



Coil and Winding Testing Notebook

SLAUGHTER COMPANY
801 HAILEY STREET
ARDMORE, OKLAHOMA 73401 U.S.A.
✉ PHONE: 1 (580) 223-4773
FAX: 1 (580) 226-5757
Email: info@hipot.com
<http://www.hipot.com>

FOR TECHNICAL ASSISTANCE
✉ **PHONE: 1 (800) 421-1921**

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EDITOR'S NOTE:

The material presented in this notebook has been gathered over a period of thirty years. Much of the information on armature and stator testing has been taken from Elmer Slaughter's original publication on that subject in January 1974. Additional material was added and the title was changed in October 1978. A synopsis was published under the title "Locating Coil & Winding Failures" in **Machine Design** issue of July 26, 1979. The 1985 edition was an update of the text of the paper of the same name presented by Elmer Slaughter at the ICWA Conference in Boston, Massachusetts, October 9th – 11th, 1979 appended with a paper by W.O. Golloway, Jr., written in January 1969. The 1990 edition is an update of the 1985 edition with the inclusion of "Testing Points to Problems In Armature Productions" by Elmer Slaughter, reprinted from **ELECTRONICS** February 1984, copyright 1984. Lake Publishing Co. "Real Time, Automatic SPC for the Coil Winding Industry" by Richard Chrisco, Manager of Software Development, Slaughter Co., reprinted from PROCEEDINGS OF THE ICWA – INTERNATIONAL COIL WINDING ASSOCIATION, Cincinnati, Ohio October 3 – 6, 1988 International Coil Winding Association, Inc. and "Cpk THE NEXT STEP IN APPLING SPC TO WOUND PRODUCTS" by Richard Chrisco, Manager of Software Development, Slaughter Co. reprinted from PROCEEDINGS OF THE ICWA – INTERNATIONAL COIL WINDING ASSOICATION, ROSEMONT, ILLINOIS October 16 – 18, 1990 copyright 1990 International Coil Winding Association, Inc.

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Coil and Winding Testing

Introduction

In one form or another, coils or windings appear as components of practically all electrical and electronic equipment. They are usually vital parts, in which case failures can be costly and critical. Furthermore, they are commonly installed in the finished product at a relatively early stage, and in such a manner that the replacement of a defective coil or winding after a preliminary or final inspection is not only inconvenient, but also expensive. Hence, the detection of defective or weak parts at the earliest possible moment in the production process is almost indispensable.

Armature and stator testing are essentially specialized segments of the general problem of coil and winding testing. Though the same techniques widely apply, there are certain peculiarities of these arts which are of importance. Therefore, these particular parts will be treated separately from the main topic of coil testing in this paper.

Variations and Defects in Coils

Depending on the application, various parameters may or may not be critical. These can include resistance, inductance, impedance and turns count. In many cases, modern processing methods can easily hold these parameters well within tolerance, and 100% testing is unnecessary. In others, a simple DC resistance test, plus an impedance test, will be adequate. In situations requiring close tolerances, assorted pieces of specialized equipment are readily available and highly satisfactory. Defects and weaknesses are another thing, and care must be taken to insure that the test and inspection methods are sufficient in order to intelligently attack this problem. A thorough knowledge of the nature and causes of coil failures is desirable.

Causes of Coil Failure

Analysis of coil and winding field failures in products incorporating motors or transformers generally reveals that the failures are quite often the result of winding failures. Winding failures,

more often than not, are the direct result of internal shorts – shorted turns. Such failures often develop over a period of time, starting out as a relatively minor internal short. This internal short, because if the existing transformer action, results in high circulating currents and localized heating within the shorted portion of the winding. As the heat builds up, insulation deteriorates rapidly until a massive internal short occurs, resulting in complete failure.

In the case of low power coils and windings, such as relay and solenoid valve coils, and subfractional motor windings, the primary causes of failures are “pigtail” or “layer-to-layer” shorts. A “pigtail” short occurs as the result of insulation failure between the starting end of the winding, where it passes along the end of the coil to the core, and the outer surface of the coil. Obviously, this is the point of greatest voltage stress. This produces a dead short situation, and the fine wire of the coil usually burns away quite quickly, resulting in an open coil and complete failure. In such cases, inspection of the failed part will commonly show a small burn spot, with the rest of the coil appearing to be in good condition, as opposed to the extensive burned area often found in motor and transformer windings.

This type of failure is usually noticed when the coil is turned on, but the actual breakdown which leads to failure generally occurs when the coil is turned off. Characteristically, in these cases the user will say, “It was working when I turned it off, and then it wouldn’t work when I turned it on again.”

There is a simple explanation for this phenomenon. When a coil is turned on (unless resonance occurs) the maximum voltage between the pigtail and the top layer is the line voltage. But when a coil is turned off, the maximum voltage which can occur depends upon the magnetic energy stored within the coil and various other parameters, especially the number of turns. This voltage can be many times the normal operating voltage. It has been determined that the voltage stress produced at turn off of 24 and 48 volts DC coils can often be as high as 3,000 to 5,000 volts. This is a more serious problem with DC coils than AC coils,

primarily because AC coils are not always turned off under peak conditions. Other characteristics which make DC coils susceptible include the fact that, for the same voltage, they usually have more turns than AC coils; and therefore the induced voltage at turn off will be considerably greater in the typical DC than in an equivalent AC coil. Heat contributes to this type of failure, because most insulation materials are temperature sensitive, and breakdown voltage decreases as temperatures rise. However, as noted, failed parts of this type commonly show little or no evidence of extensive heat.

In contrast to the pigtail type failure described above, failures due to layer-to-layer shorts are fundamentally failures due to excessive shorted turns, and these are essentially heating failures, occurring more often in AC than DC coils. This is caused by the transformer action in AC coils which causes high circulating currents, resulting in excessive localized heating and eventual burnout of the fine wire, causing an open coil. Failures of this type may occur anywhere within the coil structure and are easily identified, as opposed to less-detectable pigtail failures. In layer-to-layer failures a large area of heat is usually visible. In the case of DC coils, no transformer action is involved, and hence layer-to-layer shorts sufficient to cause failure will show evidence of heat throughout the entire coil.

Failures due to grounds are also easily identifiable, as there will be definite evidence of insulation failure between the winding and the ground plane structure. Obviously, the cure for this weakness is sufficient insulation.

Failures in very fine wire coils, which are characterized by random opens with no particular evidence of heating, are generally the result of excessive tension on the wire during winding. This tension creates physical stress within the winding which may be compounded by heating and cooling in the part during service. While this sometimes causes such coils to develop shorted turns in service, usually the wire is stressed to the physical breaking point, resulting in an open for no apparent reason. Such failures can be prevented only by careful attention to the winding technique, as there appears to be no way to effectively test a finished coil for this condition.

At this point, a bit of discussion about coil design and application may be appropriate. While we are in the testing business, there is no way to test quality into a product. It must be built in. Hence, if a coil is found to be susceptible to pigtail failures, either as a result of test or field experience, attention must be given to possible solutions. Fundamentally, there are two solutions to the problem. One is to provide sufficient insulation to eliminate the breakdown, and the second is to provide protection that will limit the induced voltage which causes the breakdown. Ideally, both solutions can be utilized. Typical of protective methods is a device called a "transorb". This component is effective on both AC and DC coils and has the effect of limiting the induced voltage at turn off. These are small, inexpensive devices which may be connected directly across terminals of the coil.

Techniques and Equipment

Parameter test techniques are well established, and in most areas there is little need for extensive discussion in this paper. Resistance testing is generally handled either on a direct measurement basis, using a precision ohmmeter or bridge, or on a deviation basis, utilizing a deviation bridge. Deviation bridge technique is often preferred for high production testing because faster response can usually be obtained. In any case, Kelvin measurement techniques are preferable overall. Impedance or inductance measurement is generally accomplished through the use of suitable bridges, either of the direct reading or deviation type. A number of instruments of this type are available on the market today.

Such measurements are often made through the use of a comparator in a suitable configuration. Figure 1 is a simplified diagram of this technique.

As referred to before, testing for defects and weaknesses is somewhat different from testing for conformance to parameters. Primarily, as previously discussed, test schedules will be aimed at detecting internal shorts or weaknesses or the turn-to-turn, layer-to-layer, or pigtail type and detection of defects or weaknesses may lead to ground failures.

Ground testing will not be covered in detail in this paper as many variations of methods and techniques and equipment exist. In addition, agency specifications introduce other variables. The serious reader is referred to a companion publication on the subject "Basic Facts about High Voltage Testing".

With typical coils and windings in the 115 to 230 volt range, most manufacturers are using Hi-Pot testers of 1000 to 1500 volts, which will reject on total current flow of 1

MA to 10 MA. Although these figures indicate acceptance of parts with a surprisingly low megohms insulation resistance, this is not generally true. Actually, the mechanism of Hi-Pot failure is not widely understood. Basically, in this test we are looking for close clearances or thin insulation. If these exist, they will break down under the voltage applied, and the resultant current that flows will be limited only by the internal impedance of the test equipment, plus the series impedance through the workpiece to the point of failure. From a practical standpoint, therefore, it is ordinarily unimportant whether the equipment will trip on a 1 MA current or a 10 MA current; the fault current will usually be considerably greater than either. Rejection on the basis of a leakage limit, as well as on the basis of a short circuit current is also becoming widespread, as such an approach is an effective continuous check on the degree of cure achieved during processing. Obviously, if the ground test is to be conducted before the coil is mounted in its design structure, a duplicate artificial structure must be utilized for test purposes. However, the user is cautioned that such a test does not eliminate the need for a final ground test on the completed project. The advantage of such a test is that it will weed out weak or defective parts before additional labor and processing cost has been accumulated.

Testing for weaknesses or defects of the shorted turn, layer-to-layer, or pigtail type is by far the most aggravating and difficult to perform. There are several reasons for this.

A resistance test cannot be sued because the tolerance of wire size is appreciable, especially in small gauges, and hence the normal DC

resistance variation of a winding can be greater than the variation that might be introduced by a shorted turns defect that would be unacceptable. In addition, while the shorted turns test might detect shorted turns, it could not detect weaknesses which might develop into shorted turns at a later time.

Another major problem is how does one determine what might or might not be

acceptable, or how bad is bad. Theoretically, any shorted turn within the winding, to the average engineer, signifies a rejectable item. This is based on the theory that shorted turns can cause lost performance and affect product durability. Practically, as has been demonstrated in extensive quality control testing, this is not always true. Fundamentally, shorted turns or internal weaknesses represent a problem only if they occur to the extent that they affect performance significantly or if they have the potential of producing sufficient overheating within the coil to shorten the life of the coil. Obviously, if there is a comfortable margin of safety in the design, some variation in performance can be tolerated. Also, if the coil design is such that there is only slight heat rise in normal operation, some additional heat will not prove detrimental. Evidence points to the fact that shorted turns of as much as 1% can usually be tolerated, and in many cases as much as 5% can be tolerated.

Even if we can resolve the problem of determining how bad is bad, we still have the problem of how to conduct the test. Since the objective is to locate weaknesses as well as existing faults, it is essential that some form of a dielectric test be utilized so as to produce enough stress at the point of weakness to create a detectable signal. In other words, we must

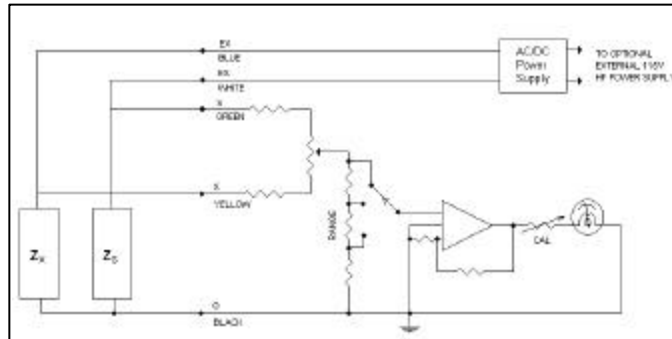


Figure 1, Simplified Diagram Series 635 with Connections for Resistance or Impedance Comparison testing.

subject the coil (or armature) to over-voltage. As indicated, this is a dielectric test, but unlike the ordinary dielectric test which is conducted between electrically isolated points, this dielectric test must be conducted within a part that is electrically conductive. This being the case, it is not practical to simply apply an over-voltage of normal operating frequency to the workpiece. To do so would cause the part to draw excessive current and risk overheating the part to the point of causing a deterioration in materials which could lead to premature failure. In other words, we must avoid making bad ones out of good ones.

