Synchronous Reluctance Motor Technology: Industrial Opportunities, Challenges and Future Direction

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Abstract: In recent years, the desire for high efficiency and high torque density electric motors without permanent magnet materials for the industrial, as well as the specialist product sectors, has increased significantly and has developed into hot research topic. This paper discusses a re-emergent type of AC electrical machine, the Synchronous Reluctance Machine. Current EU legislation aims to tackle global energy usage and reduce greenhouse gas emissions, the Synchronous Reluctance motor is discussed in this context - Its potential to become the future industry standard for high efficiency, low cost, high output industrial drives for fan, pump and mill type industrial applications is explored. The reader will be brought up to speed with Synchronous Reluctance technology, presented with both its advantages and disadvantages with the suitability of the technology for industry application being discussed and a comparison made with respect to competing technologies - the traditional induction machine and the modern permanent magnet machine. Current and future research trends are outlined and a simple engineering case study is also presented as an indication of the energy saving potential of this type of machine. This paper aims to inform students, engineers and key-decision makers in industry about this exciting technology.

1. Introduction

Synchronous reluctance technology has been available since the 1920's, but has not yet found mainstream acceptance for various reasons. The superiority of the induction motor has prevailed and with the advent of the high-energy density permanent magnet materials in the 1980's, the permanent magnet machine has become the machine of choice for specialist and high performance application. However, as of 2016, there is a research emphasis on electrical machines with low volumes of rare earth permanent magnetic material, which has been reported in the world's media [1]. There is also an emphasis on very high efficiency, or *super-premium efficiency*, electrical machines for the industrial sector [2,3]. These research areas are driven by differing factors; the former is driven by various supply issues surrounding the permanent magnet material such as material availability, pricing fluctuations and environmental impact. The latter is driven by both the light and heavy industrial sectors, coupled with local government and EU legislation to reduce electrical energy consumption and world greenhouse gas emissions [4,5]. With regard to permanent magnets, which are utilised due to their high remnant flux density and coercive force that enables high torque density, efficiency and inverter utilization, they are popular for specialist applications such as automotive traction, aerospace propulsion and wind turbines. However, due to their high cost, political and the environmental issues associated mineral extraction, alternative machines with reduced or no RE materials is a current hot research topic [1,6].

The synchronous reluctance motor (Typical machine profile shown in Figure. 1) is an interesting alternative, possessing features that are aligned with both of the identified research streams – no magnets and capable of high efficiency. However, the synchronous reluctance motor (or generator), termed the *SynRM*, is not widely known in industry. This paper focuses on informing the reader of synchronous reluctance technology, details the various advantages and perceived disadvantages of this technology with respect to the industrial sector, outlines current research streams and provides an indication on potential future research paths. A simple engineering case study is presented on the energy saving potential of Synchronous Reluctance Technology when applied to the industry sector.

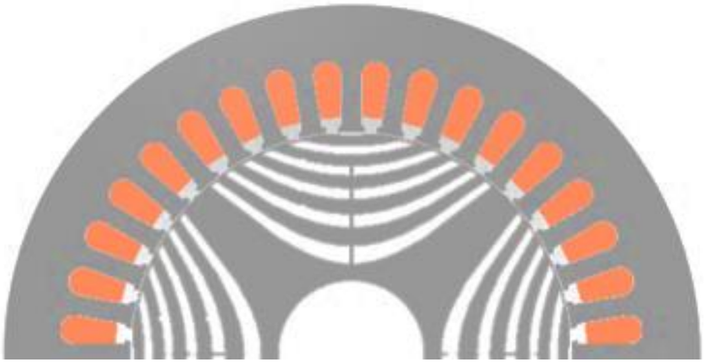


Figure 1 – Typical SynRM lamination profile

This paper aims to provide the student or non-specialist engineer with a gentle introduction to SynRM technology and highlight the perceived advantages and disadvantages of this particular machine topology compared to other common types. The paper also explores the industrial landscape by analysing commercial machine efficiency and case studies involving the application on the SynRM in practice. Routes for further research and development are suggested as an attempt to create interest and set forth a path for continued development of this technology. An extensive suggested reading list of papers, books and book chapters is provided at the end of the paper to take the readers study of the SynRM much further beyond the scope of this paper.

2. High Energy Efficiency Industrial Drives

The larger market for the two identified research areas is the high efficiency industrial drives market. Between 43% and 46% (or greater) of the 16TW [7, 8] of the globally consumed electrical power goes directly into electric motors for applications such as industrial fan, pump and mill type loads. Approximately 90% of the motors that utilise this electrical power are three phase induction motors. Therefore the global effort to reduce energy usage and greenhouse gas emissions can aided significantly by higher efficiency electric motors. As such, EU legislators have implemented a directive (2012/24/EC) which dictates that industrial motors must have an efficiency that conforms to the latest IEC 600034-30 efficiency standards, set by the International Electrotechnical Commission [3, 4]. The IE3 standard is known as *Premium Efficiency* and there is the legislation, details setting out the IE4 S*uper-premium* efficiency standard. Between each standard there is usually a 2-3% or greater change in minimum efficiency, depending on power rating and pole number. Efficiency ratings for four pole machines between 0.75 and 375kW are shown in Figure 2.

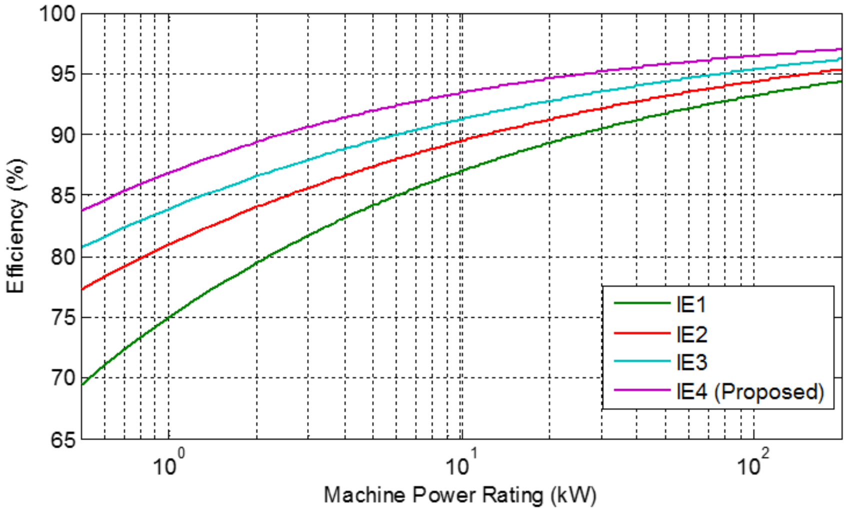


Figure 2 - IEC Efficiency Standard Ratings

To meet this demand for higher efficiency industrial variable speed drives, the first mass produced IE4 rated synchronous reluctance machine, marketed for common industrial loads such as fan, pump and mill type applications was introduced by the manufacturer *ABB* in 2011. Two variants of the ABB drive-package exist, firstly the IE4 super-premium efficiency motor and an IE3 high output motor variant, both coupled with advanced ABB electric drive systems utilizing direct torque control schemes [9]. Although by legislation variable frequency controlled drives are limited to a minimum of IE2 improved efficiency standard (as inverter fed machine typically have lower efficiency due to inverter effects on the machine), these were the first motors, and the first synchronous reluctance machines to achieve the future IE4 super premium efficiency rating and are one step in realising very high efficiency electrical machines for the industrial sector – directly competing with traditional induction motor technology.

