Short Time Rated And Protected High Voltage Ac Testing Of Generator Stators Using Parallel Resonant Circuits

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Abstract:

Power station generators require short duration HV ac testing of their insulation as part of their acceptance before being put into service. Depending on the value of the capacitance of the insulation, the rating of the test power supply can be large. One method of reducing this supply requirement is to compensate the capacitance with inductance. The paper describes a parallel resonant compensation test method which initially uses LV inductances to compensate 0.422μF of stator capacitance at 23kV. This equates to 70kvar. In a development of testing equipment, this is replaced by a HV inductance that supplied 115kvar of reactive power compensation at 23kV. As a further development, the inductor was turned into a resonant transformer by the addition of a LV primary. The magnetising reactance was matched to the generator stator insulation capacitance. A laboratory test showed that the required HV of 23kV could be obtained from energising the primary at 285V at 60A or at a rating of about 1/7th the load. A further resonant transformer was then designed for a 334kvar capacitor load to test generator stators at 31.5kV. This transformer was supplied from a nominal 400V supply and gave a gain in kVA of 16. The transformer has a finished weight of approximately 300kg. As a final test, both units were used in parallel to supply and compensate 1.06μF of stator capacitance at 32kV.

1. INTRODUCTION

Power station generator stators require HV testing of their insulation as part of their acceptance before being put into service. Traditionally this has involved the application of a high dc voltage. The equipment required to do this is relatively small and portable, as the insulation charging current can be kept small as the voltage is ramped up to its required value.

However, more and more utility owners are calling for over-voltage acceptance tests to be made at mains frequency. These tests may be of the order of 2 - 3 times rated voltage for 1 minute. Under ac conditions, the amount of current required by the insulation capacitance depends on the physical dimensions of the stator winding. It may not be insignificant. To supply this current directly from a power supply can involve a capacity greater than what is available from local services, such that dedicated test units with their own generator sets may be necessary. These can be physically very large and heavy, with consequent high test costs. Series [1] and parallel [2] resonant test sets are available which reduce the VA requirement of the supply.

This paper describes a parallel resonant ac testing setup which initially used LV inductors for compensation, but then evolved to the use of a HV inductor and on to a resonant transformer. The HV equipment has been designed around a partial core transformer concept [3]. The inductor and transformer have laminated core material only in the space enclosed by the windings. There are no limbs and yokes as found in conventional full core transformers. One of the characteristics of these devices is that they have relatively low magnetising reactance. Through judicious design, this reactance can be matched to a generator stator capacitance such that the reactive current of the insulation is provided by the magnetisation. This means that the supply only has to provide the real power losses of the transformer and in practice any mismatch between the magnetisation current and the stator capacitance. For the transformer, the primary winding can be downsized to conduct only this supply current.

In these tests, adequate protection is required to ensure that if the generator phase fails, damage is limited. This can be achieved with appropriately rated fusing, circuit breakers and test set impedance for over-current protection, and an arc-gap for over-voltage protection.

2. LV INDUCTOR TEST METHODOLOGY

Initial parallel resonant HV testing of generator stators in New Zealand involved equipment assembled according to the circuit shown in Figure 1. This reflects the equipment that was locally available for such tests. Each transformer and inductor in this circuit weighed in the order of over 1 tonne. Hence the total test circuit weight was in excess of 6 tonnes.

