FIELD EXPERIENCES USING A PROTOTYPE OPEN CORE RESONATING TRANSFORMER FOR A.C. HIGH POTENTIAL TESTING OF HYDRO-GENERATOR STATORS

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Abstract

When generator stators are rewound or undergo major repairs, there is often a requirement to perform a high potential test. These tests can be completed using d.c., very low frequency or power frequency a.c. test voltages. A.c. power frequency tests are becoming common, but such tests are difficult because of the large kVAr requirement to charge stator insulation capacitance. This is particularly a problem with hydro generator stators because of the physical size of the generator.

In many cases, the reactive power and hence the supply current cannot be provided at a local distribution board available within a power station. Resonant circuits are normally employed to minimise the distribution board loadings. In traditional a.c. high potential test sets, large variacs are employed with a high voltage transformer and multiple compensating coils.

The U of C has tested many hydro generators in New Zealand. In this paper an open core inductor and transformer is described that can provide high voltage and inductive compensation in an original and most compact manner. In one case the required reactive power was supplied by an open core resonant inductor for testing a 55.5 MVA, 11 kV rewedged hydro-generator. In a second case, an open core high voltage resonant transformer (which functions as both a high voltage transformer and compensating inductor) was used to test a 120 MVA, 15.4 kV rewedged hydro-generator. In a third case, the authors were required to test a stator with just over 1 µF in capacitance at a voltage of 32 kV. This required a single-phase controllable high voltage source rated at 286 kVAr prior to considering losses. Under such a situation, the large reactive power demand was fulfilled by employing both the open core high voltage resonant transformer as well as the open core inductor. The U of C open core high voltage testing kit not only performed well but also withstood severe electric disturbances and flashovers when multiple stator failures were experienced.

Introduction

The New Zealand electric power system is critically dependent on a majority of generators that are in excess of 25 years old. In recent times, a continuing process of stator and rotor rewind projects has been in progress. Given the significant effort and outages required for these rewind projects, most asset owners select a rewind and MVA upgrade option. Also, given fixed stator slot sizes and the need for more copper cross-sectional area, asset owners give particular emphasis to proving the integrity of the winding insulation. A result of this is that power frequency (50 Hz) a.c. high-potential tests are being listed as a contractual requirement of such generator rewind and upgrade projects.

It is also worth noting that according to one survey conducted by EPRI [1], the a.c. high-potential testing is becoming more popular among companies elsewhere. Experimental data shows that the a.c. test is more effective in detecting defects or deficiencies than the d.c. test

[2]. There is also the common criticism that d.c. stressing of insulation is not representative of what occurs in normal service [3]. A.c. high-potential testing stresses the components of generator insulation in a manner similar to normal service, except at higher a.c. voltages and in a non-induced or non-graded manner. Generally, the minimum d.c. breakdown voltage for windings under test is much higher than the crest voltage of the minimum a.c. breakdown voltage for similar windings [2]. It has been noted [1] that some machines which passed a d.c. high-potential test, failed under the a.c. high-potential test and perhaps insulation flaws that are not picked up by the d.c. test could lead to destructive, in-service failures.

A.c. high potential testing is challenging. Under a.c. conditions, the amount of current required by the insulation capacitance depends in part on the physical dimensions of the stator winding. This situation is significant in New Zealand given the large number of hydro-generating sets. These machines have large insulation capacitances. In most cases, the charging current required cannot be supplied by the power station local services without compensation. Table 1 represents an overview of the hydro generators tested in New Zealand by the University of Canterbury, their test voltages, insulation capacitances, kVAr and the amount of charging current required from a 230 V supply in the absence of compensation.

Table 1
Overview of the Hydro-generators Tested in New Zealand

Generator rating	Test voltage kV	Insulation capacitance µF	Calculated kVAr	Calculated charging current at 230 V†. A
2.35 MVA, 6.6 kV	14.2	0.084	5.32	23
8.82 MVA, 6.6 kV	14.2	0.217	13.8	60
55.55 MVA, 11 kV	13.8	0.234	14	61
88.9 MVA, 11 kV	23	0.422	70.1	305
120 MVA, 15.4 kV	20	0.75	94.2	409
40 MVA, 11 kV	23	0.57	94.7	412
135 MVA, 13.8 kV	32	1.05	338	1468

To overcome the supply current issue, series and parallel resonant systems are most popular among companies offering HV test equipment. A self sustaining resonant system requires much less current from the power station distribution board.

