AC high potential testing of large hydro-generator stators using open core transformers

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Abstract: When generator stators are rewound or undergo major repairs, there is often a desire to perform a high potential test. These tests can be completed using d.c., very low frequency or a.c. power frequency test voltages. A.c. power frequency tests are becoming common, but such tests are difficult because of the large kVAr requirement to charge the stator insulation capacitance. This is particularly a problem with hydro generator stators because the insulation capacitance is further inflated by physical size. Recently the authors were required to test a stator with just over 1 μF in capacitance to a test voltage of 32 kV, requiring a single-phase controllable high voltage source rated to 286 kVAr prior to considering losses. It is not easy to locate a distribution board to supply this at a power-station site. Resonant circuits are normally applied to complete these tests and minimise the distribution board loadings. In traditional a.c. high potential test sets, large variacs are employed with a high voltage transformer and numerous compensating coils. In this paper an open core transformer is described that can provide high voltage and inductive compensation in an original and most compact manner.

1 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 effort in stator and rotor rewind project has been in progress. Given the significant effort and outage required for these rewind projects, most asset owners select a rewind and MVA upgrade option. Given fixed stator slot sizes, and the need for more copper cross-sectional area, asset owners make particular emphasis to insulation proving.

A result of this is that the power frequency (50 Hz) a.c. high-potential test is being listed as a mandatory requirement of a New Zealand generator rewind and upgrade project. Also, according to one survey conducted by EPRI [1], the a.c. high-potential test is becoming more popular among companies elsewhere.

Experimental data shows that the a.c. test is more searching for defects or deficiencies than the d.c. test [2]. There is also the common criticism and fact that d.c. stress is not representative of normal service [3]. A.c. high-potential testing stresses the components of generator insulation in a manner more 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. Perhaps the 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 case is worsened in New Zealand by the large number of hydro-generating sets. These machines have large insulation capacitances. In most of the cases, the charging current required cannot be supplied by the power station local services without compensation. To overcome this problem, resonant systems are most popular among companies offering HV test equipment. Series and parallel resonant test systems are common for a.c. high-potential tests on generator insulation, so that under resonant conditions the energy absorbed at any instant by one reactive element is exactly equal to that released by another reactive element within the system. This 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 also expensive, especially when a hydro-generator is located remotely. These difficulties can discourage generator owners and force them to the d.c. test. Some of the companies try to optimize size and weight considerations 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.

2 A NOVEL OPEN CORE RESONATING HIGH VOLTAGE TRANSFORMER

The UofC has enjoyed many years of open core inductor and transformer research, design and builds [6], [7]. During the year 2000, the UofC performed an a.c. high voltage test on a 88.9 MVA, 11 kV hydro-electric power station 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 for this purpose, and was used successfully on a 40 MVA, 11 kV North Island hydro-electric power station generator a.c. high-potential test in 2002 [5].

Use of the open core resonator significantly reduced the weight of the UofC test set; the only heavy item was the high voltage excitation transformer. The open core resonating coil catered for more than 100 kVAr and weighed less than 100 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 and the a.c. high potential test set became most compact. The new device, an open core resonating high voltage transformer was first applied to testing a 135 MVA, 13.8 kV hydro electric power station in the South Island of New Zealand. Fig. 1 shows a light utility vehicle transporting the dry-type open core HV resonating 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.

Fig. 1: A light utility vehicle transporting the dry-type open core resonating HV transformer.

2.1. Laboratory proving the open core resonating HV transformer

Prior to commencing any power station site work it was necessary to prove that the new machine was capable of testing (i) stator back bar sets of 0.57 μF at 36.5 kV, (ii) a complete stator phase corresponding to 1.04 μF at 28.6 kV. All tests had to be carried out at mains frequency of 50 Hz for 60 seconds. The LV supply provided on the site was 415 V, 120 A single phase at the generator unit distribution board and therefore the laboratory tests needed to draw current at a good margin below 120 A.

2.1.1. Laboratory HV test using a separate source

In this test the HV winding of the open core transformer was subjected to 40 kV for 3 minutes, while the LV winding was on open circuit. Fig. 2 shows the equivalent circuit for this test . The load capacitance chosen was 0.57 μF which matched the predicted capacitance of the 135 MVA, 13.8 kV hydro-electric generator stator back bars.