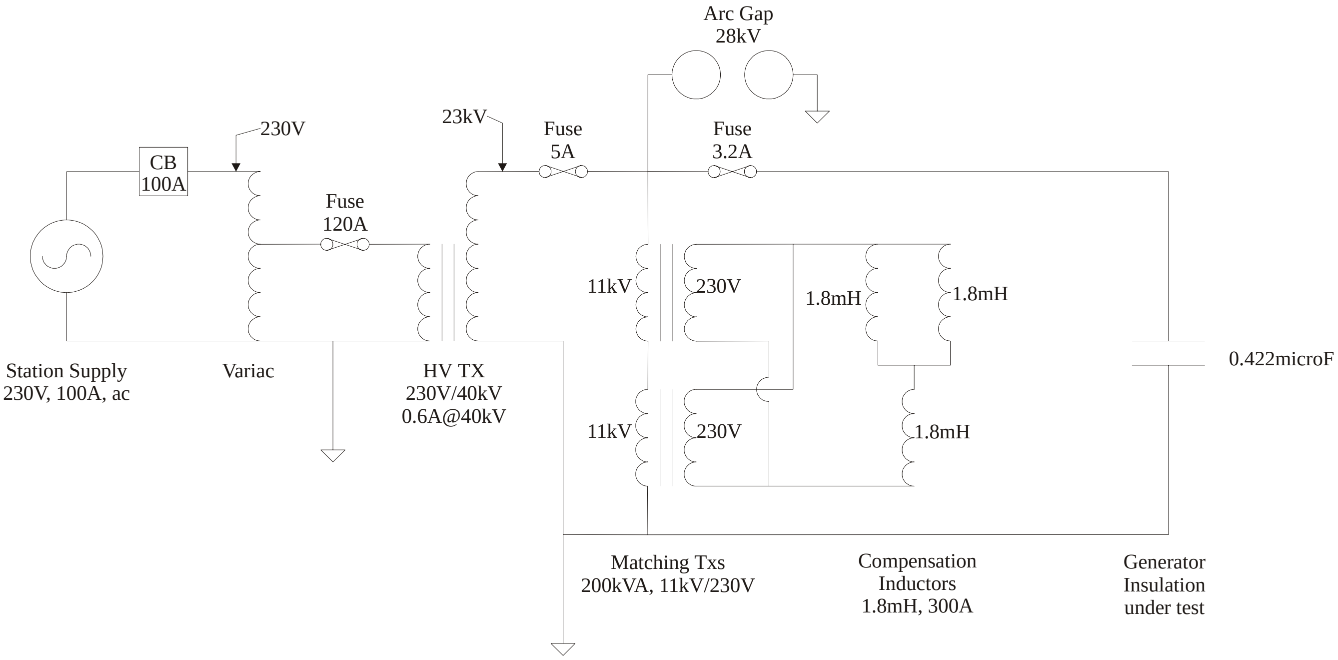

Fig. 1: HV ac test set including inductive compensation.

The two 11kV matching transformers are in series/parallel and must therefore share current and voltage evenly. All of the inductive compensation circuit components were over rated for the currents experienced under the HV test.

When referred through the matching transformers, the 1.8mH inductors provide compensation for the 0.422μF generator capacitance. In addition, the matching transformer magnetising current also provides inductive compensation in a non-linear manner.

With two inductors connected in parallel and one in series, as shown, the current supplied by the HV test transformer is inductive. Alternatively, if only two inductors are connected in series across the matching transformers, the load current supplied by the HV transformer would be capacitive. However in the capacitive case the load current is closer to the test transformer limit of 0.6A than in the inductive case, therefore the parallel/series inductor combination was selected. Minor on-site tuning was effected by adjusting the transformer taps to give the level of reactive compensation required.

Unfortunately the upper matching transformer of Figure 1 is subjected to abnormal voltage stress. At the HV lead-out, approximately 23kV is applied between the 11kV and 230V windings. To check the ability of this transformer to withstand the electric field stress, the 11kV winding was subjected to a separate source over-voltage test at 25kV for 60 seconds. At this voltage, minor partial discharging occurred around the transformer inner HV bushing electrodes, however, the transformer easily passed the test.

Protection of the generator and test circuit was provided via circuit-breakers, fusing, test set impedance, and an arc-gap. The full voltage, short-circuit current provided by the HV test transformer was 0.8A. Therefore it is unlikely that any fuse would blow upon generator flash-over. However, the 3.2A/23kV fuse ensures that only a minor current could be supplied to the generator from the stored energy of the inductors during a fault.

While the arc gap is present for over voltage protection, transformer saturation also limits the steady-state voltage that can be applied to the generator. The arc gap flash over voltage can be set accurately. It was set high at 28kV. It must be recalibrated on the test day at site, due to local atmospheric conditions. It is necessary to ensure that the arc gap does not flash over during normal test set operation. Such a flash could induce a ferroresonance between the matching transformers and the generator capacitance. In this unlikely scenario, the fusing and arc gap will be required to protect the generator stator.

Prior to transport to site this circuit was set up and operated in the HV laboratory at the University of Canterbury. The generator insulation was simulated with a 0.42μF capacitor created from appropriate parallel and series connections of an inverted Marx impulse generator built from 100kV, 0.065μF capacitors. The tests showed that at 23kV, the HV test transformer current was significantly less than 0.5A. On multiple occasions the test capacitance was shorted to simulate a generator insulation flashover. In all cases the test set impedance limited the fault current and no fuse wire was destroyed. Ferroresonance was not observed in any of the laboratory tests.