Fortunately, this is not an insurmountable problem. There are two convenient methods that allow us to apply over-voltage to a coil without risking overheating. One method is to apply over-voltage at a higher than normal frequency, and the other is to utilize a surge test. Either method is practical because the frequency, or pulse wave shape, can be adjusted so that the coil will present a high enough impedance under over-voltage conditions that excessive current flow can be avoided, thereby eliminating the risk of overheating. Of these two types of equipment, the surge tester is generally preferred because the equipment is usually lighter in weight and less expensive, and because we can adjust the pulse rise time width and amplitude relatively easily as needed to avoid the overheating problem. In the case of the high frequency test, we do not have as many options readily available.

Regardless of the method chosen, high frequency or surge, we also have options as to the manner in which the test is conducted. Over-voltage can be created by an inductive method or by direct application. When the inductive method is utilized, the workpiece must be mounted in a suitable magnetic structure which carries a winding that can be excited by the test gear. The magnetic field then interacts with the workpiece to induce the desired voltage. In the direct test, the test gear is simply adjusted to produce the desired voltage and this is applied directly to the terminals of the workpiece. Generally speaking, the direct test is preferred because less tooling is required and it is easier to control the actual voltage at the terminals of the workpiece. However, there are definite differences in the nature of the resulting test conditions. With the inductive test, the voltage distribution in the

workpiece is generally linearly distributed and the actual turn-to-turn voltage stress distribution within the workpiece is relatively constant. In addition, we have the option that an electrically isolated search coil is sometimes convenient for detection purposes.

With the direct test, the situation is somewhat different, depending on the parameters of the workpiece. The important consideration is that voltage distribution within the workpiece will not be constant. Due to distributed capacity effects, the major stress will occur in the conductors that lie near the surface and those that lie deep within the workpiece may hardly be stressed at all. So we have this situation – if the test is applied inductively, the voltage distribution is determined mainly by the inductive relationships and is reasonably constant on turn-to-turn basis. If the test is applied directly, voltage distribution is determined mainly by the capacitive relationships and is concentrated in surface areas.

Let's analyze what this means. We could jump to conclusions and say the inductive application is best, because it gives a more even distribution. But, think for a moment, does an even distribution actually exist in the workpiece in actual service? Certainly not – the maximum insulation stress in service occurs at coil pigtails, armature crossover points, between layers, and similar areas. Coincidentally, perhaps, these are the points which are stressed the most when the over-voltage is applied directly to the workpiece.

Having established these differences in the effect of the test on the workpiece with the two methods of application, let us now look at the instrumentation and its relation to these differences. No matter how the instrumentation is accomplished, its sensitivity will be directly related to the stress produced. Flaws in areas that are highly stressed cannot be detected by instrumentation that is adjusted to pass normal deviations in areas that are heavily stressed.

Boiling this down, we arrive at the conclusion that the inductively applied test is most effective for turn-to-turn shorts, no matter where they may occur in the workpiece, but the directly applied test is better for weaknesses in areas that are normally heavily stressed.

Practically, we must add another point to this. Structural limitations generally limit the stress that can be produced by inductive methods to a considerably lower level than can be accomplished by direct application.

There are still other problems that must be confronted. One problem is how much over-voltage is required to accomplish our end results. If we were not concerned with weaknesses as well as faults, the problem would be relatively simple. But when we start wondering about weaknesses, we are essentially thinking about high resistance shorts, and in some cases, the resistance can be quite high, as when we're dealing with a case of a very, very thin coating of insulation on magnet wire. Practically, we might as well forget trying to detect such a weakness on a single turn basis because this would surely require a turn-to-turn test voltage of the order of 100 volts or more. If we were to attempt to apply this much over-voltage to a coil with a large number of turns, the test would require a total terminal voltage far in excess of any voltage the workpiece could be expected to endure. Furthermore, it is a doubtful if such a weakness from one turn to the next could ever be a potential source of failure.

What about high resistance shorts – the case where magnet wire insulation is completely gone on a turn-to-turn basis. This in itself is a misnomer, as anyone who has worked with a wheatstone bridge will verify. In general, if casual contact between bare wires exists, the bridge will indicate either an open circuit, or a low resistance circuit. It is almost impossible to attain anything in between. This is quickly traced to the fact that the oxide coating on bare wire is not a very good conductor and that a definite voltage level is required to break it down and produce a circuit. Once the oxide coating is ruptured, practically normal conductivity exists.

Here again, the obvious answer is to increase the turn-to-turn voltage during test to the level necessary to break down this barrier and produce a circuit that will then be detected by the equipment as a turn-to-turn short. This sounds good until we get practical. To be effective, a turn-to-turn voltage of around 2 volts is needed. Producing such a voltage can be a real problem, but the rode awakening comes when we realize the total voltage that is produced in the full coil when we do this. Again, in most cases, it will

be above the voltage level that the workpiece can be expected to withstand and voltage applied to high stress areas such as pigtails and crossover points can be even higher. To attempt such a test would essentially be over-testing.

In summary, we must recognize that from the practical standpoint in testing for weaknesses or defects of the shorted turn, layer-to-layer, crossover or pigtail type there are a number of compromises we must be prepared to accept. We must consider the advantages and disadvantages of the inductive versus the direct method of test voltage application. We must consider the type of test gear; whether high frequency or surge type should be used. We must determine what is a practical level of test voltage, and be prepared to accept the fact that a practical level of test voltage may or may not allow us to achieve a sensitivity of a single shorted turn.

While surge testers are generally preferred for this type of testing for reasons already discussed, there is an additional disadvantage in that there are no units of measurement in surge testing. It is essentially a qualitative rather than a quantitative test, even though the results may be displayed on an arbitrary quantitative basis. In the absence of sufficient experience to make a judgement, the only practical way of establishing test levels, and sensitivity limits in this type of testing is to conduct quality control tests to establish the extent of shorted turns that can be tolerated without creating a potential failure situation or an undue loss of performance. Practically speaking, the most important limiting situation will be the one that causes premature failure, rather than the one that causes a noticeable lose in performance. Hopefully, such a determination will result in the establishment of a test voltage and sensitivity limits that will not result in over-testing. Then it becomes a simple matter to produce artificial faulty samples which can be used for setup purposes to establish rejection settings.

For convenience, the Slaughter Company has worked out a formula for defining surge tester sensitivity in terms of shorted turns equivalency. The formula is:

$$\% \text{ Equivalency} = \frac{100 \times W_e}{N \times W_a}$$

In the above formula, N represents the actual number of turns in the workpiece, W_a indicates the actual wire size used in the workpiece in circular mils, and W_e indicates the circular mils wire size to be used in single turn shorted loop closely coupled inductively to the workpiece that can be reliably detected by the instrumentation. To illustrate the usefulness of the above formula, let us use the example of a 1000-turn coil would with magnet wire of 100 circular mils. If we utilize an artificial faulty sample having a closely coupled single-turn loop of 1000 circular mil wire and adjust our equipment to reliably detect this artificial faulty part, we can then say that we are testing to a sensitivity of 1% equivalency. By transposing the formula, we can then utilize it to determine the equivalent wire size to be used in creating setup samples of various degrees of

$$W_e = \text{Desired \% Equivalency} \times \frac{N}{100} \times W_a$$

equivalency. In this case, the formula becomes as follows:

Using the formula in this form, we can then decide what equivalency we are prepared to accept, usually somewhere between 1% and 5%, and construct an artificial faulty sample, using the wire size calculated by means of the transposed formula. The test conditions and test gear can then be adjusted to reliably detect this artificial fault, providing doing so will not create an over-test condition. In the event an over-test condition occurs, then we must be satisfied with a less sensitive test and construct a new sample with a higher percentage equivalency for setup purposes.

The above is useful and helpful as it give us a means of evaluating instrumentation and techniques in a given situation. But it isn't much help to the individual handed a new product with the brief but emphatic order "set up a test station". The poor guy knows a shorted turns test should be included, and how to compare equipment and techniques, but what are reasonable test conditions limits.

While we have discussed the limitations on test voltage no concrete suggestions have been made. Obviously, if possible, the coil should be tested at a voltage significantly greater than any voltage it might be exposed to in service. Because of the transient conditions previously discussed, this is often difficult to establish, and in fact is

sometimes impractically high. In any case, we know that the actual test voltage in the workpiece whether created by the direct test or by an inductive test will vary with the type and quality of the product being tested. As a rule of thumb, in the absence of any other specific information, for ordinary windings it is suggested that a figure of 20x normal voltage be used, or 2x rated voltage plus 1000, whichever is lower.

For those who like to play with figures – mathematical ones, that is – and are willing to take the liberty of making some assumptions there is a way of arriving at approximate limits. Or perhaps we should call them educated guesses. At any rate it is a means of establishing a starting pint which hopefully can be verified and refined later in the laboratory.

We either know, or can establish certain characteristics of the winding. Specifically these usually will include normal voltage and current input, power output, power factor if AC, and number of turns in the winding. In the case of motors and transformers usually this includes locked rotor, or short circuited output information.

Armed with this information, and the conservation of energy principle, let us proceed. In normal operation, the power input must equal power output plus the internal dissipation. It's the dissipation that we are most interested in, as this is what causes heating.

Our first assumption has to be that the product was reasonably well designed and hence can readily handle the normal dissipation. In fact let's go a step further and assume that it can tolerate 1% above normal without ill effects.

Going a bit further, we can say shorted turns will be acceptable as long as they do not increase the internal dissipation by more than 1%.

Now, how do we guess at the shorted turns test limit that we can tolerate? To do this, we need to use the abnormal data – such as locked rotor test information, or short circuited output data. Obviously under theses stringent conditions, there is no power output, and all input is dissipated in the product – more specifically, in the winding we are going to test.

To use this data we must make even broader assumptions. First, that the power dissipated will be evenly distributed through the winding, and second, that the power dissipation per turn under these conditions will be approximately the same as would be absorbed by a shorted turn under normal conditions.

From here, it is only a short step to establish the shorted turn equivalency that will correspond to a 1% increase in normal dissipation. Let's try some examples.

First, a motor of 400 turns that normally will dissipate 100 watts, and under locked rotor conditions gobbles up 4000 watts. Obviously the short circuit watts per turn is 10 watts, considerably more than the 1% of 100 watts we are willing to accept. So – this motor must be tested to a rejection limit of one shorted turn.

Now, try a flea power motor with 2400 turns, a normal input of 15 watts, and a locked rotor input of 24 watts. The expected short circuit characteristics is 0.01 watts per turn, and ignoring the power output we can calculate the reasonable test limits at

Let's try a transformer of 500 turns, with a normal dissipation of only 25 watts, and a short circuit input of 250 watts. This one looks like 0.5 watts/turn on short circuit, and with only 0.25 watts extra allowable calls for testing to a rejection limit of one shorted turn.

How about a relay with 5000 turns and input of 5 watts with no perceptible increase whether blocked open or closed? This one shows only .001 watts per turn, with .05 watts allowable total – 50 turns equivalency should be OK. That's exactly 1%.

The above examples are fictitious products, but fairly representative, and they do serve to illustrate a pattern. Expressed as a rule-of-thumb, this pattern indicates that any product with a significant power output needs to be tested to a shorted turns limit of 1 turn, and low power products can be tested to a limit of 1%. As previously mentioned, cases where limits as high as 5% were acceptable have been observed.

Another interesting observation the author has made is that generally reasonable test voltage levels will result in high enough voltages to

exceed the barrier level previously discussed, when we take into account the acceptable limits. In the case of the relay example above a test level of 1000 volts across the coil will result in 10 volts applied across the 50 turn equivalency limit – quite comfortable above the barrier level of 2 volts.

Test Schedules

So far we have dealt strictly with the pros and cons of different types of testing and techniques

$$\frac{15 \times .01}{.01} = 15 \text{ turns equivalency}$$

This, of course, is $\frac{15}{2400}$, or .625% equivalency.

utilized. Typically, it is the job of the process engineer to establish a test schedule recommendation for any particular coil or winding. Reviewing briefly, it is our feeling that this schedule should include, at the minimum, some type of DC resistance test plus a surge test. To this must be added the testing for any other parameters that may be critical.

