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Soft Magnetic Composites for AC Machines - A Fresh Perspective

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Abstract - *Soft magnetic composites (SMCs) have opened up new possibilities for the design of both DC and AC machines. Since SMCs are isotropic, machine topologies such as claw pole machines, transverse flux machines and the like, which have three dimensional flux density patterns have attracted the most attention. Very little effort has gone into improving the performance of conventional AC machines such as cylindrical rotor permanent magnet machines. This paper proposes new options for design of conventional machines which efficiently utilize the SMC material.*

I. INTRODUCTION

Powder metallurgy is a well established process for producing high volumes of magnetically hard material for a number of applications such as magnets. Continued advances in materials research has realized the ability to also produce high quality material with soft magnetic properties opening up the possibility of competing with steel laminations for a similar cost [1]. Since this material, termed SMC (soft magnetic composite), is magnetically isotropic, to date the majority of investigators exploring the use of this new material have focussed on utilizing it in applications where the lines of magnetic flux have or it is useful to add a significant non-planar component. Machines of this type include claw-pole [2][4], transverse flux [3][4], universal motors [5][6] and dc motors [7]. Attempts to replace conventional laminated permanent magnet or induction machines by an SMC equivalent are far less researched with only three significant references having been identified [9][10],[11]. This paper provides some insight into the design choices employed for these machines and it is proposed that two phase machines as a possible viable alternative to these existing three phase designs.

II. BENEFITS OF SMC MATERIAL

The benefits of replacing conventional laminated machines with powdered iron composites are considerable and include

- Increased copper fill factor (66% vs. the typical 33%),
- Essentially unity iron stacking factor,
- Potential for reduced air gap length as a result of the tight tolerances maintained in manufacturing SMC material,
- Reduced copper volume as a result of increased fill factor and reduced end winding length,
- Reduced copper loss as a result of the reduced copper volume,
- Reduced high frequency tooth ripple losses since the SMC has essentially no eddy current losses,
- The above two items suggest a potential increase in overall efficiency,
- Modular construction allows the possibility of easy removal of an individual modular unit for quick repair or replacement,
- Possibility of producing three dimensional flux patterns in the SMC material,
- Reduced axial length-over-end-winding dimension as a result of the compact end winding,
- Absence of phase insulation as a result of using non-overlapping windings,
- Potential elimination of the ground wall insulation since the SMC stator itself acts as an insulator,
- No need to stress relieve the stator lamination after punching and assembling the stack, a relatively costly and time consuming task, (stress relief is, however, included as part of the manufacture of the SMC part),
- Reduced conducted EMI when machine is used with inverter supplies since the stator SMC body acts as an insulator and does not conduct current to ground,
- Reduced bearing currents in the presence of PWM waveforms again because of the use of SMC which acts as insulation against this type of current flow,
- Stator is easily recyclable since the stator can again be compressed back into powered form with pressure and the copper windings readily removed.

These advantages are, of course, accompanied by a number of drawbacks. The most significant of these is the relatively low relative permeability of roughly 500 for the most commonly used SMC material SOMALOY 500[1]. Other concerns include relatively low rupture strength 100 MPa and higher low frequency iron losses due to its increased hysteresis loss. The low permeability of this material is most readily overcome with design of permanent magnet machines since the magnetic flux produced by permanent magnets are relatively insensitive to air gap length. Several new concepts for such machines will be introduced in this paper.

III. THREE PHASE PM MOTOR DESIGNS

Conventional AC stator windings typically incorporate either lap or concentric windings in which the coil span ranges

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between 2/3 and unity pole pitch in order to link as much flux as possible. While an SMC stator could be constructed in a similar manner it would, inevitably, be accompanied by a slot packing factor not far different than a laminated stator. Such a machine would almost certainly be a poor performer since the low permeability of SMC would probably require a magnetizing current penalty which could not be overcome without the use of additional copper. A high packing factor can only be achieved if individual teeth are directly wound in so-called “race-track” fashion. Hence, an important distinction between conventional and SMC three machines is the need to wind the coils around individual teeth. This constraint, however, is not without its drawbacks.

