Electrical Machine Topologies and the Methods to Reduce Torque

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Abstract

This review paper provides a brief discussion into modulated pole machines and topologies such as single sided, double sided and multiphase modulated pole machines, ultimately leading towards material hybrid designs as these are of interest these days. It was shown that early modulated pole machines such as the one designed by Mordey mainly consist of solid laminated steel while the field was provided by a coil carrying current. However, the renewed research and availability of strong permanent magnets have reintroduced the modulated pole machines concept, especially in applications where high torque density is required. On the other hand, material hybrid machines use a combination of high permeability laminated steel and soft magnetic composite to make use of two kinds of field; one that travels in the plane and other that harness three-dimensional nature. The problem of cogging torque was highlighted and reducing this is the main aim of many design projects these days. Various techniques are presented in this paper that helps to reduce the cogging effect, however most of them either alter the machine parameters, give rise to complex manufacturing or decrease the useful torque. These ultimately either increase the cost of the machine or reduce the performance. Techniques such as rotor and stator pole shaping or using a variation/combination of tooth span was seen to be most effective method of reducing cogging torque, torque ripple and back EMF harmonics.

Introduction

Electrical machines can be thought of as a conversion device from electrical energy to kinetic energy; a two-way mutual link is formed by the magnetic field. The energy is temporary stored in the magnetic field before being converted. It is important to note that apart from the flow of current, the reaction in the electrical system is inductions of an EMF while the product of this and current gives the rate of electrical energy conversion.

The key to unified machine theory is the principle of increasing the stored magnetic energy. In order to increase the flux and the stored energy, a force of attraction will act to bring the poles together to minimise the reluctance of the air gap in the magnetic circuit.

Magnetic systems try to optimise the stored energy by distorting the magnetic core either by closing air gaps or by aligning poles. The former is associated with forces of attraction and the latter with forces of alignment. Rotating machines are based on the force of alignment principle.

When the poles are not situated opposite one another, there is a lateral force of alignment to attract poles towards each other, or align laterally to achieve greater stored magnetic energy i.e. when the poles are in contact with the maximum area of contact. This lateral movement of poles increases the area of air gap, hence reducing the reluctance. It should however be noted that this force does not necessarily act in the direction of the lines of flux.

In 1890 [1], W.M. Mordey suggested a design which consisted of a hoop coil surrounded by numerous U and I shaped laminated iron cores with a wound field rotor. A machine where a ring coil creates a two pole field and guides this by an iron structure into a multi-pole arrangement is known as Modulated Pole Machine (MPM) [2]. The coil at this multi-pole arrangement links together the flux from individual poles creating a multiplex of poles and hence the MMF of the coil can be seen across every pole. This concept allows increasing the specific torque by increasing the magnetising field strength which is achieved by increasing the pole number without actually changing the volume or speed of the machine [3-6].

Two forms of MPMs are Transverse Flux (TF) and Claw Pole (CP) machines which have been around since the late 19th century. TF machines were first put forward by Weh in his two papers [1,7] in the 1980s in which he explains that the flux 'transverses' the direction of the rotor for a part of the magnetic circuit. TF and CP machines have flux paths that are 3D and hence their construction using 2D laminations is difficult. However due to the recent emergence of soft magnetic composites, research is being carried out in this area and new topologies have come into existence.

MPMs ability to provide high torque density (for direct drive systems), low current density yet high electrical loading [8] by merely having a high pole number makes it a very useful machine. These can offer as high as five times the torque density of conventional radial machine geometries [7] as the magnetic and electrical circuits are effectively decoupled. This is due to the availability of adjusting the coil slot and iron in the teeth independently as they do not share the same plane; hence changing the pole number has no effect on the area available for the winding. This is opposite to radial machines where the area of the slot is decreased as the iron and coil share the same plane and hence the available space for iron decreases, reducing the magnetic loading.

Having a high pole number presents problems like complex and complicated construction while large amount of stray and fringing fluxes in the stator produces poor power factor. Moreover, high cogging torque and subsequently a high torque ripple presents another common disadvantage in such machines. These problems are addressed in this thesis and solutions are provided to reduce the effect of these.

