Journal of Advanced Research 17 (2019) 103–108

Contents lists available at ScienceDirect

Journal of Advanced Research

journal homepage: www.elsevier.com/locate/jare

Original article

The impact of demagnetization on the feasibility of permanent magnet synchronous motors in industry applications

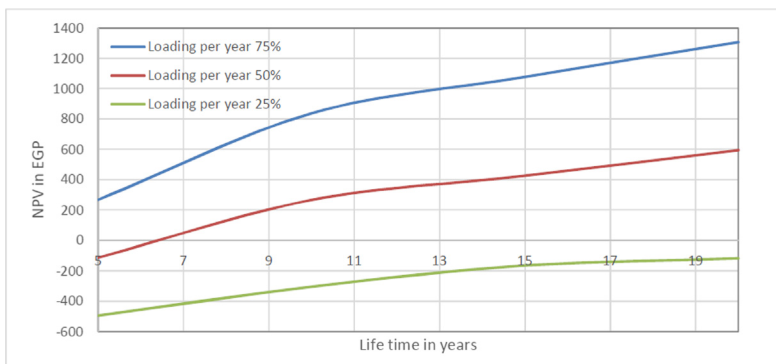
A. A. Adly [a,*], A. Huzayyin [a,b]

[a] Electrical Power Engineering Department, Faculty of Engineering, Cairo University, Giza 12613, Egypt
[b] The Edward S. Rogers Sr. Dept. of Electrical and Computer Engineering, University of Toronto, Toronto, ON M5S3G4, Canada

HIGHLIGHTS

- Permeant magnet motors are feasible to replace induction motors in Egypt.
- Magnet demagnetization decreases efficiency, lifetime and feasibility of motors.
- Despite partial demagnetization, utilization of PM motors in Egypt is feasible.
- Feasibility of PM motors in Egypt is contingent on a 50% annual utilization.
- Consideration of potential demagnetization is essential for estimating feasibility.

GRAPHICAL ABSTRACT



The change in Net Present Value (NPV) at various percentage of annual loading against PM motor reduction in efficiency.

ARTICLE INFO

Article history:
Received 6 November 2018
Revised 3 February 2019
Accepted 10 February 2019
Available online 22 February 2019

Keywords:
Permanent magnets
Permanent magnet motors
Demagnetization
Electric vehicles
Motor efficiency
Photovoltaics pumping

ABSTRACT

Permanent magnet (PM) motors are rapidly replacing the dominant induction motors in industrial applications including pumps, fans, and compressors. PM motors are also gaining ground in critical sustainable energy applications such as wind systems, photovoltaic pumping systems and electric vehicles. Compared to induction motors, PM have higher efficiency. In this paper, the financial feasibility of replacing induction motors by PM motors at various operating conditions was analyzed on a preliminary basis. The impact of partial demagnetization and full loss of excitation on the feasibility of the replacement was also preliminarily investigated. It is found that the feasibility of replacement was less sensitive to reduction in the life time of PM motors than reduction in efficiency due to partial demagnetization. While detailed and lengthy studies are planned in the future, investigation outcomes suggest that the replacement remains feasible despite risks of demagnetization when utilization rates are above 50%. Details of the investigation are reported in the paper.

Introduction

Egypt, is striving towards energy sustainability. Currently, Egypt energy consumption (electricity and primary energy for transportation, industry, as well as commercial and domestic

Peer review under responsibility of Cairo University.
* Corresponding author.
E-mail addresses: amradly@cu.edu.eg, adlyamr@gmail.com (A.A. Adly).

https://doi.org/10.1016/j.jare.2019.02.002
2090-1232/

sector) remains higher than what could be offset by local production despite natural gas discoveries and the rapidly growing renewable energy sector. To close the supply/demand gap energy efficiency of the Egyptian economy must be improved.

About 70% of the electrical energy in the industrial sector is consumed by motors [1] which drives production processes and utilities. Motors also play a major role in the irrigation and water and waste water sectors. Estimates of the industrial sector consumption amounts to about 32% of Egypt total electricity consumption [1]. Hence, electrical motors consume at least 22% of the nation electricity supply without taking into consideration consumption in domestic and commercial sectors. Accordingly, improving electrical motor efficiencies will positively contribute to achieving energy sustainability.

