CORONA PROBE MEASUREMENTS TAKEN ON HYDRO MACHINES AT GRAND COULEE DAM

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At the April 1970 Doble Conference, a paper entitled "A Peak-Pulse Ammeter-Voltmeter Suitable for Ionization (Corona) Measurement in Electrical Equipment" by Mr. L. E. Smith of Tennessee Valley Authority was presented. This paper discussed many aspects of the meter and pointed out some of its uses in detecting corona. Considerable discussion relating to this method of measuring internal discharges of corona in multi-turn hydro-stator windings was held with representatives of other utilities present at the Doble Conference.

A visit to Tennessee Valley Authority's headquarters in Chattanooga had previously been planned, and I proceeded there after the conclusion of the Doble Conference. At Chattanooga I was fortunate in witnessing the corona testing of one of TVA's units at their Chickamauga Powerplant. The test on this unit was part of an overall plan to locate coils in their machines that may fail in service. It is my understanding that TVA disconnects any coil that fails and returns the unit to service. This is possible because the majority of their units have many coils per phase (as many as 45), so the absence of one or two coils from a given phase string is not very detrimental to the output of the unit.

At Coulee Dam we have 18 main generators, each rated originally at 108,000 kVA. We are presently undergoing a program of replacing the stator windings of these units with upgraded windings rated at 125,000 kVA each. Phase structure in the Coulee units consists of split windings (two paths per phase), each phase having 12 strings of 11 coils per string. We have experienced one coil failure on a new rewind, and consulted with the manufacturer before repair. It was necessary to operate the unit for an extended period of time before we could schedule an outage for rotor removal. The Westinghouse factory representatives calculated that less reduction in output would be possible by cutting out the entire string of 11 coils that contained this one bad coil. This was one of the considerations in our search for a method to determine the condition of the total winding rather than attempting to locate any individual coils that may be bad.

TVA loaned us one of their peak-pulse meters and a corona probe for our use. We constructed a meter similar to theirs, and compared the response of our meter to theirs for calibration. We kept TVA's meter and probe approximately six weeks, and made corona probe tests using both meters on the stators. After we had assured ourselves that our meter was identical to theirs in response and performance, we returned their equipment to them. Since that time, we have developed a second model of the meter and added a feature to this second model which disconnects the power supply when changing scales or moving the probe from one coil to another. This feature eliminated the inherent delay while the meter settled out, and we are able to speed up the metering process a great deal. We are still using the basic meter design that TVA has developed, however, our meter is packaged slightly differently than TVA's. With our second meter, we have developed several different types of probes, including one "half-toroid" coil that we have experimented with. We were not satisfied with the response, nor the readings we obtained from the probe, and elected not to continue to use it. The frequency response is slightly different for the half-toroid probe, and the readings are slightly lower as a result of this. A set of curves is included in this report showing the results of this comparison made on unit G-18.

Corona probe tests have been performed on many of the older windings that are constructed of mica-asphalt insulation, and we have tested four new windings of the epoxy-mica-resin type material. Three of the four tested have Westinghouse "Thermolastic" insulation. The "Thermolastic" type insulated windings yield much lower corona readings than is measured in mica-asphalt windings, which would indicate that "hard" coils have very few voids. However, the "Thermolastic" windings have only been in service a short time, and the corona damage is minor in them compared with the 20 to 30 year old machines.

Initially, testing was performed at 6-kV, but several voltages below 8-kV have been tried on machines that were to be put back in service. We are presently using 7.5kV on machines that will remain in service, but have tested as high as 10-kV on windings that were in the process of replacement. Testing up to 10-kV has been performed on two separate mica-asphalt windings with 26-28 years of service behind them. After extensive corona probe tests were completed, we attempted to destruct each coil with an induced impulse test. We were unable to destruct any of these coils with an impulse test, even though we went to the limit of our impulse tester. This resulted in inducing approximately 3500 volts peak turn-to-turn across each coil. In other words, we were inducing an impulse of about 18-kV across the 5-turn coil. After the induced impulse tests were completed, coil groups were disconnected from the parallel rings and an attempt was made to dc hipot them to destruction. When 60 to 65kV was reached, the coils began flashing over at the sawed off ends where the coil groups were connected into the parallel rings and we had to abandon that test. The dc tests indicated that the ground-wall appeared good and the turn-to-turn insulation appeared good from the impulse tests that we had tried. The corona probe curve indicated the coils at each end of the string would show a high presence of corona damage. Corona damage was found at both ends of the string, when the coils were removed from the stator. These machines had their main lead connections reversed for several years.

During the removal of these stators, each coil was stripped down, one coil at a time. We observed each coil and recorded the actual corona damage in each coil that was visible during the removal of the old coils. Our procedure for removing coils from the slot was such that the copper began stripping out at the top of each slot in a manner such that the sidewall and a major portion of the ground-wall insulation remained in the slot until the coil was stripped out near the bottom of the stator iron. This method provided a good opportunity to observe the corona damage for nearly the full length of the coil. In cases where the coil was not tightly wedged in the slot and came out intact, we cut open the top two feet of the coil and examined it for any evidence of corona damage in this area of the front half of the coil. We did this only in the front half coil because all except one of our in-service failures have been in the front half of the coil, and all have occurred in the top two feet of the stator iron.

In our initial program we tested coils by probing them at the top of the iron in a manner similar to TVA's method. Our probe was basically the same as TVA's except it was fabricated slightly differently, photograph No. 1 shows our meter and probes. We had to fabricate our probe at a slight angle to reach underneath the top bracket on our machines. It was noticed that at times it was not possible to repeat some of the coil readings. It was thought perhaps this was due to the influence of corona discharge in the end-turns upon the ferrite rod when it was held next to the end-turns at the top of the iron. We then fabricated two probes that would permit us to reach into the air gap. We experimented by probing three or four inches into the air gap between the rotor and the stator and pressing the probe against the wedge in front of each individual coil. This gave us a slightly lower reading but the readings were more repeatable than those taken on top of the iron. This procedure was adopted and we are continuing to use it.

The conclusion was reached that more representative readings are obtained by energizing the winding a single phase at a time rather than energizing all three phases simultaneously. By energizing a single phase at a time, and only probing those coils that were energized, the result is more representative of what the corona reading should be. We believe that when you have two different phases energized in the same slot, one coil might be masked by the influence of the corona discharges in the coil that is in the other half of that slot. We then elected to make single phase tests also, but continued to make a three-phase test on some units. We have since then abandoned a three-phase test and are now making only single-phase tests.

After considerable thought and study, we decided to compute the average value of corona discharge for each coil position throughout the winding, and plot this result to see what curve would be obtained. By this procedure, an average for each coil position is obtained by using the values for all three phases and plotting this average out on a curve. The first two times we did this we came up with a curve that was similar to a standing wave. Then we tested the only machine that has NOT had its main leads reversed, and this machine did not yield a standing wave characteristic. Generator No. 18 had NOT had its winding reversed when we tested it and still remains in that condition. The characteristic curve of the averaged values of the corona test on this winding showed that the values obtained from coils near the neutral end were very nearly as high as those in the center. This characteristic is shown on the curve for unit G-18 attached to this paper. The corona measurements taken on the coils at the high voltage end (the line end) of the string yielded the lowest values. This result reaffirmed the belief that corona damage creates ionization that results in tracking, which reduces the readings obtained by corona probe measurement.