Figure 1 shows the MMF produced by a simple three phase winding having a pitch of 60 degrees (one slot per pole per phase). In a three phase AC machine, the fundamental component of stator MMF per pole is [8]

$$\mathcal{F}_{s1} = \left(\frac{3}{2}\right)\left(\frac{4}{\pi}\right)\left(\frac{k_1 NI}{P}\right) \tag{1}$$

where N is the total number of series connected turns, I is the peak AC current and P is the number of poles. The winding factor for the fundamental component of the MMF can be readily determined from conventional machine design formulas as [8]

$$k_1 = \sin\left(\frac{\gamma}{2}\right) = \frac{1}{2} \tag{2}$$

where γ is the coil span in radians, in this case $\pi/3$. Clearly a large penalty is encountered when short coil spans must be used. Also six toothed structures must be wound for each pair of poles making assembly of the stator structure relatively difficult.In this paper the value of $0.5NI/P$ is considered as a reference value of

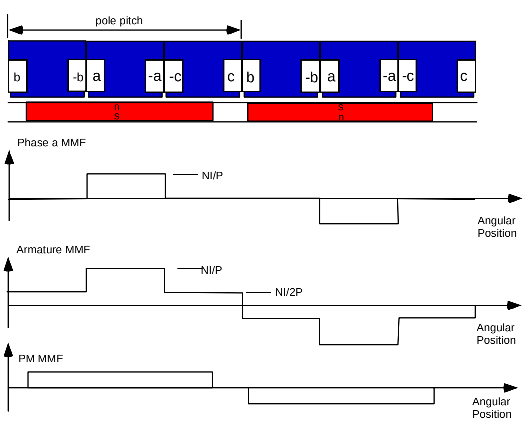


Figure 1 MMF of a simple 3 phase PM machine having one slot per pole per phase and 60° pitch, time instant shown when $i_a = I$, $i_b = i_c = -I/2$.

fundamental ampere turns per pole for wound tooth structures rather than the more familiar value of unity ampere turns per pole used for conventional windings.

Designs for practical SMC machines have chosen wider pitch angles in an attempt to reduce construction complexity. References [9] and [10] have reported a six pole and an eight pole permanent magnet machines which use a 120° pitch in order to reduce the number of toothed elements. The winding layout for this choice

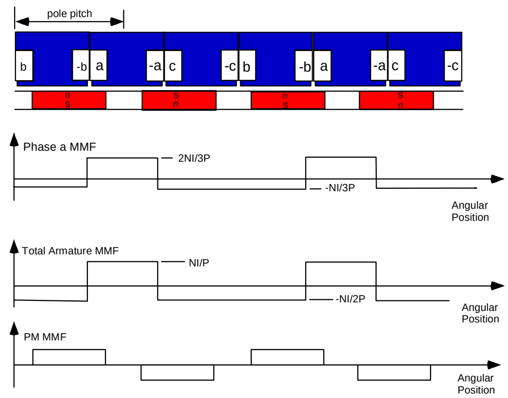


Figure 2 MMF of a 3 phase PM machine having 1/2 slots per pole per phase and 120° phase belt, time instant shown when $i_a = I$, $i_b = i_c = -I/2$.

of pitch is given in Figure 2 It can be noted that the number of toothed structures per pole pair have been reduced to only three. Since the winding factor for the fundamental component is normalized to a full pitch winding with fundamental $4/\pi$, the winding factor for this case can be calculated as

$$k_1 = \left(\frac{\pi}{4}\right) \cdot \frac{2}{\pi} \cdot \left[\int_0^{\pi/6} \left(\frac{2}{3}\right)\cos(x)dx + \int_{\pi/6}^{\pi} \left(-\frac{1}{3}\right)\cos(x)dx\right]$$
$$= 0.5 \tag{3}$$

However, since the number of toothed elements are halved, the number of ampere turns on the structures can be doubled, keeping the total amount of active copper the same. In this case, the effective value of the winding factor is

$$((k_1 NI/P)_{eff} = (0.25)2N_p I = 0.5N_p I)' \tag{4}$$

where N_p are the turns per pole. Thus, no benefit is gained in changing the winding span although the number of elements has been halved. In addition one can note the introduction of a significant amount of second harmonic in the MMF waveform.