The industrial sector worldwide has been improving its motor efficiency by replacing the motor installed base with higher efficiency motors as shown in Fig. 1. The IE standards indicates motor efficiency classes where the lowest efficiency motors are set as IE1 and the highest and IE5 [2]. It is foreseen that the mainstreaming of IE4 and IE5 motors cannot be achieved without a shift of motor technology towards synchronous types such as permeant magnet (PM) motors. Various investigations indicate that induction motors may only meet IE4 standards in limited applications with considerable technical challenges [3,4]. Furthermore, they are unlikely to meet IE5 standards by all means [3,4]. The market shift towards IE4 and IE5, seen in Fig. 1, will mean a shift of motor technology towards synchronous PM type from induction type.

About 90% of motors in the industrial sector are currently induction motors, usually of the squirrel cage design [6]. Over the past 20 years, however, rapid development in power electronics and permanent magnet material positioned PM motors as a serious competitor to induction motors. The energy density of various types of magnets has more than doubled over the past three decades from exceeding a maximum flux density per unit volume of 400 kJ/m^3 in 2012 [7,8]. While this has opened the way to the fabrication efficient and high rating PM motors, such motors were of the synchronous type and, consequently, had limited applications to those operating at a fixed speed. Nevertheless, with the impressive advancement in power electronics, it was possible to achieve excellent and flexible operating characteristics through coupling PM motors to Adjustable Speed Drives (ASD). Due to the continuous advancements of manufacturing of magnets and ASD the market share of PM motors has been growing rapidly in various industrial applications [2]. While being more expensive than induction motors, PM motors are more efficient and have a longer life time. From a speed control point of view, PM motors coupled with ASD, have superior qualities to induction motors. In markets dominated by IE3 motors, PM motors are expected to dominate over induction motors particularly for application such as pumps, fans, and compressors [2]. The penetration of PM motors in the Egyptian market can help improve the efficiency of the industrial sector and sustainability of the economy. Moreover, this penetration can provide a chance for local manufacturing to flourish since PM motors can be produced on a smaller scale and are easier to design than induction motors.

Penetration of PM motors in the Egyptian industry is governed by returns to the consumer from reliability and profitability views. While PM motors are more expensive than induction motors, various experimental assessments of market products indicate that PM motors have higher efficiency across the most power and speed ranges than induction motors [3,4,9–12]. This fact is valid for common applications such as fans, HVAC systems, wind generation applications, electric vehicles, pumps, and conveyors [3,4,9–12]. The higher efficiency of PM motors versus induction motors is

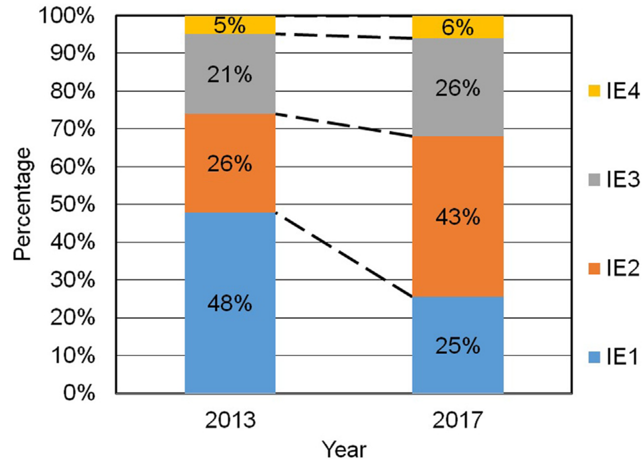


Fig. 1. The change in market share of various efficiency classes from 2013 to 2107 [5].

mainly attributed to the absence of current carrying conductors in their rotors which contribute about 20% of induction motor losses for ratings ranging between 1 kW and 250 kW [10,12]. Investigating various motor ratings and operating speeds, PM motors shows significantly higher efficiency than induction motors in small ratings below 15 kW [3,4,12]. More specifically, efficiency of PM motors can be 10% higher at 100 rpm. This efficiency edge usually reduces to 3.5% higher value at higher speeds of operation [3,4,12]. It should be pointed out here that for medium scale ratings up to 375 kW PM motors demonstrate a 2–4% efficiency lead over induction motors of 2–4% [3,12]. At higher ratings, though, generalization becomes difficult due to absence of long track record of PM motors operating at such ratings. Hence the findings of this work are limited to small and medium power ratings discussed above.