We tested solid dielectric "Thermolastic" windings, and found their curves to be quite flat with a very low value of corona probe readings. This characteristic is prevalent for all "hard" windings that we have at Coulee Dam. It would thus appear that a winding, whether it be "Thermolastic" or mica-asphalt, has a characteristic curve that probably is somewhat flat when new. As the winding is aged and deteriorated by corona, the values when measured at the high end of the string, are lower than those at the center of the string. At the center of the string, the coils have not been stressed by high voltage (perhaps only 4-kV). At the neutral end, there would be no stress placed on the insulation and result in no corona damage. During tests made at 4-kV in the laboratory on test coils, we could not detect any corona with our probe and meter. We found that corona was not initiated until about 4 1/4 to 5-kV. At 6-kV it was about half what it was at 7 1/2-kV and at 9-kV it was not much greater than it was at 8-kV. This fact was borne out by the evidence shown on the removal of the coils from the two stators we replaced during the past year. The actual evidence of corona damage existed at the line and coils for the top three or four coils and at the neutral end coils for about the bottom three or four coils. Both these machines had their windings reversed several years ago. In other words, the present neutral end showed a low reading and yet the coils showed actual corona damage because the present neutral end had been subjected to line voltage prior to lead reversal. The machine that had NOT been reversed did not show a low corona reading at the neutral end and we believe would NOT show any corona damage in the neutral end coils.

One result of our testing during the past year has been to arrive at some basic ideas that may lead to some future conclusions. Some of these ideas can be listed here for open discussion, and may be added to or improved on by some-one else in the testing field.

1. We believe that each multi-turn stator winding has a characteristic curve that can be obtained by corona probe methods. This curve has characteristics depending upon a number of things such as how tight the winding is, what type of winding it is, and whether it was wound tight or loose at the factory. If it is an epoxy-mica type winding, it should be relatively free of voids and result in less ultimate corona damage. We also believe that this curve tends to be somewhat flat when the winding is new. Under normal aging and drying conditions in the case of an asphalt winding, the curve would increase in value. In other words, it would yield a higher corona reading later in its life due to normal drying and migration of the asphalt. As the line end coils are stressed with a voltage sufficient to initiate corona, we believe that ionization or tracking occurs that tends to yield a lower value of corona measurement for those coils near the line end. If this winding is reversed at some point in its lifetime, the original neutral end coils are now connected to the high voltage of the line end. They will be subjected to voltage stresses and ionization and as damage occurs, in time, will yield a lower value of corona probe measurement than when they were connected to the neutral. With both ends of the winding damaged by corona, the result is a lower corona reading on these end coils. The coils near the middle of the string will continue to yield the highest averaged corona probe readings. This characteristic curve has displayed itself on all windings tested that have been in service at our plant for more than 15 years.

2. We believe there is an influence by corona in the top end turns of the winding which tends to mask the corona probe reading taken at the top of the iron. It is also believed that the corona probe measurement should be taken three or four inches into the air gap with the probe pickup against the wedge in front of each coil slot. This procedure will provide a more representative reading and a much more repeatable reading than taking it on top of the iron.

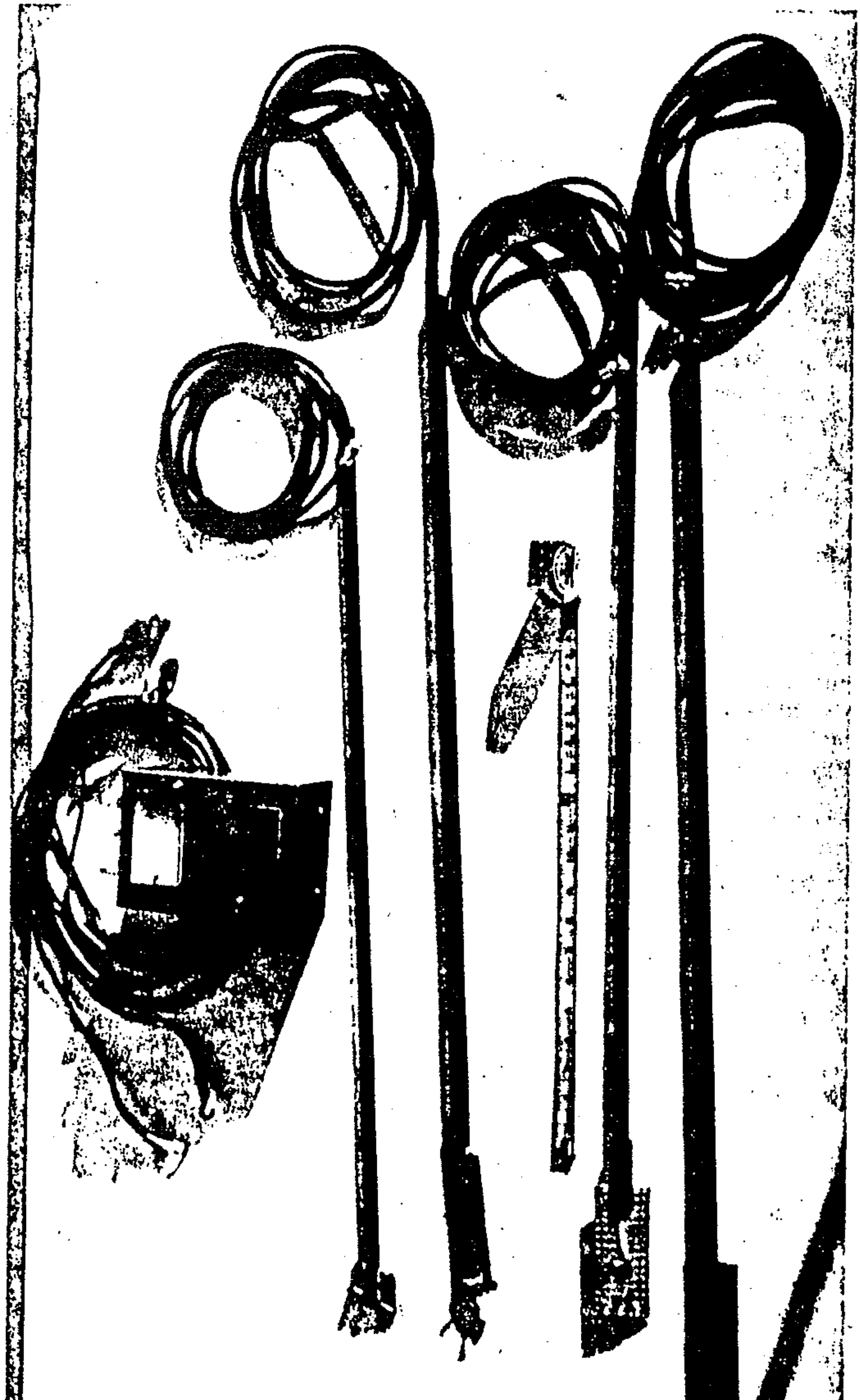
3. It has been our experience that energizing the winding in a three-phase manner has masked some of the readings. We have found that when different phases are in the same slot and energized simultaneously, the resultant corona probe measurement obtained when the probe is placed over that one slot is substantially different than would be obtained if the winding were energized one phase at a time. We have also discovered that the corona readings tend to settle out after approximately two hours of energization. Prior to that time, they yield a higher reading of corona but return to a lower more stable reading after about two hours. This is displayed by some of the curves with this report.