Armature Testing

Without doubt, the heart of the motor is the armature... after all, it's the thing that makes the motor go. Nobody will question, either, that it is the part that usually fails first. Often this is due to neglect of other parts, such as brushes or bearings, but regardless the armature generally takes the blame. This being true, the armature is the most tested and inspected part of the motor, and it is the purpose of this section to share with you the writer's observations of test methods and equipment as they have developed during the growth of our industry.

For many years, even up to and through World War II, the basic tools of armature testing were the continuity lamp and the growler. In the hands of skilled workmen these instruments detected opens, crossed connections, shorts and grounds. The resulting product was surprisingly good, not because of the effectiveness of these test methods, but because the quality was built-in... windings were inserted by skilled workman, commutator connections were carefully soldered or brazed by experts, and the final processing was handled with tender loving care. Over all of

this was a huge umbrella... most armatures were considerably over-designed.

Since World War II, there has been a revolution in the production of armatures. Improved insulating materials, better magnet wire, specialized varnishes and impregnants... all of these have come into being and are being used in armature construction. The superiority of these materials is unquestioned, and if they could be used in the same manner as the older materials, our armatures today would probably be practically indestructible. But this is impractical... today we must use automatic winding machinery, we cannot dally with processing, and we cannot afford the luxury of over-design.

Philosophically, this does not mean that we have in any way cheated on our customers, or reduced the capability of our products... after all they do perform better and we are extending our warranty periods. But we must recognize that we have reduced our allowable margin of error in our manufacturing by a tremendous amount and hence, our inspection and testing must be far more sophisticated than ever before.

All blessings are mixed ones, and with the new materials and machinery available, we have a whole new crop of problems. Modern winding machinery is almost infallible, and turns count errors are almost a thing of the past, but magnet wire insulation damage during winding is often hard to avoid. "Fusion process", or "hot staked" connections are practically perfect under normal conditions, but contaminants are variations during the process can be a real headache. Epoxy slot insulation saves copper, but it is subject to pinholes, holidays, poor coverage and insufficient cure. Conveyors move parts rapidly and efficiently, but they can be mighty rough in the process. So today, the simple problems of detecting opens, crossed connections, shorts, and grounds have been joined by the more aggravated ones of detecting insulation weaknesses due to damage, poor connections or defective welds, marginal grounds and the like.

State-of-the-Art

With this background, let us get on to a review of the state-of-the-art, and discuss the tests and methods of test being used today. Raw stack testing can be disposed of quickly. In those

cases where slot liners are still used, no testing is needed. In the case of Epoxy coating slots, most testing is done with manual probes or with fine wire bristle brushes. The stack is grounded and 500 to 5000 volts is applied with a sweeping probe, or a brush to detect defects. These methods are not too satisfactory for high-production work and automatic testers in which form fitting electrodes are used have now been perfected. We will not go into details of this as other literature is available. The biggest problem appears to be a firm definition of acceptability. Holidays and thin coverage are obviously defects. But how large must a pinhole be to be considered a defect? Almost any of the test equipment available will detect pinholes so small as to require a good magnifying glass to be seen. Most manufactures have set up standards of acceptability based on their judgement and experience.

Double-insulated armatures have generally been tested sequentially, sometimes with different voltages on the barriers. How in most cases, we supply three-lead testers which test the insulation paths simultaneously.

As previously mentioned in the section on coils and windings, ground testing can be disposed of quickly, as methods have changed little in recent years. With typical F.H.P. armatures in the 115 to 230 volt range, most manufacturers are using Hi-Pot testers of 1000 to 1500 volts, which will reject on total current flow of 1MA to 10MA.

Beyond the ground test, the most emphasis is placed on the shorted turns test. Here the question begins to get hairy, for the reasons previously discussed. Most manufactures specify that the test equipment should detect a single-turn short – and most equipment in use will detect a single turn short, provided that it is a true short, with absolute metal-to-metal contact. However, high resistance shorts or weaknesses are another problem, and as mentioned earlier, to detect such weaknesses a turn-to-turn voltage of around 2 volts is needed. Producing such a voltage can be a real problem, particularly if the inductive method, utilizing a growler, is used, but the real headache comes when we calculate the total voltage is that produced in the full coil when we do this... in many cases it is at, or near the bar-to-bar strength of the commutator. Voltages applied to high stress areas, such as crossover points, can be

even higher, so we can easily get into over-testing.

Since we have discussed this subject in more detail earlier in this paper, we will not repeat the discussion here. However, it should be mentioned that before getting too excited over this dilemma, the seriousness of shorted turns defects in the particular armature should be analyzed. Obviously, a shorted turn defect is of importance only if it affects performance of the motor, or if it leads to premature failure of the armature. Failures which are the result of shorted turns usually develop over a period of time, starting out as a relatively minor high resistance internal short. This internal short, because of the transformer action, results in high circulating currents and localized heating within the shorted portion of the winding. As heat builds up, insulation deteriorates rapidly until a massive internal short occurs, resulting in complete failure. Contributing factors, of course, are mechanical chafing, which can exist if varnish weakens or deteriorates, and operating temperature. Obviously, if there is a comfortable margin of safety in the motor design, some variation in performance can be tolerated. Also, if the motor design is such that normal heat rise is relatively small, some additional heating will not provide detrimental. As indicated before, evidence points to the fact that shorted turns of as much as 1% can usually be tolerated, and in many cases, especially in small fine wire armatures, as much as 5% can be tolerated. This is the margin previously suggested for surge testing of coils.

To be perfectly honest, most manufacturers of armatures have not gone into this problem this deeply, and are using test methods that have evolved through the years, generally as a result of refinement of the old classical growler test.

Commutator Connections

After shorted turns, the continuity test is generally looked upon as the most important. This problem is a hairy one, too, and for the same reason as the shorted turns problem. If we make the continuity test with a high enough source voltage... if there is contact at all... the continuity test will be OK. If we reduce the source voltage used, we can get down below the "barrier level" discussed before and reject most cases of "casual contact". In general, this is fine

for soldered or brazed commutator connections. But for "fusion process", "hot staked", "tang welded" and similar connections, we run into another problem. When these processes are working properly, they give a good contact over a very minute area only. Such a connection will check good under all normal techniques... but it is not a good connection.

A number of approaches have been attempted to detect these stinkers. One technique is the brute force method... a high current is passed through the connection in an attempt to "burn it out" if it is bad. Unfortunately, it appears that to be effective such a test must be extremely severe, and this is a horrible way to treat good parts. Other manufacturers are using a spin-test, on the theory that the centrifugal forces produced will loosen such a connection so that it will be rejected on the following continuity test. Unfortunately, it is extremely difficult to prove the effectiveness of any approach, and we are inclined to doubt if either of these methods is worth the effort. The spin test has something more in its favor, in that it may produce some chafing and thereby aid in the detection of shorted turns.

These types of commutator connections have another nasty little characteristic. Immediately after connecting, they will often check good but after a few days, or after the varnish and bake processing, they may check bad. Sometimes the "black Arts" can be called upon and such a part can be given a surge test which will apparently correct the problem. However, almost invariably, it returns a few days later.

As might be expected, these problems have spawned a variety of solutions which are usually described by the "buzz word" term "weld test". Many different detail test techniques are being used but basically these are all a form of resistance test. The idea, of course, is that a variation in contact quality should be detectable as a variation in resistance. Whether or not the variation that must be detected is significantly greater than normal variations is debatable and the writer feels that he has seen indications where defective connections actually showed no significant difference in resistance. Even so, this technique is the best that we have now and until something better comes along, we need to try to make it work.

The advent of new components, digitizing techniques, and on-board number crunching computers has opened new potentialities for dealing with the problem. However, we are not aware that equipment of such advanced design is yet available generally.

Another technique or idea that has been discussed academically but to the writer's knowledge never practically investigated is the burn-in technique widely used in the electronic field. Heat cycling, particularly in a mildly oxidizing atmosphere, should aggravate such defects and make them easier to detect. However, such a technique, to be useful, would probably be extremely time consuming and expensive. However, the writer would like to be informed of any experimental data available.

Mixed leads and crossed connections are less serious problems now that most production has gone to the tang type construction. Normally, these errors are rare, and if the motors receive any sort of run test before shipment, these defects cannot get out to be a source of field failure. Mixed leads will usually result in an open, and will therefore be detected on the continuity test if it is reasonably sensitive. Crossed-connections do not affect continuity, and must be detected by a test that is sensitive to the phase reversal which occurs as a result of this error or to the abrupt change in bar-to-bar resistance. In general, it is rare that any special test is made to detect either if these errors – instead, the basic test technique used is tailored for maximum by-product sensitivity to them, on the assumption that any bad parts which slip by will be rejected at the final motor test anyway.

Turns count errors are almost non-existent with machine wound parts, and special tests for this have generally been dropped. When needed, this check is almost invariably obtained by an induced voltage test. There are cases where the induced voltage test is retained, not so much because of its usefulness in detecting incorrect turns count, as because of its usefulness as a continuity test and for the detection of mixed leads and crossed connections. However, this remains a problem on hand-wound armatures, and consequently 100% testing may be required.

In some rare cases commutator index errors are a problem and test equipment must be capable of spotting this defect. However, most production

setups incorporate positive processing methods to insure bar / slot index accuracy, and hence, this types is seldom required.

Alternatively, commutator index errors can often be detected more economically through a simple mechanical inspection as opposed to making this a part of the electrical test procedure.

Summarizing... to do a good job today, our armature test equipment should perform the following minimum functions:

1. Continuity test, conducted at the lowest practical voltage level in order to detect poor connections, as well as obvious opens. This test must be conducted on a bar-by-bar basis, and should be made after all processing is complete.
2. Ground (or Hi-Pot) test, preferably with non-destructive equipment which will not damage salvageable parts.
3. Shorted turns test, conducted at the highest practical voltage level in order to detect incipient weaknesses, as well as obvious defects.

Depending on product details, additional functions that may be required include:

1. Checking of epoxy insulation lamination stacks for defects in coating before winding.
2. Checking for mixed leads and crossed connections.
3. Checking for turns count errors.
4. Checking for commutator bar alignment, or index error.

Now let us look at some of the methods being used to accomplish these tests and checks.

Growler Theory

Since so many test methods are basically simple variations of the old classical growler test, perhaps a few minutes on this subject would be wise. How does it work anyway... most of us haven't taken the time to figure it out. Really, it is quite simple when we remember that in any given slot, there are as many conductors wound in one direction as there are in the other direction. This being the case, if the slot is subjected to an alternating (or pulsating) magnetic field voltages of opposite phase will be

set-up on the two sides of the armature. Since the entire armature is symmetrical, these induced voltages will meet at a common point and will effectively cancel each other so that there is no circulating current

If a short exists, symmetry is destroyed, the voltages no longer cancel, and circulating currents are set up in the defective coil, or coils. These circulating currents in turn produce a local magnetic field in the slot containing the defective coil, and it is this effect that enables the skilled operator to locate the defect by means of a magnetic feeler.

Growler Testing

In looking over actual test methods being used today, it is apparent that the usual approach in setting up test schedules has not been one of assuming that a separate test must be made for each possible defect, but instead one of considering available techniques so as to select those of maximum mileage... the old production principle of doing the most with the least effort and time.

Practically all of these boil down to some variation of the growler test and/or some variation of the bar-by-bar resistance test. Let's consider growler test techniques first, as this test can really give more information than any other.

We have already shown how the growler test produces circulating currents if shorted turns exist. Since a definite transformer action takes place between the growler structure and the armature on test, circulating currents within the armature are reflected into the growler excitation circuit, and resulting change as the armature is scanned can be used to trigger shorted turns indicators. In actual practice this can be made quite sensitive... to 1% or one turn in a 100-turn coil, or better. Since, as previously discussed, the shorted turns test should be made at the highest practical level, maximum possible growler excitation is used. In Slaughter Company equipment, we prefer a pulse-surge excitation for this test sequence, as this usually produces higher test levels within the armature than a sine wave excitation.

