##### IEEE P1719

Draft Guide for Evaluating Stator Cores of AC Electric Machines Rated 1MVA and Higher

Prepared by the P1719 Working Group of the

Materials Subcommittee of the Electric Machinery Committee

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**INTRODUCTION**

(This introduction is not part of IEEE P1719, Draft Guide for Evaluating Stator Cores of AC Electric Machines Rated 1MVA and Higher.)

The Draft Guide for Evaluating Stator Cores of AC Electric Machines Rated 1MVA and Higher was written to inform engineers, asset managers and maintenance personnel of functional aspects of stator cores, in order to promote a better understanding of mechanisms that stress this component of their machinery. Larger electric machines have a wide variety of designs that make it difficult to precisely define technical information about a specific generator in a document of this type. Therefore it is important to discuss your unique design and maintenance related issues with knowledgeable people from the original equipment manufacturer (OEM), or other qualified source, to be sure that decisions are based on the right information.

It is generally understood that the coils and bars that reside in the cores of electric machines have a finite life; their insulation will eventually breakdown from the combined stresses of operation, at which point typically the winding must be replaced. As part of this periodic winding renewal, which can also involve equipment upgrade, the question of the longevity and or capability of the stator core will inevitably arise. Stator cores of many machines can appear to have a passive role that may lead some owners to assume that they will not require maintenance. To understand the maintenance requirements, it is necessary to appreciate the function of the stator core, and to be aware of the mechanisms that can lead to unreliable service.

Generators and motors of the class outlined in this guide have been in utility and industrial service for many years, with some in service for over one hundred years. The electric machinery infrastructure continues to age, and its reliability appears in general to be remarkably sound. However, the design life of this machinery has been exceeded in a large number of units, and prediction of continued reliable operation can represent a challenge. A stator core’s reliable life span depends on many factors, including original design and operating conditions. Eventually every core will require some type of maintenance; it’s simply a question of when.

This document is not intended to be comprehensive in all aspects of the subject. Where appropriate, other standards are referenced for specific process or test procedures and other information. This is done in part to keep this document size reasonable, and also to direct the reader to what is likely an updated reference.

**Participants**

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**FIGURES**

[Figure 1 – The stator core is designed to carry electro-magnetic fluxes during operation, and must be capable of handling the magnetic flux density in the stator teeth and core back areas. In this figure, the “conductor bars” are between the “teeth” of the core. 12](#_Toc336863172)

# Scope

This guide describes methods which may be used to evaluate the condition of stator cores of AC electric machines including generators, motors, and synchronous condensers, and summarizes background information relevant for the informed application of these methods.

This guide is not intended to provide detailed inspection, testing, and maintenance procedures. Other IEEE standards and references related to stator core evaluations and repairs are listed in Section 5.0 “References”.

The methods outlined herein are generally applicable to machines rated 1 MVA (1340 HP) and higher. However, these methods may be applicable to units of lower rating.

# Purpose

The purpose of this guide is to provide assistance to engineering and maintenance personnel responsible for planning, performing, and assessing results of stator core evaluations. The results of a successful evaluation program may be used to:

1. Identify needed maintenance and repairs.
2. Support strategic decisions relative to core replacement.
3. Provide guidance for developing purchase specifications.
4. Help to optimize the core life from an asset management perspective.

# Definitions

* Back Iron –
* Buckling Phenomenon - “buckling phenomenon”, which is a circumferential “wave” shape of the core laminations that can occur when the stator frame constrains thermal expansion of the stator core.
* Building Bolts – Part of the core clamping system. Per ASME B18.12, these components should really be referred to as “studs” or “double-end studs”, but they are actually referred to by many slightly different terms - “core studs”, “clamping bolts”, “compression bolts”, “hold-down bolts”, “through-bolts” (if they do indeed go entirely through the stack of laminations), “stud bolts” or “tightening bolts”.
* Core Clamping System – The design/equipment used to keep the laminations in the core clamped together.
* Key Bar – May also be referred to as “building bolt”, “core support bar”, or “dovetail bar”, referring to its shape. These are bars around the outer circumference of the core, typically welded to the shelves of the frame, which are used to locate the core laminations. In some designs, they may also be used as part of the core clamping system.
* “Segmented” core – this phrase is often used to mean that each lamination sheet is not a full annulus, but is divided up into smaller arclengths. These laminations are then alternately overlapped to avoid having all the splits line up in the same place.
* “Split” core – this phrase typically means that the laminations were stacked in sections, often in half-circle or quarter-circle sections. The sections are then assembled onsite, with all the lamination edges lined up at each “split”, and bolts attaching the frame sections together.
* Stacking Factor – The percentage of space occupied by magnetic material in a tightly held stack of laminations.
* Yoke -

# Safety

**5.1 General**

Personnel safety is of paramount importance. In addition, considerations of safety in electrical testing apply

to the test equipment and apparatus under test. The following guidelines cover many of the fundamentally

important procedures which have been found to be practical. However, it is not possible to cover all aspects

in this document and the test personnel should also consult IEEE Std 510-19837, ASTM F855-97,

manufacturers’ instruction manuals, union, company or government regulations.

Prior to performing any test of power apparatus, there should be a meeting of all people who will be

involved or affected by the test. The test procedure should be discussed so there is a clear understanding of

all aspects of the work to be performed. Particular emphasis should be placed on personnel hazards and the

safety precautions associated with these hazards. In addition, procedures and precautions should be

discussed which will assure the production of meaningful test results without subjecting the test specimen to

unnecessary risks. In those situations where the tests are not being conducted by owner personnel,

concurrence of the owner should be obtained on test magnitudes before the tests are performed.

Responsibilities for the various duties involved in performing the test should be assigned.

**5.2 Personnel considerations**

**5.2.1 Responsibility (qualifications)**

Personnel assigned to performing the procedures described in this document should be well trained for the

particular task to be performed. In particular, they should be aware of the safety hazards that may be created

if proper procedures are not followed. Many of the test evaluations call for a high degree of judgment on the

part of the evaluator and that can only be obtained by experience. Experience on one type of machine does

not necessarily qualify a person to conduct and evaluate tests on another type of machine.

It is the responsibility of the tester to ensure the safety of all personnel including plant personnel and those

directly working on the test. The tester should also consider the safety of the apparatus being tested and the

test equipment.

**5.2.2 Hazards**

Insulation tests in the field present a hazard to personnel unless suitable precautions are taken. Apparatus or

circuits to be tested shall be disconnected from the power system. Typical safety procedures call for a visual

check of the disconnection or, when this is not possible, a check with a voltage indicator. Solid grounds are

then applied. Personnel should be instructed to treat all ungrounded apparatus as energized.

**5.2.3 Ground connection**

Use of working grounds should comply with established company guidelines. For further information see

ASTM F 855-97. The test equipment, as well as windings, nearby components, and associated equipment

not under test, should be solidly grounded for the duration of the test, and after the test if dc is used.

**5.2.4 Precautions**

When testing, precautions shall be taken, including warning signs and barriers as listed in 5.2.5, to prevent

any personnel from contacting energized circuits. An observer should be stationed to warn approaching

personnel and may be supplied with means to de-energize the circuit. The means may include a switch to

shut off the power source and ground the circuit until all stored charges are dissipated.

**5.2.5 Warning signs and barriers**

The test area shall be marked off with signs and easily visible tape. Warning signs shall conform to the

requirements of governing bodies such as the Occupational Safety and Health Administration (OSHA) in the

United States.

**5.2.6 Hazardous materials**

On some rotating machines hazardous materials such as asbestos and lead carbonate may be present. In such

cases, work, cleaning, and disposal of hazardous materials shall be performed according to appropriate

government regulations.

**5.2.7 Machine rotation**

Some test procedures are performed with the machine rotating slowly and with cover plates, guards, and

end-shields removed. Hydro machines may be operated for test purposes with covers removed at rated speed

or at runaway speed. These tests present mechanical hazards in addition to electrical ones. Appropriate

procedures should therefore be developed to prevent injury to personnel present.

**5.2.8 Documentation**

It is recommended that the following documentation be available before commencing any diagnostic tests:

— nameplate data of machine

— relevant standards

— written test procedure

— machine instruction manual

— instruction manual for test equipment

— manufacturer's information indicating expected test values

— previous inspection and test results (if available)

— operational and maintenance history

# Normative References

ASME B18.12-2012 Glossary of Terms for Mechanical Fasteners

ASTM A343

ASTM A 345-04 Specifications for Flat-Rolled Electrical Steels for Magnetic Applications

ASTM A 664-11 Standard Practice for Identification of Standard Electrical Steel Grades in ASTM Specifications

ASTM A 976-03 Standard Classification of Insulating Coatings for Electrical Steels by Composition, Relative Insulating Ability and Application

Canadian Electrical Association Guide for Erection Tolerances and Shaft Systems Alignment Part II (CEA Guide)

EASA Technical Note No. 17 Stator Core Testing

IEEE 1095

IEEE Std 56-1997 Guide for Insulation Maintenance of Large Alternating-Current Rotating Machinery (10 000 kVA and Larger)

IEEE Std 492-1999 Guide for Operation and Maintenance of Hydro-Generators

IEEE Std 432-1992 Guide for Insulation Maintenance for Rotating Electric Machinery (5hp to less than 10 000 hp)

IEEE P62.2

ISO 7919 and ISO 10816

IEEE C50.12

ISO 3746

IEEE C37.96 Guide for AC Motor Protection, IEEE C37.101 Guide for Generator Ground Protection, and IEEE C37.102 Guide for AC Generator Protection.

Geoff Klempner, Isidor Kerszenbaum “Handbook of Large Turbo-Generator Maintenance, Second Edition, IEEE Wiley Press

# Overview

Stator core evaluations are typically performed after assembly and installation as a condition of acceptance, on a periodic basis to check for damage or deterioration, prior to a rewind to verify an in-service core’s suitability for continued use, and after repairs to ensure that the desired results were achieved.

Core evaluations may involve a physical inspection to look for damaged laminations, signs of corrosion, or other evidence of core and core retention and/or clamping system damage. A comprehensive evaluation may also include checks for looseness of the core clamping structure, tests of the inter-laminar insulation, and a review of the machine’s design and operating history.

# Stator Core 101

The primary functions of a stator core are: (1) to hold the stator windings in place, and (2) to transmit flux. A stator core in a large AC machine is constructed from thin laminated sheets of electrical grade steel such as ASTM A 345. The core is built up from these thin laminates so as to limit eddy current losses in the core iron as a result of the alternating flux induced during operation. En mass, these laminations may be referred to as “iron”. Each lamination is insulated and the stator core laminations are grounded, usually at the back of the core, ensuring that circulating currents as a result of the induced magnetic flux cannot occur; these would result in localized current flow and overheating of the laminations. See Figure 1.

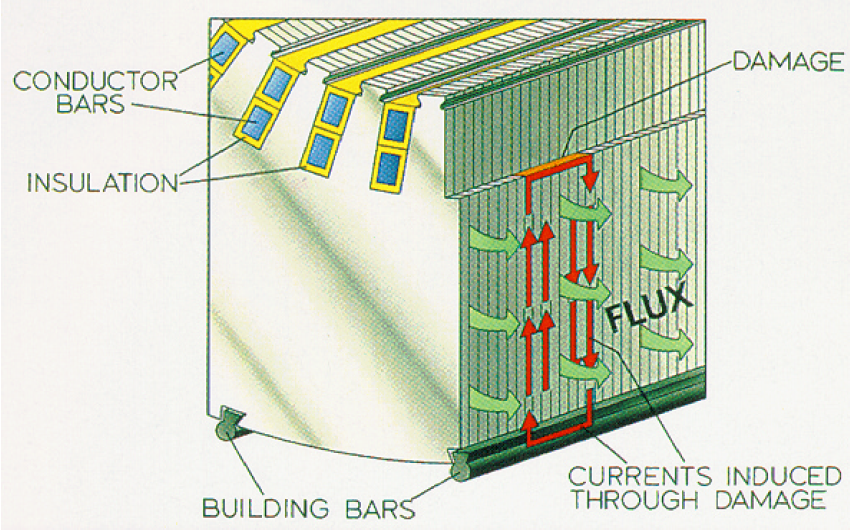


Figure 1 – The stator core is designed to carry electro-magnetic fluxes during operation, and must be capable of handling the magnetic flux density in the stator teeth and core back areas. In this figure, the “conductor bars” are between the “teeth” of the core.

Numerous types of organic and inorganic insulation materials can be applied to the core laminations as insulation. Older, organic insulation lasts much longer than moder-day insulations. Repairs to this insulation are sometimes necessary during the life of a stator. Damage can occur due to scraping and/or impact during rotor removal, a foreign object in the air gap, a winding failure, or a reduction in core clamping pressure. Very high circulating current levels may damage the core laminations beyond repair.

Much more information about stator components, including more details on the core, are included in Annex B, “Stator Component Descriptions”.

# Design-Specific Aspects of Core Evaluation

See Annex X, “Design Considerations”, for far more background information.

## Evaluating Core Losses

The steel used in stator cores is chosen for its low core loss and low magnetic hysteresis characteristics. When attempting to evaluate core losses, it is important to note that core loss measured by the supplier Epstein frame test, by a core loop test and finally by the generator efficiency test are not generally the same, since the flux direction and distribution will differ in each condition.

Core loss as defined in ANSI/IEEE C50.12 is the difference in power required to drive the machine at normal speed when separately excited to produce a voltage at the terminals corresponding to the rated voltage at open circuit, and the power required to drive the unexcited machine at the same speed. This loss is the sum of losses in the generator from the core, field pole, damper winding, end clamping fingers, vent fingers etc., which are subject to magnetically induced losses during open circuit operation of the generator. The stator core loss generated in the laminations only represents a portion of the total core loss. With a refurbishment, the losses can be reduced with the use of modern materials like high permeable stator core sheets.

## **Evaluating Lamination Insulation**

Originally, the oxide coating on steel provided sufficient insulation to prevent excess losses between laminations. But as equipment grew in size, additional insulation was required to improve the resistance between the individual steel laminations. The early insulation systems utilized natural paper, shellac, and/or Tung-oil-based varnishes. The present-day insulations have evolved to include melamine, phenolic, polyesters, or epoxies/resins.

Oxides coatings alone (mill coat) are only appropriate for small cores. The next level of insulation is organic or inorganic coatings or a combination of both, applied to the surface of the electrical steel. Refer to Table 1 of ASTM A 976 for a descriptive list of coating classifications.

After punching laminations, some large equipment manufacturers perform de-burring and then recoat the punchings, to cover any steel surfaces that may have been exposed. This process reduces the risk of burrs causing shorts between punchings and improves the stacking factor. Additional bondable coatings may also be added that cure with heat to bond sections of the core laminations or the entire core. On a failed global vacuum pressure impregnation (GVPI) winding, it is common to burnout the old winding for rewind. Prior to performing burnout, one should check with the original manufacturer to see whether the lamination insulation coating can survive the burnout temperature.