4. We believe that a loose coil, one that is susceptible to damage by corona, can be identified also by a high power factor and high power factor tip-up. We believe that this characteristic shows a coil that has a "looseness" or a poor bond between turns or between the turn insulation and the ground-wall tapes. It is this condition that allows corona to damage the insulation, and ultimately results in failure. In the cases that we have experienced at Coulee Dam, the corona appears to have damaged both the turn-to-turn insulation and the ground-wall prior to failure. This has resulted in turn-to-turn shorting which causes overheating in the coil and ultimately results in failure to ground and subsequent damage to the stator iron laminations. In all of our cases of in-service failures at Coulee Dam, failure has resulted in iron damage. We contend that this failure initially began as a turn-to-turn short.

5. We believe that this corona probe test should be developed into a test that can be used by maintenance engineers to determine the overall condition of the stator insulation systems of hydro-stator windings. It should be borne in mind, however, that one should also evaluate any Doble test data taken during initial installation to attempt to identify any coils that showed high power factor or high power factor tip-up characteristics. If dc absorption tests are performed, and these curves are available for analysis, they should be included in the process of determining when a unit should be rewound.

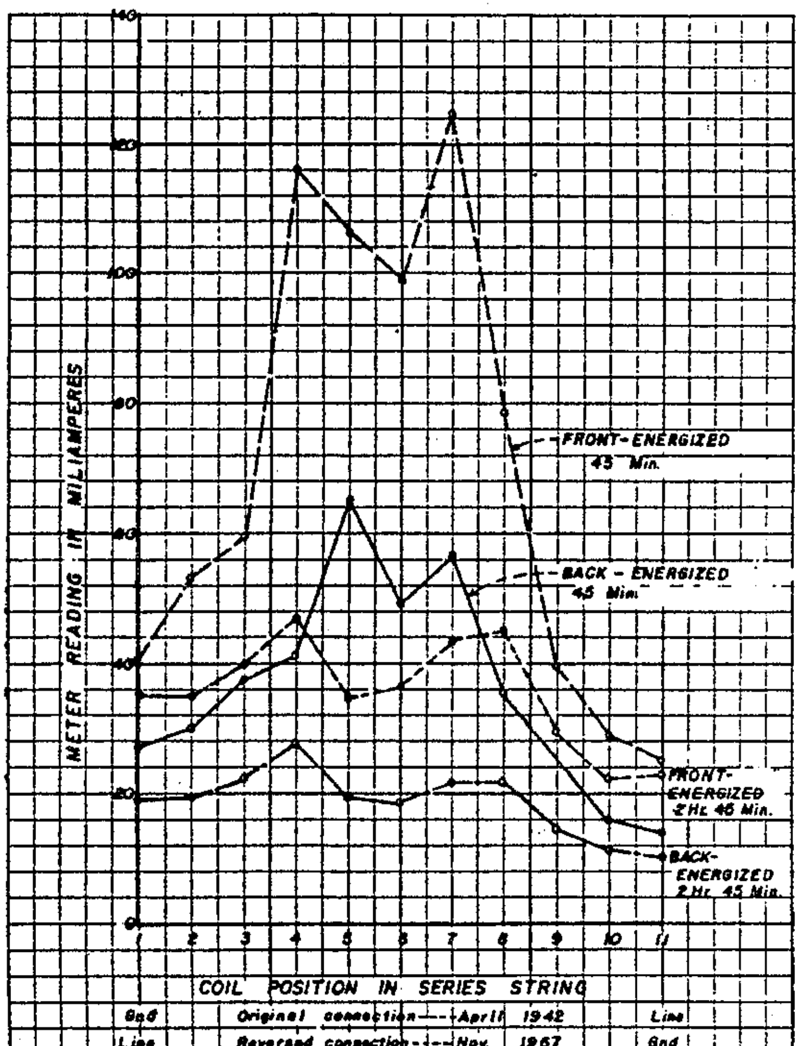
6. It has been found during our tests, and during the removal of coils, that corona damage is substantially more prevalent and more concentrated in the area of the machine that was used as the "throw" during installation. This evidence tends to point out that the coils that were moved or flexed during the original installation of the winding have resulted in loosening the bond between ground-wall and turn insulation tapes, or between ground-wall tapes. This loosening has resulted in voids being developed and ultimately yields higher corona damage.

7. I believe that there are a number of unanswered questions regarding this testing work. It is hoped that the members here at the Doble Conference will look upon this paper as the beginning of something that will help us all in our search for an answer to some very complex questions. What is the condition of the insulation system of the stator? Is it better to replace the total winding when the first coil fails or is it better to repair the failed coils? Should you repair the machine to maintain it in service and extend its life for another five years? These questions and many more are in the minds of all of us as utility engineers. Comments on our testing program would be welcomed from any of you present. Perhaps we will all gain additional insights into this subject, and between us we can find answers to some of the questions that are still in our minds.



USBR, COULEE DAM
G-1 STATOR WINDING
Asphalt Bonded Mica Insulation

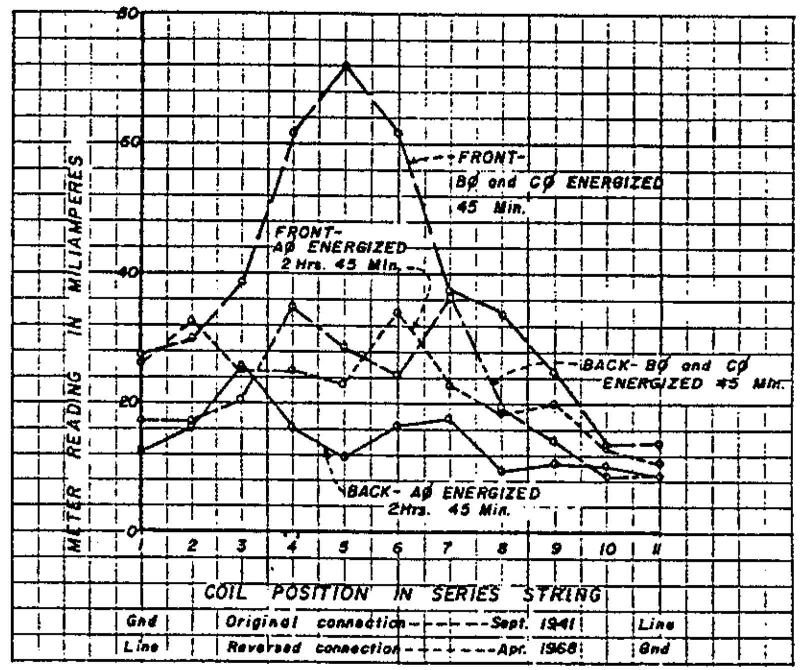
TESTED: JAN. 28-29, 1971 ______ CURVES PLOTTED BY: H.W.D.-H.D.T.
BY: H.W.D.-H.D.T. ______ CHECKED ON: FEB. 1, 1971 ___ BY: H.D.T.
STATOR RTD @ 19°C.
PEAK-PULSE CORONA TEST MADE AT 7.5KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE. THE PURPOSE OF AN INITIAL TEST AND A SECOND TEST AFTER THE WINDING WAS ENERGIZED FOR 2 HRS. WAS TO DETERMINE HOW THE CORONA READINGS VARY WITH TIME.