3. Synchronous Reluctance Technology: The Basics

3.1. A Brief History of the SynRM

The synchronous reluctance machine can trace its roots back to an invention of Nikola Tesla in 1887 but was first published in its modern form by J. K. Kostko in 1924 [10], his original ‘polyphase reaction motor’ was a different type of reluctance motor than the age old *switched reluctance motor* (SRM) which was first invented about 100 years before [11]. The first synchronous reluctance motors had relatively low performance, utilizing simple salient rotors or modified induction machine rotors. Because of the poor synchronous performance of these primitive types, this motor type was left mainly neglected until the 1960’s and 1970’s, where the work of Lawrenson [12], Cruickshank [13] and Honsinger [14], among others, aided the advancement of the SynRM where it found acceptance in variable speed and multiple synchronised machine applications such as in paper mills. Engineers investigated the SynRM and a number of new designs were developed, however with no variable frequency drives (in their current form) available at that time, application (and interest in) once again faded. In the 1980/1990’s, power electronics had developed rapidly after the computer revolution in the 1970’s, engineers in the 1980/90’s such as Miller [15] and Staton [16] then revisited this technology. Variable frequency drives were now becoming readily available and again, a renewed interest in SynRM came about, however, in this same period, the advent of Rare Earth permanent magnets once again foiled further development. The rare earth permanent magnet motors (PMSM) had inherent advantages over the existing SynRM technology at that time and thus it appears that the SynRM has been consistently upstaged by more fashionable or convenient technologies. Extensive research and development in rare earth PMSM machines has existed since their inception, but between 2008 to 2010, a pricing anomaly linked to China’s monopoly on the rare earth magnet market, caused the £/kg to spike over 300%, where the average cost increased from 75 USD/kg to 325 USD/kg in a 10 month time frame [1]. Current pricing as of early 2016 is back around 75 USD/kg. The cost has significantly dropped since 2011 to levels about the 2010 USD/kg value; however this uncertainty has induced shock into the emerging automotive markets and others. Coupled with the new IE4 efficiency standard, the synchronous reluctance motor has once again been resurrected. As of early

2016 and within the last 10 years, according to the IEEE and the IET there are over 2000 conference and journal papers concerning the switched reluctance machine, there are approximately only 1000 papers for the synchronous reluctance machine, but over 14,000 articles for the permanent magnet motor. The induction machine has a similar level of contribution as the PM motor with over 12,000 conference and journal articles being published to date.

1.1. Operating Principle

In an energised system such as that in Fig. 3, a simple salient pole rotor will tend to align with the core due when the coil is energised to maximise inductance or minimise magnetic reluctance. This is a *reluctance torque*. As the title suggests, reluctance machines do not inherently contain permanent magnet material and all rotor electromagnetic torque is produced by rotor saliency, i.e. rotors with non-isotropic magnetic reluctance that interacts with a stator magneto-motive force. Movement of a high permeability rotor component (rotary in this case) to minimise the reluctance path and maximise the inductance of the mutual flux linkage with an energised coil and the permeable rotor is the basic principle of operation for a reluctance machine.

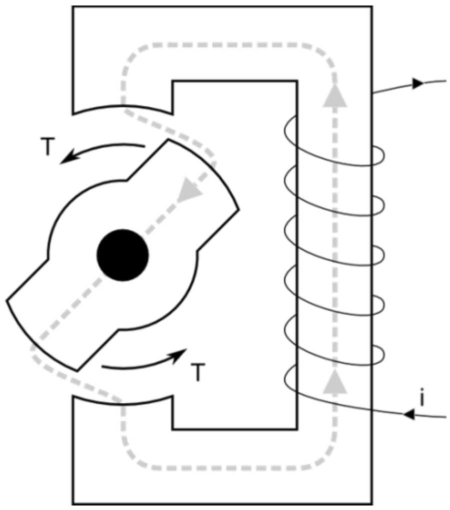


Fig. 3 Elementary Reluctance Motor

Machines that operate on this principle date back to around 1842. A locomotive traction motor designed by Scottish inventor Robert Davidson for the Edinburgh-Glasgow railway line [11], which incidentally was also the first electric locomotive, operated with a simple reluctance motor.

In a machine with a revolving field system created by polyphase electric currents, a continuous reluctance torque may be produced, as in modern synchronous reluctance motor technology. The energising field is rotating at some synchronous speed and therefore the rotor can never fully align with the magnetizing field and therefore continuous torque production can be forced. As the SynRM is a rotating field AC machine that develops only a reluctance torque, the key to operation is anisotropic magnetic reluctance in the rotor. In any reluctance based machine, within a decoupled reference frame the *d (direct)* -axis is termed the path of least reluctance and the *q (quadrature)* -axis is the path of greatest reluctance. In order to obtain good machine performance, the saliency ratio (ratio of the *d*- to *q*-axis inductances) must be maximised. The saliency ratio of the machine is mainly dictated by the electromagnetic design of the rotor – this paper will not attempt to enter the complicated world of SynRM rotor optimisation (electromagnetic-mechanical interdependencies). A typical design of a salient rotor for a synchronous reluctance machine is presented in Figure. 4.

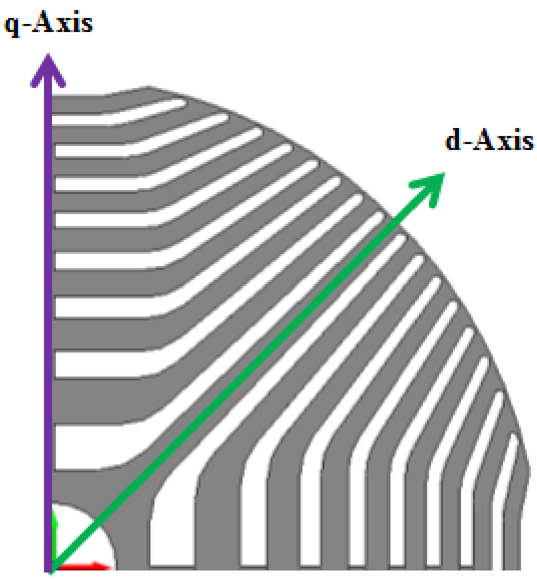


Figure 4 – IM and SynRM Lamination Profiles

It is seen from Figure 4 that magnetic flux would like to flow down the *d*-axis, however, it is faced with a large number of air-gaps in the *q*-axis, which the flux does not like to cross. This is the saliency of the rotor design, there is a preferred direction the flux naturally would like to flow, i.e. the rotor has a large degree of anisotropy. Any good SynRM has a large saliency, in other words, a high direct axis inductance and a low quadrature axis inductance; this ensures high torque production, high power factor and high energy conversion efficiency. A key term is the rotor *saliency ratio,* which is the ratio of direct axis to quadrature axis magnetic *permeance* (reciprocal of magnetic reluctance).

1.2. Modelling and Key Figures of Merit

It is common that *d-q* axis theory is the analysis of choice for AC machinery with polyphase sinusoidally distributed stator windings. The direct axis inductance is related to the 'goodness' of the flux path in that axis ad has an associated inductance L_d which the designer desires to be *as large as possible*. The q-axis also has an associated inductance L_q, which the designer requires to be *as low as possible,* indicating a high reluctance q-axis path, coupled with the high direct axis inductance leading to a *high saliency machine*. The developed electromagnetic torque of a synchronous reluctance machine can be expressed as [17];

$$T = \left(\frac{3}{2}\right) p\left(L_d - L_q\right) i_d i_d = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(L_d - L_q\right) i_s^2 \sin(2\kappa)$$

Where κ is the machine current angle, i.e. the angle between the current vector and the d-axis of the machine. It is easy to see that the current angle must be at 45 degrees (half way between the *d* and *q* axes in electrical terms) for maximum torque. The equation is similar to that of an interior permanent magnet motor *d-q* model, with the permanent magnet term (magnet torque) removed, leaving only the saliency torque term. The *d-q* theory developed in [17] leads us to two figures of merit;

- **Saliency Ratio** *–physically relating to the level of anisotropic magnetic reluctance in the rotor design and indicative of general machine performance.*

$$\xi = \frac{L_d}{L_q}$$

- **Torque Index –** *indicates the torque capability of the machine*.

$$\Omega = \left(L_d - L_q\right)$$

These figures of merit give an indicative assessment of machine performance. A rotor design must maximise the *d*-axis inductance and minimise the *q*-axis inductance for maximum power factor and torque production. The higher the saliency ratio, the more the general performance of the machine increases (efficiency, power factor & torque capability; typical saliency ratios in high performance modern designs are between 6 and 8.

1.3. Typical Construction

The synchronous reluctance motor is a true AC rotating field machine, requiring a balanced polyphase sinusoidal supply into a distributed winding, the stator therefore is for all intents and purposes identical to that of the induction machine of the same power rating. The rotor component is typical of general reluctance technology, usually consisting of only magnetic steel laminations when controlled by a variable speed drive, but has been known to also incorporate a cage for direct on-line applications. There are two key rotor variants, the transverse laminated anisotropic (TLA) type (Figure. 1) and the axially laminated anisotropic (ALA) type. The former consists of laminated steel transverse to the axial length of the machine with stamped '*flux guides'* that guide the flux in a preferred direction and ensure high saliency. The TLA motor is constructed in the same manner as induction motors and other synchronous machines, many variants of the TLA rotor exist – different shapes of flux guides etc. The latter consists of laminated steel arranged in an axial fashion with the aim of increasing saliency – the ALA rotor does this by introducing a significant number of inter-lamination air gaps to increase the *q*-axis reluctance.

