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Breakdown Voltage Performances of Aluminum and Copper Conductor Wire Under Compression Stresses

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BREAKDOWN VOLTAGE PERFORMANCES OF ALUMINUM AND COPPER
CONDUCTOR WIRE UNDER COMPRESSION STRESSES

A Thesis
Presented to
The Faculty of the Department of Architectural and Manufacturing Sciences
Western Kentucky University
Bowling Green, Kentucky

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

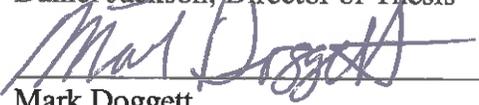
By
Rich Suchanek

May 2016

BREAKDOWN VOLTAGE PERFORMANCES OF ALUMINUM AND COPPER
CONDUCTOR WIRE UNDER COMPRESSION STRESSES

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BREAKDOWN VOLTAGE PERFORMANCES OF ALUMINUM AND COPPER CONDUCTOR WIRE UNDER COMPRESSION STRESSES

Rich Suchanek

May 2016

46 Pages

Directed by: Daniel Jackson, Greg Arbuckle, and Mark Doggett

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In the global, competitive market of energy transformation, increased operational expenses and depletion of raw materials have resulted in companies pursuing alternate materials to reduce consumer costs. In electrical applications, energy is transformed using materials with high electrical conductive properties. The conductive material used to transmit a signal is called conductor wire and is comprised of any material that has the ability to move charged particles from one point to another without propagation or delay. The conductor wire in many applications is encapsulated in epoxy resin called enamel. The enamel is the insulation system that provides necessary dielectric clearances to prevent voltage leakage. The most common form of energy transformation is the electric motor. Both copper and aluminum conductor wire are commonly used in electric motors, but copper is preferred due to thermal and electrical properties. However, there is a significant economic incentive to convert to aluminum conductor wire. Limited white papers are available comparing the performances of the two materials; the research is limited to physical and electrical performances of the raw material and does not take into considering the insulation. The conductor wire, which includes the insulation, is susceptible to damage during the manufacturing process and is an inherent risk if not fully understood. During the blocking process, the conductor wire is pushed and compressed into lamination slots. This process changes the conductor wire outer diameter to accommodate void spaces within the lamination slots. The percentage of slot

area occupied by the conductor wire is known as slot fill. The higher the slot fill, the more wire occupying the available space. The higher the slot fill, the more force required to fill the slots. High slot fill motor designs provide a performance advantage with little associated cost. The more wire pressed into the slot, the higher the potential efficiency gains. However, high slot fill motors are more susceptible to damage.

The study is designed to evaluate and measure the durability of aluminum and copper conductor wire under simulated compression stresses. Utilizing this information, electric motor manufacturers can push current design limits without affecting conductor wire quality and reliability.

Introduction

The conductor wire industry is a critical component in the spectrum of energy transformation, more specifically in electric motor applications. The quality of the conductor wire used in an electric motor has a direct impact on the product's ability to maintain dielectric clearances during the manufacturing process, as well as field operation. Electric motor manufactures are the largest consumers of both copper and aluminum conductor wire. With the complexities in the electric motor manufacturing process, the quality of the conductor wire can be compromised by mechanical stresses. Understanding the robustness of the conductor wire is essential in all electrical applications in which compression stress is exerted on the wire. Damaged conductor wire can lead to infant mortality if not detected early in the process.

Conductor wire can be made up of any conductive material, but the most commonly used are copper and aluminum. These two materials are preferred due to the relatively low cost compared to silver, gold, and zinc, which are superior in terms of conductivity. Copper conductor wire has historically been preferred over aluminum for a variety of reasons: decreased fire hazard, conductive performances, manufacturability, and overall cost.

In the early 1980s, aluminum conductor wire was believed to increase fire hazards in the housing industry. The rapid increase in electrical shorting events in buildings wired with aluminum lead to consumers questioning the durability of aluminum wire in all applications. A thorough investigation would reveal that the root cause was the splice termination process and not the aluminum conductor wire itself. In a field study conducted by the National Materials Advisory Board Committee, it was determined there

were four contributing factors to the increased failure rate among infrastructures wired with aluminum conductor wire (National Materials Advisory Board Commission on Engineering and Technical Systems, 1982). None of which, identified aluminum conductor wire as the sole contributing factor to the field events. The study revealed that suspect mechanical terminations created a high resistance connection. The reduced cross-sectional area of the connection would result in excessive thermal heat. The reduction of cross-sectional area in the wire increased the current density and thus generated heat. The elevated heat would break down the insulation system on the conductor wire and eventually result in electrical shorting across parallel paths and eventually a short to ground (Simon, 2001). A general lack of understanding in the root cause resulted in aluminum conductor wire being labeled as an inferior alternative to copper.

There was a lengthy debate on the suitability for aluminum conductor wire in electrical applications for the years to follow, especially in the competitive electric motor market. With the gradual increased copper raw material costs and the relatively stable aluminum market, electric motor manufacturers started looking to aluminum conductor wire for all applications. Large companies like General Electric have largely supported the transition to aluminum conductor wire by supplying customers with extensive white papers that compare the mechanical and electrical properties of the two materials. In the paper titled “A Comparison of Aluminum vs. Copper as Used in Electrical Equipment” (Pryor, Schlobohm, & Brownell, 2008), GE's professional engineers, Pryor, Schlobohm, and Brownell, conducted an extensive experiment to alleviate concerns of performance of aluminum wire in electrical applications. The experiment compares the physical and

electrical performance of uninsulated aluminum wire to uninsulated copper wire, with an emphasis on cost. The research provided an analytical comparison of current carrying capacity, conductivity, physical properties, termination strength, plating, and overall product offering. However, the white papers did not elaborate on the performance of insulated conductor wire. Conductor wire, which includes the insulation system, is required in all applications in which parallel current paths are prevalent (i.e. electric motors). The white paper concluded that when designed to industry standards and engineered correctly to compensate for the difference in conductivity properties, the performance between the two materials will be similar (Pryor, Schlobohm, & Brownell, 2008). The same can be said for designing electric motors, but the performances can only be equivalent if the quality of conductor wire is equal and not compromised in terms of dielectric strength. As previously stated, this is a vital component in applications with parallel current paths. Assuming all individual components of the application are of the same standard quality, the performance and life expectancy will not deviate.

With the advancements in manufacturing technologies, wire industry leaders have the mass produced aluminum conductor wire for years at a fraction of the cost compared to copper. The electric motor industry, regardless of the application, has relied heavily on the availability of aluminum conductor wire to remain cost competitive in the global market. Although this innovative technology is not new to the electric motor industry, having the manufacturability has allowed companies to provide a cost effective option to the consumer. Although the increased of aluminum wound motors provided the suppliers a cost advantage, the market demand for high efficiency motors during the transition period provided another level of complexity. Transitioning from copper to aluminum

conductor wire in itself was a challenge, but doing so at the same time while improving motor efficiency would require an extensive amount of research. A detailed analysis was necessary to understand the performance of the two conductor wire materials in an electric motor, but further consideration was required to understand the risk associated with using a softer material in the process. The conductor wire quality and robustness is a critical variable that directly affects performance and operational longevity.

The conductor wire, which includes the insulation, is susceptible to damage during the electric motor manufacturing process and is an inherent risk if not fully understood. In the construction of the motor, there are compression forces on the wire during the blocking process. If the wire is compressed beyond the design limits, the insulation will become damaged. In the blocking process, the conductor wire is pushed and compressed into lamination slots. This process changes the conductor wire outer diameter (OD) to accommodate void spaces within the lamination slots. The percentage of slot area occupied by the conductor wire is known as slot fill. The higher the slot fill, the more wire occupying the available space. The space becomes available during the blocking processes. The higher the slot fill, the more force required to fill the slots. High slot fill motor designs provide a performance advantage with little associated cost. The more wire pressed into the slot, the higher the potential efficiency gains. However, high slot fill motors are more susceptible to damage during the manufacturing process due to the elevated compression stresses.

