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Regular paper

Synchronous Generator Abnormality and Fault Analysis

The trouble-free operation of alternators is unavoidable to meet the rising demand for electrical energy. Any alternator failure causes overloading of the remainder of the units in a grid, posing a serious threat to network stability. In a stand-alone generation, production is seriously affected. The repairs of large capacity alternators require a trained workforce, which is not always locally available. When an alternator operates under typical fault conditions, it reduces its efficiency and shortens its lifespan. The synchronous generator's prolonged outage has an adverse impact on network reliability and impacts the economy. As a result, early detection of alternator anomalies significantly reduces fault extension, loss of supply, and maintenance costs, while also improving the alternator's life. In many cases, the early fault detection scheme for higher capacity alternators cannot be readily applied to a lower capacity one. The article discusses some practical root cause analyses of the commonly occurring faults in turbo-alternators. The identification, characteristics, and analysis of multiple fault occurrences have been thoroughly addressed. This article would provide utility and protection engineers impetus in determining the urgency, selecting, and implementing the appropriate protective system for various abnormality events.

Keywords: Generator; condition monitoring; core burning; vibration; insulation failure

1. Introduction

The Synchronous Generator (SG) is essential for bulk power generation and network stability. Although power generators are extremely durable and reliable, they are frequently susceptible to numerous failures usually not present in lab electrics and domestic appliances. Long-term operation in a high-stress environment and unpredictable operating conditions such as aberrant frequency, voltage, loading, leading power factor operation, local hot spot creation, slot discharge, mechanical vibrations, and insulation failure are the primary causes of generator defects. These anomalies significantly impact the generators' competence and life cycle. An early diagnosis of generator anomalies is crucial for maintaining the energy supply's sustainability while reducing equipment damage and financial losses. Several studies on anomaly detection of synchronous generators have been presented during the last few decades. Slot discharge, vibration, and sparking in large high voltage electrical machines are responsible for the life reduction of electrical machines. [1] Slot discharges are caused by loose windings, poor slot conductive coatings, and isolated slot conductive coatings. Ozone created during Partial Discharge (PD) attacks the winding insulation. In high voltage machines, severe insulation problems may arise due to this. High voltage coils are subjected to Electrodynamic forces, slot discharge, and thermo-mechanical stresses. Suitable measures are required to protect high voltage machines [2]. The asynchronous operation of the synchronous alternator under field failure causes severe damage to the machine. In the negative slip region, the mechanical power of the turbine

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equates with asynchronous electrical power developed [3, 4]. Rotor winding deformation leading to failure of turbo-alternator has also been well addressed. Softening of hard-drawn copper takes place at 130°C to 150°C. An increase in the normal rotor current accelerates the winding distortion troubles even in the case of properly packed end turns [5, 6]. The vibration patterns of end winding are disparate for different healthy and faulty operations of an alternator. A wide range of natural frequencies exists for the end winding structures. The stress is much lower at certain natural frequencies to cause any catastrophic failures. However, under certain other natural frequencies, a careful operation is required [7]. Unbalance magnetic conditions during single ground fault and the double ground fault may cause severe vibration enough to damage the bearing pedestal, causing the rotating field to drop physically on stator windings. It may require costly repair and a more prolonged machine outage. In the case of synchronous machinery, the AC armature and DC field breakers are operated as fast as possible, and if desired, the prime mover power may be shut off [8]. It ensures the avoidance of the induction generator operation of SG. Vibration Detection instrumentation for turbine-generator and stator end-windings is described in [9, 10]. Alleviation of torsional vibration problem has been presented in [11]. The stator inter-turn short circuit effect on end winding vibration has been reported in [12]. A particular requirement for force distribution in the end zone is required [13, 14].