If you were to take a salient pole synchronous motor, the simple salient rotor, which is easy to construct, and operate it without a rotor field current present, the motor would still develop a small amount of torque due to its simple saliency. This simply salient structure a very poor saliency ratio which is usually ≤ 2, and this topology therefore generally not considered in practice. However, due to its shape it can potentially run at very high speeds. Similarly, if you take a conventional induction motor and remove some of the rotor bars and then stamp out some elementary flux guides between the empty rotor bar slots, this will also produce a reluctance torque and also start as an induction motor. The cage requirement limits the electromagnetic design of the rotor and thus the maximum saliency ratio that can typically be achieved is $\leq$ 4. There is a casting and punching process, identical to that of the induction machine, but it does have the benefit of synchronism when up to rated speed. A further topology, is the cage-less flux barrier design (Fig. 1), and is usually the topology of choice due to its high achievable saliency ratios through good electromagnetic design. Typical saliency ratios for this topology are in the region $6 \leq \xi \leq 10$. They have no casting process but do require a variable frequency drive for operation and starting. The flux barriers guide the flux and thus act to minimise the q-axis inductance and simultaneously maximise the d-axis inductance.

The final design, is axially laminated (ALA), i.e. the laminations are oriented with the shaft centre axis. This type of design has high saliency ratios ($8 \leq \xi \leq 13$), which offers the best electromagnetic performance, but are difficult to construct with problems of larger eddy current losses due to lamination direction. This eddy current problem and their construction difficulty have appeared to consign them to the past, such that the TLA flux guide rotor is the rotor of choice for synchronous reluctance machine design engineer.

1.4. Differences with the *Switched* Reluctance Motor

Essentially, there are two main types of rotary electrical machine that operate on the reluctance principle and therefore develop only a reluctance torque. These are the SynRM and the more well-known Switched Reluctance motor [18,19]. There are fundamental differences in the construction and operation of these two machines. The Switched machine is known for its robustness but also its high torque ripple, acoustic noise and vibrations which are not issues in SynRM technology. It is beyond the scope of this paper to describe the operation of the switched reluctance motor in detail; however a brief comparison of the key features of the two machines is made in Table 1.

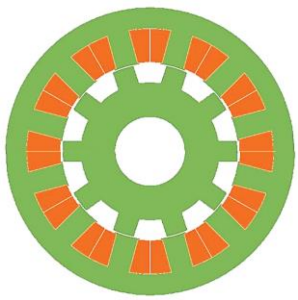
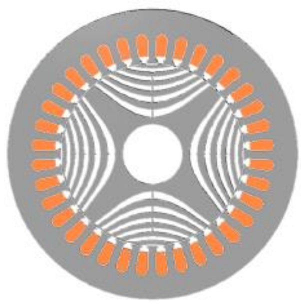
	Switched Reluctance (SRM)	**Synchronous Reluctance (SynRM)**
		
Saliency	Double (Stator + Rotor)	Single (Rotor)
Stator	Salient poles (concentrated coils)	Conventional AC machine
Rotor	Salient poles	Arrangement of internal flux guides
Winding	Single tooth windings	Polyphase distributed windings
Excitation	Pulsed DC voltage sequence	Balanced sinusoidal currents
Inductance Waveform	Triangular / Trapezoidal	Sinusoidal
Converter	Asymmetric Half Bridge	Conventional 3ph Inverter

Table. 1 Comparison of the SRM and SynRM technologies

The synchronous reluctance machine resembles more of an AC induction motor without rotor bars or windings, whereas the switched reluctance machine, which is not a true AC rotating field machine, but is better known, is of a less conventional construction. The switched reluctance machine has the benefit of single tooth coils with short end windings but requires a non-standard converter, the Asymmetric Half-Bridge (AHB) – this converter cannot be purchased *off the shelf* and is one of the reasons the SRM cannot claim mainstream acceptance and is mainly utilized in special applications. Other issues include the number of current carrying connectors required; the SRM requires two leads per phase [20], where as a conventional AC machine requires only one per phase. The SRM typically requires a separate current sensor per phase and the conventional AC machine does not.

2. Synchronous Reluctance Technology

Adoption of synchronous reluctance technology requires knowledge of the relative merits of such an adoption. This section outlines the advantages and disadvantages and proves some discussion of these in relation to industrial applications.

2.1 – Induction Motor Comparison

As, technically, the SynRM can be derived from induction machines simply by removing rotor bars and introducing slight saliency to the rotor, it has been shown that around 80% of the torque can be retained for approximately 60% of the loss or 1.2x the output for the same loss [21], hence the SynRM, *prima facie*, is a competitive technology for typical industrial applications [40]. Figure 5 shows the lamination profiles of the induction motor and the synchronous reluctance motor.

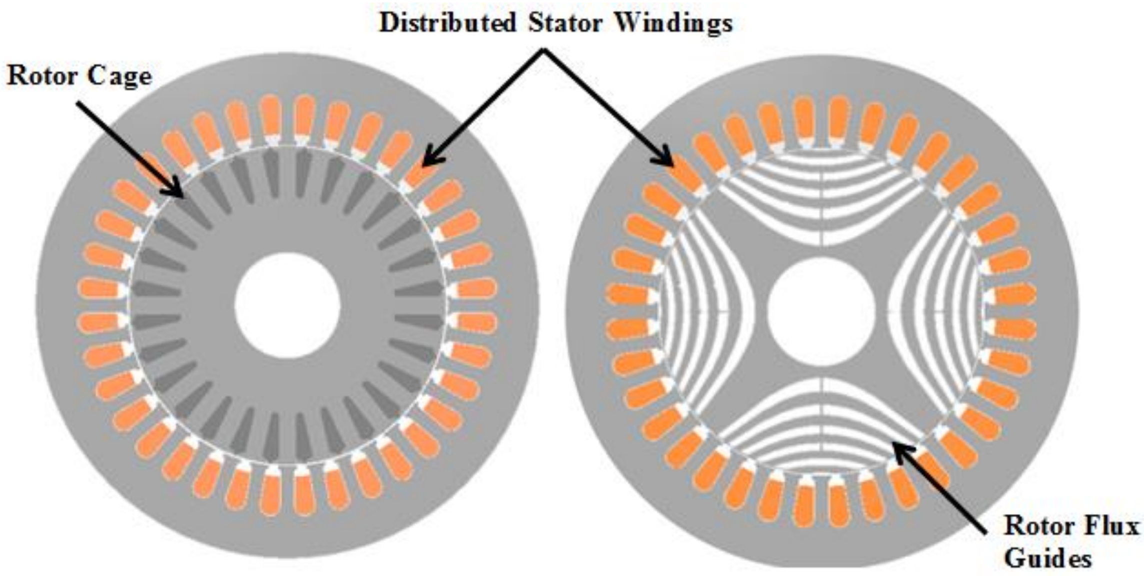


Fig. 5 Induction (left) and SynRM (right) motor topologies

The induction machine as the *workhorse of industry* for over 100 years is faced with the advent of high efficiency synchronous reluctance drives. It can be said with some confidence that the inherent advantages of SynRM technology over traditional induction machine technology includes the following [21,40, 53];

- Rotor synchronicity – no slip, true synchronised drive capability
- No rotor conductors
  - Increased robustness, lower mass & manufacturing costs
  - No rotor copper loss
  - Thermal improvements
  - Potentially lower maintenance requirement & cost
- Typically higher efficiency – same frame size (see ABB study)
- Potentially higher torque density - same frame size
- Lower rotor inertia
  - Faster dynamic operation
- Arguably simpler closed-loop control schemes – no slip estimation

The rotor conductor-less construction and slip-less operation of the SynRM brings much joy to the motor designer and the maintenance engineer. Around 25-30% of losses are generated in the induction machine rotor and is consequentially one of the most difficult areas to cool – the SynRM is essentially a *cold rotor* machine. The majority of the losses in the synchronous reluctance machine are confined to the stator copper windings, where it is generally easier to remove heat than the rotor, which is a major challenge in the IM. The realisation of these benefits is presented in the *Industrial Case Study* section. Along with these advantages, characteristics of the Synchronous Reluctance motor that could be considered disadvantages are;

- No-direct online capability (without caged rotor)
- Lower power factor – higher magnetising current [49]
  - Potentially increased inverter requirement
- Immaturity of the technology
- Not as widely manufactured or available (as of 2016)

With regard to design, in one case, the SynRM can be designed for the same frame size as an equivalent power IM, but achieve the latest IE4 efficiency standard rating – evident in ABB's offering of IE4 rated synchronous reluctance drive packages from 11 to 315kW [22]. In contrast, the machine frame size can effectively be reduced and for the same loss condition the same or increased output can be achieved, again demonstrated by ABB's offering of 'High Output' Synchronous reluctance drive packages from 1.1 to 350kW. These machines have a smaller frame size, higher output but maintain higher efficiency that their counterpart induction motors. Bolglietti provides a comprehensive review in [53] and for further reading on the comparison with the induction machine, the reader is directed to Sections 7 & 8 which provide an extensive reading list.

