

IMPROVEMENT OF AC ELECTROMAGNET PERFORMANCE

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Electromagnets are essential for the operation of relays, contactors and other electromagnetic apparatus and take part in driving, control and protective circuits of industrial processes and power systems. Performance of each electromagnet affects the driving time and the stability of operation of such circuits. This paper examines the improvement of the performance of AC electromagnets by using two diodes. The theoretical analysis lead to expressions for calculating the maximum, average and minimum values of coil-currents. Due to the electromagnetic processes in the coil, the current becomes pulsating but unidirectional and better force-gap characteristics are achieved. Considerations are made for reduction of the mass of ferromagnetic and copper materials in the electromagnets and for decreasing the responding time.

1 INTRODUCTION

Electromagnets are basic components of electromechanical apparatus such as relays and contactors which are widely used in control systems and telecommunications. Electromagnets are remotely controlled devices used to produce driving and holding forces. The following theoretical analysis and experimental investigation has the objective to improve the performance of electromagnets. It also upgrades the design methods of these devices, which is of significant practical importance.

The main parts of an electromagnet are the core and exciting coil, the armature carrying the contacts of the associated apparatus and the resetting spring(s) [1,2,3]. Typical construction of an electromagnetic relay (contactor) is shown in Figure 1. The core is "U" shaped and has two poles. There is an air gap δ between the core and the armature [4]. When the operating voltage is applied the electromagnet develops a force F_c , the armature is attracted towards the core and the air gap is closed. The most important characteristics of an electromagnet is the force-gap characteristic $F_c = f(\delta)$. An electromagnet has to develop a sufficient force at closed gap so that the performance of the associated apparatus remains stable under normal and specified extreme working conditions. The electromagnet must ensure a stable switching-on process. This means that the force-gap characteristic must be situated above the mechanical characteristic $F_m = f(\delta)$ of the associated apparatus, as shown in Figure 2.

The force F_c developed at a pole depends upon the flux Φ crossing the gap, and the cross-sectional area A of the pole. A well known formula [3,4] for F_c is:

$$F_c = \frac{\Phi^2}{2\mu_0 A}, \text{ or}$$

$$F_c = \frac{(IN)^2 \mu_0 A}{2\delta^2},$$

where IN is the magnetomotive force, applied to the gap and
 μ_0 is the free space permeability.

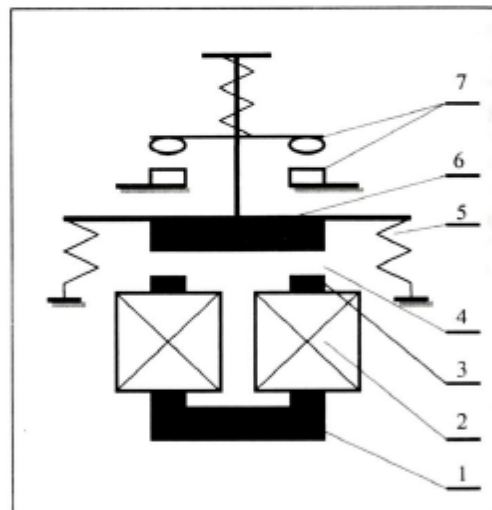


Figure 1. Arrangement of an Electromagnetic Apparatus

1 - core; 2 - coil(s); 3 - pole(s); 4 - gap;
5 - spring(s); 6 - armature; 7 - contacts

The force developed by the electromagnet increases when the armature moves towards the poles of the core, since the flux increases with decreasing gap.

Typical mechanical and electromagnetic characteristics are shown in Figure 2 [4]. The mechanical characteristic has a jump at the moment when the movable contacts meet the fixed contacts. The area between the two characteristics affects the responding switch-on time of the apparatus, the

larger the area the faster the response. The force-gap characteristic is quadratic parabola $F_c = k(1/\delta^2)$. The electromagnet develops a significant force when closed.