Problem Statement

The stressful nature of the electric motor manufacturing process exposes the conductor wire to tensile, sheer, and compression forces. Advanced technologies and

effective process monitoring have provided some level of risk mitigation, but the conductor wire is still susceptible to damage. In the wire manufacturing process, the conductor wire is extruded to acquire the correct diameter, and then dipped in an epoxy insulation to encapsulate the pure metal. The wire needs to be coated with an insulating epoxy to prevent propagation, signal distortion, and frequency or noise. The noise can lead to high loop currents, thermal breakdown, and eventually end of life (Liu & Ni, 2002). Once the pure metal is extruded and the epoxy insulation applied, the end product is called conductor wire. In the motor manufacturing process, the conductor wire is inserted into a stack of steel laminations. It is vital at this point that the conductor wire is not compromised during the insert process. High efficiency motors require more conductor wire per square inch within these stacked laminations. The more wire inserted into the lamination, the higher the slot fill. The higher the slot fill, the higher insert force required to push the wire into the back of the slot. In summary, higher efficiency motors are typically designed with high slot fill requirements, which require increased compression stress during the blocking process to allow room for the next pass. During the blocking process, the conductor wire is pushed into the slots to make room for the next set of coils. The compression force can exert enough stress to displace the conductor wire insulation and eventually result in electrical shorting. Aluminum is softer and a more malleable material than copper. The purpose of conductor wire is to transmit power efficiently from one point to another without energy losses within the motor. Compromised conductor wire, regardless of the conductive material used, will lead to thermal stresses and eventually electrical shorting. There is an increased risk of

damaging the conductor wire on high efficiency motors because more wire is being pressed into the stator slots as traditional designs.

Understanding how copper conductor wire performs compared to aluminum under the same stressful conditions is vital when designing the high efficiency motors. The scope of this study was to understand the damaging effects to the conductor wire insulation coating during the blocking operations. The researcher conducted a study to compare the performance of copper conductor wire versus aluminum conductor wire under three compression conditions. The independent variable included the material of the conductor wire, aluminum or copper, and the compression conditions of 10%, 25%, and 50% conductor wire diameter reductions. The dependent variable was the dielectric breakdown voltage of the conductor wire insulation system.

Significance of the Research

All electric motors are designed to perform a designated job with some level of efficiency and reliability. There is an increased demand of product reliability in the electric motor market because of the increase in global competitiveness and emphasis in cost reduction. In order to estimate product reliability and predict life expectancy, engineers must take a systematic approach to addressing the root cause of infant failures. One way to understand potential root cause is to establish a well-defined understanding of component reliability and the results of potential manufacturing defects. Motor design, material selection, and preventive maintenance can affect the longevity of an electric motor's life, but the largest contributing factor is the degradation of the insulation system by manufacturing process or suspect design practices. Insulation degradation will be accelerated by any undetected manufacturing defect. When undetected, the defect can

result in premature electrical shorting and eventually infant mortality. The insulation system includes ground-wall barriers and conductor wire enamel (i.e. the epoxy insulation tested in the study). These components are required to keep adequate dielectric spacing between the ground fault interrupter and adjacent conductor coils and poles. The insulation system will begin to breakdown due to thermal, mechanical, and electrical stresses; all of which can occur during the manufacturing process.

The advancements in process controls in the last decade have led to superior quality, durability, and reliability in conductor wire product offerings. However, the conductor wire is still susceptible to damage due to the nature of manufacturing processes. One inherent risk is compression stresses on the wire. Understanding the effects of compression stresses on conductor wire will allow the industry to push the limits on current induction motor design without compromise. There is a growing need to drive down energy costs because of government regulations set to address the increase in carbon dioxide emissions and ozone depletion. High efficiency motors are in high demand. The operations of electric motors consumer nearly half of all electricity generated worldwide. Any inefficiency associated with current motor designs leads results in wasted energy. Energy waste translates into wasted money for both the suppliers and consumers (Emadi, 1992). Understanding the current design limitations and inefficiencies provides the conductor wire manufacturers the necessary information to improve current products and meet future customer requirements. In order to achieve higher efficiencies with current product offering, electric motor companies have to push the limits on the conductor wire used by inserting more wire into the same slot area. This in turn stresses the conductor wire drastically. These requirements are necessary to

achieve the higher efficiency ratings. This will allow the electric motor manufactures to focus on current platforms and product offerings rather than entertain new, more expensive technologies to achieve the same objective. An example would include, but not limited to, permanent magnet motors in variable speed applications. Using rare earth magnets and variable frequency-drive (VFD) systems, electric motor manufactures can gain efficiency by loading and unloading the system across a wide range of voltages to reduce power loss.

In the traditional induction motor, line voltage is applied to achieve a fixed speed. There are typically no electronics monitoring the loading and unloading of the system. Electronics provide the customer with a wide range of operating conditions to achieve higher efficiency ratings, but also add cost to the system. Any increase in motor efficiency must be balanced with the cost of the system. Pushing the current design limits by using alternate material and putting more conductor wire in the motor will provide the electric motor supplier a competitive advantage in the industry with variable-frequency applications is not a viable option. Emadi (1992) stated that data from the Office of Industrial Technology of The Department of Energy estimates 75 to 122 billion kWh annual energy saving would be expected if cost-effective technologies and practices were implemented globally. The learning and understanding can be carried over to any electrical application design by implementing efficiency best practices. This study was designed to evaluate and measure the robustness and durability of copper and aluminum conductor wire under simulated compression stresses. The compression stresses were indicative to what occurs to the conductor wire during the blocking process where the conductor wire is pressed into the stator slots.

Purpose of the Research

The researcher conducted this study to understand the effects of compression stress on copper and aluminum conductor wire. The study was designed to test two independent variables, material and compression reduction, and measure the effects on the dielectric breakdown, the dependent variable. The term “dielectric” is defined as having the property of transmitting electrical forces without conduction. The elimination of conduction when inducing current in electric motors prevents excessive thermal heat and turn-to-turn shorting. “The word dielectric is referred to as a material that permits the passage of the electric field or electric flux, but not particles” (Kao, 2004, p XV). Dielectric performance is a vital component on conductor wire because it does not allow the passage of electrons across parallel paths.

The study was designed to dispute the perception that insulation on aluminum conductor wire is more susceptible to damage than copper conductor wire. Data analysis was used to determine whether or not there was a statistical difference in the dielectric strength between two conductor wire materials at predetermined compression ratios. This study provided a greater understanding of the importance of a robust insulation system on conductor wire, regardless of the material. Prior research, conducted by General Electric and outlined in the whitepaper “A Comparison of Aluminum vs Copper as Used in Electrical Equipment”, has been limited to the conductivity performances, mechanical/electrical comparisons, and cost of the two raw materials (Pryor, Schlobohm, & Brownell, 2008). The proposed study was to provide another level of research and information in the electrical motor industry.

Each specimen was compressed from 10%, 25%, or 50% the original thickness to represent damage that can occur during the motor manufacturing process. As previously stated, one critical attribute that is directly affected by mechanical stresses is the dielectric voltage breakdown. When the conductor wire is compressed, the insulation coating is compromised to some degree. The dielectric breakdown voltage value is an industry standard used to understanding insulation protection capabilities. It has been observed that the voltage breakdown value is a critical component within all electrical applications. The voltage breakdown value of an insulator is the minimal voltage required to become electrically conductive and allow current to pass. All insulation components have a minimal dielectric breakdown voltage specification. The minimal specification is dependent on the voltage and current being applied. This specification is especially critical in an electric motor application where performance and efficiencies can be drastically affected by current losses. The researcher used a dielectric breakdown machine to measure the voltage across two adjacent conductor wires. The equipment increased the voltage from 0-30kV at 500V per second. The researcher then measured the voltage required for the insulation to fail. A failure was detected when current was allowed to pass from one parallel path to the other.

Hypotheses

The objective of the study was to determine if dielectric performance of aluminum conductor wire is better than the copper conductor wire under three compression reductions. The researcher hypothesized the aluminum conductor wire would perform better than the copper wire because aluminum is softer and less resistance to compression stress. The softer material would allow the insulation to disperse easier

without losing integrity. There is more resistance and frictional forces in the copper conductor wire and those forces will compromise the insulation. The hardness of the copper material would reduce the dielectric performances easier because there is more resistance in the harder material. Hence, the aluminum wire would perform better than the copper conductor wire at all three compression percentages. Statistical hypotheses were developed in Methodology to test the following three hypotheses:

1. Aluminum conductor wire has a higher breakdown voltage than copper conductor wire under a 10% compressive stress.
2. Aluminum conductor wire has a higher breakdown voltage than copper conductor wire under a 25% compressive stress.
3. Aluminum conductor wire has a higher breakdown voltage than copper conductor wire under a 50% compressive stress.

