Borealis Chorus™ Motor Tutorial

Theoretical Description of the Borealis Chorus™ Motor

The Borealis Chorus™ Motor is a simple but fundamental departure from conventional motor design practice. It may be analyzed, however, by many of the same mathematical tools developed during the past century of motor design. Understanding of the sampling theorem as used in digital signal processing will assist in the understanding of how the Borealis Chorus™ Motor makes use of harmonics.

The change applied to conventional motor design is a substantial increase in the number of motor phases used, to the point where a pole phase group consists of only a single slot in the stator winding. In general, this will mean that a motor operates with upwards of twelve phases; with available stator iron, twenty-four or more phases may be incorporated without difficulty. With custom iron, there is no upper limit on phase count.

The improvement over conventional design practice can be analyzed in terms of copper utilization and harmonic factors. Harmonic factors can be further divided into temporal harmonics in the power supply current, and spatial harmonics in the airgap flux. Comparisons will be made to conventional three phase machines.

Temporal Harmonics:
The current flowing into the motor can be analyzed by Fourier series. The fundamental frequency of the applied voltage generates the major rotating magnetic field, and establishes the synchronous speed of the motor. Thus:

$$RPM = \frac{120f}{p}$$

where f is the applied frequency and p is the number of poles developed. This is true both for three phase motors as well as the Chorus™ motor. Each of the harmonics generates a rotating field as well, for which the same synchronous speed formula applies. Thus when a harmonic exists in the drive waveform, it will produce a rotating field which rotates at a speed determined by the frequency of the harmonic and the number of poles produced by this harmonic.

Examining the fifth harmonic:
In a three phase machine, the fundamental electrical angle between phases is 120°. However, because both sides of a given winding are represented on the stator, the electrical phase angle between adjacent pole/phase groups will be 60°. For fifth harmonic in the drive waveform, the electrical angle between the phases is five times this, or 300°. However, sinusoids are periodic functions, and 300° is the same as -60°; thus the phase relation between adjacent phases for the fifth harmonic is precisely opposite that of the fundamental. The net result is that in a three phase machine the fifth temporal harmonic generates a rotating field with the same number of poles as the rotating field produced by the fundamental, but with negative phase sequence. Additionally, the fifth harmonic has five times the frequency of the fundamental, thus the rotating field produced by the fifth harmonic rotates in the opposite direction and at five times the speed as that of the fundamental.

Now increase the number of phases. If, rather than using the conventional three phases, five phases are used, then the fundamental electrical angle between phases becomes 72°, and the angle between pole phase groups becomes 36°. For the fifth harmonic, the electrical becomes 360°, with the electrical angle between adjacent pole phase groups being 180°. Over a single 360° cycle of the fundamental current flowing in the stator, the fifth harmonic will cycle five times. Fifth harmonic current flowing in the five phase winding produces a 10 pole rotating field, rather than a two pole rotating field. The important point about this field is that its synchronous speed will be the same as that of the fundamental.

If more than five phases are used, then this becomes clearer. For example, evaluate a fifteen phase machine. The phase angle is 24°; between adjacent pole phase groups there is an electrical angle of 12°. For the fifth harmonic, the electrical angle between adjacent pole phase groups becomes 60°, exactly as one would see in a ten pole three phase machine. In fact, a fifteen phase two pole winding, fed with fifth harmonic current alone, will have exactly the same slot currents as a three phase ten pole winding. The net result is that in a fifteen phase machine, the rotating field developed by the fifth temporal harmonic has five times the poles of the rotating field developed by the fundamental. However, because of the higher frequency of the fifth harmonic, this rotating field rotates at the same synchronous speed as the fundamental field.

Similar reasoning applies to all harmonics. Until the harmonic order is such that harmonic phase angle is greater than 360°, the rotating field developed by the given harmonic will rotate in synchronism with the fundamental field. Analogy can be drawn to the sampling theorem, which is used in digital audio to determine the minimum sampling frequency which may be used to record a signal. The rotating stator current pattern is spatially sampled, with each slot corresponding to a sampling point. Any components of this current pattern which have a higher frequency than the sampling rate (number of phases) will be aliased. Thus, in a three phase machine, the fifth harmonic ten pole field is aliased into a two pole field of different rotational rate, whereas in a five or greater phase machine the fifth harmonic ten pole field is correctly represented.