As an illustration, the IE4 SynRM technology marketed by ABB competes with its own induction motor technology. Figure 6 shows the relative package efficiencies [23] (motor + inverter losses) over the offered power range between the synchronous reluctance motor and the equivalent induction machine – taken from catalogue. The conditions are at rated speed and rated torque, self-cooled motors, all 4 pole 50Hz controlled by an ACS850 drive under sensorless Direct Torque Control. Figure 7 shows the efficiency increase over the power range.

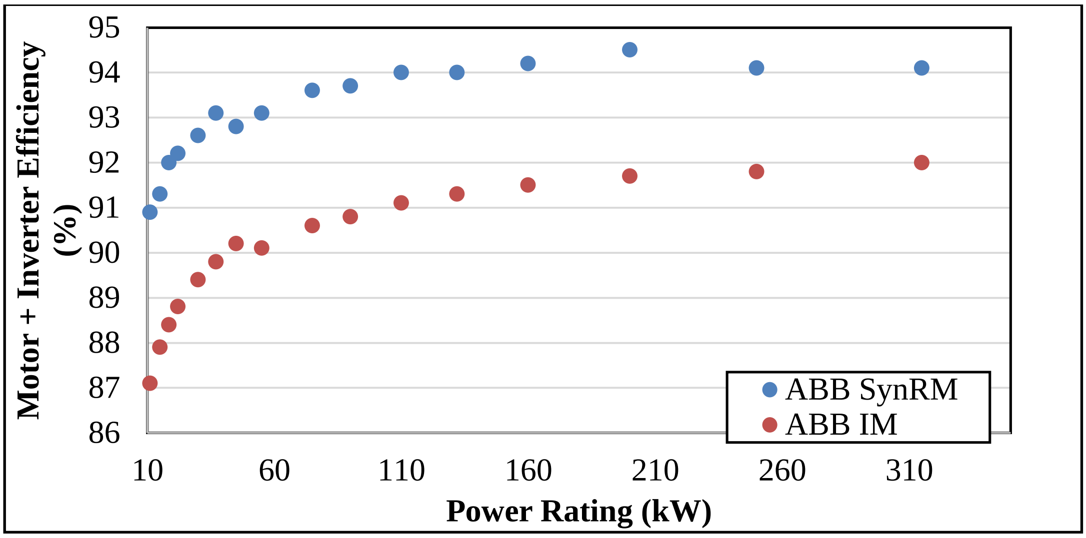


Fig. 6 Induction and SynRM motor efficiencies ((data from ABB, 2014[23])

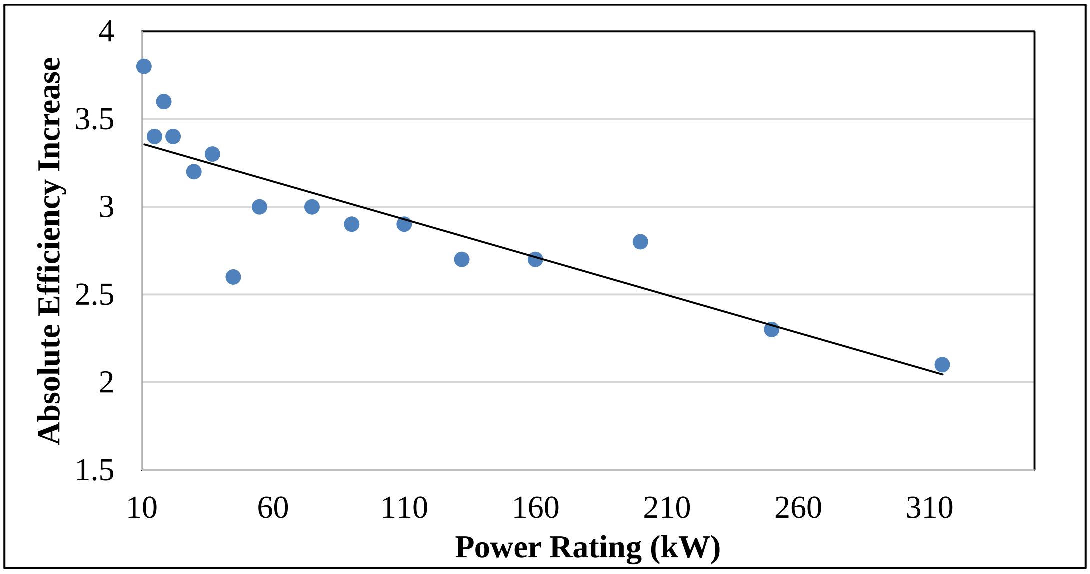


Fig. 7 Induction and SynRM efficiency difference (derived from ABB, 2014[23])

Therefore, based on the measured efficiencies of the whole motor-drive package and the other perceived benefits of synchronous operation and constructional advantages, the SynRM is extremely attractive due to its higher efficiency, especially at lower power ratings. Figure 8 shows practical lamination profiles (motor cross-sections) of the induction machine and equivalent SynRM – the stator component is identical.

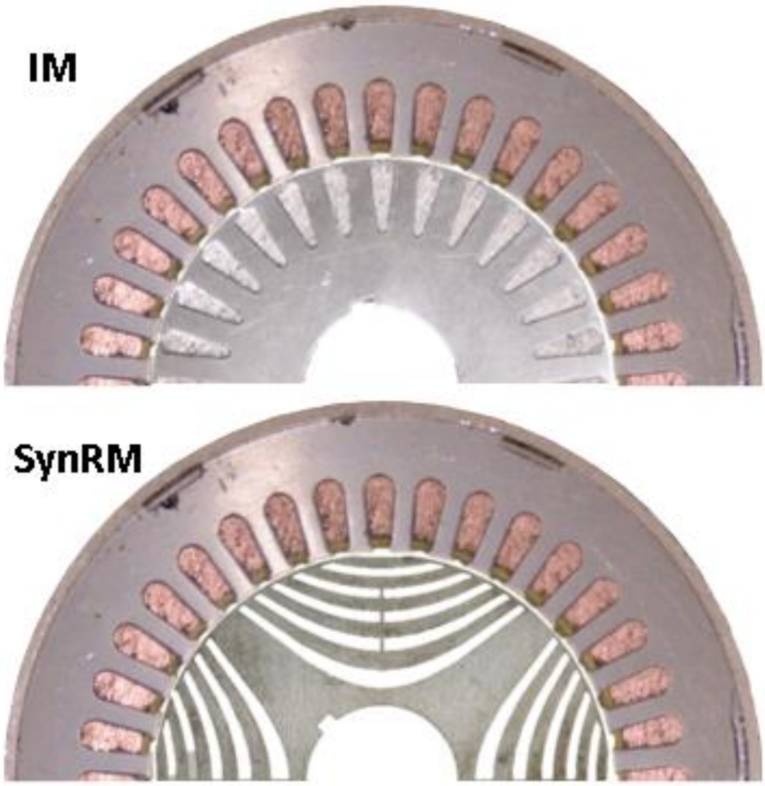


Figure 8 – IM and SynRM Lamination Profiles

2.2 – Permanent Magnet Motor Comparison

Like the SynRM, the PM synchronous machine is synchronous with the stator field and contains no rotor conductors [24]. Hence the rotor loss is much less than the IM (at low speed), however, the machine does typically contain expensive permanent magnets, which are lossy in their own way (eddy current losses in magnet surfaces). There is no doubt that the permanent magnet machine exhibits higher torque density and superior inverter utilization due to its *free flux* from the permanent magnets. However, again, there are apparent advantages of SynRM technology over PM technology which can be said to include [54,55];

- No permanent magnets
    - Significantly lower initial cost
    - Easier assembly and manufacture
    - Higher breakdown torque - No PM demagnetisation risk
    - No material supply chain issues
    - No PM short circuit current (fault condition - drag torque)
- Increased robustness

- Increased starting torque
- Wider optimal speed range – PM motor is efficiency poor at high speed

The advantages of the SynRM derives from the lack of permanent magnets, which bring along with them a whole host of undesirable issues, yet, despite these, The PM machine is still a very popular machine for the following reasons - the SynRM can be expected to have [54,55];

- Lower torque/volume and torque/mass – larger space envelope
- Lower power factor
- Increased inverter requirement
- Lower torque per unit loss (at low speed)
- Lack of availability

There are a number of benefits of removing PM material from AC machines, and much effort is now underway to develop the SynRM, so that they can better compete with the performance of PM based machines. PM machines are not a widely used in industry compared to the induction motor, thus focus must be placed on replacing induction motor drives with SynRM drives for higher efficiency systems designed to comply with current and future legislation and aid the reduction of greenhouse gas emissions.

