Synchronous Reluctance Technology – Part II

Christopher M. Spargo, Power Electronics, Drives and Machines Research Group, School of Electrical and Electronic Engineering, Newcastle University, UK

I. INTRODUCTION

This is the follow-up article to *Synchronous Reluctance Technology Part I*. The first part introduced and compared synchronous reluctance technology with induction and permanent magnet motor technologies; this article aims to inform the reader of recent developments and applications of synchronous reluctance technology in heavy industry and other markets, such as the automotive traction sector. Consideration of complications with advancements in technology such as inclusion of non-rare-earth permanent magnets and use of fractional slot concentrated windings are presented. Current in-the-field applications are also brought to the reader's attention.

I. INDUSTRIAL CASE STUDY

As mentioned in Synchronous Reluctance Technology: Part I (MagNews , Winter 14'), ABB is now marketing synchronous reluctance motors (SynRM) for common industrial loads such as fan, pump and mill type applications. Typically these would be driven by an induction motor (IM) controlled by a variable frequency drive (VFD). In some industries, migration to the VFD controlled SynRM is underway. As an example application and as 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 [1]. The Somerford station pumps 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 (Fig. 1).

Fig 1. 110kW SynRM at Somerford Pumping Station [2]

As the synchronous reluctance motor was the same frame size, it was able to be retrofitted to the borehole pump in place of the 20 year old induction motor.

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 has been achieved leading to lower operating costs. If all pumping stations adopted SynRM technology then an annual saving of over £480,000 would result, which could potentially increase if some pumping stations currently using older and IE1 rated induction motors were to be replaced. Besides the energy and operating cost savings, a 58% reduction in frame and 28% reduction in bearing temperatures were observed. This significantly increases the reliability and lifetime of the motor and reduces maintenance intervals, further lowering costs. There was also a 75 percent audible noise reduction, leading to a more pleasant environment for local communities, for wildlife surrounding the site and also for Water Company officials during inspection and maintenance.

Thus, 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 override the installation cost. Currently there are no marketed alternatives for direct on-line (DOL) applications, but this could be a reality in the future with advancements in design and manufacturing.

II. UNDESIRABLE CHARACTERISTICS

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 [3];

1) Long end windings (high copper loss)
2) Low fill factor (low torque density)
3) Low power factor (high converter VA)
4) Laborious winding process (increased cost)

The majority of the undesirable characteristics come from the fact that the windings are of the polyphase distributed winding type (Fig. 2) where a coil typically spans one rotor pole pitch –

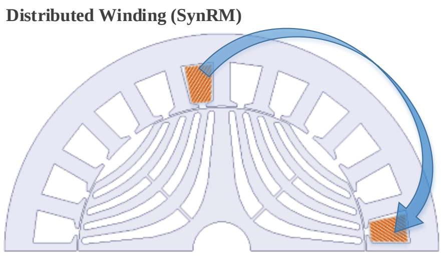

Fig 2. Coil span of a polyphase distributed winding SynRM

This winding is very common but leads to a wasteful expanse of copper in the end region and due to the placement of the coils and the winding procedure it often requires skilled operators to wind, where the achievable fill factor is typically no more than 35-40%. This effectively reduces the conductor diameter and increases the copper losses in the machine – even an IE4 efficiency motor has 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 magnetising force required to develop the reluctance torque. It is therefore desirable for new innovations in synchronous reluctance technology, in order to further advance this technology to compete with permanent magnet motors and propel them into the mass market.

III. The Permanent-Magnet-Assisted Synchronous Reluctance Machine

Firstly, in order to improve the power factor and torque density of the synchronous reluctance motor, the inclusion of permanent magnets has become popular (Fig. 3). 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).

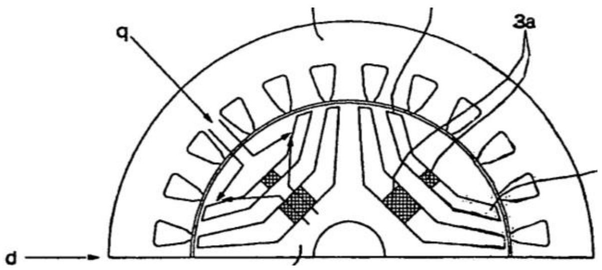

Fig 5. A 4-pole PMA-SynRM, clearly showing magnets in the flux barriers (3) [4].

The motor topology is essentially that of the interior permanent magnet motor but includes both reluctance torque and permanent magnet interaction torque. In order to distinguish between motor types, Table I allows identification of the machine types through their inductance and torque characteristics.