All temporal harmonics up to the number of phases will be co-opted into having the same synchronous speed as the fundamental. [This is discussed in more detail in the section titled "Harmonics Discussion".]

Spatial Harmonics:
The magnetic field structure developed by any given phase in a motor has a spatial structure which may again be analyzed by Fourier series into a set of sinusoidal wave functions. Each winding of the motor occupies a physical angle, which determines the minimum angular change of the developed magnetic field.

Again analyzing the fifth harmonic:
In the three phase machine, the angular difference between windings in terms of the fundamental rotating field is 60°. For the fifth harmonic, this angular difference is 300°, again equivalent to -60°. In this case, the fifth spatial harmonic is generated by the fundamental applied voltage, and has the same frequency. The rotating field associated with the fifth spatial harmonic thus has a synchronous speed one fifth that of the fundamental. Such spatial harmonics can cause dips in the torque/speed curve at low speeds, and can lead to cogging, dragging, or other torque irregularities.

As the number of phases increases, the electrical angle between phases decreases. In a five phase machine, the angular difference between windings is 36°, and the fifth harmonic is no longer aliased. The fifth harmonic will now rotate in synchronism with the fundamental rotating field, simply changing the shape of the field.

Similar arguments apply to higher order harmonics with increased phase counts. Again, spatial harmonics up to the number of phases will generate rotating fields of the same synchronous speed as the fundamental field. [This is discussed in more detail in the section titled "Harmonics Discussion".]

Benefits of Harmonic Synchronism:
There are two situations in which harmonic synchronism is of special value. The first is when there is harmonic content in the drive voltage. The second, and far more important circumstance, is when the motor is driven to high levels of saturation.

The relation between the current applied to a winding and the magnetic field developed in the motor is not linear, being subject both to hysteresis and to substantial curvature. The net result is that although a perfect sinusoidal current may be applied to a winding, a magnetic field will be generated which has harmonic content. The level of harmonic content depends upon the saturation of the iron; conventional high efficiency motors keep saturation levels low in order to minimize the generation of spatial harmonics. Higher saturation levels, however, result in increased power handling capacity for a given size motor, and are especially beneficial in starting, and intermittent overloads, both for motors and generators.

The effective use of the spatial harmonics means that higher saturation levels may be used. While iron losses and eddy current losses will be increased at high saturation levels, the losses associated with harmonic current flows and conflicting rotating fields will be greatly reduced.

The Borealis motor is capable of increased power output from a given size machine or increased efficiency at fixed power output.

Square waves are rich in odd order harmonics. Three phase motor drives which use square wave inverters are subject to noise and torque problems. However, square wave inverters are much simpler and are less expensive to design and build than sine wave inverters. The power electronic devices operate at substantially lower frequencies, and can have much lower losses. Thus there is a strong economic advantage to the ability to use square wave inverters.

The Borealis motor is capable of using square wave power because it has been designed to utilize harmonic power beneficially.

Enhanced Copper Use:
Two design techniques are used to reduce the effects of spatial harmonics on conventional three phase motor operation. These are the use of chorded windings and the use of distributed windings.

Chorded windings are windings which do not span a full 180 electrical degrees. The net result is that the voltages induced in each half winding are not in phase with each other, and the total voltage induced in the winding is reduced. In motor operation, flux density will increase unless the number of winding turns is increased. The benefit is that the phase difference between the winding sides is different for different harmonics.

The chording factor for a winding is given by:

$$k_p = \sin\frac{\rho}{2}$$

where r is the electrical span of the winding. A 5/6 span winding has a fundamental chording factor of 0.966. However, the same winding spans more than two electrical cycles of the fifth harmonic, and the fifth harmonic chording factor is 0.259. The net result of the 5/6 span winding is that the fifth spatial harmonic is reduced substantially.

Distributed windings are windings in which the same electrical phase is applied to several windings at different electrical angles. Again the net result is to reduce the total voltage induced in the windings. For motor operation, the flux density will again increase unless the number of turns is increased. Again the benefit is that the distribution factor is less for the harmonics than it is for the fundamental.