Most of the expensive and heavy resonant testing systems employ full core electromagnetic machinery such as double shielded isolation transformers, voltage regulators, excitation transformers and high voltage reactors. Such machines can reach multiple tons in mass [4], [5]. Transportation of this heavy equipment is expensive, especially when a hydro-generator is located remotely. These difficulties can discourage generator owners and sway them to accept a d.c. test. Some of the companies attempt to optimize size and weight considerations of their h.v. test equipment by increasing the frequency of the supply from d.c. to Very Low Frequency (V.L.F.) but this technique suffers from many of the criticisms already noted for the d.c. test.

† Charging current without considering any losses and assuming ideal HV transformer ratio.

A Novel Open Core Resonating Inductor and High Voltage Transformer

The U of C has enjoyed many years of open core inductor and transformer research, design and building [6], [7]. In 2000, the U of C performed an a.c. high potential test on a 88.9 MVA, 11 kV hydro-generator in the South Island of New Zealand. At this time it was realised that a high voltage open core inductor could be ideally suited to compensate the generator stator capacitance under such conditions. An open core inductor was designed and built and was used successfully on a 40 MVA, 11 kV North Island hydro-generator a.c. high-potential test in 2002 [7].

Figure 1
A Light Utility Vehicle Transporting the Dry Type Open Core Resonating HV Transformer

Use of the open core inductor significantly reduced the weight of the U of C test set; the only heavy item was the high voltage excitation transformer. The open core inductor compensated more than 100 kVAr and weighed about 120 kg. Following the North Island test it was realised that the high voltage open core inductor could have an outer winding installed and the machine would become a combined high voltage open core excitation transformer with significant inductive compensation. In this way all the heavy equipment was made redundant. The a.c. high potential test set became very compact. The new device, an open core resonating high voltage transformer was first applied to testing a 135 MVA, 13.8 kV hydro-generator in the South Island of New Zealand. Fig. 1 shows a light utility vehicle transporting the dry-type open core resonating HV transformer. This device is capable of producing 40 kV rms at 50 Hz with more than 286 kVAr of inductive compensation. It weighs approximately 300 kg.

The On-site Methodology Applied to the Open Core Resonating HV Transformer Tests

A procedure is required for successful a.c. HV resonant contract testing [8].

1. Before actually beginning any high potential test, site familiarisation is required for ensuring the proper safety of personnel and equipment to be employed for carrying out the tests.
2. Ensure that a Test Permit is issued and that all staff members have exited the test area.

3. Inspect the roped-off area available for testing. Ensure allowance has been made for suitable electrical clearances.
4. Set the arc gap flashover voltage at 120% of the test voltage and confirm the setting with five flash-overs.
5. Review Insulation Resistance and Polarisation Index results for the insulation to be tested.
6. Insulation not under test, resistance temperature detector (RTD) and embedded temperature detector (ETD) wiring should be earthed using fuse wire. Phases should be earthed at both the phase and neutral ends.
7. Set the adjustable core of the high voltage resonating test transformer such that it matches the approximate value of stator insulation capacitance.
8. Connect the high voltage resonant test transformer high voltage winding to the insulation under test. At least two high voltage leads should be tied to the insulation at the test extremities.
9. Using the high voltage resonant transformer and variac, excite the stator to the rated phase to ground voltage and check that the current drawn at the variac terminals is acceptable. This gives an indication that the test voltage can be achieved without overloading the supply variac. Record the circuit parameters such as r.m.s. current, r.m.s. voltage and test voltage Total Harmonic Distortion (V_{THD}).
10. Perform the high potential test. The voltage will be raised manually via the variac at approximately 1 kV per second. The test voltage is held for 60 seconds. Record r.m.s. voltages, r.m.s. currents, THD and load power factor. The test voltage is then lowered manually at approximately 1 kV per second. Isolate the supply and apply an earth to the phase under test.
11. If the insulation fails during the test then immediately reduce the voltage, isolate the supply and apply the earth.
12. Complete a final Insulation Resistance and Polarization Index test and check that the results are acceptable.