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 I – Difference in machine characteristics

The permanent magnets included in the PMA-SynRM can be either *ferrite* of *Rare Earth* based – the ferrite type offers a lower improvement in power factor and torque density (remnant flux density <0.5T) and has a much higher risk of demagnetisation (due to their lower coercive force) than the Rare Earth alternative (NdFeB or SmCo, remnant flux density upto around 1.3T) but has a major advantage in cost per kilogramme of material. 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 (March 2014).

With the inclusion of permanent magnets, the power factor of machines can increase from around 0.5 to 0.7-0.8 with ferrite and can be in excess of 0.9 with NdFeB materials. The torque density can be improved by approximately 45% using ferrite materials and by an astonishing 100% by using NdFeB. These performance increases act to increase machine efficiency and inverter utilisation. As well as machine advantages to using this topology, the inclusion of permanent magnets also facilitates a reduction in drive size [5]. The required inverter VA rating is reduced and therefore the switching device power rating is potentially lowered and reduced in size. This also leads to a cost reduction of the semiconductor modules, heat sink and the inverter DC-link capacitor – the cost of the magnets is minimal if ferrites are used.

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

- 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, some potential drawbacks are;

- Increased cost and manufacturing difficulty
- Risk of magnet demagnetisation (especially with ferrites)
- Magnet losses (at higher speeds)

The PMA-SynRM is a significant improvement for the synchronous reluctance motor and tackles *Undesirable Characteristics* 2 and 3, from Section II (though not through increased fill factor) - 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 with pure permanent magnet motor technology.

Another research stream in this area is the control of the machine, whereby the current angle is changed to maximise the power factor further and minimise demagnetisation of the ferrite whilst maintaining the torque density of a conventional synchronous reluctance motor – providing a major gain over the induction motor and that of the IE4 SynRM. This is currently a strong research field for the traction motor market, in particular the automotive sector where high torque density, rare-earth-less motors with a wide speed range are desired.

IV. The Fractional Slot Concentrated Winding Synchronous Reluctance Machine

One stream of research in the Power Electronics, Machine and Drives Research Group at the School of Electrical and Electronic Engineering, Newcastle University, is to migrate from distributed windings to a fractional slot concentrated winding (FSCW). Usually the choice for high torque, low speed modern permanent magnet motors [6], the fractional slot concentrated winding utilises coils that span only one tooth (Fig. 4), significantly reducing the ending winding length and losses as well as allowing a greater fill factor (up to 80%) through stator segmentation. The resultant machine topology is termed the concentrated winding Synchronous Reluctance Machine (cSynRM).

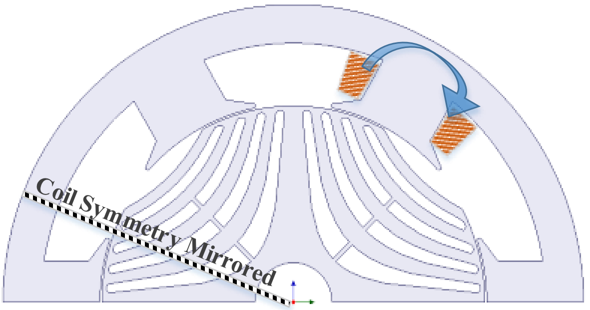

Fig 4. The proposed cSynRM with single tooth coils.

The main benefits of adopting this 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
    - Lower current density
    - Higher torque/power density
- Stator modularity
    - Ease of manufacture
    - Improved material utilisation
- Thermal improvements
    - Lower operating temperatures
    - Higher overload capability

At initial glance, the topology appears to be very desirable. 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 (Fig. 5) in the MMF and airgap magnetic fields.

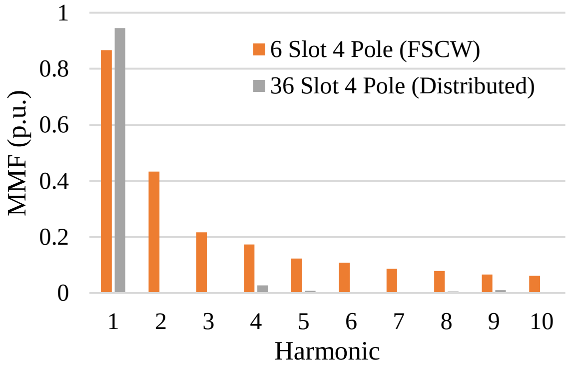

Fig. 5 Harmonic content in the airgap of the cSynRM (FSCW) and the SynRM (Distributed).