3. Current and Future Technology Development

This section describes some of the less desirable characteristics of the current SynRM technology in terms of its operation and construction and outlines some current research trends in order to overcome these shortcomings. The section concludes by suggesting future research themes that could be pursued to further improve upon synchronous reluctance technology.

3.1. What about Current Technology?

In the conventional synchronous reluctance motor, such as those commercially available, there are a number of characteristics of the machine that are undesirable, such as;

- Long end windings (high copper loss\mass – wasted active material)
- Low slot fill factor (typically <45% - low torque density + high loss)
- Lower power factor (high converter VA)
- Laborious winding process (increased manufacturing cost)

The majority of the undesirable characteristics can be attributed to the fact that the windings are of the polyphase distributed winding type, where a coil typically spans one rotor pole pitch [24]. This winding is very common in all AC machine types but typically leads to a large amount of copper in the end region (up to around 25% of total coil length) and due to the distributed placement of the coils and the laborious winding procedure it - often requires skilled operators. The achievable slot filling factor (ratio of the total copper area to the actual slot area) is typically no more than 35-40% [25] in a small to medium sized low voltage AC machine. This effectively reduces the stator winding conductor diameter and increases the copper losses in the machine – typically an IE4 efficiency motor will have higher copper losses than some machine topologies that have evolved to reject the use of polyphase distributed windings. The low power factor is due to the high stator magnetising current required [26]. It is therefore desirable for new innovations in synchronous reluctance motors to be investigated to further advance this technology and enhance the competitive edge against both induction and permanent magnet motors.

As a note, the power factor of the machine, if not too low, is inconsequential as a VFD controlled machine is not connected directly to the grid and the grid input to the drive can effectively ‘force’ the grid to ‘see’ a power factor approaching unity. However, if the machines power factor is too low, then the power switching devices may require to be upsized (silicon area) and attention paid to the sizing of the DC link capacitor in the drive. It is beyond the scope of this paper to explore this aspect further.

3.2. Concentrated Winding Synchronous Reluctance Motor

One stream of research in advancing synchronous reluctance motor technology is to migrate from distributed windings on the stator to a fractional slot-concentrated winding [27, 28], which involves winding highly concentrated coils such as those found on the rotor of a salient pole alternator, but applied to the stator of the synchronous reluctance motor. Usually the choice for high torque, low speed modern permanent magnet motors [29, 30], the fractional slot-concentrated winding utilises coils that span a single stator tooth. This winding arrangement (Figure 9) has particular advantages that are highly desirable; however adoption of this type of winding does come with some disadvantages.

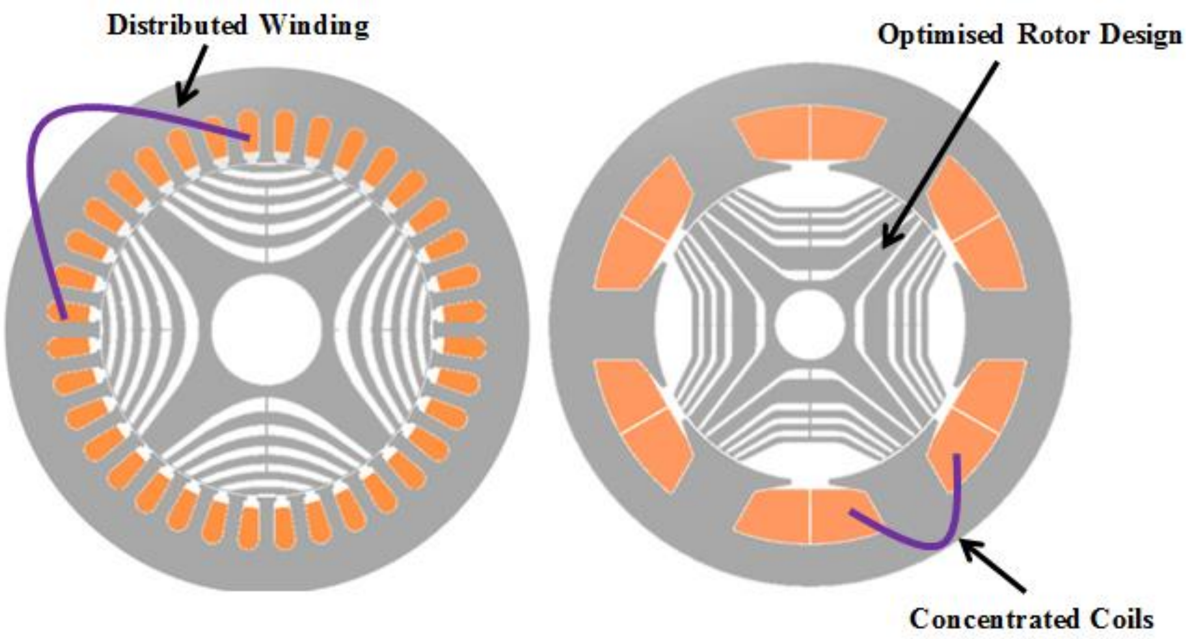


Fig. 9 Comparison of SynRM and cSynRM topologies

When adopting the fraction slot-concentrated winding into synchronous reluctance motor technology, the resultant machine topology is termed the *concentrated winding Synchronous Reluctance Machine* or *cSynRM*. This machine has been shown to exhibit high torque density and higher efficiency for the same frame size compared to both the induction motor and the conventionally wound synchronous reluctance machine [26, 27, 28]. The main benefits of adopting this cSynRM topology of machine are as follows;

- Non-overlapping coils with short end windings
    - Lower copper loss and mass
    - Reduced axial length
- Higher efficiency
- Increased fill factor
- Higher torque/power density
- Stator modularity – segmentation possible
    - Ease of manufacture
    - Improved material utilisation
- Thermal improvements
    - Lower operating temperatures
    - Higher overload capability

At an initial glance, the topology appears to be very desirable, the short end winding due to their short span now contain less copper and do not overlap other phases, aiding electrical isolation and neat coils to be wound – effectively enabling higher slot fill factors, upwards 80% in some cases when *compressed coils* are utilized [31]. However, there are associated drawbacks of selecting this topology. Due to the discrete placement of coils in the slots, this leads to high levels of space harmonic content in the stator MMF and consequentially the air gap magnetic fields [32]. Figure 10 shows the stator MMF harmonics for a 4-pole motor with 6-slot concentrated winding stator and a 36-slot distributed winding stator.

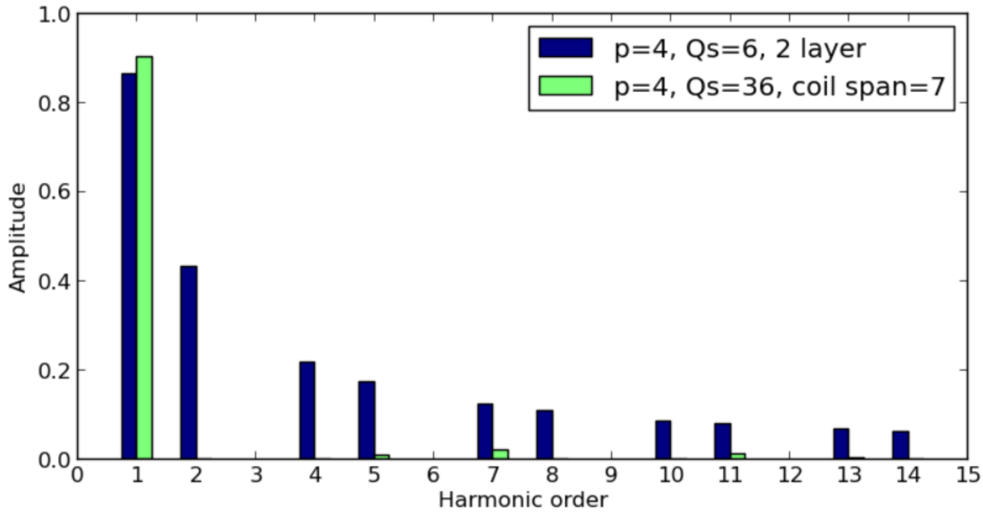


Fig. 10 Harmonic content in the airgap of the cSynRM (FSCW- blue) and the SynRM (Distributed winding - green)

These space harmonics lead to higher levels of torque ripple and a lower power factor. The higher levels of torque ripple are very undesirable and are caused by harmonic perturbations in the Heaviside-Maxwellian stress developed in the air gap, which is ultimately responsible for the electromagnetic torque [32]. The lower power factor can be attributed to the increased harmonic leakage fluxes in the machine's magnetic circuit [26]. Through good electromagnetic design, the torque ripple can be reduced [32, 38, 42] and the power factor improved, though when using direct torque control such as with the ABB marketed SynRM [9], the torque ripple problem can be reduced but the power factor challenge remains. In summary, the main drawbacks of adopting the *cSynRM* topology are [27];

- Increased torque ripple
- Increased acoustic noise and vibration
- Reduced power factor – potentially higher inverter VA rating

With these in mind, further development of the cSyRM to improve the power factor and further improve the torque density/torque ripple is an area of ongoing research. The topology has been shown to allow up to a +3% efficiency increase [26] for the same output than the conventional SynRM and up to 25% increase in torque density can be achieved with a 60% fill factor [27, 28] without the requirement for permanent magnets. The cSynRM tackles some of the conventional SynRM's undesirable characteristics and is a promising prospect, however further development is required to bring this technology to market.

