Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 4, Issue 1 / 2019, pp. 57 - 66
http://doi.org/10.56958/jesi.2019.4.1.57

E. Electrical and Electronics Engineering

Received ***28 January 2019*** *Accepted* ***27 March 2019***
Received in revised from ***11 March 2019***

Energy saving using permanent magnets on the electric machines

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Abstract. The paper deals with the energy balance of permanent magnets in their circuit of use, when its permeance varies. The focus is on the dynamic-permanent circuit, in which the magnet is magnetized in the circuit. Its main features are defined and described operation using the demagnetization curve, the load line and the return curve. It is demonstrated that performing mechanical work in a cyclical evolution is possible only by external energy input. The different types of permanent magnets are presented and described to be used at high temperature. Electric motors that use permanent magnets instead of electric excitation lead to significant energy savings.

Keywords: economy, energy, synchronous electric motor, induction motor, permanent magnet.

1. Introduction

Permanent magnets occupy today an important place in the world of magnetic materials [1]. Fig. 1[2] presents the categories of permanent magnets used today in the world, using a remanence induction (Br) - coercive field (Hc) representation. Among the permanent magnets (PM), the NdFeB-based ones are noted, with the highest magnetic energy density, magnetic energy that can reach over 400 kJ/m^3. The value that will be reached in PM production will be this year of approx. 19 billion $ [3].
Fig. 2 shows the significant importance of using PM in electric machines applications. The large share of the acoustic domain is due to the expansion of telecommunication devices and, above all, of mobile telephony.

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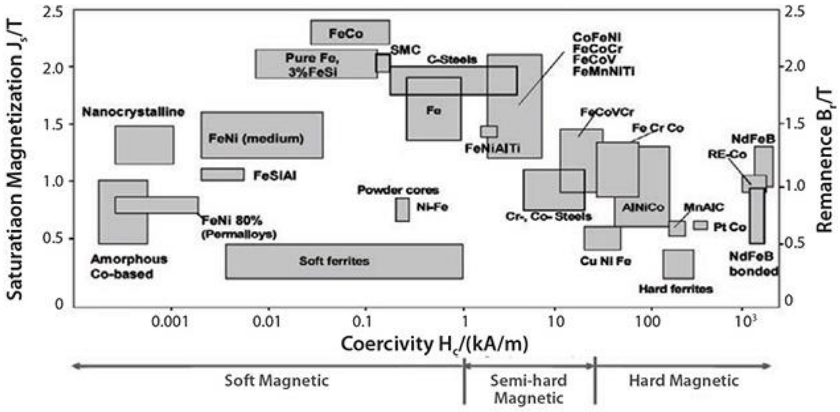


Fig. 1. Ordinary permanent magnets represented in the plane (remanence, coercitivity).

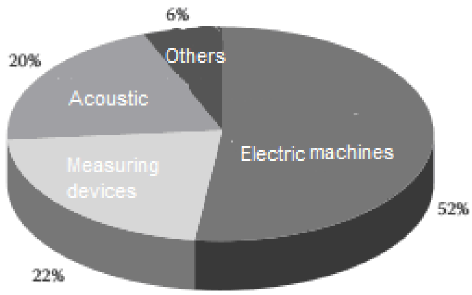


Fig. 2. Value distribution of PM production by application domains in 2017.

The value distribution of this production is shown in Fig. 2 [1]. More than half (55%) are PM [2] from ferrite (Fig. 3) due to the wide use of this type of PM (inexpensive) in the household appliances. It can be noticed the higher share of PM based on NdFeB towards those based on Sm and Co: $SmCo_5$ and Sm_2Co_{17}. PM Alnico with about 8% are produced only for applications that require high operating temperatures, although they have a prohibitive price due to the high Co concentration of up to approx. 35% of the PM mass produced.