In another paper by the same group as [9],[10] a winding span of 240° is suggested [12]. This case is illustrated in Figure 3. Here it is interesting to note that if the magnets are considered as the number of poles of

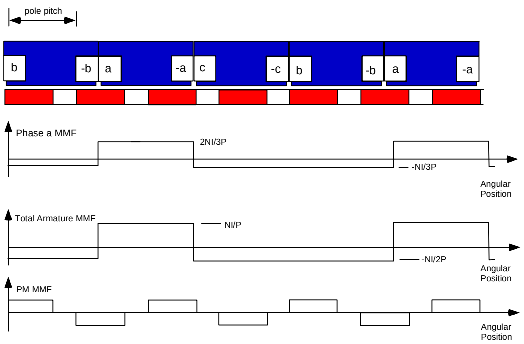


Figure 3 MMF of a 3 phase PM machine having 1/4 slots per pole per phase and 240^{o} phase belt, time instant shown when $i_a = I$, $i_b = i_c = -I/2$.

the machine then the stator produces a subharmonic of one half the number of poles. Torque is produced on only half the stator surface of the machine with half the magnets not taking part in energy conversion at this instant. If the number of magnets are considered as the fundamental number of poles of the machine then the winding factor corresponding to those poles involved in energy conversion is

$$k_1 = \left(\frac{\pi}{4}\right)\left(\frac{1}{\pi}\right)\left[\int_0^{2\pi/3}\left(\frac{2}{3}\right)\cos(x)dx + \int_{\frac{2\pi}{3}}^{2\pi}\left(-\frac{1}{3}\right)\cos(x)dx\right]$$

$$= \frac{\sqrt{3}}{8} = 0.216 \qquad (5)$$

Since the number of coils of this case is one fourth the number of coils of the reference case (Figure 1) the number of ampere turns can be increased by a factor of four. However, since the number of active poles is only 1/2 the total number of poles the effective winding factor is

$$(k_1 N_p I)_{eff} = \left(\frac{\sqrt{3}}{8}\right)(4)\left(\frac{1}{2}\right)N_p I = \frac{\sqrt{3}}{4}N_p I = 0.433 N_p I \qquad (6)$$

Thus the 240^{o} coil pitch arrangement is somewhat poorer than the other two cases.

It is interesting to consider how one can progress beyond the 0.5 winding factor which seems to be a limit for three phase machines. One possibility is to construct three single phase machines connected in tandem each with active length 1/3 that of the reference machine. Since each machine has only a single phase the coils can now be pitched 180^{o} resulting in a winding factor of unity. For the reference machine with 60 coil spans, the MMF available to produce torque is proportional to $(3/2)NI*k_1 = 3/4NI$. If the magnet strength is the same in all cases this quantity can also be considered as proportional to the torque so that the torque in a per unit form is 3/4. The ampere turns available to each of the three single phase machines is *NI*. Being single phase, each of the three single phase machines with ampere turns *NI* will produce (1/2)/3=1/6 per unit torque. The total torque produced by the three machines will therefore be 1/2 per unit which is less than the 3/4 per unit produced by the reference machine. Hence, playing such tricks with three phase machines is of no benefit.

IV. SINUSOIDALLY SHAPED POLES

Recall that the flux $d\phi$ over a differential surface of a cylindrical rotor is given by [8]

$$d\phi = BdA = N_p I dP = \frac{\mu_o N_p I}{g}(lrd\theta) \qquad (7)$$

where g, l, and r are the air gap length, stack length and radius at the air gap respectively and θ is the angular position along the air gap locating the flux element. In order to produce a sinusoidal variation along the air gap it is traditional to vary the number of turns *N* sinusoidally. Alternatively the (effective) gap *g* or air gap radius *r* can be made to vary sinusoidally resulting in reluctance torque. A third alternative, not normally considered is to make the length *l* to be sinusoidally varying. This is clearly only possible of SMC is used to form the stator since a sinusoidal variation in length would imply using a series of laminations of a continuously varying shape. The differential flux becomes

$$d\phi = \frac{\mu_o N_p I}{g} l_m r|\sin\theta|(d\theta) \qquad (8)$$

where l_m denotes the maximum length of the stator stack. If the poles are wound with concentrated coils with alternating polarities of the same current the differential flux with then spatially vary sinusoidally. A sketch of the pole arrangement is shown in Figure 4. Since the net MMF is sinusoidally distributed the winding factor for this layout is the same as for a perfect sinusoidally distributed winding,

$$k_{1,\,eff} = \frac{\pi}{4}\left[\frac{2}{\pi}\int_0^{\pi}\sin\theta d\theta\right] = \frac{\pi}{4} = 0.785 \qquad (9)$$