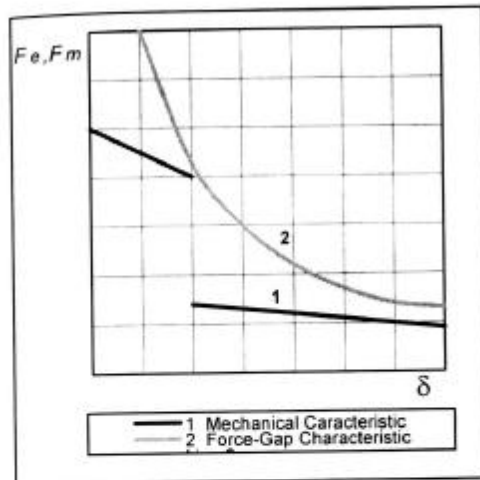


Figure 2. Main Apparatus Characteristics

2 COMPARISON BETWEEN DC AND AC ELECTROMAGNETS

The force developed by a DC electromagnet is constant for a given gap. The slope of the force-gap characteristic is large and at closed gap the force is significant. At bigger gaps the force reduces rapidly which considerably reduces the electromagnets efficiency.

The force developed by an AC electromagnet at a given gap is not constant because the flux is alternating. At a given gap the force magnitude varies between a maximum and a minimum value. The force pulsates with twice the frequency of the supply voltage. This force pulsation is undesirable and should be minimized, because it makes the electromagnet very unstable in presence of mechanical shocks or vibrations. In such cases the contacts carried by the armature can be opened or the armature can spring off the core. Both of these effects are very harmful and should be avoided by taking corresponding constructive measures. This complicates the construction of an AC electromagnet.

The average force of an AC electromagnet is half the force developed by the same electromagnet at DC conditions and equal flux density in the gap. This means that the ferromagnetic material used for DC electromagnets is twice better utilized. To get the same force the AC electromagnet becomes more bulky and heavy. The core of an AC electromagnet is laminated in order to reduce the hysteresis and eddy current losses. Due to this the volume is again

increased.

The slope of the force-gap characteristic of an AC electromagnet is less than that of the same electromagnet at DC conditions. Therefore AC electromagnets are more efficient with bigger gaps. The typical force-gap characteristics of DC and AC electromagnets are shown in Figure 3. Two other characteristics, $W = f(\delta)$, are shown in Figure 4. $W = F\delta$ is the conditional efficiency of an electromagnet. It shows the gap at which the corresponding electromagnet is highly efficient. The conditional efficiency can also be used to determine the air-gap at the off-position of the electromagnet. The ratio M/W (Mass/conditional efficiency) shows the efficiency of an electromagnet in respect to the mass of the materials used.

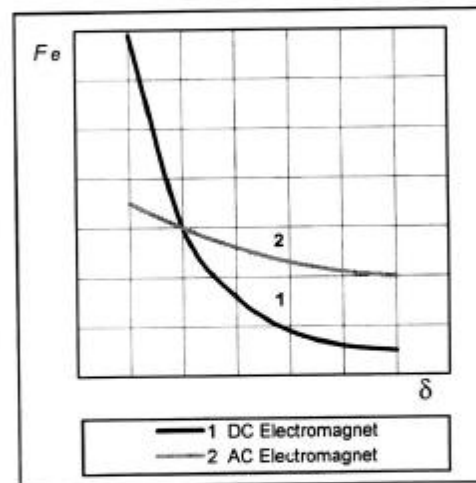


Figure 3. Force-Gap Characteristics

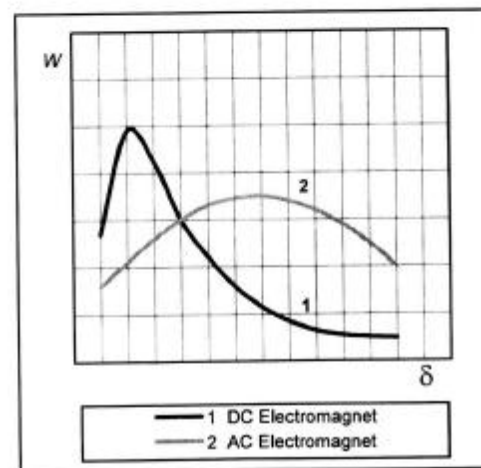


Figure 4. Conditional Efficiency

It is clear that there are significant differences between the constructions and characteristics of DC and AC electromagnets [4]. In general a DC electromagnet offers better utilization of the material used, develops constant driving and holding force, produces less heat and noise, etc. Considering, however that alternating voltage is available everywhere for industrial and domestic application, AC electromagnets are also in common use. To improve the performance of AC electromagnets diodes can be used. The processes performed in the coils of such electromagnets have a specific character due to the conversion of electrical into magnetic energy and vice versa.

