Understanding MCA™ Inductance & Impedance Unbalance

Induction Motors can be defined as a transformer with a rotating secondary. This is because power is induced from the stator electric circuit to the rotor's electrical circuit. Three Phase AC power is applied to the stator windings and creates a magnetic field which rotates around the stator at constant speed. The speed is determined by the number of poles and the applied frequency. This magnetic field rotating around the stator induces an EMF (electromotive force) into the electrical portion (squirrel cage) of the rotor. The interaction between the magnetic fields on the stator and the rotor convert electrical energy into mechanical torque. This brief discussion describes these principles and how they affect MCA™ measurements.

Inductance

Inductance is defined as the property of an electrical circuit or system that opposes any change in current. Inductance is represented by the Symbol L and the units are measured in Henry's. The amount of inductance in a coil is dependent on the physical construction of the coil. The five physical characteristics that determine the inductance of a coil are:

1) The number of turns in the coil; the inductance increases as the square of the increase in number of turns.
2) Diameter of the coil; the inductance is directly proportional to the cross-sectional area.
3) Length of the coil; the inductance is inversely proportional to the length of the coil. The further the turns are separated the lower the inductance.
4) Number of layers in the coil; the more layers the more inductance.
5) Permeability of the core material; the higher the permeability of the core the more inductance.

There are 2 types of inductances:

1. Self-Inductance is defined as the induction of an EMF (voltage) in a current-carrying conductor, when the current flowing through the conductor is changing. The magnetic field is created by the current in the circuit itself and induces a voltage in the same circuit. An inductor stores energy in the form of magnetic fields and opposes a change in current.

2. Mutual inductance is the EMF created when the magnetic field, created by current flowing through one circuit, intersects conductors in another circuit. Faradays law, states that when a changing magnetic field from the primary circuit intersects the conductors in the secondary circuit it induces a voltage in the secondary circuit.

A transformer is one of simplest electrical devices and are perhaps the best example of mutual inductance. The circuit with the AC source is the primary side of the transformer.
The circuit in which the magnetic field is induced into is the secondary. A transformer exhibits all the principles of mutual inductance. Transformers effectively changes voltage from one circuit to another by changing the number of turns in each circuit.

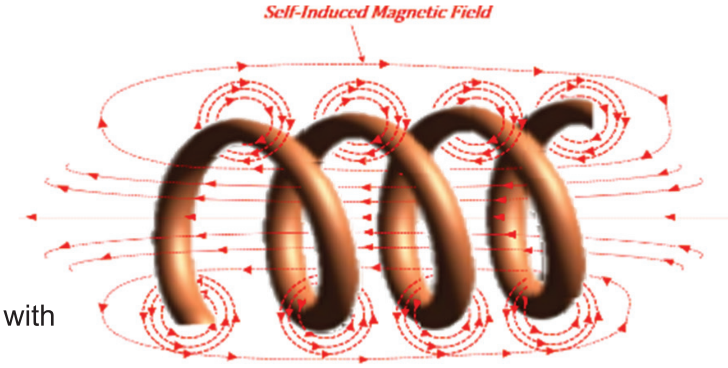

Figure 1: Self-induced magnetic field

For example, if the primary coil has fewer turns than the secondary coil, the magnetic field in the secondary will be stronger than in the primary and the induced voltage of the secondary will increase. This is a step-up transformer.

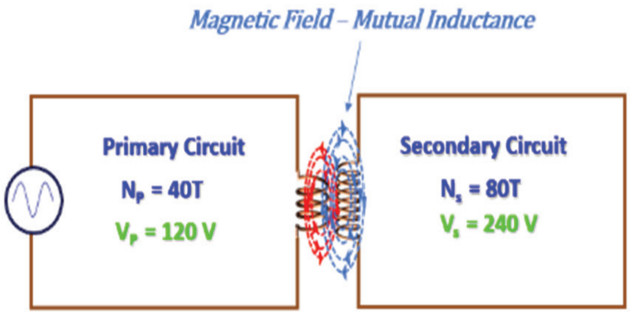

Figure 2: Manually magnetic field

Equation 1: Transformer Ratio - Vp/Vs = Np/Ns

Vp = Primary Voltage Np = Number Turns in the primary
Vs = Secondary Voltage Ns = Number Turns in secondary

Understanding MCA™ Inductance & Impedance Unbalance

AC Induction Motors

Defining the AC induction motor as a transformer the stator winding act as the primary of the transformer and primarily establishes self-inductance. During operation the rotating magnetic field relies on Faraday's law of mutual inductance to induce an EMF into the electrical portion of the rotor which is the squirrel cage. The squirrel cage consists of cast or fabricated bars (rotor bars) that provide the path for current required for mutual inductance.