The on site tests occurred at the Tekapo hydro-electric power station. The blue-phase winding of a rewound generator stator was connected to the HV transformer and compensation reactance in the manner shown in Figure 1. The red and yellow phases were shorted to earth, while both the line and neutral terminals of the blue phase winding were raised to 6.350kV. The following measurements were made:

HV test transformer primary voltage: ***Vp*** = 51.4V
HV test transformer primary current: ***Ip*** = 23.8A
Generator applied voltage: ***Vs*** = 6.36kV
HV test transformer secondary current: ***Is*** = 132mA
Matching transformer HV winding current: ***Im*** = 95mA
Compensation inductor voltage: ***Vi*** = 70V
Compensation inductor current: ***Ii*** = 83A

The wave-shape of the voltage applied to the generator was confirmed to be sinusoidal with negligible harmonic distortion.

The first attempt at testing of the blue-phase winding was aborted. At 22kV the current ***Is*** reached 0.75A, inductive. At this load the current ***Ip*** reached 128A and there was a risk of protection operation. Further calculations were then performed and it was deduced that the removal of one 1.8mH compensation inductor from the parallel combination (leaving 3.8mH across the matching transformers) would lower ***Is*** by 0.69A, inductive current. The resultant circuit would be at near unity power factor and almost perfectly tuned.

The initial test circuit had been tuned to a load capacitance of 0.422μF per phase. The actual stator capacitance was thus not approximately 0.422μF per-phase, or the test voltage applied was higher than 23kV and the matching transformer 11kV winding saturated under test.

Doble testing under GST mode is equivalent to the high-potential test, but is performed at the lower voltages of 2kV, 4kV, 5kV, 6.6kV and 7kV. During Doble GST testing the capacitance per phase was noted to increase slightly over the range 2kV to 7kV. Extrapolation of this result indicated that the winding capacitance would increase at 23kV. This would give more capacitive current at 23kV and make the HV test transformer current less inductive. This was not observed during testing.

Transformer saturation would explain the increased inductive current supplied by the HV test transformer. However saturation to this extent should not occur with each matching transformer at 11.5kV. Moreover the meter used to measure the test voltage had been recently calibrated so confidence was held in the magnitude of the applied test voltage.

Each of the generator windings was separately raised to 5% over the normal operating phase to ground voltage of 6.350kV to ascertain the level of partial discharge in the winding. The other phases were grounded during this test. With the stator windings energised in this manner acoustic measurements were made to determine areas of partial discharge.

The blue-phase results were significantly different from the red and yellow-phases. The blue-phase partial discharge test was completed with the test circuit as per Figure 1. In the red and yellow-phase tests, the circuit was altered to accommodate the HV test, with one of the parallel 1.8mH inductors being removed.

In the final HV tests, each phase of the generator winding was raised to an a.c. voltage of 23kV (rms) for 60secs at 50Hz. The other phases were grounded during each test. Table 1 displays the test set measurements made during the high potential tests.

Phase	***Ip*** **A**	***Is*** **mA**	***Vp*** **V**	***Vs*** **kV**	***Im*** **mA**	***Ii*** **A**	***Vi*** **V**	***θp***
Blue	25	138	54	6.7	-	-	-	49^{o} lag
Yellow	33	187	29	6.7	73	63	74	27^{o} lead
Red	34	189	30	6.8	75	64	75	27^{o} lead

Table 1: Test circuit partial discharge performance.

Current runaway was not observed on any phase during the test. Furthermore, no winding flash-overs were observed at 23kV. Therefore all three phases of the generator passed the test.

The measured power-factor matched the calculations with each test, being near unity. However, the movement of power-factor was non-linear with voltage. Initially the current drawn was capacitive, reaching almost the 120A variac limit at 21kV. When the voltage was increased to 23kV, the transformer saturation compensated for the capacitive current and reduced the variac current significantly to 69A.

The affect of non-linear matching transformer magnetising current on the applied 23kV voltage waveform was checked during each test. The harmonic content of the applied voltage waveform was satisfactory during all tests.

3. RESONANT INDUCTOR

A second testing requirement involved a new stator for a 50Hz, 11kV, 40MW generator at the Matahina power station in New Zealand. The design specification called for a 50Hz ac test voltage of 23kV for 1 minute, the same as at Tekapo. The stator capacitance was estimated to be between 0.217 and 0.422μF per phase, although at the time of designing, these were not firm. These capacitance values equate to reactances of approximately 14,700 and 7,500 ohms respectively.

The cost of transporting the equipment of Figure 1 across Cook Strait and up to a North Island station prompted the consideration of the design of a HV inductor using the partial core concept.

In designing an inductor to suit the test specifications, a core size of 715mm length and 125mm diameter was determined, and the copper winding wire was 1mm in diameter. These values were obtained through a process of design/performance evaluation using a computer program created for the purpose [4]. A full account of the design and performance of the device is given in [5].

