Getting to know fractional-slot concentrated windings (FSCW)

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Fractional-slot concentrated windings (FSCW) have been used for decades, primarily in small machines. But continued technological advancement in power electronics along with the need for more efficient and power-dense machines is increasing use of FSCW in a variety of machine types and sizes.

In order to introduce FSCW, it is worthwhile to review some basics related to windings seen more often by service centers. Most texts that explain the layout of three-phase windings utilize the number of slots per pole and phase (SPP) which can be defined as follows.

$$SPP = Q / (M \cdot P)$$

where

SPP is the number of slots per pole and phase
Q is the number of stator slots
P is the number of poles
M is the number of phases

Service centers most often encounter concentric windings or two-layer lap windings. For two-layer lap windings, which we'll use in this article for comparison, the number of coils will equal the number of slots, and the number of coil groups will equal the number of poles multiplied by the number of phases. In these cases, the average number of coils per group is SPP. For example, a lap wound three-phase, 4-pole stator with 36 slots will have SPP = 36 / (3·4) = 3 coils per group.

The stator winding magnetic poles are produced by current flowing through these groups of stator coils. One measure of the strength of these poles is called magnetomotive force (MMF) and it is measured in the unit of electrical current, the ampere. The MMF is equal to the current flowing through a coil multiplied by the number of turns in the coil; thus it is often expressed in ampere-turns rather than amperes to avoid confusion. When the coils within a group are placed in different slots, like in a lap winding with multiple coils per group, the MMF is also distributed according to the slot placement.

For lap wound, three-phase stators, the MMF of each phase combines to form a sinusoidal rotating magnetic field of constant magnitude. The fundamental MMF for half of a 36-slot stator winding with 3 coils per group is shown in **Figure 1**. Phase A current is shown with **A** current flowing out of the page and **–A** current flowing into the page; this depicts points in time when A phase is at maximum current. The contributions that would appear in the total MMF from C and B phases are also shown as dotted lines.

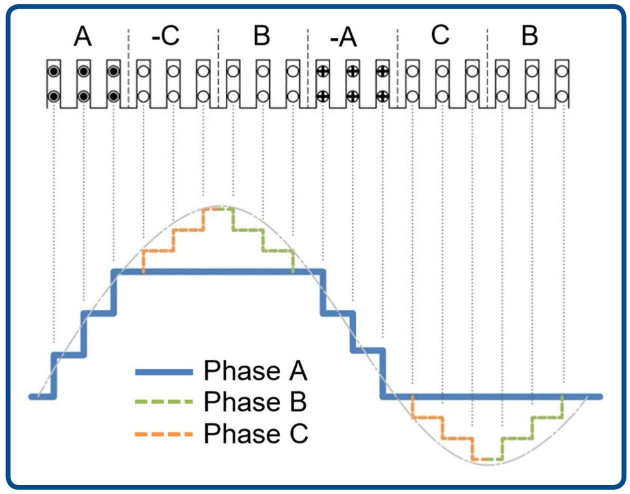

Figure 1. MMF – A phase max current.

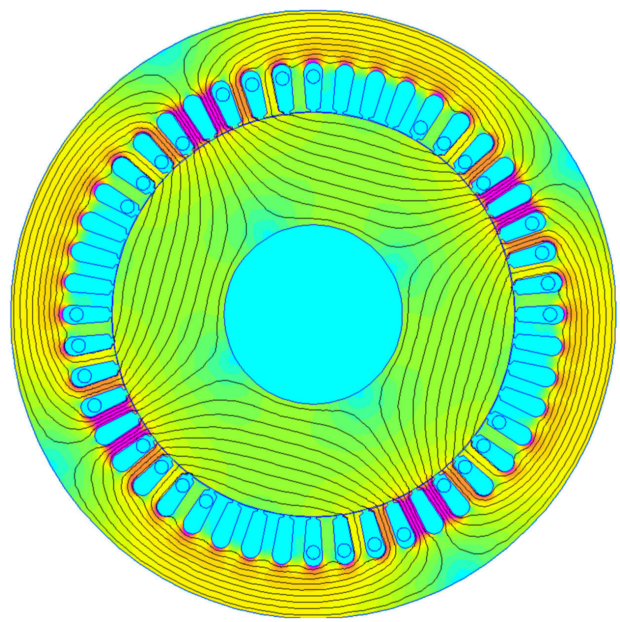

Figure 2. 4-pole phase winding FEA model.

Figure 2 shows flux patterns for one phase of a three-phase, 4-pole stator winding created using a finite element analysis (FEA) model. This winding could consist of two coil groups wound with the same polarity or four coil groups wound with alternating polarity. In both cases, the conductors would be distributed in four locations around the stator about

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90 mechanical degrees apart to create four magnetic poles.