The quality control test to evaluate the single coating insulation resistance on steel is commonly called the Franklin Test (ASTM A 717/A 717M). This test uses 10 electrodes on the surface and 2 drill points that contact the steel and run at prescribed voltage, temperature and pressure and current is measured. Current of 1 amp represents insulation failure and 0 is perfect insulation. The ASTM document recommends 300 psi and testing at room temperature and 150 C. But steel producers and equipment manufacturers should agree upon required Franklin test parameters and acceptance limits. For example, the customer of the steel manufacturer may require Franklin testing at the start and end of each steel coil at 150 C and 500 psi, with a maximum allowable current reading of 0.5 amps and an average of 0.25 amps or less. Note: For the C-0, C-1, and C-2 coatings, it is not appropriate to set maximum Franklin test values.

## Evaluating Stator Core Tightness

Core clamping pressure is an important design consideration which needs to be applied at an accurate level by the core clamping system, to maintain the design stator core tightness. Since many factors must be taken into account when this pressure is determined, the original equipment manufacturer should be contacted when issues of core clamping maintenance arise.

The core iron of a machine is clamped together such that the thousands of laminated steel plates that make up the core act as a single component. This clamping action is achieved by a combination of studs/bolts and bars that clamp the laminations in the axial direction. The pressing system has to ensure a permanent pre-stress in the clamping bolts/studs, which is maintained even after any settling of the stator core due to heat and vibration. A typical core tightness value might be between 0.8 and 1.5 N/mm^2. In turbo machines, circumferentially applied radial clamping may be used, and these devices should be checked for tightness. During normal operation of a machine, especially a two-pole machine, the core is pulled out of round by the interaction of the rotating magnetic fields. This action results in the core operating in a state of constant radial deformation. This deformation, which rotates at synchronous speed, is normally low in amplitude but will increase as the core clamping becomes loose. Such looseness can lead to the movement of laminations relative to each other, movement relative to clamping components, loosening of winding clamping components, loosening of wedges, breaking of vent fingers, and breaking of laminations. Evidence of such core looseness is an increase in core noise while in operation. Large turbo generators have cores with longer axial and smaller radial dimensions than low-speed vertical generators. Core compression plates are typically located at each end of the core, over the ends of the core building bars / key bars. The two compression plates are connected via through-studs, which are tightened in order to compress the stator core assembly. For turbo-generators and globally vacuum pressure impregnated stators, this is usually carried out in the factory during the stator build when the core assembly is compressed to approximately 90 metric tons/cm (250 tons/inch), and the studs/bolts are tightened to retain the core laminations. It is possible for these to become loose during operation and any tightening of these studs should be carried out in accordance with the manufacturer’s recommendations, taking into account any core lamination damage or interlaminar defects that may have occurred, as this may make things worse.

Red oxide type dusting between core components observed during a visual inspection can be an indication of core looseness…………...

Thousands of laminated steel plates are clamped together so that they act as a single component to form the stator core. This clamping action is achieved by a combination of studs/bolts and bars that clamp the laminations in the axial direction. The pressing system has to ensure a permanent pre-stress in the clamping bolts/studs, which is maintained even after any settling of the stator core due to heat and vibration over the design life of the machine. Since many factors must be taken into account when this pressure is determined, the original equipment manufacturer should be contacted when issues of core clamping maintenance arise.

Typical average inter-laminar pressure is between 0.7 and 1.9 megapascal distributed over the cross sectional area of the core. There are several different design methods for the core-clamping structure used to achieve this inter-laminar pressure. Evaluation of core tightness from a design point of view should include consideration of the type of compliance, the amount of compliance, and the measure-ability of the tightness.

Different types and sizes of machines such as turbo generators and hydro generators have developed different core-clamping systems to meet specific design requirements. The simplest construction uses plates on either end of the core with tensioned bolts or studs providing the compressive forces to the core. In other designs the frame of the machine provides lever action against the end plates to shift the forces toward the inside diameter. Another common design uses through-bolts imbedded in the core along with end plates to distribute the forces over the stacked laminations. Some larger machines employ special through-bolt materials to allow additional stretch to help maintain force as the core settles and shrinks over its life. Dish-type spring washers are also used in various ways to maintain tension as cores settle over their life cycle. Cores may use impregnation resin or adhesives to help consolidate the laminations over the entire length or in specific locations. Some cores also have circumferentially applied radial clamping in addition to axial clamping. Other methods and combinations of the above may also exist; therefore, contact with the original equipment manufacturer is important in evaluating the built-in compliance and life cycle of the core clamping system.

Since there are a variety of methods employed to achieve the inter-laminar pressure, there are a variety of methods to evaluate the core tightness and effectiveness of the clamping system. The various systems will have different means of checking tightness including checking on bolt torques, dished-washer compression measurements and even more complex methods. This could include devices that measure tension using hydraulic pressure or other devices that measure changes in component length with tension. These methods require knowledge of the design loads/torque and dimensions to be conducted correctly.

Other considerations of the core design are the ability to retighten and the extent of retightening/re-tensioning allowed. Certain stator core designs have welded components and do not allow for retightening/re-tensioning. Other core clamping systems only allow a limited range for compliance. There are concerns with tightening cores with globally vacuum pressure impregnated insulation systems due to the possibility of cracking the stator coil insulation.

Core tightness inspection and measurement methodologies and considerations are described in detail in section 9.

Other parts of the notes belong in the other sections (clauses 9 and 10)

## Identifying Thermal-Design-Related Issues

The need to include provisions for radial expansion in the machine design will depend on the diameter of the machine, the temperature rise of the core and frame and the flexibility of the frame.

A radial key system can seize due to lack of lubrication or misalignment of the keys. Both of these problems can produce eccentricity in the stator frame and core.

On machines that require but do not have expansion provision in the sole plate design, the end result may be core buckling or severe cracking of the concrete in and around the sole plate grout pockets or both. Machines that do not have a specific feature to accommodate radial expansion will generally have less than a 7 m diameter.

On some machines, the relative movement of the core with respect to the frame is indicated by wear marks created by the laminations rubbing on the key bars or core bolts. This can often be seen near the top of the key bar or core bolt.

# Tests for Core Evaluation

## Mechanical Tests

* Knife test
* Bolt Torque test
* Bending test

## Electrical Tests

## Core Lamination Insulation Tests

There are high-energy and low-energy methods of testing stator core lamination insulation. The oldest method is to apply a high magnetic flux of about 1 Tesla in the back iron; this may require a significantly sized single-phase power source. During this “ring” or “loop” test, if there is defective insulation between laminations or if there is looseness in the stator core, localized heating (hot spots) will result around each defect. This heating can then be detected with an infrared camera or other methods. A strong single-phase source of reactive and real power is needed to perform this test. ANSI/IEEE Std. 56-1997 and IEEE P62.2 describe in detail the application of a high flux level core test. After a high-energy test, the tightness of the core is checked and the core clamping system is re-tightened if necessary. It is important not to exceed a specified temperature difference between the average core and average frame temperatures to minimize tangential compression stresses.

The newest method applies a low flux level of perhaps 4% of the rated flux; a device to detect flux variations is moved along the core while it is energized. A primary advantage of this test method is that the low energy energizing coil requires no special current supply to force the desired flux levels. Another advantage is that the detection method provides a chart of the entire core to analyze and locate possible defects.

Both methods will locate most but not all types of lamination defects. In some cases, the low-flux test is applied to trend repairs. This can be followed by a high-flux test applied as a final proof. A low-level flux test can be used to document a finger print of the core which can be used for comparison on future tests [9].

It is important to note that cores should not be condemned based solely on hot-spot values noted during a high-energy flux test or high current values measured during the low-energy flux test. Results that are questionable should be inspected thoroughly by experienced personnel and the impact of major repairs or replacement carefully considered.

When testing is carried out as part of a warranty inspection or commissioning process, the maximum allowable temperature for hot-spots should be agreed upon between manufacturer and client before testing starts. Similarly, the maximum allowable current measured during the low-energy flux test should be agreed upon before testing starts. When using either test method, values that indicate anomalies in the core should be considered when setting acceptance limits.

## Full-Flux Test (Loop Test / Ring Test)

In general, machines rated less than 7500 kVA (10,000 hp) can often be tested using commercially available core loss testers. This equipment is specially designed to perform a full-flux test on machines within the applicable size range. The larger sets may be rated to 300 kVA. Machines above 7500 kVA will require a full-flux test (aka loop test or ring test) to identify anomalies in the core.

The full-flux test is often carried out with the core excited to 85% of its back-iron-rated flux, but should be limited to 1 Tesla. If rated flux is not known, then 1 Tesla can be used for a large generator. For motors and small generators, the recommended value of 85,000 lines/in2 could be used [EASA Technical Note No. 17]. At these levels of induction, hot spots appear quite rapidly when tightening or insulation problems exist. For this reason, a maximum test duration of 60 minutes is enough to detect hot spots.

Higher levels of excitation could be used but should be carried out with caution. Since the DC saturation curve tends to flatten at or near the 100% rated flux level, when approaching these levels it is quite easy to over excite the core unless a variable voltage supply is available. In common practice the voltage supply is fixed. The excitation current can only be changed in discrete values, so dropping a turn when excitation is already at the inflection point can result in a substantial increase in current, over-exciting the core. This can damage the core laminations and support components. Higher levels of excitation would also require a very large power source which could be unjustified and sometimes impractical.

When doing the test, ensure that the excitation cables are supplied by a circuit breaker that can be used to interrupt the current, stopping the test. This will require the installation at the test site of some temporary controls for the breaker. Core temperature should be monitored with an infra-red camera. The mean temperature of the core should be monitored closely to avoid overheating and should be limited to 15 - 30ºC rise to account for the physical characteristics of the machine such as frame expansion, sole plate condition etc. [IEEE P62.2]. In addition, the temperature differential between the core and frame on large hydro units should not be allowed to exceed 10 - 15ºC. Attention should be brought to the upper part of the core because local temperature rise may be observed. Temperature detectors should also be installed on these spots. Hot spots are identified by regions in the core that are 5-10ºC hotter than the mean temperature of the core. The actual temperature variation requires knowledge of the machine history, previous test data, operating conditions, and finally, expertise for interpretation.

This test generates high level of noise due to vibration of the core. An increase of this vibration noise normally indicates looseness in the core. The test should then be stopped so that the tightness of the core can be checked and the core clamping system can be re-tightened if necessary. In some cases, vibration frequency will match the natural frequency of the core, considerably increasing the testing vibrations. If this is the case, vibration levels should be monitored carefully. For a well-tightened core and maximum test duration of 60 minutes, there should not be any damage. However, if there is looseness in the core, longer test duration could damage the core.

For turbine generators, with long cores, an infrared mirror is often required to monitor hotspots [10]. An infrared mirror is designed to reflect visible light and enhance the reflection of the Infrared (IR) spectrum. It is used to eliminate the need for a camera operator to enter the bore of a machine when the cables providing the energy for magnetizing the core are energized (sometimes at high voltage).

The duration of the test should be limited to ensure that hotspots do not continue to heat and cause more damage to the core. The duration of this test should be at least 30 minutes to ensure that deep-seated core insulation defects are found, and should be significantly longer for large turbine generator, hydro generator, salient pole generators and motor cores.

Watt meters can be used to measure the watt loss during the test and the value can be compared to previous tests or tests of similar equipment. This information can be trended over time to determine the overall condition of the core. If a commercial core-loss tester is used, it will calculate the watt loss/lb based on the volume of core steel behind the stator slots, and this can also be used to help assess overall core insulation condition.

## Low-Energy Flux Test (EL CID™)

The principle underlying this method is that measurable currents will flow through failed or severely deteriorated inter-laminar insulation when a flux of only a few percent of the rated value is induced in the core. Prior to commencement of the test the stator should be inspected for any conductive material which would short the laminations together and the Chattock-Rogowski-type coil should be adjusted to ride smoothly and freely on the outside edges of two adjacent teeth but should be prevented from wobbling or binding. Good practice should also include numbering the core teeth to provide an easy means of referencing any faults located.

When performing this test, the core is energized by either a preformed (supplied with equipment) or wound multi-turn excitation winding to induce about 4% of its rated back-of-core (aka yoke or back-iron) flux. The energy required for this test is often less than 3kVA. There is no limit to the duration of this test. The magnetic excitation field is in a circumferential pattern around the stator bore, and is to be the datum phase to which all other quantities are referenced. This excitation field induces currents to flow between laminations with weakened insulation. These resultant eddy currents due to the interlaminar insulation defects are detected using a Chattock or Rogowski type pick-up coil, which is also known as Maxwell's worm. The Chattock type coil is constructed from many turns of fine wire wound on a flexible, non- magnetic core. The number of turns per unit length and cross-sectional area of the core are kept constant so that a calibrated output from the coil can be obtained.

The test is performed by scanning each stator slot with a “Chattock Potentiometer” (which can be remotely operated with the rotor in place) which is connected to a signal-processing instrument that gives readings in mA. The instrument provides a trace of mA versus position along each slot. Locations that show 100 mA current or higher quadrature current in the detection equipment should be investigated. Alternatively, regions that show marked changes from the average may also require investigation; at the very least, these locations should be identified for future testing. Special care should be taken when measuring the current in the stepped lamination packets at the ends of the core. These are often most vulnerable to damage from overheating by stray flux, so it is important to ensure that the measurements taken in these areas are accurate to allow any anomalies to be identified. Hydro generators with split cores generally give very high readings at these discontinuities. A more detailed analysis, which involves evaluating both quadrature and phase current recorded by the instrument, is required to determine whether core insulation defect exists.

When interpreting results, bear in mind that this test has high sensitivity, hence it can detect magnetic disturbances which may not prejudice the reliability of the stator. Consequently, interpretation of the results is not simple and there may be some difficulty in determining an appropriate level of response which warrants further investigation and/or repair. In general, responses of greater than 100 mA (expected temperature rise for each 100 mA of fault (quadrature) current measured is 5-10 ˚C) should be regarded as significant faults and should be further investigated. Apart from absolute magnitude, some indication of the location of the fault may be obtained by examination of the polarity and number of slots affected. For a fault that is within the span of a Chattock, the quadrature signal must go in the **opposite** direction to the polarity of the in phase signal.

It should be recognized that no reading will be obtained at a fault location if the electrical circuit is not completed elsewhere, i.e. no electrical contact between laminations and building bars. However, it also should be noted that such a fault will not create a hot spot in normal operation due to the same reason.

## Core End Flux Management System Insulation Resistance

The following typically applies to turbo machines. Historically, as machine size increased, the need to increase the radial air gap to hold down the short circuit ratio has increased the core end leakage flux. In addition, movement of the generator rotor farther out beyond the ends of the stator core as a result of thermal expansion of the turbine rotors, operating near unity or in the region of under excitation, increases end leakage flux. Design modifications were needed to prevent core damage due to this end leakage flux. One solution was to add a flux shield to act as a damper to direct the flux away from the stator core ends. In order to protect from harmful circulating currents within the laminated flux shield, some manufacturers provided additional insulation to reinforce the inter-laminar insulation. Tests should be performed to ensure electrical separation between the various laminated flux shield components.