MPMs have been used to manufacture propulsion systems for buses [9,10] ships [11], railways [7], wind turbine generators [4-7] and wave energy converters [12-15]. This literature review will provide an overview of the linear and rotating machine designs as well as the history and development of MPMs. Moreover, a detailed review is presented of the Soft Magnetic Composite and its production, properties and use in manufacturing of machines such as MPMs.

First generation of Electrical Machines

The growing interest in electrical machines, power and its distribution led to various inventions and many patents being filed in the late 19th century and early 20th century. One of the early patents granted to W. M. Mordey in 1890 for an electric generator can be classified as the backbone of today's transverse flux machine as it had the same constructional and operational conceptual properties [1].

Figure (2.1) (left) shows the inner rotor design as proposed by Mordey, composed of a simple ring coil enclosed by I and K components spread out circumferentially around the machine. In order to reduce the eddy current losses, the iron segments are designed to provide a flux path that has similar reluctance whether the rotor aligns with I or K component; change in flux in the rotor is reduced hence the magnetic circuit should appear to be the same [1].

The pole number of the machine is quantified by the number of teeth on the rotor and is equivalent to the number of iron segments. This meant that an increase in the number of sections led to an increased number of electrical cycles for a coil in one full rotation of the rotor.

There are many other rotor topologies offered too and one such design is presented in Figure (2.1) (right). It can be seen from

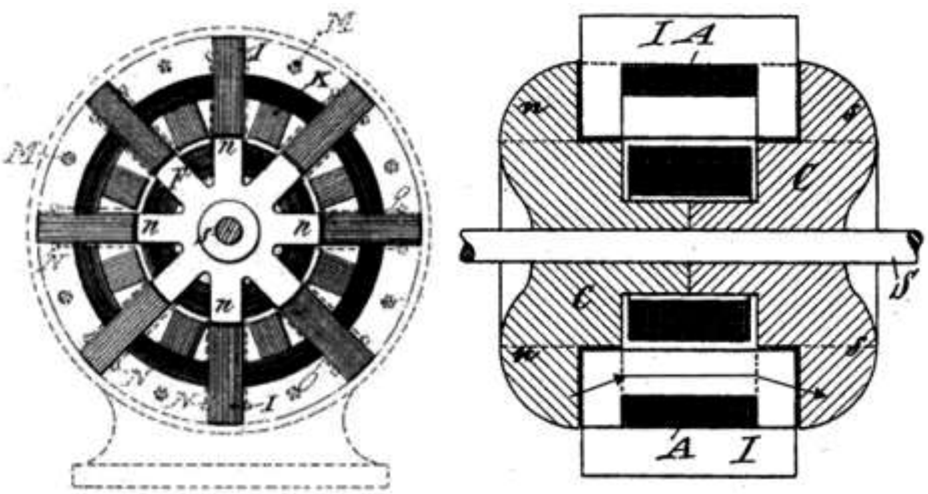


Figure 2.1: Mordey's electric generator (left) in 1890 and another rotor topology (right) [1]

this that there is an iron core, C which is referred to as a 'magnet', mounted on a shaft S and wound with a field coil to create the field distribution shown. Upon inspecting the design in Figure (2.1) (left), the flux path can be seen to start from the top 'north' pole making its way into the U core piece, along the core-back, down the other side of the U core into the bottom 'south' pole of the rotor and returning back to the 'north' pole through the rotor iron.

Rotor parts labelled K in (Figure 2.1) are referred to as 'magnetic short circuiting pieces' as these does not link the coil as they are aligned with an inner U core, therefore not contributing to the output. This concept is quite common in modern machines as these are merely added to avoid stray fields that may occur in the parts of rotor that are not used to link the coil.

Other patents that use flux paths similar to MPMs include Nicola Tesla's high frequency generator in 1891 [15], Ernest Alexanderson's 100 kHz alternator in 1911 [16] and Robert Lundell's claw-pole alternator in 1960 [17]. Tesla's generator, shown in Figure (2.2), consists of an iron 'C' core labelled 'N', contains a homopolar winding labelled 'I' while the triangular surface within the air gap produces an assembly of poles. An alternating voltage is induced when the rotating winding is wound (as shown in Figure (2.2) right) and placed between the triangular air gap of the stator.

A few years later, Ernest F.W. Alexanderson built a 100 kHz alternator [16] for radio communications, shown in Figure (2.3). The concept of this machine is similar to the double sided machine (which will be described later in this chapter) and William Stanley's 1887 invention of producing fluctuating magnetic field [17,19].