The distribution factor for a set of series connected windings is given by:

$$k_b = \frac{\sin(n\alpha / 2)}{n\sin(\alpha / 2)}$$

where n is the number of slots per pole phase group and a is the electrical angle between slots. In a conventional three phase machine, a pole phase group will span about one third of a pole and have a fundamental winding distribution factor of about 0.955. For the same winding, the fifth harmonic winding distribution factor will be 0.191. Again, the harmonics are selectively reduced in intensity as compared to the fundamental.

However, the fundamental is affected, and the number of winding turns must be increased to maintain proper flux density. The combination of the chording factor and the distribution factor in a conventional three phase 5/6 span machine is that the number of turns is increased by about 8%. Neglecting end copper changes, this means that the length of the copper wire used is increased by about 8% (the end copper is shorter, depending upon the length of the motor -- this may eliminate any length increase). Furthermore, because there are more turns, the size of wire which may be used is reduced. The net result is to increase by 10% to 17% the electrical resistance of the winding over that which would be expected were concentrated full span windings used. Some motor designs make use of 2/3 span windings; in these machines winding resistance is increased by upwards of 47%.

Additionally, while winding distribution and chording have the effect of reducing spatial harmonics, they can enhance sensitivity to temporal harmonics. Thus the penalty for enhanced torque quality in conventional motors is decreased efficiency.

The Borealis motor makes use of concentrated full span windings with unity chording and distribution factors.

Such winding technique is possible because the polyphase nature of the motor makes harmonic elimination unnecessary. As a result, fewer turns are needed for a given voltage, and the resistance of the windings is reduced. Effectively, the Borealis winding increases the apparent conductivity of the copper wire.

The net result of the Borealis winding and drive technique is a motor with enhanced efficiency in normal conditions, with enhanced overload capability, which makes use of more inverters which may be smaller and simpler (and cheaper) than conventional three phase inverters.

Extended Harmonics Discussion

Describing Harmonics Other Than The Fifth:
In the description above, an example was made of the fifth harmonic flowing in the fifteen phase machine. This particular example was used so that the phase angles would correspond to those found for the fundamental in a three phase machine of higher pole count. However, other than their familiarity, there is nothing particularly beneficial about these phase angles. All that is necessary is that the phase angle of the current feeding a particular winding match the electrical angle of that winding.

In the case of a 15 phase machine, two pole machine, windings are 12 degrees apart. The currents feeding adjacent windings have a timing difference which corresponds to 12 degrees of an electrical cycle. We consider driving the machine with fifth harmonic rather than fundamental current. Obviously, the motor is not driven with fifth harmonic in actual operation; the actual drive waveform is composed of the fundamental accompanied by various superimposed harmonics.

The timing difference between the fifth harmonic waveforms is exactly the same as that of the fundamental; however because the fifth harmonic is at five times the frequency of the fundamental, when this timing difference is measured in terms of degrees relative to a fifth harmonic cycle, the phase angle between adjacent windings is 60 degrees. A concrete example: consider a 10Hz fundamental. Each cycle is 100 milliseconds long. Adjacent windings are driven 1/30th of a cycle apart, or 12 degrees, for a time delay of 3.33

milliseconds. We now consider the fifth harmonic. The fifth harmonic is locked in time with the fundamental, so each winding is still driven with a 3.33 millisecond time delay. But the period of the fifth harmonic is 20 milliseconds, so this delay corresponds to 1/6th of a cycle, or 60 degrees. (Note: this is a 15 phase machine, but each winding has two sides, so there are 30 phases of current to be considered. We drive 15 phases, but get 15 more 'for free' on the opposite coil sides.)

As we circle around the stator, the fifth harmonic phase angle cycles through the entire 360 degree cycle, five times. While the machine is a two pole machine with respect to the fundamental drive waveform, it is a 10 pole machine with respect to the fifth harmonic. For any given number of poles, the fifth harmonic will turn five times faster than the fundamental. At the same time, for any given frequency a 10 pole machine will turn at one fifth the speed of a 2 pole machine. These two effects exactly balance out, and fifth harmonic excitation produces a rotating field with 5 times the number of poles, but turning at the same frequency as the fundamental.