Tests of insulation resistance should be made between adjacent core support plates, between the laminated flux shield and each core support plate, and between the laminated flux shield and the grounded frame.

These tests should be made with an insulation resistance tester. A typical test value is 250 Volts DC; consult the manufacturer for the recommended level. For the test leads, it is important that the paint surfaces are pierced, which can be accomplished by using an awl. Each of the tests should be continued until a stabilized reading is observed, then the data should be recorded. The insulation resistance should be greater than 1 MΩ for each test.

The following typically applies to turbo machines. Due to the increased size of these machines and the high current densities, the core end leakage flux may be quite high. In addition, movement of the generator rotor beyond the ends of the stator core as a result of thermal expansion of the turbine rotors, as well as operation near unity or in the region of under excitation, increase end leakage flux. Design features are required to prevent core damage due to this increase in end leakage flux. One solution is to add a conductive flux end shield, such as an aluminum end plate, to act as a damper that allows eddy currents to buck the flux and direct the flux away from the stator core ends. Another solution is to add an inductive flux shunt, typically made of laminated steel, to pass the flux circumferentially around a pole pitch and minimize direct flux impingement on the end surfaces of the core.

These alternative components will have different considerations when inspecting and testing. Some components of the conductive shield require sound electrical connections to ensure proper operation while components of the inductive shunt may require additional insulation to reinforce the inter-laminar insulation. Tests should be performed to ensure electrical separation between the various laminated flux shunt components that are required to be isolated. Consult the manufacturer for the specifics of the recommended component testing if it is not clear from inspection.

For designs where tests of insulation resistance are possible, these should be made between insulated core components such as between the core support plates, between the laminated flux shunt and each core support plate, and between the laminated flux shunt and the grounded frame. These tests should be made with a dc insulation resistance tester. A typical test value is 250 Volts DC; consult the manufacturer for the recommended level. For the test leads, it is important that the paint surfaces are pierced, which can be accomplished by using an appropriate test probe or an awl. Each of the tests should be continued until a stabilized reading is observed then the data should be recorded. The insulation resistance should be greater than 1 MΩ for each test.

## Through-Bolt/Stud Insulation Resistance

One method of axially clamping the laminated core of a horizontal machine is to utilize axial key bars at the back-iron area, and a set of bolts/studs approximately midway between the bottom of the slot and the outside diameter of the core. Since these two pieces of steel are in contact with the lamination segments at two points, the stud near the bore is insulated to prevent circulating current. These are called through-bolts or through-studs. The through-stud assembly consists of insulated studs, overlapping insulation bushings on the stud ends, and insulating washers.

In order to test the integrity of the insulation, it should be checked with a DC insulation resistance tester. A typical test value is 1000 Volts DC; consult the manufacturer for the recommended level. To accomplish this, one test lead of the insulation resistance tester has to be in contact with the stude or the nut by cleaning a spot on the surface of the stud end or nut or utilize an awl, which can pierce the paint on the stud or nuts. Attach the other lead to a clean surface (ground) on the stator frame. Allow the insulation resistance tester display to stabilize, then record the value. This process should be repeated for each insulated stud in the stator. A reading over 1.0 MΩ is acceptable per IEEE 62.2 2004. For values lower than 1.0 MΩ, the manufacturer should be consulted.

# Evaluating Core Deterioration Due to Operating Conditions

## Aging Mechanisms of Laminated Stator Cores

The mechanical, electrical, thermal and environmental stresses that electric machines are subjected to will result in aging of the laminated stator cores. Provided the machine is operated within normal limits, the rate at which aging occurs will be very slow and can be initially difficult to detect, but eventually can lead to degraded performance and eventually even complete failure of the stator core function. Operation outside normal limits may accelerate the aging and may introduce additional mechanisms that damage the stator core system. The original design, materials, and installation quality may influence its rate of aging.

Although the voltage between laminations is extremely low, in the order of 0.05V, the mechanical load on the insulation can be very high. Thus, virtually all of these insulation systems are vulnerable to failure, if duties are excessively increased in relation to the capability of the insulation system. However, maximum operating temperatures on the lamination insulation generally are not high, since the core iron is in direct contact with the organics-containing stator bar insulation. Thus some modest materials have been found reliable at the highest temperatures permitted by other machine components, such as the stator bar insulation.

## Mechanical Aging - Vibration and Wear

An important aging mechanism is vibration or relative movement between laminations. This movement can be subsequent to loss of core pressure. The primary causes for loss of pressure of the laminated core structure are; settling of laminations, loss of insulation volume, collapsing of vent supports, improper assembly, core wave, excessive core temperature and therefore possible buckling and even meltdown, failed clamping components, and other design-specific issues.

It is possible for movement between laminations to occur even when proper core pressures are applied. This may occur if: (1) there are large differences in temperature between one part of the core and another, (2) high machine vibrations occur or high forces are applied during abnormal operation or system disturbance, or (3) there is a loss of core-to-frame attachment.

When laminations move relative to each other, insulation is abraded and this may quickly lead to shorts and core or winding failure of a catastrophic nature. The movement can allow for flexing of the laminations and the electrical steel can undergo cyclic fatigue and become brittle, crack and break. The lamination edge can move out of position and impact the windings resulting in insulation damage. Broken or displaced core clamping / vent fingers can result in lamination / winding degradation.

Vibration measurement is one way to evaluate whether your core is likely being subjected to mechanical aging & wear. Vibration measurement methods should be in accordance with ISO 7919 and ISO 10816. It is difficult to determine a specific vibration limit to apply to the stator and frame where exceeding this limit will have a quantifiable reduction in life expectancy of the stator core. However, it is suggested that 30 microns peak-to-peak is a reasonable value for operation of a stator core where vibrational stresses should not be at a dangerous level. Figure 2 is an excerpt diagram from a well known OEM for large machine vibration limits for the core according to curve ‘C’ [11].



Figure 2 – Curve ‘C’ Vibration limits for stator core and frame

Noise limits are defined in IEEE C50.12 Clause 9.2.1 and the sound measurement should be made in accordance with ISO 3746.

## Electrical Aging

## General

* Slot Discharge Activity
* Intense Partial Discharge Activity in the slots.
* High interlaminar voltages from system upset breaking through interlaminar insulation.
* Interlaminar shorts from transients and winding faults.
* Overfluxing.
* Burning of core near coils from winding failures.

## Vibration Sparking

A relatively rare stator winding failure process called vibration sparking (also known as spark erosion) may deteriorate the stator core lamination insulation in the tooth area, adjacent to the stator bars or coils. This winding insulation failure process produces high-energy sparking between the bar/coil surface and the stator core tooth. In addition to eroding the bar/coil insulation leading to a ground fault, the sparking can damage the interlaminar insulation, resulting in shorted laminations. Vibration sparking is thought to occur when the surface resistance of the bar/coil slot conductive coating is low enough to allow significant axial conduction of 50/60 Hz currents along the coating between points of contact of the conductive coating to the stator core. If the coil or bar is loose in the slot, under the magnetic forces during normal operation, the distance between the points of contact to the core may be several centimeters. The current flows:

* + - Axially along the stator coil/bar surface, then
    - Radially through the lamination at one point of contact, then
    - Axially along the keybars, then
    - Radially through another lamination back to the point of contact to the bar/coil surface, completing the loop.

This loop encloses the main magnetic flux in the core, and it is this flux which induces the current. When the coil/bar vibration causes the bar/coil to lose contact with the core, the current is interrupted and a spark or arc is formed [Ref 1]. Since it is driven by the magnetic field, vibration sparking can occur in any slot in the stator core.

The main risk to the core is from shorted core laminations due to damage to the lamination insulation. The current loop increases the local core temperature in the region of shorted laminations, and may continue to extend the insulation damage at each side of the initial damage. The extension of the shorted laminations along the core length may reach the critical length at which a thermal runaway will melt the core steel and lead to a major core failure.

## Thermal Aging of Core Steel

Thermal aging means magnetic aging by the migration of carbon to the grain boundaries. Electrical steel used in the manufacture of laminated cores must have a low carbon content to prevent thermal aging from reducing its performance. Prior to the 1960, the carbon content of electrical steel may have been higher and more difficult to control. These steels may undergo a slow aging process that increases the losses in the material and reduces the machine capability, as can be evidenced by repetition of the original mill tests, though this is seldom considered worthwhile after manufacture. Modern electrical steel manufacturing methods are capable of producing material with very low carbon content, so aging is controlled.

* Thermal cycling which over many years, can cause fretting in attachments to frame and clamping systems.
* Transient loss of cooling water to hydrogen or air coolers. The core thermal expansion strains the core end clamping system beyond the elastic range of the system and causes loss in core pressure, particularly in the core teeth.

## Environmental Aging Mechanisms

Such as Contamination…

* Water condensation and corrosion or attack interlaminar insulation by contaminates.
* Element contamination and higher carbon alloys aging causing reduced magnetic properties.

## Damage due to Mechanical Impact

A common and typically very rapid way to damage a core is mechanical impact. Causes may include a rotor rub, foreign objects that were left in the machine after maintenance work, or debris that breaks off inside the machine during operation. This can result in the immediate formation of inter-laminar shorts at the impact site. These shorts, in turn, can result in local heating and can in some cases cascade the formation of shorts.

## Core Buckling

Core buckling is not uncommon to some degree in vertical / horizontal hydro machines and is unlikely in turbo generators. Buckling occurs in a core that has circumferential compressive forces that overcome the axial core clamping forces. The extent of the buckling and the type of core clamping will determine whether secondary effects will create looseness in the laminations. Waves can also be created due to installation techniques or very small variations of lamination thickness as manufactured.

The magnetic core may be considered buckled if it presents a wave exceeding a zone delimited by two parallel straight lines 8mm apart from each other on a length equal to two spaces between the key bars.

## Deterioration Mechanisms & Indications in Core Splits

Certain operating conditions are specific to split cores. Large rotating machine stator cores are manufactured in sections for several reasons. The splits between sections inevitably present a degree of vulnerability, and are best avoided if possible. The magnitude of the gap between core sections depends upon the manufacturer’s practice. Packing material inserted when the gaps are large is difficult to retain.

When a split core is factory-assembled, application of a core ring test, or high flux ring test (HFRT) helps consolidation, allows detection of damaged laminations via thermal imaging, and indicates, by noise level, looseness at core joints.

Core split location, for inspection with a machine in-situ, can usually be identified by observation at the stator bore. If necessary, a drawing reference is used.

At the recommended annual inspection, the following indications of deterioration at core splits may be identified:

* Red dust, or when the machine is heavily contaminated with oil, a black paste, indicating fretting. This may be found both at the inner and outer peripheries.
* Movement of core split packing.
* A “chevron” effect of laminations adjacent to the splits, indicative of crushing at joint faces.
* Excessive penetration by a calibrated knife blade, showing core slackness.
* Hot spots, globally, as well as at core splits (located either by sight or by the EL CID technique) are evidence of interlaminar insulation deterioration, due to lamination looseness, or distortion of adjacent laminations.
* Clamping fingers cutting through end laminations, due to deterioration in core clamping.
* Relative radial movement of laminations arising from detachment of the fixing at the outer periphery.

Significant core deterioration, especially circular distortion, should be referred to an appropriate design authority before an attempt is made to rectify the situation. Remedial work should only be carried out by experienced operators. Renewal of the core, and even the frame, may be appropriate; especially when a rewind is to be made, to ensure equal future reliability of both core and winding.

Rectification measures, apart from the radical action of complete renewal, may include the following:

* Packing core looseness, using suitable insulation material and adhesive, after cleaning up rough lamination edges.
* Retightening core studs.
* Repositioning distorted core regions, possibly by jacking.
* Re-securing broken key bars (this is very difficult to accomplish)
* Retightening the core clamping structure.

Split cores merit special care. Remedial action may be difficult. Modern techniques for building large diameter machines away from the factory now usually permit avoidance of split cores. A number of references to relevant technical literature are provided in the Split Core Annex.

Vibration and noise

* Change in vibration
* Cause of vibration – design, temperature, loose rim, air gap eccentricity, concrete growth, core splits (if packing has vanished)
* Change in noise level
* Replacement core design changes should be done carefully

As a rule, horizontal rotating machines are not constructed with split cores.

## Evaluation of Core Temperature Distribution

During operation, it is important that core temperatures remain reasonably uniform over the length and circumference. In addition, for large hydro generators, the temperature difference between the core and frame is also a critical factor. The less variation there is in these values, the lower the risk of buckling of the core laminations and distortion of the air gap.

For large hydro generators (core length greater than 2 m), the difference between the temperature at the top and the bottom of the core should be maintained within 5 degrees Celsius. The measurements for this are taken at the back of the core. Also, for large hydro generators the temperature difference between the stator core and frame should be maintained within 20°C. Once again the core temperature should be measured at the back.

If the temperature difference exceeds 20°C, an analysis of the core compressive stress in the tangential direction under thermal and magnetic load should be carried out. Resulting stress in the yoke portion of the stator core should not exceed 20 MPa average.

Temperature variations around the circumference should be maintained within 10°C to avoid uneven expansion and contraction of the core and frame assembly. Limiting the temperature variations can ensure more uniform stator circularity and more even distribution of stresses on the sole plates and concrete.

For small to medium 5-50MVA hydro generators, the temperatures outlined above are less critical, but the operator should avoid excessive differences in these temperatures to ensure trouble-free operation of the core and frame assembly and the stator winding.

For turbo machines, core temperature differences between the two ends should be limited to 10 °C.

In large turbo generators with directly cooled stator and rotor windings, this limit could apply to temperature measurements at no load. At load, the winding temperature differential between the inlet and outlet of the coolant may be in the range of 20 to 30 °C and this differential will also be reflected in the core, especially in the teeth region. In machines with rotor gas discharge in the middle of the machine, the central core region may be the hottest. The core temperatures are not regularly measured on turbo generators, either in the factory or in service, except indirectly by monitoring the hot gas discharge from the core. Only a few users insist on application of the core temperature sensors within cores in their specifications, although they are available from most OEMs.

## Evaluating Core Damage After a Fault

The damage to stator cores in motors or generators during fault events can be minimized if the machines are adequately protected. Protection can take many forms, mechanical and electrical. The selection of the protection scheme for a particular motor or generator is often a compromise between the cost of the protection equipment and the cost of the motor or generator or its repair. Knowing what kind of protections are in place on a unit can help when evaluating the risks of damage after a known fault event.

Generator and large motor stator cores are indirectly protected by the stator winding protection systems that may be installed on any particular machine, and to some extent the bearing temperature or vibration monitoring equipment. In addition, some large turbo machines may be equipped with condition monitors that can identify by-products of thermal deterioration that can be used to identify core overheating. The latter can be a result of defects in the core or a result of stator winding faults that go undetected by the electrical protection systems.