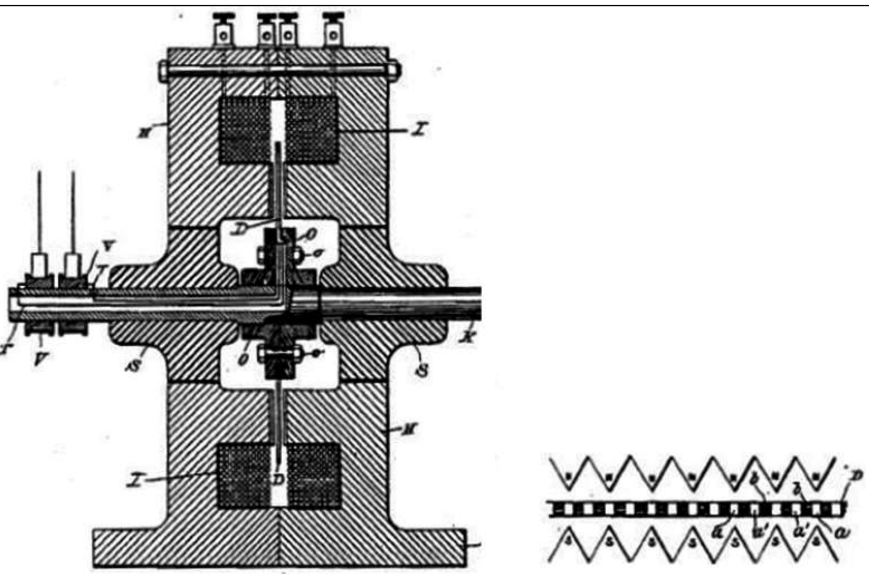


Figure 2.2: Diagram of Tesla's high frequency generator [18]

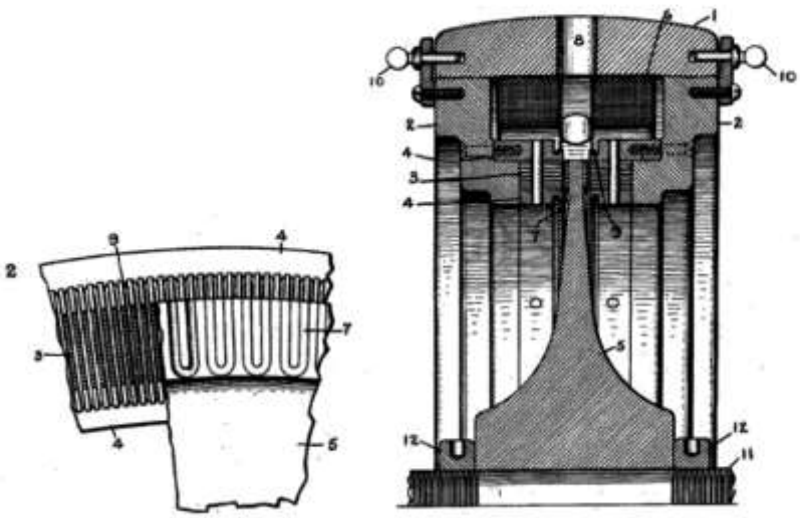


Figure 2.3: Diagrams from patent of E. F. W. Alexanderson showing 100 kHz alternator [20]

It is seen from Figure (2.3) (right) that the armature coil (6) is integrated into the stator (1) and a 'solid magnetic inductor' rotor (5) is used to create an alternating field by placing it in between two laminated rings. These rings are separated by two air gaps positioned in the circumferential/radial plane.

The flux path of this can be described as being perpendicular to that of an MPM. The field created by the stator coil passes through one ring, crosses the first air gap in the rotor, across the second air gap into the second ring and finally around the core-back to the original ring completing a full magnetic circuit.

Figure (2.3) (left) shows a cut out of rotor; zigzag winding (9) is shown held between two clamps (4). A high strength non-magnetic material (7) is used to fill the gaps between the rotor windings in order to give the rotor a smooth finish ultimately reducing the wind age which can often cause problems at the high speeds at which this machine works.