3 AC ELECTROMAGNET WITH TWO DIODES

A circuit diagram of an AC electromagnet with two diodes D1 and D2 is shown in Figure 5, where A Tr is an auto-transformer and Z_{coil} is the impedance of the coil.

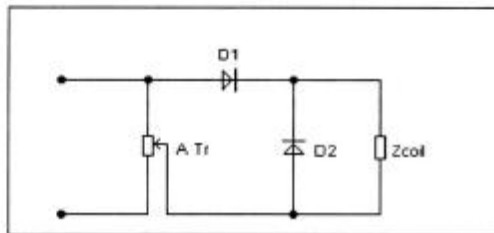


Figure 5. Electrical Circuit with Two Diodes

The diode D1 is connected in series and the diode D2 in parallel with the coil of the electromagnet. D1 conducts during the positive half cycles of the voltage. During the negative half cycles it is blocked but the diode D2 opens and offers a path for the coil current. During the negative half cycles the coil current is maintained in the same direction by the emf, induced in the coil.

The source voltage, the coil current and the induced emf are represented in Figure 6. During the interval $0 < \theta < \theta_1$ the diode D1 is conducting and the coil current is i_1 . The voltage balance equation for the positive half cycle can be given as [5,6]

$$V_m \sin \theta = Ri_1 + L \frac{di_1}{dt},$$

where $e_L = L \frac{di_1}{dt}$ is the emf induced in the coil.

Solving this equation for the current, gives

$$i_1 = \frac{V_m}{Z} \sin(\theta - \varphi) + A_1 e^{-\frac{\theta}{\tan \varphi}},$$

where $\theta = \omega t$;

$$\varphi = \tan^{-1} \frac{\omega L}{R}$$

is the phase displacement;

$$Z = \sqrt{R^2 + (\omega L)^2}$$

is the impedance and R and L are the resistance and the inductance of the coil respectively;

A_1 is the integration constant.

At θ_1 the current i_1 has a maximum value and the emf $e_L = 0$. The source voltage is enough to balance the voltage drop across the resistance of the coil.

For the interval $\theta_1 < \theta < \pi$ the current i_1 decreases and the emf e_L changes its direction and begins to increase.

At $\theta = \pi$ the source voltage is zero, the emf e_L is balanced by the resistive voltage drop and the diode D1 is blocked. After that, during the negative half cycle, the diode D2 starts to conduct and the current continues to flow through the coil and D2, keeping the same direction.

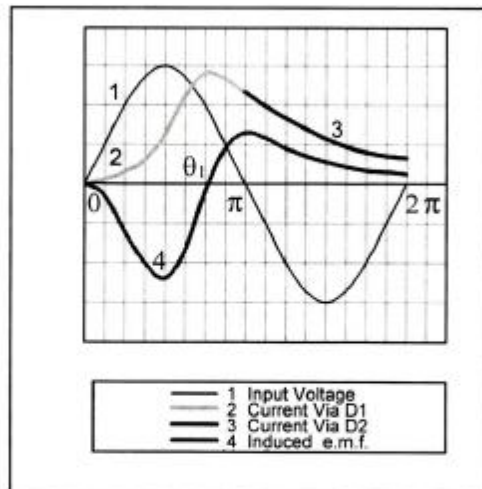


Figure 6. Voltage and Current Characteristics

During the interval $\pi < \theta < 2\pi$ the coil current i_2 decreases exponentially maintained by the emf e_L . The voltage balance equation for this interval is given as

$$Ri_2 + L \frac{di_2}{dt} = 0.$$

The solution for the current is given as

$$i_2 = A_2 e^{-\frac{\theta}{\tan \varphi}},$$

where A_2 is the integration constant.

At $\theta = 2\pi$ the diode D2 is blocked and D1 starts to conduct and the coil current transfers from D2 to D1.