Typical protection schemes on large motors and generators may include some or all of the following:

1. Over-current protection
2. Ground-fault protection
3. Differential current protection
4. Split-phase protection
5. Over-voltage protection
6. Over-frequency protection
7. Under-frequency protection
8. Bearing over-temperature protection
9. Shaft or bearing vibration protection
10. Surge suppression
11. Static exciter field reversal
12. Volts / Hz protection

The above is not intended to be an exhaustive list of protection schemes but a list of those that, directly or indirectly, provide protection for the stator core. That is, protection against ground faults. Obviously protection for ground faults can be achieved directly using protective devices dedicated to this application. However, the others listed above detect faults that if left unchecked or if they are not cleared in time can seriously damage a stator core. It should be noted that for simple ground faults the extent of the damage is limited by the protection scheme in use which will also be affected by the method by which the machine is grounded. One can expect more severe core damage from ground faults on machines where the neutral point of the winding is solidly grounded. Damage will be much less severe where the neutral point of the winding is grounded via a high impedance path.

For a detailed explanation of most of the above schemes, refer to IEEE C37.96 Guide for AC Motor Protection, IEEE C37.101 Guide for Generator Ground Protection, and IEEE C37.102 Guide for AC Generator Protection.

Generator cores are relatively insensitive to direct damage from system faults that are cleared by protection in short periods, such as transient overvoltages and short circuits. In already damaged cores, such events may increase the pre-existing damage. Any core damage is likely to result from a winding failure. The most direct core protection is Volts/Hertz, protecting the core from overfluxing, particularly during off-line runs before synchronization or during off line tests.

# Maintenance and Repairs

## Core Cleaning

Common contaminants of machine stators are oil and dirt. Rust can be a problem if moisture levels have been high. The cleaning methods utilized should remove contamination but not damage the thin insulation on the laminations. Techniques also differ depending on whether the winding is in place or has been removed. More aggressive techniques are needed to remove old materials from the stator slots after a winding has been removed. Blasting with walnut shells, corn cob or high pressure water (for smaller machines that can be oven-dried) can be utilized. CO2 pellets, sponge or baking soda blasting, safety solvents, or citrus based water cleaners are often applied if the winding has not been removed. The appropriate safety and environmental procedures should be observed while cleaning.

Although light surface contamination may not affect the core function, it is an indicator of debris from other sources, such as from insulation abrasion in the stator and rotor windings, or from rubbing between metallic components, including copper dusting from rotor winding. These sources must be identified and corrected. Severe accumulation of deposits may partly or fully close core cooling ducts, causing core overheating. The removal of such contamination may require special techniques.

## Painting

Covering/painting the stator core after a winding has been installed and tested provides protection of the core iron from contamination and facilitates future cleaning. Usually the color and resin type desired for the winding is applied to both winding and core. Common coating types are epoxy-, polyurethane- or alkyd-based. Other resins are also available and can be considered. Heavy coatings of paint may reduce heat transfer and should be avoided. Some suppliers apply a conductive paint in the slots of high voltage machines to facilitate contact between the stator bars and the core iron. The core surface preparation is very important as it must be free from all oils and contaminants to allow proper bonding of the insulating paint. Proper local safety and environmental precautions and rules should be observed while applying the paint. As discussed in the “Stabilizing / Maintaining Compression” paragraph below, penetrating epoxies are often used on portions of the core to enhance lamination stability prior to winding or finish painting. Discolored/darkened paint can be a visual indication of contamination. Also, there are “tagging compounds” which can indicate, via particle emission, whether the coated surface reached a certain temperature.

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## Tests for Core Tightness

Laminated stator cores are pressure-loaded during the assembly of the stator. In operation, the stator core is subjected to continuous mechanical and thermal stresses. In some cases, forces causing movement of the core components may result in reduction of core’s original tightness. The common consequence of this condition is abrasion of the inter-laminar insulation, which can lead to deterioration of stator winding insulation due to hot spots in the core. If core loosening is severe, it can increase level of vibrations, especially in two-pole machines. In addition, stator core tightness is necessary to prevent the buckling phenomenon.

One way to determine tightness of the core is to check the torque of the stator core’s compression bolts. The measured torque should be compared with values recommended by the stator core manufacturer. It is defined during the design concept and must be as high as possible without exceeding the mechanical capacity of the stator core and stator frame components. Standard values are set between 0.8 and 1.5 N/mm2. When torque values are used, designers must specify if they have to be applied in dry or greased conditions. Since the precision of a torque procedure is ±20%, designers must include provision for that kind of process. Hydraulically pre-stressed bolt processes are more accurate. Core tightness/clamping is important because it:

* Creates a homogeneous core structure.
* Prevents vibration, maintaining inter-laminar insulation integrity.
* Is designed to allow the core to withstand faults, 120 Hz vibrations, temperature rises, temperature differentials, torsion forces, etc.
* Helps prevent core wave.
* Helps prevent core skewing.

Électricité de France patented device called Crabe. Its purpose is to measure the core teeth compression when pressed by a hydraulic jack. Hence, with this tool, the remaining core pressure is easily found out. When followed over the years, a trend can be drawn and a long-term maintenance plan can be drafted.

Core clamping systems are designed in many different ways. The following list contains some checks that can be made on some commonly found designs.

* In turbo-machines, radial clamping tightness can be verified by using a torque wrench or by measuring bolt tension to verify proper tightness of the bolts at the circumferential band splits.
* Axial looseness of laminations can be checked by careful pushing of a knife between laminations, “knife test”, or gentle tangential pushing on vent fingers. The pushing force for either test can be approximately 12.5 kg. In a properly clamped core, a knife blade cannot be inserted between laminations and a vent finger cannot be deflected at this force. A standard winder’s knife with the leading edge of the blade not thicker than 0.25 mm is inserted between laminations at several locations around the bore and/or back iron of the core. The body of the knife should be in the range of 1.0 to 1.5mm thick. If the blade penetrates more than 5-6 mm in the middle of an individual core pack, the core may not be sufficiently tight. This test should be performed carefully, to avoid damage to winding and prevent breaking of the end of the knife tip.
* Core end fingers are essential for maintaining the core teeth clamping pressure and they should show no signs of finger misalignment with respect to the laminations.
* Looseness of the core may result if the core clamping hardware has locking plates found out of position, nut and bolt peen marks are not aligned, greasing is found at the interfaces, or broken locking welds on the nuts are found.
* Axial clamping consisting of bars, bolts and nuts can be checked for proper compression of the core by measuring the torque of the clamping nuts, if accessible. Care should be taken not to leave metal filings in the machine when removing lock material in preparation for checking the torque. The OEM of the machine can supply the proper range of acceptable torques for all bolted clamping assemblies. In some cases, stretch of clamping bolts is used to control core tightness. In these cases, a measurement of bolt tension is used to measure the tightness.
* On hydro machines, the core should be checked for out-of-roundness, tilting out of parallelism with the axis of the rotor, and excessive waviness. Cores can be checked for the degree of these types of distortion by using a plumb bob, a square and various linear measuring instruments.

## Core Consolidation

Consolidation is required to ensure that the laminations are sitting firmly against the laminations below. Friction against the dovetail / key bar or core-clamping stud and stacking pins can prevent a lamination from properly resting against the one below. In some cases, the lamination can become slightly distorted from the punching process. This distortion prevents intimate contact between laminations. Another feature is the minute hills and valleys that occur in the coating. The lamination stack has to be compressed to plastically deform some of the high spots to achieve the maximum percentage of steel in the core. This may be referred to as maximizing the “stacking factor”.

During the stacking of the stator core laminations, they may be consolidated or compressed several times. For hydro machines, this is approximately every 450 mm to 500 mm. For turbo machines, compression is carried out every 300 to 500 mm. For large motors, techniques are quite varied; compression might be carried out only once or at multiple stages. For equipment small enough to be stacked in the factory, pressure is applied using a large press that may be able to apply pressures up to 250 tons. For large turbine generators, hydraulic rams may be used, capable of compression loads in excess of 1200 tons. If the core is stacked in the field, pressure is usually applied using jacks, temporarily installed for this purpose, placed between the lamination stack and the upper pressure plate. Pipes or other suitable devices are used to span the distance between the top plate and the jack.

Once fully stacked and the proper torque applied to the core bolts/studs, additional consolidation can be achieved during the ring test or loop test. As described under “Tests for Core Evaluation”, this test is often performed to identify hot spots in the core, and it also heats and vibrates the core. After completion of the loop test, the core is allowed to cool and the core studs are torqued to the original value.

## Stabilizing / Maintaining Compression

Large machines usually employ one or more circles of bolts that tighten clamping plates at both ends of the stator core. Details of the clamping arrangement vary with supplier, machine age, speed and size. A few of the newer machines may have epoxy-bonded laminations. It is not unusual for a Hydro-Generator core to require tightening during normal service, whereas core tightening on a Turbo-Generator air or hydrogen-cooled is considered more unique, and for large motors is impractical.

There are several different designs for core tightening that affect the ability to tighten as the core ages. Below are some examples of what these designs may include:

* Core studs/bolts located for access with the winding in place.
* Core studs/bolts located such that the winding must be removed to access and tighten them.
* Core studs/bolts that can be tightened at both ends
* Core studs/bolts with one end welded, allowing tightening at one end only.
* Belleville endplate(s), where the end plate is dished, such that it applies a more constant pressure on the laminations, often this design is welded rather than studded and cannot be tightened after manufacture.
* Welded end plate(s), where compression is applied during manufacture and the end plates are welded in place under compression to retain the required design compression. Often used on large motor designs.

Thus not all machines will have core bolts that can be tightened; designs with a welded core compression system will require other tightening techniques to be considered.

It is important to always be sure a core is tight, inspected, and/or flux tested before a new stator winding is installed. Bolt torque values, tightening procedures, and compression values recommended by the OEM should be adhered to. It is recommended that:

* A physical torque check (to OEM procedures and torque values) be carried out, rather than relying solely upon a visual examination, as the core may appear tight but can indeed be slack.
* The core clamping system be rechecked after a high energy full flux test is performed. This test vibrates the core laminations, and can result in loosening of the clamping system. A lack of noise (rattling) resulting from loose laminations during high energy full flux testing can be a good sign of a tight core, but is by no means a guarantee of a tight core.
* Through-bolt insulation be tested to ensure integrity.

Torquing of core clamping nuts/bolts should be carried out with extreme care as compression of the lamination, compression bolts and core plates can result in an uneven torque application. This can result in over-tightening of some areas of the core and no tightening effect in other areas. In some instances, it may be possible to carry out torquing between flux tests or at reduced flux levels so as to reduce the unevenness of torque application.

Care should be taken, as over tightening of the core can result in a multitude of problems, including distortion and cracking of the vent duct support beams, and damage to the laminations due to vent duct supports imprinting into the laminations. Uneven compression of core plates can also occur, resulting in either: (1) a loosening of the back of the core combined with a over tightening at bore, OR the opposite effect, (2) a loosening of the bore combined with a over tightening at back of the core.

Caution should be taken if the core clamping system becomes relaxed during refurbishment , as the individual laminations can shift, leading to a serious problem. Examples of such potential problems include:

* Shifting of the laminations within the winding slot. This can result in the thin, sharp lamination edge causing damage to semi-conductive systems on the windings, and then cutting into stator bar insulation, hence resulting in winding failures.
* Shifting of the laminations such that axial cooling passages may become restricted, affecting localized core or winding cooling.
* Laminations overlapping, resulting in uneven core lamination compression and potential loose areas.
* Large diameter machines (Hydro Generators) can develop waves in the iron.

It should be noted that repositioning migrated laminations is often not possible, without causing potentially unseen damage elsewhere to the core. In this case, the need for the core to be restacked or partly restacked should be seriously considered.

If the core still appears to be loose after tightening, or if the design is such that core bolts are not accessible or present (welded design) to facilitate tightening of the core teeth in the bore region, here are two remedial actions that can be considered:

* A thin, low-viscosity or “weeping” epoxy can be applied to bond laminations to provide additional insulation. The use of a very thin resin is used to facilitate capillary action and pull the resin into the space between laminations, thus filling the space and bonding adjacent laminations as well as providing additional insulation. Several commercial products are available with a desired viscosity consistent with OEM recommendations.
* Stemming of the core laminations can be considered. In this case, thin, arrow-shaped epoxy glass laminate or epoxy glass wedges are placed between loose laminations and bonded into position using air-drying epoxy resins. It is sometimes possible to insert steel wedges under the compression fingers at the ends of the core. In either case, extreme care needs to be taken to ensure that the stemming is carried out in such a manner that the stems do not work loose and get carried into the air gap, causing subsequent projectile damage elsewhere in the generator.

It should be cautioned that future repairs or core restacking will be more difficult when laminations have been bonded together and/or stemmed. However, this should not be a reason for not repairing a loose core.

## Application of Fillers (Stemming)

When shorts develop between laminations near the machine bore or when laminations become loose, repairs can be attempted without removing the windings. Fillers inserted between loose or missing laminations will re-establish insulation and prevent future cascading core damage. Mica sheets (due to the strong thin plates available from repeated splitting) or epoxy glass laminates / wedges are the most common filler used between laminations. Insertion of thin fillers between all the loose laminations in the damaged area is preferred when repairing two pole and four pole machines, but installation between alternate laminations may be acceptable with slow-speed machines. Insertion of one large filler at the centre of the loose section is not recommended.

If the core back iron is tight but the bore remains loose, then long, tapered wedge-shaped fillers of epoxy glass laminate can be inserted at several locations. This application of “arrow heads” has been successfully applied to various large machines for many years.

If the damaged area covers numerous missing or severely damaged laminations and restacking is not an option, these areas of the core laminations can be ground away. The area should be given a high energy flux test to verify overheating is no longer present. Then the missing material can be filled with a nonmagnetic insulation laminate cut to replace the removed laminations. Entire core sections that had severe damage in localized areas have been repaired with this replacement method. The goal is to prevent movement of the adjacent stator winding and adjoining undamaged laminations.

The original lamination insulation system will also play a factor. Older insulation materials include oil based / organic varnish C3 and water-based systems. It should be noted that modern epoxies will not stick to the older insulation systems and should therefore be borne in mind when using fillers to eliminate potential projectiles in the air gap.

Depending on the core consolidation, design and condition, it is also possible to consider re-habilitation of the laminations. This involves un-stacking the laminations, inspecting and re-conditioning for re-use / re-stacking. This could involve refurbishment of the laminations, including removal of insulation and re-insulating, or simply shuffling the laminations such that they are put back in different areas of the core, spreading damaged laminations evenly throughout the core. Consideration of this is often based upon OEM recommendations and/or results from flux testing and visual inspection.