Assumptions

The researcher identified two critical assumptions during the design of the study.

1. Globally, many suppliers produce insulated conductor wire for the electric motor industry. In order to represent the population of suppliers with some level of confidence, the research assumed that all supplier quality is equivalent in terms of dielectric breakdown strength. The researcher understood that it would be very difficult to test a sampling of all conductor wire suppliers. The assumption is that all conductor wire suppliers have a minimum quality specification, regardless of the supplier. It was assumed that all the conductor wire suppliers had the same level of quality, durability, and reliability.

2. Electric motors are built from a wide range of conductor wire sizes for thousands of applications; ranging from 60G wire to single digit gage. It would be very difficult to conduct a comprehensive study to understand all products in the industry. It was assumed in the study that the wire size and insulation build represented a large portion of the electric motor population.

Limitations and Delimitations

The researcher identified one major limitation in the study. The researcher was limited on what information could be shared regarding the technical specification on conductor wire insulation. The sensitivity of the material specification and engineering requirements led the researcher to refrain from referring to minimal requirements for dielectric performances of the conductor wire. Information pertaining to the conductor wire's insulation construction and build was limited in the study for proprietary reasons. Per quality standards, all conductor wire received was required to meet or exceed a set of predetermined critical test parameters. Although these values are critical to the construction of the electric motor, this information was not required in the study. The researcher was able to share the variable data collected during the dielectric voltage breakdown testing.

In order to limit the scope of the study, the researcher identified a critical delimitation. The researcher delimited the study to one conductor wire supplier. There are many conductor wire suppliers globally, so the researcher selected one supplier that produces product in both copper and aluminum. This wire supplier was not identified by name because of the sensitivity regarding the nature of the research.

Definition of Terms

Conductor Wire – Extruded metal wire used to transmit an electrical signal from one point to another. Conductor wire is encapsulated in a nonconductive enamel epoxy that prevents current signal distortion or propagation.

Conductivity – The degree to which specified material conducts electricity, calculated as a ratio of current density to the material to the electric field that causes the flow of current (Simon, 2001).

Circular mills per amp or CM/A – The unit of area equal to the area of a circle with a diameter of one thousandths of an inch.

Dielectric – Having the property of transmitting electric forces without conduction; insulating (Kooiman, 2011).

Dielectric Voltage Breakdown – Refers to the reduction in the resistance of an electrical insulation when voltage is applied across two parallel paths (Kooiman, 2011).

Electrical Shorting – A low-resistance connection established by accident or intent between two points in an electrical circuit.

Electrical Conductor Wire – An object that permits the flow of electrical current in one or more directions (Stone, Boulter, Culbert, & Dhirani, 2004).

Electric Motor – An electromechanical energy transformer comprised of a stator and rotor. The electric motor has the ability to convert electrical energy to mechanical and vice versa (Deal, 2004).

Stator – The stationary part of a rotary system found in electrical generation or motor, especially in an induction motor. The stator is made up of three main components; conductors, core, and insulation (Stone, Boulter, Culbert, & Dhirani, 2004)

Review of Literature

Energy Transformation

Energy transformation, or energy conversion, is the process of changing one form of energy to another efficiently and without compromise. In electrical applications, energy is transformed using electrical-to-electrical, electrical-to-mechanical, and mechanical-to-electrical through conductive materials. The electrical-to-electrical transformation includes, but not limited to batteries, induction heating, and most electronic communication devices. The electrical-to-mechanical is used in electric motors, linear actuators, or any piece of machinery that requires an induced current to mechanically move an object. The mechanical-to-electrical includes any application where mechanical energy induces a current and generates electricity (Bakshi & Bakshi, 2007). An example is an electric motor generator. The necessity of energy transformation has resulted in a wide spectrum of material options for conductor wire in all applications. To be more specific, the electric motor industry has been building motors with various conductive materials in the last 25 years. Historically, copper has been preferred by due to quality performance, durability, and electrical conductivity properties. One cheaper and more abundant alternative to copper is aluminum. Regardless of the material used, one critical component in energy transformation is wire insulation.

Electric Motor Physics

As with electric motors, most electrical machines are inductive rather than capacitive, meaning the operation is based on the law of electromagnetic induction (Kuz'min & Shpatenko, 2013). The strength and magnitude of the electromagnetic field

depends on the orientation of the conductor coils and the efficiency of the current passing through the conductor wires. In order to generate an efficient magnetic field, the conductor wire needs to be properly insulated to prevent resistance/voltage leakage across parallel paths, or turns. The voltage across the conductor wire is less than a few tenths of volts when energized, so the insulation thickness can be very thin in most applications. However, the reduced thickness in insulation thickness makes the wire more susceptible to damage during the manufacturing processes (Stone, Boulter, Culbert, & Dhirani, 2004). The efficiency at which the electrons flow from the beginning of the coil to the end is a critical variable when designing an electric motor. If the conductor wire is compromised and the insulation damaged, turn-to-turn shorting will occur within the stator's coils.

Ohm's Law states that the induced current, or flow of electrons, will always take the path of least resistance. When electrons fail to pass through the desired path set forth by the conductor wire, the stator resistance and inductance will result in a large circulating current flow. The increased flow generates thermal heat because one of two reasons. Either the reduction in cross-sectional area caused essentially a bottleneck for the electrons to flow, resulting in heat, or the deviations in resistance from leakage across adjacent coils reduces the resistance and increases the current per Ohm's Law ($V=IR$). The reduced area will increase the circular mill/amp in the damaged location and will eventually generate shorting. This damaged can even be detrimental to the motor in normal operating conditions (Herrick, 2003, p. 242). The increase in thermal stresses will compromise the electric motor's insulation system and will result in infant mortality.

Assuming the conductor wire insulation is not comprised, and there are no other mechanical issues, the electric motor should not experience issue during operation.

Risk of Damaged Conductor Wire

Although the ground-wall insulation is extremely important for the life of the motor, as well as safety, ground faults can be detected in the early stages of the manufacturing process. This can be accomplished by measuring the leakage currents through high potential testing. High potential, or hipot testing, is the process of applying a high voltage to an electrical system and measuring the leakage to ground. A hipot test failure indicates a ground wall insulation component has been damaged and repair is required to prevent infant failure (Stone, Boulter, Culbert, & Dhirani, 2004). Hipot testing is considered a best practice in the industry to ensure safety to the end user. However, it is slightly more difficult to detect damaged conductor wire insulation through the same processes. More importantly, it is very difficult to define and measure the amount of stress the conductor wire can be exposed to before the insulation begins to breakdown or dissipate. The compromised insulation directly affects the dielectric performance of the wire.

Damaged or compromised wire insulation will reduce the life expectancy of any electrical application due to potential voltage breakdown. The wire insulation is designed to maintain a specific dielectric voltage breakdown value when energized with parallel currents. When the conductor wire insulation is damaged, the voltage breakdown value decreases significantly. The damage that ensues grows at an exponential rate due to the thermal-physical properties associated with electrical arcing and the buildup of carbon (or carbon tracking). Damaged conductor wire insulation also makes the application more

susceptible to failure under normal operating conditions, such as voltage surges. Voltage surges occur when power is applied to the application over time. This eventually creates large voltage spikes due to issues within the power grid. Voltage surges and spikes are common in developing countries where the power supply is not stable. If a voltage surge occurs and the insulation is damaged, the result will be high loop currents and ground faults (Toliyat & Kliman, 2004, p. 411-414). It is vital to understand the effects of mechanical stresses on the insulation system and the impact on life expectancy. There are many opportunities to damage the wire insulation because of the multi-tiered supplier operations and customer manufacturing process. In every operation in which the material is touched or handling, there is potential for damage. Understanding the robustness and durability of the conductor wire insulation is vital to improving yield throughput and overall product quality.

Field Analysis

Field root cause analysis shows a distinct linear relationship between conductor wire quality and product reliability in these applications. Assuming the design and application is per specification, poor quality and manufacturing practices can result in infant failures if defects are undetected. In a survey conducted by the institute of Electrical and Electronic Engineers (IEEE) on induction motor faults, approximately 20% of all field failures were the result of electrical shorts in the stator's windings. The 20% represents turn-to-turn shorts, phase-to-phase shorts, and ground faults, which can be, but not limited, to damaged conductor wire (i.e. windings) during manufacturing. The field claim rate is higher for larger horsepower motors because the electrical stresses related to higher locked rotor amps and voltages (Thorsen & Dalva, 1995). The stator windings are

comprised of wraps of insulated conductor wire. This wire is considered the most susceptible to damage during the manufacturing process. As conductor wire manufacturers innovate and develop new products, it is essential to maintain exceptional product quality performances across all critical characteristics. The quality and reliability of the components used to assembly an electric motor directly affects the life expectancy of the application.