The Lundell 'claw-pole' alternator was patented 49 years later and can be regarded as one of the most profound examples of a modern modulated pole machine and formed the basis of the modern day automotive alternator. Robert Lundell was the pioneer inventor of the iron core like structure, modulating flux for a single dc stator winding; this idea was developed by General Electric in 1902. Lundell's technique was further revised and got used to form the modern day automotive alternator [21] once the silicon diodes were introduced. However, the introduction of affordable silicon components meant the birth of silicon thyristors, which replaced the induction alternators bringing them to an end.

Second generation of Electrical Machines

In the last twenty-five to thirty years, with the introduction of higher energy density magnets [18], availability of rare earth magnets for a realistic cost, semiconductors replacing valves and the development of materials such as soft magnetic composites, attention turned back to MPMs with its popularity touching skyline. There was an increasing curiosity with research being carried out more than ever before to figure out the result of replacing field windings by permanent magnets. This paved the way to many papers being published presenting different topologies for MPMs out of which was one published by H. Weh in 1986 presenting a MPM which formed the base of current day machines [2]. He realised the path of the flux trans-versing the direction of motion of motor and hence named the machine 'transverse flux machine' which is the name used today for such types of machine.

In [2], Weh puts forward the need to develop new soft magnet materials to avoid saturation, increased tooth widths were needed in conventional machines which in turn reduced the size available for the coil. Therefore to keep the electrical loading the same, higher current density and cooling was required [2].

This was one of the main reasons why MPMs became popular as this type of machine allows increasing the number of pole numbers without reducing the space for the coil due to the electrical and magnetic circuits being decoupled from each other. This meant that one does not need to reduce the electric loading to increase the magnetic loading. Conductor losses in MPMs were also reduced due to high current loading as each pole saw the whole coil MMF and hence high current densities were not required.

All these features meant that there were many designs created amongst which were single sided modulated pole machines (SSMPM), double sided modulated pole machines (DSMPM) as well designs with combined stators. A few designs from the literature are discussed in the following sub sections.

Single sided machines

In a Single sided modulated pole type of machine, flux is taken from one side of the magnet (mounted on the surface) by the armature and returned via the iron core-back via a return flux path. The most relevant arrangement to explain a single sided modulated pole machine is shown in Figure (2.4) where several U shaped laminated iron cores, spaced two pole pitches apart, enclose the ring shaped winding. The purpose of this arrangement is to direct the flux around the coil across the air gap, up to the rotor where the magnets efficiently alternate the direction of the magnetising circuit [22]. The return path for the flux to return from the rotor is provided by an iron segment situated below the magnets.

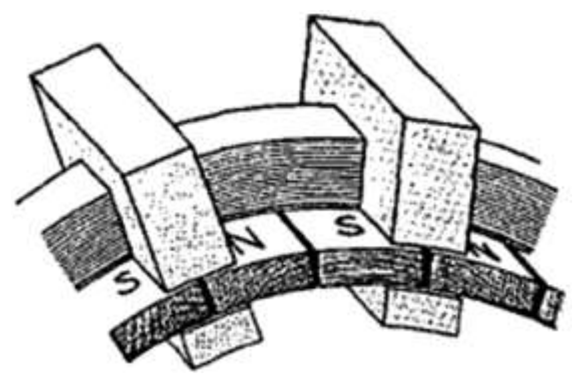


Figure 2.4: A single sided modulated pole machine arrangement designed by Weh [23]

It was also noted by Arshad et al [24] that the topology presented in Figure 2.4 only utilises half the coil and uses only half the magnet material at any one time, which leads to stray fields.

To tackle these issues, Mordey provided a solution by implementing magnetic short circuiting bars [25] which were used by Bork et al [20] and many other machine users [7,25] to guide the flux from unused magnets. Bork not only used Mordey's solution but also took this one step further by removing the iron link between the magnet; shown in Figure (2.5). The removal of iron from the