Nevertheless, a major drawback in PM motors, which are rarely accounted for in comparisons with induction motors as well as in financial models, is the possibility of demagnetization due to intrinsic material magnetic viscosity (refer, for instance, [13–15]). More specifically, the PM magnetization $M(t)$ as a function of time t may be expressed in the form:

$$M(t) = M_i - S(H,T)\ln(t), \tag{1}$$

where M_i is the initial magnetization,S is the material magnetic viscosity coefficient, H is the magnetic field acting on the magnet and T is the temperature [15].

Impact of potential demagnetization on performance of PM motors is rarely quantified. Usually, the key element of focus while designing PM motors is efficiency and flux maximization rather than robustness and avoidance of demagnetization. This paper aims at offering a genuine preliminary quantification of the impact of the demagnetization of PM motors on financial returns while replacing induction motors. Within this goal, consideration is given to the financial impact of demagnetization with respect to the increased efficiency of PM motors. Although the work is universally relevant, its relevance increases in countries having high peak days of heat about the yearly average temperatures on which the motor specifications are provided such as Egypt [13–15]. Furthermore, the recent electricity tariffs in Egypt could also attribute to make the impact of demagnetization on the feasibility of the various applications such as photovoltaic (PV) pumping and electric vehicles (EVs).

Methods and models

Outline of financial model

Financial model which compares the feasibility of purchasing a PM motor instead of an equivalent rating induction motor are developed. The financial model must include the critical parameters which affect feasibility. In addition, accounting for demagnetization effects should be explicitly included. The key elements of the financial model are the capital cost, energy savings, cost of maintenance, and lifetime. The model is developed in per unit terms where analysis is relative to a kW of motor rating. This allows generalization of results across a variable range of ratings.

Capital cost: The capital cost of motors can be tied to their ratings (in kWs or HP). PM motors are used with an ASD in most applications. For ease of generalization of the findings, the comparison between PM and induction motors is limited to applications where the induction motor is used with an ASD as well. These include key applications such as fans, pumps, and compressors systems in the industrial sector. It also includes applications of utmost future importance to the Egyptian economy; photovoltaics pumping (PV) and electrical vehicles (EVs). PM motors which are driven by an ASD can be 170–295% more expensive than induction motors which are also driven by ASD of the same ratings and assuming an identical cost of ASD in both cases [7,16]. In many cases the ASD for PM motors is less expensive than that of the induction motors however this difference is neglected in the present work [7]. In the present work the cost of kW of the PM is taken as 1.7 times that of the induction motor. The capital cost of per kW of motors typically decreases rapidly as the rating increase up to 10 kW and starts to level off up to 110 kW. The data in the present work relied on those of 30, 50, and 80 kW motors. However, results can be generalized in the range between 10 kW and 110 kW. It should be mentioned that the current cost per kW in this range in about 70 USD/kW which is equivalent to 1250 EGP/kW.[1]

Energy savings: The key factor in the higher efficiency of PM motors is the lower losses rotor losses compared to induction motor. For the ranges under consideration, PM motors typically are 4–7% higher in efficiency due to the absence of rotor losses where the field interacting with the stator is provided by the permanent magnets [4,16–18]. Not only PM motors have high efficiency but they can also maintain such high efficiency from 60% to 100% of full load [18]. In contrast, induction motors achieve their highest efficiency at about 60–70% of full load and this efficiency drops as loading increases. PM motors can achieve a flat efficiency profile of above 97% from 60 to 100% of full load which is higher than premium efficiency motors which can achieve 93–94% efficiency [10,18]. The efficiency of PM motor considered in the present work is taken as 4% higher than its induction counterpart. More specifically, a base case of an induction motor whose efficiency is 88% [17] is compared to a PM motor having an efficiency of 92%. The motor is assumed to operate for 75% of the annual 8670 h of full operation. Hence, in the per unit system analyzed each 1 kW of installed motor capacity of PM motors saves 325 kWh per year in comparison to its induction motor counterpart. The electricity tariff was taken as that of the average price of kWh for Egyptian industrial installations of 1.05 EGP/kWh. This results in savings of approximately 341 EGP per year for every 1 kW of motor capacity of PM type replacing that of an induction type.