The integration constants A_1 and A_2 can be determined by the condition when the coil current is not interrupted. It follows that:

$$\begin{aligned} \text{at } \theta = \pi \quad i_1(\pi) &= i_2(\pi) \quad \text{and} \\ \text{at } \theta = 0 \text{ or } \theta = 2\pi \quad i_1(0) &= i_2(2\pi). \end{aligned}$$

The solutions for A_1 and A_2 are given below:

$$A_1 = \frac{V_m}{Z} \frac{1}{1 - e^{-\frac{\pi}{\tan \varphi}}} \sin \varphi,$$

$$A_2 = \frac{V_m}{Z} \frac{1}{\left(1 - e^{-\frac{\pi}{\tan \varphi}}\right) e^{-\frac{\pi}{\tan \varphi}}} \sin \varphi.$$

The currents i_1 and i_2 are given as

$$i_1 = \frac{V_m}{Z} \left[\sin(\theta - \varphi) + \frac{e^{-\frac{\theta}{\tan \varphi}}}{1 - e^{-\frac{\pi}{\tan \varphi}}} \sin \varphi \right],$$

$$i_2 = \frac{V_m}{Z} \frac{e^{-\frac{\theta - \pi}{\tan \varphi}}}{1 - e^{-\frac{\pi}{\tan \varphi}}} \sin \varphi.$$

The average value of the coil current for a period of $0 - 2\pi$ can be determined by the equation:

$$I_{av} = \frac{1}{2\pi} \int_0^\pi i_1 d\theta + \frac{1}{2\pi} \int_\pi^{2\pi} i_2 d\theta$$

and it becomes

$$I_{av} = \frac{1}{\pi} \frac{V_m}{Z \cos \varphi} = \frac{\sqrt{2} V}{\pi R}.$$

At a given voltage the current depends upon the coil resistance only like in a DC electromagnet. The air gap, the inductance of the coil and the source voltage frequency do not affect the current unlike the case of an AC electromagnet. The coil current has one direction but it changes in magnitude. It has a maximum value at $\theta = \pi/2 + \varphi$, which is given as

$$I_{max} = \frac{\sqrt{2}V}{R} \left(1 + \frac{\sin \varphi e^{-\frac{\varphi}{\tan \varphi}}}{e^{\frac{\pi}{2 \tan \varphi}} - e^{-\frac{\pi}{2 \tan \varphi}}} \right) \cos \varphi.$$

The minimum current occurs at $\theta = 2\pi$ and it is given as

$$I_{min} = \frac{\sqrt{2}V}{R} \frac{\sin \varphi}{e^{\frac{\pi}{\tan \varphi}} - 1} \cos \varphi.$$

4 EXPERIMENTS AND ANALYSIS

The experiments were performed on an electromagnet with a core shown in Figure 7. The core was laminated and had a mass of 600 g.

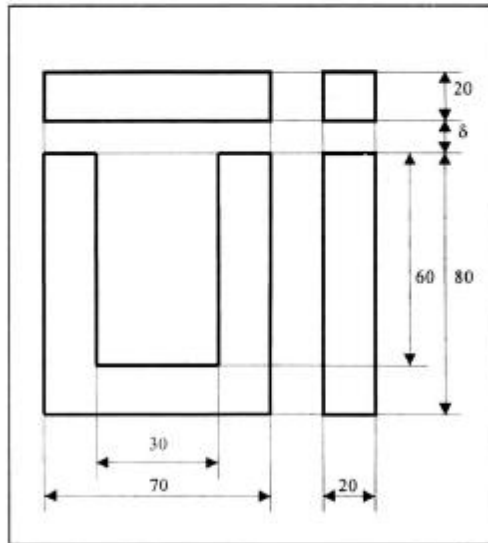


Figure 7. Core of the Electromagnet

Two different electrical circuits were used, without diodes for AC and with two diodes, for DC performance. The source voltage was varied up to 220V at 50Hz. Two coils connected in series were used, one on each leg. The total number of turns was 4000 and the total resistance 94Ω. The experiments were performed for static conditions, i.e. armature static and fixed air gap.