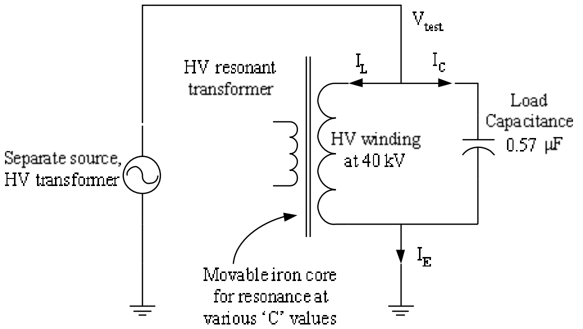

Fig. 2: Schematic diagram for testing HV winding of resonating transformer at 40 kV for 3 minutes.

It was confirmed that HV winding of the newly built open core transformer withstood 40 kV for three minutes without causing any failures or unexpected behaviour. Table 1 shows the characteristics of the machine during the separate source excitation.

Tab. 1: Test results for open core transformer HV winding.

V_{test} kV	I_C A	I_L A	I_E mA	Load 'C' μF	kVAr $V_{test} \times I_C$
10	1.79	1.82	24	0.57	17.9
40	6.78	8.72	890	0.57	271

2.1.2. HV test using the resonating HV transformer

In order to first test the resonating behaviour of the open core HV resonating transformer, the LV winding was exited by a 230 V variac and the HV side was gradually raised up to 31.5 kV. Before that, a resonance condition was confirmed at the relatively lower potential of 10 kV to ensure that the supply variac would not be overloaded once 31.5 kV was achieved. This assumes that the capacitance and the resonant transformer characteristics do not change with voltage. Fig. 3 shows the test set up for this investigation.

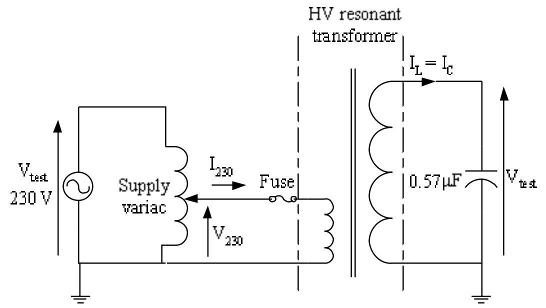

Fig. 3: The open core transformer providing high voltage and compensation in the laboratory.

Tab. 2: Test results of resonance condition at 31.5 kV.

V_{test} kV	$I_C = I_L$ A	I_{230} A	V_{230} V	Load 'C' µF	kVAr $V_{test} \times I_C$
10	1.78	6.06	72	0.57	17.8
31.5	5.43	46.2	224	0.57	171

2.1.3. HV test to represent a large hydro stator

The winding capacitance of an actual rewound 135 MVA, 13.8 kV generator was estimated at 1.04 µF per phase. The capacitive load of 1.04 µF was assembled at the UofC using sixteen 0.065 µF, 100 kV capacitors in parallel.

A feature of the open-core transformer design is its movable iron core. This core can be displaced from the windings in an adjustable manner. By adjusting the iron core position , the open-core transformer magnetising reactance can be matched to the capacitive stator load reactance. The machine is designed with an isolated turning handle such that tuning can be completed live at up to 10 kV a.c. rms. Mechanical locks and structures are provided to stop the movable core and windings re-centering at full rated flux or under short circuit conditions.

To complete the test shown in Fig. 4 the iron core was displaced 320 mm. The supply voltage in this case was across a phase at 415 V. The open core machine was built with a fully isolated LV winding with both 415/230 V configurations.

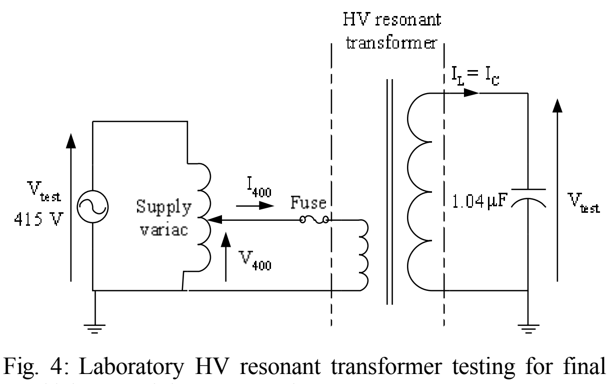

Fig. 4: Laboratory HV resonant transformer testing for final a.c. high potential test at 28.6 kV.