Life time and other operating costs: A major challenge in the analysis is accounting for the cost of maintenance. It is assumed that the cost of regular preventative maintenance is the same for both types of motors.

Impact of demagnetization on performance

PM motors can experience gradual and partial loss in magnetization (gradual demagnetization) as well as sudden loss of magnetization (loss of excitation) due to a host of reasons [19–21]. Magnetic viscosity as expressed by Eq. (1) could lead to a slow demagnetization where the rate intensifies as temperature increases. There are also the so-called irreversible demagnetization events which take place when the magnet operates below the knee point in the BH curve [19–21]. This can take place when the magnet is subjected to fields or temperature beyond the design values. In addition, physical impact can cause demagnetization. Depending on the intensity of the incident, the magnet can either be partially or fully demagnetized. High temperatures can be caused by loss of cooling elements, eddy current in the magnet and heating due to neighboring equipment [20]. Particularly in hot countries, the motor cannot be specified according to the highest temperature over the year as it may lead to an over design. This over design can increase the cost of the already expensive PM motor. Hence, motors can be subjected to higher temperatures than design ones for few days each year. Exceeding operating temperatures could lead to an irreversible demagnetization which can permanently limit the efficiency [22]. Moreover, coercive force is highly affected by temperature with coefficients which can reach −0.8% per °C of maximum flux [23].

Irreversible demagnetization can also easily occur due to electric faults or long incidences of exposure to high temperature [22–26]. A combination of high ambient temperature and over loads or faults can hence push the PM into demagnetization [22,23]. PM motors were analyzed while operating in reversible demagnetization due to temperature rise and irreversible due to a mix of temperature rise and fault conditions. The percentages of demagnetization (reduction of flux density) based on various literature investigations are given in Table 1. Hence it may be concluded that PM motors are likely to experience reversible and irreversible partial demagnetization operating conditions [20,22–29].

Partial demagnetization can reduce the PM flux density by 10–20% over the lifetime of the motor [5,29]. This reduction of flux density leads to a decrease in energy efficiency of the PM motor. An attempt to roughly quantify the expected change in copper losses with change in flux density analytically is presented below. This is not meant to be a comprehensive correlation of flux density in PM motors and losses but rather a guide to the range of change in efficiency to be considered in the present paper. Reduction in flux density is expected to decrease iron losses and increase copper losses. The iron losses are typically determined through the Steinmetz's equation which correlates frequency, flux density, and material properties with losses in magnetic material at large [30] as shown below

$$P_{iron} = kf^{n}B^{m}, \tag{2}$$

where P_{iron} is the iron losses, f is frequency and B is the magnetic flux density. In (2), the constants k_s, m, n are material dependent. It should be pointed out that constant m is usually equivalent to 2 for most modern magnetic materials [30].

Based on Steinmetz's equation the iron losses will decrease as the flux density is reduced. On the contrary, copper losses will increase with the increase of the flux density. A PM motor operated through a field-oriented control scheme (as typical in most PM motors) maintains its output torque at a constant preset value up to rated speed [31]. In this case a reduction of the flux density would result in an increase in current which would increase stator

[1] The data for motor system pricing were collected through offers provided by various suppliers in the Egyptian market in the October and November 2018.

Table 1
Percentage of various forms of demagnetization based on experimental and computational work in literature.