Testing a 55.5 MVA, 11 kV Rewedged Hydro-generator with an Open Core Resonating Inductor

Measurement of Generator Insulation Capacitances

A circuit model of a 3-phase generator insulation system, which is simplified to a capacitive load, is presented in Fig. 2. The electrical engineer who performs the a.c. high potential test requires an estimation of the capacitive load prior to testing. This information is often not available. It can be found if a power factor and capacitive test is performed prior to the a.c. high potential test. It is also possible to obtain this approximate value from the insulation resistance (IR) and polarization index (PI) test results using a state of art Megger, e.g. AVO S1-5005 gives the capacitance at the completion of the test.

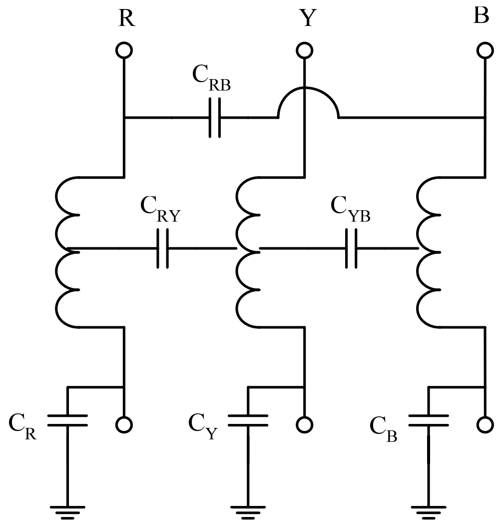

Figure 2
Circuit Configuration showing Generator Stator Windings and Associated Insulation Capacitances

At this power station, for ‘Y’ and ‘B’ phases earthed, the power factor and capacitance test set showed that

$$C_R + C_{RY} + C_{RB} = 0.218\ \mu F \qquad (1)$$

This was the insulation livened during the a.c. high potential test. The AVO S1-5005 gave a value of C = 0.24 µF for this insulation. These results can be compared to the capacitance of 0.234 µF measured under a.c. high pot testing where for higher voltages, electrical streamers can form which increases the capacitance of the insulation.

High-potential Test Set Up Employing an Open Core Resonant Inductor

An a.c. high potential test was conducted on a 55.5 MVA, 11 kV rewedged hydro-generator in the North Island of New Zealand. Normally the final high potential test of a generator would be conducted at 2 × rated line to line voltage + 1 kV, but as this generator was only rewedged and not rewound the Electrical Apparatus Service Association (EASA) recommendation [9] stated that the test voltage should be reduced to 65%. A high-potential test at 13.8 kV was instructed by the generator owner. The test set up is shown in Fig 3. The electrical measurements made during this test are presented in Table 2. The open core resonant inductor actually over compensated the stator capacitance.

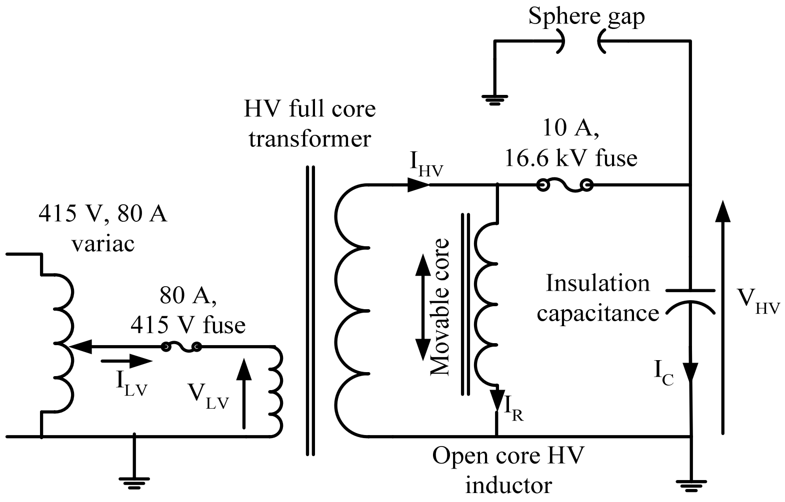

Figure 3
Circuit Diagram for Performing HV Power Frequency Test with an Open Core Resonating Inductor

Table 2
Results when an Open Core Resonant Inductor was Employed for Testing a 55.5 MVA, 11 kV Rewedged Hydro-generator.

