Asphalt Stator Winding Insulation

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Abstract – **Asphalt stator bar insulation was first used in about 1915 and quickly became universal in the industry for large generators until about 1950. Numerous tape migration ("girth crack") problems occurred beginning in about 1950 on large units, <40 MW. The problems were so great that the industry generally abandoned asphalt in favor of thermoset resins, e.g., Thermalastic, Micapal, Micadur. But asphalt was not entirely abandoned; its use was continued on smaller coil windings until the early 1990s by at least one major OEM, General Electric.**

Most of the large, high speed generator with asphalt windings have either been retired or rewound with thermoset insulation, although there are perhaps 100 with their original winding still in reliable service. There are large numbers of low-speed, hydro generators in service with asphalt windings. There are also 1000s of the smaller high-speed generators still in service, and because they were designed to considerably higher duties, they have also experience the migration problem.

This paper will briefly discuss stator winding design evolution but will focus on the exceptionally complex and generally poorly understood design/manufacturing parameters that result in insulation migration. The paper will also provide recommended operation and maintenance guidelines to maximize on-going winding reliability and to minimize unnecessary maintenance.

I. GENERAL

Before the turn into the 20th century, insulating materials were natural products: shellac, cotton, paper. The rudimentary designs were at low voltage and low temperatures, and apparently functioned fairly well as long as duties were kept sufficiently low. With inevitable trends toward higher voltages and higher thermal and mechanical duties, much better materials were required. Late in the 19th century, mica flake was discovered to have remarkable electrical and thermal properties. But still with shellac, cotton and other relatively primitive materials incorporated in the systems, troubles continued.

By the mid-teen years, 1915, it was discovered that by using a vacuum-pressure cycle, mica/cotton tapes could be impregnated with a hot asphalt compound to obtain a major electrical duty improvement. The asphalt insulation systems provided excellent performance. It was rugged, forgiving, not prone to mechanical vibration. Some early winding installed in hydro generators are still in service after 100 years of service.

But asphalt had recognized duty limitations and thus designs were conservative: low electrical stress (45 volts/mil vs. 65-90 vpm on modern systems), low operating temperature (while commonly rated Class 130, reliable operation required designing at below Class 105 temperature), and low magnetic vibrational forces (in the range of 3 or 4 pounds/inch in the slot vs. up to 110 #/in. in modern windings).

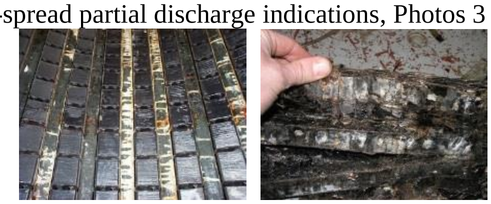
Still as MW rating evolved upward problems began to occur, e.g., puffing Photo 1

Photo 1

asphalt bleeding, Photo 2,

Photo2

wide-spread partial discharge indications, Photos 3 and 4,



Photos 3 and 4

vulnerable to CO_2 ("dry ice") cleaning damage, Photo 5,

Photo 5

and most damaging – tape migration, Photo 6,

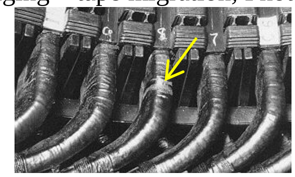


Photo 6.

The latter, tape migration, was very troublesome and was extremely difficult to understand. It was also difficult (almost impossible) to accurately reproduce under laboratory conditions. As a result tape migration was not well understood in the industry. As will be discussed below, GE termed the phenomenon a mis-leading "girth cracks"; Westinghouse engineers understood the phenomenon much better and termed the phenomenon more accurately, "tape separation". [1]

Description of Phenomenon

Probably the reason the tape migration phenomenon was never well understood is because it was subtly dependent on many variables (more or less in descending order of importance):

1. Load cycling (required in order to have differential expansion between copper and core).
2. Core length (thus the amount of differential expansion).
3. Cooling gas temperature (directly affects asphalt hardness).
4. Bar copper temperature (directly affects differential expansion and resulted in separations greater on top bars which operated hotter than bottom bar).
5. Selected asphalt softening point (directly affects asphalt viscosity).
6. Load power factor (higher power factor gives hot iron at core ends, causing tape separations to concentrate at ends of core).
7. Tightness of the bar in the slot (tighter fit for unknown reasons correlated with increased tendency to migrate).
8. Direction of tape application. (On GE bars, tape separations were greater on top bars collector end, and bottom bars turbine end). Taping direction was *presumed* to be the explanation.