A simple continuity test based on this same effect is in use. Since the above technique will detect shorted turns, it will also detect shorted

coils. Therefore, if a bar-to-bar shorting contact is placed on the commutator in the proper location, every coil passing through the growler will show a short-circuit, unless it is open. This converse effect is used to detect open coils and/or open bars. Most test setups using this approach for opens are not very effective in detecting poor connections because the test is conducted at the same level as the shorted turns test, and is much too high. As previously noted, the continuity test should be conducted at the lowest possible level if poor connections are to be detected. Unfortunately, this shorted-bar technique has not proven too satisfactory at low levels.

The bar-to-bar voltage induced in the armature during growler scanning is proportional to the growler excitation, the air-gap, and the number of turns in the growler coil. This effect is used for turns-count checking. Usually, the induced voltage is measured by high impedance equipment so as to avoid loading effects, and the effects of growler excitation variation and air-gap variation are either cancelled, or minimized by holding these factors to close limits. This can be somewhat tricky, as any actual measurement requires a reference standard of some sort, and if all coils in the armature are not identical, lower accuracy, or a programmable reference standard is required. We will discuss this subject in more detail later.

If this induced voltage test is arranged to measure voltage over a wider span than bar-to-bar, it then becomes effective in detecting crossed connections. However, its accuracy in turns-count checking is diluted. Regardless, such a wider span is often used. For example, if alternate coils have a different number of turns, the checking span is adjusted accordingly so as to avoid the need for programming the measurement reference.

By conducting the bar-to-bar test at a very low induced voltage level, using an optimum fixed load during the test, the induced voltage test described above has been made quite sensitive to poor connections as well as to opens. For this purpose, growler excitation is generally a sine wave, often of a relatively high frequency; up to 50 Khz.

Reference Standards

Perhaps this is as good a time as any to stop and discuss this whole problem of reference standards. It keeps coming up, and will continue to do so as we go on to other methods.

Ideally, when one conducts a measurement, one should be able to use a fixed reference. But, if the value to be measured is subject to a normal variation, even if it is on a regular pattern, then some means must be provided to vary the reference accordingly, unless accuracy can be sacrificed. Most armatures will exhibit a very definite normal variation. As mentioned, some are actually wound with different numbers of turns in different coils, on a fixed pattern. Double-flyer wound armatures exhibit different characteristics on a 180° pattern. Programming limits, or programming reference standard levels can be a real headache, especially in a high speed scanning type of test.

For this reason, in setting up an armature test system, one must immediately face up to a decision as to whether a positive fixed (though possibly programmed) reference is to be used, or whether one will be satisfied with what we call a “discrepancy scan”. Since all armatures are symmetrical in some manner, the test can be arranged so that equivalent coils can be compared with each other, and variation or discrepancies between the two can be used as the basis of rejection.

As a concrete example, we can use the previous illustration of the armature with alternate coils of different turns count. If we test on a bar-to-bar basis or reference standard, or our limits must be programmed accordingly, or we must accept

broader limits. In this case, if we use a wider span (3 bars) we can avoid the programming problem, but we still require a reference that will either cancel excitation and air-gap variations, or we must try to hold these factors constant and widen limits as necessary to accommodate whatever inconsistency they have.

Alternatively, if we arrange our test so that we compare the induced voltage in two coils with that of two other similar coils, then we need not be concerned with the excitation and air-gap variations, nor with any programming. We are concerned only with discrepancies during the scan and can use limits that are quite close. Of course, there are dangers here... if the entire armature is equally bad, it will pass... (some wise guy can put an armature on with all bars shorted, and make us look silly.) Practically, this is rarely a problem, as most procedures incorporate enough separate tests that such a part

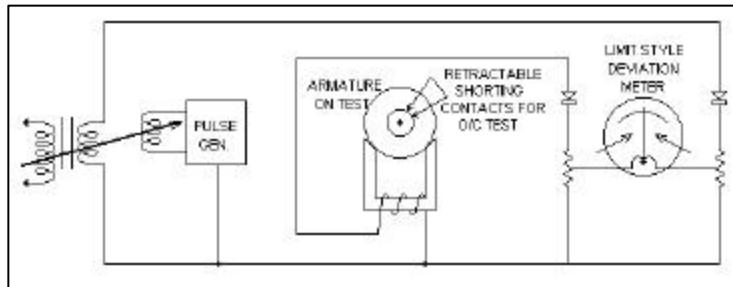


Figure 2, Growler Test for Opens and Shorted Turns, using Proportional Reference System.

would not pass all tests.

We will see later on how this same concept applies in resistance testing and in surge testing.

Growler Test Examples

The simplified diagram of Figure2 is an example of a growler test arrangement for short circuit and open circuit testing. Negative pulses from

the pulse generator are used to excite the growler. The return positive pulses are used as a signal for indication. The reference is taken from a positive voltage output of the pulse generator which is directly proportional to the negative pulse input to the growler. The signal from the growler

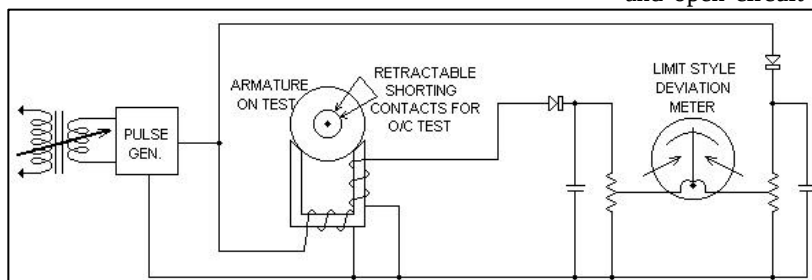


Figure 3, Growler Test for Open and Shorted Turns, using Discrepancy Scan System.

is compared with the reference voltage on zero center instrumentation. During the short circuit test, rotation of the armature in the growler field results in a steady signal which balances the reference voltage. Passage of a shorted turn through the growler field will result in a low signal and a corresponding down scale deflection of the instrumentation.

During the open circuit test, contacts which short-circuit the commutator bars corresponding to the coil centered in the growler field are used. This results in a low level signal as the armature is rotated in the growler field. The necessary readjustment in the reference voltage is made so that the instrumentation remains centered under this condition. When an open coil traverses the growler field, the signal rises appreciably, resulting in an up-scale deflection of the instrumentation.

Stability of this system depends upon the stability of the reference, and consistency in the armatures being tested. If either is a problem, the arrangement of Fig. 3, which is a discrepancy scan system, can be used.

Operation of this system is the same as that of Fig. 2 with the exception that the reference voltage is taken from an auxiliary winding on the growler. The time constant of the reference circuit is relatively long, while that of the signal circuit is relatively short. This results in indications of the same type as obtained in the proportional reference system of Fig. 2. However, sensitivity is not as great and circuit values are somewhat more critical than those of Fig. 2.

Fig. 4 is an example of turns count checking by growler test methods. In this arrangement, the growler is excited by a sine wave, generally in the 60 to 1000 cycle frequency range. For best accuracy, the highest practical level, and higher frequencies are preferred. The induced voltage between two or more commutator bars is compared with a reference voltage taken from an auxiliary winding on the growler.

In addition to checking turns count, this test will detect shorted turns, bar-to-bar shorts, mixed leads, and crossed connections, to the extent that these other defects result in output voltage variations greater than that allowable for the normal turns count variation. It will also detect open circuits, but is not effective for poor connections because the voltage levels are generally too high.

Fig. 5 is an example of the manner in which this same arrangement can be used to detect poor connections as well as opens. Here, the growler excitation level is reduced so that the induced

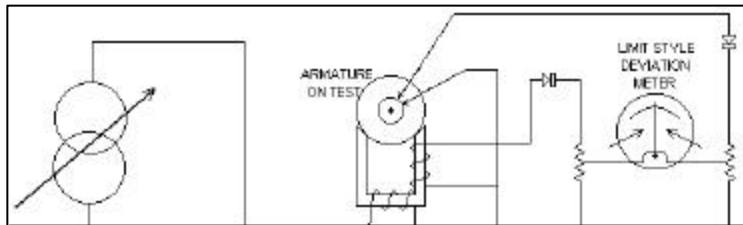


Figure 4, Growler Test for Turns Count.

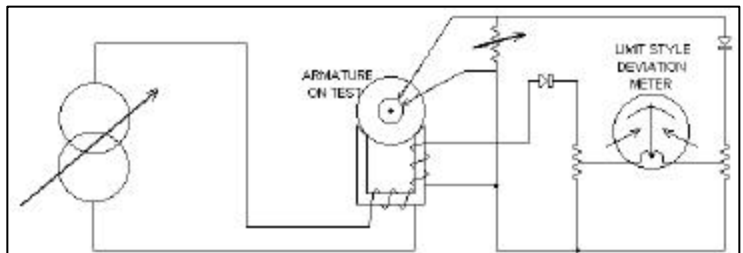


Figure 5, Growler Test for Poor Connections.

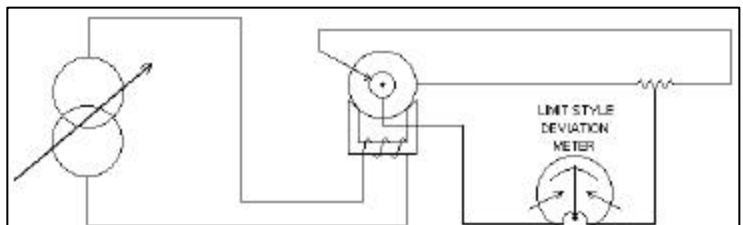


Figure 6, Growler Test for Commutator Alignment.

voltage is under the critical 2 volt level. The maximum practical loading is placed in the circuit, and unless a certain minimum current flows, the part is considered to have poor connections.

Fig. 6 is an example of the manner in which a growler set up can be used to check commutator bar alignment. This is obviously based on the

principle that, at the neutral plane, voltage induced on opposite sides of the armature will be exactly equal.

From the practical standpoint, growler test set-ups can be somewhat difficult, especially if a wide variety of armatures are to be tested. Setup changes are often time consuming, and for this reason, growler tests are no longer used in many general purpose test stations. This is possible because other methods of test, particularly variations of the surge test, can achieve the same results more easily. However, a working knowledge of growler theory and growler test methods is desirable for anyone engaged in the testing of armatures.

Resistance Testing

As mentioned, the growler test can yield a great deal of information, and hence, has been widely used. The bar-by-bar continuity, or resistance test does not have nearly as great a yield, and hence, is rarely used as a sole method of test. Instead, it is often used as a supplementary test in an effort to pick out some specific defect or error that may not be so readily detectable by any other method.

In essence, this test is one of scanning the armature and using bridge, or ohmmeter methods to establish either continuity as such, or, resistance levels specifically. Usually, this test is conducted with DC, and as mentioned earlier, it should be conducted at the lowest possible voltage if poor connections are to be detected. Properly applied, with test voltage levels under 2 volts DC, we believe this is the most effective method of detecting poor connections on tang-welded and similar armatures.

However, this has been a very difficult test to perform on a production basis because it is always checking the quality of contact between the instrumentation and the commutator, as well as the armature itself, and any variation at this point will result in false

rejects. Current Slaughter Company equipment utilizes the Kelvin technique of resistance testing, which virtually eliminates contact problems. With this technique, separate contacts are used to carry the necessary DC current into the armature. This, of course, is a low impedance circuit. A separate set of contacts is used to measure the voltage drop, and since these are in a high impedance circuit, the quality of contact is not a serious problem.

In addition, on a bar-to-bar test, the ugly problem of programming limits or the reference, or broadening limits, is here with a vengeance. To be effective in detecting flaws, this test may require setting limits that are closer than the normal magnet wire tolerance. Obviously, this is impractical, so some compromise must be made. One compromise is to use the discrepancy scan system of test.

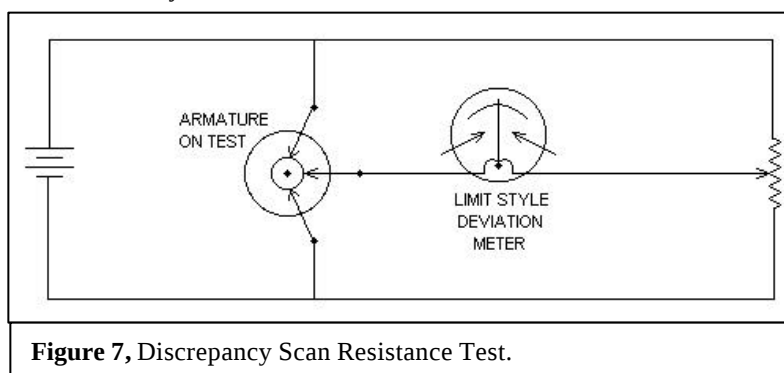


Figure 7, Discrepancy Scan Resistance Test.

