x^6 - 0,04875 \cdot x^5 + 0,3254 \cdot x^4 - \\ -0,9443 \cdot x^3 + 0,8405 \cdot x^2 - 0,4438 \cdot x + 12 \quad (2)$$

$$FB_r(\mathrm{Hf}) = 0,002656 \cdot x^6 - 0,04875 \cdot x^5 + 0,3254 \cdot x^4 - \\ -0,9443 \cdot x^3 + 0,8405 \cdot x^2 - 0,4438 \cdot x + 12 \quad (3)$$

$$FB_r(\mathrm{V}) = 2,769 \times 10^{-5} \cdot x^6 + 0,0005505 \cdot x^5 - \\ -0,004751 \cdot x^4 + 0,02434 \cdot x^3 - 0,8509 \cdot x^2 - \\ -0,4179 \cdot x + 12 \quad (4)$$

$$FB_r(\mathrm{Ta}) = 9,06 \times 10^{-5} \cdot x^6 - 0,003284 \cdot x^5 + \\ 0,04315 \cdot x^4 - 0,02561 \cdot x^3 + 0,6518 \cdot x^2 - \\ -0,8792 \cdot x + 12 \quad (5)$$

$$FB_r(\mathrm{Nb}) = 1,69410 \times 10^{-5} \cdot x^6 - 0,0006699 \cdot x^5 + \\ 0,04315 \cdot x^4 - 0,04354 \cdot x^3 + 0,03859 \cdot x^2 - \\ -0,1106 \cdot x + 12 \quad (6)$$

$$FB_r(\mathrm{Cr}) = 0,0001103 \cdot x^6 - 0,003334 \cdot x^5 + 0,03832 \cdot x^4 - \\ -0,209 \cdot x^3 + 0,4847 \cdot x^2 - 0,9313 \cdot x + 11,99 \quad (7)$$

$$FB_r(\mathrm{W}) = 7,928 \times 10^{-5} \cdot x^6 - 0,002619 \cdot x^5 + \\ +0,03346 \cdot x^4 - 0,2043 \cdot x^3 + 0,5359 \cdot x^2 - \\ -0,9768 \cdot x + 11,99 \quad (8)$$

$$FB_r(\mathrm{Mo}) = -5,397\times10^{-5}\cdot x^6 + 0,001243\cdot x^5 - \\ -0,00874\cdot x^4 + 0,01178\cdot x^3 + 0,01955\cdot x^2 - \\ -0,4964\cdot x + 12,01 \quad (9)$$

$$FB_r(\mathrm{Mn}) = 9,515\times10^{-6}\cdot x^6 + 0,0002207\cdot x^5 - \\ -0,0008097\cdot x^4 - 0,02473\cdot x^3 + 0,3136\cdot x^2 - \\ -1,579\cdot x + 12 \quad (10)$$

$$FB_r(\mathrm{Ni}) = -1,097\times10^{-5}\cdot x^6 + 0,0001658\cdot x^5 + \\ +0,0004199\cdot x^4 - 0,01631\cdot x^3 + 0,0453\cdot x^2 - \\ -0,2002\cdot x + 11,98 \quad (11)$$

$$FB_r(Sb) = 0,1\cdot x^2 - 2,74\cdot x + 12,01 \quad (12)$$

$$FB_r(\mathrm{Ge}) = 0,002315\cdot x^5 + 0,0429\cdot x^4 - 0,279\cdot x^3 + \\ +0,7251\cdot x^2 - 1,489\cdot x + 12 \quad (13)$$

$$FB_r(\mathrm{Al}) = -0,0001244\cdot x^6 + 0,004023\cdot x^5 - \\ -0,04979\cdot x^4 + 0,2833\cdot x^3 - 0,7224\cdot x^2 + \\ +0,03448\cdot x + 12,05 \quad (14)$$

$$FB_r(\mathrm{Bi}) = 0,008333\cdot x^4 + 0,075\cdot x^3 + 0,1667\cdot x^2 - \\ -0,4\cdot x + 12 \quad (15)$$

2.3 BH_{max} and H_c Functions

From the alloys formed to observe the effects of Nd and B; The effect of B with 15Nd-(85-x)Fe-xB and the effect of Nd with xNd-(92-x)Fe-8B alloy were investigated and Br and Hc functions were established for % B change and % Nd change.The obtained B_r, H_c and BH_{max} functions for 15Nd-(85-x)Fe-xB are given in Eqs. (16) to (18). The obtained B_r, H_c and BH_{max} functions for xNd-(92-x)Fe-8B are given in Eqs. (19) to (21).