Parameter						Value		Unit
Sphere gap flash set point						16.6		kV
Stator core temperature						Not measured		^{0}C
Ambient temperature						12.5		^{0}C
Ambient humidity						64		%
Ph.	**V_{HV} kV**	**I_{HV} A**	**V_{LV} V**	**I_{LV} A**	**I_R A**	**I_C A**	**Load 'C' µF**	**kVAr $V_{HV} \times I_C$**
R	13.87	0.32	299	15.3	1.34	1.02	0.234	14.14
Y	13.89	0.32	299	15.4	1.34	1.02	0.234	14.16
B	13.87	0.32	299	15.3	1.35	1.02	0.235	14.14

Testing a 120 MVA, 15.4 kV Hydro-generator with an Open Core HV Resonating Transformer

A request came to test a 120 MVA, 15.4 kV stator of another hydro power station in the South Island of New Zealand. This time the load capacitance was 0.75 µF; a much larger load. The open core HV resonating transformer could complete this test, providing both h.v. and compensation. No full core traditional HV transformer was required here. The test set up was as per Fig. 4.

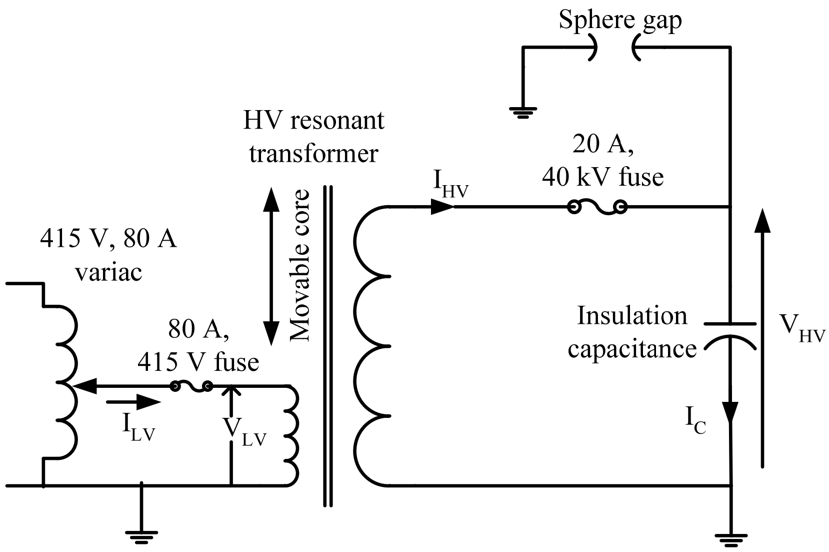

Figure 4
Circuit Diagram for Performing HV Power Frequency Test with only a HV Open Core Resonating Transformer.

Table 3
Results when Each Phase of the Fully Assembled 120 MVA, 15.4 kV Generator was Tested at 20 kV.

Parameter					**Value**	**Unit**
Sphere gap flash set point					30	kV
Stator core temperature					20	^{0}C
Ambient temperature					18	^{0}C
Ambient humidity					54	%
Ph.	**V_{HV} kV**	**I_C A**	**V_{LV} V**	**I_{LV} A**	**Load 'C' µF**	**kVAr V_{HV}×I_C**
R	20.23	4.78	281	20.3	0.752	96.7
Y	20.07	4.73	279	19.8	0.750	95.0
B	20.22	4.78	281	20.4	0.752	96.6

As this was also a rewedged hydro-generator, the EASA recommendation [9] is that the test voltage should be reduced to 65% of its actual value. A final high-potential of 20 kV was instructed by the generator owner. Table 3 gives the electrical measurements of this test.

This large stator was excited with approximately 20 A being drawn from the power station distribution board, corresponding to 5.6 kVA.

Testing a 135 MVA, 13.8 kV Hydro-generator where an Open Core HV Resonant Transformer was Assisted by an Open Core Resonating Inductor

The U of C was asked to carry out a.c. high-potential tests on the rewound 135 MVA, 13.8 kV generator stator at a hydro-electric power station in the South Island of New Zealand. This power station is in a remote part of New Zealand. There are no roads to the site and equipment access is via a 3 hour barge journey across a lake. Transportation of equipment is expensive. The U of C open core a.c. high potential test set offered a much reduced transportation load. Being of dry-type construction, the open core resonating transformer removed concerns regarding an oil spill into the lake which lay within the boundaries of a National Park and World Heritage Park.

