Analysis on Transients Recovery Voltage of Circuit Breaker according to different loads condition at 345 kV MTR tertiary side

J.W.Woo, K.S.Han, J.Y.Yoon, D.J.Kweon, Y.J.Won

Abstract – By several purposes in KEPCO, there are the different loads at 345 kV MTR tertiary side, which are connected by circuit breaker. There are reactors, condensers and transformers. During normal operation of a power system, circuit breakers will be operated several times in a day. During opening, interruption of inductive/capacitive currents will cause overvoltages. In contrast to fault interruption duties, where the breaker may never be exposed to its full rated fault duty in its lifetime, the breaker is exposed to the same severe stress each and every time it switches inductive/capacitive currents.

In these conditions, we had experienced the several circuit breaker's failures. So, we had investigated the transient phenomena by switching different loads. When these different loads were opening between the circuit breaker contact gaps could lead to very steep overvoltages. This study has been carried out by the simulation calculation using the software ATP/EMTP. For analysis, we had considered the normal operation and fault clearing operation per different loads condition. From calculation results by APT/EMTP, we had compared with TRV standards of KEPCO, IEC and IEEE.

Keywords: TRV(Transient Recovery Voltage), Circuit Breaker, Substation, Overvoltages, EMTP(Electro-magnetic Transient Program)

I. INTRODUCTION

A reactor, a capacitance, and a substation transformer, etc., are connected for several purposes to the tertiary side of a main transformer in a 345 kV substation via a circuit breaker.

In case of various kinds of faults, or if a circuit breaker is activated in normal state, temporary recovery voltage (TRV) occurs between the contact gaps of the circuit breaker. As such, the state of temporary voltage varies according to the condition of load connected to the condition of the bus. Whether or not to meet these conditions is decided by the temporary recovery voltage rating.

Currently, major circuit breaker related standards include IEC 56 and ANSI C37.06. In general, all countries worldwide apply circuit breaker related standards that are based on these two standards, and ES, Korea's own standard, is no exception. The two standards described above differ slightly with each other in terms of system characteristics, with IEC standards applying mostly to European countries. In contrast, ANSI standards are used mostly in North America. Furthermore, IEC is based on the actual measurement value, whereas ANSI is based on the value derived from model system interpretation.

Recently, KEPCO experienced several accidents involving the burnout of a circuit breaker connected to the tertiary side of the main transformer.

This paper examined the relevant circuit breaker accidents, analyzed the temporary voltage according to the condition of the connected load, and evaluated whether the appropriate rating was met. In this study, we had been carried out by the simulation calculation using the software ATP/EMTP. For analysis, we had considered the normal operation and fault clearing operation per different loads condition. From calculation results by APT/EMTP, we had compared with TRV standards of KEPCO, IEC and IEEE.

II. OUTLINE OF ANALYSIS

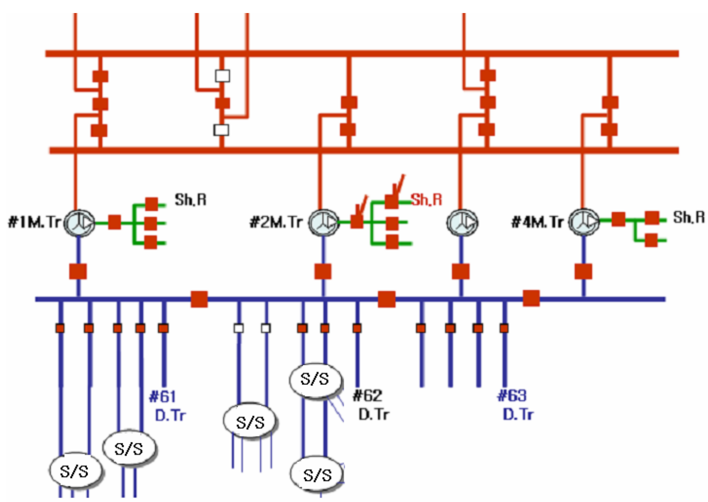

Fig. 1. Modeling case

The phase angle and equivalent impedance of the power supply terminal in the case of an equivalent system were obtained through PSS/E calculation. To consider the mutual effects among the primary, secondary, and tertiary sides of the main transformer, phase-to-phase and phase-to-ground capacitance values were also taken into account. In the case of the 345 kV main bus, electricity is received by the adjacent

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power station and substation terminal; in the case of the 154 kV bus, the 154 kV line nearby is also connected.

The equivalent model based on PSS/E equivalence was also applied to each line and substation.