Integral-slot winding

When the number of slots divided by the number of groups is an integer, we refer to the winding as an integral-slot winding. The example discussed above for the 36 slot, 4-pole with 3 coils per group is an integral-slot winding. When the number of slots divided by the number of groups is not an integer, we refer to the winding as a fractional-slot winding. For example, a three-phase, 4-pole stator with 30 slots will have SPP = 30 / (3·4) = 2.5 or 2 + 1/2 coils per group. In this case, the two-layer lap winding would have 6 groups of 2 coils and 6 groups of 3 coils. Most service centers are familiar with this type of winding as well. Additional information related to this material can be found in a variety of sources including the *EASA Technical Manual*.

There is another type of three-phase, fractional-slot winding used predominantly in brushless DC machines (BLDC), permanent magnet synchronous machines (PMSM), synchronous reluctance machines (SynRM), switched reluctance motors (SR), and others. Some EASA members have encountered these windings and found confusion in applying the basic grouping rules from the *EASA Technical Manual* or similar sources. These are machines where the number of slots per pole and phase is less than one (SPP < 1). That is, if using the grouping calculations we apply to most windings in the service centers, the result will be less than one coil per group. Most of these machines have salient poles, whether magnets or just steel, that can easily be counted, though many of the SynRM salient features are hidden beneath the rotor surface.

A typical scenario is a winder given a stator with 42 slots and he finds 36 salient poles on the rotor. For a three-phase winding, the winder expects that even with a consequent pole winding, he would need 54 groups of coils – but there aren't even that many slots: confusion.

Different set of rules

It's not that these windings don't follow rules – they're just a different set of rules than what we're accustomed to with integral-slot windings and fractional-slot windings where SPP is greater than one. They have more complicated rules than our conventional windings too, and because these machines require complex power electronics to operate, they are state-of-the-art with development on-going. These designs are usually referred to by the number of stator slots and rotor poles. For example, a machine with 6 stator slots and 4 rotor poles may be referred to as a 6/4 machine. One key difference here with most of these machines is that the number of rotor poles and the number of stator poles either need not be the same or cannot be the same.

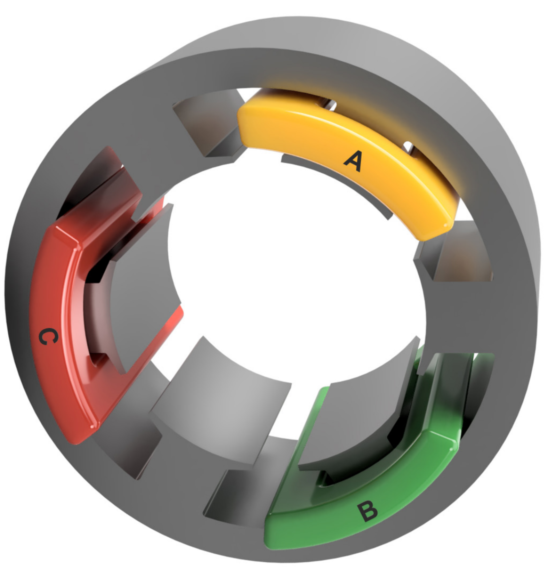

Figure 3. Single layer fractional-slot concentrated winding.

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The winding shown in **Figure 3** is a three-phase, single-layer, fractional-slot concentrated winding (FSCW). Since each coil is placed over one tooth, they all have a coil pitch of 1 to 2 (1 tooth spanned). This winding is known to be used in small 6/4 machines (6 stator slots, 4 rotor poles) and it has SPP = 6 / (4 * 3) = 1/2. There are several advantages to this type of winding. The coil end extensions can be made very short, reducing losses and increasing power density because of the smaller machine volume. Next, coils are separated by a sufficient distance to prevent any sort of phase to phase or coil to coil failures from occurring. Also, with single layer, open slot designs, the manufacturer can achieve very high slot fill. One disadvantage is that losing the distribution of conductors results in a non-sinusoidal MMF and large harmonic presence. This is accounted for in the design, but it is not trivial and complicates the design greatly. With SPP less than or equal to 1/2, the machine may not operate on the fundamental MMF like typical lap windings described above. Rather, it may operate on a synchronous harmonic which is a function of the number of slots and poles.

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For a PMSM, the machine will rotate at the speed defined by the number of rotor pole pairs and supply frequency (e.g., 10 pole / 60 Hz = 720 rpm, 10 pole / 50 Hz = 600 rpm, 10 pole / 15 Hz = 180 rpm). The motor design and drive topology used for these will typically cover a large speed range.