Alloy Formula: 15Nd-(85-x)Fe-xB

$$FB_r(\mathrm{B}) = 9,754\times10^{-6}\cdot x^5 - 0,0009972\cdot x^4 + \\ +0,03813\cdot x^3 - 0,6705\cdot x^2 + 4,959\cdot x + 0,05367 \quad (16)$$

$$FH_c(\mathrm{B}) = -8,322\times10^{-5}\cdot x^4 + 0,006099\cdot x^3 - \\ -0,1613\cdot x^2 + 2,004\cdot x - 1,316 \quad (17)$$

$$FBH_{max}(\mathrm{B}) = -0,0001754\cdot x^4 + 0,02022\cdot x^3 - \\ -0,7541\cdot x^2 + 9,474\cdot x - 6,858 \quad (18)$$

Alloy Formula: xNd-(92-x)Fe-8B

$$FB_r(\mathrm{Nd}) = -0,0001578\cdot x^4 + 0,01715\cdot x^3 - \\ -0,6637\cdot x^2 + 10,21\cdot x - 40,84 \quad (19)$$

$$FH_c(\mathrm{Nd}) = -8,242\times10^{-5}\cdot x^3 - 0,01436\cdot x^2 + \\ +1,217\cdot x - 6,966 \quad (20)$$

$$FBH_{max}(\mathrm{Nd}) = 0,00026\cdot x^4 - 0,006882\cdot x^3 - \\ -0,4002\cdot x^2 + 13,11\cdot x - 63,16 \quad (21)$$

Using the above functions, the following virtual laboratory was prepared. Screen shot of the developed virtual laboratory software is given in Fig. 1.

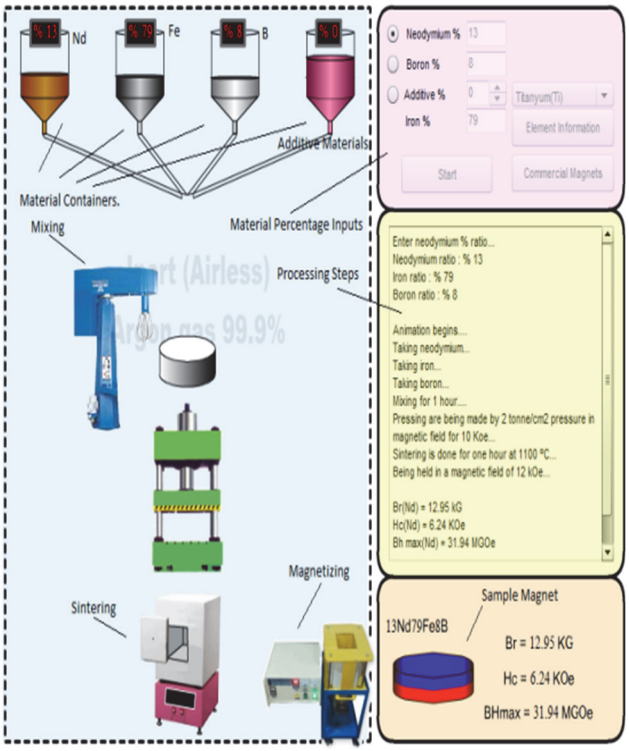

Figure 1 Screen shot of the developed virtual laboratory software [1]

When we want to produce magnet based on Nd element, when we input Nd value as % in our virtual laboratory, the system works and the alloy formula and BH_{max} values of the sample are obtained. We can obtain NdFeB alloys by doing the same steps for element B. When we select the additive and enter the % ratio in our virtual laboratory we get the residual magnetization value of the alloy 15Nd-Fe-8B-xM to investigate the effect of additives on the residual magnetism (B_r) of the NdFeB magnet (M = Additives).