For the ninth harmonic, the same sort of discussion applies. In this case, the 12 degree fundamental time delay corresponds to a 9*12=108 degree time delay for the ninth harmonic. Adjacent windings are thus driven 108 degrees apart. As we circle around the stator, the ninth harmonic phase angle cycles through the entire 360 degree cycle nine times. So the ninth harmonic produces an 18 pole magnetic structure, and excites it at nine times the frequency. The net result is an 18 pole structure turning in synchronism with the fundamental.

As I write this, I see a potential point of confusion, so I will digress: For the ninth harmonic, as we circle the stator, we see relative phase angles of: 0,108,216,324,432=72,540=180... It is noted that we have 30/18 = 1.667 slots per pole, rather than a nice integral number. For a star connected half bridge drive, this introduces some drive balance issues for these harmonics, but does not alter the fact that a harmonic rotating field is produced with a higher pole count, and this higher pole count field is energized at higher frequency, producing a rotating field that rotates at the same speed as the fundamental rotating field.

For the eleventh harmonic, the 12 degree fundamental time delay corresponds to a 132 degree time delay. Adjacent windings are driven 132 degrees apart, and a 22 pole magnetic field structure is produced. There are 30/22 = 1.364 slots per pole. This 22 pole rotating field rotates in synchronism with the fundamental.

Let us consider an 11 phase machine. There are 22 stator slots, and each winding is 360/22 = 16.364 degrees apart. The fundamental phase difference is similarly 16.364 degrees. For the eleventh harmonic, the phase difference is 180 degrees, meaning that adjacent slots are being energized in inverse relation. We have reached the limiting case of 1 slot per pole. For the eleventh harmonic, the currents flowing in the slots are exactly the same as those in a 22 pole single phase machine.

Limits of Temporal Harmonic Co-Option – Harmonics Higher than the Phase Count:
The above examples show several cases of harmonic fields which are produced by harmonic drive waveforms. Owing to the inverse relation between number of poles in the rotating field and the speed with which the field rotates, it may be understood that as long as the number of poles in the harmonic rotating field is the same as the order of the harmonic, then the harmonic rotating field will rotate in synchronism with the fundamental.

Since the above examples show cases where this works, it becomes useful to provide examples of where this synchronism fails.

Consider again the 15 phase machine, but now consider the 17th harmonic. The fundamental electrical angle is 12 degrees, so the 17th harmonic electrical angle will be 12*17=204 degrees. A list of the relative phase angles is:

0 = 0 = 0
204 = 204 = -156
408 = 48 = -312
612 = 252 = -108
816 = 96 = -264
1020 = 300 = -60
1224 = 144 = -216
1428 = 348 = -12
1632=192=-168
…

For the 17th harmonic, the electrical phase angle is now greater than 180 degrees. Rather than producing the 34 pole rotating field needed to bring the 17th harmonic into synchronism with the fundamental, a lower pole count field is produced. A minimum of a single slot per pole is needed to define the current structure which produces a rotating field. If we examine the third column, we note that the positive increase of 204 degrees per winding corresponds to a negative value of 156 degrees; less than the 180 degrees required for a single slot per pole. For the 15 phase machine, the 17th harmonic, rather than producing a 34 pole rotating field, will alias, and produce a 26 pole negative sequence rotating field.

In general, for a 2N pole, M phase machine, all harmonics H up to M will produce rotating fields with a number of poles equal to 2N*H. When excited with a fundamental frequency F, these rotating fields will rotate at a speed equal to (F * H) / (N * H) = F/N, the same frequency as the fundamental. All harmonics greater than M will produce rotating fields with a pole count aliased to be less than or equal to M. All harmonics from ((2n+1)*M +1) {one greater than odd multiples of M} to ((2n +2)*M -1) {one less than even multiples of M} will be aliased to negative sequence rotating fields, with pole counts ranging from 2 to 2(M-1). All harmonics of the form 2M {even multiples of phase count} correspond to zero sequence currents, and will not flow in star connected machines. All harmonics from ((n2+2)*M +1) {one greater than even multiples of M} to ((2n+3)*M -1) {to one less than the next odd multiple} will be aliased to positive sequence rotating fields, with pole counts ranging from 2 to 2(M-1). Finally, all odd multiples of M will produce non-rotating fields akin to the field produced by a single phase machine.