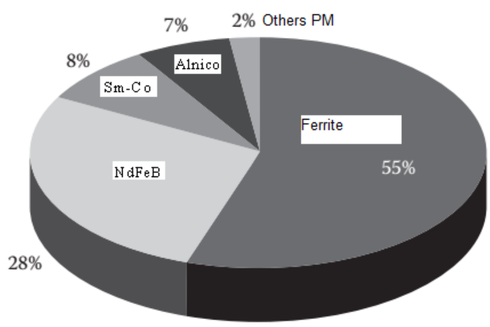


Fig. 3. The value share of different types of PM in world production, 2017.

2. Parameters of the magnetic circuit

Permeance Λ of a magnetic circuit is defined as

$$\Lambda = \Phi/\Theta, \tag{1}$$

where Φ is the magnetic flux in the circuit and Θ the corresponding magneto-motor voltage.

Using the equation (1) we can define the permeance coefficient λ:

$$\lambda = \Lambda \frac{l_m}{S_m} = \frac{B_m}{\mu_0 H_m} = \frac{1 - N_d}{N_d}, \tag{2}$$

where Nd is the demagnetization factor, defined by the following equation

$$H_d = - N_d M, \tag{3}$$

and l_m, S_m are the length, respectively the area of the PM section , B_m, H_m are magnetic induction, respectively the magnetic field of PM, $\mu_0 = 4\pi 10 \mathrm{Exp}(-7)$ H/m is the vacuum permeability, the magnetic induction being defined by the equation $\mathbf{B} = \mu_0(\mathbf{H}+\mathbf{M})$.

For a cylindrical PM with the length-to-diameter ratio r = l / d, the demagnetization factor has the expression [4]:

$$H_d = -N_d M = (1 - \frac{1}{\sqrt{1 + 1/r^2}})M. \tag{4}$$

In Fig.4 there are indicated the permeance coefficients for different dimensional ratios r , the load lines corresponding to the respective working points, intersections of the demagnetization curves B(H) and $4\pi M(H)$ (expressed in Gs in the electromagnetic system, respectively polarization $\mu_0 M$ in SI and expressed in T), for an anisotropic PM [2].

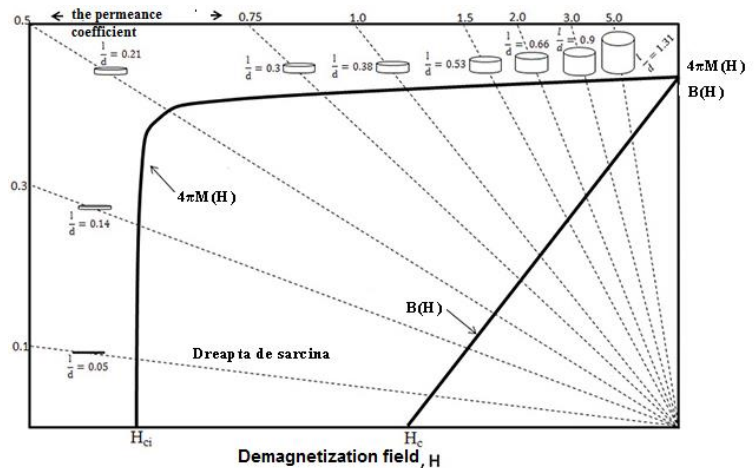


Fig. 4. Permeance coefficients for a PM with different dimensional ratios, corresponding load lines in B (H) and $4\pi M(H)$ representation.

3. **PM behaviour at temperature**

Irreversible losses of magnetization with temperature occur at PM only if the inherent coercive field is less or comparable to the residual magnetic polarization, I_r. The losses become reversible if

$$H_{cI}\mu_o >> I_r$$

which means that we can define a maximum temperature, T_{max}, of reversible operation when

$$H_{CI}M_0 = I_R$$

or, the condition rewritten according to the temperature:

$$H_{CI0}M_0\ [1+\alpha_H(T_{MAX}-T_0)] = I_{R0}\ [1+\alpha_I(T_{MAX}-T_0)], \qquad (5)$$

From equation (5), the temperature maximum increase results as follows:

$$\Delta T_{MAX} = (1-K)/(K\alpha_I - \alpha_H)\ \ CU\ K = I_{R0}/\ M_0\ H_{CI0} \qquad (6)$$