Today's commercial magnets are also included in the virtual lab. B_r, BH_{max} and commercial magnets can be selected according to operating temperatures. We can also investigate the chemical and physical properties of all the elements.

3 CONTROLLING OF VIRTUAL LABORATORY WITH ARTIFICIAL NEURAL NETWORK

The block diagram of the controlling of virtual laboratory with artificial neural network (ANN) is given below (Fig. 2).

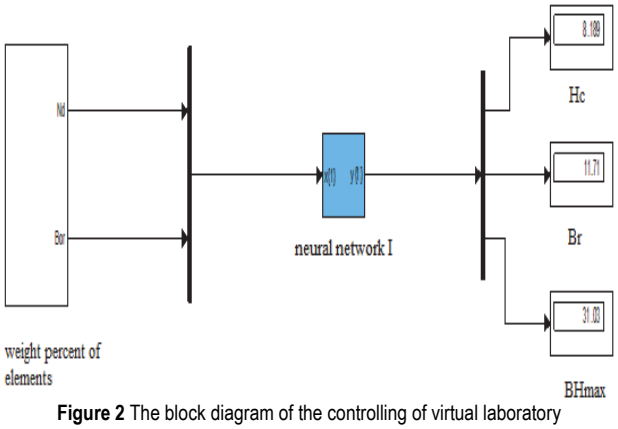

Figure 2 The block diagram of the controlling of virtual laboratory

5-layer ANN block and internal structure are shown below (Fig. 3) [29, 30].

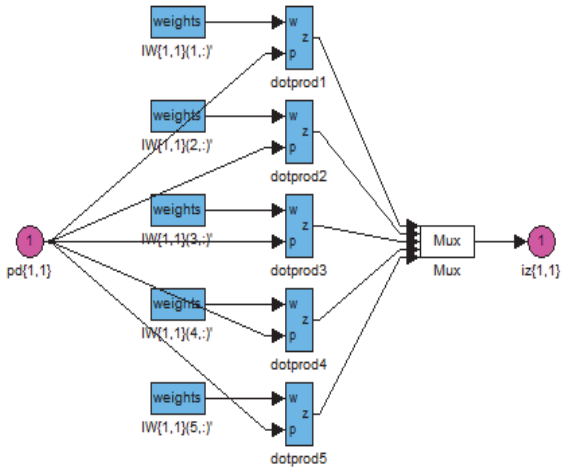

Figure 3 5-layer ANN block. [24, 25]

The graphs of B_r, H_c and BH_{max} for Nd and B changes are shown below (Fig. 4 and Fig. 5) when the above ANN block diagram is run for all input values.