Five settings of the air gap were used of 1.5, 2.7, 5.7, 8.7 and 10.7 mm. The armature weight was 2N. Additional weights of 2N were attached to increase the total weight up to 8N. Experiments of attraction and releasing of the armature were performed separately. In the attraction procedure the gap was fixed, the voltage was gradually increased until the instant of armature attraction to the pole. The voltage and current of attraction were measured. In the releasing procedure the gap was fixed by inserting an insulating pad and maximum voltage was applied so that the armature was kept attracted to the pole through the insulated gap. The voltage was then gradually reduced until release of the armature. The voltage and current at the moment of release were measured. The average power $S = VI$ drawn from the source was calculated. The power-gap characteristics $S = f(\delta)$ of an AC electromagnet without diodes and constant weights of armature are shown in Figure 8 and with two diodes, in Figure 9.

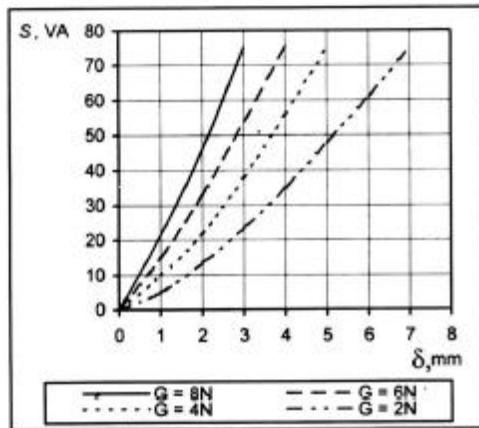


Figure 8. Power-Gap Characteristics of an AC Electromagnet without Diodes with Different Constant Weights (G) of Armature

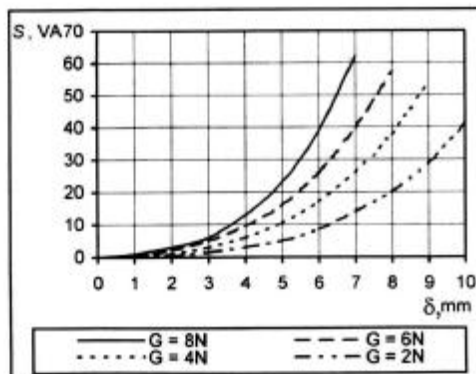


Figure 9. Power-Gap Characteristics of an AC Electromagnet with Two Diodes with Different Constant Weights (G) of Armature

These power-gap characteristics are used to get force-gap characteristics at constant powers. The force-gap characteristics $F_e = f(\delta)$ of an AC electromagnet without diodes at constant powers are shown in Figure 10 and of an AC electromagnet with two diodes, in Figure 11.

The graphs of Figure 10 and Figure 11 have the same shape, but in the two diodes case are shifted to the right.

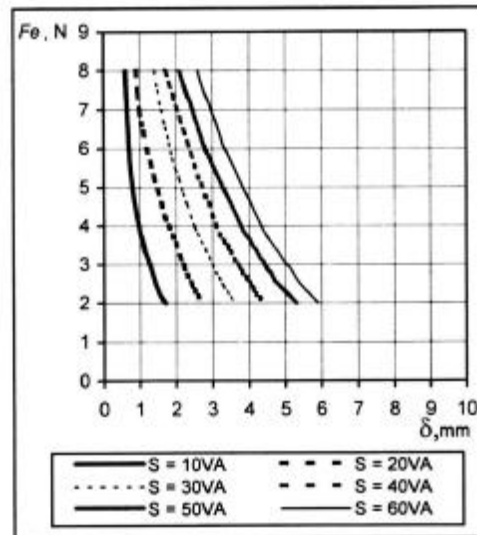


Figure 10. Force-Gap Characteristics of an AC Electromagnet without Diodes at Different Constant Powers (S)