From (6) it is noted that if

$$k \to 0 \Rightarrow \Delta T_{\max} \to -1/\alpha_H$$
$$k \to 1 \Rightarrow \Delta T_{\max} \to 0$$
$$k_1 \geq k_2 \Rightarrow \Delta T_{\max 1}/\Delta T_{\max 2} \leq 1.$$

It follows that if two PM have the same coercivity, then the one who has the lowest remanence will have the highest maximum operating temperature (e.g. agglomerated PM towards the sintered ones by the same magnetic material).

When choosing a permanent magnetic material, we must take into account if it preserves the above presented advantages at room temperature also at the operating temperature, the room temperature being the one at which the magnetic properties of PM are displayed in the catalogues. Due to the variation of the magnetic parameters values with T, it can be happened that a magnet such as with $(BH)_{max10}$ at room temperature T_0 higher than $(BH)_{max20}$ at the same temperature of another magnet, and the energy densities ratio for the two magnets to reverse at the operating temperature (similar situations for remanences or coercivities may occur). We can appreciate the temperature T_e at which the reversal of the specific energy sizes occurs based on the linear approximation

$$(BH)_{max} = (BH)_{max0}[1+\alpha_{BH}(T_e - T_0)],$$

where

$$\alpha_{BH} = \alpha_I + \alpha_H, \qquad (7)$$

from the impose condition at T_e:

$$(BH)_{max1}(T_e) = (BH)_{max2}(T_e). \qquad (8)$$

By replacing the corresponding equations (7) in (8) we can deduce the value of T_e:

$$T_e = T_0 + \Delta T_e = T_0 + \frac{1-k_{12}}{k_{12}\alpha_{BH1} - \alpha_{BH2}}, \qquad (9)$$

where $k_{12}=(BH)_{max10}/(BH)_{max20}$.

An example is the IUNDK8AA type of Alnico alloy (mono-crystalline PM with coercive field of about 1500Oe), which has $(BH)_{max10}=100$ kJ/m^3 at room temperature $T_0=20^0$C and for which α_{BH1} = - 0,04% / K at approx. 120 ° C reaches the same specific energy with a PM from NdFeB for which we have $(BH)_{max20}$= 300 kJ/m^3 and α_{BH2} = - 0,70 kJ/m^3: from equation (9) resulting $\Delta T_e = 100^0$C. Fig. 5 confirms these quantitative assessments.

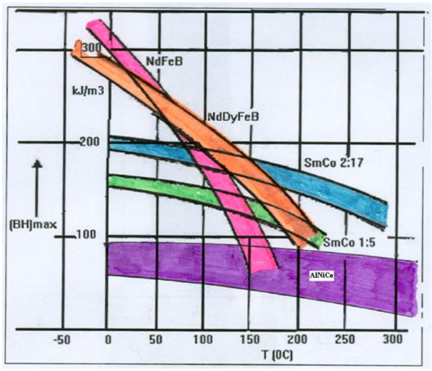


Fig. 5. The specific magnetic energy variation at PM from NdFeB, Alnico and SmCo families.

Fig. 5 shows the advantage of using PM from NdDyFeB or Sm_2Co_{17} families at high temperature. Similar results are reported in Fig. 6 [5].

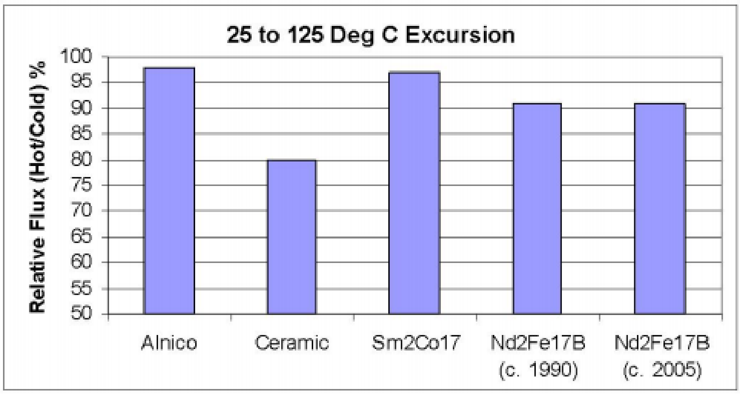


Fig. 6. Reversible losses at 125°C for various materials used to produce PM.