Wire manufacturers such as Southwire and Eaton have remained competitive through the development and integration of alternate materials to replace the traditional copper wire for all applications. Historically, copper has been the preferred material for electrical applications because of conductive, metallurgical, manufacturing advantages. An electric motor, consisting of an arrangement of conductor coils, steel laminations, and a rotor, is a very efficient energy converter. An electric motor converts electrical energy into mechanical energy through the process of energy transformation. When an electric motor is induced with line voltage, AC or DC, the current carrying conductors in the stator creates an electromagnetic field. The magnetic field generated during this process will allow the rotor to rotate because of the magnet properties of the conductor wire and steel (Drury, 2013). In simplest terms, all electric motors use the changing of magnetic fields to produce mechanical motion.

Study Design

The researcher designed an experiment to compare the dialectic performances of insulation on copper and aluminum conductor wire under various stressful conditions. These stressful conditions tested in the study represented the conditions the conductor wire would be subjected to in the manufacturing processes. It is critical that the

insulation properties are not compromised during the stator manufacturing process because the reduction in dielectric breakdown voltage will directly affect the life expectancy.

Methodology

Research Design

The researcher followed a quantitative research methodology to collect the information and data necessary to test the hypotheses. A quantitative model was selected because the study was designed to statistically compare two groups with three subsets of variable data. This methodology allowed the researcher to measure two independent variables at a time to determine the effect on the dependent variable for each test. In the study, variable data was collected from each specimen within each subset group. These data allowed the researcher to determine if there was a significant statistical difference between the groups by conducting a t-test for differences between two populations for each subset group.

Population and Sample Size

A sample size of ten was selected because of the time-consuming nature and expense of preparing the samples within each subset group. Ten specimens per subset provided enough data to conduct a t-test for difference between means, while maintaining a decreased expected standard error. The sample size and method allowed the researcher to establish statistical significances between two critical populations (Hoyle, 1999 p.200). In the study, the major variable was the conductor wire material and the subset variable was the three compression reduction percentages. The insulation was a constant between the two conductor wire materials. With a sample size of ten per subset group, the total population for each major variable was 30 specimens, or 60 total specimens for the study. The sample size of 10 provided enough data to construct the graphical models representing the data. The graphical representation of the data was used to identify

outliers that could have been the result of noise or unexpected variation in the test instrumentation procedures.

Test Variables

The two independent variables tested in the study were conductor wire material and compression percentage. The conductor wire material consisted of copper (Cu) and aluminum (Al). The compression percentage independent variables were 10%, 25%, and 50% reduction in thickness while maintaining original cross-sectional area. By maintaining original cross-sectional area the researcher verified the samples would not overheat during testing because the material was only displaced and not removed. Maintaining the same area prevented any increase in circular mils/amp (CM/A). A circular mil is the unit of area equal to the area of a circle with a diameter of one thousandth of an inch.

These percentages were selected because they represent a variety of compression ratios that incur during the manufacturing process. Regardless of the material used in production, conductor wire is still susceptible to damage. This damage can range from minor thickness reduction of 0%-5% to extreme compression ratios up to 70%. Compression reduction greater than 70% typically results in material reduction and/or severed conductor wire. The wire can and will be compressed into the stator slots to make room for additional wire to achieve higher slot fill volumes. The objective of the study was to compare the performance of the insulation on both conductor wire materials at the various degrees of compression. Using the three defined percentages allowed the researcher to confidently represent real life situations observed in the manufacturing process.

Each specimen was identified by the conductor wire selected, the percent at which the wire thickness was reduced by, and the sample number within the subgroup. For example, the first sample of aluminum wire compressed from a 10% reduction of the original shape was identified as Al-10-1. The eighth copper wire sample compressed to 25% reduction was identified as Cu-25-8, and so on.

Instrumentation and Materials

The equipment required to prepare and test the samples included a Chatillon DC 1000 compression/tensile tester, Mitutoyo dial calipers, braided-pair machine, and an Ampac NOVA 1401 dielectric voltage breakdown tester. The Chatillon DC 1000 compression/tensile tester, Mitutoyo calipers, and braided-pair machine were used to prepare each sample to the correct compression value, and the Ampac NOVA 1401 dielectric voltage breakdown tester was used to measure the voltage breakdown of each sample (dependent variable). The NOVA 1401 tester is an automated piece of equipment used to measure the voltage required to breakdown the insulation film on conductor wire. The NOVA 1401 has a range of 0 to 30K Volts AC and is equip with a variable ramp rate setting from 50-500V per second. The NOVA 1401 meets all specifications as outlined by National Electric Manufactures Association (NEMA) and International Electro-technical Commission (IEC) to test insulated conductor wire.

The researcher used a set of dial calipers provided by Emerson Climate Technology's Engineering Lab. Per quality certification procedure, all test and measuring equipment used at Emerson's Russellville facility are controlled and calibrated annually by the Calibration Lab. The Mitutoyo caliper and the Ampac International dielectric tester were calibrated in the first quarter 2015, so the researcher did not conduct

a gauge R&R. The researcher established confidence in the measurement and test equipment by verifying calibration stickers and record retention.

The Chatillon DC 1000 compression/tensile tester was used to apply pressure on each specimen until the desired compression thickness was achieved. The wire was placed between a stationary hard stop mounted to the base of the tester and a guide block made of stainless steel. The Chatillon's pressure sensor probe was positioned to apply pressure to the guide block. The guide block measured 1 inch in width and provided the correct compression area width for all samples.

The conductor wire used in the study was described by the National Electrical Manufacturers Association (NEMA) as 200°C-220°C thermal class magnet wire. Section 1.8 of NEMA MW 1000 discussed the thermal classes for engineering design, but did not indicate the dielectric voltage breakdown requirements (NEMA, 2013). The researcher has a confidentiality agreement with the wire supplier; therefore, the technical specification of the wire material regarding the insulation material was not shared. However, the researcher was able to verify that the insulation used for both materials share the same composition, dimensions, and manufacturing process. The wire size selected for the research was 16.5G. The conductor wire used in the study is considered an industry standard in the electric motor industry.

Procedures

To prepare the samples, the researcher collected thirty pieces of copper conductor wire and thirty pieces of aluminum conductor wire measuring approximately 30" in length. The researcher then used an insulation removing tool to remove the conductor wire insulation on both ends of each sample (see Figure 1). Removing the insulation

exposed the copper and aluminum conductive material required to make the connection on the dielectric tester. The exposed area needed to be approximately 1.5 inches in length. The insulation was removed on both ends because each sample was divided in to two independent wires (or circuits) after the wire was braided.

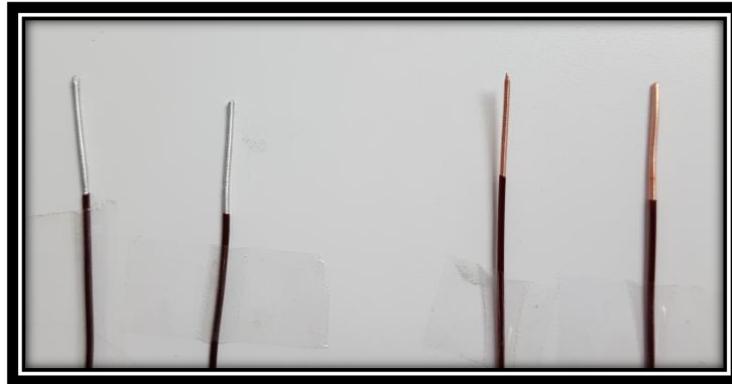


Figure 1. Insulation removed from the end of each sample

Once the insulation was removed from each sample, the researcher marked the test area where the sample needed to be compressed to the desired thickness. The area of compression was referred to as the test zone. The middle of test zone was approximately 7.5” from one end of each sample. The 7.5” measurement ensured the test zone was in the center of the braided pair. It was important that the test zone be marked prior to the compression and braiding process (see Figure 2).

