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The Rediscovery of Synchronous Reluctance and Ferrite Permanent Magnet Motors

Tutorial Course Notes

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Chapter 1
Overview of PM/Reluctance Synchronous Machine Opportunities and Challenges

Thomas M. Jahns

Abstract The dramatic rise and fall of the price of rare-earth metals neodymium and dysprosium during the period between 2010 and 2014 has led to an energetic search for alternative machine topologies to replace high-performance PM synchronous machines using sintered NdFeB magnets. This chapter introduces the major alternative brushless synchronous machine configurations that are the subject of this book. These include PM synchronous machines that use either much smaller amounts of NdFeB magnets or alternative magnet materials such as ferrite magnets, as well as synchronous reluctance machines that require no magnets at all. A historical perspective is presented that introduces each of these machine alternatives in roughly chronological order in order to highlight the motivations and technical breakthroughs that both enabled and drove the new developments that continue to influence research efforts today. The chapter closes with summary comparisons of the strength and limitations of the major classes of brushless synchronous machines, providing a foundation for the detailed discussions of these alternative machine topologies that are presented in the following chapters.

Keywords History of PM/reluctance machines · Rare-earth magnet price volatility · Early surface and interior PM machines · Early synchronous reluctance machines · Magnet and reluctance torque · Inductance saliency ratio · Characteristic current · Flux weakening · Fractional-slot concentrated winding (FSCW) PM machines · Feature comparisons of PM/reluctance machine types

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1.1 Introduction

Many veteran professionals in the PM synchronous machine industry will never forget the severe stress they suffered during the period from early 2010 to mid-2011 when the price of the rare-earth metal neodymium (Nd) skyrocketed on the world market by a factor greater than 20:1. This unprecedented price increase was extremely painful for even large companies that were heavily dependent on neodymium as a key ingredient in their high-strength rare-earth magnets, and it forced some smaller companies without the necessary financial resources to go out of business.

One of the more common and understandable responses by survivors of this spectacular price rise and its subsequent fall was “Never again!” As a result, there has been a dramatic surge of activities during the period since 2010 to investigate the viability of developing alternative types of machines that would provide comparably high performance without being so exposed to the volatility of future price swings for the neodymium-iron-boron (NdFeB) magnets. Some researchers have pursued alternative types of synchronous machines in search of the best candidates. Others have instead investigated entirely different types of brushless machines including high-performance versions of switched reluctance and induction machines. This tutorial is focused on reviewing progress that has been achieving pursuing the former of these two approaches, shining a spotlight on several very interesting alternative types of synchronous machines both with and without magnets.

The objective of this chapter is to provide an introductory review of the wide range of brushless synchronous machines that use permanent magnets, variable reluctance, or a combination of the two to develop torque in variable-speed applications. This introduction will begin by briefly reviewing the basis for underlying concerns about the future availability of affordable rare-earth magnets. This background material will be followed by a discussion of the history of synchronous machines without classic field windings. This historical review will provide opportunities to introduce all of the alternative synchronous machine topologies that are now being seriously investigated as candidates to replace the incumbent PM synchronous machines using high-strength sintered NdFeB magnets.

The final section of this chapter is devoted to providing summary comparisons of the major advantages and limitations of three major classes of brushless synchronous machines. These comparisons set the stage for evaluating the alternative synchronous machine topologies that seek to challenge the dominance of PM synchronous machines using high-strength NdFeB magnets in high-performance applications. The following chapters then focus attention on each of the most promising alternative machine candidates, including discussions of machine models, analysis, design, and control of these machines.

1.2 Rare-Earth Magnet Price Volatility

The commercialization of NdFeB rare-earth permanent magnets that began in the 1980s has had a profound effect on the successful development of high-performance PM synchronous machines that have appeared in so many important applications during recent years ranging from passenger electric vehicles to elevators and wind turbines. Neodymium-iron-boron magnets represented a major advance in permanent magnet technology that is reflected in the family of normal *B-H* curves for several different types of permanent magnets shown in Fig. 1.1. The remanent flux density B_r and coercivity H_c values associated with the sintered NdFeB magnets are higher than those of any of the other types of magnets shown in the figure, including those of samarium-cobalt (Sm_2Co_{17}) magnets that were the first major breakthrough in the development of rare-earth magnets in the 1970s.