## Evaluation

The existing core should be evaluated for its ability to function for the life of a stator rewind. This is approximately 35 years. It is beneficial to have the assistance of generator designer during the evaluation process. The evaluation should address:

* Visual inspection
* High-intensity slot discharge
* Winding faults that cause core damage
* Thermal limits
* Temperature distribution
* Magnetic limits
* Magnetic stiffness
* Operational vibration and resonant vibration
* Noise
* Air gap (CEATI)
* Inspection of core-to-frame attachment for signs of fretting.
* Structural limits (this should extend into the frame and sole plate areas)
* Existing damage
* Split sections versus continuous stacking (See Annex I for more details.)
* Insulating varnish temperature class
* Low or high energy flux test
* Clamping system – finger cracking, broken welds
* Skewed slots / closed slots
* Changing the core for uprate (number of slots, slot width, core height)
* Reliability
* Fatigue
* Clamping design
* Core losses
* Maintenance history of the machine or sister units
  + Failures and repair
  + Testing
  + Intervals at which major parts of the machine are inspected
  + Intervals where consumables are replaced
* Consequences of unscheduled or extended outages
* Foreign material in the air gap causing damage
* Rotor / Stator collision
* Contamination of the core (oil, dust, and the like)
* Ventilation reduction due to contamination
* Vent duct distortion and anomalies
* Grounded through-bolts
* Enhancing monitoring (vibration, condition monitor, etc.)
* Application of core temperature sensors (feasible on new and partially restacked cores)

Removal of a lamination from the unit may be required to perform the evaluation. This comes with some risk.

# Core Replacement

## Decision

The core laminations should be replaced when they have reached the end of their reliable operating life. When the core interlaminar insulation has aged or been mechanically abraded to the point where unacceptable core heating is occurring or will become probable in the near future, or when there is core damage from interlaminar shorts, or when the mechanical properties of the laminations become brittle to the point where slot wedging or core attachment breaks down, a replacement core should be considered. Problems with core splits, excessive slot noise, excessive core loss, closed slot design, ineffective core clamping, or a large planned increase in unit capacity may justify the replace of the core with design or material improvements.

Replacement core lamination procurement can be a reasonably long delivery item. It is advisable to attempt to establish the core condition before the unit is taken out for major maintenance to possibly avoid an extended outage. The future operating parameters of the generator may indicate that although a rewind is necessary, if the unit will not be operated near full rating, a core in less than perfect condition will suffice.

## Ramifications

Once the decision is made to replace the core laminations, a number of design-related issues must be addressed. As an example, iron used today can be thinner than that used when the unit was manufactured yielding lower losses and a cooler running unit, but requiring more laminations and overall effort than a direct replacement. Also, the remainder of the frame and support structure must also be examined to insure that the new core will be secure, and that the air gap will be uniform. Below is a list of caveats and options to be considered as part of core replacement work.

* Consider switching to non-magnetic fingers or vent spacers.
* For hydro machines, consider thicker laminations to reduce stacking time – newer steels have better losses but permeability may not be as good. Consider flux levels, and consult with the OEM.
* Thinner laminations can affect the core stiffness. This will need to be checked by the OEM.
* Consider changing the clamping arrangement if problems existed previously – this will likely require modification of the frame.
* Consider changing from a split core design to a continuously stacked design.Adjustments to the wedge groove size or shape may be beneficial if problems were evident with the original design or with the new coil insulation system; consult the OEM.
* Confirm that the core pressure is adequate to prevent buckling and to maintain a tight core.
* Adjustments to the vent duct size and number of ducts to optimize cooling and machine performance may be required; consult the OEM.
* Core expansion to the key bars must be verified with the new expected core temperature. This is to prevent fretting and core buckling in this area.
* Effect of the new core design on shaft currents must be taken into account.
* For turbo generators, lamination grounding may be added.
* Changes to slot size and winding configurations may make the unit more suitable for increased power.

When redesigning a replacement core, care must be taken to ensure that changes are managed by those qualified in new machine design. A minor change in core shape can have a significant effect on the natural frequency response of the core structure.

1. Stator Core Evaluation Table

Put in the “score” column the eligible values shown adjacent to the conditions described under “evaluation criteria”. The evaluation criteria may not describe exactly the conditions being observed. A column is provided for the adjustment of evaluation criteria weight. This “weight” column is intended to provide the Owner with a method to change the importance or relative contribution of the various criteria to the resulting total. Try to match the observed condition to the evaluation criteria most closely representing it. If a particular applicable condition is unknown or does not apply, set the score to zero and change the one in the confidence column to a zero. Add the values in the total column to obtain an aggregate score which is then compared to the values in the evaluation table.

Confidence percentage is calculated by totaling the number of 1s in the confidence column divided by the number of applicable asset criteria sections all multiplied by 100. This confidence percentage is intended to highlight the degree of un-certainty associated with the evaluation.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **No.** | | **Evaluation Criteria** | **Score** | | **Weight** | **Total** | | **Confidence** |
| **Design** | | | | | | | |  |
| D1 | There are known design conditions that has been proven to adversely impact the long term reliability of the core and therefore will likely fail or cause the winding to fail in the following time frame:  0 – core or winding life should last more than 30 years  5 – core or winding life will be limited to 20 to 30 years  10 – core or winding life will be limited to 10 to 20 years  30 – core or winding life will be limited to less than 10 years | |  | | X 1.0 = |  | | 1 |
| D2 | Inter-laminar insulation temperature rating. Early materials were low temperature materials such as paper, tung oil, shellac etc. with Class A and or Class B temperature ratings. The advent of more robust materials designated ASTM A976 C2, C3, C4, C5 or C6 are materials that have proven long term thermal stability.  0 – core lamination insulation made from and ASTM A976 C2, C4, C5, and C6 (organic with inorganic fillers) materials or equivalent  5 – core lamination insulation made from Class B or ASTM A976 C3 (organic with no inorganic fillers) materials  10 – core lamination material made from Class A material | |  | | X 1.0 = |  | | 1 |
| D3 | Approximate era of generator core  0 – core manufactured after 1940  5 – core manufactured between 1920 & 1940, no sign of distress  10 – core manufactured before 1920, no sign of distress | |  | | X 1.0 = |  | | 1 |
| D4 | Value of machine production  0 – extended rehab outage from core problems < 1% of core replacement cost per day  5 – extended rehab outage from core problem > 1% & < 3% of core replacement cost per day  10 - extended rehab outage from core problem > 3% of core replacement cost per day | |  | | X 1.0 = |  | | 1 |
| D5 | Core life of identical units  0 – core life of identical units have been > 60 years  1 – core life of identical units have been <60 & >40 years  5 – core life of identical units have been <40 & >30 years  10 – core life of identical units have been <30 & >20 years  30 – core life of identical units have been <20 years | |  | | X 1.0 = |  | | 1 |
| D6 | Redesign of core to accept a winding configuration change, change number of stator slots, change of frequency, replace frame to accommodate larger coolers, changing from CO2 to water spray fire protection, or other redesign items?  0 – no design related improvements are beneficial  10 – benefit of design change represents less than half the cost to replace the core  20 – benefit of design change represents more than half but less than the full cost to replace the core  30 – benefit of design change equals or exceeds the cost of core replacement | |  | | X 1.0 = |  | | 1 |
| M1  M2 | Core Maintenance History (repairs to laminations, clamping structure, or core reshaping)  0 – none required over the life of the core  5 – minor lamination repairs, tightening, or adjustment to the clamping structure carried out at least twice over a 15 year period  10 – regular minor grinding or stemming repairs to laminations and clamping structure, possible partial restack or reshaping over life of the core  20 – core structural integrity reduced due to removal of damaged core material, frequent replacement of core packing material  Lamination Migration   1. No migration   10- Migration that can be corrected  30- Migration that cannot be corrected | |  | | X 1.0 =  X 1.0 = |  | | 1  1 |
| **Operational Events** | | | | | | | |  |
| E1 | | Operational over-fluxing events  0 – no over-fluxing events  5 – limited over-fluxing with no signs of distress  10 – over-fluxing distorting core shape  10 – over-fluxing causing signs of heating of surfaces at core ends  30 – over-fluxing causing core mechanical damage |  | | X 1.0 = |  | | 1 |
| E2 | | Operational over temperature events  0 – no known or documented over temperature events  5 – limited over-heating with no signs of distress  10 – over-heating distorting core shape  30 – over-heating causing core mechanical damage |  | | X 1.0 = |  | | 1 |
| E3 | | Mechanical damage caused by foreign objects passing through the air gap  0 – no foreign object damage  5 – minor foreign object damage resulting in an outage to make repairs.  10 – major foreign object damage requiring major repairs to the core or even replacement of laminations. |  | | X 1.0 = |  | | 1 |
| E4 | | Mechanical damage caused by rotor contacting the stator  0 – no rotor to stator contact at any time  5 – some contact during assembly of rotor, repairable  10 – contact during operation, minor damage repairable  30 – contact during operation, major damage | |  | X 1.0 = |  | 1 | |
|  | | **Inspection** | |  |  |  |  | |
| I1 | | Loss of core clamping compression   1. - No loss of compression   1 – limited, repairable with no shorted or broken laminations indicated  5 – limited, repairable with minor localized fretting and heating from shorts or limited loss of lamination pieces  7 – widespread looseness front and or back, repairable  10 – wide spread looseness, repair difficult  30 – wide spread looseness, not repairable | |  | X 1.0 = |  | 1 | |
| I2 | | Core clamping system  0 – core clamping pressure adequate  3 – core clamping pressure too low, repairable  10 – core clamping stud tension too low, not easily repairable  10 – loose core with clamping by frame without studs, not easily repairable  30 – core clamping studs breaking | |  | X 1.0 = |  | | 1 |
| I3 | | Broken or missing laminations in core teeth  0 – No broken or missing laminations  4 – limited number of locations, winding insulation un-affected  10 – limited number of locations, winding erosion occurring  30 – widespread, causing loss of winding ground insulation | |  | X 1.0 = |  | | 1 |
| I4 | | Broken or missing wedge profile areas  0 – No broken or missing wedge profile areas  4 – limited number of locations, wedging un-affected  30 – widespread, affecting winding security | |  | X 1.0 = |  | | 1 |
| I5 | | Core buckling  0 – No wave  1 – wave longer than end clamping plates,  5 – wave longer then end clamping plate, higher amplitude causing core lamination looseness, loose laminations repairable  5 – Wave period shorter than end clamping plates low amplitude, core compression un-affected, core shape appears to be stable 10 – wave period shorter than end clamping plate, requiring frequent repairs to maintain core compression  30 – severe core wave, loss of compression, not repairable | |  | X 1.0 = |  | | 1 |
| I6 | | Core slot damage from stator winding insulation failures  0 – No slot damage  3 – slight erosion or melting on laminations – repairable  10 – extensive erosion and melting – repair difficult  30 – extensive damage - loss of electrical & mechanical function | |  | X 1.0 = |  | | 1 |
| I7 | | Spare Spot | |  | X 1.0 = |  | |  |
| I8 | | Wear between core and core attachment bars  0 – no wear observed  1 – minor wearing with no affect on core to frame attachment  1 – minor fretting with limited deposits of fretting corrosion  5 – heavy fretting with significant fretting corrosion deposits  30 – significant wear affecting core/frame attachment security | |  | X 1.0 = |  | | 1 |
| I9 | | Oil contamination between lamination layers  0 – no oil observed  1 – minor oiling - no sign of inter-laminar friction loss or movement between laminations  5 – heavily oil saturated – no sign of inter-laminar friction loss or movement between laminations  10 – oil saturation causing inter-laminar core motion & wear | |  | X 1.0 = |  | | 1 |
| I10 | | Loose, missing, collapsed or broken vent spacers  0 – vent spacers in good condition  3 – limited number of loose vent spacer locations, core compression ok, repairable  10 – limited number of loose or broken vent spacer locations, winding insulation affected, repairable  10 – limited number of loose, missing, collapsed or broken vent spacers locations causing, compression loss, repairable  30 – widespread vent spacer instability, causing compression loss, repair difficult | |  | X 1.0 = |  | | 1 |
| I11 | | Short period bending (chevron) at core splits  0 – no chevron effect  3 – minor stable amplitude, winding unaffected  10 – significant chevron amplitude, split slot winding affected  30 – major chevron distortion causing winding faults, core wear and heating at core splits | |  | X 1.0 = |  | | 1 |
| I12 | | Loose or missing core split packing  0 – split packing still in place  3 – split packing with insufficient compression, repairable  5 – split packing missing winding unaffected – insufficient compression – not repairable  10 – packing loose with abrasion of winding in split slot  10 – packing loose with abrasion of core to frame attachment | |  | X 1.0 = |  | | 1 |
| I13 | | Core loss test per IEEE 115  0 - No change in losses  3 – Losses have increased 10%  5 - Losses have increased 20%  10 – Losses have increased 50% | |  |  |  | | 1 |
| I14 | | Spare Spot | |  |  |  | |  |
| I16 | | Spare Spot | |  |  |  | |  |
|  | | **Test** | |  |  |  | |  |
| T1 | | Core axial temperature distribution or difference limits when operating at rated capacity  0 – temperature distribution across core outside diameter within 5°C  3 – temperature distribution across core outside diameter between 5 and 10°C  10 – temperature distribution across core outside diameter between 10 and 20°C  30 - temperature distribution across core outside diameter greater than 20°C | |  | X 1.0 = |  | | 1 |
| T2 | | Noise and or vibration attributed to the stator core  0 – Noise level is less than 85 dBA when measured according to ISO 3746.  1 – Noise level is between 85 and 95 dBA when measured according to ISO 3746.  3 – Noise level exceeds 95 dBA when measured according to ISO 3746.  10 – Core vibration is greater than 30 and less than 60 µm p-p radial vibration at twice power frequency  30 – Core vibration exceeds 60 µm p-p radial vibration at twice power frequency | |  | X 1.0 = |  | | 1 |
| T3 | | Full flux or ElCID test results  0 – core testing does not indicate any insulation weakness  3 – full flux test with hotspot >5°C and <10°C after repairs  5 – ElCID with 4% flux and Quad amps <100 on core with splits  10 – full flux test with localized hotspots between 10C and 20°C after repairs  30 – full flux test with wide spread hotspots >20°C not repairable | |  | X 1.0 = |  | | 1 |
| T4 | | Air gap uniformity  0 – air gap static dimension within +/- 20% of the average air gap  5 – rotor shape causing minor cyclic fatigue of stator core with an air gap static dimension within +/- 50% of average air gap  10 – rotor shape causing major cyclic fatigue of stator core with an air gap static dimension variation greater than +/- 50% of average air gap | |  | X 1.0 = |  | | 1 |
|  | |  | |  |  |  | | 27 |

|  |  |
| --- | --- |
| **Stator Core Evaluation Tabulation** | |
| Criteria | Tabulation Value |
| Stator core is suitable for rewinding as is | Value < 5 |
| Stator core requires minor rework during rewind outage | Value between 5 and 10 |
| Stator core should be inspected by OEM or expert consultant prior to outage | Value between 10 and 20 |
| Stator core may require replacement, or extended outage for extensive repairs during rewind outage | Value between 20 and 30 |
| Stator core replacement should be seriously considered | Value > 30 |
| Confidence percentage (number of 1s in the confidence column divided by the number of applicable asset criteria sections all multiplied by 100.) | 100 |
|  |  |
| **Stator Core Evaluation Tabulation (alternate weighting)** | |
| Criteria | Tabulation Value |
| Stator core is possibly suitable for rewinding as is | Value is between 22 & 55 |
| Consult OEM for repair or replacement options | Value is greater than 55 |

1. History

The stator core, which is the stationary magnetic circuit of AC motors and generators, is made up of individual laminations of thin magnetic steel. On large generators there may be up to a few million such individual pieces in the core. Since the steel is conductive of electric current (in addition to magnetic flux), it was recognized immediately by the designers of the first, primitive AC equipment, that this steel must be laminated and insulated, to reduce losses and thus temperatures. Lamination thickness has typically been a tradeoff between manufacturing costs and machine performance (losses). Specifically, it depended on the energy densities of the design (how hard the materials were being worked), on the magnitude of losses that were considered acceptable (efficiency of the machine), and on the acceptable temperature limits of the core. Typically thickness is in the order of 0.35 mm (0.014”) to 0.50 mm (0.019”) on large equipment, and thicker on smaller units or those with lower operating frequencies.