Table 3 gives the electrical characteristics of the machine when energising the 1.04 µF load to the specified test level of 28.6 kV. The supply current of 42 A is well below the 120 A limit. Also the ratio of resonating kVAr to distribution board supply kVAr is in this case 267/16.9 = 15.8.

Tab. 3: Test results of resonant condition at 28.6 kV.

V_{test} kV	$I_C = I_L$ A	V_{400} V	I_{400} A	Load 'C' µF	kVAr $V_{test} \times I_C$
10	3.27	141	11.6	1.04	32.7
28.6	9.34	402	42	1.04	267

3 ON-SITE TESTING AT THE HYDRO-ELECTRIC POWER STATION

After successful testing of the open core resonating transformer in the laboratory, approval was given 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 each way barge journey across a lake. Transportation of equipment is expensive and the UofC open core a.c. high potential test set offers a much reduced transportation load. Being of dry-type construction adds further comforts in that concerns regarding an oil spill into the lake are removed.

3.1. 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 UofC 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.

The load capacitance offered by 120 stator back bars was as predicted at 0.57 µF. The 135 MVA stator had 360 slots so the back bar tests could be completed with three tests. The three tests could be completed within two hours, which was of assistance to the contractor who had allowed 2 days for the back bars testing via a conventional full core high-voltage transformer. Most of the testing time was taken up by the Polarisation Index testing of the back bar sets prior to and after each a.c. high potential test. There were six of these tests and they each took 10 minutes.

3.2. The on-site methodology applied to the open-core resonating HV transformer tests

A set of protocols is required to be followed for successful a.c. HV resonant testing.

(i) Before actually beginning any high potential test, site familiarization is a must for ensuring the proper safety of personnel on site and the equipment to be employed for carrying out the tests.

(ii) Ensure that a Test Permit is issued and that all staff have exited the test area.

(iii) Inspect the roped-off area available for testing. Ensure allowance has been made for suitable electrical clearances.

(iv) Set the arc gap flash over voltage at 120% of the test voltage and confirm the setting with five flash-overs.

(v) Review Megger Polarisation Index test results for the insulation to be tested.

(vi) Insulation not under test, resistance temperature detector (RTD) and embedded temperature detector (ETD) wiring should be earthed via fuse wire. Phases should be earthed at both the phase and neutral ends.

(vii) Set the adjustable core of the high voltage resonating test transformer such that it matches the approximate value of stator insulation capacitance.

(viii) 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.

(ix) Using the high voltage resonant transformer and variac, excite the stator to the rated phase to ground insulation (7970 V) and check that the current drawn at the variac terminals is acceptable. This is a best indication that the test voltage (31.5 kV or 28.6 kV) can be achieved without overloading the supply variac. Record the circuit parameters such as currents, voltages and Total Harmonic Distortion (THD).

(x) Perform the high potential test. The voltage will be raised manually via the variac; an attempt is made to raise at 1 kV per second. The test voltage is held for 60 seconds. Record voltages, currents, harmonics and load power factor. The test voltage is then lowered manually at approximately 1 kV per second. Replace the test set earth.

(xi) If the insulation fails during the test then immediately reduce the voltage and apply the earth.

(xii) Complete a final Megger Polarization Index test and check that the results are acceptable.

3.3. A. c. high-potential tests on stator back bars

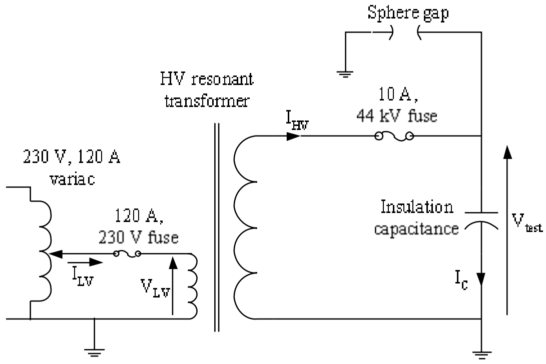

Fig. 5: Stator back bar test at 36.5 kV with open core HV resonant transformer.