A final example: again the 15 phase, two pole machine, considering the 29th harmonic. The phase angle between adjacent windings is 12*29 = 348 degrees, which corresponds to -12 degrees. Calculating the relative phase angle for this harmonic for each phase, we find that the 29th harmonic produces a two pole rotating field which is negative sequence, meaning that it rotates in the opposite direction from the fundamental, and it rotates at 29 times the frequency of the fundamental.

In general, the intensity of harmonics goes down as the order of the harmonics goes up. By using a large phase count, all low order harmonics can be brought into synchronism with the fundamental, leaving only very low intensity high order harmonics out of synchronism.

Spatial Harmonics – Co-opted like Temporal Harmonics:
The sampling theorem states that a bandwidth limited signal spanning frequency F may be represented by samples taken at a frequency of 2F. In the baseband case, this boils down to "A continuous waveform may be uniquely represented by samples, as long as you have at least two samples per each of the highest frequency cycles in that waveform." In the case of the temporal harmonics, the stator slots essentially sample the rotating current structure which generates the rotating magnetic field. When there are at least two stator slots per pole pair, the sampling is correct, and the harmonic magnetic field is correctly produced. When there are fewer than two stator slots per pole pair, the harmonic magnetic field is aliased into one of the baseband harmonic fields, and synchronism is lost.

In the case of spatial harmonics, we are again dealing with a sampling issue.

Just as the temporal harmonics have the same time relation as the fundamental, leading to different angular variations relative to the harmonic, the spatial harmonics produced by each winding are held to the same angular relation to their respective fundamental.

Again considering the 15 phase machine. Adjacent windings are 12 degrees apart. Consider the 'north pole' of the flux distribution of each winding. Each winding produces a 'north pole' that is 15 degrees away from that of the adjacent winding. Now consider the fifth harmonic. Each winding produces 5 fifth harmonic north poles, each 72 degrees apart. The angular displacement between the north poles produced by adjacent windings is still only 12 degrees. As adjacent windings are energized, both the fundamental magnetic field and the harmonic magnetic field shift by 12 degrees, in synchronism.

As before, it is instructive to examine where this breaks down. Again consider the 15 phase machine, but now examine the 17th harmonic. Each winding produces 17 north poles for the 17th harmonic, each 360/17= 21.2 degrees apart. When adjacent windings are energized, the magnetic field shifts by 12 degrees, however for a 17th harmonic north pole, this shift is greater than the spacing between the north poles. As far as the 17th harmonic is concerned, rather than shifting 12 degrees in one direction, the field has shifted 9.2 degrees in the other direction.

The break occurs when the spacing between adjacent phases is greater than the spacing between poles, or greater than 1/2 the spacing between north poles.

To complete this description, we will explore a series of harmonic fields on the 11 phase machine.

The angular spacing between windings is 16.36 degrees.

For the fundamental, there is a single north pole. The pole spacing is 180 degrees. When an adjacent winding is energized, this pole shifts by 16.36 degrees.

For the third harmonic, there are three north poles. The pole spacing is 60 degrees. When an adjacent winding is energized, this pole shifts by 16.36 degrees, in synchronism with the fundamental.

For the fifth, seventh, and ninth harmonics, the same analysis applies.

For the eleventh harmonic, there are 11 north poles. The pole spacing is 16.36 degrees. When an adjacent winding is energized, the poles shift by 16.36 degrees; there is no difference between a forward and a backward shift. For the 11th harmonic in an 11 phase machine, the harmonic rotating field is akin to that of a single phase machine; determined by the rotation of the machine.

For the thirteenth harmonic, there are 13 north poles. The pole spacing is 13.85 degrees. When an adjacent winding is energized, the poles shift by 16.36 degrees, however, if we simply examine the 13th harmonic, we find that the 'nearest neighbor' north pole after the adjacent winding is energized is only -11.34 degrees away. The thirteenth harmonic no longer rotates in synchronism.

Cost

There are two elements to the cost of the Chorus™ Motor: the motor, and the drive.

Motor
A Chorus™ Motor will cost essentially the same as AC motors built on the same frame sizes (and far less than DC motors). When compared on the basis of cost/performance, the Chorus™ will be far less expensive than comparable variable frequency motors, and potentially competitive with fixed frequency motors, depending on the application and increase in continuous torque capability.