Originally, the normal oxide coating on steel provided sufficient insulation to prevent excessive current flow between laminations. But as equipment became larger, it was found that additional insulation must be provided. The evolution of these additional coatings involved numerous alternatives, e.g., mill coats as found on the surface of the processed lamination steel, shellac, paper, varnish, varnishes based on highly stable tung oil, enamel, enamel loaded with inorganic materials (finely divided silica), epoxies, and high-temperature non-organic materials.

Mill coats were used on very large generators until recent times, with mixed results, e.g., some susceptibility to thermal run away failure when subject to relatively modest mechanical damage, and some exposure to wear-out failure (mill coat rubbed away) after many years of normal service. The addition of silica to the insulating varnish provided a more robust design against mechanical damage and high resistance to wear-out failure.

During the first half of the 1940s, tung oil, which came from China, became difficult to obtain. Several larger generators, when insulated with the “normal” varnish from which the tung oil was omitted, had spontaneous core failures after very brief operation. This became a major problem for at least one OEM, since the cores on all the large generators failed when placed in service.

Volunteer Needed!!!!!!!!!!!!!

1. Stator Component Descriptions
2. **Laminations**

Stator core laminations are thin sheets of electrical grade silicon steel, typically 0.35 mm (0.014”) to 0.50 mm (0.019”) thick. Laminations are sometimes referred to as punchings or core plate. Each sheet may be a single annulus-shaped piece for smaller machine ratings; they are segmented for large machines. There are slots in the steel punchings to accommodate the stator windings, ventilation ducts (some designs), and core support bars (aka “key bars”, “dovetail bars”, etc.) used to circumferentially locate the laminations if they are segmented. Segmented laminations are laid next to each other to form a completed 360 degree ring and then the next layer is laid on top, staggered so that the joints do not overlap. In some designs, there may be holes in the laminations to accommodate through-bolts/through-studs as part of the clamping mechanism.

The stator core laminations are typically slotted at the inner diameter to accommodate the stator winding, which is normally held by non-metallic wedges. Units with small cores may have a semi-closed slot instead of an open rectangular slot. Most machines with voltage ratings of 2300V and above and some low voltage machines have stator windings that are form-wound with multi-turn diamond coils, or single-turn bars. In both of these winding types, the sections that fit into the slots are rectangular in shape and consequently the core slots for them are also rectangular in shape. The lamination slots for this type of winding have grooves towards the inner diameter (one on each side of the slot) to retain the wedges that hold the winding coils, or bars, tightly in the core slots.

The majority of low voltage machines have random, single-layer or two-layer windings with coils made from strands of round copper wire insulated with a high temperature varnish. For this type of winding construction, the core slots have narrow openings at the inner diameter that allow just one or two coil strands to be inserted at a time during winding. Also the slots themselves are not always rectangular in shape, but may be trapezoidal to give teeth that are more uniform in width. The cores for this type of construction are usually assembled, wound and then shrunk into the frame and also keyed to the frame to prevent rotation in service.

1. **Clamping Systems**
   1. **Core Clamping - General**

A stator core can contain 100,000’s of laminations. These must be held together radially and circumferentially, to ensure the laminations are clamped together consistently and effectively in the axial direction.

In cores with single-piece laminations, the core clamping system can either (i) be built into the stator frame and clamped by tooth support fingers and steel rings at each end and then welded to the core support bars, or (ii) built as a separate assembly and then fitted into a stator frame with core support bars that have been machined with a profile and dimensions that provide a tight fit between the two assemblies. In either case, vent ducts are installed during the core building process and the core has to be placed under a high axial pressure before the end support structures, consisting of end fingers and clamping rings, are fixed in place.

In cores with segmented or full circle laminations, the core clamping system can use either: (i) electrically insulated through-bolts/studs that are installed through holes punched in the core laminations, or (ii) tightening bolts/studs located at the core back, which are attached to the stator frame to avoid vibration or transmit torque. In either case, an even axial force is applied over the surface of the laminations by the use of ring flanges or pressure plates. Fingers or spacer blocks are used, to ensure that the tooth pressure is spread evenly towards the axis of the machine. The core design and thereby the tightness must be able to accommodate the steady-load machine torque as well as the transient torques experienced at startup and during fault conditions. These torques are transmitted through the laminations to the stator frame, via the key bars mounted on the stator frame.

The applied pressure during core assembly must be balanced to avoid core damage from overpressure or from lack of sufficient tightness, causing loosening of the core in service. Over-tightening of the stator core can result in damage to the laminations and ventilation duct “I” beams, resulting in a weakening or even cracking of the beams and thin steel laminations, which in time will result in slackening of the core. Conversely, not tightening the core sufficiently will result in lamination vibration, producing a low-pitched hum and resulting in fretting of the lamination insulation followed by potential burning, cracking and breaking of the lamination steel and also a high potential for damage to the stator bar insulation installed in the slots. Also a loose stator core will not be able to withstand the additional forces during fault conditions and may result in premature failure of the stator. Furthermore, a low clamping force will decrease the core capacity to resist the buckling phenomenon.

* 1. **Turbo Generator Core Clamping**

Turbo generators have core clamping requirements that are related to the specific design, dimensions and fleet history of a given manufacture’s style of machine. These requirements are normally defined, retained and managed by the original equipment manufacturer. The OEM is responsible to assess the suitability of a specific core assembly process needed to manage the complex forces at work in the stator of larger 2 and 4 pole units. The radial stability of the core is one of the important considerations that demands precise application of proprietary process for axial and radial clamping.

1. **Frame**

The basic purpose of the stator frame is to provide support and attachment for the stator core and to form the ventilation circuit for the stator cooling system which may include the coolers. On vertical generators, the frame may also support the weight of the upper bracket, which carries the weight and thrust of the rotor. The stator frame includes an outer shell, which is a steel fabrication or casting used to secure the motor or generator to the foundation and is designed to withstand the radial and tangential torques experienced during sudden short circuits or system disturbances. In hydrogen cooled machines, the casing contains the operating gas pressure as well as the pressure from a possible explosion of the hydrogen-air mixture.

Stator cores with building bars/key bars are attached to the stator frame using various core-to- frame attachment arrangements. These attachments must transmit the torsional, radial, and axial loads from normal operation, transient events, and gravity from the stator core to the frame. On large 2-pole turbo generators, there is typically a flexible or spring-type connection that limits the amount of vibration transmitted to the frame and foundation, see also the Core-To-Frame Attachment paragraph in Annex D Design Considerations.

1. **Frame Support Structure**

Stator frames of horizontal and vertical machines are typically bolted to sole plates. Bulb type generators may be attached by other methods. Normally, the attachment must sustain the maximum machine torque and allow the thermal expansion of the stator frame. This could be achieved by the use of dowel pins or a key system. In some hydro generator designs, the stator frame is not free to move radially to accommodate its thermal expansion. Those units are more susceptible to experience a stator core buckling phenomenon.

1. **Cooling and Ventilation System**

There are a variety of electric machine ventilation system types. A machine can be open-air-cooled (OAC), totally enclosed water-to-air cooled (TEWAC) or hydrogen-cooled (H2). The type of ventilation is generally associated with the type of machine and the type of environment where the machine is used.

In a specific electric machine, the ventilation can be radial, axial, or a combination of both. For example, large hydro-generators normally have radial ventilation whilst bulb type generators may have axial ventilation. Also, small and medium size high-speed salient poles machines may have axial ventilation between field poles and radial ventilation in the stator.

The rotation of the rotor is normally used to pump the primary coolant gas (see Primary Coolant paragraph below) through the stator core ventilation ducts. The axial height of the duct and the total number of ducts for a given core length is governed by the manufacturer’s approach to design, but modern designs will typically have ventilation ducts not more than 60 mm apart.

The majority of small and large cylindrical rotor synchronous and induction machines have axial fan blades installed at both ends of the rotor in conjunction with radial rotor vent ducts (if fitted); in these machines, stationary air baffles are used to provide the pumping effect on the primary coolant. However, there are some designs that use a single radial fan at one end of the rotor; this does not provide as uniform cooling as two axial fans.

Generally, in synchronous machines the primary coolant flows axially below the field coils and then radially through holes in the field coil conductors before reaching the machine air gap. The air flow then continues radially in the stator core through ventilation ducts in the core stack.

In two-pole induction motors, there may be no cooling air-flow through the rotor; in this case, the rotor is cooled by air that passes through the air gap and a duct in each stator slot between the wedge and stator core inside diameter. Induction machines with 4 or more poles usually have radial ventilation ducts in the rotor core which work in conjunction with the cooling air fan(s) to pump air through the rotor. Once the cooling air enters the airgap it flows through the stator via radial ventilation ducts in the core stack.

* + 1. Primary Coolant

The primary coolant is a fluid medium, either liquid or gas, which, being at a lower temperature than a part of a machine and in contact with it, removes heat from that part. For openly ventilated air-cooled synchronous machines, the primary coolant is the air entering the machine. For closed-circuit indirectly-cooled synchronous machines, the primary coolant is air or hydrogen. For directly cooled windings, the primary coolant is air or demineralised water. The primary coolant of closed-circuit-cooled synchronous machines is cooled by a secondary coolant.

* + 1. Secondary Coolant

The secondary coolant is also a fluid medium, liquid or gas, which, being at a lower temperature than the primary coolant, removes heat given up by the primary coolant by means of a heat exchanger or through the external surface of the machine. The secondary coolant is normally water in an open-loop system (may be river water for a hydro unit), or a mixture of water and glycol in a closed-loop system. In this last case, there is a tertiary coolant which is air that removes heat given up by the secondary coolant by means of a heat exchanger.

* + 1. Salient Poles Rotors

For small electric machines, the pumping effect on the primary coolant can be simply obtained from the rotational effect of the field poles. It can also be assisted by the use of axial or radial fan blades installed at both ends of the rotor in conjunction with stationary air baffles. For large electric machines, the rotor spider is normally used as a large radial fan in conjunction with rotor rim ventilation ducts. In this case, primary coolant leaks at the machine air gap are controlled with the use of a combination of fan blades and stationary or rotary air baffles, depending on the manufacturer’s approach to design the generator ventilation system. For bulb type hydro-generators, due to their low speed and relatively small diameter, the pumping effect on the primary coolant is obtained by external fans.

* + 1. Cylindrical Rotors

The majority of small and large cylindrical rotor machines have axial fan blades installed at both ends of the rotor in conjunction with radial rotor vent ducts (if fitted); in these machines, stationary air baffles are used to provide the pumping effect on the primary coolant. However, there are some designs that use a single radial axial fan at one end of the rotor; this does not provide as uniform cooling as two axial fans. Generally, the primary coolant flows axially below the field coils (such as in synchronous machines) or between the rotor core inside diameter and shaft (such as in induction machines) and then radially through holes in the field coil conductors or radial core ducts before reaching the machine air gap. The air flow then continues radially in the stator core through ventilation ducts in the core stacking. In two-pole induction motors, there may be no cooling air-flow through the rotor; in this case, the rotor is cooled by air that passes through the air gap and a duct in each stator slot between the wedge and stator core inside diameter.

* + 1. Stator Core

The laminations are usually built up in 25 mm to 60 mm thick packets, with non magnetic “I” beams or “H” spacers, installed between packets to form ventilation ducts, to ensure adequate cooling of the core. Ventilation ducts ensure that temperature rise of active components stays within temperature Class 130 (B), generally. The shape and distribution of the spacers are chosen to ensure uniform transfer of core pressure as well as smooth flow of the primary coolant.

* + 1. Stator Winding

Indirectly cooled stator windings are those in which the heat generated within the principal portion of the armature winding must flow through its ground insulation and in large part into the core before reaching the cooling medium. The winding losses, together with the losses generated in the core, are typically removed from the core by a primary coolant gas flowing radially through ventilation ducts which divide the laminated core into short axial packs.

Directly cooled stator windings are those in which coolant flows in close contact with the conductor, so that the heat generated within the armature winding reaches the cooling medium without flowing through its ground insulation and into the core. Cores for directly cooled windings therefore may not require the same cooling approach as cores for indirectly cooled stator windings.

* + 1. Ventilation Design Change

In case of changed number and size of cooling ducts in a refurbishment project, the impact on the cooling air velocity as well as the pressure drop in the ventilation system to be checked.

An optimization of the air cooling system usually requires a detailed network simulation of the whole air flow circuit of the old machine. In order to validate calculations, measured data of the existing machine are very helpful.

1. Design Considerations
   1. Lamination Materials and **Magnetic** Properties

As stated above, the steel used in stator cores is chosen for its low core loss and low hysteresis characteristics. Core loss refers to the sum of heat losses generated during the reversal of the AC cycle (hysteresis) and the resistive losses associated with small stray currents (eddy currents) between (or within?) laminations. The machine manufacturer strictly specifies a maximum core loss value. Typical core loss values range from 2.5 W/kg for the highest efficiency 0.35 mm (0.014”) thick grain oriented steels to 4.6 W/kg for 0.64 mm (0.025”) thick non-oriented M27 sheet. Core loss is the sum of losses arising from hysteresis and eddy currents. Hysteresis is largely a material property, while eddy currents are related to the lamination thickness and the type and quality of insulation used to separate the laminations. It is important to note that core loss measured by the supplier Epstein frame test, by a core loop test and finally by the generator efficiency test are not generally the same as flux direction and distribution will differ in each condition.

Steel is a ferromagnetic material, meaning that has a strong response to an external magnetic field. Steel contains small regions known as “domains” in which magnetic dipole moments produced by characteristic electron spins within the metallic crystal lattice align themselves with the magnetic field. The result is a net residual magnetic effect that acts to concentrate the field within the steel, thereby increasing the flux density.

Magnetic steel is characterized by low carbon content (typically < 0.1%) and increased silicon (2.5-6%). The addition of silicon encourages the formation of large ferrite grains and the more silicon that is present, the easier it becomes to orient the domains within the steel. Maintaining a low carbon content minimizes losses through stabilization of the inter-atomic spacing within the metallic crystal lattice.

