Stator earth fault detection & evaluation of delaminated stator bar ground wall-insulation of generator G-4 of HPP Chhukha – A case study

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DOI: https://doi.org/10.17102/bjrd.rub.10.2.014

Abstract

Protective devices are employed to monitor and isolate the faulty equipment whenever faults occur in the power system. In the generator protection system, a conventional stator earth fault protection, which is based on residual over voltage (aka neutral voltage displacement) principle, is observed to be inadequate. The paper thus, discusses on how helpful a modern approach of 100% stator earth fault protection scheme is, and proven effective in generator G-4 of Chhukha Hydropower Plant (CHP). Also, to assess the health of stator windings, insulationresistance (IR) measurement is the foremost test that needs to be performed to qualify for go-ahead with other insulation tests. HV DC ramp and tan δ tests are not uncommon as the tests have been proven useful in evaluating the condition of the groundwall insulation of stator coils.Therefore, this paper also illustrates on investigation and analysis of the test results obtained for a bar, suspected to have groundwall insulation breakdown, due to a number of factors. Thetest results obtained are compared with that of the other test specimens.

Keywords – *Delamination, dielectric strength, HV DC ramp, insulation resistance, statorearth fault*

Introduction

Generator is a composite equipment that comprises of stator (core & winding) and the rotor (field coils). One of the key parts of a generator is the dielectric insulation and thus, its timelycondition assessment may save the consequential damages. The age factor combined with mechanical and electrical stresses, and dirt & moisture contamination are key attributes whichcontribute to the failure of the insulation of a stator winding. Inadequate design & manufacturing, or negligence during transportation and installation are other factors.

A generator is protected with a number of protection schemes. However, in this paper, stator earth fault protection schemes, the conventional type as well as the 100% stator earth fault protection schemes, available with respect to generators of HPP Chhukha, are illustrated. HPP Chhukha generator G-4 comprises of 192 stator slots of nominal voltage 11 kV, 84MW, with double layered wave winding, arranged in two parallel paths per phase. Stator windings, insulated with class F insulation, having mica on a glass fibre backing tape impregnated and consolidated with polyester resin, were installed in mid 1980s.

This paper is arranged in different sections, with each section sequentially highlighting the introduction, stator earth fault protection schemes, diagnostic tests with analyses of results andeventually the recommendations & conclusion.

100% stator earth fault protection scheme and its benefits

The conventional stator earth fault protection scheme based on overvoltage principle is said toprotect only up to 90-95% of the stator winding, which means, this protection scheme is inadequate especially if the earth fault occurs near the generator neutral (Rahman, Reza, Chakraborty, Hassan, & Hossain, 2015). The fault had triggered 100%, not 95%, stator earth fault protection setting on August 3, 2019 in generator G-4 of HPP Chhukha. This, indeed, has made the fault troubleshooting relatively easier as the fault location was suspected within 5- 10% of the stator winding from the neutral end. Fig. 1 depicts the two types of stator earth faultprotection scheme. Conventional type stator earth fault protection scheme uses the residual over voltage principle while 100% stator earth fault protection scheme uses a low voltage of sub-harmonic frequency, typically 15-20 Hz, signal that is injected to monitor the residual current (Rahman, Reza, Chakraborty, Hassan, & Hossain, 2015; Mozina). The injector measures the total line-to-neutral capacitive reactance X_{CO} contributed by stator windings, connected buses and the generator transformers, and it's given by (1).

$$X_{CO} = \frac{1}{2\pi f_0 C_0} \tag{1}$$

Use of low frequency subharmonic makes the capacitive reactance a high impedance (Mozina). When a ground fault occurs anywhere in the stator winding, the capacitance is shorted in that phase and a higher current flows which is then detected by an overcurrent element of relay 64S. Its added advantage besides protecting 100% stator winding over the conventional stator earthfault protection is, this scheme can detect a ground fault in off-line condition as well, prior to it being put into service.