Tests required

During a stator build or rewind, the a.c. high potential tests may well be contract milestones. It is therefore critical that the a.c. high potential test set is reliable and does not cause delays. The U of C open core resonating transformer was required to perform three on-site tests per stator as follows.

A. Back bar tests at 36.5 kV for 60 secs.
B. Each completed phase at 32 kV for 60 secs with the stator out of the machine pit and without the rotor in place.
C. Each completed phase at 28.6 kV for 60 secs with the generator fully assembled, i.e. the rotor in and the covers on.

A.c. High-potential Tests on Stator Back Bars

The load capacitance offered by 120 stator back bars was estimated to be 0.57 μF. The 135 MVA stator had 360 slots so the back bar tests could be completed with three tests. As shown in Fig. 5 the HV winding of the open core HV resonating transformer was connected to 120 stator back bars. The bars under test were linked top and bottom via fuse wire.

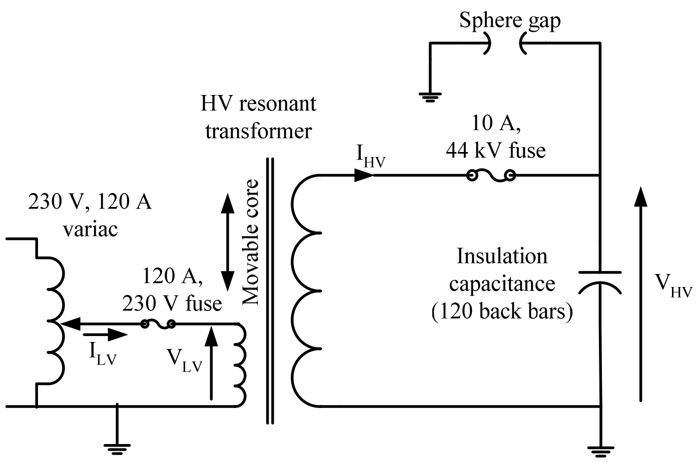

Figure 5
Stator Back Bar Test at 36.5 kV with Open Core HV Resonant Transformer
The HV resonating transformer performed the three stator back bar tests without any issues at near to its 40 kV rating and provided up to 212 kVAr each time. A 40 kV steel tank full core HV test transformer was also on site. This device was able to charge 5 bars at a time at rated capacity. If this device had been used, then 72 high voltage applications would be required, plus associate fuse wire bar bonding and earthing/h.v. reconnections.

Table 4
Results of the Stator Back Bar Test at V_{HV} = 36.5 kV

Parameter			Value		Unit
Sphere gap flash set point			44		kV
Stator core temperature			20		^{0}C
Ambient temperature			21		^{0}C
Ambient humidity			82		%
Back bar nos.	**I_{HV} A**	**V_{LV} V**	**I_{LV} A**	**Load 'C' µF**	**kVAr $V_{HV}\times I_{HV}$**
1-120	5.70	231	73.0	0.497	208
121-240	5.80	233	70.3	0.506	211
241-360	5.82	233	71.8	0.507	212

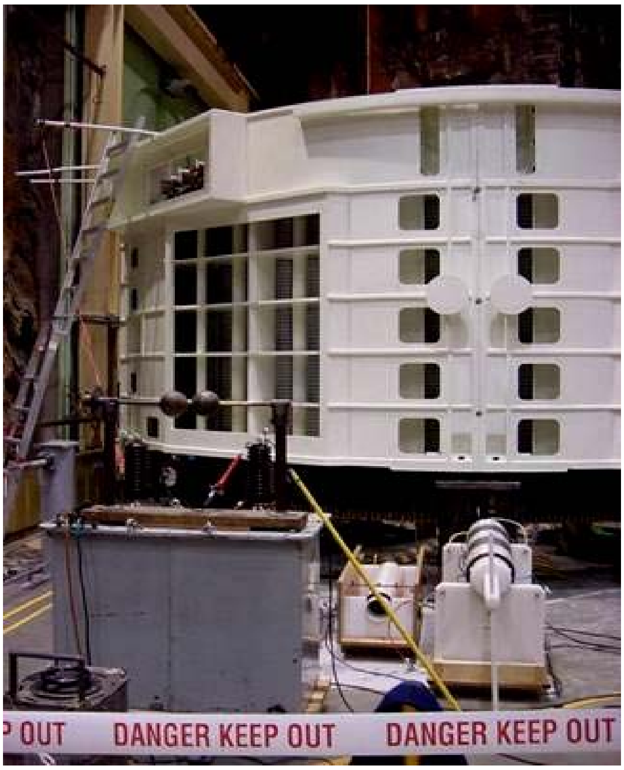

Figure 6
40 kV Steel Tank HV Transformer (left) and the Open Core HV Resonant Transformer (far right)