As shown in Fig. 5 the HV winding of the resonating open core HV transformer was connected to 120 stator back bars. The bars under test were linked top and bottom via fuse wire bonding. Bars not under test and any RTD/ETD wiring were earthed via fuse wire and appropriate earth leads. Table 4 shows the electrical characteristics of the back bar tests.

Tab. 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 $V_{test} \times I_C$**
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

3.4. 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 with the phase and neutral ends tied to the open core resonating transformer's HV terminal and the other phase/neutral ends earthed. This capacitance value matched the UofC set up. Thus there was confidence that the new machine would successfully charge the 135 MVA, 13.8 kV stator phase. During the laboratory testing it was noted that displacing the core 320 mm resulted in a reasonable force on the winding sets. It was decided to use the resonator designed for the 40 MVA, 11 kV 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. 6.

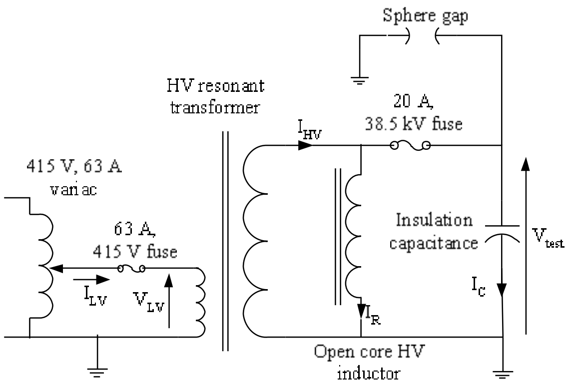

Fig. 6: Complete stator phase test with HV resonant transformer and inductor, both designed in open core technology.

Using the open core resonating HV transformer the total supply current required was about 70 A, as shown in Table 5, which is less than 1/10th of the current that would have been required without compensation.

Tab. 5: Test results for each completed phase at 32 kV for 60 seconds with the stator out of the machine pit and without the 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 $V_{test}\times I_C$**
R	7.14	443	69.6	4	10.65	1.06	341
Y	7.06	441	68.2	3.9	10.53	1.05	337
B	7.13	443	70	4	10.61	1.06	340

3.5. 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 section 3.4 but the voltage being applied was now 28.6 kV.

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.

Tab. 6: Test 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 $V_{test}\times I_C$**
R	6.6	398	67.2	2.79	9.4	1.046	269
Y	6.56	400	66	--	--	Test failed	
B	6.5	400	73.2	--	--	Test failed	

Once 'Y' and 'B' phases were repaired, an attempt was made to retest the 135 MVA, 13.8 kV stator. Table 7 gives the retest results.

Tab. 7: Test 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 $V_{test}\times I_C$**
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

This time, although the phases 'R' and 'B' withstood and passed the final high-potential test, phase 'Y' failed consecutively, three times at the 12th, 10th and 4th second. The repeat failures were deliberate. Here the instruction to UofC was to flash the stator such that the damaged bar could be located. There was no damage to the resonating open core HV transformer during these stator failures.

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

Tab. 8: Test results after repairing phase 'Y' and each phase 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 $V_{test}\times I_C$**
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

4 TESTING A 120 MVA, 15.4 kV HYDRO-GENERATOR IN THE SOUTH ISLAND OF NEW ZEALAND

Following the 135 MVA, 13.8 kV stator tests a new request came to test a 120 MVA, 15.4 kV stator in another hydro power station in the South Island of New Zealand. This time the load capacitance was smaller at 0.75 µF. Only one open core HV resonating transformer was required to do this job with the core displaced.

Normally the final high potential test would be (2 × rated line to line voltage + 1 kV) but as this generator was only rewedged and not rewound, then EASA standard [8] states that the test voltage should be reduced to 65%. A final high-potential of 20 kV was instructed. Table 9 gives the electrical characteristics of this test. The test set up was as per Fig. 5.

Tab. 9: Result 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 $V_{test} \times I_C$**
R	20.23	4.78	281	20.3	0.752	96.7
Y	20.07	4.73	279	19.8	0.750	95
B	20.22	4.78	281	20.4	0.752	96.6

This large stator was excited with less than 20 A being drawn off the power station distribution board.

5 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 distribution board loading at the power station. A further feature of the UofC open core HV resonating transformers is that they are of a dry type construction. The difficulty in transporting oil filled machines is thus removed.

The UofC 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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