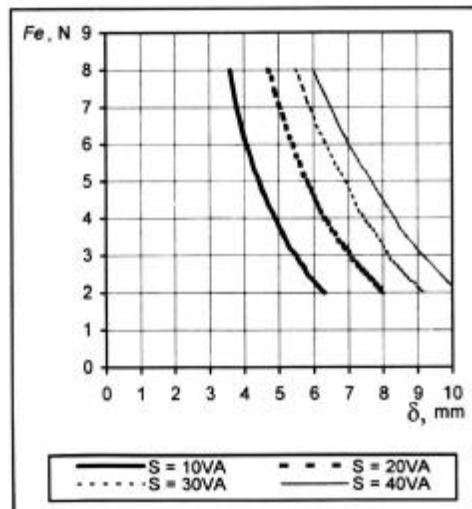


Figure 11. Force-Gap Characteristics of an AC Electromagnet with Two Diodes at Different Constant Powers (S)

Due to the inclusion of the diodes the electromagnet develops a given force at a bigger gap. For example a force of 4N at 20 VA is developed at a gap of 1.8mm by the electromagnet without diodes and at a gap of 6.3mm by the same electromagnet with two diodes.

From this very good result showing the improved performance of the electromagnet the following analysis can be made:

If a ready-made electromagnet is equipped with diodes, it can be used to drive relays or contactors of higher rating, since it develops the necessary forces at bigger gaps. By such application the volume and the mass of the higher rated apparatus is able to be reduced, i.e. ratios volume/power and mass/power are improved. In this way the production expenses are also reduced.

When diodes are added to the electromagnet of a ready-made apparatus, it can be operated with reduced power. This power is enough to generate the required force-gap characteristic to coordinate to the mechanical characteristic of the associated apparatus. For the electromagnet being experimented, the required power could be reduced approximately six times. For example, comparing the graphs at 60 VA (Figure 10) and at 10VA (Figure 11) it can be seen that they almost coincide.

If diodes are used, the force-gap characteristic of an electromagnetic apparatus is shifted also upwards in respect to the mechanical characteristic. As a result the responding switch-on time of the apparatus reduces. The switch-on time is inversely proportional to the area enclosed between the force-gap and mechanical characteristic. In this way the transient response of the apparatus is considerably improved, which can be taken into account when designing control circuits in power plants and industry.

Table 1. Experimental Data

δ mm	G N	V_{av} V	I_{av} mA	I_{max} mA	I_{min} mA	S_{av} VA
2	2	10	55	90	20	0.55
	4	16	70	115	25	1.12
	6	20	90	150	30	1.80
	8	25	115	190	40	3.12
4	2	26	120	205	35	3.00
	4	36	170	290	50	6.12
	6	45	207	350	65	10.1
	8	53	245	405	85	13.0
6	2	43	220	360	70	9.46
	4	59	300	520	80	17.7
	6	75	350	600	100	26.2
	8	90	440	735	145	39.6

By examining the AC electromagnet with two diodes, the coil currents were determined. These currents were compared with the calculated ones, for the same experimental conditions, by using the equations given above. The results are presented in Table 1 and Table 2. The differences between the measured and the calculated average currents are negligibly small as seen from the data. This shows that there is reasonably good correlation between the experimental results and the theory as given.

Table 2. Calculated Data

δ mm	G N	V_{av} V	I_{av} mA	I_{max} mA	I_{min} mA	S_{av} VA
2	2	10	48	87	15.5	0.48
	4	16	76	136	25	1.21
	6	20	96	174	31.2	1.91
	8	25	120	218	39	3.00
4	2	26	124	226	41	3.20
	4	36	172	314	56.3	6.20
	6	45	215	393	70.3	9.70
	8	53	253	463	83	13.4
6	2	43	206	376	67	8.90
	4	59	282	516	92	16.6
	6	75	360	656	117	27.0
	8	90	432	787	141	38.9

5 CONCLUSIONS

Application of two diodes, connected in series and in parallel to the coil of an AC electromagnet, improves its performance in respect to the power needed for proper operation.

Another advantage achieved by using diodes, is that the volume and hence the mass of the ferromagnetic materials and copper for a given electromagnet can be decreased which reduces the cost of materials and the size of the device.

When diodes are incorporated into an AC electromagnet the core does not need to be laminated since its performance is like the one of a DC electromagnet. The core can be made of solid material, which enables a further reduction in cost and simplifies the construction and manufacture.

By using diodes, the transient response of the electromagnet is improved, reducing switch-on time and increasing holding forces.

6 REFERENCES

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