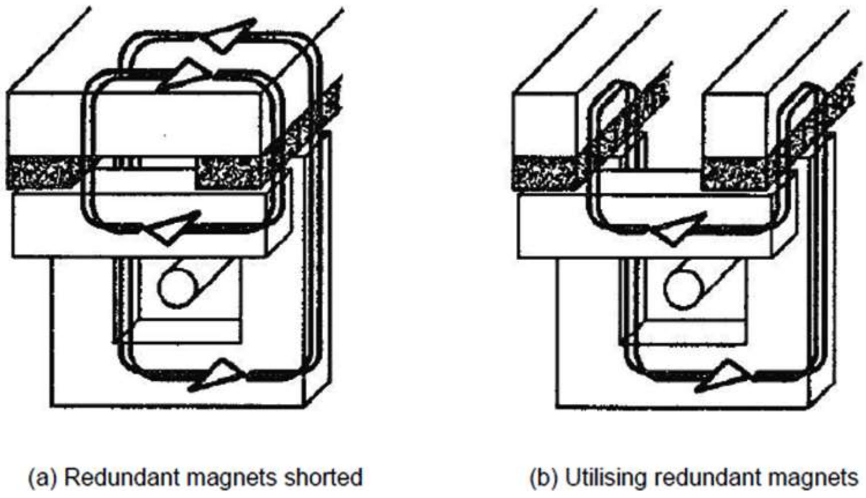


Figure 2.5: Magnet utilisation in a single sided Modulated Pole machine by M. Bork et al [27]; solid rotor (left), separated rotor parts (right)

rotor reduced the overall cost and weight of the machine as well as reducing eddy currents in the magnets, which are big advantages in machine manufacturing. It was seen that the main flux path links all the magnets however the presence of two air-gaps which the field must cross, an increase in current density for a given torque and reduced available area for the winding [26] reduces the extent of the initial advantage.

A big problem in single sided MPMs is the high armature leakage due to iron cores being in close proximity of each other and hence the reluctance of these is very close to the reluctance of the air gap. High armature leakage means low power factor, at times as low as 0.35 [26].

Double sided Machines

There are many benefits of a double sided machine over a single sided one, the main one being the doubling in force density [28]. In a double sided machine, several U cores and the coil usually covers the rotor from both sides [2,23]. These rotors can be surface mounted [2,22,23,25], where currents in the coils flow in opposite directions or flux concentrated [4,7,12-27], where current flows in the same direction in coils, as shown in Figure (2.6).

The double sided machine concept was first brought into existence by Weh [7] by simply removing the magnet core back in Figure (2.5a) and replacing it with a second stator in an aim to achieve 100% magnet utilization. The concept of removing the magnetic short circuiting bars in the stator was the back bone of Weh's paper [27] in which he explained the idea of using a flux concentrated rotor so both sides of the magnets can be used at all times.

This flux concentration causes the flux density of the air gap to be greater than the residual value of the magnet which provided it, providing a huge advantage to the overall performance of the machine. This benefit, united with better magnet utilization and a stator made up on modulated pole topology, delivers high force densities with much better power factors.

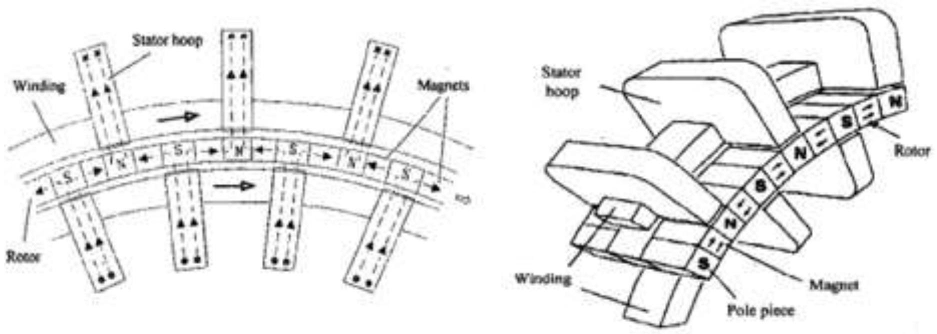


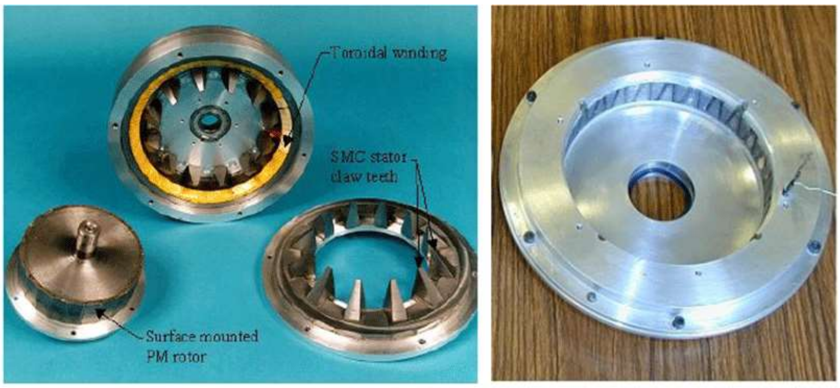
Figure 2.6: A double sided MPM with flux concentrating rotor in a zero torque position; rotor iron pieces and U cores are aligned [18]