A two phase machine can now be constructed by placing two sets of sinusoidal poles back-to-back as shown in Figure 4(b). One can express the differential fluxes of the two windings as

$$d\phi_a = \mu_o r l_m |\sin\theta| d\theta \qquad (10)$$

$$d\phi_b = \mu_o r l_m |\cos\theta| d\theta \qquad (11)$$

When averaged over the total length of the machine l_s, the flux densities of the two stator phases is

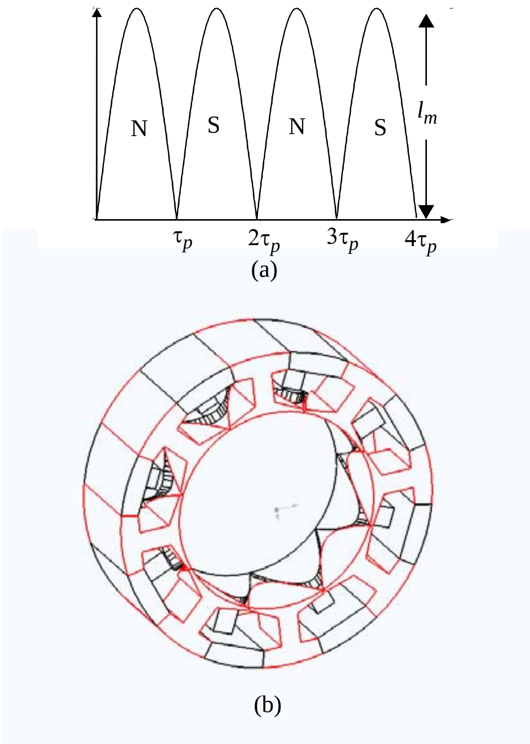


Figure 4 (a) pole pattern with sinusoidally varying axial length, (b) unwound stator of two phase machine utilizing sinusoidally varying poles.

$$B_{a,\,eff} = \frac{d\phi_a}{rl_s d\theta} = \mu_o\left(\frac{l_m}{l_s}\right)\left(\frac{N_p I_a}{g}\right)|\sin\theta| \qquad (12)$$

$$B_{b,\,eff} = \frac{d\phi_b}{rl_s d\theta} = \mu_o\left(\frac{l_m}{l_s}\right)\left(\frac{N_p I_b}{g}\right)|\cos\theta| \qquad (13)$$

If the poles of the machine are consecutively numbered and if $I_a = I\sin\omega t$ and $I_b = I\cos\omega t$, in poles 1,3,5,.., *p*–1 of the *p* pole machine and the negative of these values in poles 2,4,6,..., *p*, the total effective flux density in the air gap becomes,

$$B_{eff} = \mu_o\left(\frac{l_m}{l_s}\right)\frac{N_p I}{g}\cos(\omega t-\theta)\,. \qquad (14)$$

Hence, the effective air gap flux density created by this machine is ideally sinusoidal in both space and time.Here, the effective flux density is defined at the flux density as experienced by a magnet or rotor coil of active length l_s. The machine has only four toothed structures per pole which compares favorably with the three phase machines discussed previously. Being a two phase machine, the amplitude of the flux density is, as expected, 2/3 that of the three phase machine. However, with ampere turns *NI* the amount of copper used for this machine is also 2/3 that of the three phase machine. The same flux density and torque can be produced by simply increasing the number of turns of each pole by 50%.