Fig. 7 is an example of bar-by-bar resistance discrepancy scanning. This is basically a conventional bridge circuit with the armature forming two branches of the bridge, and the other two being formed by an adjustable tap resistance. The system is balanced with a good part, and variation as unknown parts are scanned

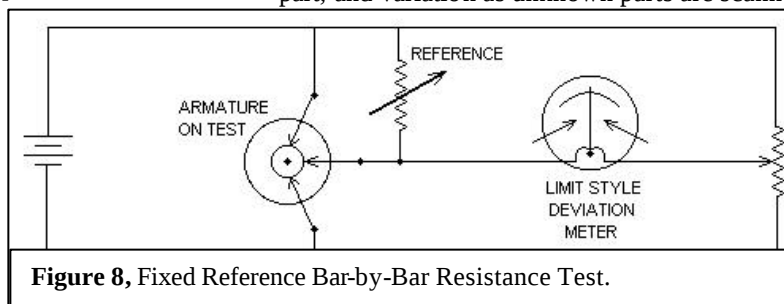


Figure 8, Fixed Reference Bar-by-Bar Resistance Test.

results in fluctuation of the instrumentation. If the armature being tested exhibits a regular pattern of resistance variation, contact locations should be selected to compensate for this

variation. For example, the extreme contacts with double-flyer wound armatures should be at 180°.

While the discrepancy scan system of Fig. 7 is quite effective in detecting poor commutator connections, opens and shorts, it does not provide a continuous monitoring of armature resistance to catch such defects as out-of-tolerance wire size, nor is it particularly effective in detecting crossed connections. In contrast to this system, the arrangement of Fig. 8 illustrates a bar-to-bar test system using a reference standard.

The reference standard test system of Fig. 9 is quite effective in detecting poor connections, shorts, opens, and out-of-tolerance wire size. Depending on the situation, test contacts can be arranged to check the armature on a 180° basis, on a bar-to-bar basis, or on an intermediate spacing. Smoother operation is obtained with double-flyer wound armatures if the test is conducted with the contacts at 180°. This is because the normal pattern of resistance fluctuation around the armature balances at the 180° point.

Through the use of the Kelvin technique, systems can be made quite accurate and resolutions of as little as one milliohm are practical. By using digital techniques, data storage and data analysis, readings are now taken on a routine production basis on a bar-to-bar basis completely around the armature and on a 180° basis at selected points. This information is then digitally compared with stored limits in order to insure "in-tolerance" parts on an absolute basis. Diametrically opposed bar-to-bar coils on double flyer wound armatures are compared for differential resistance. Due to the characteristics of the double flyer armature, these coils should be essentially identical and it is practical to insist upon balance as close as 5 milliohms between the two sides of the armature.

The Discrepancy Scan technique is based on the premise that only diametrically opposed coils within a double flyer wound armature with an even number of bar segments will exhibit essentially identical resistance characteristics. Normally resistance progressively increases from Coil 1 to Coil 5 due to an increase in wire length from coil over-lay.

Resulting resistance differentials between these identical diametrically opposed coils are generally indicative of poor weld connections and can be detected.

Additionally, a DCR test with programmed high and low tolerance limits can monitor such variables as wire gauge; shorted turns, layers or windings; wire stretch; connection integrity; proper lead hook-up.

However, detection of crossed connections will sometimes be a problem. This will be true on armatures having a large number of coils, which results in each coil being a relatively small percentage of the total resistance and also "2 in hand" winding configurations. If the number of coils is such that the resistance of a single coil is a smaller percentage than the normal wire tolerance, it will not be possible to set limits sufficiently close to detect a crossed connection. In such cases, it may be better to test on a bar-to-bar basis, even though limits must be broadened to allow for acceptance of the normal bar-to-bar resistance variation existing in the typical armature. Even with this configuration, the bar-to-bar test is still quite effective in detecting poor connections, bar-to-bar shorts, opens, and out-of-tolerance wire size, as well as crossed connections.

When it is impractical to use the bar-to-bar spacing, it is often possible to obtain adequate sensitivity to crossed-connections in the surge test, so this is not an impossible situation.

An often over-looked phenomenon in coil and winding testing is the Direct Current Resistance (DCR) change within windings as a result of product heat rise usually generated by some production process such as a varnish bake oven, turning operation, welding or hot stake operation. Even changes in ambient temperature inside the factory can adversely affect DCR readings. As a rule of thumb, the DCR of copper wire will exhibit approximately a 4% change in resistance for every 10°C change in temperature.

An optional temperature compensation feature minimizes DCR error caused by product temperature variations.

Ambient temperature sensing is suitable for most applications.

For applications where testing follows a heat production appellation, the use of a high resolution, quick responding infrared detector positioned to focus on a specific area of the product under test is suggested.

Incidentally, commutator finish is a very important item in armature processing. Most manufactures utilize the diamond turning technique. Included as an appendix to this paper is a paper on diamond turning, which may be of interest.

Surge Testing

In any field everyone is always searching and hoping for a magic cure to all ailments and armature testing is no exception. Unfortunately, eager proponents of surge testing have hailed it as the magic answer in the armature testing field. Some claims have been almost as fantastic as to imply that if a defective armature is brought near a surge tester, it will immediately blow whistles, ring bells, and may even dig a hole and bury the offending part. Perhaps so, but we haven't been able to train ours this well yet.

Seriously speaking, surge testing has a very definite place in this field if it is properly applied. By this, I mean that it is a supplement to, or a part of other methods and not a 100% substitute for all others. Before getting in to applications, let us spend a few moments in discussing the fundamentals of surge testers.

Basically, a surge tester is nothing more than a pulse generator plus some instrumentation that will respond in some logical manner to the effects created by the pulses from the generator. Broad definition, isn't it? Necessarily so, because the instrumentation varies widely. The prime consideration lies in the fact that in surge testing a pulse generator is used as opposed to a sine wave, or DC. The important thing about this is that it allows us to apply an extremely severe test, but still to limit the energy applied to the part under test so that damage to good parts will not occur. This is possible because we control the amplitude of the pulse, as well as its duration.

Since the total energy in a pulse is proportional to the product of its amplitude and duration, if

we keep the duration down, we can use very high amplitudes, and still stay out of trouble.

Understanding this fundamental, it is easy to pick out the areas in which surge testing is beneficial in armature testing, as well as those in which it is not particularly desirable. Looking back at our summary, we find that the round tests and shorted turns tests should be conducted at the highest practical level, while continuity testing should be conducted at the lowest practical level. Beyond these fundamental tests, no comment was made regarding the desirable level for the supplementary tests such as epoxy insulation quality, mixed leads, crossed connections, turns count and commutator bar alignment. In this group, obviously the epoxy insulation test must be made at a high level, while others can be made at any convenient level desired.

The primary characteristics of surge testing have already been discussed in some detail in the previous section dealing with coil testing in general. However, there are certain characteristics of surge testing of armatures worthy of particular attention, and some items described earlier should be emphasized. So in the following paragraphs there will be some repetition. We might start with the example that in the case of coils, the greatest stress and most problems generally occur in the pigtail and layer-to-layer areas. In the case of armatures, similar areas of high stress occur at coil crossovers at both ends of the armature, and at the commutator. What that in mid, let's concentrate for a moment on what the surge, or pulse, does to the armature.

First let's consider the nature of the pulse itself. In most equipment, it is a sudden application of voltage, with a rise time of only a few microseconds. This means that we are dealing with a wave form that is effectively of much higher frequency than our familiar 60 c.p.s., and therefore, consideration must be given to all of the parameters of the load. In particular, such items as distributed capacity which can generally be ignored at 60 c.p.s. are very important.

Next, let's consider how the pulse is applied to the armature. As noted previously, there are only two ways to do it. Either we apply it inductively using a magnetic structure such as a

growler, or we apply it directly to the winding, in this case, to the commutator.

If it is applied inductively, there will of course be a corresponding magnetic field in the armature which results in proportional induced voltage in the winding. This is true... this happens, and possibly something more. Those hidden parameters within the system that we can ignore 60 c.p.s. come forth, and we may find that the whole system "rings", or resonates, and instead of having a simple pulse-like effect we may have a damped oscillation. While this may be surprising, it is not undesirable... we are doing what we wanted to do and that is give the armature a good "belt". Furthermore, since we are doing it inductively, it is quite well distributed, and the actual turn-to-turn voltage distribution within any given coil is relatively constant... regardless of whether the system "rings" or not.

If we apply the pulse directly to the commutator, the situation is somewhat different. As before, the system may "ring", or it may not, depending upon the parameters of inductance, distributed capacity, pulse rise time, and the like. The important consideration is that the voltage distribution within the armature coils will not be constant. Due to the distributed capacity effects the major stress will occur in the conductors that lie near the surface, and those that lie deep within the slots may hardly be stressed at all.

So, we have the same situation that has been discussed earlier in this paper. If the surge test is applied inductively, the voltage distribution is reasonably constant on a turn-to-turn basis, while if the surge test is applied directly, voltage distribution is generally concentrated in surface areas and areas of high stress. Since these interrelationships have already been outlined in detail, we will not go through this again, other than to point out that in the test we must be prepared to accept certain compromises. In most applications, we prefer the direct application compromise primarily because test systems utilizing growlers require more careful attention during set up and operation and more time for setup changeover, and because it is easier to obtain the high stresses desired through the direct application method than through the inductive method using a growler.

Surge test systems using the inductive application are quite straight forward, as by their very nature, they become essentially a "discrepancy-scan" type of system. When direct application is used, the old headache of reference standards returns to haunt us, and it is particularly bad here because the normal variation in distributed capacity can be quite large.

One approach is to use a master sample as a reference on the theory that identical surges applied to identical parts will yield a balanced condition. Defective parts will not be identical with the master, and hence, will be rejected. This approach can become quite difficult mechanically because to be consistent, the reference standard should be scanned in exact index with the unknown. This is rarely done and most applications use a passive master, and limits are broadened as necessary to take care of the normal variations. Practically speaking, the same results can be achieved by using a proportional reference, i.e., a system in which the reference voltage is directly proportional to the applied pulse voltage and as in the case of the passive master, limits are broadened as necessary to accommodate normal variations. Results are practically identical with the passive master system, with the advantage that a master sample part is not needed.

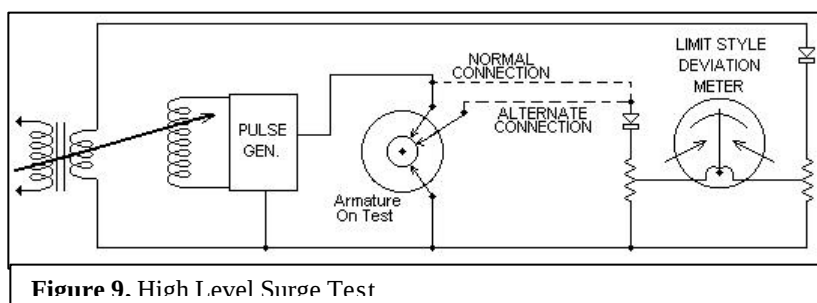
The "discrepancy-scan" method of instrumentation can also be used here.

Products with multiple windings of like magnetic characteristics, such as armatures or 3-phase stators, can, in addition to absolute tolerance verification of each winding, be surge tested in a discrepancy scan manner. That is to say that magnetic properties of individual windings within a specific product can be compared to each other. This discrepancy scan technique is especially desirable in applications where iron permeability of the product varies significantly from unit to unit.

Here also the wider application of digitizing computer techniques and computerized analysis techniques are opening new avenues to explore. Work is already being done to investigate the effectiveness of computer analysis of surge test wave form in diagnosing work pieces. This field appears to have tremendous potentialities.