There were many ideas and machines that were manufactured to reduce the redundancy of magnets; one such machine was built by Jack et al [29] and tested by Madison [30] shown in Figure (2.7a). This was similar to the machine developed by McLean, a claw pole machine (CPM), shown in Figure (2.7c) [31] in which he took full advantage of SMC's isotropic permeability by introducing a surface mounted magnet rotor and a claw pole structure in the armature stator. CPMs have been used in cars [32], stepping motors such as hard drives and digital cameras [33,34] and recently in an induction motor made from SMC [35]. Mclean showed that torque is not just dependent on peak flux density and electrical loading (and the machine constant [31]), but also on the number of poles.

Figure (2.7c) shows Mclean's double rotor single stator axial field claw pole machine [31] where the claw pieces are split, half pointing inwards and half pointing outwards to direct the magnet's flux linking the coil. The machine proved advantageous when compared against conventional machines however it also had its disadvantages such as high stator leakage, poor power factor and high core loses [29]. Overall, the machine topology presented by Mclean was unusual for a claw pole machine because of its axial design; more common are the radial type machines found in [8,29].

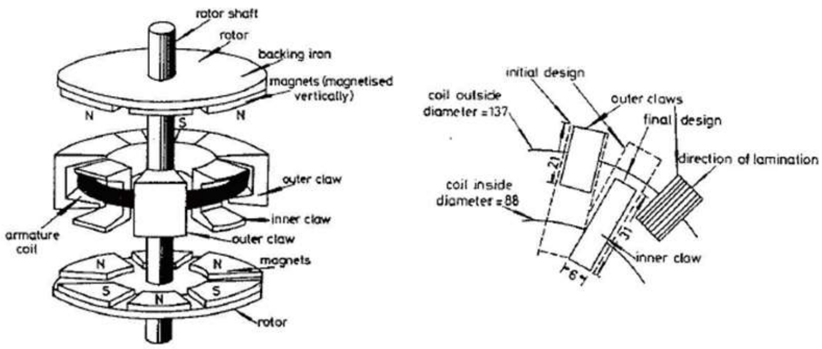
The machine design by Jack et al [29] provided a close complex structure of claw teeth which resulted in high amount of armature flux reducing the power factor, a low torque density of 3.3 Nm/kg for active material; however the simple structure of the armature eased the manufacturing.

Dickenson et al [36,38], on the other hand, increased the pole number to 50 in order to optimise the design, by changing the claw topology to reduce the armature flux which resulted in a torque density of 9.3 Nm/kg; the machine design is shown in Figure (2.7b).



(a) Jack's single sided 'claw pole' MPM [29] machine [36]

(b) Dickinson's optimised



(c) McLean's general topology [37]

(d) McLean's method to allow iron claws to be laminated

Figure 2.7: Various Claw pole Modulated Pole Machines

Other advantages of a double sided MPM include high torque densities as shown by Mecrow et al [11] where the machine was built out of SMC and achieved a torque density of 12.35 Nm/kg, torque per unit volume of 45.3 kNm/m^3; compared to 28.3 kNm/m^3 for a single sided design. The downside of a DSMPM when compared to a SSMPM is the complex construction [11] though the power factor shows improvement as the amount of armature leakage is lowered. Use of SMC material is recommended for double sided MPM as pointed out by Guo et al [39] due to eddy currents in the laminated material.

It can thus be concluded that double sided topologies offer higher power producing capabilities compared to single sided topologies: however they are more complicated to manufacture. In order to find a good compromise between performance and simplicity, a claw pole transverse flux permanent magnet machine is often considered by researchers [8].