Despite their many attractive performance characteristics, NdFeB magnets suffer from a relatively low Curie temperature that puts them at a disadvantage compared to other types of magnets, including samarium-cobalt magnets, for use in demanding electric machine applications that often push the thermal limits of their wire insulation systems. Material scientists soon learned that one of the most effective means of increasing the maximum temperature range of NdFeB magnets is

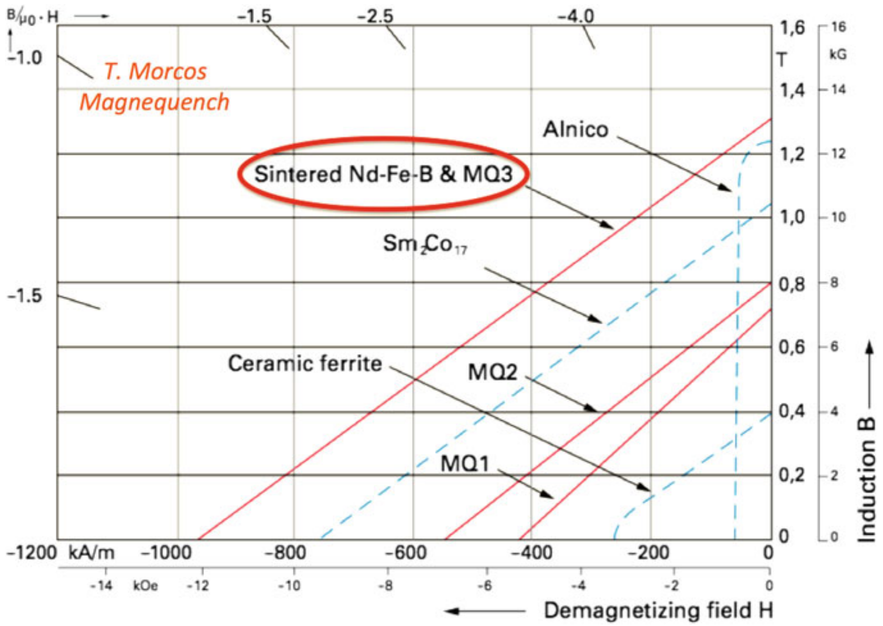

Fig. 1.1 Second quadrant normal *B-H* curves of several different types of permanent magnet materials currently used in PM synchronous machines, showing superior characteristics of sintered NdFe magnets in terms of both remanent flux density (*B* axis intercept) and coercivity (*H* axis intercept). *Source* Magnequench