Two more points should be covered before we leave the subject of surge testing. In the direct test, instantaneous currents through the commutator can be quite high. If a poor connection exists, local heating can be extreme and a minute weld will be created, superficially correcting the poor connection. This effect can be quite puzzling. Armatures can be rejected on a low level continuity test, then run through a direct surge test, and then they will pass when re-tested on the low level continuity test.

They still aren't good armatures, but this is the "nature of the beast." A similar effect can occur with shorted turns. Burns or chips in



commutator undercuts can cause shorted turns rejects. If we retest such an armature after the direct surge test, these parts are often good because the surge test literally "burns-out", or "blows-out" these particles.

Fig. 9 is an example of a high-level test arrangement. High-level negative pulses from the pulse generator are applied to the commutator contacts. The corresponding return positive pulses are used as a signal that is compared with a voltage proportional to the original excitation pulse. As in previous arrangements, this is displayed on zero center instrumentation and any fluctuation from balance is a basis of rejection. This test is quite effective in detecting turn-to-turn weaknesses and shorts, especially at cross-overs, as well as in detecting shorted bars, and opens. If crossed-connections are a problem, and these cannot be detected on the resistance test, the surge test can be made quite effective in detecting these faults by placing the signal pick-off contact at an intermediate point. This is illustrated by the lower dotted line alternate connection on Fig. 9.

Conclusions

At this point, the author is always expected to come up with some conclusions. This is

essential because it gives the critics something to sink their teeth into. We have tried here to review the most common defects in armatures, what the test equipment must do, and the test methods that are being used to accomplish this in such a way that the reader can analyze these things in relation to his own problem and draw his own conclusions. But, it wouldn't be fair not to stick our neck out, so here goes.

Generally speaking, we feel that at this moment in time, the best armature test schedule must include:

1. If required, epoxy lamination coating tests of the raw stack.
2. Ground or Hi-Pot test by conventional methods.
3. Shorted turns test by means of a high level growler test, using pulse, or surge test methods.
4. Continuity test, by means of a very low level DC resistance test, on a bar-by-bar basis.
5. Direct surge test to detect coil-to-coil weaknesses and crossover defects.
6. If required, turns count test by induced voltage method.

The above is an extremely rigorous test schedule and it is rare that one can afford the luxury of the time required to conduct all of the above. Instead, a compromise schedule is generally used, and we will discuss this in more detail later.

Regardless of what compromise schedule is utilized, we must emphasize that to be effective, the test program must, at one point or another, scan the armature bar-by-bar. This is essential if one is to avoid the embarrassment of finding an open bar in an armature that is otherwise properly wound... particularly, in tang type constructions.

The method of scan utilized depends upon a number of factors. Mechanical scanning fixtures are simply to maintain and easy to change over from one type of armature to another. However, care must be taken in using these to keep the contacts in good condition and to select the proper type contact structure for the particular

communicator involved. For example, simple silver alloy faced contacts are quite satisfactory for most turned undercut commutators. Bifurcated types are generally required for commutators with flush insulation. Other commutator constructions may require other types of contacts.

In contrast to the mechanical scanning fixture, electrical scanning fixtures can be used. Such devices have the advantage that better contact with the commutator is generally obtainable. However, there is a distinct disadvantage in that tooling costs become significant if a number of different armatures are to be handled on the same equipment. In addition, the switching mechanism is somewhat more difficult to maintain.

Since our neck is already out, now is as good a time as any for a short sermon. We have had a great deal of experience in this field; we have seen dirty laundry on the line and skeletons in the closet. For our own selfish reasons, we have tried to analyze every such situation and it has been quite interesting. Almost invariably, we have found that either a "Sacred-Cow" was involved or someone sacrificed test time to achieve higher production rates. To elaborate, we often find that armature test schedules, methods, and equipment have their roots in antiquity... they have been handed down for so long that they have become a "Sacred-Cow" and nobody dares to question them or change them. In the other situation, too often someone decides that a particular type of defect is unlikely, and hence, testing for that defect can be eliminated. Everything goes fine, until that defect or a related defect suddenly appears, usually in great volume.

Our points should be obvious... first, don't hesitate to question because maybe what you have is not as good as it appears; and second, don't sacrifice. Be sure your set-up is capable of a full test procedure. If time is a problem, arrange it so that some of the schedule can be dropped when things are going okay, but keep the full system available and alert for those trouble periods that are bound to come sooner or later. Alternatively, don't hesitate to change test conditions when an unusual situation develops. For example, surge test voltages can be reduced when poor connections are the major problem,

and can be increased when crossover weaknesses are the major problems.

Every program has its commercial and this one is no exception. To be blunt, we build test equipment and we want your business. To be persuasive, we point out that there is much more to a test system than just the instrumentation.

Returning to our previous comment as to what constitutes a particle compromise schedule, it has been our experience that good quality control can be maintained on wound armatures by a simple test schedule which includes the continuity test, Hi-Pot test, and surge test. During the past 20 years, millions of armatures have been tested under this schedule on our older Series 910, 920, 930, and 720 systems. Our current standard Series 1720 / 1730 equipment is fully automatic, and operates on a Go – No/Go basis. Since this equipment is all solid state, PC controlled, it is extremely versatile and useful for testing of armatures, stators, and all types of coils. General purpose, or custom built test fixtures can be supplied, and the system arranged, or turns can be retrofitted in the field, for the use of dual alternately operated test fixtures so as to eliminate any loss of test time during the load/unload period. More information is available – just let us know.

Actually, we do not need to beat the drums for any particular test schedule, method, or instrumentation because our line includes basic test units, control systems, et cetera, that enable us to build exactly what the customer wants. As the old peddler used to say, "If you don't see what you want, ask for it."

Stator Testing

AS previously discussed, the armature is the heart of the motor and it is the part that usually fails first. This, of course, is the reason that an effective test schedule is a MUST. By comparison, the stator is a relatively simple structure, and is not subject to the same type of abuse as the armature. In the typical production facility, the finished motor rejections due to stator defects is considerably less than those due to armature defects.

Even so, most volume manufacturers are now finding it desirable to pretest stators in very much the same manner as armatures. This is

primarily for economic reasons. The cost of assembling, and tearing down even a small percentage of motors because of defective stators is often greater than the cost of 100% testing.

Generally speaking, a relatively simple schedule is used, consisting of a resistance test, a Hi-Pot test, and a surge test. The resistance test is effective in detecting opens, gross turns count errors, and incorrect wire size. The Hi-Pot test is obviously effective in detecting grounds. As in the case of armatures, the primary advantage of the surge test is that it will detect turn-to-turn shorts and weaknesses; especially at crossovers. An incidental advantage of the surge test is that it will detect a reversed motor coil – but not a complete reversal of a winding. To detect a complete reversal of the winding, a polarity test is needed.

The Series 1720 / 1730 electronics can be used interchangeably for stator or armature testing. Fixturing is, of course, somewhat different but designed for simple changeover from armature to stator testing.

In some special cases, a more rigorous schedule is called for. A particular example of this is the multitapped stator windings often used on blenders. These are often wound with several strands in parallel which are then separated and connected to provide the required configuration. Such construction is susceptible to shorts between windings and to connection errors.

If connection errors are no problem, the schedule described above is generally effective. However, care must be taken in applying this test to be sure that all windings are connected in series at the time of test. If this is not done, it is quite possible some windings may not be stressed.

If connection errors are a problem, a test sequence is added which is usually an induced voltage type of test. In this technique, the stator under test is magnetically excited by means of a dummy armature and the various taps checked to determine that induced voltage fall within the normal limits for a good part. This test technique has the added advantage that it can also provide an effective polarity check as well as a check of reversed coils.

The complexity of the test equipment required is directly related to the number of taps to be checked. Also, this generally determines the time required for the test. If time is a serious factor, the test equipment can often be arranged to check all taps simultaneously. However, such a system is generally considerably more expensive than the scanning type.

As in the case of armature testers, stator test equipment is being combined with the automatic winding equipment in such a manner that the test requires no operator. Such installations are, of course, only suitable for very high volume applications.

TESTING POINTS TO PROBLEMS IN ARMATURE PRODUCTION

By Elmer Slaughter

In any field of endeavor, the participants are often too busy “putting out fires” to take a long, hard look at the overall picture.

In the area of testing armatures, it may seem like a lot of changes have occurred in years past. Surprisingly, there have not been a lot of changes where the basic testing principles are concerned. There have been many changes in such things as tools, instrumentation, mechanical handling methods, and peripheral controls, but the actual testing techniques have changed very little.

As a matter of fact, it sometimes becomes rather amusing. Quite often, someone comes up with a variation in technique and trumpets it as a radical new discovery. Usually it is recognizable for what it is: a simple variation, sometimes an improvement and sometimes not.

It is very difficult to totally separate the testing function from the manufacturing. In the production of armatures, there have been many changes in techniques and processes – some good and some not so good.

This is an important consideration because changes in the manufacturing area have always had a major influence on testing methods. The emphasis in testing is controlled primarily by the weak or marginal areas in the actual manufacturing process, whether the products are armatures or toy pistols. After all, if the quality of our manufacturing techniques was perfect, there would be no need for testing.

Evolution of Testing

Looking back, it is interesting to see the evolution that has taken place. For instance, years ago the problem areas were insulation failures and crossed connections at the commutator. Both of these generally were due to human factors – manhandling of the winding or mistakes. Regardless of the reasons, the fact that these were the trouble areas led to refinements in high voltage testing and in surge testing techniques. These are fundamentally the techniques still used today.

Later, the wide application of automatic winding machinery using the tang winding technique effectively eliminated the crossed connections problem. It also reduced the insulation defect problem drastically by default. Designers simply had to acknowledge the fact that automatic winders could not fill the slot so full that the winding had to be forced into place by main force and awkwardness – factors which often damaged the insulation in the process.

Another problem formerly encountered was angular displacement of the commutator in relation to the laminations. In fact, as late as the 1960's, inexpensive motors were being built on production with adjustable brush structures to compensate for these sins. This problem rarely is encountered now and when it is, it usually is due to poor quality control in the operation of commutator installation. The result if this problem being cured at the source was that there was never a great deal of emphasis on commutator alignment testing. The techniques have been developed and are available but there is little need for them in today's manufacturing world.

These examples effectively illustrate what can be called the classical normal progression. Testing is emphasized by problem areas. Testing also emphasizes the problem areas with the result that

methods are refined to either eliminate, or at least reduce to manageable proportions, these problem areas.

So much for the past. It seems we again are in a cycle in which the problem areas are emphasizing the testing. The testing should be emphasizing the problem areas to the extent that refinements in manufacturing techniques should relieve the problem. It is essential that this be the solution. Regardless of how good the test equipment is, it cannot test quality into a product. The quality has to be in the product and all the test equipment can do is confirm that quality exists.

For several years, major emphasis in testing has been on commutator connections on tang wound armatures. The response of the test equipment industry has been the so-called "weld" test, which is essentially some form of resistance test. A number of different test techniques have been devised, each manufacturer claiming his to be the best. As little variation as on milliohm can be detected, however, from one bar to the next.

What should be Rejected?

Again, regardless of the sophistication of the test techniques, this does not solve the problem of rejects. In fact, it causes another problem: creating arguments about what should be rejected. In any testing operation, there always will be a gray area – an area in which the work piece may be good or bad. This area is even greater when there are normal variations which may or may not be indicative of a fault.

This description fits the situation very well. It is not unusual to go on a trouble call, (sometimes at the company's expenses and sometimes at the customer's expense), to answer a complaint about inconsistent resistance readings. We often find that we can take the finished parts and physically "wiggle" the loops under the tangs, or lift the tangs and show no bonding at all. Let's face it, such a product is not good, and no amount of testing is going to make it good. However, it is quite possible that at the moment of test, this part will show in tolerance resistance and it will pass. It also is possible to have a well bonded part fail to pass because of some slight variation in wire stretch, wire gauge, or some other valid reason. This is the reason that there are valid complaints that any given group of

armatures can be run through the test equipment several times and yield different quantities of rejects.

Classically, if the industry responds to this problem in the same manner as in the past, we should expect very shortly to see some major changes in the manner in which tang connections are processed. Clearly, this is where the challenge is – not in the testing, but in responding to what the testing is telling us. As manufacturers of test equipment, we don't feel we have the equipment or the qualifications to handle this problem. However, a few suggestions can be offered from experience.