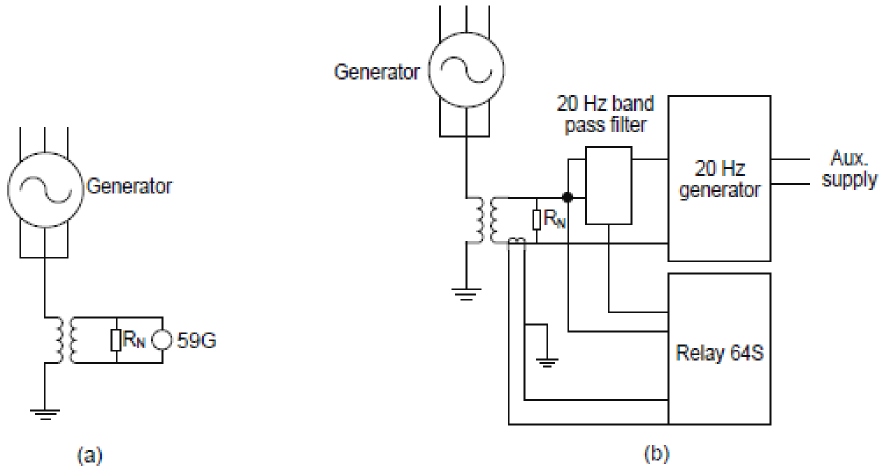

Fig. 1 Schematic of stator earth fault protection (a) Conventional type

(b) 100% stator E/F sub-harmonic frequency based

In case of HPP Chhukha, an injector of 25V, 20 Hz, connected across the secondary of neutral grounding transformer, is available. The protection setting is in terms of impedance, where threshold is computed by taking account of capacitances and the applied voltage signal.

Diagnostic tests on stator winding bar specimens & result analysis

The stator earth fault detection by 100% stator earth fault protection scheme of G-4 at HHP Chhukha then called for a thorough insulation diagnostic tests of its stator winding. The diagnosis was inevitable so as to properly locate the fault and make necessary assessment of other remaining stator bars to be resorted back to service. The diagnosis was necessary as well for the insulation assessment of new spare stator bars, considered then as a replacement for the faulty bars identified. Insulation test is conducted in the factory, in the field during installation, as a condition of acceptance, to verify the efficacy of repairs or maintenance, after a system disturbance or extended outage, or on a routine basis during the lifetime of the machine (IEEE,2002). Generally, two or more types of diagnostic tests (insulation resistance (IR), DC ramp, polarization index (PI), dissipation factor (DF), and/or partial discharges (PD)) are performed to establish that the insulation has deteriorated. However, in this paper, IR, DC ramp and DF only have been accounted to evaluate the integrity of the dielectric insulation of the sampled specimens as detailed hereunder.

Insulation resistance (IR)

IR is the capability of the electrical insulation of a winding to resist the direct current, which is determined by ratio of applied direct voltage to measured insulation current, corrected to 40˚C.

The voltage application time is usually 1 min (I_{R1}) or 10 min (I_{R10}), however, other values can be used (IEEE Power and Energy Society, 2013; IEEE Power Engineering Society, 2000). The total resultant current (I_T) is the sum of four different currents: surface leakage (I_L), geometric capacitance (I_C), conductance (I_G), and absorption (I_A). I_C usually does not affect the measurements as it disappears within 1 min, I_A decays at a decreasing rate, I_L is almost constantover time and I_G is essentially zero if the insulation is dry. A significant decrease in IR value with the increase in applied voltage may be an indication of deterioration of the insulation aggravated by contaminants and moisture. Table 1 shows the guideline for DC voltage to be applied during IR test.

Table 1 Guideline for DC voltage to be applied during IR test (IEEE Power and EnergySociety, 2013)

Winding rated voltage (Vac)	IR test voltage (VDC)
< 1000	500
1000 – 2500	500 – 1000
2501 – 5000	1000 – 2500
5001 – 12000	2500 – 5000
> 12000	5000 – 10000

Prior to conducting HV DC voltage ramp and tan δ hipot tests, the specimen bars were subjected to a specified voltage for 1 minute and IR & current were recorded as in Table 2. Since test voltage 5kV couldn't be applied on the *old bar 69*, other bar specimens were also tested with 1kV to get a fair comparison of the measured IR. The IR of *old bar 69* was noted to be little lower than the IR of other sampled bars, which was the first indication of insulationquality being deteriorated.