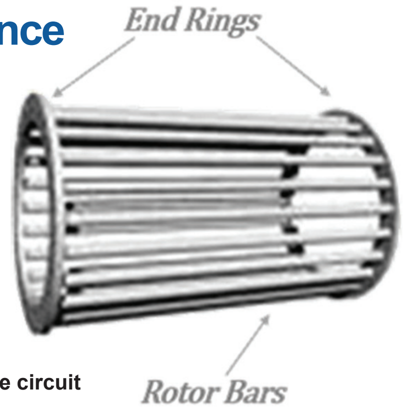

Figure 3: Squirrel cage circuit

Inductive Reactance (XL)

By definition, inductance opposes a change in current, this opposition to the changing current reduces the current flow through the conductor and is known as inductive reactance. X is measured in ohms.

Equation 2: Inductive Reactance - $X_L = 2\pi fL$

Where: f = frequency   L = inductance

Therefore, if the applied frequency or either the self or mutual inductance increases, the X_L will increase.

Impedance (Z)

Impedance is the comprehensive resistance in a circuit and consists of DC resistance, inductance reactance and capacitive reactance. The symbol for impedance is Z and the units are ohms (Ω).

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

Equation 3 : Impedance

In AC induction motors the R (resistance) is produced by the resistance of stator winding, the X_C (capacitive reactance) comes From any C (capacitance), created by insulating material between the conductors in the stator windings. However, most of the Z comes from the large contribution of inductance created by self–inductance of the stator coils and the mutual-inductance between the stator coils and the rotor bars.

Motor Circuit Analysis MCA™

Motor Circuit Analysis™ applies a series of low voltage AC and DC signals to the motor's stator windings. If the coils are all the same, the response to these signals should be all the same or "Balanced". Generally, any changes in the condition of the winding insulation will cause one or more of these measured values to change. However, due to the design and position of rotor inside the stator the MCA™ results will show an unbalance in the L (inductance) and Z (impedance) measurements in the phases even on motors in perfect condition. The MCA™ Software and AT7™ will provide a "WARN" indication when any of the phase's L or Z deviate by more than 5% from the average of the three phases. This WARN doesn't necessarily indicate a developing or existing fault but could be the result of "Rotor Position" which is addressed in the rotor reposition test below.

Stator Core

Three phases AC stator windings that create the rotating magnetic field are placed in slots located in the stator core. The number of stator slots vary from different motors. This is based on the different engineering principles. However, they are generally in multiples 6 and 12.

Figure 4: Stator Core

Stator Windings

The stator windings which form the primary of the transformer are very methodically arranged in the insulation lined slots in groups of coils to form poles. The poles are then connected to form 3 phases. The actual placement of the windings is dependent on number of poles and number of slots. Since each slot holds 2 coils and each coil

Understanding MCA™ Inductance & Impedance Unbalance

requires 2 slots it would seem there would be the same number of coils as slots. So, a stator that has 24 slots would require 24 coils. For a 2 pole 3 phase (A, B, C) motor would require 8 coils per phase, each phase would have 2 poles per phase (A1 -A2, B1 – B2, C1 -C2) or 4 coils per pole.

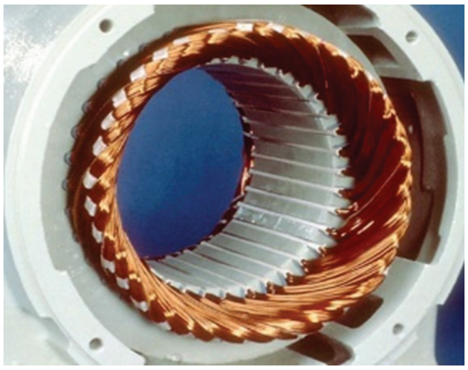

Figure 5: Stator Coils

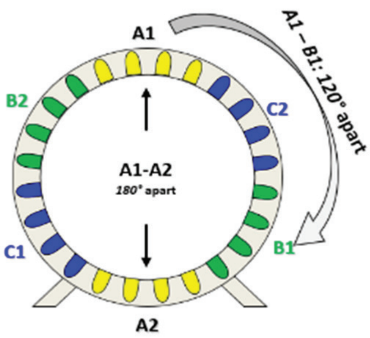

Figure 6: Motor Poles

Stator Poles

For 2 pole motors the 2 poles are located 180° apart A1 is directly across from A2, B1 & B2 are 180° apart as are C1 & C2. The phases windings have 120° separation from the other phases. A1 & B1 & C1 are all 120°apart. A2 & B2 & C2 are also separated by 120° See figure 6.