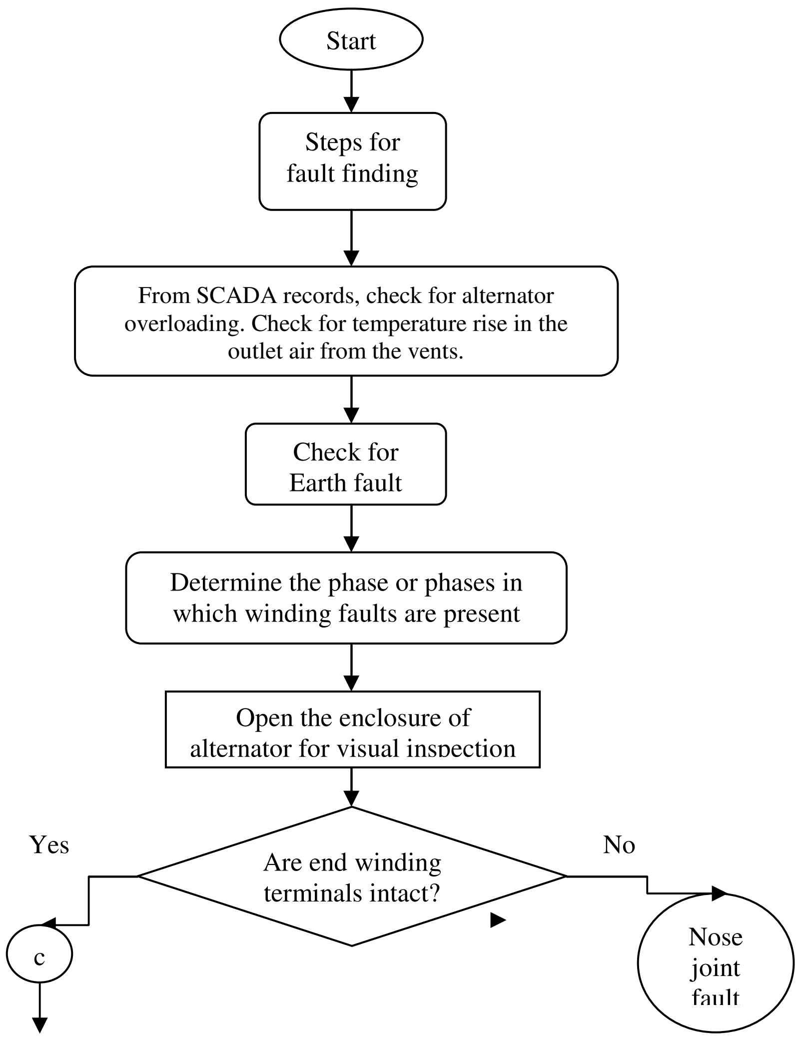
Most researchers interpret an alternator as mathematical equations and execute fault analysis based on that assumption [15, 16], neglecting any possible physical damage to the alternator caused by some defects both within and outside the alternator. Severe fault conditions cause the alternator to entirely stop functioning, necessitating costly maintenance and repair and loss of productivity. Any circuit breaker tripping due to a line fault may be quickly restored with minimal effort, while significant alternator problems might take longer to fix and use.

As a result, synchronous generator condition monitoring (CM) is necessary to protect the generators from catastrophic damage. Most of the alternators of higher capacity are fitted with the sophisticated SCADA system, which records essential input-output parameters for condition monitoring and fault analysis. Such a CM system is highly efficient in triggering the warning alert and detecting issues early on. The CM system improves machine availability, performance, and lifespan while reducing damage and maintenance expenses. The calibration of sensitive instruments measuring electrical, mechanical, and thermal parameters used in power industries is required yearly. Most faults occur due to non-compliance with annual mandatory calibration, even with SCADA. The reliability of an effective CM system depends on the calibrated measuring instruments connected to it. In insurance-related claims, it is always advisable for the owners to undergo mandatory calibration of the measuring equipment and maintain the online data before the fault. The findings, characteristics, and the consequences of several practical fault scenarios on the synchronous generator are comprehensively discussed in this article. The manufacturing and production sectors have dominated in recent decades, particularly compared to the maintenance system. According to [17], a substantial portion of maintenance money is lost due to inappropriate maintenance techniques, which is the leading cause of maintenance inefficiency.

2. Generators with abnormalities

Synchronous generators are technically relatively complicated in manufacturing standards, but they have inherent reliability and are built for a longer lifespan. Continuous operation in a high-stress environment, overloading and loss of load, and similar unpredictable operating conditions will cause the machine to fail, thereby reducing its usefulness and lifespan. The winding of any electrical machine is "the heart" of the machine where most of the faults occur. According to a CIGRE investigation of 1199 hydro-generators, insulation breakdown is responsible for around 56 percent of all anomalies. Mechanical and thermal problems are among the other significant abnormalities [18].

The flowchart for Root cause analysis for the air-cooled alternator is depicted in Fig. 1.