Major examination conditions are ;

- Examination pursuant to the tertiary side load conditions: reactor, condenser (substation transformer)
- Examination of TRV of the circuit breaker at opening case in normal state
- Examination of TRV of the circuit breaker considering the effects of ground-fault conditions and time difference in circuit breaker opening (voltage phase difference)
  - In case of phase A ground fault
  - In case of phase C ground fault
  - In case of phases B and C ground fault
  - In case of phases A, B and C ground fault

III. ANALYSIS RESULTS

For the abovementioned interpretation case, the temporary recovery voltage waveform of the circuit breaker was analyzed, and the initial increase rate of the temporary recovery voltage (kV/μsec), its crest value, and the fault current (kA) were presented in each figures. The symbols in figures showing the interpretation results have the following meanings ;

- V_C [kV] : Peak value
- RRRV [kV/μsec] : Initial increase rate of the temporary recovery voltage
- I_F [kA]: Fault current running in a circuit breaker

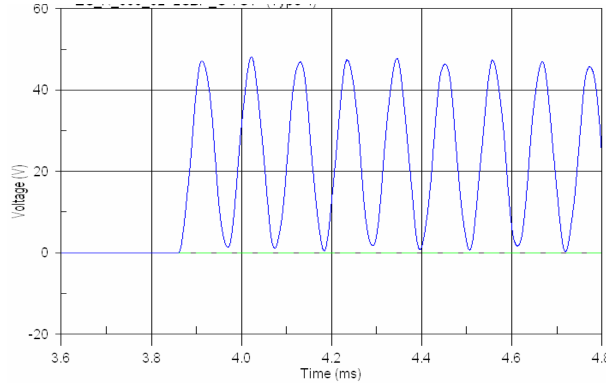
(1) Interpretation results in the case of reactor loads

Table 1. TRV Interpretation results in the case of reactor load (normal state)

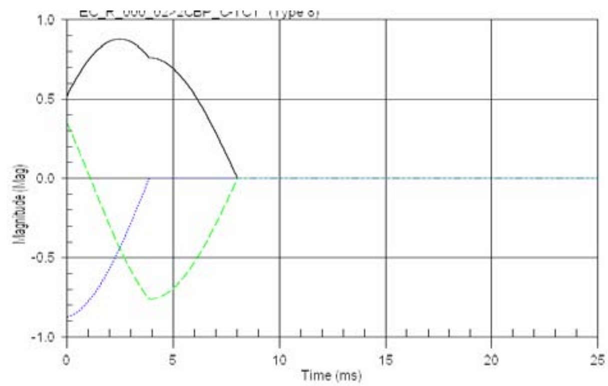
Case	CR02	CR05	CR08	CR11	CR14	
CB Open time	2msec after	5msec after	8msec after	11msec after	14msec after	ES 150
Vc	47.184	47.425	47.297	47.207	47.452	47
RRRV	0.907	0.912	0.910	0.891	0.895	1.12
I_F	0.879	0.879	0.879	0.879	0.879	T10

First, for the reactor loads, the TRV between the contact gaps of the circuit breaker in case of cutoff in normal state was examined. Table 1 shows the examination results of the opening case of one bank of the reactor in normal state. As shown in figure 2 and table 1 on the breaking current, the opening condition was about 0.9 kA, thereby falling under T10 of the standard (10% of the rated current should be cut off).

Based on the ES standard value, the peak value of the temporary recovery voltage (V_C) slightly exceeded the standard value of 47 kV; since calculation was made under a severe condition, however, the peak value could be said to satisfy the requirement. The increase rate (RRRV) of 0.9 kV/μsec or less also satisfied the standard value of 1.12.



(a) Voltage



(b) Current

Fig. 2. Interpretation results in the case of reactor load (normal state)

Next, we had examined TRV between the contact gaps of the circuit breaker in case of phase A ground fault. Table 2 shows the examination results of the opening case of one bank of the reactor in normal state in case of phase A ground fault. As shown in the figure and table on the breaking current, the opening condition was about 1.046 kA, thereby falling under T10 of the standard(10% of the rated current should be cut off). Based on the ES standard value, the peak value of TRV(Vc) satisfied the requirement.