Assuming that future motors, like the present prototype, are made on standard frame sizes, the other motor material and assembly costs should be identical to those of existing motors.

Drive
It is clear that the Chorus™ uses many more components than a comparative (larger) 3-phase motor which has the same performance. However, this is countered by a number of cost-reducing features:

- Increased harmonic tolerance will allow for slower switching speeds, and thus slower active devices. Per unit power handling capacity, SCR devices can be considerably less expensive than IGBTs. However because of switching complexity, these devices are currently only suitable for slow switching, e.g. for so-called six step drive. The Chorus™ Motor will enable the use of SCR and GTO slow switching devices, for increased savings. SCRs are approximately 1/3rd the cost of IGBTs, and when their overload capacity (6-10 seconds for SCRs as opposed to fractions of seconds for IGBTs) is taken into account, an SCR costs 1/9th that of an equivalent IGBT.
- For large motors (over about 180 kW), the ability to use smaller transistors (a result of having more phases) will reduce the cost of the electronics by at least a factor of 3.
- The higher efficiency of the motor slightly reduces the size of the electronics for a given application size.
- The Chorus™ is harmonic-tolerant enough to permit the use of square wave drives. Performance would be slightly degraded, but the cost reduction in the drive is expected to be dramatic. For this reason, it is expected that many Chorus™ motors with square wave inverter drives will enter the marketplace.

Reliability

Chorus™' drive will be more reliable than other inverters because of the high redundancy inherent in having many phases instead of 3. The loss of a phase, or even 3, would not be catastrophic to an 18 phase motor, though efficiency and performance would suffer accordingly.

The reliability of Chorus™ motors is equal to that of 3-Phase motors. For larger motors, the ability to use low voltage drive and insulation systems will increase the reliability of the motor itself.

This redundancy should make the Chorus™ more reliable than any competing DC or AC motor.

Chorus™ vs. DC: Theoretical Maximum Torque

When a DC machine is spinning, each commutator section is used in turn, passing current to the rotor winding. Each commutator section is heated for an instant, and then being cool down. When the machine is in a locked rotor condition, or turning very slowly, then the commutator sections are used for very long periods of time before the load is passed to the next conductor.

When the motor is locked, one conductor is carrying all of the load, while the entire rest of the commutator is sitting unused. It gets worse than this, however: resistance heating scales as the square of the current. A particular amount of current, run through a given wire, will produce a certain amount of heating. Half that current through the same wire would yield only 25% of the heating. If two wires are used, with half the current running through each, then the same total current flows, with half the heating. In order to limit commutator and brush heating, the cross section of the commutator must be much larger than that of the wire used in the rotor. The commutator can take up considerable space, and current limitations of the commutator are often the limiting factor in motor overload performance.

In an AC machine, the current is distributed throughout the entire rotor winding, smoothly varying from zero current to full current. This distribution of current means that for the same amount of total rotor wiring, and for the same effective current, there will be less heating in the rotor. Additionally the rotor is much simpler, with no complex insulation system and no commutator, meaning that one can wind more copper into a less expensive rotor of the same size. Finally, even when the rotor is locked, the AC field is still rotating, meaning the rotor heating is distributed to the entire rotor. The more-even heating of the rotor means that a given level of overload can be maintained for a longer period of time.

Finally, the voltages seen in the AC rotor are much lower than those seen in the DC rotor; meaning that simpler, higher temperature capable insulation systems can be used. Most production AC induction rotors use aluminum cast into rotor slots, with no insulation at all.

All of these factors combine to mean that the Chorus™ overloads to a higher level, for longer periods, and with less damage, than a DC machine. Experimental results support this conclusion.

Losses and Efficiency

Saturation Losses

Actual core losses are not significantly larger in the Chorus ™; true losses in the iron core result from the area between the two branches of the hysteresis curve, and do not significantly change once the iron is being well saturated. However, there is a significant loss associated with increasing saturation, specifically harmonics associated with the change in permeability of the iron. This loss is quite reasonably called core loss, as for a machine at no load, increasing saturation will result in increasing losses. The distinction is relevant in order to differentiate the Chorus motor.