The asphalts used typically had a flow (liquid) temperature around 100C. The copper temperature at load was designed to be around 90C. Thus at load operating temperatures the asphalt was near a liquid and gave no mechanical stability to the groundwall insulation. Load cycling would cycle the length of the bar, typically 1/4 to 3/8", depending on core length. For reasons not well understood, due to some of the 8 factors listed above, e. g., 4, 5, 7, and 8, there was a slight tendency for the groundwall insulation to follow copper length more closely during load reduction than load increase. In worst measured case the net migration of the *top layer of tape* was 11 mils/cycle, thus it is apparent that tape migration could be an aggressive deterioration mechanism.

But this migration only occurred in the slot portion of the bar, thus causing the tape separation to occur at the core end region, and giving the appearance of a crack, thus the mis-interpretation, Girth Crack.

But in the slot portion, the layer of tape directly against the copper would be expected to remain un-migrated, and if the spirally apart at the core ends did not occur at the same axial location of the bar on each layer of tape, then even though the top-layer migration was great, >1", the integrity of the groundwall may be only slightly impacted.

That this was true was proven on "badly deteriorated" windings that when hipot tested did not fail at new-unit hipot value, 2E + 1.

II. BRIEF HISTORICAL SUMMARY

Experience on Large Generators

Asphalt/mica systems served the industry well for 35 years, although by the late 1920s the tape migration phenomenon had surfaced. At General Electric, this occurred on 2 *very* long, very large 4-pole generators. The engineers mis-diagnosed the root cause of the condition as cracking of a "brittle" stator groundwall insulation, thus applied the term, "girth crack", still used 90 years later. They believed the problem was due to too hard a system and lowered the softening point of the asphalt used in the groundwall. This was exactly the wrong change, since the "cracks" were actually resulting from the groundwall migrating in the slot toward the axial centerline of the core.

In retrospect the better solution would have been a higher temperature softening point. But somewhere around 1935 for reasons not recorded, the GE engineers diluted the asphalt with about 1/3rd linseed oil. Linseed oil has the interesting property of becoming more viscous if held at elevated temperature, thus if a GE generator was not load cycled for 3 or 4 years after placing in service, the asphalt/linseed oil became more viscous (stable), and insulation migration tendencies were much reduced.

The net result of these 2 changes (lowering of asphalt flow point and adding linseed oil) was that these GE generators over about 40 MW had serious tape migration problems if load was cycled immediately on being placed in service, Photo 7. Otherwise, migration was minor or not at all. Of the ~400 large asphalt-insulated generators built by GE, about 1/3rd were rewound; the remainders are still in service without migration or have been retired.

Examples of tape separations are seen in Photo 6 above and 7 and 8 below.

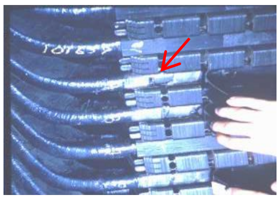


Photo 7. Huge 2-5/8" separation after 19 months operation, 11 mils/load cycle. Separation is inside the core due to high power factor load.

Westinghouse engineers better understood the tape migration phenomenon, but weren't sufficiently lucky to have added linseed oil. By the mid-1940s, most of their stator windings on their larger generators were experiencing fatal migration. On a crash basis they developed an entirely new groundwall insulation system – Thermalastic. This system used a polyester resin binder to replace the asphalt and was a remarkable accomplishment, particularly in view of the relatively primitive resins available at that time.

During the ensuing years, all OEMs developed resin-based groundwall systems: Micapal (a polyester-like epoxy), Micapal II (a true epoxy), Thermalastic-Epoxy (a true epoxy), Micadur (a true epoxy) . . .