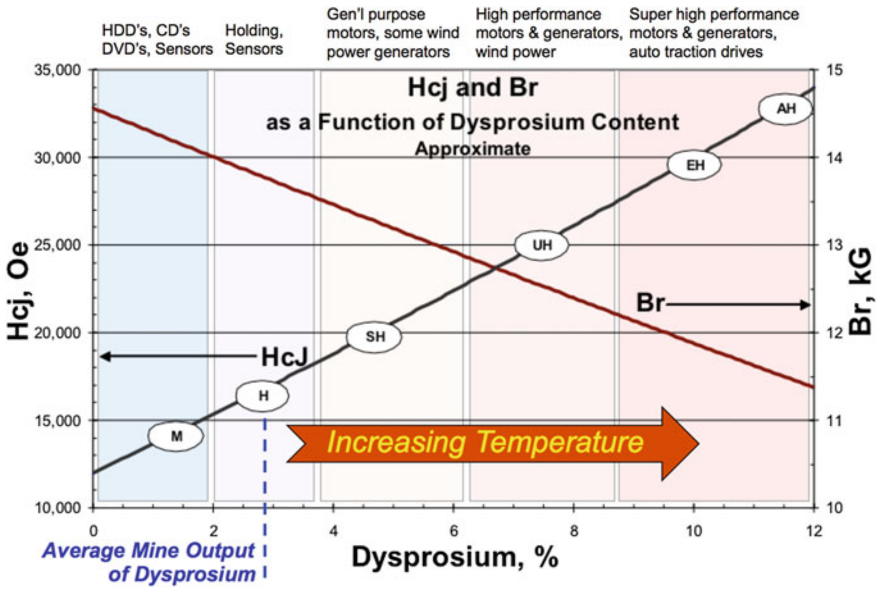

Fig. 1.2 Impact of increasing dysprosium content on the coercivity H_{cj} and remanent flux density B_r of NdFeB magnets. Associated magnet temperature grades are identified in ovals along the coercivity line, indicating higher temperature capabilities as the dysprosium content is increased. *Source* Arnold Magnetics

to add small amounts another rare-earth element, dysprosium (Dy). Figure 1.2 shows that the maximum useful operating temperature of NdFeB magnets increases monotonically as the percentage of dysprosium by mass is increased from 0 % to greater than 10 %. Despite the appeal of this approach from the standpoint of maximum operating temperature, the impact of adding dysprosium on magnet cost becomes increasing significant as its percentage content grows because Dy is significantly rarer and more expensive than Nd. In fact, the cost per kilogram of dysprosium is typically on the order of 7 to 8 times more expensive than Nd, signifying that even small percentages of Dy in the NdFeB magnets will have a significant impact on the cost of the final magnet material.

Although the price of NdFeB magnets was initially quite high, China played a major role in driving down their price during the late 1990s and early 2000s. China was in a strong position to play such an important role in the NdFeB magnet market because of its very large reserves of rare-earth materials compared to any other country. During this time period, Chinese magnet producers became the dominant NdFeB magnet manufacturers in the world.

Figure 1.3 shows that the prices per kg for neodymium and dysprosium increased in tandem between the beginning of 2010 and mid-2011 by factors of 25 and 22 times, respectively, due to a combination of factors that included a large component of market speculation. After hitting their peak, prices of both materials

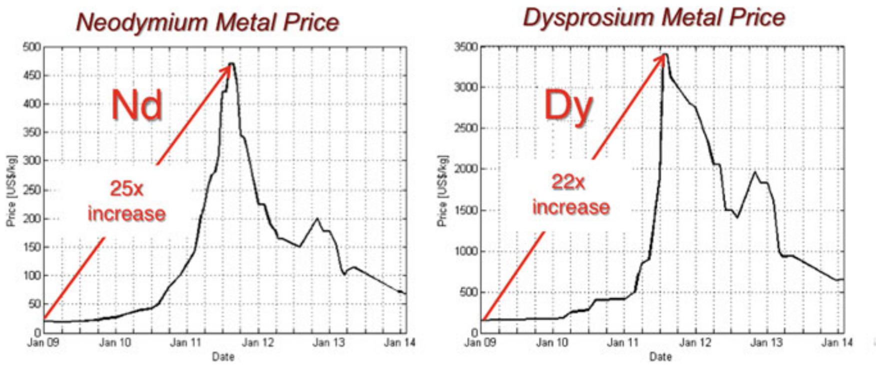

Fig. 1.3 Prices of Neodymium and Dysprosium metal during 5-year period beginning in Jan. 2009, displaying wide price swings with increases >20:1 between Jan. 2009 and July 2011

dropped almost as rapidly and have settled to values that approach their pre-bubble prices. As noted in the introduction, this spectacular increase has had a major financial and psychological effect on PM machine manufacturers that had become increasingly dependent on both of these materials as the basis for the growing amount of magnet material that they needed to builds their PM machines.