Table 2 Measured IR of the test specimens

Sl. No.	Test specimen	Applied voltage (V)	IR (GΩ)	Measured current (nA)
1a	New bar		78.2	13.0
1b	Old bar 77	1000	116.4	6.61
1c	Old bar 69		28.30	40.8
2a	New bar		12.11	549

2b	Old bar 77	5000	17.46	293
2c	Old bar 69		Test voltage couldn't be applied	

Tan δ or dissipation factor

Tan δ or DF determines how much power is dissipated through the dielectric insulation. It's given by tangent of the loss angle δ. The resultant current I_T, which appears due to applied voltage V, comprises of charging component I_C and resistive loss component I_R. I_C aka geometric capacitive current depends on the capacitance of the winding and thus, lower the capacitance value, the better it is.

Phasor representation of DF is as shown in the Fig. 2, and it is determined as,

$$\tan\delta = \frac{I_R}{I_C} \quad (2)$$

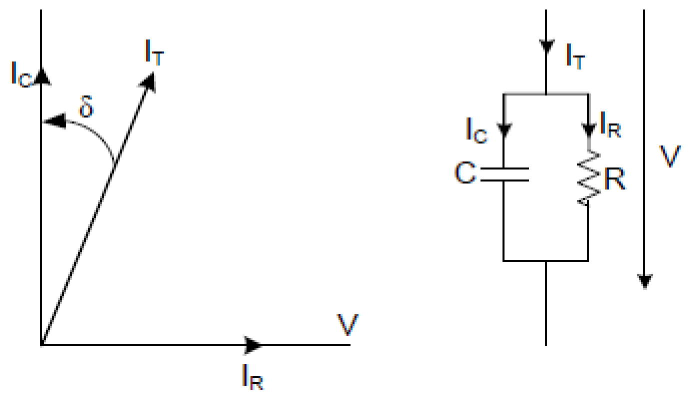

Fig. 2 Phasor representation of tan δ value & its equivalent circuit

Table 3 shows the standard tan δ values as specified in reference (IEC Central Office, 2015) for the single coils and bars, which is widely being followed during the test of stator coils.

Table 3 Maximum values of tan δ of single coils and bars (IEC Central Office, 2015)

Characteristics values of tan δ measured at room temperature		
1	Initial value of tan δ at $0.2U_N$	20×10^{-3}
2	Δ tan δ per $0.2U_N$	5×10^{-3}
3	tan δ tip-up between $0.2U_N – 0.6U_N$	5×10^{-3}

Table 4 shows the result of tan δ test conducted on the sampled specimens. Tan δ of *new bar* has been observed in compliance to the standard recommended in Table 3, while the *old bar 69* couldn't withstand the test voltage beyond $0.2U_N$, where U_N is the rated generator voltage (in this case 11 kV).

Table 4 Measured tan δ and capacitances of specimens

Test specimen	Test kV	mA	Tan δ	Cap. (pF)	tan δ tip-up ($0.6U_N$ - $0.2U_N$)
	2.200	2.481	9.95×10^{-3}	3587.07	
	4.400	4.967	11.25×10^{-3}	3592.38	
(new bar)	6.599	7.464	12.67×10^{-3}	3597.65	2.72×10^{-3}
	8.800	9.971	14.32×10^{-3}	3603.22	
	11.001	12.491	16.19×10^{-3}	3609.91	
	2.200	2.228	9.65×10^{-3}	3218.02	-
Old bar 69	4.400 <	Test voltage couldn't be appliedbeyond $0.2U_N$, indicating a breakdown of insulation			

DC ramp test

DC hipot test is performed to evaluate the dielectric strength of winding insulation and to ascertain the efficacy of the equipment in service. In this test, current which is the sensitive indicator, is recorded as a function of applied voltage (Mc Dermid & Bromley, 2001; Sedding,et al., 2004). It is claimed that the V-I curve would indicate the defects and modes of deterioration, if any, on the insulation.