Multi-Phase Machines

The concepts, designs and topologies presented so far all consisted of single phase synchronous machines. The simplest way to design a multiphase machine is by stacking multiple machines in series displaced by an appropriate angle to produce a smooth net output. There are many examples of such machines such as Mecrow et al's [40] and others such as [41,42] which uses the technique to integrate variations in an induction machine's stator, while Cros et al [43] have a hybrid machine comprising a conventional and modulated pole machine, presented in Figure (2.8).

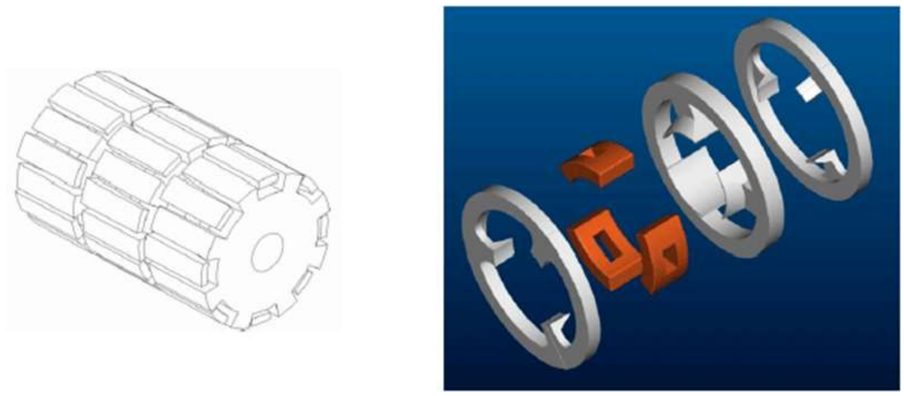


Figure 2.8: Two examples of multiple phase MPMs; Mecrow's [57] multiple phase MPM (left), Cros's [43] hybrid multiphase MPM (right)

General properties of Transverse Flux Machines

There are many advantages of TFM topology over the classical longitudinal concept; the main ones being the increase in pole numbers does not reduce the MMF per pole therefore producing higher power densities if needed. Secondly, there is a lot more design freedom as the magnetic flux and the coil geometry can be varied without compromising on the dimensions of either giving a higher torque/volume ratio. Moreover the armature coil is very simple and the total conductor length is relatively short. Last but not the least, the control method is simplified due to magnetic decoupling as the phases in a TFM are magnetically independent.

On the other hand, the reasons that can prevent companies from manufacturing mass production of TFM comprises of low power factor, three dimensional magnetic fields causing complex and complicated construction. This means that the use of lamination is replaced by the use of isotropic materials like soft magnetic composite materials as well as 3D numerical design tools, increasing the production costs significantly. However, for critical applications where the demand revolves around the performance and the compactness of machine, TFMs fulfil the criteria perfectly.

TFM designs can be based around three concepts. The first design is when there is an active rotor i.e. the exciting permanent magnets are placed on the rotor. The second concept is when the rotor is passive i.e. the exciting permanent magnets are on the stator. The third concept of a TFM is when the permanent magnets are replaced by an electrically excited reluctance motor. These three concepts can either be single sided or double sided, though single sided are easier to manufacture and have better prospects in practical applications.

There have been various designs and prototypes recently developed in the field of TFMs investigating regarding the geometries and their characteristics. To conclude, TFMs have a higher torque/volume ratio when compared to conventional ones, but because of three dimensional flux paths, the topologies require the use of isotropic materials like soft magnetic composites, as well as 3D numerical design tools.

Cogging torque

Cogging torque in an electrical motor is produced exclusively due to the interaction between the permanent magnets on the rotor and the teeth on the stator, which have a tendency to align such that the reluctance seen by the rotor is minimised. It is position dependant and hence depends on the number of magnetic poles and the teeth on the stator.

In a MPM, there are an equal number of rotor poles and stator teeth (poles) and hence the number of positions where the rotor will find this position of low reluctance will be equal to the number of poles. In the case of this these, the MPM discussed is 50 poles, hence there are possible 50 positions where production of cogging torque can take place. It was shown in [44-47] that a suitable selection of slot/pole combinations with a high common multiple can decrease the cogging torque produced by a conventional machine; this however is not true for MPM.

