Detailed Study on Insulation Coordination of a 25kV Power System Connected with a VCB and Transformer

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Abstract – Recently, unusual transformer failures have been reported in 25kV power systems connected with a VCB and transformer. In this study, performance of the protection system, dielectric strength of the transformers, characteristics of switching surges and resonance phenomena were analysed and assessed. All investigations regarding the insulation breakdown of the transformers were carried out by simulations, laboratory tests, factory tests and on-site measurements in order to thoroughly investigate the root causes. Furthermore, experimental methods for investigating the resonance phenomenon were derived and tests were conducted applying the derived method to recreate the phenomenon in the transformer. It is found that resonance between the transformer and switching surge generated by closing a VCB can initiate the breakdown of internal windings of a transformer.

Keywords: Insulation coordination, Switching surge, Resonance phenomena

1. Introduction

Since the beginning of the operation in 2009, several unusual transformer failures were reported in 25kV power systems connected with a VCB and transformer. The first investigation on the transformers showed that all the failures had occurred at high voltage windings. It was also shown that these insulation breakdowns had occurred only when the VCB was closed under unloaded condition in depot. The following investigations reported that there was no overvoltage or lightning surge at power line at the time. Subsequently, the investigation found out that the failed transformers not only had passed all the tests in compliance with IEC-KS standard code and buyer's request tests, but also had had protective devices installed on their power systems.

Several similar transformer failures had been reported in the literatures [1-4]. In particular, the resonance between the transformer and vacuum circuit breaker (VCB) arises when VCB closes within the power system. However, the previous studies have not described the detailed experimental results and systematic analysis process of searching the root causes of a transformer failure. They have introduced the guide line, effects, modeling and analysis methods for switching transients induced by transformer/breaker interaction in distribution transformers.

In this paper, in order to thoroughly investigate the root causes, quality of feeding voltage, performance of the protection system, dielectric strength of the transformer, characteristics of switching surge(VCB) and resonance phenomena were analysed and assessed. Fig. 1 shows the

Fig. 1. Failed transformer with its coil-to-coil flashover

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All investigations regarding the breakdown of the insulation of transformer were carried out by simulation, laboratory tests, factory tests and on-site measurements. The root causes were examined systematically. Furthermore, an attempt has been made to assess the possibility of resonance between chattering frequency of the circuit breaker(VCB) and natural frequency of the transformer based upon experimental results.

2. Analyzes and Experiments

2.1 Evaluation of feeding voltage

Firstly, Fig. 2 shows the power system connected with a VCB and a failed transformer(MTR). Power from the feeding substation is sequentially supplied to the transformer via protective devices with VCB. Protective devices consist of FC(ferrite core), VCB(vacuum circuit breaker), LA (lightning arrestor) and SG(spark gap)[5,6]. There are traction motors and general facilities as loads of secondary windings of the transformer.

The feeding voltage supplied on the system ranges between 19kV~29kV according to IEC 60310 shown in

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Table 1. Transformer design criteria

Rated voltage	AC 25 kV, 60 Hz
Voltage range	19 kV~29 kV
Power frequency test voltage	AC 60 kV
FLI(Full Lighting Impulse)	150 kV(170 kV)
Transformer capacity	6.2 MVA

Fig. 2. 25 kV power system **Fig. 3.** Test setup of protective system

Table 1. The power line voltage was measured to see the voltage of the normal operation which was stable at 27.5kV. We found out that the range of the power line voltage is between 26kV~28kV from a long-term monitoring result. Sometimes instant voltage momentarily reaches up to 28.5kV~30kV. However, insulation breakdown of the transformer may not be caused by this instant voltage, judging from the experimental results and relevant IEC-KS standard codes [7-9].

2.2 Evaluation on performance of protection system

The protection system of the transformer which supplies large electric power to loads from grid is consist of a VCB(Vacuum Circuit Breaker), LA(Lighting Arrester) and SG(Spark Gap), as shown in Fig. 1. In this system, the rated voltage and current of VCB are 29kV, 1,000A and the residual voltage of LA is 108kV(8/20us). In addition, the specification and BIL(Basic Insulation Level) of SG are 28kV, 400A and 170kV(1.2/50us).

Fig. 3 shows the test setup for the evaluation on performance of the protection system and its performance was investigated considering the diverse front and tail waves of impulse test voltage.