USBR, COULEE DAM
G-3 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 1-26-71 ______ CURVES PLOTTED BY: H.D.T.-H.W.D.
BY: H.D.T.-H.W.D. ______ CHECKED ON: 2-3-71 ______ BY: H.D.T.
STATOR RTD @ 21°C.

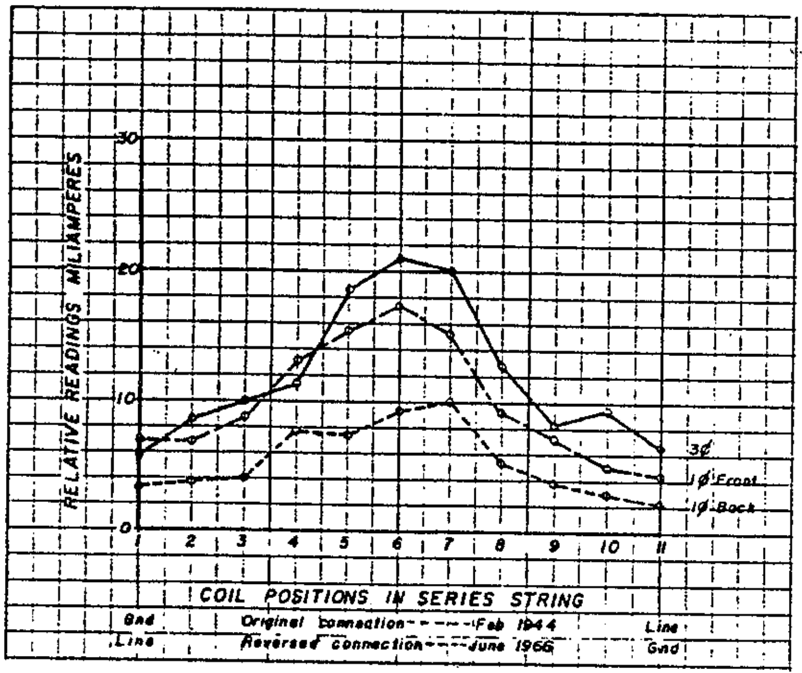
PEAK-PULSE CORONA TEST MADE AT 7.5 KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.
THE PURPOSE OF AN INITIAL TEST AND A SECOND TEST AFTER THE WINDING WAS ENERGIZED FOR 2 HRS. WAS TO DETERMINE HOW THE CORONA READINGS VARY WITH TIME.



USBR, COULEE DAM
G-4 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 7/14/70 – 7/15/70 CURVES PLOTTED BY: T.A.G. AND H.D.T.
BY: T.A.G. AND H.D.T. CHECKED ON: 7/21/70 BY: H.D.T.

PEAK-PULSE CORONA TEST MADE AT 6 KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.

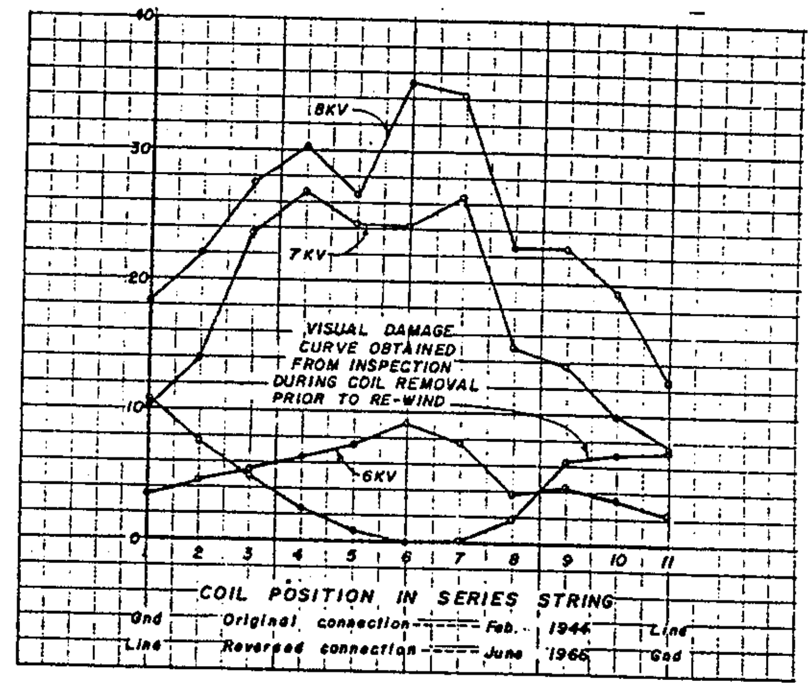


USBR, COULEE DAM
G-4 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 9-70 CURVES PLOTTED BY: H.D.T. - H.W.D.
BY: T.A.G. - H.D.T. - H.W.D. CHECKED ON: BY: H.D.T.

PEAK-PULSE CORONA TEST MADE AT 3 POINTS ON THE COIL, USING 5 MEGAHERTZ PROBE. ROTOR REMOVED.

The 6KV, 7KV and 8KV curves represent the "front leg" averaged values of three sets of readings taken at the following points: (1) 3" below the top of the iron; (2) The center of the iron; (3) 3" above the bottom of the iron.
The Visual Damage curve was obtained from inspection during coil removal. A "Damage Factor" was obtained by adding the following; (1) "Area" of corona damage on a scale of 0 to 10. (2) "Severity" of damage oi a scale of 0 to 3. The Corona Damage Factor figured for the curve below was Area + 5 times "severity."

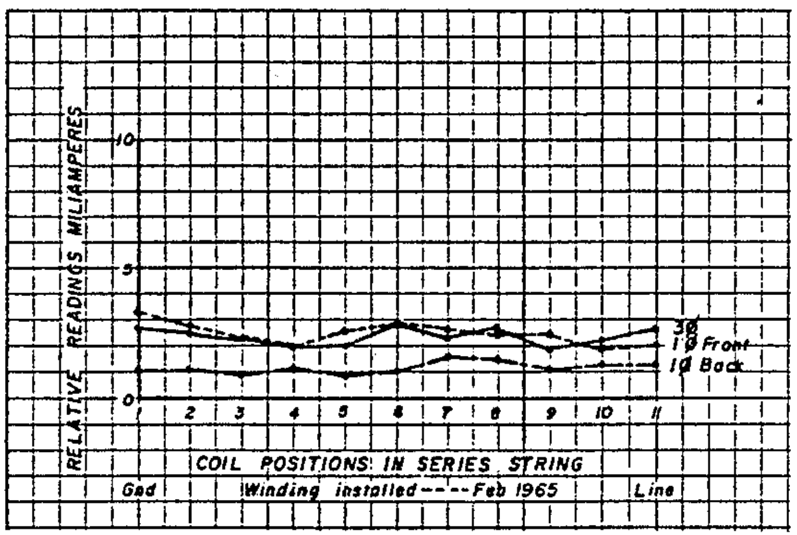


USBR, COULEE DAM
G-5 STATOR WINDING

Westinghouse Thermolastic Epoxy-Mica Insulation

TESTED: 7-8-70 CURVES PLOTTED BY: H.D.T. - H.W.D.
BY: T.A.G., H.D.T., H.W.D. CHECKED ON: 7-9-70 BY: H.D.T.
STATOR RTD @ 23°C.