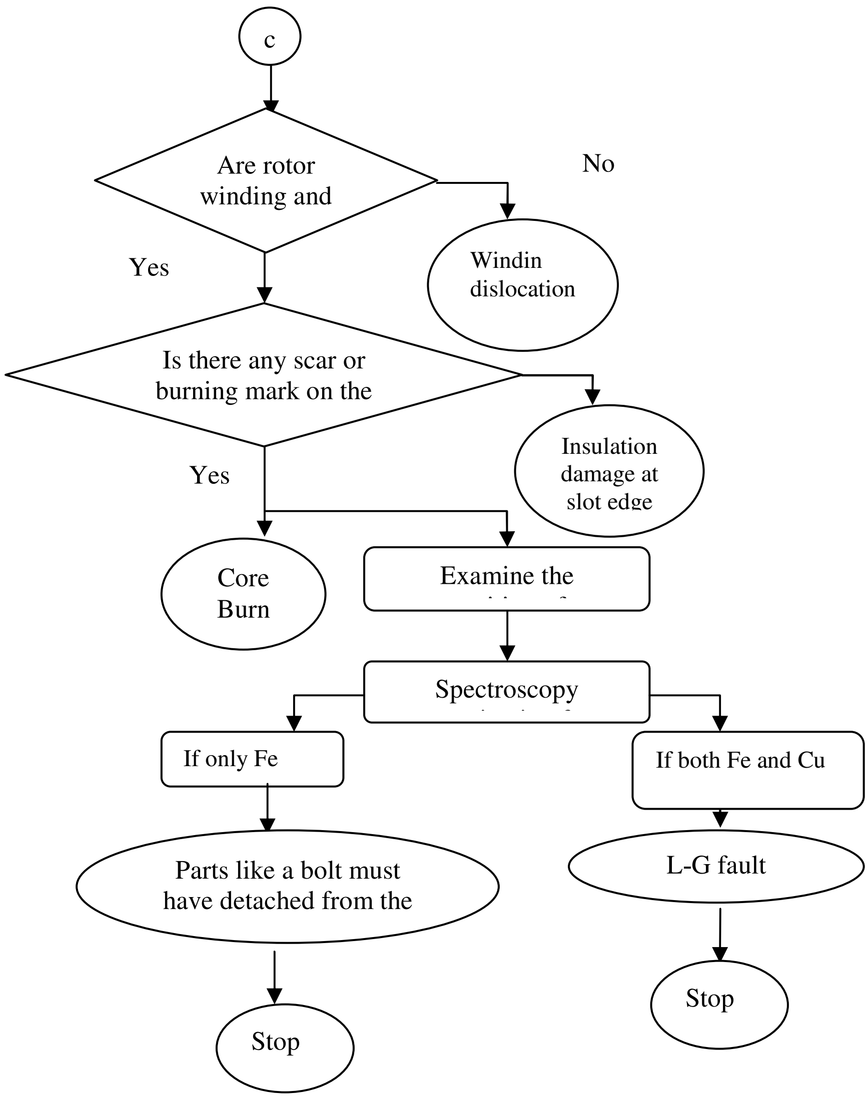


Fig. 1. A flow of the accomplished work.

3. Root cause analysis

The findings and consequences of several practical fault scenarios on the SG are discussed in this section. A fault in the coil winding like L-G, LLG, or LLLG is induced by different reasons like (i) fault in winding material, (ii) core burning, and (iii) insulation failure. Almost all are present, and it is challenging to pinpoint which fault started in the beginning, leading to catastrophic failure. The primary culprit in all the above faults is mechanical vibrations in different parts of the rotating structure.

3.1. Core Burning

In 150 MW alternators, the diameter of the stator bore is of the order of a few meters and is made using segmented stampings. All the insulated Silicon hot-rolled stampings form the stator stack. Several packets of stampings are assembled in such a way as to create radial ducts for cooling purposes. As per existing conventions in tropical countries, after a packet of 10 cm, a gap of 1 cm is provided while stacking. It reduces the effective iron length and increases the coil line parameters, which calls for a larger copper volume for windings. A typical packet of stampings with radial ducts, partially burnt teeth, and loosened stampings are shown in Fig. 2. A single tooth along the axial length on the stator surface is discontinuous and segmented because of the stacking of stampings in packets with spacers inserted. Each packet of a tooth has proper insulation and bindings, which protects it against vibration. These are subjected to the magneto-striction phenomenon in which each stamping in a packet of tooth dances macroscopically in a haphazard manner when subjected to alternating magnetization [19]. It causes the loosening of specific tooth stampings. Due to prolonged use, a particular tooth packet may be subjected to several stresses mentioned earlier. Loosening of stampings ensues due to wear and tear, as shown in Fig. 2, in which slot insulation degradation can be initiated. When the insulation between the stampings degrades, there are chances of more significant eddy current losses in those packets of the tooth. Due to magneto-striction, the stampings devoid of insulation regularly appear in contact with each other in cyclic magnetization resulting in a rise in local eddy-current losses and a rise in local hot spot temperature.