It is now useful to compare the winding factor for this machine versus the three phase machines. Neglecting the small spacing between sets of poles (as has been assumed up to this point for the other winding patterns) so that the poles of the two phases are just touching, the overall length l_s of this machine is $\sqrt{2}l_m$. Normalizing to the same active length the effective ampere turns become

$$(k_1 N_p I)_{eff} = \frac{1}{\sqrt{2}}\left(\frac{\pi}{4}\right)NI = 0.555N_p I \qquad (15)$$

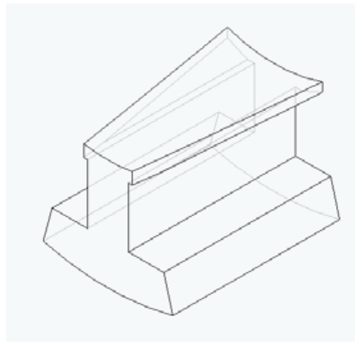
Thus, the two phase sinusoidal pole machine is capable of producing 11% more flux linkage for the same amount of active copper, and thus at least 11% more torque than any of the three phase machines of Section III.

It should be mentioned here that the major issue with this type of structure lies not in torque ripple (which is ideally zero) but in lateral (axial) forces produced when the alternate sides of the machine produce the rotating flux density. It would be necessary to solve this problem before such a machine can be successfully applied.

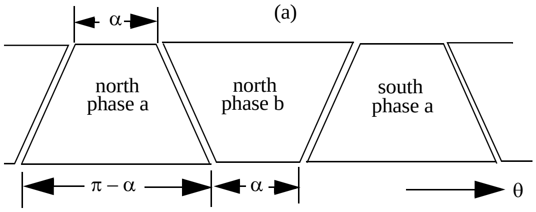
V. Two Phase Machines with Trapezoidally Shaped Poles

Other two phase pole shapes have been developed which can improve the fundamental winding factor. It is useful to also consider the effectiveness of a trapezoidally shaped pole as shown in Figure 5. Because the two phases are interdigitated, the top and bottom sides of the trapezoid are constrained such that the sum of the top and bottom lengths is one pole pitch. Thus when $\alpha = 0$, the poles form triangular poles while if $\alpha = \pi/2$, rectangular poles are formed. Figure 6 shows how the fundamental and third harmonic winding factors vary with α. Since the machine is two phase, the third harmonic represents the lowest undesirable component, (a positive sequence component in a two phase system). The value of k_1 reaches a maximum near $\alpha = 60^o$ but little change is observed over the range $0 < \alpha < 30^o$. Regrettably the third harmonic component varies almost in direct proportion to the fundamental component so that little room exists for optimization.

It is important to note that the maximum value of $k_1 = 0.783$ represents over a *56% improvement* in flux linked for the same ampere turns as the three phase motors of Section III. While the stator layout has a significant 10% third harmonic component, the rotor can be designed with a magnet pole arc of 120^o for which potential torque pulsations arising from this component can be eliminated.



(a)



(b)

Figure 5 Two phase stator poles with trapezoidal pole shape (a) single pole, (b) illustrating constraint on pole sides. .

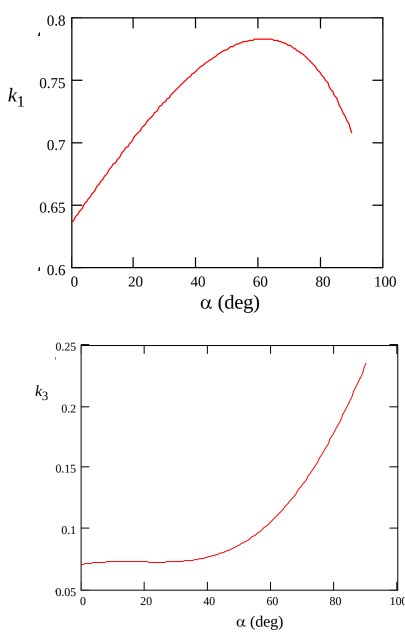


Figure 6 Variation of fundamental and third harmonic winding factors with α.