Fig. 6 shows the 40 kV steel tank HV test transformer in the foreground on the left hand side. The HV resonating transformer performing the back bar tests is shown in the foreground on the far right hand side. Table 4 shows the electrical measurements for the back bar tests.

Complete Phase Test at 32 kV

This a.c. high potential test was performed on each individual completed stator phase at 32 kV for 60 seconds. The completed 135 MVA, 13.8 kV stator phases gave an insulation capacitance of 1.04 µF. During the laboratory testing it was noted that displacing the core 320 mm resulted in a significant axial force on the winding sets; attempting to recentralise the core about the windings. It was decided to use the open core resonator described earlier (applied to the 55.5 MVA, 11 kV rewedged hydro-generator) as extra compensation during the 1.04 µF stator tests to limit core displacement to 225 mm. This set up is shown in Fig. 7.

The total supply current required was approximately 70 A, as shown in Table 5, which is less than 1/10th of the current that would have been required without compensation.

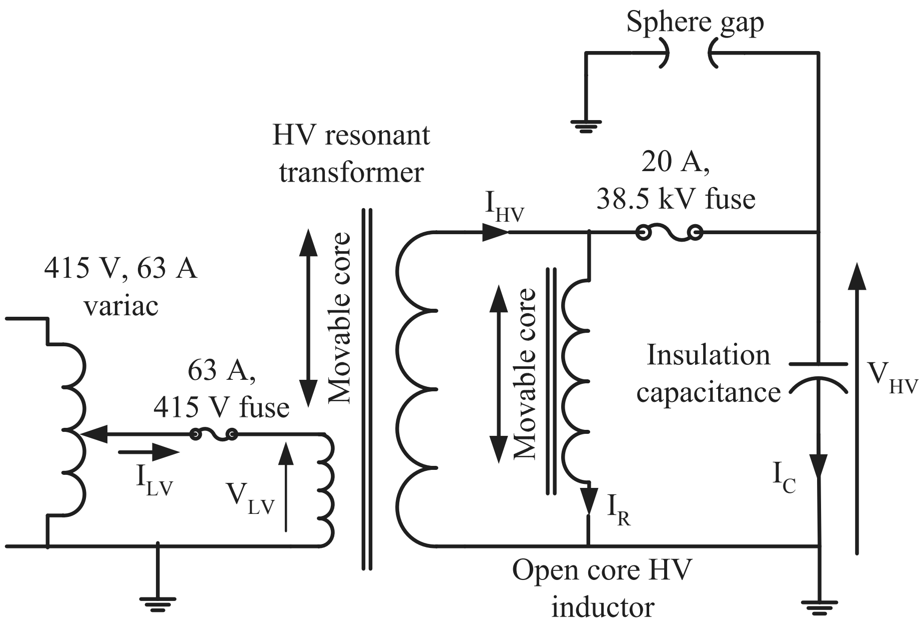

Figure 7
Complete Stator Phase Test with HV Resonant Transformer and Inductor, both Designed in Open Core Technology.

Table 5
Results for Each Completed Phase at 32 kV for 60 seconds with the Stator out of the Machine Pit and without Rotor in Place

Parameter					**Value**		**Unit**
Sphere gap flash set point					38.5		kV
Stator core temperature					23		^{0}C
Ambient temperature					22.5		^{0}C
Ambient humidity					64		%
Ph.	**I_{HV} A**	**V_{LV} V**	**I_{LV} A**	**I_R A**	**I_C A**	**Load 'C' µF**	**kVAr $V_{HV}\times I_C$**
R	7.14	443	69.6	4.0	10.65	1.06	341
Y	7.06	441	68.2	3.9	10.53	1.05	337
B	7.13	443	70.0	4.0	10.61	1.06	340

Final A.c. High-potential Test at 28.6 kV

The final a.c. high potential test was performed on the completed and assembled generator phase as described in the previous section but the voltage being applied was now 28.6 kV. Again the open core HV resonant inductor and the transformer were employed as shown in Fig. 7.