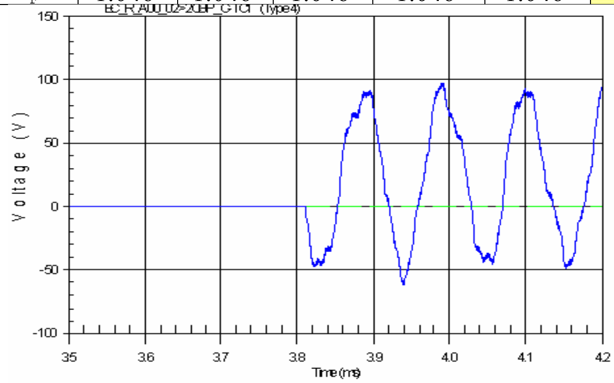
Note, however, that part of the increase rate(RRRV) satisfied the standard value, whereas part of it exceeded the standard value. In addition, the resulting value differed according to the opening time. This is because the voltage phase varies according to the start time of opening of the circuit breaker after ground fault in opening case.

Also, we had examined TRV of opening case in phase C ground fault. Based on the ES standard value, both the peak value(Vc) and increase rate(RRRV) satisfied the requirements.

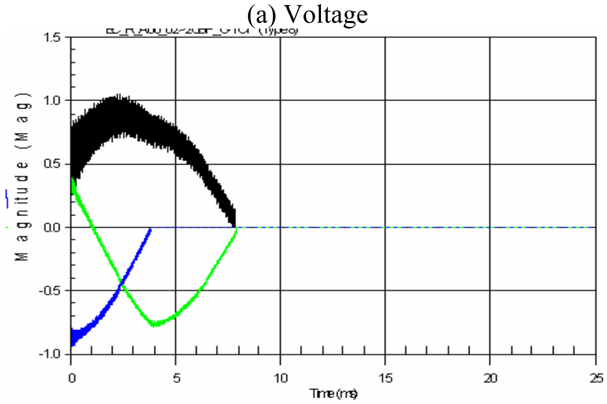
Table 2. TRV Interpretation results in the case of reactor load (phase A ground fault)

Case	CRa02	CRa05	CRa08	CRa11	CRa14	
CB Open time	2msec after	5msec after	8msec after	11msec after	14msec after	ES 150
Vc	47.682	4.445	12.475	24.114	34.239	47

RRRV	3.668	4.445	1.248	2.010	0.376	1.12
I_F	1.046	1.046	1.046	1.046	1.046	T10



(a) Voltage



(b) Current

Fig. 3. Interpretation results in the case of reactor load (phase A ground fault)

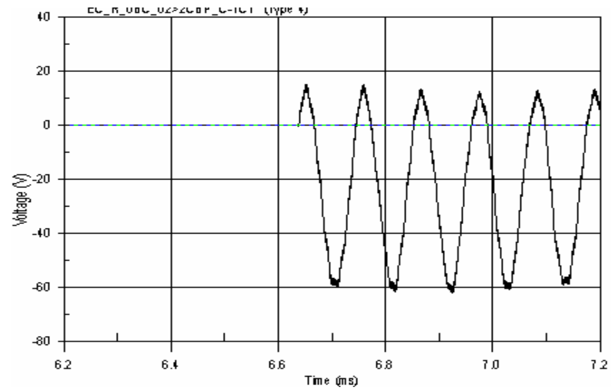
Table 3. TRV Interpretation results in the case of reactor load (phase B and C ground fault)

Case	CRbc02	CRbc05	CRbc08	CRbc11	CRbc14	
CB Open	2msec after	5msec after	8msec after	11msec after	14msec after	ES 150
Vc	14.931	14.931	3.733	3.733	8.635	44
RRRV	0.995	1.066	3.733	3.733	0.664	0.42
I_F	32.073	32.073	32.073	32.073	32.073	T100

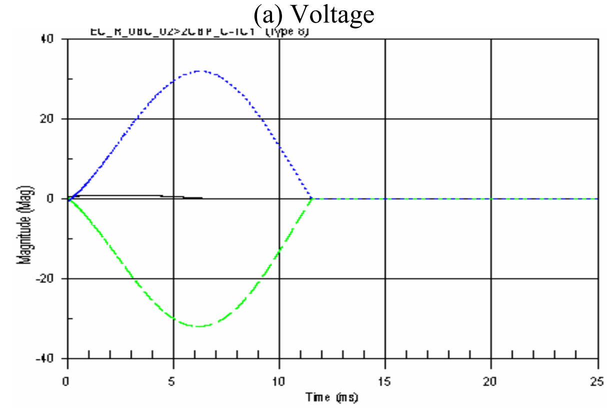
Finally, we had also studied about phases B and C ground fault. The increase rate(RRRV) exceeded the requirements. But, when CB open in case of phases A, B, and C ground fault, part of the peak (Vc) satisfied the standard value, although part of it exceeded the standard value. The increase rate(RRRV) was higher than the standard value.