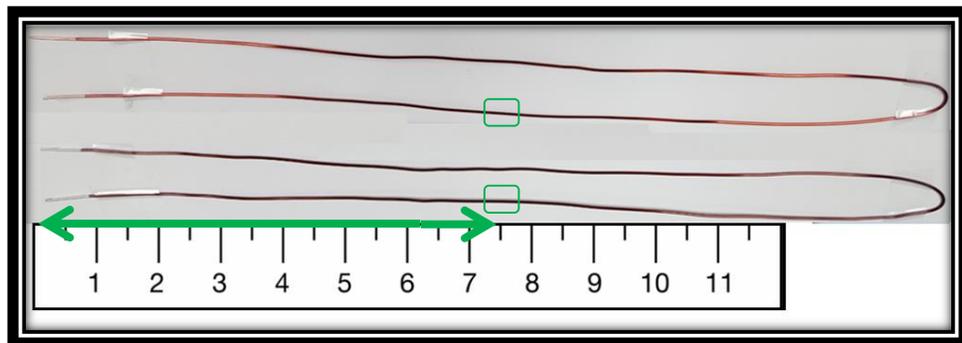


Figure 2. The test area is approximately 7.5” from one end of the sample

Once the insulation was removed and the test area identified, the researcher then compressed each sample to the desired percentage thickness using a Chatillon TCD 1000 compression/tensile tester (see Figure 3).



Figure 3. Chatillon DC 1000 compression/tensile tester

Per engineering specification, the conductor wire outside diameter (OD) for both 16.5 aluminum and copper specimen should measure between 0.0425” and 0.0437”. To verify the correct percent reduction was achieved, the researcher measured each sample in the test area and calculated the desired thickness measurement using the equation listed in formula (1).

$$X = Y - (Y \times Z) \quad (1)$$

X = Final thickness measurement +/- 0.001”

Y = Average of five readings at the test area

Z = Numerical percentage reduction value for the sample (i.e. 10% = 0. 10)

The researcher then prepared the test area for each sample to the correct thickness using the Chatillon DC 1000. The test area on each sample was placed between a steel block and the Chatillon pressure sensor (The test setup can be seen in Figure 4). Using the calculation from formula (1) for each sample group, the Chatillon DC 1000 was set up to travel 0.0005” at a time until the desired thickness reduction was achieved. The researcher verified the compression thickness using the Mitutoyo calipers. The researcher completed the compression and measurement on the sixty samples. If the sample was compromised during the compression process, the sample was discarded and the process repeated.

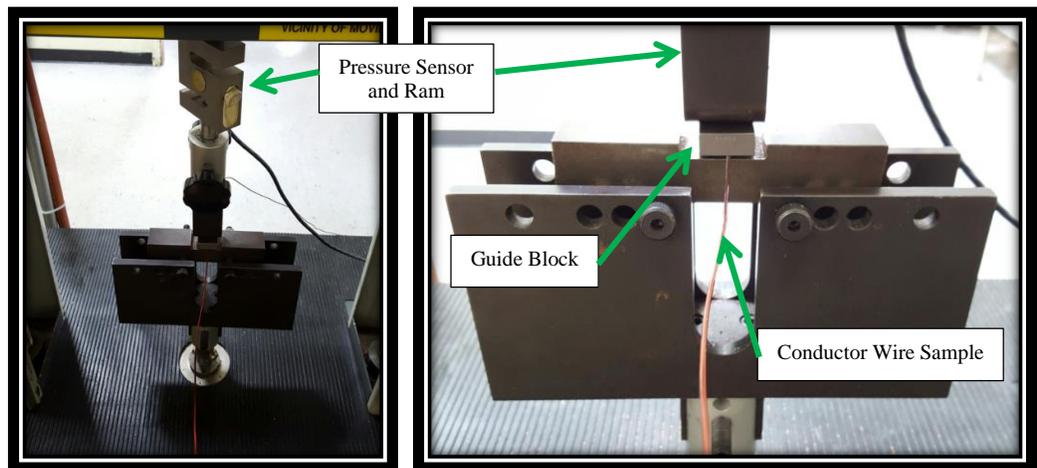


Figure 4. Compression fixture setup

After the test area on each sample was preped and the thickness verified with the calipers, the researcher created each braided-pair using braided-pair machine (see Figure 5). The braided-pair machine is used to twist each sample into a braid using a weighted force to maintain constant tention as a spindle was rotated. The researcher repeated the test procedure for each sample within the study to ensure accuracy and repeatability between the sample groups. The test setup is shown in Figure 5 with the critical

components numerically labeled. The sample was fed through the rotating spindle labeled as 1 and the two ends were anchored with the wing nuts labeled 2 and 3. A two pound weight, labeled 4, was suspended from the sliding track to apply tension during the braiding process. The researcher then rotated the spindle arm for ten complete revolutions (see Figure 6 and Figure 7).



Figure 5. Braided-pair machine

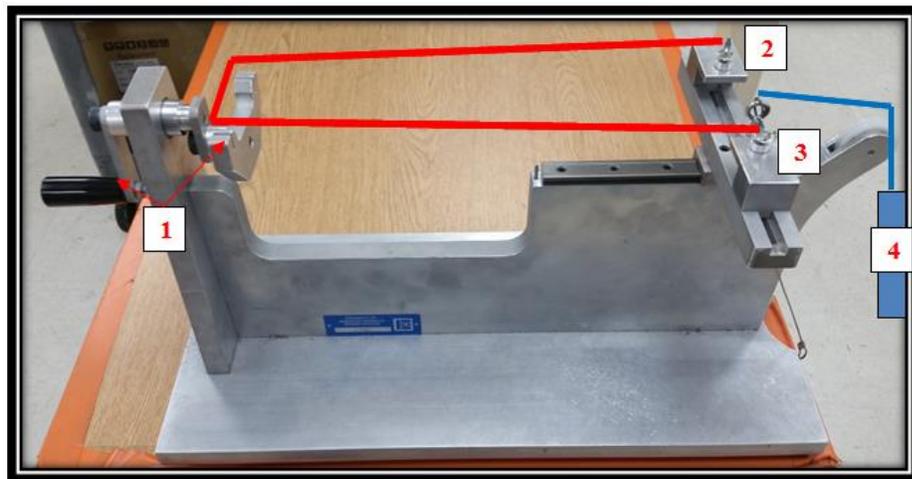


Figure 6. Braided-pair machine –test setup

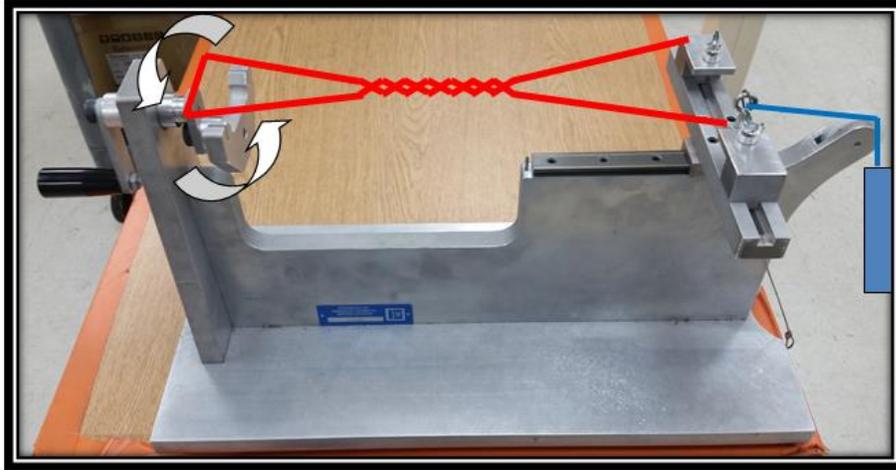


Figure 7. Braided-pair machine – after turning spindle

The last step in the braiding process was to remove the sample from the fixture, label as needed, and then cut the wire creating two independent paths for the current to flow (see Figure 8).



Figure 8. Cut the wire to create two independent circuits

To verify the samples were not compromised during the braiding process, the researcher measured the resistance values for each sample. Each sample had two readings because there were two independent circuits for each braided pair. A total of 120 measurements were collected and reported in the Conclusion section. If the resistance value was open on any lead, the entire sample was discarded and a new sample was built. An open resistance, or infinite Ω reading, indicated the sample was damaged during the process, creating an open circuit condition. The resistance data provided the

descriptive statistics necessary to determine if the samples were adequate to continue with the study.