Type	Cause	Demagnetization percentage	Reference and conditions
Reversible	Temperature rise	30%	[22] – temperature rise to 200 C
Irreversible	Faults	Average 30%	[26] 16 magnets subjected to 12 types of faults
Irreversible	Faults	75%	[20]
Reversible	Temperature rise	21%	140 C [12]
Irreversible	Temperature rise	50%	[28]

copper losses. The motor developed torque (T) in this scenario can be given as [31]:

$$T = \frac{3}{2}p\left[\lambda I_q + I_q I_d (L_d - L_d)\right], \tag{3}$$

where p is the pole pair, λ is the motor flux, I_d and I_q are the motor direct and quadrature currents, and L_d and L_q are the stator direct and quadrature self-inductances. The first term in the bracket is the PM torque while the second is the salient torque.

To maintain a constant torque the current and/or the field angle (determining the ratio between direct and quadrature currents) would have to be changed. In the present paper the analysis focuses on a single scenario without exploring the full spectrum of how the drive will react to maintain torque. The scenario assumes the rated torque is its maximum [32] and it is achieved through maximizing the quadrature current to reach the motor rated and minimizing the direct current to zero. Accordingly, the copper losses can be related to the stator resistance and quadrature current reported elsewhere [33]. From Eqs. (2)–(4) and considering the previously recorded motor parameters [31], the percentage change in losses versus percentage reduction in magnetization is shown in Fig. 2 below:

A more thorough analysis to correlate reduction in magnetization with motor efficiency at various operating scenarios will be sought in future work. However, the analysis above demonstrates that 10% reduction in magnetization can lead to at 30% reduction in efficiency. Similar value based on numerical simulation of PM motors also demonstrated that reduction of 10% in magnetization can cause a 30% reduction in efficiency [5]. In normal operating condition, this 10% demagnetization can be reached in 30 years of operation of the PM motor [30]. That can be translated into an average demagnetization of 5% across the lifetime of the PM motor. In the present work demagnetization effect is analyzed in the ranges leading to increase in losses by 5–30%. The loss of excitation is reflected on a shorter lifetime of the PM motor down to 10 years form the expected 20 years.

Assumptions and key parameters of base case

The base case studied had parameters shown in Table 2. Other cases and sensitivity analysis were carried out around the base case.

Results and discussion

Base case analysis

Using the parameters above, the replacement of induction motor by PM motor is feasible in the base case. The simple payback period is 2.5 years and the Net Present Value (NPV) per kW is 1307

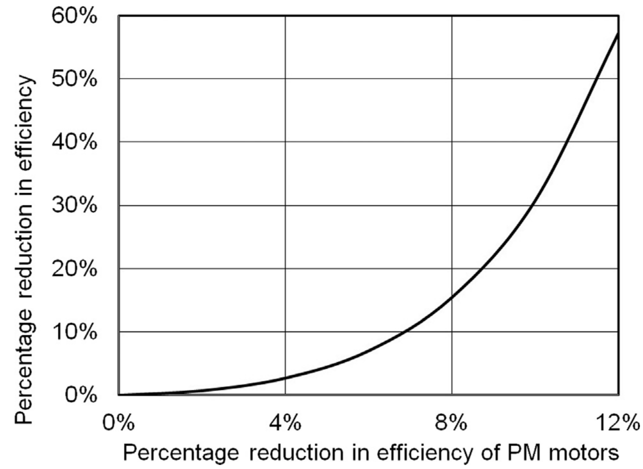


Fig. 2. The reduction in motor efficiency against the decrease in magnetization.

Table 2
Details of financial model.

Type	Cause
Financial assumptions	• Annual interest rate is 18% • Motors are purchased in cash in one installment • No inflation is considered • Exchange rate is 17.9 EGP per 1 USD
Technical parameters	• Life time of induction motor and PM motor is 15 years • Efficiency of induction motor is 88% • Efficiency of PM motor is 92% • Utilization rate is 75% equivalent to 6570 h per year
Cost and revenue	• Cost per 1 kW of induction motor is 1250 EGP • Cost of inverter is similar for PM and induction motors • Cost of PM motor is 290% of induction motor • Cost of rewinding is 30% of cost of induction motor • Tariff per kWh is 1.05 EGP • Tariff is fixed without future increases

EGP (compared to extra capital investment of 1250 EGP). This leads to a profitability of 5%. The profitability would improve with the increase of electricity tariff and the reduction in cost of PM magnets which are both foreseen market trends.