PEAK-PULSE CORONA TEST MADE AT 6 KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.

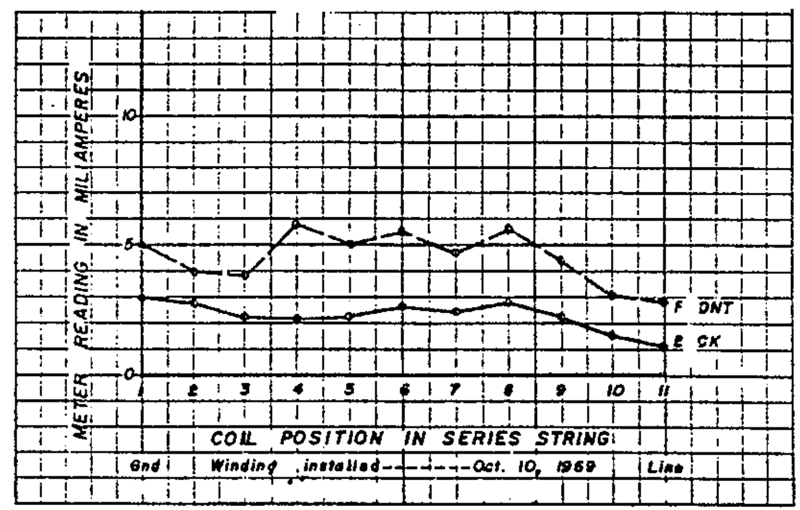


USBR, COULEE DAM
G-6 STATOR WINDING

Allis Chalmers Epoxy-Mica Insulation

TESTED: 12-30-70 CURVES PLOTTED BY: H.W.D.
BY: H.W.D., H.D.T., T.V.C. CHECKED ON: 1-13-71 BY: H.W.D.
STATOR RTD @ 21°C.

PEAK-PULSE CORONA TEST MADE AT 7.5 KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



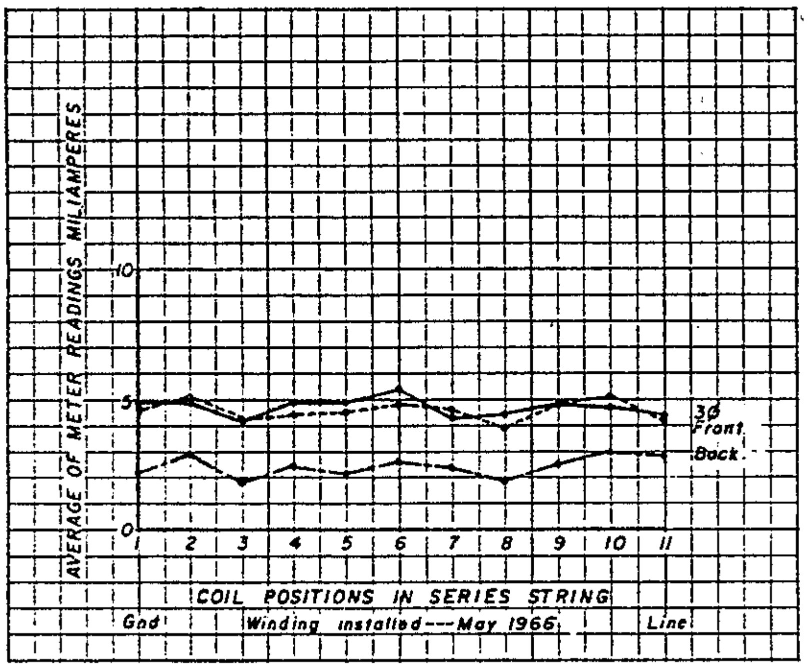
USBR, COULEE DAM

G-7 STATOR WINDING

Westinghouse Thermolastic Epoxy-Mica Insulation

TESTED: 6/25/70 CURVES PLOTTED BY: H.D.T. AND H.W.D.
BY: H.D.T., T.A.G., H.W.D. CHECKED ON: 7/9/70 BY: H.D.T.

PEAK-PULSE CORONA TEST MADE AT 6KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP.



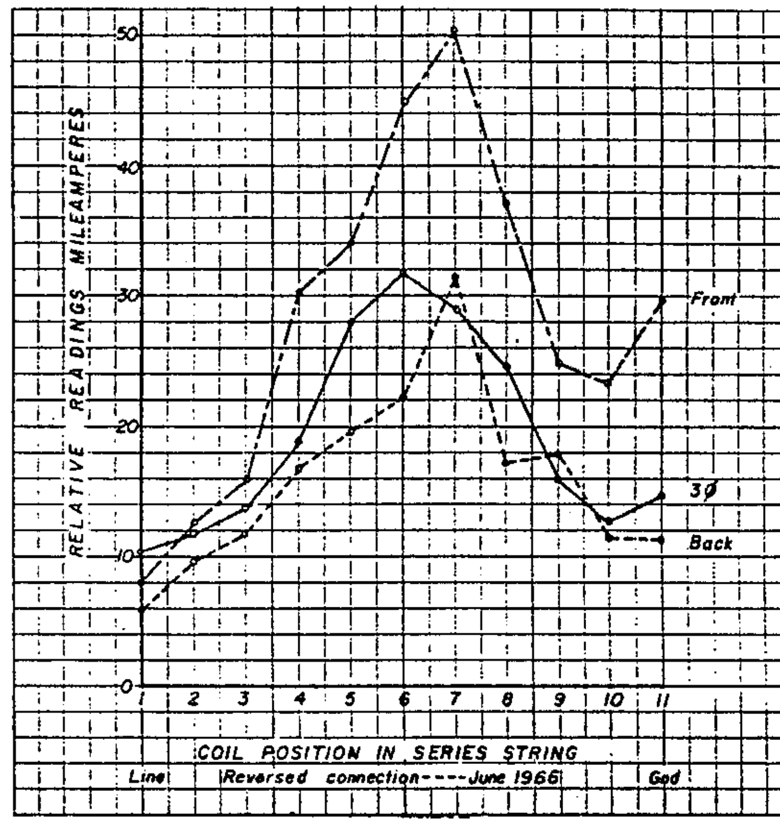
USBR, COULEE DAM

G-8 STATOR WINDING

Asphalt Bonded Mica Insulation

TESTED: 7/1/70 & 7/2/70 CURVES PLOTTED BY: H.D.T., H.W.D. & T.C.
BY: H.D.T., H.W.D. & T.C. CHECKED ON: 7/2/70 BY: H.D.T. & H.W.D.