Figure 11 shows the stator and rotor of a 4kW prototype cSynRM motor, 4pole 6 stator slots with a slot fill factor of 60% [28].

Fig. 11 Rotor (left) and Stator (right) of a prototype cSynRM machine

3.3. Permanent-Magnet Assisted Motors

One of the main issues cited in synchronous reluctance motor technology is that of tits lower power factor, compared to the induction machine. This is because the machine requires a larger magnetizing current than an equivalent induction motor. In order to improve the power factor, permanent magnet flux can be introduced into the q-axis, oriented such that the permanent magnet flux effectively albeit *artificially* improves the saliency ratio by countering any *q*-axis flux caused by magnetizing the machine with the stator current. This q-axis flux is reduced, the *q*-axis inductance is therefore artificially reduced, the saliency improved and hence the power factor, torque capability and machine efficiency generally improve as a result [26, 33]. The permanent magnets can simply be placed in the usually empty air slots between the rotor flux guides. An added benefit of this topological addition is to introduce a ‘magnet’ torque, just as a conventional interior permanent magnet or surface permanent magnet machine has the advantage of utilizing. Typically, in this type of machine the polyphase distributed windings remain but permanent magnets are placed in the rotor flux barriers; this topology is usually termed the Permanent Magnet Assisted Synchronous Reluctance Machine (PMA-SynRM) [34,42,45,46,55]. The motor topology is essentially that of the interior permanent magnet motor that utilizes both reluctance torque and permanent magnet interaction torque, the reluctance component being the dominant torque producing mechanism.

A distinction must be drawn between all of the various types of machine which appear to be similar. Their inductance and torque characteristics are important in classifying the following machines: Synchronous

Reluctance (SynRM), Interior Permanent Magnet (IPM), Surface Permanent Magnet (SPM) and the Permanent Magnet Assisted Synchronous Reluctance Motor (PMA-SynRM). Table 2 outlines the key differences.

Machine Type	Inductance Characteristic	Torque Characteristic
SynRM	$L_d >> L_q$	$T_{magnet}=0$
Interior Permanent Magnet (IPM)	$L_d > L_q$	$T_{reluctance} < T_{magnet}$
Surface Permanent Magnet (SPM)	$L_d = L_q$	$T_{reluctance}=0$
PMA-SynRM	$L_d >> L_q$	$T_{reluctance} > T_{magnet}$

Table. 2 Inductance and torque characteristics of various machines

The permanent magnets included in the PMA-SynRM can be either ferrite of 'eare earth' based – the ferrite type offers a lower improvement in power factor and torque density (remnant flux density would typically be <0.5T) and have a much higher risk of demagnetisation (due to their lower coercive force) than the Rare Earth alternative - NdFeB or SmCo remnant flux densities run up to around 1.3T. Typically the ferrite magnets' cost is negligible at around £3/kg whereas NdFeB magnets would offer the best power factor and torque density improvements but the cost would significantly increase to around £75/kg. The use of ferrites results in more economically and ecologically sustainable product, without any supply chain or geo-political issues that are associated with the Rare Earths.

These performance increases act to increase machine efficiency and inverter utilisation, facilitating a reduction in electric drive size [33]. The required inverter VA rating can reduce and therefore the switching device power rating is potentially lowered and reduced in physical size. This also leads to a potential cost reduction of the semiconductor modules, heatsink and the inverter DC-link capacitor – the cost of the magnets is minimal if ferrite type permanent magnets are used.

In summary the main benefits of adopting the PMA-SynRM are *potentially*;

- Increased torque/power density

- Higher efficiency
- Increased torque per unit volume
- Increased power factor
- Lower inverter VA rating
- Drive component cost and size reduction

However, as always there are associated drawbacks which could be considered to be;

- Increased cost and manufacturing difficulty (magnet material and insertion)
- Risk of magnet demagnetisation (especially with ferrite type permanent magnets)
- Magnet losses (at higher speeds)

It can be said that the PMA-SynRM is a good improvement on the conventional synchronous reluctance motor and tackles some of their undesirable characteristics. If optimal designs can use ferrite materials with their low cost, improved power factor and torque density, then this represents a major step forward technologically in competing alternative motor technologies – ABB are again leading the field in this respect and have recently introduced their “SynRM-squared” motor range, essentially a range of permanent magnet assisted synchronous reluctance motors [34]. This package claimed to exceed the IE4 efficiency ratings and would hypothetically fall into an IE5 efficiency range, the technology can, it is claimed, “reduce energy losses by an additional 20%”.

3.4. Future Research and Development

The future of Synchronous Reluctance technology is exciting. Besides industrial adoption in VSD applications, assisting in the reduction of GHG emissions and global energy usage, new and special technology/applications may arise and new research routes be explored. The following list serves as a guide to potential researchers in what may be interesting avenues of investigation to either continue or to expand into;

- Singly and doubly fed synchronous reluctance generators (wind/wave power applications *etc*.)
- Single phase or direct on-line synchronous reluctance motors
- New axially laminated designs (higher saliency, low loss)
- High speed designs (electro-mechanical design challenges)
- PMA-SynRM with single tooth coils
- General power factor, efficiency and torque density improvements through novel design techniques

Of course, this is only a small representative list of technology possibilities. The applications of current and future technology are numerous, electric power generation, land, sea and air propulsion drives, industrial loads, special devices and even linear machines all based on synchronous reluctance machine technology are all possible. It is for the current and next generation of electrical machine research engineers to shape any technology development. Perhaps the invention of new materials or power devices would be of use in developing novel synchronous reluctance machine technology. Advancement of ABB’s technology (SynRM and SynRM-squared) will most likely be focused on the manufacturing of such machines for even higher efficiency, lower manufacturing costs and simpler manufacturing processes for the mass market.

4. Industrial Case Study

4.1. General Energy Savings

With the drive energy savings between the SynRM and induction motor shown in a previous section, it is clear that the key figure of merit here will be energy savings over the lifetime of the product. For arguments sake, if we take the average induction motor used for plant in a typical factory as 30kW and that the average load is 80% of peak load with an energy cost of £0.10/kWh – consider an IE4 Synchronous Reluctance drive replacing a single induction machine drive package and typically operates 330 days per year, 24 hours per day. For the initial induction motor drive, the efficiency of the total drive system is 89.8%, the total annual energy consumption is 264kWh. If this single motor is replaced by an IE4 SynRM drive with efficiency of 93.1% [23], the annual energy consumption is reduced to 254kWh, saving 10kWh per year per motor and £1000 per year per motor. In a large factory with in excess of 100 motors, that savings can be over 1MWh per year, allowing over £100k in energy savings. Whilst these figures are approximate, the expected trend is that the energy saving will only increase as the expected life of a SynRM is longer than that of an induction motor. Other operating costs may also aid savings; reduced maintenance (required maintenance work and also extended intervals) coupled with extended intervals between asset replacement make the SynRM very attractive for factory and plant scenarios, but also to machine builders.

Payback periods for initial asset purchasing can therefore be expected to be reduced if the initial capital cost is the same as or not too inflated against traditional induction motor drive packages that are available.

4.2. Application of ABB's IE4 Synchronous Reluctance Technology

As ABB is now marketing synchronous reluctance motors (SynRM) drive packages, the applications that are applicable would traditionally employ an induction motor (IM) controlled by a variable frequency drive (VFD). In some industries, trialling of the VFD controlled SynRM has begun and an example application and an illustration of some of the benefits that switching from induction to synchronous reluctance technology can bring, a case study of the Somerford Pumping Station ran by South Staffordshire Water Company, UK, is presented as detailed by ABB in [35]. The Somerford station pumps around 2.5 million litres of water daily to serve the local community and the project was to replace an existing 115kW IE2 induction motor and VFD drive system with an IE4, 110 kW SynRM Direct Torque Control (DTC) drive system and observe the benefits to the operator. As the synchronous reluctance motor can be the exact same frame size, it was able to be retrofitted to the borehole pump, in place of the two decades old induction motor.