The first suggestion, naturally, is to recognize the problem and solve it.

Secondly, we should consider that few expert welders will attempt to weld two pieces of copper together with or without the contamination of magnet wire insulation. On the other hand, any good mechanic will solder two pieces of copper with low or high temperature

solder, whichever is preferred. From this, it appears that the problem is more one of chemistry and metallurgy than anything else. The source of the heat really doesn't matter. Whether it's from welder current or sonic, it seems that something else besides pressure is needed to consistently get a good bond.

Conclusions

Some people in the welding and sonic bonding industries are going to challenge some of these statements. They may say the present day equipment will do a good job if properly adjusted. There is no argument with this point; the statements simply reflect observations made in the field. If it is not practical to keep the equipment working this way consistently, then perhaps this is the correction that is needed. To state the point another way, the testing of armatures is pointing to a problem in the fusion process in commutator connections. The solution is not known, but the signals are clearly there and somebody should be doing something about them.

REAL TIME, AUTOMATIC SPC FOR THE COIL WINDING INDUSTRY

By Richard M. Chrisco

Abstract

In the past, production-line testers were limited to separating good parts from bad ones. Now, using immediately generated and automatically monitored Statistical Process Control (SPC) charts, computerized coil testers can actually alert the user to trends which, if corrected, can prevent the production of bad parts.

Introduction

Statistical Process Control (SPC) has recently received wide coverage in the industry press. It is a term that encompasses a wide range of techniques by which variation within a manufacturing process may be first identified and then controlled. In the coil winding industry, electrical measurement data is frequently used as a basis for product acceptance and is therefore generally available for Statistical Process Control. However, SPC requires the accumulation and processing of numerical data on a regular basis. If done manually, these tasks

are considered tedious or distasteful by many. Hence, SPC tends to be perceived as something to be dreaded. Even in the best of circumstances, SPC is often abandoned as too time consuming when there are fires to put out.

As the sophistication level of automatic electrical coil testers has increased, such systems have become more and more capable of carrying-out the "distasteful" tasks related to the application of SPC. In fact, recent advances have even given the tester the ability to constantly monitor the sometimes numerous control charts for out-of-control indications. The following pages will attempt to trace the changing role of the tester in the application of SPC to coil manufacturing, to examine some advantages of today's state of the art testers and to predict, or at least guess at what the future may hold regarding advances in this area.

Applying SPC to Wound Products Manufacturing

In nearly every modern factory where wound products are made, some type of electrical testing is performed (i.e. resistance, hipot and/or high voltage surge). Usually, the measurements

are performed by an automated tester which sends it the scrap/rework bin any part that does not pass within particular limits. The Statistical Process Control technique best suited to detecting variation in such measurement data is the X-bar and R chart technique.

Table 1, Statistical Process Control Worksheet for Armatures

Trend Categories	Product Faults	Process problem Indicated	Material Program Indicated	Pertinent Data on an Individual Armature Basis	Output of SPC Values for Armatures
High DCR	Open Winding	Winder		180? DCR	X-bar, R Values
	Wire Size (Too Small)		Wire Tolerance		
	Weld Integrity	Welder			
	Wire Stretch	Dereeler			
Low DCR	Chips in Slot	Brushing		180? DCR	X-bar, R Values
	Wire Size (Too Large)		Wire Tolerance		
	Comm. Drag-Over	Lathe Cutting Tool			
Differential DCR (Electrical Balance)	Weld Integrity	Welder		Maximum Differential DCR	X-bar, R Values
	Missed Tangs	Winder			
	Wire Stretch	Dereeler			
Surge (Magnetic Balance)	Shorted Turns		Wire Insulation	Average Surge Deviation	X-bar, R Values
	Chips in Slot	Brushing		Spread of Deviation	
	Comm. Drag-Over	Lathe Cutting Tool			
	Lam Stack Height	Stacker			
	Open Winding	Winder			
Ground	Slot Insulation	Epoxy Coating		Hipot Measured Leakage Current	X-bar, R Values
	Comm. Insulation		Molding Impurities		

X-bar and r charts are relatively easy to understand and can be quite powerful. They provide a picture of the process results over a period of time that can be visually analyzed to detect changes in the measured parameters. Furthermore, the statistical techniques minimize the effects of random variation. The result is that non-random variation can be identified as it enters the process. Once identified, these trends are traced back to their source within the process, adjustments are made and the process returns to its optimum operating level. Ideally, no parts are rejected during the described sequence of events. The reader is referred to the bibliography for more thorough explanation of the theory and application of Statistical Process Control.

The student of SPC will find that there exist many ways to graphically indicate the link between trends in the charts for specific data to their source within the process. Some are quite complicated and, to be complete, all require specific knowledge of the particular line. A simple, tabular analysis of the relationship

Examples of X-bar and R Charts generated by an automated tester can be found in Figure .

The source of such non-random, or assignable, variation might be a worn piece of equipment, a change in material characteristics or something more obscure. Generally, the more complicated the wound product the more involved the manufacturing process becomes. As the number of components that make up the line grows, so does the number of factors that can contribute to undesired variation between individual parts. Furthermore, each system is different and has its own characteristics, many of which are learned only by experience.

between trends in the electrical parameters of armatures to their sources within a typical armature manufacturing process can be found in Table 1. A similar chart for a typical stator is presented in Table 2.

The trends in the left column of the tables are caused by the process or material problems

Table 2, Statistical Process Control Worksheet for Stators

Trend Categories	Product Faults	Process problem Indicated	Material Program Indicated	Pertinent Data on an Individual Armature Basis	Output of SPC Values for Armatures
High DCR	Open Winding	Winder	Wire Tolerance	DCR	X-bar, R Values
	Wire Size (Too Small)	Dereeler			
Low DCR	Wire Stretch		Wire Tolerance	DCR	X-bar, R Values
Surge (Magnetic Balance)	Wire Size (Too Large)		Wire Insulation	Surge Deviation	X-bar, R Values
	Shorted Turns	Stacker			
Ground	Lam Stack Height	Winder	Molding Impurities	Hipot Measured Leakage Current	X-bar, R Values
	Open Winding	Epoxy Coating			
	Insulation				

identified in the center columns. The specific charts to be monitored for each trend type can be found in the right columns. As an example, say the X-bar and R charts indicated that the 180 degree resistance of an armature was beginning to rise. From the table this could indicate a degradation of the weld integrity or perhaps that the dereeler had begun to stretch the wire.

Of course, a specific production line might have other components in addition to those mentioned in the tables. Furthermore, combinations of these trends might be found to further differentiate between the individual components. However, these tables are certainly useful as a

starting place for anyone attempting to apply SPC to the manufacture of wound products.

The Role of the Tester

In the past, all aspects of applying Statistical Process Control to electrical test data in this industry have fallen entirely on human shoulders. Today, however, the tasks of collecting the data and creating and monitoring the charts can all be performed by the tester without human intervention. The evolution of the tester's changing role in the application of SPC to coil manufacturing can be traced historically in Table 3.

Time Frame	Type of SPC	Description
DISTANT PAST: Tester not involved in SPC	Measurements made by technician-charted manually	Very slow-Human error likely- May be abandoned in crisis. Very expensive.
INTERMEDIATE PAST: Tester has limited role in SPC	Measurements made by tester than recorded by technician-charted either manually or by offline computer.	Slow-Humana error likely- May be abandoned in crisis – Expensive.
RECENT PAST: Tester taking central role in SPC	Offline SPC: Data automatically transferred to separate computer where charts are created.	Fast-Requires batch processing and off line, after the fact analysis – Expensive.
TODAY: Tester performs all aspects of SPC including chart monitoring.	Automatically-monitored, Online, Real time SPC- Tester not only collects data and displays charts while testing parts, but also notifies operator if any of the process is out of control.	Very Fast – Immediate response to problems is possible, charts are automatically monitored- Inexpensive.

Starting at the top, where the tester played no role, the table illustrates significant steps in the historical application of SPC by the tester. Major characteristics of each era are noted in the center and right-hand columns. As indicated, more and more SPC tasks have become

automated until today, when modern computerized automatic test equipment can actually sample at programmable intervals and maintain and monitor the charts providing instant feedback to the operator. Thus the term "Automatic, Real Time Statistical Process Control".

Advantages of Today's Testers

Creating and Monitoring Charts

Today's state-of-the-art coil testers not only carryout the routine tasks necessary to maintain X-bar and R charts, but also relieve the operator of having to constantly monitor each of these sometimes numerous charts. Suppose five individual tests are performed on the parts. Data would then be available for five pairs of X-bar and R charts. Monitoring all then of these charts could certainly become overwhelming, especially on higher production-rate lines.

Fortunately, recent advances have given the automatic tester the ability to monitor each chart which it maintains for the occurrence of one or more points falling outside the upper and lower control limits – recognized as the most important characteristic of X-bar and R charts indicating the influences of non-random variation¹.

Sampling Interval Flexibility

Another, perhaps less obvious, advantage of today's state-of-the-art testers is the flexibility they allow in choosing a sampling interval. Traditionally, this choice has been strongly influenced by economics even though it might have been better, in terms of controlling the process, to have sampled more often. Two points were generally considered; 1) the cost of making checks and 2) the rapidity with which the process was likely to change². That is, sampling could be performed as frequently as necessary to maintain control of the process as long as the amount of money saved by reducing rework and scrap could be shown to be clearly greater than the cost of collecting and charting the data.

Modern testers, by performing the sampling, charting and monitoring all in just a few seconds per sample without human intervention, have made selecting the sampling interval more a question of what is optimal to quality rather than what is economically feasible. This becomes

especially important in more complex, automated lines where the odds of something needing attention are greater and also, in higher production-rate lines where wear and adjustment problems can quickly escalate to the point of causing parts to be rejected. It is also important in cases where sampling more often than normal is desired such as when a line is first started-up or when a particular component has been performing poorly. Each additional sampling-charting-monitoring cycle takes but a few seconds between tests while the next part is being loaded into the test fixture. Thus, the sampling interval can now be shortened at will without requiring any additional manual effort and with almost no impact on tester throughput.

What About the Future?

The tester's role in the application of SPC to this industry will no doubt continue to change. As artificial intelligence becomes a more mature science, it will become practical to implement it in almost any situation where data must be continuously evaluated. One can imagine that, in the not too distant future, the tester will have the ability to further interpret X-bar and R charts to determine the source of any non-random variation in the process.

As additional advances are made in automating the individual components of a coil winding line, a tester with artificial intelligence capability could go from merely telling the operator the probable source of the variation to actually adjusting the individual machines to eliminate it. At any rate, the coil winding industry will continue to benefit from the effortless application of SPC that the automatic tester afford.

Conclusion

The difficulty, tedium and expense once associated with applying Statistical Process Control within the coil winding industry have all been eliminated by a new generation of automatic electrical coil testers. Today's testers not only perform the traditionally human tasks of data collection, X-bar and R chart creation and even chart monitoring, but also, in doing so, allow the sampling interval to be trimmed as desired without increasing personnel workload or impacting tester throughput. Technology in

¹ ***DataMyte Handbook*** – 3rd ed. Minnetonka, MN: DataMyte Corporation, 1987.

² Western Electric Company, Inc. ***Statistical Process Control Handbook*** – 2nd ed. 11th printing. Charlotte, NC: Delmar printing Company, 1985.

this area has advanced to the point that it is truly a pleasure to reap the benefits of SPC.

Cpk: The Next Step in Applying SPC to Wound Products

Richard M. Chrisco

Abstract

Real time, automatic SPC (statistical process control) was made available in production-line, electrical testers several years ago. The immediately generated and automatically monitored X-bar and range charts have proven useful in bringing a process under control and monitoring process changes. The next logical step is to utilize Cpk to correlate this valuable control information to actual engineering tolerances (reject limits). Calculated from data on the X-bar and range charts, Cpk reflects process results relative to engineering tolerances. Thus, by monitoring Cpk, wound product manufacturers can tell if a process is capable of producing their product and, if so, to what degree. Recently, the SPC functions of computerized, wound products testers have been enhanced to include automatic calculation and monitoring of Cpk for each tested parameter.