The researcher then measured the breakdown voltage for each sample using the NOVA 1401 dielectric voltage breakdown tester (see Figure 9). The NOVA 1401 dielectric voltage breakdown tester was set to a rate of rise of 500 volts per second in the automatic test set up. This setup allowed the equipment to automatically ramp the voltage until the breakdown occurs. At the breakdown point, the test is terminated automatically and the voltage breakdown value is displayed. The researcher's setup eliminated the opportunity for operational error during the tests.



Figure 9. NOVA 1401 dielectric voltage breakdown tester

To provide the parallel current paths needed to breakdown the insulation, the researcher anchored each leg around the terminal posts, labeled A and B in Figure 10. Then, the researcher anchored the two braided legs to the test platform using the plastic wing nuts. The researcher verified each exposed copper or aluminum material on each sample made adequate contact with the two terminal posts. It was vital that each sample was connected to the test platform correctly so that adequate current would pass through each leg of the braid.

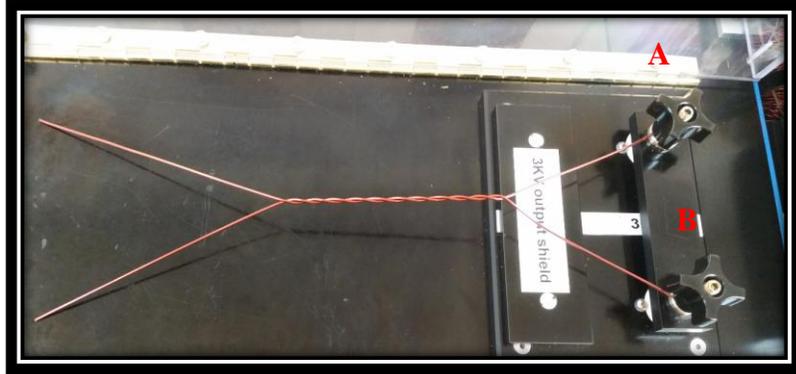


Figure 10. Test platform setup

The researcher then energized each sample by turning the tester to the *High Voltage On* position. The NOVI 1401 Dielectric breakdown tester then ramped the line voltage at 500V per second until the conductor wire insulation became compromised enough to allow the current to pass through. Once the arc was created between the two legs, the test was automatically terminated and the voltage required to breakdown the insulation was provided on the digital display. The test setup and procedure was repeated for all sixty samples. Data were collected accordingly and recorded in Appendix B.

Method of Data Analysis

The researcher conducted the study to evaluate the impact of mechanical stresses on the dielectric voltage breakdown value of two insulated conductor wire materials. The purpose of the study was to statistically show how each conductive material performed relative to the other under the defined stressful conditions. Using a one tailed t-test with an $\alpha=0.05$ and the degrees of freedom = 18, the researcher tested the hypotheses that the aluminum conductor wire would perform better than copper at all three compression ratios. Table 1 provides a compressive summary of the defined alternate hypotheses (H_a) tested, as well as the null hypotheses (H_0). The researcher rejected the null hypothesis

(H_0) if the t-test falls into the rejection region. Otherwise, the null hypothesis would be retained. The aluminum population was represented as μ_1 and copper was represented as μ_2 . The aluminum sample group was identified as x_1 and copper as x_2 . The test was designed to minimize variation by utilizing samples processed the same as production and prepared in a lab environment. This allowed the researcher to assume independence between the two samples; along with equal sample size, of equal variance.

Table 1

Hypothesis Summary

<u>Experiment #</u>	<u>Null Hypotheses</u>	<u>Alternate Hypothesis</u>
Experiment 1	H_0 (10%): $\mu_1 = \mu_2$	H_a (10%): $\mu_1 > \mu_2$
Experiment 2	H_0 (25%): $\mu_1 = \mu_2$	H_a (25%): $\mu_1 > \mu_2$
Experiment 3	H_0 (50%): $\mu_1 = \mu_2$	H_a (50%): $\mu_1 > \mu_2$

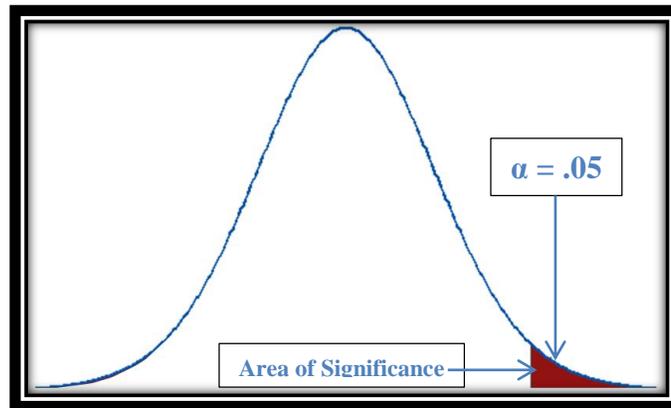


Figure 11. Test statistic (T.S.) rejection region

The rejection region (R.R.) (highlighted area in Figure 11) starting with the critical value (CV) of 1.734 (with $\alpha = 0.05$) was determined using the standard critical values of the t distribution. The degrees of freedom (df) was calculated as follows: $n_1 + n_2 - 2 = 10 + 10 - 2 = 18$.

Each test statistic (T.S.) was computed as follows:

$$\text{T.S.: } t_{(10\%, 25\%, 50\%)} = (x_1 - x_2) / (S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}})$$

Using a pooled variance of:

$$S_p = \sqrt{[(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2] / (n_1 + n_2 - 2)}$$

Threats to Validity

The researcher identified the threats, both internal and external, to validity and addressed countermeasures to ensure the experiment provided an accurate conclusion and without compromise. The threats and countermeasures are as listed.

1. The complexity of the study, small sample size, and expected variation in the manufacturing process, the researcher could not predict with 100% confidence that causation was established between the independent variables and dependent variables. Too many secondary variables contributed to the performance of the insulation and the two materials. To alleviate the threat, the researcher collected samples from the same manufacturing date code and from a group that passed preliminary electrical and physical testing from the manufacturing facility. The data provided by the supplier was used to verify the material was conforming and the same quality for all samples. The researcher could not eliminate random variation from all sample groups, but could verify the material was of the same quality by pulling all samples from the sample production run.
2. The test setup and operator bias was an internal threat to validity. In order to reduce test setup interference and operators bias, the researcher requested a quality control auditor to conduct all the testing per industry standard work instruction and

without information regarding the premise of the study. The samples were provided to the operator in random order and the testing was conducted blind. The operator was blind to the compression reduction variable but not the material variable. There was a distinct visual difference between the copper and aluminum wire after the insulation was removed.

3. The generalization of the designed test and the assumption that it represents the wire in all electric motors was an external threat to validity. The study was dedicated to heavy build induction motor wire only and outlined by The National Electrical Manufacturers Association in MW 1000-1012 technical paper (NEMA, 2012). Therefore, additional testing would not need to be conducted to measure the insulation performance on other build conductor wire and wire suppliers.

Findings and Results

During the preparation procedure, the researcher concluded each sample was per design specification by analyzing the resistance data. As described in the Methodology section, the resistance of each lead wire was recorded to verify no damaged occurred during the compression process. The calculated mean of all sample groups, aluminum and copper, was 0.00049Ω with a standard deviation of 0.00013. The standard deviation calculated is very low for the entire population. A very low standard deviation insures the data are closely spread around the mean and there is very little variation between length and cross-sectional area. These results indicated the population as a whole, and not just each subset, was equivalent. These variable data can be found in Appendix A.

After the data were collected from the NOVA 1401 dielectric voltage breakdown tester, they were imported to Microsoft Excel for statistical evaluation. The voltage breakdown variable data for each subset group can be found in Appendix B. The descriptive statistics were calculated for the six sample groups. To conduct the one tailed t-test for each hypothesis, the mean, standard deviation, and variance was calculated. Refer to Table 2 for the test descriptive statistics for each sample group.