Sudden loss of magnetization

Sudden loss of magnetization can be modeled as a decrease in the life time of PM motors. The change of life time from 20 years down to 5 years was investigated and shown in Fig. 2. A positive Net Present Value (NPV) indicates that the investment in PM motor is feasible. The analysis is also carried out for various utilization rate of continuous annual operation. Utilization rates of 25%, 50%, and 75% are considered. As can be seen in Fig. 3, the investment is not profitable up to a life time of 20 years at utilization rate of 25%. At utilization rate of 50%, the investment is profitable if the PM life time exceeds 6 years. It is unlikely that the total loss of excitation would take place before 6 years. Hence, sudden loss of magnetization is not a threat to investing in PM motors in Egypt.

Gradual demagnetization

Partial loss of magnetization (gradual demagnetization) which leads to decrease in the efficiency of 5–30% was analyzed as shown

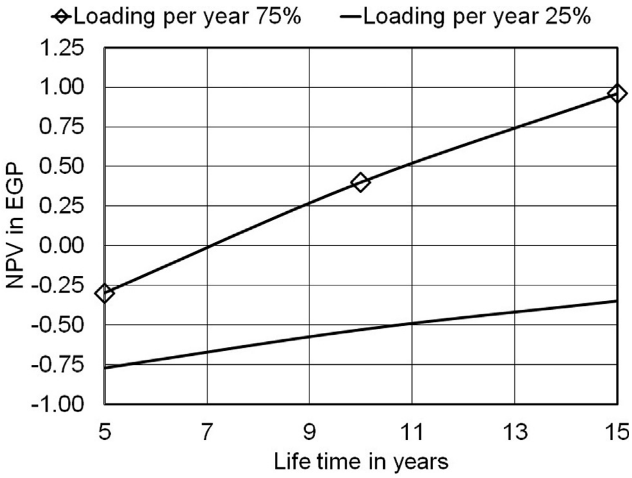


Fig. 3. The change in NPV at various percentage of annual loading against PM motor lifetime in years.

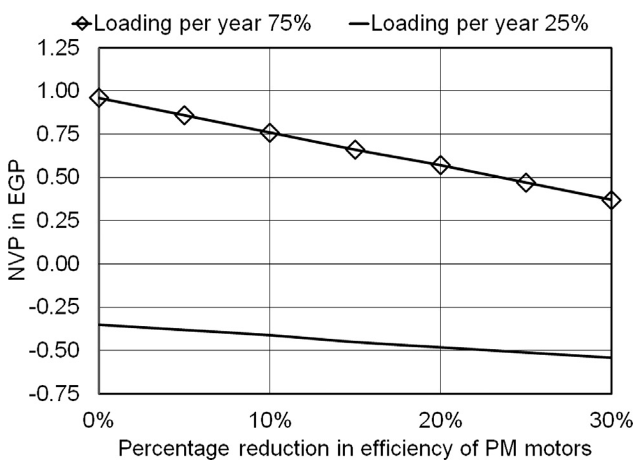


Fig. 4. The change in NPV at various percentage of annual loading against PM motor reduction in efficiency.

in Fig. 4. A positive NPV indicates that the investment in PM motor is feasible. The analysis is also carried out for various utilization rate of continuous annual operation. Utilization rates of 25%, 50%, and 75% are considered. At a utilization rate of 25% and regardless of demagnetization, the NPV is negative and hence the investment in the PM motor is not positive. At 75% utilization rate, the investment is profitable even at a decrease in efficiency of 30%. At 50% utilization rate, the PM is profitable till a deterioration in efficiency exceeds 27%.

The profitability of investing in PM instead of induction motor is more sensitive to changes in efficiency than in life time. A 25% reduction in efficiency form the base case decreases the NPV by 40% while a 25% reduction in life time from the base case by 18%; less than half. For utilization rates of 25% or less, PM motors are not yet profitable for implementation in Egypt in comparison to induction motors. In PV pumping applications the utilization rates are usually low. At most, the PV pumping system would be used for 6 h daily (usually not daily since irrigation of crops works for certain times of the year). For electric vehicles, driving an intercity car would imply 2–4 h of utilization every day (assuming 2 h commute to work at most). For both applications the utilization rates are less than 25%. This means that applications such as PV pumping or Electric Vehicles at present electricity tariff rates might not be suitable (feasibility wise) for the replacement of induction motors by PM motors.