Introduction

Many manufacturers already utilize electrical coil test systems capable of automatically generating and monitoring X-bar and range charts of measurement data in real time. These systems have eliminated much of the tedium of manually creating and monitoring such charts required to bring a process to a state of statistical control and keep it there³. In practical application, however, once control is established, the relationship between the output of the process and its specification limits becomes the subject of interest. Examining this relationship takes one beyond the realm of control chart theory into an area called process capability. As one authority defines it: "Capability is the proportion of process output that stays within the

product specification"⁴. Process capability, by taking specification limits into account, provides a figure of merit for how well a process in a state of statistical control will likely meet tolerance requirements. Thus, to study capability, an indicator or "index" representing this proportion must be available.

Cpk (Capability in Relation to Specification mean)⁵ has become a widely accepted capability index. Its popularity may be primarily attributed to two factors; first, Cpk is a single number which is easy to monitor and compare, and second, Cpk is simple to calculate directly from X-bar and range chart features. How a companion to control charts in real time, statistical process control software, Cpk has become a ready indicator of process performance. It provides simple, on-going, process capability feedback where it is needed the most; on the factory floor. The following pages are intended to provide the reader with a working knowledge of Cpk.

Calculating Cpk

One of the reasons Cpk is so widely accepted in industry is, no doubt, the ease with which it can be calculated. Once X-bar and range charts exist for a measurement, its Cpk is found by applying the following equation:

Cpk = The lesser of

$$\frac{USL - \bar{X}}{3 \left(\frac{R}{d_2} \right)} \quad \text{or} \quad \frac{\bar{X} - LSL}{3 \left(\frac{R}{d_2} \right)}$$

In this equation, USL and LSL are the upper and lower specification limits, d₂ is a textbook constant (dependant upon the sample size used to create the control charts), and X-double bar and

³ Richard M. Chrisco, "Real Time, Automatic SPC for the Coil Winding Industry" in **1988 Coil Winding Proceedings: Proceedings of the conference in Cincinnati, Ohio, October 3-6, 1988**, by the International Coil Winding Association, Inc., 224.

⁴ **DataMyte handbook**, 3rd ed., (Minnetonka, MN: dataMyte Corporation (1987), p3-2.

⁵ Ibid., p3-14.

R-bar are directly from the control charts. In the case where there is only one specification limit, upper or lower, only the corresponding part of the Cpk equation is used⁶.

Perhaps it should be emphasized at this point that Cpk is only valid when calculated using features from control charts that reflect a process which is in a state of statistical control. Simply put, to say a process is not in a state of statistical control with respect to the measurement being sampled is to say that it is uncertain what the value of that measurement will be on any future product sample is to say that it is uncertain what the value of that measurement will be on any future product of that process. It follows that, in such a case, it is not possible to make any meaningful estimate of what specifications the process is capable of staying within. The reader is referred to the bibliography for a complete discussion of control chart theory.

Understanding the Cpk Equation

As a first step toward understanding it, the above Cpk equation can be rewritten to reflect certain truths. First, $\bar{X}$, the average of the sample $\bar{X}$ -bars, is used in the Cpk equation as an estimate of the average of the entire population. The "population" is the larger body of all process output from which the control chart samples are taken. The implicit assumption is that, as the number of samples used to calculate it becomes "statistically large", $\bar{X}$ becomes a very good estimate of the mean of the entire process⁷. To stress this assumption, the symbol μ (the Greek letter mu) is used to represent the estimated mean of the population in the remainder of this paper.

A second clarifying substitution is also used herein. The ratio $\bar{R} / d_2$ which is an estimate of the standard deviation of the population about its mean (σ), is replaced by the symbol σ (sigma-prime).

The Greek letter sigma is the accepted symbol for standard deviation, whereas, the prime is intended to emphasize that this is not, and should not be confused with the standard deviation of the sample $\bar{X}$ -bars about $\bar{X}$ on the $\bar{X}$ -bar control chart. (Recall that, on control charts, the plus and minus three standard deviation lines are often referred to as the upper and lower control limits). The importance of this statement will become apparent later in the text.

With these substitutions, the Cpk equation becomes:

Cpk = The lesser of

$$\frac{USL - \mu}{3\sigma} \quad \text{or} \quad \frac{\mu - LSL}{3\sigma}$$

The next step toward understanding this equation is to recognize that the two numerators represent the "distance" from μ to the corresponding specification limit and, because the denominator of the two ratios is the same, the lesser ratio will be the one calculated with the "closer" limit. This illustrates the point that Cpk is a "worst case" indicator based upon the specification limit that is closer to μ and therefore more critical. It should be apparent that the best (largest valued) Cpk possible for a given USL, LSL, and μ is when μ falls exactly half way between USL and LSL. At this point, either numerator is as large as it can be without the other being smaller and therefore, more critical. This would indicate a process that is "centered" with respect to specifications.

Finally, to understand the Cpk equation, one must recognize the underlying assumption that the measurement of interest would follow a normal distribution (also called a bell curve) if the distribution of the entire population were plotted. This is the reason the estimated three standard deviations (3σ) of the mean (μ) appears in the denominator. Since a normal distribution is symmetrical about its mean and 99.73 percent of all its points fall within plus and minus three standard deviations of its mean, it follows that, by knowing 3σ of the normally distributed measurement's μ , one knows the range within which nearly the entire population's measurement will fall. Thus, in the Cpk equation, the numerator is the acceptable range

⁶ Kenneth E. Case, PH.D., P.E., and James S. Bigelow, "Capability and performance Indices: Proper Use in the process Industries" (Cincinnati, Ohio: American Chemical Society, Rubber Division), 4, photocopied.

⁷ John S. Oakland, **Statistical process Control**, (New York: John Wiley & Sons, 1986), 69.

for the measurements on that side of μ and the denominator is the range that all the measurements on that side of μ are expected to be within. The assumption of normality will be subject to more discussion in later paragraphs.

A normally distributed population, its μ , plus and minus 3σ , and the “distances” from μ to both the USL and LSL are each illustrated in Figure 10.

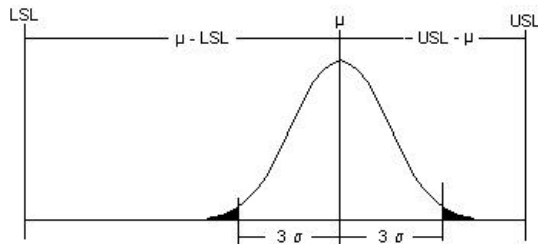


Figure 11, A normally distributed population. USL and LSL are upper and lower specification limits. 3σ is estimated three standard deviations of “ μ ” the estimated mean of the distribution.

Interpreting Cpk

In industry, Cpk minimum limits of 1.33, 1.67, and even 2.00 are being required of manufacturers. To understand what these limits mean, recall that when a ratio equals one, its numerator and denominator are equal. These industry limits, therefore, simply require that the distance from μ is the most critical (closer) specification limit be greater than 3σ ; the range within which all the population on that side of μ is expected to measure-up. Respectively, the distance to the most critical limit must be one-third, two-thirds, and twice as large as 3σ . For example, note that the distance to the closer limit, USL, is roughly twice 3σ therefore indicating a Cpk of approximately two for the process illustrated back in Figure 10.

If Cpk were equal to one, it would indicate that the 3σ range would run right up to the most critical limit. In such a case, assuming a perfectly normal population, something like 0.13 percent of the process output (half of what falls outside $\pm 3\sigma$ of the normal curve) would be expected to be beyond that limit. (If the process is centered when Cpk is equal to one, the “fringe area” of both sides of the distribution would fall outside the specification limits and all the product outside $\pm 3\sigma$ of the normal distribution,

about 0.27 percent, would be out of spec). Both cases are illustrated in Figure 11.

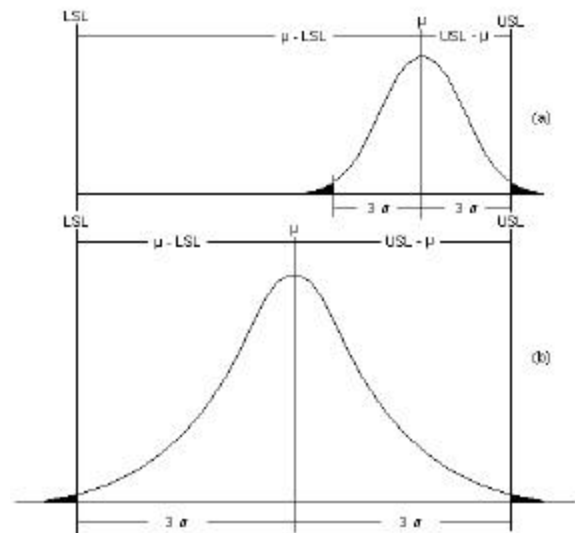


Figure 10, Two distributions where $USL - \mu$ is equal to 3σ , and, therefore $Cpk = 1$. The portion of each distribution outside the specification limits is darkly shaded. The process illustrated in Figure (b) is centered whereas, the one in Figure (a) is not.

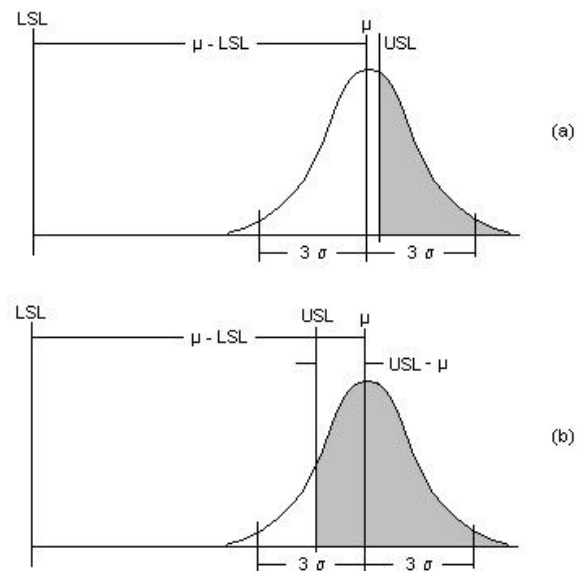


Figure 12, Distribution (a) has a Cpk that is just greater than zero. If μ is exactly equal to USL, Cpk equals zero. Distribution (b) has a negative Cpk. The shaded areas of each are out of spec.

Two other cases are of particular interest. First, as Cpk decreases from one, it indicates that μ is

moving toward the critical limit until, at the point where Cpk becomes equal to zero, half the normally distributed population is actually outside that limit and presumably scrap. The other case, when Cpk becomes negative, indicates that $\bar{x}$ actually exceeds a limit and more than half of the product can be expected to be out of spec. Either of these cases indicates a process in need of attention. They are illustrated in Figure 12.

Cpk in Practice

A Cpk of less than one is obviously undesirable. However, it may not be entirely apparent at this point why a Cpk of 2.00 is any better than a Cpk of, say, a little over 1.00. The motivation for requiring a greater Cpk can be attributed, at least in part, to the fact that the above mentioned assumptions are not always correct. For instance, no process is ever “totally” in the state of statistical control and it is unlikely that a process will ever produce a population which “exactly” follows a normal distribution⁸. Therefore, it is prudent to raise the minimum Cpk limit to give some “margin of safety” to be more certain that all delivered product is within specifications.

A current industry trend, in fact, is to push suppliers toward “continuous process capability improvement”. Taguchi, a noted expert in quality, promotes the idea that no level of process capability is “good enough”. He recommends a program of continued reduction in inherent process variability. He further argues that, all things considered, this is the most economical approach in the long run⁹.

There are three ways to improve process capability; 1) center the process mean ($\bar{x}$) between the specification limits if not already centered, 2) reduce the inherent variability (σ) of the process, and 3) broaden the specification limits if they are unnecessarily tight. Although any of these actions will increase the Cpk number, they are not all practical in every instance. For example, limits are often inflexible due to customer requirements and a process may already be centered. The final option, reducing

inherent process variability, may involve little more than adjusting a machine or replacing worn tooling. It may, on the other hand require that part of the process be completely re-designed.

Cpk Complex but Necessary

By now the reader should realize that Cpk

⁸ Ibid., p3-14.

⁹ Greg D. Stocker, CPM., “Reducing Variability – key to Continuous Quality Improvement,” **Manufacturing Systems**, March 1990, 33.