Two phase machines can also be designed to span greater pitches than 90^{o} in much the same manner as three phase machines. Figure 7 shows the MMF for a two phase motor with a 180^{o} pole pitch. In this case the winding factor for the first harmonic is clearly unity. Since the ampere turns for one of the phases is concentrated at every other pole, the copper can be doubled to compare with Figure 5 doubling the MMF per pole. However, upon closer examination it can be determined that the field produced by this distribution only pulsates in space. Thus, only half the MMF produces a positively rotating sequence. The effective ampere turns per pole is again

$$(k_1 NI)_{eff} = (2)\left(\frac{1}{2}\right)\left(\frac{1}{2}\right) = 0.5 \tag{16}$$

Again, other choices of pole pitch do not improve the performance of the two phase machines beyond 0.78

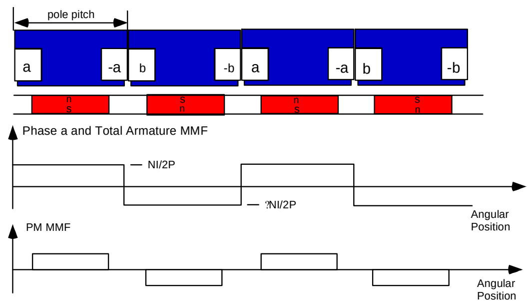


Figure 7 MMF of a two phase PM machine having 1/2 slots per pole per phase and 180^{o} phase belt, time instant shown is when $i_a = I$, $i_b = 0$.

VI. Axial Air Gap PM Machines

The concept of a sinusoidal pole shape in the axial direction can be extended to axial air gap machines in which the poles must now be varied sinusoidally in the radial direction. In effect the rectangular air gap surface $\pi D l_s$ must be mapped to a toroidal shaped surface $\pi(R_o^2 - R_i^2)$ where R_o and R_i are the outer and inner radii of the torus shaped stator. It is assumed that the radial edges of the magnets are straight lines perpendicular to the inner and outer circumferences. Poles spanning 90 degrees with their bases on the inner and outer circumferences are formed The pole shape must vary such that the radial distance along the surfaces of the poles vary sinusoidally with θ. The radii for the inner and outer "flower shaped" poles can be solved as

$$R_1(\theta) = \sqrt{R_i^2 + (R_o^2 - R_i^2)\left|\sin\left(\frac{P\theta}{2}\right)\right|} \tag{17}$$

$$R_2(\theta) = \sqrt{R_o^2 - (R_o^2 - R_i^2)\left|\cos\left(\frac{P\theta}{2}\right)\right|} \tag{18}$$

For a four pole machine the flower petal shaped poles of Figure 8 are formed. It should be mentioned, that pulsating torque will again be negligible. In this case the lateral force exerted on the bearings does not

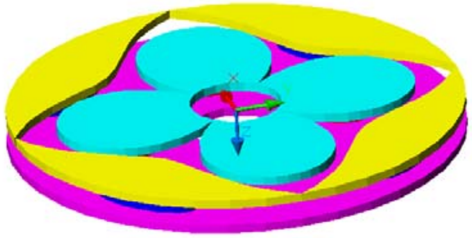


Figure 8 "Flower petal" shape four pole, two phase axial air gap machine producing sinusoidal voltage induced by the rotor permanent magnet.

exist for the axial motor case since the analogous forces are radially whereupon cancellation occurs.

An axial air gap equivalent of the trapezoidal machine of Figure 5 can also be considered. In this case the radii for the two sides of the trapezoid equivalent pole shape is

$$R_1 = \sqrt{R_i^2 + (R_o^2 - R_i^2)\frac{\theta}{(3P)}}, \quad 0 < \theta < \frac{\pi}{3P} \qquad (19)$$

$$R_2 = \sqrt{R_o^2 - (R_o^2 - R_i^2)\left(\frac{\theta - \frac{\pi}{2P}}{\left(\frac{\pi}{3P}\right)}\right)}, \ \frac{\pi}{P} \le \theta \le \frac{4\pi}{3P} \qquad (20)$$

A sketch of the pole shapes for a trapezoidal axial air gap machine with $\alpha = 30^o$ is shown in Figure 9.

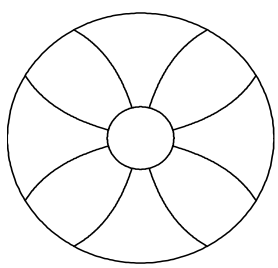


Figure 9 Trapezoidal shaped four pole, two phase axial air gap machine.