Conclusions and future perspectives

At the present electricity tariff rates the replacement of induction motors by PM motors in Egypt is feasible. However, this feasibility is most reliant on having utilizations rates exceeding 25% of annual hours. This implies that applications such as PV pumping and electric vehicles might not yet be economically feasible for the replacement of induction motors by PM motors. On the other hand, the sudden loss of magnetization is less of a risk to profitability than gradual demagnetization. The preliminary investigation presented in this paper suggests that the feasibility of the replacement of induction motors by PM motors is twice as sensitive to reduction in life time compared to reduction in efficiency. This points to the importance of ensuring PM motors have low gradual demagnetization pace rather than focusing on improving avoidance of incidences leading to sudden loss of magnetization. Tentatively, every 1% drop in efficiency due to gradual demagnetization is equivalent to a loss in the NVP of about 1% of the PM motor cost. While designers focus on having a high flux density in PM motors, avoidance of demagnetization is an important objective to be focused upon due to its strong impact of PM motor financial feasibility.

Future work includes developing a more rigorous and comprehensive mathematical model to correlate percentage of demagnetization to percentage decrease in efficiency. The planned model is to incorporate PM material through its magnetic viscosity coefficient as well as the impact of PM geometrical configurations on their intrinsic demagnetization fields and/or prone extent to external fields resulting from motor faults. In this quest, more experimental validation is planned to verify the accuracy of the planned comprehensive model.

Conflict of interest

The authors have declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

References

[1] United Nations Development Organization. Industrial energy efficiency baseline assessment report. Ind Energy Eff Proj Egypt; 2014.
[2] Lu SM. A review of high-efficiency motors: specification, policy, and technology. Renew Sustain Energy Rev 2016 Jun;1(59):1–2.
[3] De Almeida AT, Ferreira FJ, Baoming G. Beyond induction motors—technology trends to move up efficiency. IEEE Trans Ind Appl 2014 May;50(3):2103–14.
[4] De Almeida AT, Ferreira FJ, Quintino A. Technical and economical considerations on super high-efficiency three-phase motors. In: Industrial & commercial power systems technical conference (I&CPS). IEEE/IAS 48th 2012 May 20. IEEE; 2012. p. 1–13.
[5] Meza M. Industrial LV motors & drives: a global market update. In: Presentation at the motor and drive systems conference. Orlando, Fla; January 2014 Jan. p. 29–30.
[6] Electric AC motors market analysis by type (synchronous, induction), by voltage (integral, fractional), by end-use (industrial, motor vehicles, HVAC, transportation, household), and segment forecasts; 2018–2025.
[7] Widmer JD, Martin R, Kimiabeigi M. Electric vehicle traction motors without rare earth magnets. Sustain MaterTechnol 2015 Apr;1(3):7–13.
[8] Cui WB, Takahashi YK, Hono K. Nd2Fe14B/FeCo anisotropic nanocomposite films with a large maximum energy product. Adv Mater 2012 Dec 18;24(48):6530–5.
[9] Demmelmayr F, Troyer M, Schroedl M. Advantages of PM-machines compared to induction machines in terms of efficiency and sensorless control in traction applications. In: IECON 2011-37th annual conference on IEEE industrial electronics society 2011 Nov 7. IEEE. p. 2762–8.