As the generator stator capacitance was somewhat unknown, the inductor was wound with a total of 13 layers of wire. Taps were made from layer 9. This gave a range of measured magnetising reactances from about 4,700 to 11,900 ohms for 9 to 13 layers respectively. It was also observed that the amount of corona was affected by the proximity of the inductor to the ground, because of the asymmetric electric field set up in coupling to the ground. The inductor was raised on insulated upstands to reduce this.

The inductor was subjected to a 30kV voltage applied for 3 minutes to prove its insulation integrity. On site, as shown in Figure 2, the inductor was used on the tap at layer 9. It drew 4.9A at 23kV for a rating of 113kvar.

Fig. 2 Resonant inductor in use at Matahina

The generator stator insulation was measured at 0.56µF, corresponding to about 5700 ohms. This was almost twice the design value. Fortunately, the flexibility and relative conservatism in the design of the inductor allowed an appropriate tap selection to accommodate the actual load. Under test, the stator insulation drew 4.1A at 23kV, implying some over-compensation of reactive current by the inductor. Nevertheless, the supply current was reduced to 0.75A, significantly below that which would have been necessary without the inductor in circuit. Thus a VA gain of 5.5 from the supply to the load was obtained. This allowed the use of a lower VA rating HV test supply transformer, supply variac, with smaller station supply and protection considerations.

3. RESONANT TRANSFORMER

There was still some difficulty in providing an appropriate test transformer as the high voltage supply. This was a limit of what was available in New Zealand. An alternative presented itself in that the partial core compensating inductor concept could be modified to be its own transformer.

The inductor was altered by placing a LV winding around the HV winding. This was made from a single layer of 68 turns of 5.0 by 2.5mm rectangular aluminium wire. The wire size was selected more by what would best cover the primary to reduce leakage, than for current density optimisation, although the number of turns was selected to allow the transformer to be excited from a 230V supply. The neutral connection to the HV winding was made at the outer layer and the core left floating at the high voltage. The LV winding thus shielded the HV winding for electric field coupling to grounds external to the device. This reduced corona from the windings.

To test the effectiveness of the resonant transformer, 10 capacitors of an inverted Marx impulse generator were connected in parallel to give a nominal load capacitance of 0.65µF. This equated to an impedance of 4,900 ohms, which was almost equivalent to the transformer impedance for 9 layers, and corresponded to the tests undertaken on site with the resonant inductor.

The low voltage winding was energised from a 230V variac. The transformer showed linear behaviour through to rated high voltage. However, to get 23kV on the HV winding, 285V was needed to be applied to the LV winding. This gave a voltage ratio of 81, well below the rated value of 90. The HV winding current was measured at 4.9A, equivalent to the Matahina stator and consistent with a load impedance of 4,700 ohms. The LV winding current was 55A. This gave an input volt-amperes of 15.7kVA for a load value of 113kvar, or a gain of 7.2. The real power losses in the transformer were measured to be 3.5kW.

The loss in voltage ratio was considered to be due to the LV winding, which was 500mm in length, not completely covering the HV winding, 720mm in length. It was surmised that there was significant leakage flux in the 110mm long regions between the end of the LV winding and the HV winding end.

This transformer cannot be operated on open circuit as the LV winding was not designed to take the high magnetising current under steady state conditions. The calculated open circuit current of 490A would give rise to a current density of 39A/mm2, which would soon overheat the winding.

However, this transformer, weighing approximately 120 kg, replaces the entire 6 tonne HV circuit of Fig. 1.

4. TUNABLE RESONANT TRANSFORMER

A new request came to design a resonant transformer to test a 50Hz, 13.8kV, 135MVA generator stator at the Manapouri underground power station, at 31.5kV. The stator capacitance was estimated to be 1.083μF. The completed resonant transformer is shown in Figure 3.

Fig. 3 Manapouri resonant transformer in front of equipment previously used at Tekapo power station in the circuit of Fig 1.

The core dimensions were 175mm in diameter and 1200mm in length. It weighed 217kg. The HV winding was made of 9 layers of 1.8 mm diameter copper wire, weighing 72kg. Taps were made at layers 3 and 6 and also 7, 8, and 9 to allow voltage tuning under test conditions. The device was also tuneable to a specific capacitance load by adjusting the position of the core. This altered the magnetising impedance of the transformer.

A LV winding of twin strand 7.1 x 3.55 rectangular insulated aluminium wire was put over the HV winding.
It was wound in 2 equal 31 turn sections to allow the sections to be connected in either parallel or series. This allowed supply from either nominal 230V or 400V excitation. These windings added only 7kg to-give a total metal weight of about 295kg.