Magnetic steel is specified by its AISI designations. Typically, within a given composition and processing route used to produce the steel, the core loss is strongly dependent on lamination thickness. Non-grain oriented steels measuring from 0.50 mm to 0.64 mm (0.019” to 0.025”) thick are typically used for the stator cores of industrial motors. Large hydro-generators employ non-grain oriented steels of 0.35 mm to 0.50 mm (0.014” to 0.019”) thick, while for turbine generators the requirement for increased flux densities often necessitates the use of 0.35 mm to 0.50 mm (0.014” to 0.019”) thick grain oriented steel. Naturally, the more specialized alloys have increased purchase cost.

* 1. Core-to-Frame Attachment

The core-to-frame attachment system transmits many types of forces between core and frame that can be created during all normal and abnormal operating conditions. Through this attachment, the stator frame is designed to maintain the core roundness and concentricity. Many kinds of stator core-to-frame attachment designs can be found. Designs are different from one manufacturer to another. A single manufacturer may also have multiple designs, depending on the machine vintage and on the type of machine (i.e.: high or low speed machines and small or large machines) and core construction (i.e. single piece, or segmented laminations).

In some single-piece lamination designs, the core is stacked in the frame and welded to key bars machined to fit its outside diameter. Another approach for this type of core construction is to build the core as a separate assembly, then install stator winding, slot wedges, end winding bracing and perform winding resin impregnation before installation in the stator frame. For this latter construction, the core is keyed to the frame to prevent it from rotating under torsional forces imposed on it under machine operation.

The most common method of core-to-frame attachment for segmented cores is made through the use of dovetail-shaped key bars welded to the stator frame with steel angles or stirrups. In some machines with this type of core construction, the stator core tightening rods at the back of the core are also used as key bars. Very old machines may have cast key bars, dovetail slots machined in the stator frame casting or dovetail key bars bolted to the stator frame.

The stator core-to-frame attachment must be designed to accommodate the maximum machine torque. This torque is obtained during an unusual and sudden system anomaly such as a line-to-line fault. Furthermore, it must be able to transmit any radial loads due to the thermal differential expansion between the stator core and the stator frame. During the core construction process, clearances between frame attachment and the stator core must be evaluated appropriately in order to have a positive radial reaction between the two components in normal operating conditions without exceeding the stator core limit capacity to sustain the buckling phenomenon. For most machines, the limitation of a particular design is either in the welding between the key bar and its steel angles or stirrups, or between the steel angles or stirrups and the stator frame flanges. The maximum machine torque is calculated by the machine manufacturer. This type of connection between the stator core and the stator frame ensures that the bore tolerance is maintained. It also permits a clearly defined transfer of the operating torque and other forces to the stator frame and from there to the foundation. The connection between the frame and core has to be designed for the torque transmission at any specified load condition and also for faulty operation.

The ability of a rotating machine to maintain a stable air gap during operation is called the air gap stability. More formally, air gap stability is defined to be the ratio of the mechanical stiffness of the machine structure over the magnetic stiffness. An air gap stability calculation is based on an equivalent stiffness concept of the various elements interacting together. These elements are the rotor stiffness (rotor spider and rim), the stator stiffness (the core stacking and frame) and the associated stiffness of the magnetic attraction.

* 1. Temperature Considerations

Laminated cores must be designed such that the temperature limits of the stator components will be safely managed while operating within the machine’s rated capacity. In addition, the design needs to allow for thermal expansion of the winding, core and frame.

* 1. **Temperature**

Stator cores will be heated from hysteresis and eddy current losses when conducting magnetic flux. These losses are minimized in the assembled core by building it with heat treated silicon steels that are rolled in thin sheets and coated with very thin insulation.

The core assembly on most generators must be maintained at a reasonably low and uniform temperature level for the following reasons:

* To allow suitable heat transfer to the core from indirectly cooled stator windings to ensure that the winding insulation and associated slot packing stay safely below their rated class temperatures.
* To maintain a safe temperature difference between core and stator frame so that mechanical stress limits in the frame or clamping system components are not exceeded.
* To have a suitably small temperature difference in the core itself to minimize cyclic mechanical stresses within the core structure.

There are many ways of managing temperature rise from losses in and around a laminated core, for smaller machines, radiation of heat from the exterior surface without forced ventilation may be sufficient. As the machine increase in size and rating, forced ventilation will be needed by adding fan blades to the rotor or using external motor driven fans. Ventilation ducts between core sections are employed to further increase core surface area exposure to increase the rate f heat removal from the core. Air is used as a primary coolant on all open ventilated generators and the majority of totally enclosed machines together with air to water heat exchangers. Hydrogen gas is used instead of air in larger totally enclosed turbo-generators when increased heat capacity of the coolant is required. Some special cores on a small number of machines are direct water cooled.

* 1. Thermal Expansion

As the temperature of a machine increases from start-up all components will experience dimensional increases. It is important that the machine design be able to accommodate the resulting changes without physical damage or distortion of the components.

* 1. Horizontal Machines

Horizontal machines such as large motors require little in the way of design provisions to accommodate radial and axial expansion. The difference in temperature and hence the amount of differential expansion between core and frame is not sufficient to cause mechanical distress to either component. This is due to the fact that none of the dimensions of the core or frame combined with the temperature changes are sufficient to create differential movement to result in forces large enough to damage or distort either component.

Two-pole turbo alternators usually have the core mounted on a spring mechanism to reduce the transmission of vibration to the frame. This type of structure will also accommodate any differential expansion between the core and frame. Axially, large two and four pole alternators allow the non-drive end of the machine to move as the whole core and frame assembly expands. The end turns of the winding in these machines are supported in such a manner that they can move relative to the core. In this way damage to the coils is prevented due to differential expansion.

* 1. **Vertical Machines**

Large vertical motors also require little in the way of design provisions to accommodate differential axial and radial expansion of the core and frame. Machines that require the most attention in this regard are large hydro generators.

As the temperature of the core and frame increases, the radial and axial dimensions of the stator assembly increase. Expansion in both the radial and axial directions present challenges to the designer. This is particularly true as the physical size of the machine increases. The core increases in temperature faster than the frame and the core temperature also stabilizes at a higher value than does the frame. Although the two components are structurally linked, from a thermal standpoint they are quite distinct.

* 1. Axial Expansion

As the temperature of the stator increases, the axial length of the stator core and frame increases. Most of the growth will usually occur at the top of the machine, which can expand freely as the temperature increases, as it is essentially unrestrained.

Since the core heats more quickly than the frame, and the core achieves a higher equilibrium temperature than the frame during operation, there will be differences in the amount of growth of the core with respect to the frame. This difference is accommodated through a core clamping structure that allows the core to expand more than the frame. The additional growth of the core may cause one or all of the following to occur; the clamping bolts to stretch slightly, the clamping plates to bend or if the core bolts are equipped with spring washers these will compress slightly as the core expands. Since the core itself is not a solid body, some of the growth may be accommodated by an increased clamping force on the laminations which would reduce the air content of the core structure.

* 1. Radial Expansion

For hydro machines, the sole plate design will likely include a provision for radial expansion of the stator frame, such as radial keys or flexible pedestals. The system must accommodate radial movement of the stator frame and at the same time provide secure attachment to the foundation to prevent movement in the vertical and circumferential directions. It has been proposed by some that springs be installed between the foundation plate and the frame to provide a restoring force to ensure proper sliding of the frame along the keys and to control eccentricity.

As mentioned above, there will be a temperature difference between the core and the frame. Some manufacturers provide specific design features to allow the core to expand radially, independently of the stator frame. These usually provide some form of clearance between the core and the frame. In addition, the temperature difference between the core and frame may be limited at the design stage to 5 or 10°C. This places a maximum limit on the differential expansion of the core with respect to the frame.

Still other designs pre-tension the core with respect to the frame so that when the core is at its maximum temperature, the pretension is virtually zero. The need for these design considerations will again depend on the specific machine design, the physical size of the machine, the temperature difference between the core and the frame and the overall radial stiffness of the frame. If none of the above mentioned design features are part of a specific machine, then ultimately it is the radial flexibility of the frame that will control core expansion.

The above mentioned features may not be suitable candidates for inclusion in a retrofit or rehabilitation package. Installing radial expansion provisions on a frame that did not originally have such a feature has to be approached with caution. Freeing up the base of the frame can affect the manner in which the top of the frame behaves during faults and in the presence of unbalanced field forces. **Installing radial expansion on machines as part of a refurbishing project should only be attempted with the assistance of the OEM or a competent machine design specialist.**

* 1. Stacking Factor

A tightly held stack of laminations will have a percentage of space occupied by magnetic material. This percentage is called the “stacking factor”, and is determined by comparison of the measured density to the theoretical density of pure electrical steel. This value is dependent upon the number of layers, the thickness of the lamination insulating layer, the amount of space between layers due to surface conditions, and the interlaminar pressure. The higher the stacking factor, the higher the magnetic permeability per unit volume of the core.

With today's state of the art lamination insulation a stacking factor of 0.97 can be achieved. As old machines are built with more insulation on the laminations, a new stator core with an increased stacking factor enables optimization towards better efficiencies.

The stacking factor of the core is less than the stacking factor of the electrical steel by itself. It is dependent on the stacking factor of the lamination and the configuration of the core. Slit iron, core splits, ventilation holes and gaps in the laminations will reduce the stator core stacking factor. The core will consolidate over time under pressure and dependent on the thermal profile, consolidate increasing the stacking factor.

* 1. Flux Densities & Other Things

When designing a new stator core, the flux density and consequently the excitation system must be checked for all operating conditions.

* 1. **End Region Flux Management Systems**

There are several different systems for protecting the core from the potentially detrimental effects of the stray flux surrounding the machine stator winding end turns. These flux management systems also serve the mechanical function of clamping the core together; however, electrically, they shield the flux, shunt the flux or perform some measure of both.

Non nonmagnetic, low resistivity devices like aluminum plates with copper shields perform this flux management function by repelling the flux by the action of eddy currents induced in them. Since the induced eddy currents shield the flux from the core end, they are called flux shields.

An alternate commonly employed system is laminated structures or high resistivity magnetic ductile iron with relatively little capability to have any substantial eddy currents induced in them. They are made of laminated core steel with support members designed so that no large currents can flow, like segmented and insulated from each other core support plates. The laminated part of these structures provides a good path for the stray flux. They stand in the flux's path on its way to the core end so the flux prefers to enter into them rather than to go to the core end. Since this looks like shunting off the flux from the core, they are called flux shunts. Sometimes they are also called flux traps, since the flux "falls" into the trap before reaching the core end.

Another approach to solving the same issue is to use magnetic steel plates that are somewhat more resistive than regular construction steel, but still sufficiently conductive to allow substantial eddy current. These currents repel the flux somewhat, but the high permeability also collects some of it, so they are somewhere between the shields and the shunts. There are also other types of systems used in smaller machines that combine the shields and the shunts.

* 1. Core Splits

Large rotating machine stator cores can be manufactured in sections, two or more. Major reasons for such designs are shipping limitations and uncertain site core assembly conditions. Boundary areas of core sections, known as core splits, could present problems, and it might be desirable to avoid them. See the Core Splits Annex for more information.

1. Manufacturing Components
   1. Lamination Materials

Core laminations are punched or laser cut from a master roll of continuously cold-rolled sheet. The steel can be grain-oriented or non-oriented; the appropriate orientation is chosen by the manufacturer based on design and application criteria. The core laminations may or may not be heat treated or enameled after punching. Many lamination manufacturers have a 100% de-burr process where the laminations are sanded on both sides, and a micro thin layer of insulating varnish is reapplied and then baked in an oven. For manufacturers that do not perform 100% de-burr, the suggested burr tolerance is 0.0005”. The edges of punched laminations are de-burred to avoid short-circuiting the laminations, which produces “hot spots” in the core.

Magnetic steel may or may not have an insulating coating applied to its rolled surfaces from the mill. In the case of motors and hydro-generators, the specified coating is mostly inorganic, with small amounts of organics or completely organic varnish coatings. The mostly inorganic coating insulates the laminations from one another and can withstand annealing temperatures but may not act as a good die lubricant. Organic coating acts as a die lubricant for punching and also offers a good surface resistance, but cannot withstand annealing temperatures like the mostly inorganic coatings. Further references can be found in ASTM 976 Table 1.

* 1. **Lamination Material Testing**

Laminated material loss is measured using an Epstein tester, whereby strips of lamination steel are stacked within an enclosed iron frame containing a solenoid. The sample is energized and the losses of the magnetic circuit are measured according to ASTM A343. The Epstein test unit can also be used to calculate the steel permeability from the exciting magnetizing currents. This test is normally done on each master coil of steel at the beginning and end of the coil. Stamped laminations do not normally provide enough surface area to accurately complete the test. The factory should have the core loss and permeability test reports in the mill certificate.

Lamination insulation integrity can be tested using a Franklin test of the surface insulation resistively, measured according to ASTM A717.

A ductility test is a test of the material, not the coating. This test is addressed in ASTM A720.

The coating is usually tested as follows:

* Flexibility Test – bending over a ½” mandrel creating a 90º bend, then checking for any coating that is cracking. This is a pass / fail type of ASTM A976.
* Complete Curing – this test involves using a clean cotton swab dipped in alcohol. By rubbing the swab on the coating, no removal of the coating is allowed.

These tests are all done at the source of application and may often be overlooked by the OEM if a mill certificate exists with these tests already done.

* 1. Quality Control / Tolerance

Quality control should insure that initial steel tests have been performed prior to punching any laminations. The first lamination should be checked for overall dimensional requirements (shape, thickness, burr height, etc.). Periodic checks should be made throughout the punching process. Burr height should not exceed 0.0005 inch (5 ten thousandths of an inch). Laminations which are bent or otherwise permanently deformed during the manufacturing process should be discarded. Laminations adjacent to vent ducts and finger plates shall be checked for weld quality.

* 1. Other Components
     1. Stator Frame

The stator frame is constructed using heavy steel plates and tubing or angle iron that is welded together to give the desired profile. The steel plates form what is known as “shelves” in the form of large rings held together by heavy steel tubing or angle iron. The frame can be built in one section for smaller diameter machines or can be built in sections, usually half, third, or quarter, depending on the diameter of the machine. Normally, shipping restrictions will guide the fabrication process at the factory. At site, the half or quarter sections are doweled and then bolted and/or welded together. The tolerance on circularity of the stator frame during construction should be closely observed.

* + 1. Keybars

The keybars hold the laminations to the stator frame and prevent the core from being pulled into the rotor due to the high magnetic field produced while in service. The keybars are made of mild steel and are precision machined to tight tolerances to ensure a good fit when the laminations are stacked. Each keybar is carefully welded to the stator frame and careful tolerances are kept for keybar chords, radial placement from the ideal stator centre, and for keybar surface flatness in the radial direction. Sometimes the keybar is also used as part of the clamping mechanism to provide axial pressure to tighten the core. The ends of the keybar are threaded to accept bolts that are used to secure the clamping plates.