These space harmonics lead to high levels of torque ripple and a low power factor. The high levels of torque ripple are very undesirable and are caused by harmonic perturbations in the Maxwellian stress, responsible for the electromagnetic torque [3], whereas the lower power factor is attributed to the increased harmonic fluxes in the machine's magnetic circuit. Through good electromagnetic design, the torque ripple can be reduced [7] and the power factor improved, though when using direct torque control such as with the ABB marketed SynRM, the torque ripple problem can be essentially eliminated and only the power factor challenge remains.

In summary, the main drawbacks of adopting the cSynRM topology are;

- Increased torque ripple
    - Acoustic noise and vibration
    - Unsuitable for some loads
- Reduced power factor
    - Higher inverter VA rating
    - Drive component cost and size increase

With this in mind, further development for the cSynRM idea to improve the power factor and further improve the torque density is an area of ongoing research. The topology has been shown to allow up to a +3% efficiency increase for the same output than the conventional SynRM and up to 25% increase in torque density can be achieved with a 60% fill factor, without the requirement for permanent magnets. The cSynRM tackles *Undesirable Characteristics* 1, 2 and 4 from Section II and is a promising prospect, however further development is required to bring this technology to market.

V. Possible Further Advancements in Synchronous Reluctance Technology

There are a number of ways that synchronous reluctance machines could potentially be improved. This section briefly surveys some avenues of investigation.

A. Synthesis of the PMA-cSYnRM

A very recent and interesting research stream is synthesising the cSynRM and PMA-SynRM topologies [8]. Fractional slot concentrated windings (single tooth coils) are used on the stator, gaining the benefits of that particular topology but then incorporating the benefits of the PMA-SynRM topology – synthesising a new machine that exhibits a truly superior performance. The resulting machine is expected to have a higher torque and power density coupled with high efficiency and a high power factor – though one must be careful to design the machine with minimal permanent magnet material such that the machine is not classed as an interior permanent magnet motor. Migration to fractional slot concentrated windings with higher pole numbers, which may be desirable in such a topology, presents its own challenges such as an increased airgap leakage factor. Research in this area is ongoing and it is expected that this topology will become the most desired option.

B. Caged Rotor SynRM

With the introduction of VFD synchronous reluctance motors into the mass market, the variable speed application (fan/pump/mill) types of industry processes are covered by this advent. However, a large proportion of the industry demand for motors (which is primarily induction motors) are of the single phase direct on-line type of motor. Recent research has refocused on the Caged-Synchronous Reluctance Motor [9]. Such motors start as an induction motor and lock into synchronism once near to the rated speed – a good starting characteristic is required, demanding a high starting current, but when the rotor locks into synchronism the rotor current is effectively zero and therefore is 'cold rotor' under synchronous operation. Optimisation of such machines, for starting and good synchronous performance, is key and will no doubt become increasingly desirable as energy and efficiency legislation becomes tighter.

C. Radical Rethinks

In electrical machine design, often progress in advancing the machine in question is due to small changes in topology. As a field that has been in existence for over 150 years, it is often said that 'it has all been done before'. In order to design the machines of the future to meet efficiency, torque and power density coupled with high recyclability, radical new designs should be considered. The engineers of today and tomorrow will strive to continue to produce ever-innovative machine designs with ever-innovative electric drives attached, however only relatively small gains in performance can be realistically achieved. It was Nikola Tesla who said '*Ere many generations pass, our machinery will be driven by a power obtainable at any point of the universe.*'[10], thus we must look to new means and methods for true advancement.

VI. Summary

The synchronous reluctance motor is now a viable alternative for industrial applications. Significant energy savings and lower maintenance can be readily achieved through adoption of this technology as demonstrated by the Somerfield pumping station. Though synchronous reluctance technology has the potential to revolutionise, there are some undesirable characteristics such as a lower torque density and power factor compared with permanent magnet motors. Two methods of improving the situation have been explored. The PMA-SynRM uses permanent magnets to increase torque density and power factor and excellent improvements can be made, however the inclusion of permanent magnets increases cost and manufacturing complexity. The cSynRM utilises single tooth windings (fractional slot concentrated windings) in order to improve the torque density without permanent magnets, however the power factor is adversely affected. Synthesis of these two topologies is a recent and exciting research stream where benefits of both are moulded into a machine exhibiting superior performance. Development of direct on-line machines for single phase applications is also a research topic focused on supplying industry with the next generation of high efficiency motors.

Synchronous reluctance technology is gaining momentum and continued investment and development will see increased take-up in industry as well as in niche applications such as automotive traction.

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