With the rotor removed from the stator and measuring the self-inductance of the stator coils only. Both the Z and L measurements will be “balanced” if all coils are in the same electrical condition.

Table 1: Unassembled Motor rotor removed

Measurement	Status	32	21	13	
Impedance	OK	49.5	49.5	49.5	0.00
Inductance	OK	23	23	23	0.00

For discussion they will all have 23mH and 49.5 Ohms.

Squirrel Cage Rotor

The rotor bars are the conductors that form the electrical circuit for the secondary coil of the transformer. The rotor bars are connected at the ends with the end rings to form a closed loop (See Figure 3). Unlike the number of stator slots which are multiples of 6 the number of rotor bars on the rotor are not dependent on rotor speed. A review of multiple tables listing motor speed indicates that power, frame size, number of rotor bars, and number of stator slots have no set and fast relationships for the number of rotor bars. In fact, motors from the same manufacture will use the same rotor design on motors with different speeds, power or frame size motors.

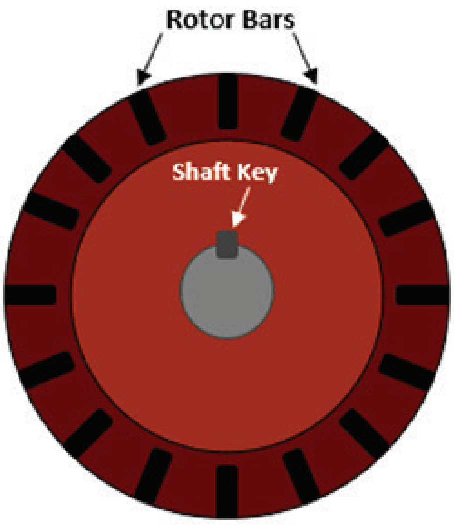

Figure 7: End View Rotor

Some motors have even number of rotor bars while others have an odd number. However, on all rotors each rotor bar is a single conductor connecting from one end ring to the other, meaning that each rotor bar represents a single turn. Figure 7 represents the drive end view of a squirrel cage rotor. In the figure there are 16 rotor bars equally distributed around the rotor, being spaced 22.5° apart (360/16 = 22.5°). The shaft key is presented as an indicator of the rotor orientation or position. In figure 7 it is oriented pointing to the twelve o’clock position.

Assembled Motor

Centering the rotor inside the stator will now introduce mutual inductance to the MCA™ results since the squirrel cage rotor now becomes the secondary of the transformer. When the rotor is positioned with the shaft key at the 12 o’clock position an inductance unbalance will occur resulting from the unequal number of rotor bars residing under each of the phase winding with the rotor in that orientation. inductance unbalance of >8% and an impedance unbalance of >5%.

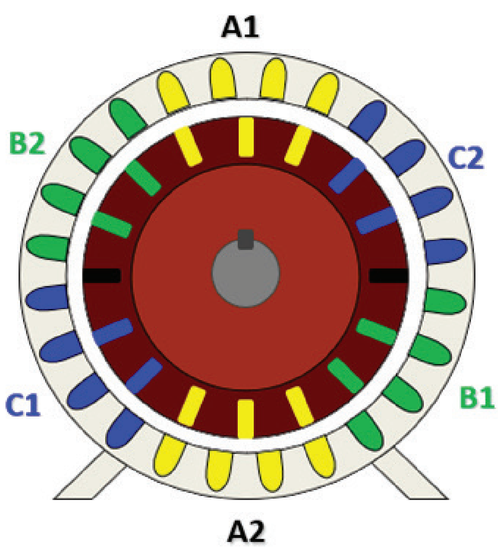

Figure 8: Assembled Motor

Understanding MCA™ Inductance & Impedance Unbalance

“A” phase will have 6 rotor bars residing in the magnetic field created when the low voltage AC signal is applied to this will add 18 mH to the overall L measurements, “B” phase only has 4 rotor bars positioned under the coils in “B” phase so this only 15mH of mutual inductance while “C” also has 4 rotor bars but they are slightly offset from the center of the field coils so this creates slightly less mutual inductance than “B” phase of it has 13.5 mH. This creates an inductance unbalance of >8% and an impedance unbalance of >5%.

Table 2: Assembled motor with rotor key at 12 O’clock

Measurement	Status	32	21	13	
Impedance	OK	61.3	65.7	59.5	0.052
Inductance	OK	28	31	26.5	0.087
		MED	HIGH	LOW	

It is important to note that there are no faults in the rotor, and it is centered in the stator. The only reason for the unbalance in the L & Z is because of the unequal number of rotor bars positioned under the phase windings.