According to the study [35], the South Staffordshire Water Company spends approximately £9m per annum on electricity, 90% of which is used in pumping the water from the borehole to the customer. By switching to the super-premium efficiency IE4 SynRM, a 6% energy saving was claimed to have been achieved, leading to lower operating costs. If all of the pumping stations ran by South Staffordshire Water Company adopted SynRM technology then an annual saving of over £480,000 is claimed, which could potentially increase if some pumping stations currently using older and IE1 rated induction motors were to be replaced. This must be agreed as a significant saving in operating costs.

The energy and operating cost savings were not the only benefit to be claimed by ABB and the water company, a 58% reduction in frame and 28% reduction in bearing temperatures seem to have been observed [36]. This potentially significantly increases the reliability and lifetime of the motor and reduces maintenance intervals, further lowering associated costs of running the pumping stations. Additionally, the study claims that a 75% audible noise was achieved, leading to a lower background noise environment for local communities, wildlife surrounding the site and also for Water Company officials during inspection and maintenance. Further information can be obtained from ABB [35, 36].

Thus, based on this example, the adoption of synchronous reluctance technology appears to be worthwhile in a number of respects and makes perfect practical sense for applications where variable speed induction motors are currently used and the lifetime energy savings would outweigh any additional installation cost. If an asset is due for replacement it makes both economic and engineering sense to consider SynRM technology over induction motor technology, where appropriate.

5. Conclusion

Based on the qualitative and quantitative arguments presented in this paper, it appears that the Synchronous Reluctance motor has some good advantages over competing motor types, especially when applied in the industrial sector. Energy efficiency and the simplicity of the technology have propelled this technology into the research arena and now manufacturers are producing synchronous reluctance motors for the fan, pump and mill type industrial applications. Considerable energy savings and operational benefits of the SynRM are clear when compared to the induction motor – the case for adopting the SynRM in industry for those common industrial loads has been presented. This case has been reinforced by industrial case studies. Whilst this technology is slowly being accepted, there is continuing research that aims to tackle some of the perceived disadvantages of this machine and research & development is opening up new topologies. The number of potential avenues for future research is wide, both in terms of technology and specialist/niche applications – a few have been suggested for further development. This paper has presented an introduction to the technology for students, non-specialist academics and engineers who are interested and it is suggested that the reader undertake further study to understand the technology completely. In terms of the global challenges of energy efficiency, reduction of greenhouse gas emissions and reducing dependence on rare earth permanent magnets, the SynRM has been presented as a viable alternative.

6. Acknowledgments

The author would kindly like to acknowledge ABB in relation to publishing key efficiency data for the IE4 SynRM packages & existing induction machine technologies that has been used in this paper. Their results from the Somerford water pumping station study must also be acknowledged, which have been referenced in this paper as a good demonstration of the benefits of SynRM adoption.

7. Key Journal Publications

The following authors have published key journal papers that will serve as important reading relating to the design, application and technology development of synchronous reluctance machines. These are highly important works and should be considered in any serious study of this machine; Kostko [10]; Lipo [21]; Vagati, *et al* [37-41]; Bianchi, *et al* [42-45]; Morimoto, *et al* [46,47]; Honsinger, *et al* [14,48]; Miller, *et al* [49-52]; Spargo, *et al* [27,28,32]. This list is by no means comprehensive, but serves as a useful bibliography as an extension to the introduction to the subject.

8. Further Reading

The aim of this paper is to provide a 'first introduction' to synchronous reluctance motor technology, there are many good existing works that analyse the SynRM in great detail - this paper does not intend to rival those. The following books/chapters will serve as good further reading on Synchronous Reluctance Motor Technology.

1. I. Boldea, "Reluctance Synchronous Machines and Drives", Oxford University Press, 2002
2. R. Betz, Chapter 8: Modelling and Control of Synchronous Reluctance Motors, in "Control in Power Electronics: Selected Problems", Academic Press, 2002
3. E. G. Janardanan, "Special Electrical Machines", Chapter 5: Synchronous Reluctance Machines (SynRM), Prentice-Hall of India Pvt.Ltd, 2014

4. J. Pyrhronen, “Design of Rotating Electrical Machines”, Chapter 7.2.11: Synchronous Reluctance Motors, Wiley, 2008
5. Pellegrino, G., “The Rediscovery of Synchronous Reluctance and Ferrite Permanent Magnet Motors, Springer, 2016

9. References

[1] “*Reluctant Heroes*”, The Economist, http://www.economist.com/news/science-and-technology/21566613-electric-motor-does-not-need-expensive-rare-earth-magnets-reluctant-heroes: Accessed: 01/03/16

[2] A. T. de Almeida, F. J. T. E. Ferreira and A. Quintino Duarte, "Technical and Economical Considerations on Super High-Efficiency Three-Phase Motors," in *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 1274-1285, March-April 2014

[3] IEC 60034-30-1 - Rotating electrical machines - Part 30-1: *Efficiency classes of line operated AC motors*, International Electrotechnical Commission, 2014

[4] *Energy Efficiency Directive*, EU Directive 2012/27/EU, 2012

[5] “*Energy Efficiency Strategy: 2013 update”*, Department of Energy and Climate Change, UK Government, 2013

[6] “*Rare earth mining in China: the bleak social and environmental costs*”, Guardian Newspaper Online, http://www.theguardian.com/sustainable-business/rare-earth-mining-china-social-environmental-costs Accessed: 01/03/15

[7] Waide,P. and C. Brunner (2011), "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems", *IEA Energy Papers*, No. 2011/07, OECD Publishing, Paris.

[8] European Commission Regulation (EC) No 640

[9] *DTC - A motor control technique for all seasons,* ABB White Paper, https://library.e.abb.com/public/0e07ab6a2de30809c1257e2d0042db5e/ABB_WhitePaper_DTC_A4_20150414.pdf Accessed: 02/03/15

[10] Kostko, “Polyphase Reaction Synchronous Motor”, Journal of AIEE, vol 42, 1923, pp. 1162-1168

[11] J. Reid, 'Robert Davidson – Pioneer Electrician', The Scientific Tourist: Aberdeen, Aberdeen University

[12] Lawrenson, P.J.; Agu, L.A., "Theory and performance of polyphase reluctance machines," Electrical Engineers, Proceedings of the Institution of , vol.111, no.8, pp.1435,1445, August 1964

[13] Cruickshank A.J.O. et al: "Theory and performance of reluctance motors with axially laminated anisotropic rotors", Proc. IEE, vol 118, no. 7., 1971

[14] Honsinger V.B.: "The inductances Ld and Lq of reluctance machines", IEEE Trans. PAS, vol 90, no. 1., 1971

[15] Miller, T. J E; Cossar, C.; Hutton, A.J., "Design of a synchronous reluctance motor drive," Industry Applications Society Annual Meeting, 1989., Conference Record of the 1989 IEEE , vol., no., pp.122,127 vol.1, 1-5 Oct. 1989

[16] Staton, D.A.; Soong, W.L.; Miller, T. J E, "Unified theory of torque production in switched reluctance and synchronous reluctance motors," Industry Applications, IEEE Transactions on , vol.31, no.2, pp.329,337, Mar/Apr 1995

[17] I. Boldea, “Reluctance Synchronous Machines and Drives”, Oxford University Press, 2002

[18] T. J. E. Miller, "Optimal design of switched reluctance motors," in IEEE Transactions on Industrial Electronics, vol. 49, no. 1, pp. 15-27, Feb 2002.

[19] T. J. E. Miller, "Switched Reluctance Machines and Their Control", Magna Physics Publishing, 1993

[20] J. D. Widmer, B. C. Mecrow, C. M. Spargo, R. Martin and T. Celik, "Use of a 3 phase full bridge converter to drive a 6 phase switched reluctance machine," *Power Electronics, Machines and Drives (PEMD 2012), 6th IET International Conference on*, Bristol, 2012, pp. 1-6.