(2) Interpretation results in the case of condensor loads

Also, we had considered for the condenser loads. First case is for in case of cutoff in normal state. Table 4 shows the examination results of the cutoff of the condenser banks in normal state. The peak value of the temporary recovery voltage satisfied the ES standard requirement, however, that the increase rate exceeded the standard value of 1.12.



(a) Voltage



(b) Current

Fig. 4. Interpretation results in the case of reactor load (phase B and C ground fault)

Table 4. TRV Interpretation results in the case of condensor load (normal state)

Case	C_02	C_05	C_08	C_11	C_14	
CB Open time	2msec after	5msec after	8msec after	11msec after	14msec after	ES 150
Vc	10.789	10.831	10.982	10.755	10.760	47
RRRV	1.798	2.166	2.196	2.151	2.152	1.12
I_F	0.188	0.188	0.188	0.188	0.188	T10

Table 5. TRV Interpretation results in the case of condensor load (phase C ground fault)

Case	Cc02	Cc05	Cc08	Cc11	Cc14	
CB Open time	2msec after	5msec after	8msec after	11msec after	14msec after	ES 150
Vc	79.179	4.967	16.311	25.915	9.244	47
RRRV	0.861	4.967	4.078	0.305	1.541	1.12
I_F	0.337	0.337	0.337	0.337	0.337	T10

Table 6. TRV Interpretation results in the case of condensor load (phase B and C ground fault)

Case	Cbc02	Cbc05	Cbc08	Cbc11	Cbc14	
CB Open	2msec	5msec	8msec	11msec	14msec	ES
Vc	14.064	14.064	40.849	40.849	9.565	44
RRRV	2.813	2.813	2.269	2.269	1.594	0.42
I_F	32.679	32.679	32.679	32.679	32.679	T100

Table 5 shows examination results of TRV of the circuit breaker in case of phase C ground fault. In this case, the peak value of the temporary recovery voltage satisfied the requirement; however, that part of the increase rate satisfied the standard value, whereas part of it exceeded the standard value. Moreover, the resulting value differed according to the time of cutoff. This is because the voltage phase varies according to the start time of cutoff of the circuit breaker after ground fault in case of cutoff.

Table 6 is examination results of TRV in case of phases B and C ground fault. The peak value was less than the standard value of 47kV, however, that the increase rate exceeded the standard value.

In case of phases A, B, and C ground fault, the cutoff condition was about 36~39kA, thereby falling under T100 of the standard (100% of the rated current should be cut off).

Part of the peak value satisfied the standard value, although part of it exceeded the standard value; the increase rate was higher than the standard value.

(3) Interpretation results in the case of substation transformer load

Table 7. TRV Interpretation results in the case of of substation transformer load (normal state)

Case	ST_02	ST_05	ST_08	ST_11	ST_14	
CB Open time	2msec after	5msec after	8msec after	11msec after	14msec after	ES 150
Vc	3.999	3.990	3.988	3.998	3.993	47
RRRV	0.129	0.133	0.125	0.129	0.129	1.12
I_F	0.065	0.065	0.065	0.065	0.065	T10

Table 8. TRV Interpretation results in the case of substation transformer load (phase C ground fault)

Case	STc02	STc05	STc08	STc11	STc14	
CB Open time	2msec after	5msec after	8msec after	11msec after	14msec after	ES 150
Vc	17.042	36.300	19.770	19.232	15.660	47
RRRV	1.704	2.269	0.115	1.282	1.205	1.12
I_F	0.129	0.129	0.129	0.129	0.129	T10

Table 9. TRV Interpretation results in the case of substation transformer load (phase B and C ground fault)

Case	STbc02	STbc05	STbc08	STbc11	STbc14	
CB Open	2msec after	5msec after	8msec after	11msec after	14msec after	ES 150
Vc	18.656	3.964	3.964	3.964	34.315	44
RRRV	1.555	0.305	0.305	0.305	4.289	0.42
I_F	32.580	32.580	32.580	32.580	32.580	T100

In KEPCO, for power supply of substation, the substation transformer was connected at 345 kV MTR tertiary side. For this case, we had examined. Table 7 shows the examination results of the cutoff of the substation transformer load in normal state. As shown in the table on the breaking current, the cutoff condition was about 0.065kA, thereby falling under T10 of the standard (10% of the rated current should be cut off). The peak value and the increase rate satisfied the standard.

Table 8 is for the case of the substation transformer load in case of phase C ground fault. Based on the ES standard value, the peak value satisfied the requirement. However, that part of the increase rate satisfied the standard value, whereas part of it was higher than the standard value. In addition, the resulting value differed according to the time of cutoff. This is because the voltage phase varies according to the start time of cutoff of the circuit breaker after the ground fault in case of cutoff.