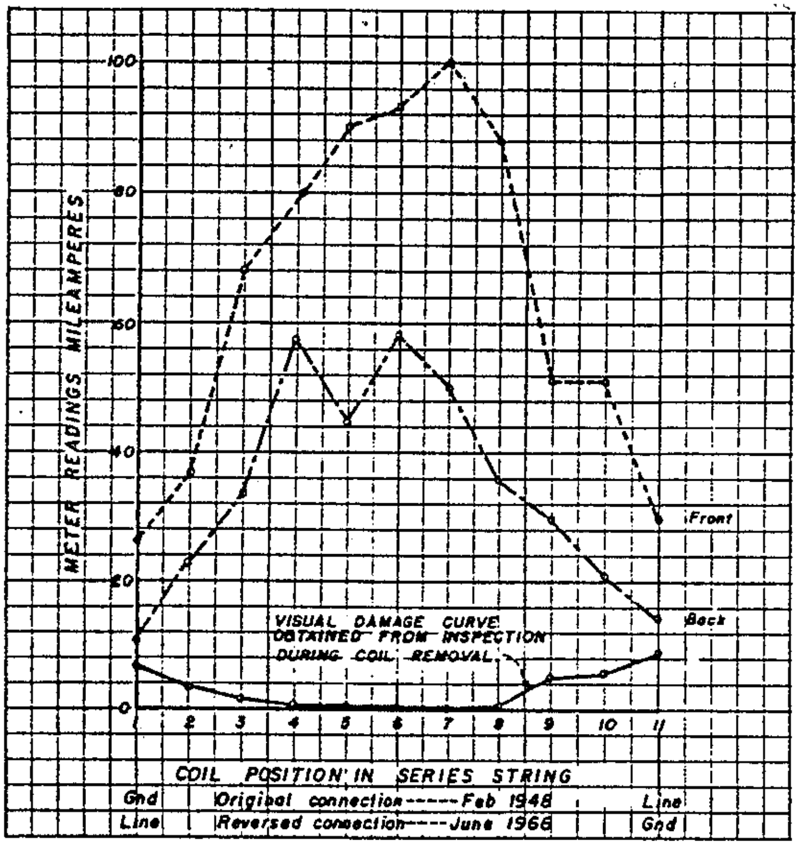
PEAK-PULSE CORONA TEST MADE AT 6KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP.



USBR, COULEE DAM
G-8 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 11/20/70 .... CURVES PLOTTED BY: H.W.D. AND T.C.
BY: H.W.D. AND T.C. .... CHECKED ON: 12/7/70 .... BY: H.D.T.

PEAK-PULSE CORONA TEST MADE AT 7.5 KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.

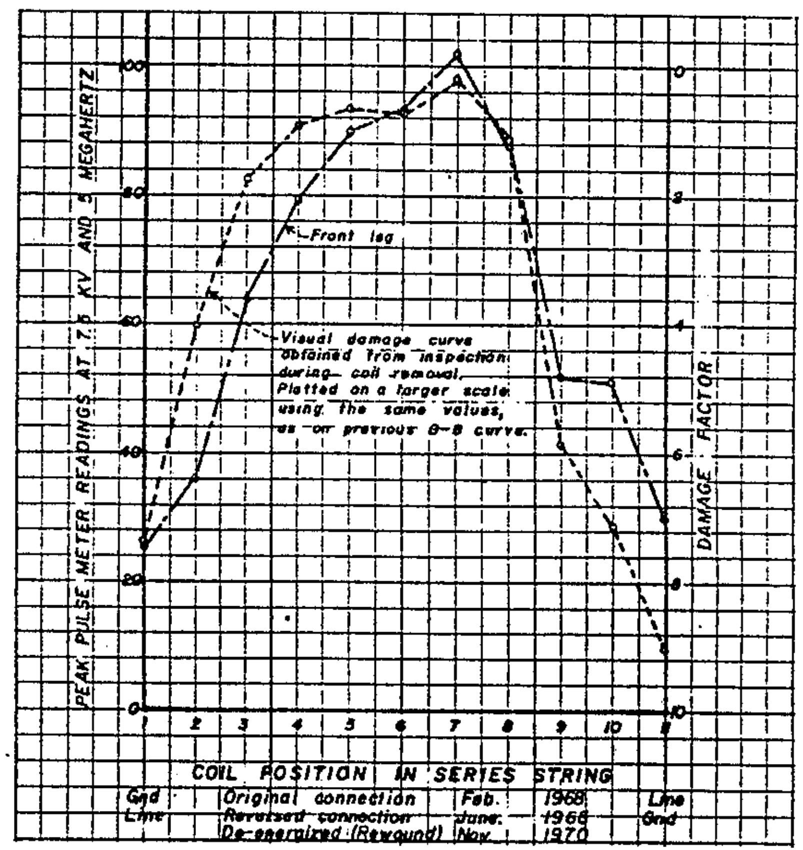


USBR, COULEE DAM
G-8 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 11/20/70 .... CURVES PLOTTED BY: H.W.D. AND T.C.
BY: H.W.D. AND T.C. .... CHECKED ON: 12/7/70 .... BY: H.D.T.

PEAK-PULSE CORONA TEST MADE AT 7.5 KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.

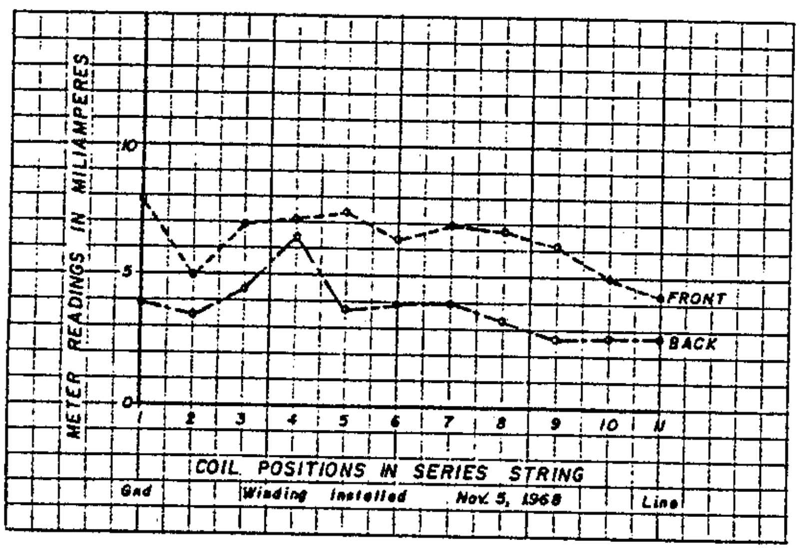
THIS CURVE SHOWS THE CLOSE SIMILARITY OF THE CORONA PROBE CURVE AND THE "CORONA DAMAGE" CURVE WITH ITS ORDINATE REVERSED.



USBR, COULEE DAM
G-9 STATOR WINDING
Westinghouse Thermolastic Epoxy-Mica Insulation

TESTED: 2-11-71 CURVES PLOTTED BY: H.D.T.-H.W.D.
BY: H.D.T., H.W.D., N.H.S. CHECKED ON: 2-17-71 BY: H.D.T.
STATOR RTD @ 21°C.