The performance of the resonant transformer was demonstrated to the client through three tests. With the core centralised, the induced overvoltage test on the HV winding was conducted at 40kV for 3 minutes, charging a capacitance of 0.57μF. The winding current was 8.7A. The second acceptance test showed that the transformer could be excited from a nominal 230V supply, and allowed a number of stator bars to be tested during the installation phase. For a 0.57μF load, the LV winding operated at 224V and 47A. The HV winding voltage was the required stator bar interim test voltage of 31.5kV. The load current was 5.4A. The LV winding rating was about 11kVA, as compared to the compensation value of 170kvar on the HV winding.

The final acceptance test was the supply of 28.6kV to a capacitor of 1.04μF, being essentially the design value of the completed stator. The core was displaced at 350mm from the centre. The secondary current was 9.3A to give a rating of 267kvar. The primary was excited to 402V and 42A to give a power rating of 17kVA. The VA ratio was thus 16.

Having passed these tests, the resonant transformer has since successfully been used on site at the Manapouri power station to test the initial batch of installed generator stator bars. The test voltage was 36.5kV and the capacitance of the installed stator bars was measured at 0.49μF. During the test, a flashover occurred on the stator. The resonant transformer showed no damage from this full circuit condition at high voltage, proving the electrical and mechanical integrity of the winding system.

In a follow up test, the Matahina resonant transformer was reinsulated to operate 32kV and inserted as an inductor in parallel with the Manapouri resonant transformer. Each complete phase of the generator stator of 1.06μF was tested. The stator current was 10.6A to give a reactive power of 339kvar. The Matahina and Manapouri resonant transformers had currents of 4.0A and 7.1A respectively. The primary was excited at 443V and took 70A, to give a VA rating of 31kVA and an output to supply VA ratio of 11.

5. CONCLUSIONS

Generator stators require high voltage testing of their insulation as part of their acceptance before being put into service. Traditionally this has involved the application of a high dc voltage. However, more and more utility owners are calling for over-voltage acceptance tests to be made at mains frequency. Under ac conditions, the amount of current required by the insulation capacitance may not be insignificant. To supply this current directly from a power supply can involve a capacity greater than what is available from local services, such that dedicated test units with their own generator sets may be necessary. These can be physically very large and heavy, with consequent high test costs.

The capacitance of the generator can be compensated by the use of inductive reactance in a parallel resonant circuit. The initial tests undertaken in New Zealand at 23kV involved a complex arrangement of series/parallel matching transformers and LV inductors. While successful, the apparatus weighed over 6 tonnes.

An alternative test apparatus has been designed around a partial core concept. The device has laminated core material only in the space enclosed by the windings. There are no limbs and yokes as found in conventional full core transformers. One of the characteristics of these transformers is that they have relatively low magnetising reactance. Through judicious design, this reactance has been matched to generator stator capacitance such that the reactive current of the insulation is provided by the transformer magnetisation. This means that the supply only has to provide the real power losses of the transformer and in practice any mismatch between the magnetisation current and the stator capacitance. The primary winding can thus be downsized to conduct only this supply current.

To test the resonant concept in practise, a high voltage inductor was designed and used in the testing of a generator at a New Zealand power station, Matahina. It supplied 115kvar of reactive power compensation at 23kV. The inductor weighed 120kg. The inductor was subsequently modified by the addition of a low voltage primary. A laboratory test, with an appropriate capacitive load, showed that the required high voltage of 23kV could be obtained from energising the primary at 285V at 60A or at a rating of about 1/7th the load.

A further resonant transformer was then designed for a 334kvar capacitor load to test Manapouri power station generator stators at 31.5kV. This transformer was subjected to an induced overvoltage test of 40kV for 3 minutes, before demonstrating compensation of a 0.57μF load from a 230V supply. It also provided 28.6kV to a 1.04μF load, essentially being the design value of the actual generator stator. It was excited from a nominal 400V supply, and gave a gain of 16 in VA. The transformer has a finished weight of approximately 300 kg.

On site, the resonant transformer was used to supply 36.5kV to the initial batch of installed stator bars at 0.49μF. This is the equal to a capacitive load of 205kvar. It also withstood a stator flashover proving the electrical and mechanical integrity under short circuit.

In a follow up test, the Matahina resonant transformer was reinsulated to operate 32kV and inserted as an inductor in parallel with the Manapouri resonant transformer. Each complete phase of the generator stator of 1.06μF was tested. The output to supply VA ratio was 11.

6. REFERENCES

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