Many varieties of these basic concepts can be imagined including single stator-single rotor, double stator-single rotor, and double rotor single stator versions. The single stator-single rotor version is particularly attractive for small motors used to rotate platters such as computer hard disc drives.

VII. USE OF SMC FOR INDUCTION MACHINES

Because of its relatively low permeability, the use of SMC for induction machines appears to be quite limited [11]. However, continued improvement of the quality of the material could lead to practical applications. One such possibility is the axial air gap induction machine of Figure 10. While use of SMC as part of the rotor construction appears impractical for radial air gap machines, this is not necessarily the case for axial air gap machines. Figure 10 illustrates a concept in which the rotor cage is constructed by simply punching trapezoidal slots in a sheet of copper. Several copper sheets can be layered to form the desired thickness for the rotor cage. The slots can then be filled with special "T" shaped SMC segments which are inserted into the copper slots on alternate sides and which act to gather the flux produced by the stators. The two stators are wound so that the flux lines pass across both air gaps. Hence the SMC segments act as a conduit to pass flux through the rotor and thus link the copper segments formed between the punched slots. In effect the concept of slotting of the iron to accommodate copper winding has been replaced by slotting the copper to accommodate SMC iron. The stators can be constructed in the usual manner or with SMC in accordance with the two phase flower shaped petals of Section VI. Clearly the practicality of the approach clearly hinges on the ability of the relatively brittle SMC material to withstand centrifugal forces and this issue needs to be carefully examined.

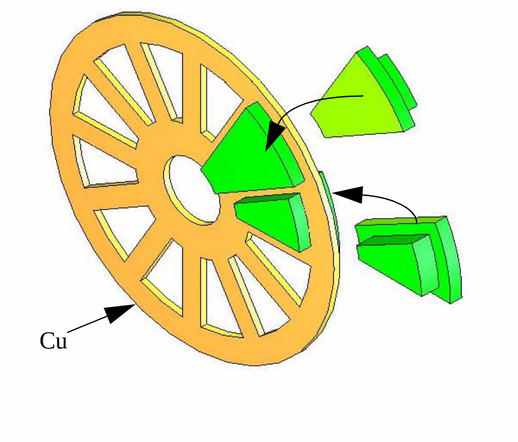


Figure 10 Rotor of axial air gap induction motor utilizing SMC to form rotor teeth, only two of twelve SMC tooth elements are shown.

VIII. TWO AND THREE PHASE STATORS MADE FROM BOTH SMC AND LAMINATED IRON

Because of their short flux paths, SMC appears to be more attractive for machine requiring many poles. When 4 or 6 pole machines are desired the MMF drop in the stator core becomes a major concern. This problem can be greatly diminished if the SMC material is used only for the pole tops as shown in Figure 11. The

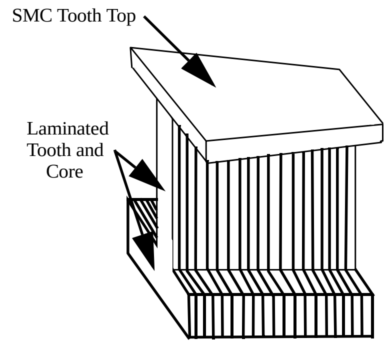


Figure 11 Stator phase segment with core constructed of laminated iron and with a pole surface using SMC material.

stator can be still be constructed from individually wound segments as done for stator made entirely from SMCs or entire stator laminations can be punched without the pole (tooth) tops. The windings, preformed by a separate process, can be slipped over each of the stator teeth and the SMC pole tops then fastened to the teeth. In this case, identification of the proper fixative needed to attach the SMC to the laminated teeth to allow for differences in thermal expansion is clearly the issue to be solved.