Fig. 2. Start of Loosening of Core stampings in 150 MW alternator.

The Core burning is shown in Fig. 3. The core burning appears slowly and worsens gradually. The outlet air temperature recording cannot detect the tooth insulation burning and subsequent wear and tear and loosening of packets of stampings. It results in creating a local hotspot in the heart of the core. The melting temperature of electrical grade sheet steel is around 1500 degrees Celsius, whereas the melting point of winding copper is about 1100 degrees Celsius. Due to the melting of the copper coil, insulation, and core material, just after the intense heating due to a fault, a lump of hot material protrudes, touching several teeth on the rotor, shaft, etc.

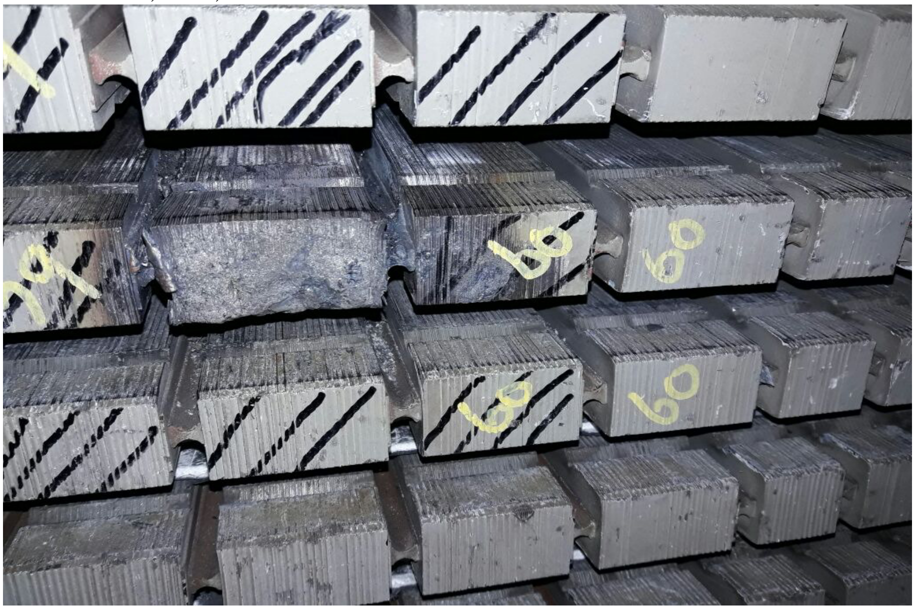


Fig. 3. Burning of packets of tooth stampings in the core.

Upon coming in contact with the teeth, the hot lump leaves a scar which eventually short circuits the stampings on the face, as shown in Fig. 4. However, when such stamping packets are used again, it leads to core burning unless properly treated with care. It calls for an online chemical analysis of outlet air, which can detect the possible faults of core burning at an early stage. However, these schemes are not available for 150 MW alternators. Core burning causes the local degradation of Class F insulation above 155° C (coil insulation) and the subsequent grounding of the coil with the core. The core burning (of a tooth) in a 150 MW alternator makes a portion of the stator core unusable. In a refurbished alternator's core, such portions of the core are removed, resulting in lowering the alternator's capacity.

Fig. 4. Molten lump of stator winding coming in contact with slot-tooth, leaving a mark.

3.2. High Voltage Coil fault

A typical cross-section of the coil of an 11 kV, 50 Hz, 150 MW, the grid-connected air-cooled alternator is shown in Fig. 5. It has two conductors per slot in single-layer windings. The preformed casted coil has several strips wrapped using Kapton tape insulation, and Class F insulation binds the coil. These strips are short-circuited on both the ends of windings to allow a large current to flow. Two conductor groups are separated by insulation.