Table 2 indicates the measured data of residual voltage of LA as a function of the front wave time of test voltage

Table 2. Results of measurement of residual voltage of LA

Case	0.3μs/43μs		1.3μs/48μs		7μs/93μs		FLI spec.
	100(kV)	150(kV)	100(kV)	150(kV)	100(kV)	150(kV)	
Residual voltage LA downstream (kV)							-
1	86.1	88.6	75.0	80.6	75.4	75.6	No break-down of spark gap
2	83.8	85.5	75.1	78.6	74.5	74.3	
3	85.5	88.7	74.7	79.9	75.6	75.4	
4	82.1	84.9	76.5	83.0	75.5	75.6	
5	81.8	94.9	75.2	80.1	76.2	76.0	

Table 3. Voltages on VCB on

Case	Vrms(kV)	Vpeak(kV)	Vpeak-peak(kV)
1	31.6	92	146
2	28.7	55	101
3	27.9	53	98

Fig. 4. Voltage waveform of FLI 230kV

(FLI). From the results, the residual voltages of LA which is one of the protective components in this system were restricted below 90kV when 100 and 150kV impulse test voltages were supplied to the system. We can see the measured residual voltages were increased inversely proportional to the front wave time of impulse voltage. Fig. 4 shows the measured wave of residual voltage of LA when 230kV impulse test voltage is applied. From the wave form, it is shown that the residual voltages of LA was restricted to 79.161kV

2.3 Evaluation on VCB switching transient

Switching transient on an unloaded transformer having a reactance-capacitance network has an impact on overstressing insulation system of a transformer. Therefore, evaluation on the magnitude of switching voltage in a 25kV power system with protective device is required. Table 3 shows the on-site measured data of VCB switching on. As a result, the magnitude of switching on was higher than that of switching off. Maximum residual voltage of this LA as shown Table 3 was recorded as 92kV, which is below 150kV, basic insulated level of the transformer. An example of VCB switching on of an unloaded 6.2MVA, 25kV transformer is shown in Fig. 5. Meanwhile, the chattering frequency of this circuit breaker was measured to be 30~34kHz during the closing operation.

Fig. 5. Transient voltage waveform of VCB on

Fig. 6. Electric field distribution between layers of high voltage winding

Fig. 7. Test setup and specimen for breakdown test of high voltage winding layers

2.4 Evaluation on insulation system of a transformer

The subject transformers require the dielectric strength to be higher than that of industrial transformers [10,11]. Normally, an insulation design which meets 150kV BIL(Basic Insulation Level) is required by international test standard. Fig. 6 shows the simulated results of analysis on the electric field distribution between layers of high voltage winding under a condition of 49.4kV potential difference between these layers. As the result, the minimal insulation safety margin of layers 10- to-11 of HV winding is 2.51 times compared to the breakdown voltage of the designed insulation structure as shown in Fig. 6.

Fig. 7 indicates the test setup and specimen for the breakdown test of high voltage winding layers to get the actual breakdown voltage values of the transformer in this paper.

Table 4. Test results of breakdown of layers of high voltage winding

Case	Average voltage(kV)	2% Breakdown voltage(kV)	Breakdown photo
HV Coil Turn-Turn · 0.23T/one side · 0.46T/both sides	55.09	41.08	
HV Coil Layer-Layer · 0.23T/one side · 0.46T/both sides	164.46	122.51	

Table 4 shows the average and 2% probability breakdown voltages of the layers and turns obtained from the full lightning impulse test.

From the result of breakdown experiment applying 1.3 μ s/48 μ s impulse test voltage, the measured average breakdown voltage of specimens was about 164.46kV. Therefore, it was found out that the dielectric strength has sufficient margin to insulation breakdown of the transformer because the calculated maximum voltage distribution of layer to layer was 50.1kV.

2.5 Evaluation on system resonance

Numerous papers have presented a possibility of resonance between the natural frequency of transformer and the chattering frequency of circuit breaker in such this power system connected with a VCB and transformer. In this paper, we applied an experimental method in order to closely find out the resonance phenomena in this system. Backgrounds of detailed experiments are as follows;

- Basic insulation level(BIL) of transformer was designed according to IEC std. and passed all the performance tests of the transformers.
- There have been occasional breakdown following the sparkgap(SG) operation installed at protection system in depot even though transient voltages are suppressed by Lightning arrester(LA) below approximately 90kV.
- There are some similar cases in a number of instances where the transient overvoltage by the resonance phenomena exceeds transformer BIL, resulting in failures. For examples, Shinkansen railway power system in Japan and railroad substation in USA [12-14] had gone through similar failures.

At first, the measured chattering frequency range of this

Fig. 8. Transient waveforms of VCB switch operation

Fig. 9. Test circuit of sweep frequency resonance analysis

Fig. 10. Characteristic of sweep frequency resonance analysis

Fig. 11. Test circuit for resonance phenomena experiment

circuit breaker was 30 kHz~34 kHz during the closing operation. Fig. 8 shows the instant frequency at closing of the VCB. Meanwhile, in order to check the natural frequency of the transformer, a test consisting of a system with the same transformer and SFRA (Sweep Frequency Resonance Analysis) measurement device for HV windings was conducted. This is shown in Fig. 9.

