Chorus™ Motor Tutorial
Meshcon (Optimized Variable Torque) Derivation

Analysis of *Meshcon* Winding Voltages

In the Chorus™ 'Meshcon' system, a high phase order inverter is connected to a high phase order concentrated winding induction motor using a mesh connection. This permits a change in the 'V/Hz' ratio which the inverter sees, which allows the full inverter output capability to be used at both high speed and low speeds.

With a conventional inverter drive system, the inverter will deliver maximum power when producing full output voltage at full output current. For low speed operation, the output voltage of the inverter is restricted by the terminal voltage of the motor, meaning that the inverter cannot deliver full output power. By increasing the motor V/Hz ratio, say by increasing the number of turns, the terminal voltage of the motor for low speed operation can be increased, thus increasing the low speed output capability of the inverter. However this will also increase the terminal voltage of the motor at high speed, and adversely affect high speed capability.

With Chorus™ 'Meshcon' the V/Hz ratio can be changed electronically, during motor operation. This means that full inverter capability is available for both high and low speed operation. The change in V/Hz ratio is accomplished without the use of contactors or otherwise changing machine connection during operation.

In a mesh connection, each winding termination is connected both to an inverter output leg and to a termination of a different winding. This means that each inverter output leg is connected to two windings, and the current flowing out of each inverter leg is the <u>difference</u> between the current flowing into each winding. Each winding is connected between two inverter legs, and the voltage across the winding is the <u>difference</u> between the voltages applied to each side of the winding. This voltage difference can be changed by changing the phase relationship of the inverter output legs.

Below is a derivation of the voltages placed across each windings for various balanced drive conditions.

Given an inverter with *m* odd output phases, producing sinusoidal output with peak instantaneous voltage relative to neutral V_{MAX}, and operated with harmonic order *h*, the output voltage V_K of phase *K* is given by:

$$V_K = V_{MAX} * \mathrm{Re}(e^{ih*(\omega t + \frac{2K}{m}\pi)})$$

The harmonic order changes both the frequency and the relative phase angles. This may be understood by recognizing that the phase angle measures a time offset in terms of fractions of a sinusoidal cycle; when operating at higher frequencies with the same time offset, the apparent phase angle will be larger.

The exponential description is quite useful because it allows the time varying parts to be separated from the fixed phase angle parts, which will facilitate the derivation:

$$V_K = \mathrm{Re}(V_{MAX} * e^{ih\omega t} * e^{i\frac{2hK}{m}\pi})$$

The voltage placed across a winding depends upon the two inverter terminals to which the winding is connected. In a three phase machine, there is only one possible mesh connection, known as the delta connection. For high phase order machines, there are many possible mesh connections. More importantly, there are several possible symmetric connections which would be suitable for operation with a balanced drive. For these symmetric connections, each winding is connected to inverter terminals with the same phase angle difference, thus the same voltage is applied across each winding.

These symmetric connections may be described by the number of inverter phases 'spanned' by a winding. For example, if each winding is connected to phase K and phase K+1, then the 'span value' L is 1. In the well known three phase machine, the delta connection is given by a span value L of 1. Winding K is the winding connected between inverter output terminals K and K+L. The voltage across winding K is given by:

$$VW_K = V_K - V_{(K+L)\%m}$$

$$= \mathrm{Re}(V_{MAX} * e^{ih\omega t} * e^{i\frac{2hK}{m}\pi}) - \mathrm{Re}(V_{MAX} * e^{ih\omega t} * e^{i\frac{2h(K+L)}{m}\pi})$$

$$= \mathrm{Re}(V_{MAX} * e^{ih\omega t} * (e^{i\frac{2hK}{m}\pi} - e^{i\frac{2h(K+L)}{m}\pi}))$$

$$= \mathrm{Re}(V_{MAX} * e^{ih\omega t} * (e^{i\frac{2hK}{m}\pi} - e^{i\frac{2hK}{m}\pi} * e^{i\frac{2hL}{m}\pi}))$$

$$= \mathrm{Re}(V_{MAX} * (1 - e^{i\frac{2hL}{m}\pi}) * e^{ih\omega t} * e^{i\frac{2hK}{m}\pi})$$

This equation can be interpreted as being composed of three terms: 1)a scaling function of the number of inverter phases spanned by the winding, 2) a time periodic term which is the same for all of the phases, and 3) a rotation term which is specific to each phase. The rotation value for each phase is proportional to *2hKB/m*, which properly balances the drive.

As a consequence of the basic Chorus™ system, operation with harmonic waveforms changes the number of poles developed in the machine, but does not change the synchronous speed. As long as the harmonic order h is less than the number of phases in the machine, the same operational frequency *T* will result in the same rotor synchronous speed, although the frequency of the current feeding each phase will increase. In the star connected Chorus™ machine, the phase angle of the voltage feeding each phase *K* is *2hKB/m*; these same phase angles are fed to the machine when mesh connected. Thus the mesh connected Chorus™ machine will operate properly with harmonic drive.

The important issue for 'Meshcon' is what occurs to the magnitude of the voltage applied to the windings when the harmonic order *h* is changed. The magnitude scaling term at the front of the equation for the voltage applied to a winding will vary from near zero to near two, depending upon the selection of harmonic order, number of phases, and winding span. While the number of phases and the winding span are fixed by the physical layout and connection of the machine, the harmonic term may be changed purely by electronic variation of the currents synthesized by the inverter system.

Of particular interest for the present discussion are systems in which the phase angle placed across a winding is approximately, but not exactly, 120/ when operated with fundamental drive, that is with a harmonic order *h* of 1. This occurs when *L/m* is about 1/3. When a machine with such a phase count and connection is operated with a harmonic order of 3, the phase angle placed across a winding approximates 0. For example, in an *m*=17 phase machine with a spanning value *L*=6:

$$\left|(1-e^{i\frac{2hL}{m}\pi})\right|:$$

$$\left|(1-e^{i\frac{2*1*6}{17}\pi})\right| = 1.7903$$

$$\left|(1-e^{i\frac{2*3*6}{17}\pi})\right| = 0.3675$$

This means that for a given fixed inverter output voltage, the change between *h*=1 and *h*=3 operation results in a change in the voltage applied to the windings by a factor of about 1/5. Another way of looking at this is that for a given desired winding drive voltage, the change to third harmonic raises the necessary inverter output voltage by a factor of 5.

For a given fixed winding <u>current</u> and voltage, the power delivered to the winding is fixed. Since the inverter output voltage is being changed, the inverter output current must vary in an inverse fashion. This means that if a particular harmonic change will raise the required inverter output voltage, it will lower the required inverter output current. The above example is of particular benefit for improved overload capability during low speed operation.

For low speed operation, the inverter is operated with *h*=3 harmonic output. This raises the terminal voltage presented to the inverter output for a given synchronous speed, and means that for a given inverter limited output current, the winding current can be about 5 times larger than the winding current with h=1 harmonic. In this operational state, the base speed of the motor is effectively lowered by the same factor of 5, since the inverter voltage limit will be reached at a much lower synchronous speed. For high speed operation, the inverter is operated with h=1 harmonic order, which lowers the necessary inverter output voltage and enables full saturation at high speed without exceeding the inverter voltage limit.

The Meshcon system is particularly suitable for starter/generator applications, in which a single rotating machine has low speed, high torque motoring requirements to start an internal combustion engine, followed by high speed, low torque generation requirements after the engine starts. Other applications include inverter-limited traction systems, in which full power may be delivered both at low and high speeds, without needing high current switching elements for the low speed operation. The Meshcon system permits the full inverter capabilities to be used both at high and low speeds.