While the concept of winding stator coils around individual stator teeth may appear undesirable as a result of the poor winding factor, the approach should, perhaps, be reconsidered even for use with conventional AC induction and synchronous machines. While the winding factor for three phase machines with phase wound teeth has been shown to be only about 3/4 compared to 5/6 to unity for lap or concentric windings, it has already been demonstrated in the literature that the winding space factor doubles [10]. Thus, more flux can potentially be linked even though the winding factor is reduced. Also, since the end winding length is reduced in the case of phase wound teeth, less copper losses and smaller leakage inductance can be anticipated. Such a machine could be constructed with laminations forming the core and tooth bottoms with the tooth tops formed by SMC as discussed above.

IX. THREE PHASE VS. TWO PHASE INVERTERS

Three phase machines have been favored over two phase machines for generations and it is useful to revisit the reason for this choice and discuss the practicality of using a two phase rather than three phase inverter supply. Since conventional three phase machines are invariably constructed with 60 degree phase belts, the distribution factor which is normally roughly 0.95 whereas the distribution factor for a two phase machine with a 90 degree phase belt is 0.9. Thus about a 5% reduction in output power exists for a two phase machine even if the amount of active copper is the same. However, the distribution factor for either three phase or two phase machines with windings concentrated around a single tooth is unity for both cases. Thus, the historical argument for three phase does not hold for this situation.

It is also commonly believed that the inverter supplying a two phase motor is somehow inferior to a three phase inverter since 41% more current flows in the neutral return path than in the current paths feeding the two phases. While this is the case, the increase in current is not 41% in a per unit sense. In the case of three phase, the inverter voltage is impressed from line to line across two phases. The KVA rating of the three phase inverter is (for unity Modulation Index M)[13]

$$VA_3 = 3V_{l-n}I_3 = \sqrt{3}V_{l-l}I_3 = \sqrt{\frac{3}{2}}V_{dc}I_3 \quad (21)$$

In the case of the two phase system, the inverter voltage is impressed directly across the two motor phases from line to neutral

$$VA_2 = 2V_{l-n}I_2 = \sqrt{2}V_{dc}I_2 \quad (22)$$

Equating VA_3 and VA_2,

$$I_2 = \frac{\sqrt{3}}{2}I_3 \quad (23)$$

so that the line current for a two phase motor actually decreases by about 13.5% when compared with a three phase motor operating from the same inverter. The current in the neutral return leg is then

$$\sqrt{2}I_2 = I_{neutral} = \sqrt{\frac{3}{2}}I_3 = 1.22I_3 \quad (24)$$

Thus, the neutral return current for a two phase inverter drive is only 22% greater then the phase current of a three phase drive and not 41%. In general, this amount of additional current can often be accommodated since it is well within the design limits of the device. Since two of the switch legs carry less than rated current, the overall heating is essentially the same as a three phase system so that the size of other components such as heat sinks are unaffected. A similar statement applies for the dc link capacitor.

If desired, the issue can be completely resolved by redesigning the inverter switches to take care of the current unbalance. Assuming that the current in each of the six transistors of a three phase inverter carry current I the silicon area required by the switches is proportional to $6I$ that is

$$A_3 \propto 6I \quad (25)$$

In the case of the two phase system, the transistor area required is proportional to

$$A_2 \propto 2\left(\sqrt{\frac{3}{2}}\right)I + 4\left(\frac{\sqrt{3}}{2}\right)I = 5.913I \quad (26)$$

Hence, the total silicon area needed to supply a 2 phase load is actually 1.5% smaller than the area needed to supply a 3 phase load.

Today's IGBT switch packages are typically supplied in a single module containing three switch legs. The transistors inside the switch package generally number a dozen or more which are internally connected in parallel to implement the three switch legs. A suitable module for a two phase load could be readily obtained by simple reassignment of the transistors within the package to bolster the current carrying capability of the neutral phase leg.

X. CONCLUSIONS

This paper has presented an overview of attractive research directions for the application of soft magnetic composites in the design of AC machines for conventional applications. It has been shown that two phase machines could offer advantages over three phase machines when the windings must be pitched to embrace only a single stator slot. Both radial and axial air gap machines including both PM and induction machines have been discussed and attractive alternatives to conventional designs proposed. Possible extensions to two or three phase machines using a combination of laminations and SMC have been discussed. In summary, it appears that the use of SMC materials in machine design will remain an interesting and challenging research area for the foreseeable future.

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