[10] Goetzler W, Sutherland T, Reis C. Energy savings potential and opportunities for high-efficiency electric motors in residential and commercial equipment. EERE Publication and Product Library; 2013 Dec 4.
[11] De Kooning J. Optimal current waveform shaping and intelligent maximum power point tracking for wind turbines (Doctoral dissertation, Ghent University).
[12] Sebastian T. Temperature effects on torque production and efficiency of PM motors using NdFeB magnets. IEEE Trans Ind Appl 1995 Mar;31(2):353–7.
[13] Mayergoyz ID, Adly AA, Korman C, Huang M, Krafft C. Scaling and data collapse in magnetic viscosity. J Appl Phys 1999 April;85(8):4358–60.
[14] Korman C, Adly AA, Mayergoyz ID, Rugkwamsook P. A model for magnetic aftereffect in the presence of time varying demagnetizing fields. IEEE Trans Magn 2000 September;36(5):3182–4.
[15] Mayergoyz ID, Adly AA, Huang M, Krafft C. Scaling and data collapse in magnetic viscosity (Creep) of superconductors. IEEE Trans Magn 2000 September;36(5):3208–10.
[16] Burwell M, Goss J, Popescu M. International copper association, performance/cost comparison of induction-motor & permanent-magnet-motor in a hybrid electric car. Int Cu Assoc 2013.
[17] Yang Z, Shang F, Brown IP, Krishnamurthy M. Comparative study of interior permanent magnet, induction, and switched reluctance motor drives for EV and HEV applications. IEEE Trans Transp Electrif 2015 Oct;1(3):245–54.
[18] Melfi MJ, Rogers SD, Evon S, Martin B. Permanent magnet motors for energy savings in industrial applications. Petroleum and chemical industry conference 2006. PCIC'06.
[19] Ruoho S. Demagnetisation of permanent magnets in electrical machines. OH presentation, Helsinki University; 2006.
[20] Akar M, Eker M. Demagnetization fault diagnosis in permanent magnet synchronous motors. Przegląd Elektrotechniczny 2013;89(2a):229–33.
[21] Sjökvist S, Eriksson S. Investigation of permanent magnet demagnetization in synchronous machines during multiple short-circuit fault conditions. Energies 2017 Oct 18;10(10):1638. Record of conference papers-IEEE industry applications society 53rd annual 2006 Sep 11 (pp. 1–8). IEEE.
[22] Bilgin O, Kazan FA. The effect of magnet temperature on speed, current and torque in PMSMs. In: Electrical machines (ICEM), 2016 XXII international conference on 2016 Sep 4. IEEE; 2016. p. 2080–5.
[23] Gieras JF. Permanent magnet motor technology: design and applications. CRC Press; 2009 Aug 26.
[24] Nair SS, Patel VI, Wang J. Post-demagnetization performance assessment for interior permanent magnet AC machines. IEEE Trans Magn 2016 Apr;52(4):1.
[25] Fu WN, Ho SL. Dynamic demagnetization computation of permanent magnet motors using finite element method with normal magnetization curves. IEEE Trans Appl Supercond 2010 Jun;20(3):851–5.
[26] Ruoho S, Kolehmainen J, Ikäheimo J, Arkkio A. Interdependence of demagnetization, loading, and temperature rise in a permanent-magnet synchronous motor. IEEE Trans Magn 2010 Mar 1;46(3):949.
[27] Cui JG, Xiao WS, Zhao JB, Lei JX, Wu XD, Wang ZG. Development and application of low-speed and high-torque permanent magnet synchronous motor. In: Applied mechanics and materials, vol. 229. Trans Tech Publications; 2012. p. 888–94.
[28] He H, Zhou N, Sun C. Efficiency decrease estimation of a permanent magnet synchronous machine with demagnetization faults. Energy Proc 2017 May;1 (105):2718–24.
[29] Huger D, Gerling D. An advanced lifetime prediction method for permanent magnet synchronous machines. In: Electrical machines (ICEM), 2014 international conference on 2014 Sep 2. IEEE; 2014. p. 686–91.
[30] Sudhoff SD. Power magnetic devices: a multi-objective design approach. John Wiley & Sons; 2014 Jan 30.
[31] Kim JM, Sul SK. Speed control of interior permanent magnet synchronous motor drive for the flux weakening operation. IEEE Trans Ind Appl 1997 Jan;33 (1):43–8.
[32] Ruoho S. Direct torque control of a permanent magnet synchronous motor. Royal Institute of Technology in Stockholm; 2005.
[33] Guo Q, Zhang C, Li L, Zhang J, Wang M. Maximum efficiency per torque control of permanent-magnet synchronous machines. Appl Sci 2016 Dec 12;6 (12):425.