A damaged coil showing a strip conductor is shown in Fig. 6. Due to manufacturing defects of possibly undetectable void in copper strips or possible bend or presence of foreign material during manufacturing, the creation of a hot spot surrounding the void/bend remains undetectable. The copper strip manufacturer and high voltage coil winding company should ensure void-free strips after rigorous testing of copper winding strips and the binding process. Over longer run under overloading conditions may cause a break in such defective conducting strips. The current interruption in a broken strip result in a higher current density in healthy conducting strips. It also results in partial discharge (PD) between an embedded conductor's minute gap and between the conductor and the slot. Both the ends of a broken coil are at higher potential. This sudden discharge may eventually melt the healthy strips, thermal failure of coil insulation, which results in the coil getting earthed through the grounded core, resulting in the L-G fault. A break in the continuity of any strip due to unforeseen reasons will cause the coil’s parameters to change, resulting in a slight dip in the voltage and vibration-related issues due to magnetic unbalance. The winding faults often remain undetectable when a fault is close to the neutral ground.

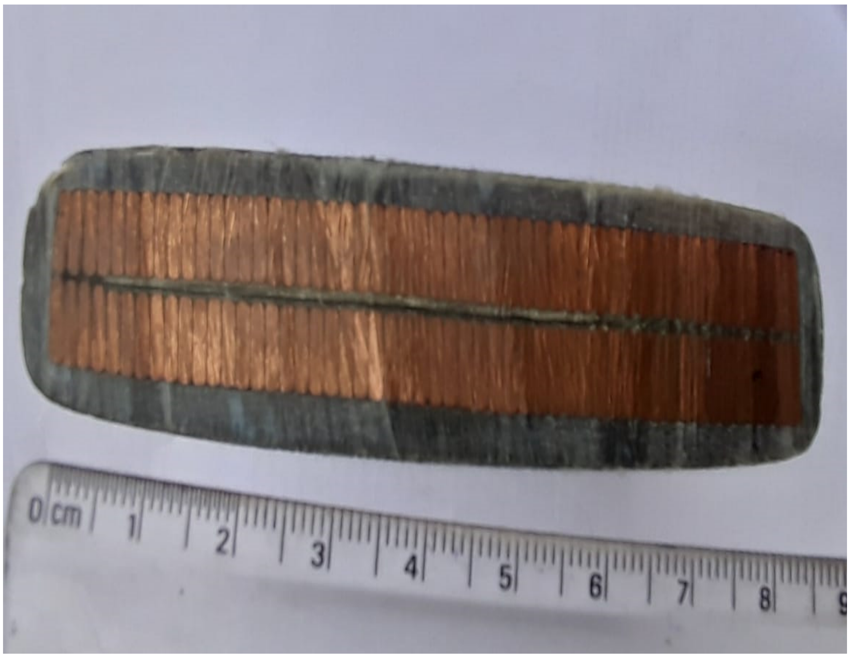


Fig. 5. Cross Section of the coil of a typical High Voltage 150 MW alternator winding.

Fig. 6. A damaged coil showing burnt strip conductors in a typical high voltage alternator (Courtesy: Proclaim).

The rating of an alternator is 187.5 MVA, 150 MW, 15.75 kV, 3000RPM. Each phase had two parallel paths, and one of the R phase windings was found to be earthed 45% from neutral when it was providing 145.50 MW to the grid at 15.78 kV, 5,642.71 A, 49.62 Hz.

Due to unforeseen reasons, such pre matured faults cannot be detected in advance unless real-time chemical fume detection of outlet air technique is available for lower capacity alternators. According to IEEE SG protection rules [20], thermal protection for the SG stator core and windings may be given for (a) Generator overloading, (b) Leading Power factor operation, (c) Faulty cooling system, and (d) Localized hot spots caused by core lamination insulation failure or by localized or rapidly developing winding failures. In the present case, both the core burning and LG fault were present. There is no scheme to detect hot spot creation in 150MW alternators. It is also difficult to pinpoint which fault supported the other fault.

3.3. Dislocation of winding- slot wedge & Winding overhang

The process of L-G faults' occurrence in an alternator has been described in section (3.2). Multiple L-G faults may be present in an alternator given a complex vibration phenomenon within the turbine–alternator structure. The preformed/casted HV coils demand an open slot configuration for the alternator's higher capacity high voltage stator. Each slot opening is provided with a suitable wedge. These open slots in the stator and the alternator's rotor permit housing of larger and heavy preformed-casted coils having parallel strip conductors with insulation. Slot wedges prevent the tightly fitted coils in the slots from coming out due to electrodynamic, vibration, and thermo-mechanical forces.