Table 2

Descriptive Statistics

<u>Aluminum Sample Groups</u>	<u>Mean – X</u>	<u>Standard Deviation - σ</u>	<u>Variance - σ^2</u>
Aluminum at 10% (X_{10})	15.798	0.958	0.918
Aluminum at 25% (X_{25})	15.967	1.894	3.588
Aluminum at 50% (X_{50})	16.071	1.382	1.909
Copper 10% (X_{10})	14.746	1.696	2.877
Copper 25% (X_{25})	14.579	1.956	3.826
Copper 50% (X_{50})	13.990	3.264	10.655

Using the descriptive statistics, the researcher calculated the standard pool variance and test statistics using the equations below and in the methodology section:

The test statistic (T.S.) was computed as follows:

$$T.S.: t_{(10\%, 25\%, 50\%)} = (x_1 - x_2) / (S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}})$$

Using a pooled variance of $S_p =$

$$S_p = \sqrt{[(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2] / (n_1 + n_2 - 2)}$$

Using $10 + 10 - 2 = 18$ as the degree of freedoms, and an $\alpha = 0.05$, the rejection region started at $CV = 1.734$. Each experiment was conducted and the t value was plotted as the T.S. respectively in Figure 12, Figure 13, and Figure 14. The experiment yielded the following: at 10% compression, $T.S._{(10\%)} = 1.708$, at 25% compression $T.S._{(25\%)} = 1.6.13$, and at 50% compression $T.S._{(50\%)} = 1.857$. The experiment and the t-test for each experiment can be found below.

The completed experiment for aluminum versus copper conductor wire at 10% compression ratio is as follows:

$$H_{o(10\%)}: \mu_1 = \mu_2$$

$$H_{a(10\%)}: \mu_1 > \mu_2$$

$$T.S._{(10\%)} = 1.708, \text{ with a } df = 18 \text{ and } \alpha = 0.05$$

R.R.: Starts at CV = 1.734

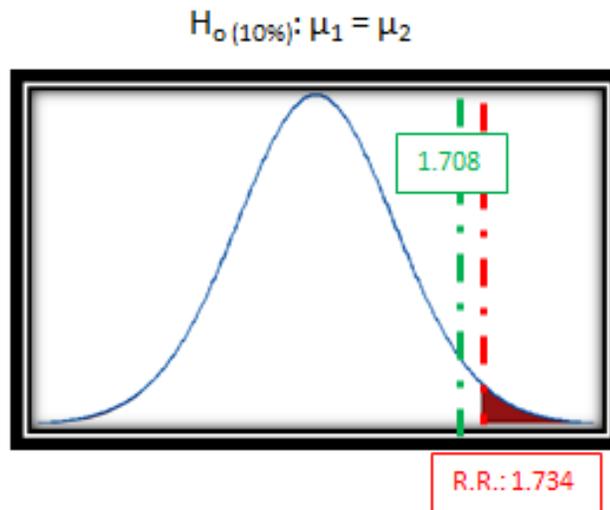


Figure 12. Hypothesis test for 10%

The completed experiment for aluminum versus copper conductor wire at 25% compression ratio is as follows:

$$H_{o(25\%)}: \mu_1 = \mu_2$$

$$H_{a(25\%)}: \mu_1 > \mu_2$$

$$T.S._{(25\%)} = 1.613, \text{ with a } df = 18 \text{ and } \alpha = 0.05$$

R.R.: Starts at CV = 1.734

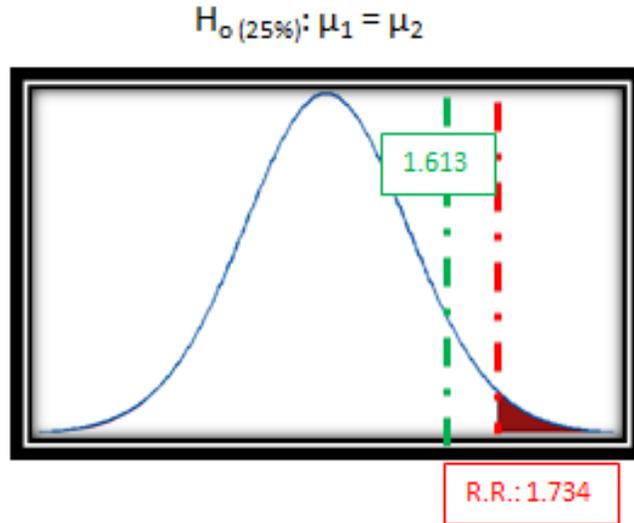


Figure 13. Hypothesis test for 25%

The completed experiment for aluminum versus copper conductor wire at 50% compression ratio is as follows:

$$H_o(50\%): \mu_1 = \mu_2$$

$$H_a(50\%): \mu_1 > \mu_2$$

$$T.S.(50\%) = 1.857, \text{ with a } df = 18 \text{ and } \alpha = 0.05$$

R.R.: Starts at CV = 1.734

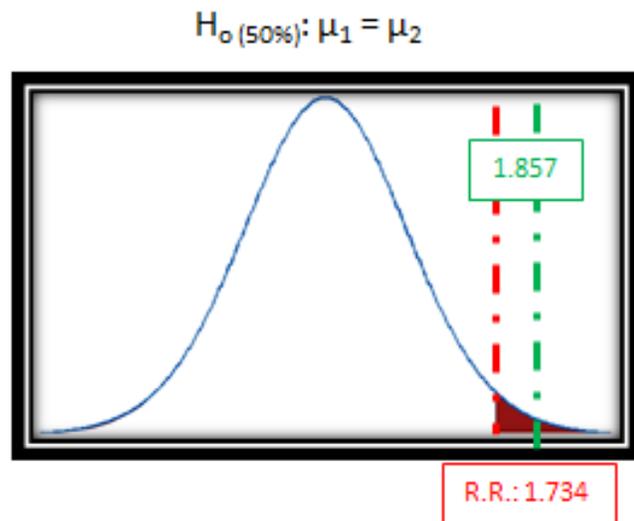


Figure 14. Hypothesis test for 50%

Conclusion

Analysis Results

Using the one-tailed t-test for each experiment, the researcher concluded no statistical difference between the aluminum and copper sample groups at 10% and 25% compression ratio at the 95% confidence level. The researcher concluded there was a statistical difference at 50% compression ratio. Based on an $\alpha=0.05$, the researcher failed to reject the null hypothesis at 10% and 25%, but can comfortably reject the null hypothesis at 50% with a 96% confidence level. Figure 12 and Figure 13 clearly show the calculated t for 10% and 25% reduction is between the population mean and the C.V. of 1.734. However, an examination of p-values provided further clarity. The $t_{(10\%)}$ corresponded to a p-value of 0.0524 and the $t_{(25\%)}$ corresponded to a p-value of 0.0622, meaning there is a significant difference between both sample groups within a confidence of 93%, but not a 95% confidence established in the analysis methodology section.

Figure 14 clearly shows the calculated t for 50% to be well beyond the C.V. and within the rejection region (R.R.). The researcher rejects the null hypothesis and concludes the alternate hypothesis to be true. The p-value was calculated to verify the researcher's claims. The p-value for the experiment was $p = 0.0399$, which provided the researcher with further evidence to conclude there is a statistical difference between aluminum and copper conductor wire at 50% reduction. With a p-value of 0.0399, the researcher can conclude with a 96% confidence level that dielectric voltage breakdown performance of aluminum conductor wire will be better than copper at a 50% compression reduction.

The data collected will provide electric motor manufactures additional information regarding the durability and reliability of both aluminum and copper conductor wire under compression stresses. Using the information, the manufactures can confidently transition conventional copper wound motors to aluminum without losing quality or reliability performance. Additionally, engineers can use the information to push design limits and insert more wire into each slot without increasing the risk of damaging the conductor wire insulation. The wire can be damaged blocking process but the research provides significant data that can alleviate the concern of risk on aluminum. Using aluminum conductor wire in electric motor applications provides the manufacture added cost saving, while alleviating the risk of damaging the wire on high slot fill designs. The high slot fill motor designs provide efficiency gains with minimal added cost. The implementation of both aluminum conductor wire and high efficiency designs provides an overall competitive advantage to electric motor manufacture.

Further Consideration

During the voltage breakdown testing, the operator observed some samples did not fail in the test area (the compressed area). Further consideration was required to understand the impact to the results. The researcher reviewed the data and found two aluminum samples and three copper samples at the 10% reduction was suspect, one aluminum and one copper at 25% reduction was suspect, and zero 50% reduction samples were suspect. Zero samples at the 50% reduction failed outside the test area, the sample population did not change and thus the data analysis was not repeated. The researcher rejects the null hypothesis and concludes the alternate hypothesis to be true.