The current flowing in an inductor depends upon the voltage applied to that inductor, the duration of the applied voltage, the inductance of the inductor, and the resistance of the inductor. The inductance of an inductor depends upon the change in magnetic flux which couples the windings as a function of the change in current flowing through the windings. When the permeability of the iron changes as a result of saturation, the inductance of the inductor itself changes. Specifically, the inductance decreases, and the current flowing in the windings increases.

We thus see two effects which will both decrease efficiency. The first is that there is distortion of the magnetic field created by the individual windings, specifically the creation of harmonics. The second is that there is a substantial increase in winding current flow, and thus more heating of the windings.

In the Chorus(TM) motor, we see both of these effects; as saturation is increased, there are greater losses associated with increased current flow, and there is increased distortion of the magnetic field. The distortion-created harmonics have much less effect on a Chorus™ motor than upon a three phase machine, however the increased winding heating affects the two motors in a very similar fashion.

Winding/Spatial Harmonics Efficiency Gains

In the first case, we compare machines operating on pure sinusoidal drive, both at the same low saturation level. In this case, the high phase order machine has two points of benefit over the three phase machine: spatial harmonics and improved winding use.

Spatial harmonics are used by the high phase order machine, and thus do not present the serious loss term that they may present for three phase machines. However, proper winding techniques on the three phase machine can greatly reduce the effects of spatial harmonics.

In order to reduce the effects of spatial harmonics, three phase machines use winding distribution, and short pitch, or chorded windings. Both of these techniques eliminate most of the negative effects associated with spatial harmonics, but only by increasing the number of turns of wire required. The three phase machine, for the same slot area, must use a greater number of turns of wire, and the wire must be thinner. This longer, thinner wire has more electrical resistance, and thus presents a loss term greater than in the high phase order Chorus™ machine.

The increased power handling results directly from the reduction in winding resistance; harmonic losses are ignored as having been solved by the winding. In this case, using conventional values for distribution and chording, winding resistance will be reduced by roughly 10% -15%. This translates directly to an improvement in power handling capability of approximately 1/2 the reduction in resistance, both for continuous run and for overload. As resistance losses scale as the square of the current, the improvement is proportionally better during overload.

Increase in Power Handling; Conventional Saturation
We consider machines used at conventional saturation levels, but operated with a variable voltage, variable frequency inverter system. In this case, there are harmonics present in the drive waveform.

All of the comparisons in terms of winding efficiency apply, giving a 5-7% benefit to the high phase order machine. Additionally, the winding techniques used in three phase machines in order to cancel spatial harmonics cause the machines to act as 'short circuits' for temporal harmonics. Common practice is to de-rate conventional three phase machines with supplied with inverter power by 10%. This de-rating does not apply to the Chorus™ motor. The net result is a 15-20% power handling improvement. As resistance losses scale as the square of the current, the improvement is proportionally better under overload.

Hard data is available at the Borealis web site: http://www.borealis.com/motor

Increase in Power Handling; Increased Saturation
As the motor iron becomes saturated, its magnetic permeability decreases, meaning that for a given change in magnetic field strength, a disproportionate change in current flow is required. As the motor is saturated, larger amounts of harmonic currents flow in the windings. In order to avoid this, three phase machines are built to saturation levels on the order of 110,000 to 130,000 lines per square inch. However, the greater the magnetic field strength, the greater the torque for a given current flow. Since winding heating is proportional to the square of the current flow, an increase in flux density means a decrease in current flow, and a decrease in winding heating.

The permissible maximum saturation depends on the particular details of the magnetic iron used. Chorus™ has efficiently achieved higher torques at lower slips than the original motor, which indicates increased saturation.

Power handling will be increased by the various winding factors above, and then multiplied by the increase in operating flux density.

Increase in Power Handling; Extreme Overload
The final example is motor operation under extreme overload conditions.

As applied drive voltage is increased, both the magnetic flux and the available rotor current increase. For a given power output this means that rotor current decreases, but that more power output is available. In general available rotor current scales linearly with saturation, and available torque scales as the square of the saturation. We have operated at 30 second overload levels, meaning that over the course of thirty seconds a maximum temperature rise was reached. The torque measured was 3 times the nominal breakaway torque of the unmodified three phase machine, implying a saturation increase of 73% over the saturation seen in a three phase machine at breakaway.