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Rare-earth-free propulsion motors for electric vehicles: A technology review

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ABSTRACT

Several factors including fossil fuels scarcity, prices volatility, greenhouse gas emissions or current pollution levels in metropolitan areas are forcing the development of greener transportation systems based on more efficient electric and hybrid vehicles. Most of the current hybrid electric vehicles use electric motors containing powerful rare-earth permanent magnets. However, both private companies and estates are aware of possible future shortages, price uncertainty and geographical concentration of some critical rare-earth elements needed to manufacture such magnets. Therefore, there is a growing interest in developing electric motors for vehicular propulsion systems without rare-earth permanent magnets. In this paper this problematic is addressed and the state-of-the-art of the electric motor technologies for vehicular propulsion systems is reviewed, where the features required, design considerations and restrictions are addressed.

Contents

1. Introduction

Fossil fuel price uncertainty, resources scarcity and greenhouse gases emissions (GHG) are forcing the current energy system to be based on more efficient, sustainable and renewable technologies [1,2]. The transportation sector is one of the main oil users,

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consuming almost half of the oil resources [3], so it is especially sensible to supply disturbances and price volatility. Road transport accounts for roughly 75% of transport GHG emissions [4]. This is forcing the transportation sector to improve due the need of enhanced efficiency [5], reduce the dependency on foreign resources and lower GHG and noise emissions [3]. The use of green transportation systems is of paramount importance in modern cities due to the current pollution levels, environmental issues and severer emission standards for vehicles [6]. One of the greatest challenges is to develop near zero-emission vehicles [7]. Automotive electrification is experiencing a notorious increase since this technology allows facing most of the aforementioned issues [3,8]. Therefore power electronics devices, and propulsion and energy storage systems for electric vehicles are receiving much attention [9]. It is worth noting that with the growing installation of fluctuating power generation systems based on renewable energy sources (RES), in both generation and demand sides, more flexibility is required and electric vehicles can help to balance this fluctuation on the demand side [10,11].

Features required for electric propulsion motors include high efficiency, high torque and power per unit volume, that is, compactness, [12] good dynamic response, simple construction and high reliability (brushless operation). To achieve these challenging requirements, the state-of-the-art technologies for new generation of propulsion systems for electric vehicles with improved features is currently based on different materials, including soft magnetic laminations and rare-earth elements (REEs) [2], among which rare-earth neodymium magnets (NdFeB) [13] highlight. In addition progresses in power and control electronics, and design and analysis systems based on finite element methods [5] highly impact these technologies.

In recent years rare-earth permanent magnet machines have gradually replaced traditional motors and generators in many applications [14], including automotive drives, wind generators or home appliances since they exhibit enhanced efficiency and power density [15–17]. As an example, modern low-speed direct drive generators for wind turbines have a rare-earth magnet content of around 650 kg/MW [18]. This had led to concerns of rapid depletion of REEs resources [2]. It is widely recognized that there is a geographical concentration of the REEs resources [19], since today China is the predominant supplier [20], with about 96% of the REEs' worldwide production [19,21], [21] although it has less than 40% of the proved reserves [22]. Although new mines are planned, they take several years to be productive [1,20]. In 2011, REEs products experienced a sudden price rise of about 600 percent due to reductions in export quotas from China [23]. According to [24], the current price of some REEs is too low to reflect their value, does not represent the shortage of the resources and does not compensate the environmental damage. An interesting option consists in recycling and reusing REEs, since it can help in reducing the total amount of primary rare-earth mineral to be used. However, REEs recycling rates are still extremely low, less than 1% [22]. Due to the multiple uses of REEs, their demand is expected to increase considerably in the future [19], so the risk of a limited supply chain is a focus of concern [25]. According to the European Commission [26] and the US Department of Energy (DOE) [27], some REEs are considered critical for the respective economies, since they can place regional industries in a vulnerable situation due to possible shortages or even to an imminent risk of supply interruption [28], and some of them, and especially dysprosium, show symptoms of serious scarcity [18]. Dysprosium and other REEs are often added to the NdFeB formulations to enhance their coercivity [14,29].

The cost of permanent magnets (PMs) can significantly determine the final cost of PM motors used in electrical propulsion applications [30]. Due to the above-described economic, environmental and geopolitical issues, nowadays there is a growing need to produce efficient electric motors which do not use rare-earth PMs [31]. Therefore the automotive industry is exploring different technologies based on environmentally friendly and available materials.

This paper reviews the state-of-the-art in electric motors technology without rare-earth PMs for vehicular propulsion systems. The paper intends to make a comprehensive review of the most popular technologies under research or under development/application, thus identifying the strong and weak points of each technology and the challenges to be faced. A comparative analysis based on the torque density, machine constant of mechanical power and maximum efficiency of the different technologies is also performed, which is based on data published in recent scientific publications.

2. Rare-earth materials for permanent magnets

This section reviews the rare-earth materials commonly used for PMs in electrical rotating machines, their main features and environmental issues.

Rare-earth elements (REEs) are more abundant in the earth's crust than the name suggests [32], since the name refers to the historical difficulties in identifying and purifying REEs [2], although some heavy REEs are less common [33]. However, REEs mining is only cost-effective in a limited number of locations due to the separation complexity and the ore grade of the deposits [32]. REEs mining also produces environmental problems such as the ones related to the radioactive minerals associated with REEs [33].

REEs have a wide range of applications, including automobile and petroleum refining catalysts, fiber optics, electronics, lamp phosphors for color flat panel displays, compact electric motors for electric vehicles (EVs) or direct drive generators for wind power applications [1,21]. REEs are key elements in the change to a low-carbon greener economy [22]. According to the IUPAC there are 17 REEs (scandium, yttrium and the 15 lanthanides) [1,22,34,35] from which samarium (Sm), terbium (Tb), neodymium (Nd) and dysprosium (Dy) highlight to manufacture high performance PMs. The last two elements are of especial importance to produce PMs for efficient and compact electric propulsion machines. Although neodymium is quite common, dysprosium is one of the rarest ones [32]. Samarium cobalt magnets exhibit higher operating temperature than neodymium magnets (NdFeB) [36] but neodymium magnets offer the maximum energy product, a measure of the capacity to retain and provide magnetic flux [21], so they exceed the magnetic properties of samarium cobalt magnets [35].

PMs can be classified in three main groups, i.e. alnico, ferrite and rare-earth magnets. However, the PMs market splits approximately 2:1 between neodymium and hard ferrite magnets, whose costs are in a proportion of more than 25:1 [37].

Alnico magnets mainly contain aluminum, nickel, cobalt, iron, and some grades may also include copper and titanium or other elements like silicon or zirconium [38]. These magnets exhibit high remanent magnetic induction B_r and allow high temperature operation. However, they can be easily demagnetized because of the low coercive field H_c [39]. Worldwide there is a reduced but stable demand for this kind of magnets [37].

Ferrite magnets, also known as ceramic magnets, are mainly composed of ferric oxide, which is abundant in supply, but they may also contain strontium or barium or a combination of both elements [39]. The most common formulations are $SrFe_{12}O_{19}$ and $BaFe_{12}O_{19}$. Ferrite PMs also present a very high electric resistivity, therefore minimizing eddy current losses when used in electric motors but they present a low energy product $(BH)_{max}$. Ferrites are inexpensive magnets [38], quite easy to produce and represent