It can be difficult to visualize the interaction of the magnetic fields in some of these machines without use of a finite element model. Again, **Figure 2** is a finite element model of one phase of a three-phase, 4-pole, distributed, 2-layer lap winding. It is straight-forward for most learners to grasp the concept of a 4-pole machine using this type of visual aid. **Figure 4** is a finite element model of one phase of the stator shown in **Figure 3**, which in this case is a 4-pole permanent magnet synchronous machine. In **Figure 4**, the permanent magnets are modeled as air so that only the magnetic field from the stator phase winding is shown, and for most, it is difficult to visualize the functionality of the winding. In **Figure 5**, the permanent magnet air space has been replaced by magnets and the interaction of the stator and rotor fields makes it much easier to understand this machine as a 4-pole.

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For FSCW stator windings with more than one coil per phase, the coils will almost always be connected with alternating polarity and it is common to bring out six leads or have an internal wye. Depending on the construction of the machine and the cause of damage to any failed coils, it may make sense to replace individual stator coils in some cases.

Also, these coils can be tested similarly to shunt fields, e.g., winding resistance test, insulation resistance test, high-potential test, surge test, impedance test, voltage drop test. A stator loop test should also be performed.

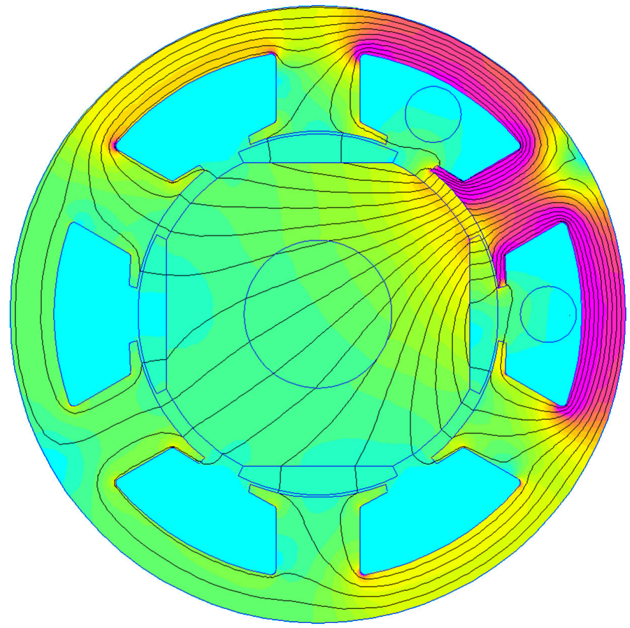

Figure 4. FSCW phase winding FEA model for 6/4 PMSM with no PM.

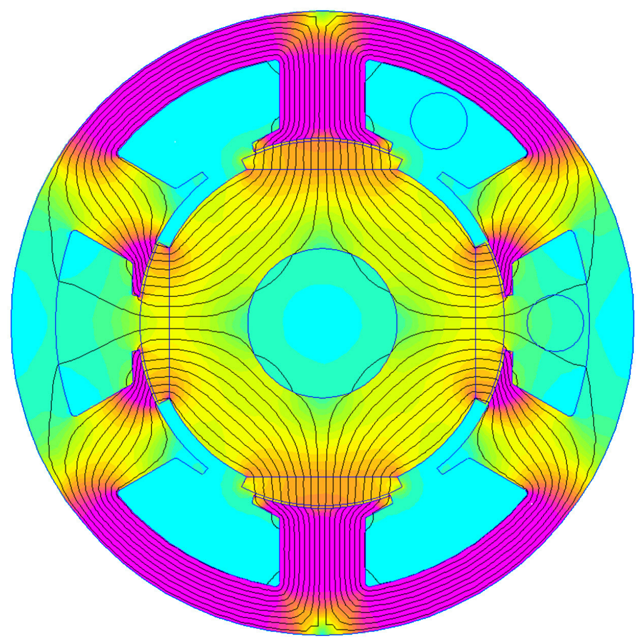

Figure 5. FSCW phase winding FEA model for 6/4 PMSM with PM.

Increasing presence

Even though service centers don't see many stators with fractional-slot concentrated windings at present, they are gaining ground in a variety of different electrical machines for some of the reasons discussed above –

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lower cost, short coil extensions, fault tolerance, etc. Recent research [1] even includes a 1000 kW 2-pole machine rated 6 kV with 12 slots utilizing a combined wye-delta connection like those seen in triple-rated motors or used in 230/460/575 stator connections.

Since it may not be possible for the service center to test run the machine after repair, it is recommended to carefully duplicate windings and connections to minimize the chance of problems after delivery. And remember, these may "seem wrong" when trying to apply rules for other types of windings. ●

[1] O. Moros, G. Dajaku, et. al., "*New high voltage 2-pole concentrated winding and corresponding rotor design for induction machines,*" in The 41st Annual Conference of the IEEE Industrial Electronics Society (IECON-2015), Yokohama, Japan, 2015.