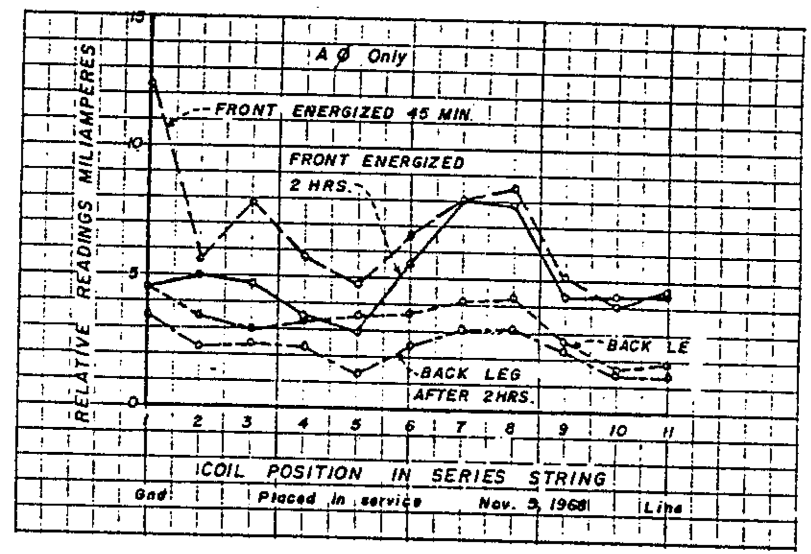
PEAK-PULSE CORONA TEST MADE AT 7.5KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



USBR, COULEE DAM
G-9 STATOR WINDING
Westinghouse Thermolastic Epoxy-Mica Insulation

TESTED: 2-11-71 CURVES PLOTTED BY: H.D.T.-HWD.
BY: H.D.T.-H.W.D.-N.H.S. CHECKED ON: 2-19-71 BY: H.D.T.
STATOR RTD @ 22°C.

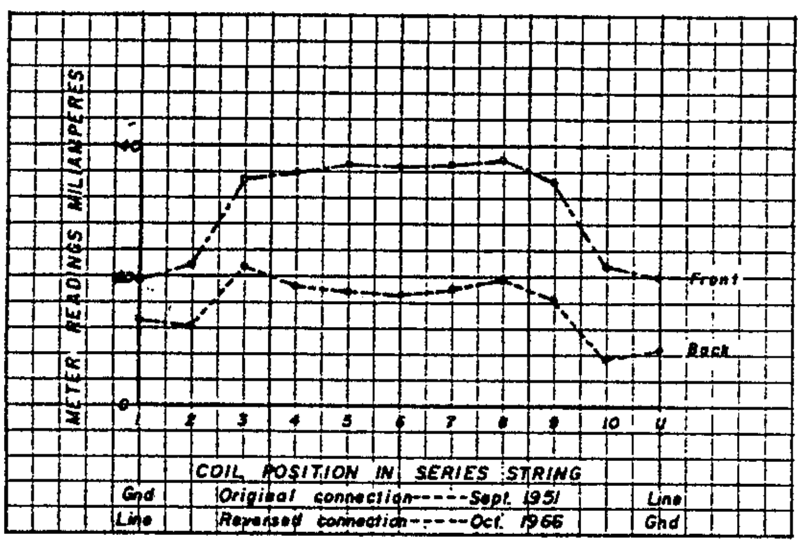
PEAK-PULSE CORONA TEST MADE AT 7.5KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



USBR, COULEE DAM
G-10 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 11/18/70 CURVES PLOTTED BY: H.D.T. AND H.W.D.
BY: H.D.T. AND H.W.D. CHECKED ON: BY: H.D.T.
STATOR RTD @ 25° C.

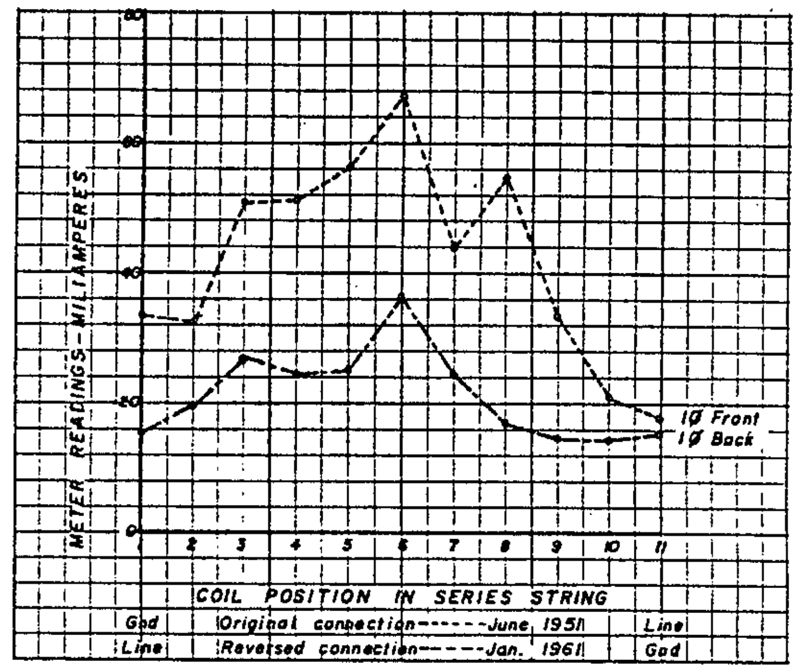
PEAK-PULSE CORONA TEST MADE AT 7.5 KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



USBR, COULEE DAM
G-11 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 11/30/70 CURVES PLOTTED BY: H.D.T. AND H.W.D.
BY: H.D.T. AND H.W.D. CHECKED ON: 12/7/70 BY: H.D.T.
STATOR RTD @ 25° C.

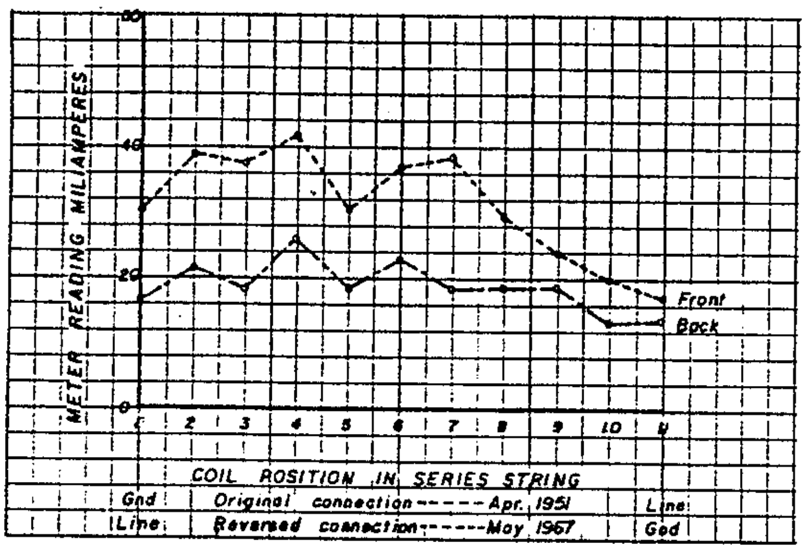
PEAK-PULSE CORONA TEST MADE AT 7.5 KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