[21] Lipo T.A.: " Synchronous reluctance machines – a viable alternative for AC drives ," Electr Mach Power Syst, vol. 19, pp. 659-671, 1991

[22] “Synchronous reluctance motor-drive packages”, ABB, http://new.abb.com/motors-generators/iec-low-voltage-motors/frequency-controlled-motors/synchronous-reluctance-motor-drive-packages Accessed: 01/03/16

[23] ABB 'Synchronous reluctance motor-drive package for machine builders: High performance for ultimate machine design', 2014, https://library.e.abb.com/public/9864acc1853bb0b4c1257de4002e153c/EN_SynRM_Brochure_3AUA00000120962_RevE.pdf Accessed: 01/03/16
[24] J. Pyrhronen, "Design of Rotating Electrical Machines", Wiley, 2008
[25] D. Staton, A. Boglietti and A. Cavagnino, "Solving the More Difficult Aspects of Electric Motor Thermal Analysis in Small and Medium Size Industrial Induction Motors," in IEEE Transactions on Energy Conversion, vol. 20, no. 3, pp. 620-628, Sept. 2005.
[26] C. M. Spargo, B. C. Mecrow and J. D. Widmer, "Higher pole number synchronous reluctance machines with fractional slot concentrated windings," Power Electronics, Machines and Drives (PEMD 2014), 7th IET International Conference on, Manchester, 2014, pp. 1-6.
[27] C. M. Spargo, B. C. Mecrow, J. D. Widmer and C. Morton, "Application of Fractional-Slot Concentrated Windings to Synchronous Reluctance Motors," in IEEE Transactions on Industry Applications, vol. 51, no. 2, pp. 1446-1455, March-April 2015
[28] C. M. Spargo, B. C. Mecrow, J. D. Widmer, C. Morton and N. J. Baker, "Design and Validation of a Synchronous Reluctance Motor With Single Tooth Windings," in IEEE Transactions on Energy Conversion, vol. 30, no. 2, pp. 795-805, June 2015
[29] A. El-Refaie, "Fractional-Slot Concentrated-Windings Synchronous Permanent Magnet Machines: Opportunities and Challenges," in IEEE Transactions on Industrial Electronics, vol. 57, no. 1, pp. 107-121, Jan. 2010
[30] A. El-Refaie, "Fractional-slot concentrated-windings: A paradigm shift in electrical machines," Electrical Machines Design Control and Diagnosis (WEMDCD), 2013 IEEE Workshop on, Paris, 2013, pp. 24-32
[31] J. D. Widmer, C. M. Spargo, G. J. Atkinson and B. C. Mecrow, "Solar Plane Propulsion Motors With Pre-compressed Aluminum Stator Windings," in IEEE Transactions on Energy Conversion, vol. 29, no. 3, pp. 681-688, Sept. 2014
[32] C. M. Spargo, B. C. Mecrow and J. D. Widmer, "A Seminumerical Finite-Element Postprocessing Torque Ripple Analysis Technique for Synchronous Electric Machines Utilizing the Air-Gap Maxwell Stress Tensor," in IEEE Transactions on Magnetics, vol. 50, no. 5, pp. 1-9, May 2014
[33] R. Vartanian, H. A. Toliyat, B. Akin and R. Poley, "Power factor improvement of synchronous reluctance motors (SynRM) using permanent magnets for drive size reduction," Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE, Orlando, FL, 2012, pp. 628-633
[34] "ABB's new SynRM² motor technology will deliver IE5 efficiency without rare earth magnets", ABB, 2014 http://www.abb.co.uk/cawp/seitp202/ad26393b09a61275c1257caf00217a16.aspx Accessed: 01/03/16
[35] 'World's first IE4 SynRM from ABB' South Staffs Water UK, 2012 https://library.e.abb.com/public/6b51ab52ab74e71dc1257abe00641a6c/South%20Staffs%20Water%20SynRM%20Nov22_2012_EN.pdf Accessed: 01/03/16
[36] "Energy savings at UK's South Staffs Water", ABB, 2013, http://www.abb.com/cawp/seitp202/1649894f9af951e6c1257b390057195d.aspx Accessed: 01/03/16
[37] A. Vagati, G. Franceschini, I. Marongiu and G. P. Troglia, "Design criteria of high performance synchronous reluctance motors," Industry Applications Society Annual Meeting, 1992., Conference Record of the 1992 IEEE, Houston, TX, 1992, pp. 66-73
[38] A. Vagati, M. Pastorelli, G. Francheschini and S. C. Petrache, "Design of low-torque-ripple synchronous reluctance motors," in IEEE Transactions on Industry Applications, vol. 34, no. 4, pp. 758-765, Jul/Aug 1998.
[39] A. Vagati, M. Pastorelli and G. Franceschini, "High-performance control of synchronous reluctance motors," in IEEE Transactions on Industry Applications, vol. 33, no. 4, pp. 983-991, Jul/Aug 1997.
[40] A. Vagati, A. Fratta, G. Franceschini and P. Rosso, "AC motors for high-performance drives: a design-based comparison," in IEEE Transactions on Industry Applications, vol. 32, no. 5, pp. 1211-1219, Sep/Oct 1996.
[41] A. Vagati, A. Canova, M. Chiampi, M. Pastorelli and M. Repetto, "Design refinement of synchronous reluctance motors through finite-element analysis," in IEEE Transactions on Industry Applications, vol. 36, no. 4, pp. 1094-1102, Jul/Aug 2000.

[42] N. Bianchi, S. Bolognani, D. Bon and M. Dai Pre, "Rotor Flux-Barrier Design for Torque Ripple Reduction in Synchronous Reluctance and PM-Assisted Synchronous Reluctance Motors," in IEEE Transactions on Industry Applications, vol. 45, no. 3, pp. 921-928, May-june 2009.

[43] N. Bianchi, S. Bolognani, D. Bon and M. Dai PrÉ, "Torque Harmonic Compensation in a Synchronous Reluctance Motor," in IEEE Transactions on Energy Conversion, vol. 23, no. 2, pp. 466-473, June 2008.

[44] M. Barcaro and N. Bianchi, "Air-Gap Flux Density Distortion and Iron Losses in Anisotropic Synchronous Motors," in IEEE Transactions on Magnetics, vol. 46, no. 1, pp. 121-126, Jan. 2010.

[45] M. Ferrari, N. Bianchi, A. Doria and E. Fornasiero, "Design of Synchronous Reluctance Motor for Hybrid Electric Vehicles," in IEEE Transactions on Industry Applications, vol. 51, no. 4, pp. 3030-3040, July-Aug. 2015.

[46] S. Morimoto, M. Sanada and Y. Takeda, "Performance of PM-assisted synchronous reluctance motor for high-efficiency and wide constant-power operation," in IEEE Transactions on Industry Applications, vol. 37, no. 5, pp. 1234-1240, Sep/Oct 2001.

[47] M. Sanada, K. Hiramoto, S. Morimoto and Y. Takeda, "Torque ripple improvement for synchronous reluctance motor using an asymmetric flux barrier arrangement," in IEEE Transactions on Industry Applications, vol. 40, no. 4, pp. 1076-1082, July-Aug. 2004.

[48] V. B. Honsinger, "Steady-State Performance of Reluctance Machines," in IEEE Transactions on Power Apparatus and Systems, vol. PAS-90, no. 1, pp. 305-317, Jan. 1971.

[49] D. A. Staton, T. J. E. Miller and S. E. Wood, "Maximising the saliency ratio of the synchronous reluctance motor," in IEE Proceedings B - Electric Power Applications, vol. 140, no. 4, pp. 249-259, July 1993.

[50] T. J. E. Miller, A. Hutton, C. Cossar and D. A. Staton, "Design of a synchronous reluctance motor drive," in IEEE Transactions on Industry Applications, vol. 27, no. 4, pp. 741-749, Jul/Aug 1991.

[51] D. A. Staton, W. L. Soong and T. J. E. Miller, "Unified theory of torque production in switched reluctance and synchronous reluctance motors," in IEEE Transactions on Industry Applications, vol. 31, no. 2, pp. 329-337, Mar/Apr 1995.

[52] R. E. Betz, R. Lagerquist, M. Jovanovic, T. J. E. Miller and R. H. Middleton, "Control of synchronous reluctance machines," in IEEE Transactions on Industry Applications, vol. 29, no. 6, pp. 1110-1122, Nov/Dec 1993.

[53] A. Boglietti and M. Pastorelli, "Induction and synchronous reluctance motors comparison," Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE, Orlando, FL, 2008, pp. 2041-2044.

[54] H. Murakami, Y. Honda, H. Kiriyama, S. Morimoto and Y. Takeda, "The performance comparison of SPMSM, IPMSM and SynRM in use as air-conditioning compressor," Industry Applications Conference, 1999. Thirty-Fourth IAS Annual Meeting. Conference Record of the 1999 IEEE, Phoenix, AZ, 1999, pp. 840-845 vol.2.

[55] Y. Guan, Z. Q. Zhu, I. A. A. Afinowi, J. C. Mipo and P. Farah, "Design of synchronous reluctance and permanent magnet synchronous reluctance machines for electric vehicle application," Electrical Machines and Systems (ICEMS), 2014 17th International Conference on, Hangzhou, 2014, pp. 1853-1859.