The standard recommended hipot test level is (2E+1) kV for the power frequency AC test and1.7(2E+1) kV for DC test for a new stator winding, where E is the line-to-line voltage. However, in most cases, 57-80% of 1.7(2E+1) kV is applied, and in some cases, voltages 1.25E, 1.7E, 1.13E and 25µA leakage current limit are also reported to apply during maintenance tests. As a part of regular maintenance program, the winding in service may be tested, including hipot tests, every 3 to 6 years (Gupta, Stone, & Stein, 2009).

Fig. 3 shows the DC ramp test V-I characteristics of old stator bars compared with a new bar specimen, wherein, 2kV/min. was the ramp rate, applied until around 20kV. The *old bar 69* could withstand only up to 5kV (approx.), which indicates, the insulation has become so weak.During the test, the insulation breakdown occurred too on *old bar 77* at the verge of disconnecting the test voltage. These results are shown by sudden upturns of V-I characteristicsas plotted in Fig. 3.

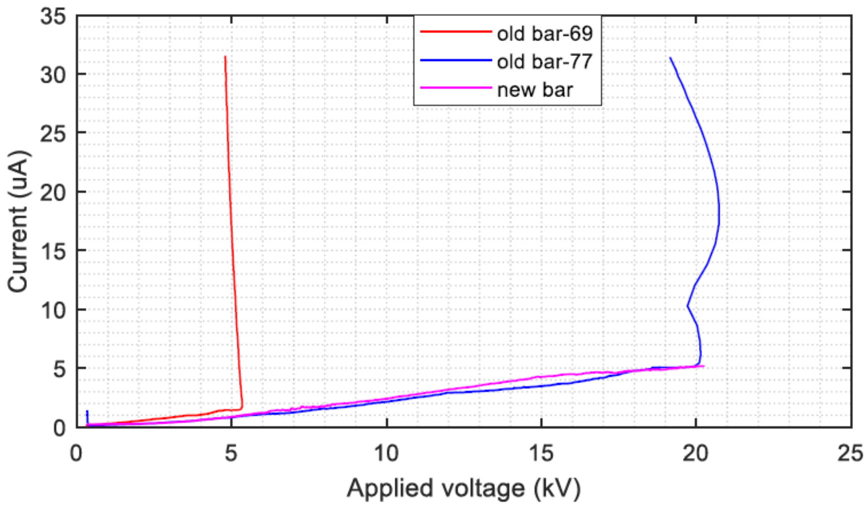

Fig. 3 DC ramp test V-I characteristics

Conclusion

A typical stator earth fault on G-4 of CHP on August 3, 2019, detected by 100% stator earth fault protection scheme, combined with neutral voltage displacement-based protection scheme, has helped troubleshooting and locating the fault faster. Had there been no ‘low frequency injection method’ based protection scheme integrated, the weakened insulated bar positioned near the neutral point might have failed eventually with severe consequential damages. Thus, this protection scheme, which wasn’t available until the recent upgradation of protection system, was well treasured in this particular case. It is, therefore, opined that both the protection schemes for protection of stator winding must be enabled. With the paradigm shift in the maintenance practices of the electrical equipment by the utilities, diagnostic tests may be conducted periodically on the generator stator windings as well. Such tests results indeed would keep track records of the condition of the generators and could be used as future references. The combined diagnostic tests detailed in this paper, if not more, deemed adequate to draw an inference and get the firsthand information on the health of the electrical insulation.

Acknowledgement

Fund for this paper sponsored by the authors’ parent organization, Druk Green Power Corporation Limited is acknowledged. Gratitude is further extended to all the co-authors for their invaluable contribution for this paper.

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