Table 9 shows the examination results of the cutoff of the substation transformer load in case of phases B and C ground fault. As shown in the table on the breaking current, the cutoff condition was about 32kA, thereby falling under T100 of the standard (100% of the rated current should be cut off). The peak value was less than the standard value of 47kV. The increase rate exceeded the standard value, however.

Finally, we had examined in case of phases A, B, and C ground fault. On the breaking current, the cutoff condition was about 36~39kA, thereby falling under T100 of the standard (100% of the rated current should be cut off). Part of the peak value satisfied the standard value, although part of it exceeded the standard value. The increase rate was higher than the standard value.

IV. Conclusion

A reactor, a capacitance, and a substation transformer, etc., are connected for several purposes to the tertiary side of a main transformer in a 345 kV substation via a circuit breaker. Recently, KEPCO experienced several accidents involving the burnout of a circuit breaker connected to the tertiary side of the main transformer.

So, we had examined the relevant circuit breaker accidents, analyzed the temporary voltage according to the condition of the connected load, and evaluated whether the appropriate rating was met. The abovementioned examination results per case can be summarized as follows:

Table 15. Summary of TRV Examination Results (reactor load)

Load	Classification	Normal State	1-Phase Ground Fault		2-phase Ground Fault	3-phase Ground Fault
			Phase A	Phase C		
Reactor	Vc	S[1)]	S	S	S	E
	RRRV	S	E	S	E	E

• S : Satisfactory, E : Excessive

Note 1) The maximum calculation value was 47.452 kV or slightly more than the standard value of 47kV; since calculation was made under a severe condition, and the excessive value was deemed insignificant, however, the peak value could be said to satisfy the requirement.

Table 16. Summary of TRV Examination Results (condenser load)

Load	Classification	Normal State	1-Phase Ground Fault		2-phase Ground Fault	3-phase Ground Fault
			Phase A	Phase C		
Reactor	Vc	S	S	S	S	E
	RRRV	E	E	E	E	E

Table 17. Summary of TRV Examination Results (substation transformer load)

Load	Classification	Normal State	1-Phase Ground Fault		2-phase Ground Fault	3-phase Ground Fault
			Phase A	Phase C		
Reactor	Vc	S	S	S	E	E
	RRRV	S	E	S	E	E

○ Based on the ES standard value, both the peak value of the temporary recovery voltage and increase rate satisfied the requirements in the case of the reactor load and normal state. This suggests that TRV has no bearing on an actual accident.

○ Based on the ES standard value, part of the peak value of the temporary recovery voltage satisfied the standard value based on the load and ground fault conditions; note, however, that the increase rate exceeded the standard value.

○ The simulation results are severer than the actual situations. Likewise, the temporary recovery voltage conditions of the 345-kV M.Tr tertiary-side circuit breaker may considerably vary according to the existing conditions in the entire system; hence the need for an interpretation per individual condition of workplaces.

○ Although the TRV of the 23-kV circuit breaker of a specific substation was not the direct cause of burnout, the examination results showed that all the requirements were met if the substation transformer was cut off in case of a fault per phase.

○ Nonetheless, only in the case of the three-phase ground fault – short circuit did the RRRV from among the intrinsic temporary recovery voltage standards exceed the standard value.

○ Although the simultaneous occurrence of the three-phase short circuit and ground fault is remotely likely, such possibility cannot be completely discounted. Therefore, preventing the three-phase short circuit and ground fault is believed to be the best way to protect the appropriate CB.

In conclusion, to prevent a single fault from developing into a multiple-phase fault, the following plans shall be implemented:

- Plan for installing an insulating barrier between phases in the case of an existing outdoor substation transformer
- Installation plan in relation to a new substation transformer using the enclosed structure such as a pad transformer, etc.

V. References

[1] A. R. Hileman, "Insulation Coordination", ABB Power Systems Inc., 1991

[2] EPRI, "Transmission Line Reference Book 345 kV and Above", 2nd Edition, 1982

[3] EMTP Rule Book, ATP Salford Version, □, □, 1987

[4] KEPRO Report, "The Report of Analysis Results of VCB Fault at SIC Substation", KEPRO Head Office, 2007

VI. Biographies

Jung-Wook Woo received his B.S., M.S. and Ph.D. degree in Electrical Engineering form Kyungpook National University, Daegu, Korea in 1992, 1994 and 2007 respectively. He has been worked for Korea Electric Power Corporation since 1994. He is currently a project manager in the Substation Technology Group of KEPRI. His research interests include the analysis of power system overvoltages and lightning observation.

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