Experience on Smaller-size GE Generators

While on large generators use of asphalt windings was discontinued by 1950 by Westinghouse and 1960 by GE, asphalt was used on 2-turn coil windings until 1990 by GE. These generators generally were rated less than 25 MW. The asphalt used was the blend of asphalt and linseed oil used by GE from the mid-1930s. To address the migration issue, the designers added a 3" wide strip of glass clothe at each core end to give resistance to migration of the tape. But the designers also went to somewhat higher copper operating temperatures. The windings apparently have given good operating performance.

A known exception. The writer was involved 10 years ago in a law suit where a 30-year-old asphalt coil winding had failed during Doble test, line-to-neutral voltage. Laboratory evaluation of several half-coils from this winding was conducted. Failures occurred at low hipot test values. The groundwall insulation was delaminated and shattered, Photo 4. Measurements of the groundwall on the bar that had failed site Doble test revealed necking of insulation from insulation migration exceeding 40%, Photo 8.

Photo 8. Necking from tape migration.

While definitive information on this fleet of high-speed asphalt windings and on low-speed asphalt windings is limited, the available design and performance information suggests reasons for concern.

III. RECOMMENDATIONS

Because of the intrinsic nature of asphalt windings to the specific deterioration mechanisms discussed at the beginning of this paper, certain fundamental operating and maintenance recommendations seem appropriate, and are summarized below.

Operation and Maintenance

Since higher temperatures adversely affect insulation stability, avoid as far as practical operating at overload conditions or elevated cold gas temperatures.

Do not rewedge the winding as slot tightness correlates with tendency for the insulation to migrate. Also, bar vibration cannot occur for two reasons: a) the vibrational driving forces are very low, and b) because the groundwall is soft, bouncing from the downward mechanical driving forces cannot occur.

Inspection

In general, do not be overly concerned if some bar puffing and some asphalt flow throughout the winding is observed. These windings tend to be old and some puffing is inevitable due to the nature of the groundwall. Unless the asphalt flow is high, the groundwall integrity should not be significantly impacted.

However, if individual bars stand out as highly puffed and high asphalt flow, shorted strands may be suspected and winding quality may be suspect.

Vertical shaft hydro units have the special considerations relating to the possibilities of the winding moving down through the core.

Test

Groundwall and copper resistance values should be measured at every convenient opportunity. The groundwall resistance will be primarily affected by moisture and/or contamination. If groundwall resistance is low, drying and cleaning may correct the condition. But special care in cleaning should be taken. Solvents can attack the asphalt, and CO_2 cleaning can easily damage the groundwall. Photo 5.

High copper resistance may suggest failing connections. Low resistance is unlikely since the main cause would tend to be shorted turns, and a coil with shorted turn should have already failed in service catastrophically.

None of the common low voltage tests are likely to give useful maintenance information, e.g. powerfactor, tipup.

By far the most definitive test for groundwall condition would be hipot, even at a test value as low as 1.1E. But of course there is the possibility of failure and this is likely to force a rewind. Individual bars can normally be replaced on 4-pole and hydro generators as end-arms are short.

On 2-pole units the long arm and compliant insulation allowed wide deviation from design location. Also there is the intrinsic removal/installation interference issue. GE had a system, termed "Conforming Micapal", for individual bar replacement, though it is doubtful this system is still available.

With a hydro machine the failed coil and corresponding coils in each phase belt can be isolated and service continued.

A paper suggesting a method of ac over-potential testing to assure a reliable service life of steam turbine was published in 1970 [2]. The basic premise is that high voltage insulation systems deteriorate more or less linearly with time. This idea was successfully applied to allow postponing or eliminating stator rewind on many generators. [3]

IV. CONCLUSIONS

There are many 1000s of asphalt stator windings still in service. A few would be the large GE 2-pole units. The behavior of these units is fairly well understood, and if still operating after 65 years of reliable serve, those windings are unlikely ever to need replacement.

Of the 1000s of "newer" GE coil windings in service, little is recorded as to their operating, maintenance history. But the Recommendations above should be applicable to maximizing their ongoing reliability.

And there are many hydro generators with asphalt winding still in service. So far as the author is aware, there is no available recorded history of the performance of these units, but again, the Recommendations above should be applicable to maximizing their ongoing reliability.

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