Rotor Reposition Test

Rotating the shaft ≈ 15° The number of rotor bars, positioned under each coil changes. This effectively changes the turns ratio of the transformer and the amount of mutual inductance measured. In this position now there are 6 rotor bars under the coils in C phase and 4 under A & B phases. The new readings are in the table below.

Table 3: Assembled motor shaft key rotated 15 degrees

Measurement	Status	32	21	13	
Impedance	OK	61	60.2	67.2	0.079
Inductance	OK	27.6	26	32	0.12
		MED	LOW	HIGH	

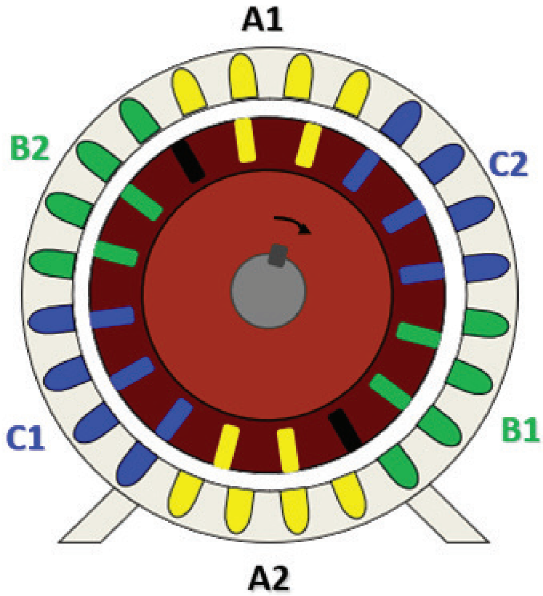

Figure 9: Shaft rotated 15 degrees

Since the turns ratio of the transformer change caused the mutual inductance to change between the stator windings with the rotor position.
To evaluate the change in these measurements, relative values are used instead of the absolute values. In table 2 above, reading the relative values left to right they were MED, HIGH, LOW in table 3 they are MED, LOW, HIGH. This indicates the unbalance follows the rotor position and strongly suggests that the unbalance is the result of rotor position. Since this is a normal condition the alarm level will not exceed a WARN level. If there no (phase angle) Fi or (current frequency response) I/F alarms present, then generally no additional testing is needed (Figure 9).

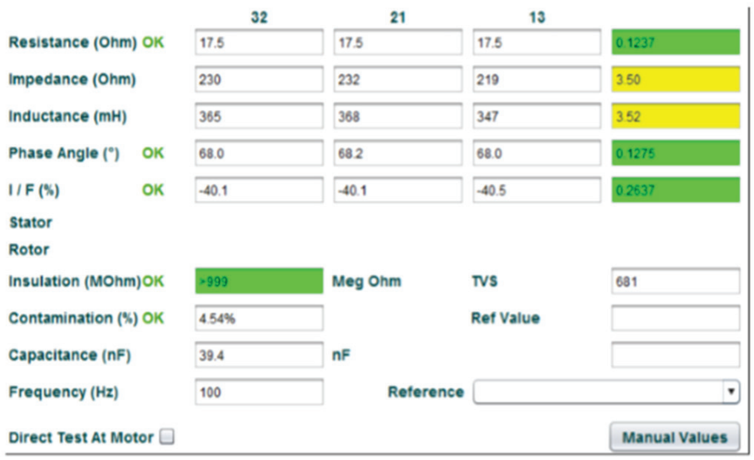

Figure 10: L & Z unbalance Fi & I/F balanced

However, if either Fi or I/F are in a WARN or BAD condition, this could be the result of the rotor position and a rotor compensated test following the procedures detailed in the MCA™ manual should be performed before condemning the motor.

		32	21	13	
Resistance (Ω)	OK	17.7	17.7	17.7	0.200
Impedance (Ω)		274	244	238	8.66
Inductance (mH)		435	388	378	8.71
Phase Angle (°)	BAD	59.7	66.3	66.6	4.48
I / F (%)	BAD	-46.3	-40.9	-40.9	3.61
Stator					
Rotor					
Insulation (MΩ)	OK	>999	MΩ	TVS	756
Contamination(%)	OK	3.57%		Ref Value	
Capacitance (nF)		20.0	nF		
Frequency (Hz)		100		Reference	
Direct Test At Motor ☐					Manual Values

Figure 11: L & Z Unbalance Fi & I/F alarm