1.3 Historical Perspectives on Synchronous Machines and Drives

1.3.1 PM Synchronous Machines

Although the concept of mounting permanent magnets on spinning rotors to produce electric motors and generators predates the 20th century, the commercial implementation of PM synchronous machines had to await the development of magnet materials with sufficient remanent flux density and coercivity to make them practical. One of the first permanent magnet materials that was developed with sufficient remanent flux density to attract serious attention for electric machine materials was magnetic cobalt-steel which first became commercially available in the vicinity of 1920 with an energy product of approx. 1 MGOe. Like several of the early magnet materials, it suffered from low coercivity values, making it challenging to use in practical machine designs. Two early examples from a paper published in 1925 are shown in Fig. 1.4 [1], including an interior PM alternator machine that is one of the earliest examples of interior PM machines found in the literature.

Magnet materials improved during the following decades with the development of a family of different Alnico magnet alloys with energy products eventually reaching 10 MGOe over a >30-year period extending from 1931 to the 1960s.

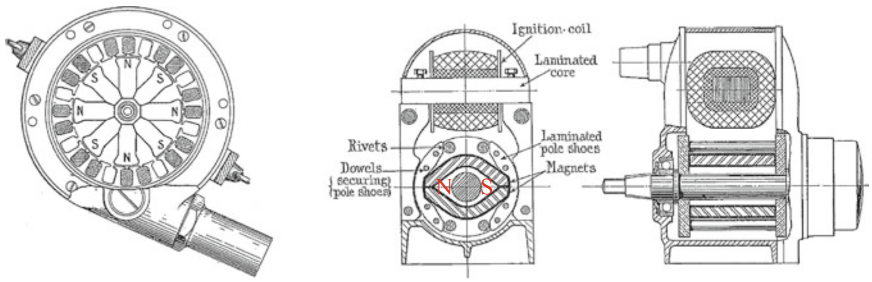

Fig. 1.4 Early examples (1925) of PM machine topologies and applications using cobalt-steel magnets [1]. *Left* Surface magnet topology applied in air-driven brushless alternator for miner's lamp. *Right* Interior magnet topology designed for aircraft "magneto" ignition alternator

Although Alnico magnets suffered from low coercivity values, clever engineers learned to design high-performance ac machines that could tolerate this limitation. One example is a 75 kVA PM synchronous alternator designed with 28 poles for 400 Hz operation at 1714 r/min that is shown in Fig. 1.5 [2]. This is another example of an interior PM machine in which the steel rotor pole shoes act to protect the buried magnets from some components of the demagnetizing magnetomotive force (MMF) that is applied by the stator current as the load amplitude increases.

The availability of high-grade Alnico magnets also led to development and commercialization of some of the earliest examples of line-start PM synchronous machines, representing the hybridization of induction and synchronous machine features in the same rotor. Rotor construction details for the family of Permasyn line-start machines are provided in Fig. 1.6, showing the large Alnico rotor magnets that were required to stand off the large time-varying demagnetizing MMF's during the starting transients [3]. Permasyn machines were available with ratings from 0.2 to 2.2 kW.

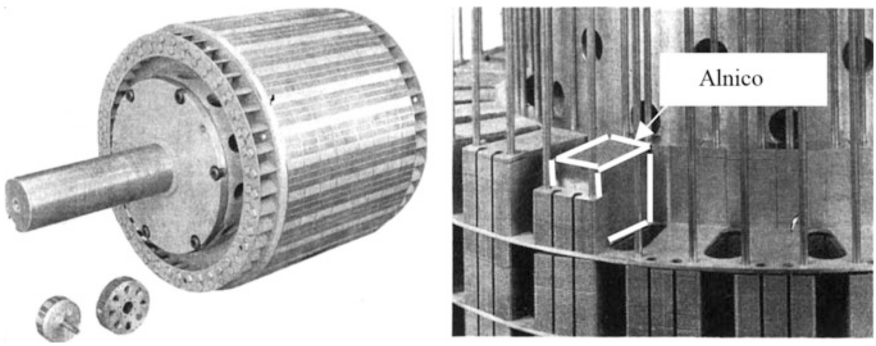

Fig. 1.5 75 kVA, 1714 r/min PM synchronous alternator designed with 28 poles for 400 Hz operation. Interior magnet construction partially protects the buried Alnico magnets from demagnetizing MMF applied by the stator current when operating under load [2]