Fig. 10 shows that impedance inflection points of the transformer are 0.9kHz, 38kHz and 75kHz respectively.

Fig. 11 shows the test circuit used to measure the voltage of internal windings of the identical transformer at a resonance frequency. As a result, it was verified that measured voltages are 1.5~2.1 times higher than the supplied voltage of HV windings of the transformer at 32 kHz~36 kHz and 1.2~1.7 times at 68 kHz~75 kHz respectively.

Fig. 12. Voltage magnification at resonance frequency (1kHz) in transformer

Fig. 13. Voltage magnification at resonance frequency (32.7kHz) in transformer

However there was no magnification of voltages inside the transformer at 1kHz range as shown in Fig. 12.

Fig. 13 shows that a resonance oscillation occurs at 32.7kHz. From the wave form, when the input of 2 V_{peak-peak} is applied to the HV windings of the transformer, the voltage is magnified, yielding 4.1 V_{peak-peak} as the output.

5. Conclusion

In this study, detailed investigations on insulation coordination of a 25kV power system connected with a VCB and transformer was carried out experimentally and analytically with the real-use system in order to look for the root causes of unusual transformer failures. The results are summarized as follows;

1) The root causes of a transformer failure induced by abnormal surge such as the disturbance of feeding voltage, switching surge, and lightning impulse could not be found from the results of experimental and systematic analysis.

2) Meanwhile, both of the measured frequency of SFRA (Sweep Frequency Resonance Analysis) and chattering frequency of the circuit breaker fell within the same range of 30~34kHz during the closing operation. From the experimental results, it was also investigated that the

measured voltage between transformer's HV winding layers was increased by 1.5 ~ 2.1 times the supplied input voltage at 32.7kHz. It was found that resonance voltage between transformer and switching surge by closing the VCB can initiate the breakdown of internal windings of a transformer.

In summary, it is required to check that, in a power system connected with a VCB and transformer, insulation breakdown caused by resonance may occur without external disturbance. This kind of failures can be not prevented by the current codes and guide. Therefore, a thorough examination is needed between customers, contractors and manufacturers during a transformer design phase. As all the data and results acquired through this research are from the experiments based on real-use power system in operation, this paper should be a useful reference in evaluating and designing a power system.

References

- [1] Transformers and Switchgear Committee of the IEEE Power & Energy Society "IEEE Guide to Describe the Occurrence and Mitigation of Switching Transients Induced by Transformers, Switching Device, and System Interaction," *IEEE Std C57.142™-2010*, April 2011.
- [2] T. Van Craenenbroeck and et al, "Detailed study of Fast Transient Phenomena in Transformer and Substations Leading to an Improved System Design," 15th International conference on Electricity Distribution CIRED, June, 1999.
- [3] T. Van Craenenbroeck and et al, "Experimental and Numerical Analysis of Fast Transient Phenomena in Distribution Transformers," *IEEE Power Engineering Society Winter Meeting*, vol. 3, 2193-2198, 2000.
- [4] Ulisses R.R. Massaro, Ricardo Antunes, "Electrical Transient Interaction between Transformers and Power System," *IPST2009*, Japan June 3-6, 2009.
- [5] A. Haddad and et al, "Co-ordination of spark-gap protection with zinc-oxide surge arresters," *IEE Proc.-Gener. Transm. Distrib.*, vol. 148, no. 1, January 2001.
- [6] W. Piasecki, G. Bywalec and et al., "New approach towards protecting electrical equipment insulation systems against Very Fast Transients," *IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, 2007.
- [7] IEC 60076-1 std., "Power transformers-Part 1: General," 1976.
- [8] IEC 60076-3 std., "Power transformers-Part 3: Insulation level and dielectric tests," 1980.
- [9] KS C IEC 60850 std., "Supply voltage of traction systems," 2012.
- [10] IEC 60310 std., "Railway applications-Traction transformer and inductors on board rolling stock," Third edition, 2004.
- [11] KS C IEC 60349 std., "Electric traction – Rotating electrical machines rail and road vehicles," 2012.
- [12] Yoshifumi Mochinaga and et al, "Occurrence and Countermeasures for High-frequency Reignition Oscillation in Vacuum Switch for Shinkansen Changeover Section," *T.IEE, Japan*, vol. 111-D, no. 9, 1991.
- [13] David D. Shipp and et al, "Transformer Failure Due to Circuit Breaker Induced Switching Transients," *IEEE Central Tennessee Section*, May 1, 2012.
- [14] CIGRE Working Group C4.307, "Resonance and Ferroresonance in Power Networks," Feb., 2014.

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