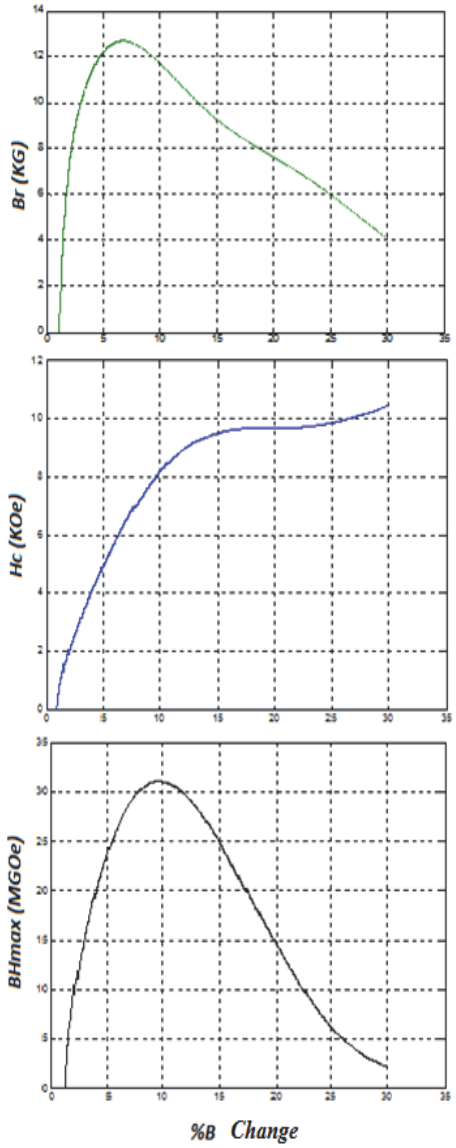

Figure 4 B_r, H_c and BH_{max} graphs versus % B change in the results of ANN

When the above chart is analysed, the highest value of the BH_{max} of the magnet is about 10% of the B (Boron) value.The graph of magnetic property which is important for the magnet (BH_{max}, B_r and H_c) should be examined in detail. In some magnets, the coercivity (H_c) may be more important than BH_{max}. In these cases, the graphical values of the coercivity (H_c) should be chosen in the most ideal way.

When the below chart is analysed, the highest value of the BH_{max} of the magnet is about 15% of the Nd (Neodymium) value. If the B_r value is more important than BH_{max}, the Nd value should be around 10-15%. Which properties of the magnets produced are more important should be determined and the % Nd value should be adjusted. The obtained values using by ANN provided a more robust and reliable virtual laboratory.

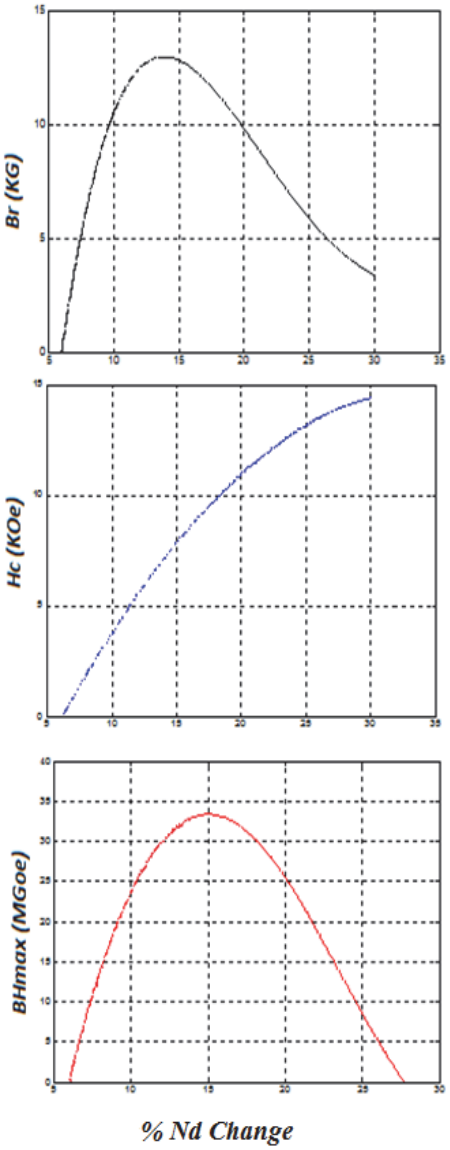

Figure 5 B_r, H_c and BH_{max} graphs versus % Nd change in the results of ANN

4 CONCLUSION AND SUGGESTIONS

In order to test the prepared virtual laboratory, studies with the same values as the environment values (mixing time, pressure, applied magnetic field, sintering temperature and sintering time) in the preparation of the

data we use were used. The following results were obtained when we compared the results. Comparison of all results is given in Tab. 5.

The algorithm, which was followed when performing experiments in the real laboratory environment, was also used in preparing the virtual laboratory environment. In this way it is possible to compare actual test results with software results. The values of results of virtual labs are close to the averages of ANN results with real experiments. The results in each section are very close together. Through virtual laboratory, it is possible to make magnet experiments by mixing materials in desired rate. The software can simulate interim values for the currently manufactured magnet alloys. In this way, both the time spent in the production of samples and the material costs are eliminated.