USBR, COULEE DAM
G-12 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 12/3/70 CURVES PLOTTED BY: H.D.T. AND H.W.D.
BY: H.D.T. AND H.W.D. CHECKED ON: 12/7/70 BY: H.D.T.
STATOR RTD @ 20°

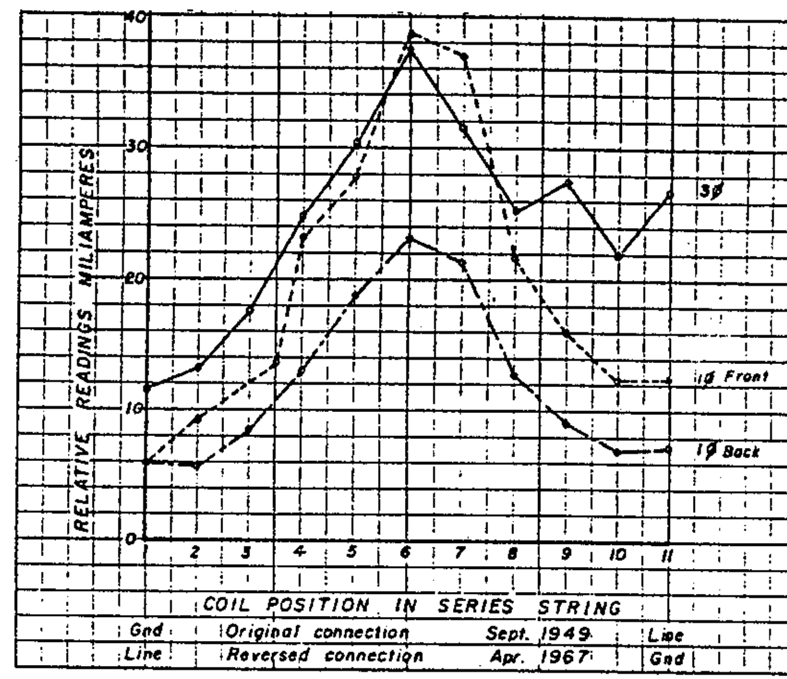
PEAK-PULSE CORONA TEST MADE AT 7.5KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



USBR, COULEE DAM
G-16 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 7/21/70 CURVES PLOTTED BY: H.D.T. AND H.W.D.
BY: H.D.T., H.W.D AND T.C. CHECKED ON: BY:
STATOR RTD @ 34° C.

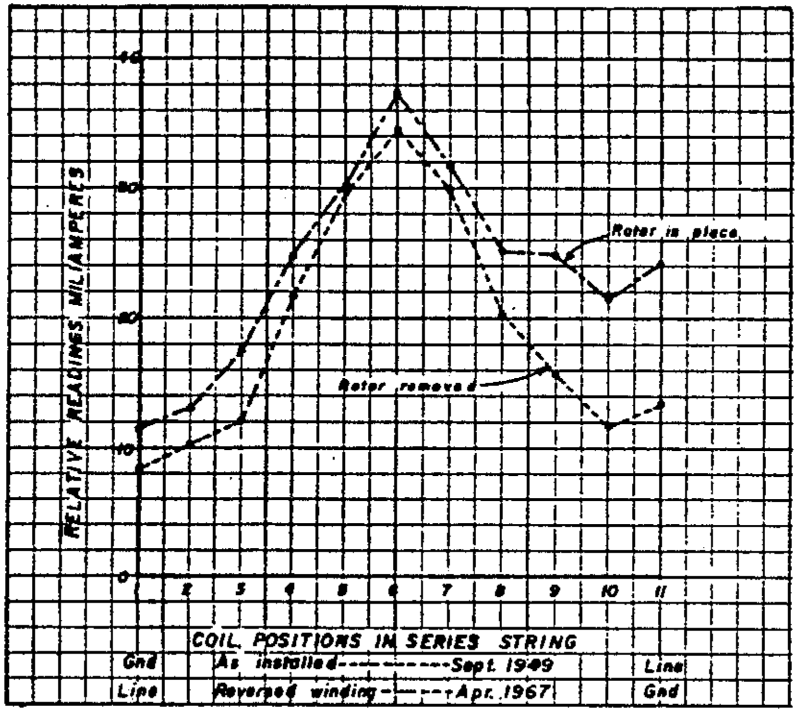
PEAK-PULSE CORONA TEST MADE AT 6KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



USBR, COULEE DAM
G-16 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 7/21/70 - 7/22/70 CURVES PLOTTED BY: ____
BY: ____ CHECKED ON: ____ BY: ____
STATOR RTD @ 34° C.

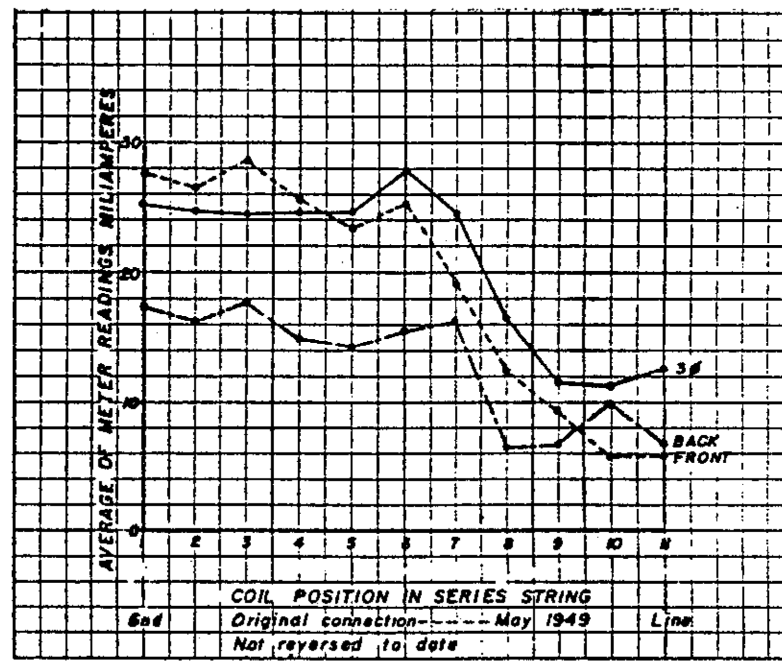
PEAK-PULSE CORONA TEST MADE AT 6KV WITH 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



USBR, COULEE DAM
G-18 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 7/20/70 CURVES PLOTTED BY: T.C.-H.D.T AND H.W.D.
BY: H.D.T. AND H.W.D. CHECKED ON: 7/20/70 BY: H.D.T.
STATOR RTD @ 33° C.

PEAK-PULSE CORONA TEST MADE AT 6KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.



USBR, COULEE DAM
G-18 STATOR WINDING
Asphalt Bonded Mica Insulation

TESTED: 7-28-70 CURVES PLOTTED BY: H.D.T. AND H.W.D.
BY: H.D.T.-T.A.G.-H.W.D. CHECKED ON: BY:
STATOR RTD @ 33°C.

PEAK-PULSE CORONA TEST MADE AT 8KV USING 5 MEGAHERTZ PROBE 3" BELOW TOP OF IRON IN AIR GAP. ROTOR IN PLACE.