The rotor overhang and stator overhang portions of windings, through properly reinforced, have their multiple natural frequencies of oscillations. Vibrations in the turbine-alternator set are required to be appropriately monitored. The vibration signature varies due to different normal operating conditions, switching, changes in load, and several initial abnormal conditions that may lead to major breakdown conditions if not checked. The overhang portion of an alternator requires special reinforcement against several dynamic forces of different origins, as described earlier. The overhang portion may be subjected to mechanical resonance, which is enough to destroy the reinforcement, wedges, and slot tightening provisions. Sustained vibrations over a longer operating time may result in the loosening of specific coils from the slot. Such coils may have axial movement of coil sides in a slot of a fraction of a millimeter. Due to this, the Class-F insulations that wrap the coils come out in white dust, particularly at the edges of the slots. These are detected when the alternator undergoes necessary repair and maintenance.

Such loosening of coil sides due to the macroscopic movement of coil sides remains undetected. However, with the present technological development, it is possible to visually inspect coils when the alternator is still operating. Thinning of the insulation layer causes the conductor at the slot edge to have insulation breakdown resulting in an L-G fault. The location of the L-G fault is of utmost importance. In an alternator, multiple L-G faults can be present, causing a complex winding fault that ultimately results in a complete breakdown. Depending on the position of the L-G fault in any phase winding, insulation damage due to the L-G fault may escalate into an entire L-L-L-G fault over the period of time. Under severe transients and fault conditions, the loosening of heavy stator windings in their slots was accompanied by significant gravitational and electromagnetic pressures (electrodynamic-force and thermo-mechanical stresses) in the radial downward direction. The significantly displaced windings can occasionally damage the restraining slot wedge and reinforcing bands. Under dynamic situations, this may produce a severe dislocation of the stator winding coils in the upper half in horizontal shaft machines, which may come in contact with the rotating structure in overhang regions. A typical deformation due to dislocation of the stator winding of a 15 MW, 11kV, 50 Hz, 1500 RPM, 4-pole Steam Turbo stand-alone generator supplying arc furnace has been shown in Fig. 7. A portion of the stator winding came in direct contact with the rotor overhang, thereby puncturing glass insulation on the overhang portion of the rotor, as shown in Fig. 8.

Fig. 7. Deformation of 15 MW, alternator due to dislocation.

Fig. 8. Puncturing of glass insulation covering the overhang portion of the rotor due to dislocation of stator winding causing direct contact with the rotor.

It shows the dislocation of the windings and insulation rupture in the overhang region of the rotor. It may be due to excessive vibration, non-operation of the field failure relay, leading to the induction generator operation, or ruling power factor operation, ultimately breaking the restraining band that holds the overhang portion firmly. Such a type of fault is difficult to predict unless visual inspections of the alternator's rotating and stationary coil structures are recorded online, and corrective measures are taken in advance. Such instrumentation requires inexpensive digital cameras and online recording of crucial moving and static structures.

3.4. Nose joint failure

Nose joints connect the end terminals of phase windings to the bus bars connecting it to the panel. The end windings typically consist of several strip conductors which are insulated from each other, but at the end, these are short-circuited and fused with the connecting conductor to the bus bars. It is achieved by applying certain chemical compounds, which help forge the end winding terminals with the bus bars uniformly. Any flaw during the manufacturing process, formation of an air pocket or void inside the copper material increases the current density in the vicinity of the void/air pocket, causing hot spots. Over long runs, the metallurgical composition inside the copper material gets altered. Along with this and other environmental stresses such as vibrations, electrical heating due to overloading may dislodge the bus bar connecting the cable terminals with multiple ends winding conductors, causing insulation damage and disconnection of that phase.

Fig. 9. Nose Joint Failure.

In an alternator with multiple parallel paths, the requirement of connecting multiple thick conductors, each having several strip conductors, to a common conductor is a more stringent manufacturing process. Fig. 9 shows a typical dislodging of the nose joint in a high voltage alternator.

4. Conclusion

Core burning causes insulation failure and destruction of the core requiring costly repair. Such faults in an alternator of smaller capacity cannot be determined in advance unless a suitable scheme is available. Chemical fume detection for sensitive elements responsible for core burning in the outlet air from vents should be developed for smaller capacity alternators. The dislocation of windings and the nose joint failure can be detected in advance if the visual recording is mounted inside the enclosure to monitor rotating and sensitive parts. Akin to these power machines, similar faults may occur in high voltage rating energy machines operating in stressful conditions such as compulsators and electromagnetic aircraft launchers.

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