Before taking the complete readings for 'Y' and 'B' phases, the insulation failed at 33 seconds. When the stator failed, the resonance collapsed and due to the heavy magnetising current, the LV fuse operated. The results are given in the Table 6.

Table 6
Results when Each Completed Phase was Tested at 28.6 kV for 60 seconds with the Generator Fully Assembled

Parameter					Value		Unit
Sphere gap flash set point					35		kV
Stator core temperature					18		^{0}C
Ambient temperature					19		^{0}C
Ambient humidity					46		%
Ph.	**I_{HV} A**	**V_{LV} V**	**I_{LV} A**	**I_R A**	**I_C A**	**Load 'C' µF**	**kVAr $V_{HV}\times I_C$**
R	6.60	398	67.2	2.79	9.4	1.046	269
Y	6.56	400	66.0	--	--	Test failed	
B	6.50	400	73.2	--	--	Test failed	

Once 'Y' and 'B' phases were repaired, an attempt was made to retest the stator. Table 7 gives the retest results. This time, although the phases 'R' and 'B' withstood and passed the final high-potential test, phase 'Y' failed consecutively three times at 12, 10 and 4 seconds. The repeat failures were deliberate. Here the instruction to U of C was to flash the stator such that the damaged bar could be located. There was no damage to either of the resonating open core HV devices during these stator failures.

Table 7
Results after Repairing Phases 'Y' and 'B' and Each Phase of the Fully Assembled Generator when Tested at 28.6 kV

Parameter					Value		Unit
Sphere gap flash set point					35		kV
Stator core temperature					26		^{0}C
Ambient temperature					20		^{0}C
Ambient humidity					68		%
Ph.	**I_{HV} A**	**V_{LV} V**	**I_{LV} A**	**I_R A**	**I_C A**	**Load 'C' µF**	**kVAr $V_{HV}\times I_C$**
R	6.67	400	66.1	2.82	9.53	1.06	272
Y	----	401	65.5	Test failed three times			
B	6.70	402	62.7	2.86	9.63	1.07	275

Once the 'Y' phase was repaired, the retest was performed. This time the stator windings successfully passed all the tests. Table 8 gives the test measurements.

Table 8
Results after Repairing Phase 'Y' of the Fully Assembled Generator when Tested at 28.6 kV for 60 seconds

Parameter					Value		Unit
Sphere gap flash set point					35		kV
Stator core temperature					20		^{0}C
Ambient temperature					17		^{0}C
Ambient humidity					60		%
Ph	**I_{HV} A**	**V_{LV} V**	**I_{LV} A**	**I_R A**	**I_C A**	**Load 'C' µF**	**kVAr $V_{HV} \times I_C$**
R	6.70	402	62.7	2.86	9.63	1.07	275
Y	6.69	403	63.0	2.88	9.63	1.07	275
B	6.68	401	62.3	2.83	9.56	1.06	273

Conclusions

The open core resonating HV transformers presented in this paper provide a reliable high voltage supply with significant inductive compensation. One of the devices presented offers a proven 40 kV rms, 50 Hz voltage rating with at least 286 kVAr of inductive compensation. The open core machines can be tuned in a continuous manner while connected to the stator. This minimises low voltage a.c. distribution board loading at the power station. A further feature of the U of C open core HV resonating transformers is that they are of a dry type construction. The risks associated with transporting oil filled machines are removed.

The U of C has built open core a.c. high potential test sets and applied them to numerous large hydro-generator stators for proving tests. There have been cases where stators have passed and failed. The findings and test methodologies associated with these open core experiences have been presented in this paper.

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Biography

Dr Wade Enright is a senior lecturer at the University of Canterbury. He also offers electrical engineering services to the industry via his own company "Viva." This company is in its 9th year of business. Wade specialises in power transformers and high voltage. Wade has worked for the Electricity Corporation of New Zealand Ltd in their technical specialist group. During 1996 he worked for the Manitoba HVdc Research Centre in Winnipeg, Canada. He completed his BE (Hons) and PhD degrees in electrical and electronic engineering from the University of Canterbury in 1992 and 1995 respectively.

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