* + 1. Through-Bolts/Studs and Tightening Bolts/Studs

This solid tubular steel bar is used exclusively as part of the clamping structure to provide axial pressure on the laminations. Both ends of the stud are threaded to accept nuts used to secure the clamping plates.

* + 1. Clamping Plates / Fingers

The clamping system is designed to keep pressure on the laminations (yoke and teeth) in the axial direction throughout the life of the machine. The pressure created will serve to prevent the core from vibrating and fretting over time.

For small generators or motors, the clamping system may consist of a thick steel circular plate or semi circular plates. For large hydro generators, the clamping ring is segmented and system consists of thick steel plates having generally the width of the core laminations. These steel clamping systems have “fingers” which press on the teeth of the core while the plate presses against the yoke of the core. The clamping assembly is designed to fit over the through bolts in the core yoke or tightening bolts at the back of the core and is then bolted together and the proper torque is applied to achieve design core pressure.

* + 1. Laminations and Vent Plates

The construction of laminations has already been discussed. The vent plate structure allows ventilation to flow through the generator. It consists of a thin solid or I-beam style spacer measuring typically about 3/8” or 1/4” in height and sometimes as little as 4 mm (0.157”). This is a non magnetic material that is spot welded to the lamination parallel to the air flow to prevent it from moving. In the core assembly, the laminations next to the flanges of the I-beams in the vent plate structure are typically 0.5 mm (0.019”) or 0.635 mm (0.025”) thick. This vent plate is placed in the core every 1.5” or so creating the next lamination packet.

1. Assembly and Commissioning
   1. Hydro Generator Core Construction

Stator core installation guidance for construction of large hydro generators is in IEEE 1095. Generally, the process involves centering the shaft, tightening the bolts supplying tangential pressure at the frame splits, measuring the verticality and circularity of the frame, installing key bars and core clamping bolts/studs, installing the bottom clamping plates, stacking the iron, and installing the remainder of the core-clamping system. The stator support pad area, dowels, and jacking screws are examined for general condition and for evidence of abnormal movement. Splits in the stator core may be eliminated during a restack (See Annex on spilt cores). Presses of the iron (aka stack of laminations) should be made every 15” or less. Hydraulic jacks should be used to press the iron such that the fasteners for the core clamping bolts/studs are not the only means used to apply pressure. Following successful completion of all inspections and testing, two coats of capillary-action epoxy are often applied to consolidate the bore surface.

When the stacking of the core is completed and before the winding is installed, the insulation varnish of the laminations should be removed in the core slots and a semi-conducting paint or varnish should be applied in order to provide a good electrical connection between the winding anti-corona protection in the slot and the ground.

* 1. Turbo Generator Core Construction

Turbo generator cores are normally constructed at the equipment manufacturer’s factory using proprietary processes specific to the manufacturer.

Larger capacity turbo generators have long axial core dimensions; this results in many thin laminations piled (stacked) in depth. Small variations in lamination manufacturing thickness and settling after clamping have a more significant influence on piling dimensions as the core length increases. Shims or fillers placed to maintain a level build as the core is assembled must be continuously applied. Multiple high pressure clamping operations or other suitable methods must be employed during core construction to accelerate gradual settling of the laminations after piling.

* 1. Core Inspection

There are numerous intermediate checks of verticality, circularity, lamination alignment, and core level during the stacking process. Lasers and sweep fixtures have been used successfully to perform the intermediate and final dimensional checks. At the completion of the restack, one should measure the circularity, verticality, alignment and level, to verify compliance with the Canadian Electrical Association Guide for Erection Tolerances and Shaft Systems Alignment Part II (CEA Guide). Alignment of the laminations in the slot section requires constant attention throughout core construction, since the weight of laminations will prevent adjustment if stacking is little as 150 mm past areas that require alignment. Alignment is done by using a soft mallet and gently striking the laminations into position on the face of the bore as well as a special “paddle” tool used inside the slots of the laminations. The “paddle” is moved from side to side once inserted using the soft mallet. This will ensure the slot section is aligned optimally to accept the stator winding.

Stator Core Splits

1. **Introduction**

Manufacture of large rotating machine stator cores in sections was adopted when the bore diameter became either too large to allow shipment of such units in one piece from the factory to the installation site, or required a special procedure for assembly. This requirement is much reduced in recent times for two reasons. Much good experience has been obtained in carrying out performance tests in situ**1,2**, which encourages customers not to require these tests in the factory before shipment, although this may still be included in some customer’s specifications. In addition, considerable good experience3 has been achieved in building very large diameter stator cores at the ultimate location. This requires care, both in establishing clean working conditions and in precise building practice.

Core splits have always presented some degree of vulnerability, and it is now generally regarded as desirable to avoid them, wherever possible. Weaknesses may only become apparent after a significant period of machine operation.

Construction of split stator cores has varied among manufacturers. Some have sought to produce a relatively close-contact core joint, by building for a given gap between core joint faces with shims of half the thickness of those between the core frame joints. When the core build is complete, the core shims are removed, and the frame shims reduced to the thickness used during the build between core sections. Roughness of the joint faces, due to lamination shuffle during the build process, as permitted by essential tolerances, results in a gap at the split of varying width. Others have deliberately aimed to complete the build with a relatively large gap at the splits to allow substantial packing of insulation material to be inserted for mechanical reasons, which experience has shown is difficult to retain.

Introduction of core splits to the machine design inevitably and undesirably requires additional core lamination parts. Clamping of the core at core splits often necessitates more complex and difficult arrangements.

1. **Inspection of Stator Core Condition at Core Splits**

When a split stator core has been assembled in the factory, it is usual to apply a core ring test, often known as a High Flux Ring Test (HFRT), sometimes referred to as a “loop test”. This serves more than one purpose. First, it helps to consolidate the core pack, especially if intermediate core pressing is not part of the core build procedure, which is the practice of some manufacturers. Secondly, any damage to core laminations in the course of the core build may be detected by means of thermal imaging, particularly at the core splits. Thirdly, looseness at the core splits may be detected, especially by ear.

Location of the core splits, for an inspection when the machine is in situ, is usually achieved by observation of the stator bore, especially when the split is on a tooth. If the split is at a slot, it may not be immediately evident at the bore, although the pattern of core segments may provide identification. Core splits are evident at the back of the core, if there is sufficient access. In cases, where it is not feasible to find core splits by observation, reference should be made to the maker’s drawings.

Annual visual inspection is normally recommended during the operational life of the machine. This includes checking machines, embodying a split stator core, for signs of fretting at the splits, as indicated by the presence of a red dust, at both the inner and outer peripheries of the core. If there is a significant presence of oil in the machine, the appearance of fretting corrosion products will be a black paste. Inspection can be difficult, due to restricted access, particularly at the outer periphery. Movement of any core split packing is also checked by sight.

An additional feature, to look for during a core inspection, is the possibility of a “chevron” effect at the core splits, which is indicative of the joint faces crushing together. This indicates looseness of the clamping structure, but is not necessarily of immediate great concern, although it should be kept under close observation during subsequent inspections. The core interlaminar insulation is not necessarily degraded by this phenomenon. If the core is split on a slot, joint crushing will not be immediately obvious, due to the presence of the stator winding. If a joint coil or bar requires replacement, the reduced slot width will necessitate manufacture of special width winding components. The need for such a measure will contribute to consideration of the need for renewing the stator core.

A simple test for slackness of core laminations anywhere, but particularly at core splits, is the “knife” test. This is described under “11.3 Tests for Core Tightness”.

A global visual inspection of the stator core is quite valuable in assessing the likelihood of problems, particularly developing or established hot-spots. These are most frequent in the core split regions. If core looseness is occurring, the clamping fingers may well have begun to cut through the end laminations. Deterioration of core clamping generally must be checked.

A particular feature of split cores, which have been in service for some time, is possible radial movement of laminations in the region of the splits. This is usually the result of a ratcheting action of the clamping fingers on the end laminations.

A further possible feature, to which splits cores are particularly susceptible, is distortion from being truly circular to an oval shape; often referred to as ovalization. This phenomenon implies that the anchorage of the laminations at the outer periphery of the core has become impaired by tearing of laminations from the core build (or key) bars, and/or cracking of the welds securing the core build bars to the frame. It is recommended in cases of such stator frame deterioration, that the specific situation is referred for appraisal by an appropriate design resource. Looseness at the core back most probably breaks the path for the flow of circumferential currents, resulting in arcing. Degradation of the interlaminar insulation may occur, resulting in erosion (burning) of laminations at the core bore, leading to serious damage to the core**4**.

Whenever possible, by virtue of time and/or access, it is recommended that an EL CID test is carried out on stator cores generally, but particularly if of the split type. The split does, however, introduce particular problems in assessment of EL CID results, and requires careful analysis by an experienced operator. The EL CID test is particularly useful in providing an easy method of assessing the efficacy of remedial action.

1. **Application and Analysis of an EL CID Test at a Stator Core Split**

There may be a number of phenomena contributing to the PHASE and QUAD EL CID signals (Ridley**5**), which need to be recognized before an adequate analysis can be achieved, whether at a core split or elsewhere round the periphery of the core bore. It has also been identified (Ridley**5**) that the original simplistic EL CID theory which equated the QUAD signal to the circulating, or fault, current due to interlamination insulation degradation, in general, does not hold. The procedure for an EL CID test at a split in a stator core, therefore, is basically as for the core generally. Indeed it will normally be part of a global application, of which details have also been published (Ridley**5**) elsewhere.

The “Evolution” version of the EL CID equipment is adequately scaled for all magnitudes of signal likely to be encountered. Some EL CID users have routinely reset the PHASE reference in the past, which significantly reduces the indicated QUAD signal. If that is the case, then the PHASE Reset effect must be eliminated, by applying knowledge of the PHASE Reset Angle, before analyzing the EL CID results in the way published by Ridley**6**. The built-in feature of the EL CID kit to remove the so-called D.C. component also reduces the detected signals. This does not affect the analysis.

Although further correlation of the results from the EL CID test with those of the HFRT remains to be achieved, data so far obtained (See Appendix 4.1 of Reference 5) indicate an encouraging degree of confidence. Nevertheless, it is still the recommendation that where a seriously defective condition is indicated, then an HFRT may be considered desirable, although its deficiencies need to be recognized, i.e. indications of defects below the bore surface are significantly attenuated. It is theoretically acceptable to carry out an HFRT with the stator winding in-situ, but the impracticalities of doing so are even greater than with an unwound core, ie. sourcing an adequate electrical power supply, man-handling the heavy electrical cabling required, gaining the necessary access, and the labor intensity of the activity.

1. **Routine Methods for the Maintenance of Split Stator Cores**

It is a standard Instruction Book (or Operations & Maintenance manual) requirement that core studs (sometimes referred to as clamping bolts) are checked for tightness at recommended intervals. This is basically by the application of a calibrated spanner/wrench, but this can be inconvenient. Sometimes, specially calibrated core studs are provided which allow a check on the tension by measurement of the extension. A further alternative is that of checking the natural frequency of the core stud, as an indication of the tension applied.

As indicated above, a basic procedure during outages for maintenance is visual inspection. This is to be carried out carefully and the details noted for future reference, both to assist immediate assessment of the core condition, and for comparison during subsequent inspections. Such an inspection usually requires some degree of dismantling of stator covers and other items in order to afford adequate access. In the case of the very large machines which are typical of hydrogenerators, it is usually necessary for the person making the inspection to gain physical entry to the inside of the machine. Therefore, the machine operator needs to make adequate provision in the maintenance inspection outage time-table. This must allow for adequate ventilation of the machine, especially if mechanical brakes have been applied. Care should be taken to ascertain whether brake pads embody asbestos, as used to be the practice, and may still exist on old machines.

All the problems likely to be encountered anywhere in a stator core apply to split stator cores, plus those noted previously, i.e. emerging joint packing, fretting of joint laminations, looseness of the clamping structure and consequently of laminations, creeping of laminations in the joint vicinity (most usually radial inwards, but may be outwards), crushing at stator joint faces, ovality of the core, cracking of welds between core build bars and the stator frame, tearing of the lamination at the core build bars.

If distortion of the core is not a serious matter, attention to lamination looseness will be as usually applied, namely restoration of interlamination insulations. This will involve cleaning up any damage, physically and/or by etching, followed by packing with suitable pieces of an insulating material. Before attempting to re-tighten the core, an engineering judgment is necessary to ascertain any fundamental weakness in the design of the clamping structure**7**.

Where core distortion is significant, a design judgment is required concerning the remedial action required. It may be acceptable merely to refurbish the frame and core clamping structure, but considerations, such as magnetic pull imbalance, may require core shape correction. If possible, this is achieved by jacking the core at the stator bore.

1. **Radical Stator Core Correction Measures**

When the condition of a stator core has seriously deteriorated, or a stator rewind is to be undertaken, consideration will be given to renewal of the core, and possibly the frame. Some power generation authorities have developed the policy, from experience, of renewing the stator core, whenever replacement of the stator winding is required. This is based on the desirability of the stator as a whole being thoroughly reliable for the life of the new winding.

It may be that stator core condition deterioration is sufficient on its own to merit renewal, with or without replacement of the stator frame. It will usually be economical to replace the stator winding at the same time. Epoxy-insulated coils are not easily removed and replaced without damage. The same criterion applies to long-term integrity of the stator, regardless of whether the condition of the core or the winding initiates renewal action.

It should be noted that renewal of the stator core provides the opportunity for radical redesign of the stator winding with consequent improvement in machine performance for output or efficiency or both**8**.

1. **Conclusion**

Maintenance of machines embodying a split core is essentially as for other machines, but merits special care and attention. Remedial action is usually possible, but may not be easily undertaken. Attention to other factors, such as the core clamping structure, the stator frame and the condition of the stator winding, is required before a major decision on corrective action is undertaken.

For new machines, it is not usually necessary to adopt a split stator core, since good experience now exists of large machine core building in-situ. The same techniques are available should replacement of a split core be required.

Some authorities have advanced an argument in favor of a split core design, on the basis of providing a facility for replacing only one core section in the event of a major fault and consequent core damage. However, in view of the inherent problems associated with split cores, the recommended policy is avoidance of this feature.

G. K. Ridley

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1. Guidance for Stator Core Purchasing Specifications

In order to preserve the integrity of generator components, including laminations, during transportation and storage, certain packaging requirements must be established. It is important for the final assembly that the individual components be properly handled and stored so they are clean and free from damage.

A distinction must be made between domestic shipments and export shipments as well as short-term packaging versus long-term storage packaging. Domestic shipments are those shipments where the source and destination are within the boundaries of the same continent and transportation is by truck and/or aircraft and/or rail. Export shipments are shipments of components by water-borne carriers (i.e. vessel or barge) and will typically require more substantial packaging. Packaging for long-term storage will typically need to be more substantial than for short-term storage. Different components require different levels of environmental control to provide adequate protection during storage to eliminate deterioration of the product. Specific packaging requirements should be developed to address these factors.

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