By means of the prepared virtual laboratory, we can obtain the properties of the produced commercial magnets. In this section you can see whether there is a magnet in the desired properties. The properties of the magnet you need are also available from this part. In addition, physical and chemical properties of the used elements can be studied.

Table 5 Comparison of virtual laboratory results, artificial neural networks and other study results

Comparison of Laboratory Results		
Virtual Laboratory	ANN	Simulink
Nd = 20, B = 8 20Nd72Fe8B Alloy		
B_r = 10.15 kG H_c = 10.97 kOe BH_{max} = 25.5 MGOe	B_r = 9.843 kG H_c = 10.9 kOe BH_{max} = 25.58 MGOe	B_r = 9.832 kG H_c = 10.96 kOe BH_{max} = 25.55 MGOe
Nd = 10, B=8 10Nd82Fe8B Alloy		
B_r = 10.48 kG H_c = 3.68 kOe BH_{max} = 23.63 MGOe	B_r = 10.51 kG H_c = 3.717 kOe BH_{max} = 23.61 MGOe	B_r = 10.46 kG H_c = 3.684 kOe BH_{max} = 23.67 MGOe
Nd = 15, B = 10 15Nd75Fe10B Alloy		
B_r = 11.72 kG H_c = 7.86 kOe BH_{max} = 30.93 MGOe	B_r = 11.71 kG H_c = 8.189 kOe BH_{max} = 31.03 MGOe	B_r = 11.7 kG H_c = 8.118 kOe BH_{max} = 30.94 MGOe
Nd = 17, B = 8 17Nd75Fe8B Alloy		
B_r = 12.16 kG H_c = 9.16 kOe BH_{max} = 31.95 MGOe	B_r = 11.99 kG H_c = 9.156 kOe BH_{max} = 32.09 MGOe	B_r = 12 kG H_c = 9.159 kOe BH_{max} = 31.99 MGOe
Nd = 7, B = 8 7Nd85Fe8B Alloy		
B_r = 3.61 kG H_c = 0.82 kOe BH_{max} = 7.26 MGOe	B_r = 3.604 kG H_c = 0.7575 kOe BH_{max} = 7.359 MGOe	B_r = 3.612 kG H_c = 0.8205 kOe BH_{max} = 7.287 MGOe
Nd = 27, B = 8 27Nd65Fe8B Alloy		
B_r = 5.75 kG H_c = 13.8 kOe BH_{max} = 1.78 MGOe	B_r = 4.685 kG H_c = 13.78 kOe BH_{max} = 2.012 MGOe	B_r = 4.695 kG H_c = 13.77 kOe BH_{max} = 1.812 MGOe
Nd = 15, B = 15 15Nd70Fe15B Alloy		
B_r = 9.18 kG H_c = 8.82 kOe BH_{max} = 24.94 MGOe	B_r = 9.273 kG H_c = 9.491 kOe BH_{max} = 24.94 MGOe	B_r = 9.294 kG H_c = 9.487 kOe BH_{max} = 24.94 MGOe
Nd = 15, B = 20 15Nd65Fe20B Alloy		
B_r = 7.73 kG H_c = 9.72 kOe BH_{max} = 14.67 MGOe	B_r = 7.635 kG H_c = 9.673 kOe BH_{max} = 14.59 MGOe	B_r = 7.602 kG H_c = 9.82 kOe BH_{max} = 14.68 MGOe
Nd = 15, B = 25 15Nd60Fe25B Alloy		
B_r = 6.47 kG H_c = 10.76 kOe BH_{max} = 6.1 MGOe	B_r = 6.006 kG H_c = 9.847 kOe BH_{max} = 6.235 MGOe	B_r = 6.074 kG H_c = 9.848 kOe BH_{max} = 6.101 MGOe
Nd = 25 B = 8 25Nd67Fe8B Alloy		
B_r = 6.7 kG H_c = 13.19 kOe BH_{max} = 8.49 MGOe	B_r = 5.91 kG H_c = 13.17 kOe BH_{max} = 8.503 MGOe	B_r = 5.926 kG H_c = 13.17 kOe BH_{max} = 8.544 MGOe

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