From Fig. 6 it is observed that the most stable magnets are the Alnico type, and the most unstable (in terms of reversible magnetization losses) are those from ferrite (Ceramic).

4. Energy balance of PM in magnetic circuit

Considering the magnetic circuit in Fig. 7, we can apply the Ampere law on the closed circuit drawn in red:

$$\oint H dl = 0 \text{ or } H_m l_m + \gamma H_g l_g = 0 \qquad (10)$$

and Gauss theorem after the surface drawn in blue in the section

$$\oint_S Bds = 0 \text{ or } B_m S_m - \sigma B_g S_g = 0. \tag{11}$$

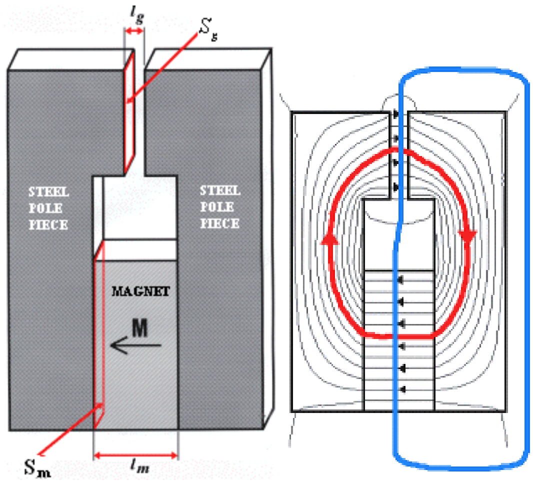


Fig. 7. Magnetic circuit indicating the circuit of applying Ampere law (red) and Gauss theorem (blue).

From (10) and (11), it results that

$$B_m \left| H_m \right| V_m = \gamma \sigma B_g H_g V_g \,, \tag{12}$$

i.e. the energy in the PM is $\gamma\sigma$ times higher than those in the circuit air gap, where γ represents the coefficient of t.m.m. (losses in iron) and σ the flux coefficient (magnetic flux losses of the circuit).

If we now consider a permanent magnet with the right demagnetization curve, we magnetize it out of the circuit, then it would have the point of operation in S with the permeance coefficient $\lambda s = \lambda t$ (here, the leakage coefficient is equal to the total one due to lack of useful air gap), i.e. equal to PM load line slope.

If we put PM in the circuit, then the point of operation moves from S to F. The useful permeance coefficient $\lambda_u \equiv \lambda_g = \lambda_t - \lambda_s$ appears. If PM is magnetized in the magnetic circuit, then it is called permanent dynamic, and the point of operation is in F '. If we now open the circuit, the point of operation goes down to S and at a new closure of the circuit (partial), the point climbs to point F approximately on a line whose slope is equal to the permanent or reversible permeability μ_{rev}. Since divB = 0, we have

$$\int_{\infty} BHdV = 0 \text{ or } \int_{\infty - m} BHdV = -\int_{m} BHdV$$

That means that the energy outside the PM (∞-m) is equal and of opposite sign to the one inside the PM (as shown in Fig. 8, the fields inside the PM are negative, i.e. they are demagnetizing).

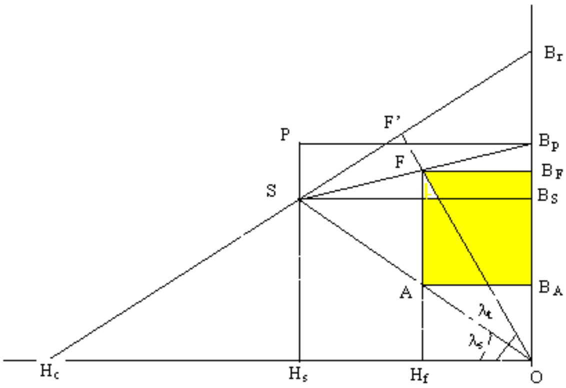


Fig. 8. PM in the representation of (B, H), defining the main circuit elements.