Although an MPM has equal numbers of stator teeth and rotor poles, these still line up twice in positions of low reluctance per electrical cycle. During one electrical cycle the rotor lines up in the d-axis twice (at 180° and 360°) and twice in q-axis (at 90° and 270°) and hence a large amount of rated torque is in fact the cogging torque [34, 48]. Moreover, improper designing of the machines can also cause a high cogging torque, sometimes as high as 25% of the rated torque; though many commercial machines, the value of cogging torque usually ranges around 5% to 15% [11].

Another factor influencing the performance of the machine is the torque ripple which is not just made up of the cogging torque, but the harmonic content in the back EMF waveform too. It is vital to consider this, especially when the application demands a low torque ripple, as machines of this type can show a high harmonic content especially on load as was shown in [49]. It is vital that in high performance applications, the cogging torque of the machine does not exceed 1% to 2% of the rated torque and therefore detailed analysis and computation techniques are required to design optimal machines which meet the specifications.

Phases of an MPM usually consist of three identical stator sections stacked axially and separated by a gap for magnetic isolation to reduce the mutual coupling between adjacent phases. Each of these three phases produces their own cogging torque [50] which is summed together on the shaft to create the resultant cogging torque for the whole machine. This allows for the possibility of reducing cogging torque by appropriate phase alignments and orientation.

It was shown in [51] that most of the even harmonics in a three phase MPM cancel out, leaving only the 6th and 12th harmonics and hence techniques to reduce these will be investigated in this thesis. It was also shown that cogging torque for a SSMPM is usually significantly lower than that of DSMPM, as was discussed earlier in the section.

There have been many literature publications on axial [52] and radial [53-55] PM machines however not many can be used directly in flux switching PM machines. Techniques that can reduce cogging torque include skewing the stator stack or magnets [56-57], using fractional slots per pole, optimising the magnet pole arc or width, shaping stator tooth tips [58], notching of teeth [59,60] and modulating the drive current waveform to compensate the torque ripple from a control viewpoint [61]. These techniques however are either difficult for some topologies, adds to the complexity of the machine or reduce the motor's back-EMF therefore reducing the resultant running/useful torque.

It is also suggested in [62] that the cogging torque can be computed by calculating the co-energy around the edges of the magnet in proximity to the nearest tooth and slot opening. A limited amount of research work is conducted to reduce the noise and vibrations in the machine [63-65], however due to the emerging interest in this field on part of the manufacturer, progress is being made to address the problem of cogging torque in much more detail.

It was shown in a paper [66] that by changing a simple geometry such as the tooth span, cogging torque, torque ripple and harmonic content can all be significantly reduced without a significant effect on the overall torque output. This paper presented a retrospective design investigation into a combined phase machine conducted in order to reduce the harmonic content of the back EMF and the cogging torque of the machine; two common problems with modulated pole machines.

Authors of [67] presented a method of reducing the cogging torque of transverse flux machines (TFM) by shaping the poles of the rotor. This successfully reduced the cogging torque in a single span unpitched TFM. The proposed solutions, with stator combinations of spans and pitching specific harmonics were more effective than the rotor variations. The rotor itself was not as compelling as the stator outcome, it could be used as a possible alternative to lessen the cogging torque while adding an increase in the efficiency peak.

Summary

A brief history into the literature of modulated pole machines and topologies such as single sided, double sided and multiphase modulated pole machines were discussed, ultimately leading towards material hybrid designs as these are of particular interestthese days.

It was shown that early modulated pole machines such as the one designed by Mordey mainly consist of solid laminated steel while the field was provided by a coil carrying current. However, the renewed research and availability of strong permanent magnets have reintroduced the modulated pole machines concept, especially in applications where high torque density is required. On the other hand, material hybrid machines use a combination of high permeability laminated steel and soft magnetic composite to make use of two kinds of field; one that travels in the plane and other that harness three-dimensional nature.

The problem of cogging torque was highlighted and reducing this is the main aim of many design projects these days. Various techniques are presented in the literature to reduce the cogging effect, however most of them either alter the machine parameters, give rise to complex manufacturing or decrease the useful torque.

These ultimately either increase the cost of the machine or reduce the performance. Techniques such as rotor and stator pole shaping or using a variation/combination of tooth span was seen to be most effective method of reducing cogging torque, torque ripple and back EMF harmonics

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