The researcher repeated the t-test for the 25% reduction sample group with an $\alpha=0.05$ and degrees of freedom of 16. The population size for the aluminum and copper was reduced by one but was equal, so the researcher used a t-test for equal variance to calculate the test statistic (T.S). Using the t distribution table, an $\alpha=0.05$, and degrees of freedom of 16, the CV was calculated to 1.746. The reduced samples size shifted the rejection region further away from the mean. The $t_{(25\%)} = 1.516$ and corresponds with a p-value of 0.074. The recalculated analysis did not change for the 25% reduction sample group. The researcher failed to reject the null hypothesis.

The researcher used a t-test for unequal variance for the 10% sample group using $\alpha=0.05$ and a degrees of freedom of 5. The $t_{(10\%)} = 1.395$ corresponded with a p-value of 0.052. The rejection region for the 10% sample group was calculated as $CV = 2.015$ using the t distribution table. The researcher concluded the results did not change and thus failed to reject the null hypothesis at 10% reduction.

Recommendations for Further Research

In order to increase confidence in the research, it is recommended that the study be conducted again to address test and procedural variations that may have occurred. Revalidating the data collected through additional research will provide the necessary information to support that claim that aluminum conductor wire performs better than copper at 50% compression ratio with a 96% confidence level. Increasing the population sample size and improving the test procedure by means of repetition may provide different results regarding the 10% and 25% reduction groups.

As stated, the first recommendation is increasing the sample size population for each subset groups. With exponential law of errors in statistics, it is suggested to test at

the minimum of 30 pieces per subset group, for a total of 180 tests. The study conducted by the researchers was limited to 10 pieces per group because of the time consuming nature of the preparation. Increasing the sampling provides an increased level of statistical validity by reducing the impact of random variation and outliers identified in the data.

In future studies, it is also recommended that all measurements be done on a laser micrometer. A laser micrometer is a high-speed optical measurement tool used to measure the outer diameter of conductor wire with an accuracy of 0.0004". This measurement tool will replace the handheld dial calipers the researcher used in the study. The laser micrometer should be used to verify the original diameter of the conductor wire, as well as the final diameter after compressed to the desired percentage. The precision and repeatability of the laser micrometer mitigates the risk of measuring errors, pre and post compression. The equipment has the ability to automatically correct of misalignment and vibration during the measurement process; thus increasing measurement confidence. Although the dial calipers were calibrated, there is some level of risk associated with human error. The laser micrometer removes human error from the equation entirely. A laser micrometer was not available during the study.

The last recommendation is to document the location on each sample where the insulation failed during the dielectric testing. In some instances, the location of the breakdown is visible due to carbon tracking, but other times it was not obvious. It is possible during testing, the insulation on some samples failed outside of the compression location. The location of the voltage breakdown could be identified by using a video camera to record each test. If the location of the breakdown is questioned, the researcher

can review the footage to verify. Knowing the exact location is not necessary to make a conclusion, but knowing whether the breakdown occurred inside the compression may provide important information. If the breakdown occurs outside the compression area, it suggests the compressed area was either stronger than the rest of the wire or there was a test step-up error that could have occurred. If the twisted pair is not tightly wound, an air gap can provide additional dielectric strength between the two leads. The air gap may provide the researcher with inaccurate data and result in false conclusions.

Appendix A Resistance Data Set

Copper Sample Group (Resistance in Ohms)							
10% Reduction Samples	Resistance 1	Resistance 2	25% Reduction	Resistance 1	Resistance 2	50% Reduction	
Cu-10-1	0.00030	0.00035	Cu-25-1	0.00030	0.00030	Cu-50-1	0.00040
Cu-10-2	0.00040	0.00040	Cu-25-2	0.00040	0.00040	Cu-50-2	0.00040
Cu-10-3	0.00035	0.00035	Cu-25-3	0.00035	0.00040	Cu-50-3	0.00040
Cu-10-4	0.00040	0.00035	Cu-25-4	0.00040	0.00035	Cu-50-4	0.00040
Cu-10-5	0.00035	0.00035	Cu-25-5	0.00040	0.00040	Cu-50-5	0.00035
Cu-10-6	0.00040	0.00030	Cu-25-6	0.00040	0.00035	Cu-50-6	0.00040
Cu-10-7	0.00040	0.00040	Cu-25-7	0.00035	0.00040	Cu-50-7	0.00035
Cu-10-8	0.00040	0.00040	Cu-25-8	0.00035	0.00035	Cu-50-8	0.00040
Cu-10-9	0.00040	0.00040	Cu-25-9	0.00035	0.00035	Cu-50-9	0.00040
Cu-10-10	0.00040	0.00040	Cu-25-10	0.00035	0.00040	Cu-50-10	0.00035

Aluminum Sample Group (Resistance in Ohms)							
10% Reduction Samples	Resistance 1	Resistance 2	25% Reduction	Resistance 1	Resistance 2	50% Reduction	
Al-10-1	0.00075	0.00080	Al-25-1	0.00060	0.00060	Al-50-1	0.00065
Al-10-2	0.00070	0.00080	Al-25-2	0.00060	0.00060	Al-50-2	0.00065
Al-10-3	0.00055	0.00050	Al-25-3	0.00055	0.00055	Al-50-3	0.00060
Al-10-4	0.00055	0.00055	Al-25-4	0.00060	0.00060	Al-50-4	0.00060
Al-10-5	0.00050	0.00055	Al-25-5	0.00055	0.00060	Al-50-5	0.00060
Al-10-6	0.00050	0.00050	Al-25-6	0.00060	0.00060	Al-50-6	0.00060
Al-10-7	0.00060	0.00060	Al-25-7	0.00060	0.00060	Al-50-7	0.00060
Al-10-8	0.00060	0.00055	Al-25-8	0.00060	0.00060	Al-50-8	0.00065
Al-10-9	0.00055	0.00055	Al-25-9	0.00060	0.00060	Al-50-9	0.00060
Al-10-10	0.00050	0.00050	Al-25-10	0.00055	0.00060	Al-50-10	0.00065

Data Analysis: Calculations are on all copper and aluminum resistance readings

Mean of entire data set	0.00048542
Standard Deviation of all data set	0.00012475

Appendix B Hipot Breakdown Voltage Data Set

Copper Sample Group (kV Breakdown)					
10% Reduction	Breakdown Voltage	25% Reduction	Breakdown Voltage	50% Reduction	Breakdown Voltage
Cu-10-1	12.2	Cu-25-1	13.5	Cu-50-1	10.39
Cu-10-2	12.45	Cu-25-2	16.7	Cu-50-2	11.9
Cu-10-3	12.5	Cu-25-3	14.56	Cu-50-3	7.36
Cu-10-4	15.75	Cu-25-4	14.8	Cu-50-4	15.3
Cu-10-5	15.5	Cu-25-5	11.22	Cu-50-5	16.65
Cu-10-6	15.12	Cu-25-6	16.39	Cu-50-6	12.8
Cu-10-7	16.58	Cu-25-7	16.8	Cu-50-7	17.3
Cu-10-8	15.47	Cu-25-8	16.2	Cu-50-8	16.6
Cu-10-9	16.5	Cu-25-9	13.22	Cu-50-9	16
Cu-10-10	15.39	Cu-25-10	12.4	Cu-50-10	15.6
Mean	14.746	Mean	14.579	Mean	13.990
Standard Deviation	1.696	Standard Deviation	1.956	Standard Deviation	3.264
Variance	2.877	Variance	3.826	Variance	10.655

Aluminum Sample Group (kV Breakdown)					
10% Reduction	Breakdown Voltage	25% Reduction	Breakdown Voltage	50% Reduction	Breakdown Voltage
Al-10-1	17.2	Al-25-1	16.7	Al-50-1	16.7
Al-10-2	14.87	Al-25-2	17.5	Al-50-2	16.5
Al-10-3	15.92	Al-25-3	16.3	Al-50-3	15.72
Al-10-4	15.56	Al-25-4	14.5	Al-50-4	14.97
Al-10-5	16.63	Al-25-5	11.07	Al-50-5	16.87
Al-10-6	16.9	Al-25-6	16.7	Al-50-6	15.7
Al-10-7	14.5	Al-25-7	16.8	Al-50-7	16.8
Al-10-8	16.3	Al-25-8	16.3	Al-50-8	17.9
Al-10-9	15.5	Al-25-9	17.1	Al-50-9	12.87
Al-10-10	14.6	Al-25-10	16.7	Al-50-10	16.68
Mean	15.798	Mean	15.967	Mean	16.071
Standard Deviation	0.958	Standard Deviation	1.894	Standard Deviation	1.382
Variance	0.918	Variance	3.588	Variance	1.909

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