From Fig. 8 we can noticed that the maximum magnetic energy in the air gap (marked with yellow in the above figure) is given by the relation $E_{gmax}= B_pH_s/4$, and the maximum magnetic energy convertible into mechanical energy $E_m= B_pH_s/2 = 2\ E_{gmax}$. The maximum theoretical energy that can be converted into mechanical energy is $E_{tmax}= B_rH_c/2$, because in this case the magnet is ideal [4], Fig. 9.

The equation of the return line in Fig. 8 is $B_m=\mu_0\ (\mu_{rev}H_m+M_r)$, which with $\mu_{rev}=1$ becomes $B_m=\mu_0(H_m+M_r\ )$, i.e. the equation of the main demagnetization curve. At this ideal PM, irreversible magnetization losses appear unless the demagnetizing field exceeds the intrinsic coercive magnetic field.

For this PM we will have

$$(BH)_{max} = (B_r)^2/(4\mu_0)= \mu_0(H_c)^2/4.$$

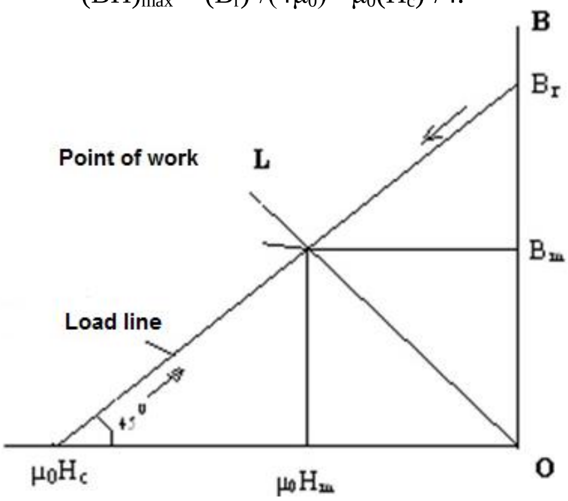


Fig. 9. The demagnetization curve of an ideal magnet.

It can be concluded that the maximum energy density that can be converted into mechanical energy, $E_m=B_pH_s/2=2E_{umax}$, indicates the amount of energy that can be extracted from PM without adding energy.

It follows that if no other energy is transferred to the circuit after its opening, then only the mechanical work performed at the opening and stored as magnetic energy in the circuit can again be converted into mechanical energy (mechanical work or other form of energy) [6].

5. Energy savings by using electric motors with PM

The use of PM in electric machines leads [7] to the following advantages: giving up the electrical energy needed to generate machine excitation, greater torque and / or output power and improved dynamic performances compared to the induction motor. In synchronous motors, PM is mounted on the rotor [8] in various geometries, Fig.10.

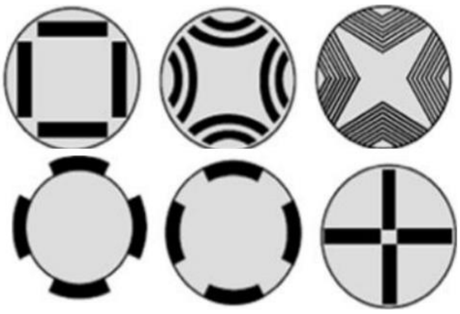


Fig. 10. Layout modes of PM in the rotor of a synchronous motor, shown here in a section perpendicular to the machine axis.

Analysing the different sources of energy savings in PM synchronous machines versus those with induction, it results the approximate quantitative expression in Table 1 [9].

Table 1. Comparison of power losses at a PM synchronous motor towards an induction one, power of 5kW, 1800 rpm.

Source of losses	**Losses related to total losses, induction motor**	**Losses in PM motor/ losses in induction motor**
Stator winding	0,35	0,63
Rotor	0,20	0
Losses	0,15	0
Core	0,15	1,47
Friction	0,10	0,8
Total	1,00	-

In absolute values, for a 75CP motor, we obtain the values presented in Table 2 [5].

Table 2. Performances of a PM motor towards an induction motor

Motor features	PM motor	Induction motor
Power, CP	75,4	75,5
Speed, rot/min	1800	1768
Total losses, kW	2,23	3,88
Temperature rising, °Celsius	70,7	111,5

A comparison of the different electric motors in terms of energy efficiency is shown in Fig. 11 [5]. The superiority of PM synchronous motors is observed.

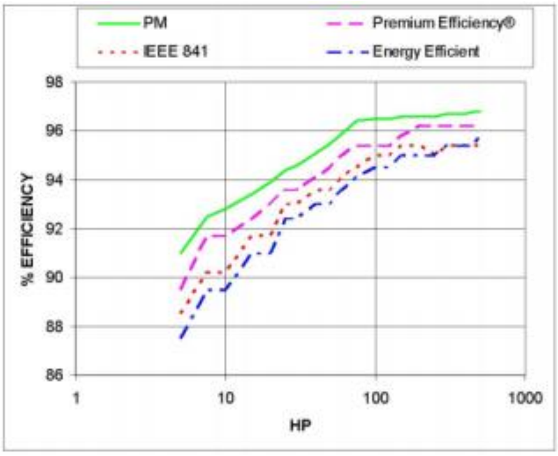


Fig. 11. Comparison of the efficiency of different types of electric motors.

Major energy savings are recorded in the use of PM motors in the railway system, Fig.12 [10].

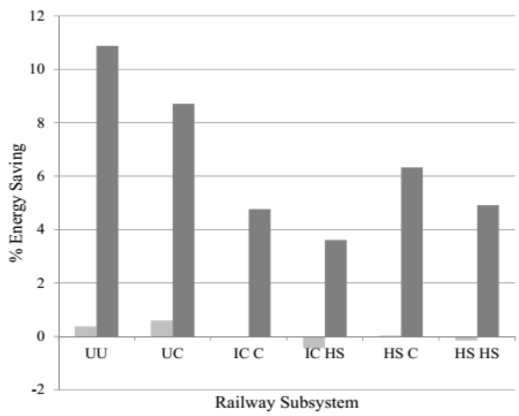
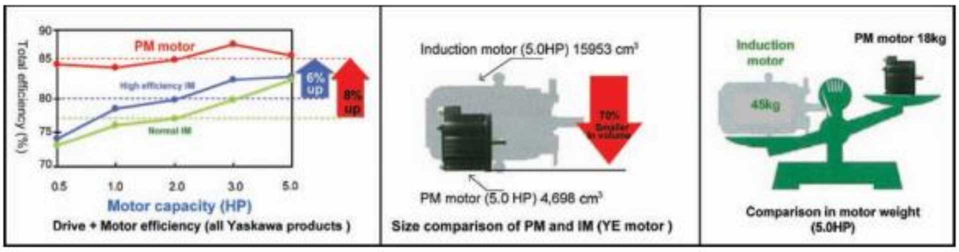


Fig. 12. Energy saving when replacing the induction motors with PM ones in different railway systems.

Major savings are achieved for PM motors also in total volume and weight, as Fig.13 [11] suggests!



3. Some advantages of a PM motor over an induction motor (IM). Reproduced with permission.[33]

Fig. 13. Some advantages of the PM motors

6. Conclusion

The use of synchronous electrical machines with PM leads to significant energy savings. Other direct advantages facilitated by the use of PM in electric machines which have to be noticed, are the following: saving of raw materials, reducing the overall dimensions of electric machines, lower operating temperatures, cheaper maintenance of installations fitted with PM synchronous machines.

Due to the wide variety of available PM features, there is an optimized PM for any application. Particular attention must be paid to the operating temperature of PM machines to avoid irreversible magnetization losses.

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