

Transient Recovery Voltage Investigation in the Application of 15 kV Circuit Breaker Failure

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Abstract—Circuit breakers can fail to interrupt fault current when the power system has transient recovery voltage (TRV) characteristics that exceed the rating of the circuit breaker. There were two incidents of failures of outdoor switchgear at a power plant substation. The cause of the failure for these breakers was investigated in order to determine if transient recovery voltage is a contributing factor in the failures. This paper presents the investigation of the substation power system and determines if TRV was likely the cause of the 15kV breaker malfunction. The investigation was carried out by digital simulation using PSCAD/EMTDC to analyze TRV waveforms. This paper present the detailed setting-up of the digital model of the substation based on the on-site measurement of the substation data. Based on the output, the peak values and rate of rise of the TRV waveforms can be determined. These values were compared with breaker ratings calculated by IEEE C37.011-1994. The studies indicate that breaker TRV risk exists in the substation. One of the failed breakers had the most severe TRV stress condition of all locations studied.

Keywords: circuit breaker, transient recovery voltage, substations, electromagnetic transient, digital simulation.

I. INTRODUCTION

THERE are two incidents of failure of outdoor switchgear at a substation. The cause of the failure for these breakers needs to be investigated in order to determine if Transient Recovery Voltage (TRV) is a contributing factor in the failures.

The main objective of this study is to investigate the substation power system and determine if TRV was likely the cause of the 15kV breaker malfunction. This power system will be studied to determine the worst case TRV, and to recreate the system operating condition leading to breaker malfunction. TRV studies are required to determine if the failure is related to a TRV problem. The purpose of TRV study is to identify if the breaker ratings for TRV are exceeded for power system operations.

The two breakers that failed were Square D, SF6, FLUARC, and Type FG-4. They were model FGS1121140

breakers with nameplate ratings of

- Nominal Voltage Rating: 15.5kV
- Continuous Current Capability: 1200A
- BIL: 110kV
- Maximum Interrupting Rating: 40kA.
- Capability Standard: ANSI/IEEE C37 series. [1]

Circuit breakers can fail to interrupt fault current when the power system connected has transient recovery voltage (TRV) characteristics that exceed the rating of the circuit breaker.

Transient Recovery Voltage (TRV) is the voltage across the opening contacts of a fault-interrupting circuit breaker immediately after the arc is extinguished. The actual shape of the transient is determined by the connected lumped and distributed inductive and capacitive parameters defined by the bus equipment connected. For successful interruption, the breakdown voltage of the interrupting medium must always exceed the recovery voltage. If the TRV peak value is above the breaker rating, the increasing TRV to the gap will re-strike the arc and break down the interrupting medium.

In some other circumstances, even when the TRV peak is within the breaker rating, current re-ignition could occur because the interrupting medium, during the first few microseconds following current interruption, is not yet a good insulator; it may still have a relatively high conductance. If the TRV has a high rate of rise in those first few microseconds, it may re-establish a current flow sufficient to heat the arc column and restore conduction [2].

The circuit TRV can be modified by the circuit breaker's design or by the use of additional components. The most common adopted solutions are:

1. Replacing the existing breaker by one of higher voltage class, higher interrupting rating, or both when the TRV peak value is above the breaker rating. ZnO devices can also be used as an alternative to reduce TRV peak [3];
2. Adding capacitors to the circuit to change the characteristic impedance when the rate of rise of the TRV exceeds the specified value.

The investigation was carried out by digital simulation using PSCAD/EMTDC V4.1 to analyze TRV waveforms. Based on the output, the peak values and rate of rise of the TRV waveforms can be determined. These values were compared with breaker rating calculated by IEEE C37.011-1994 [4]. Any excess of the breaker rating indicates that there is a TRV stress which could lead to breaker failure.

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II. BREAKER TRANSIENT RECOVERY VOLTAGE CAPABILITY

Transient recovery voltage of a circuit breaker is the difference in voltage measured between each side of the circuit breaker to ground. Study of this phenomenon is extremely important to ensure that breaker electrical insulation limits, as defined by the appropriate standards, are not violated due to power system characteristics.

The most severe TRV from an amplitude point of view follows the interruption of the first phase to clear an ungrounded three phase fault. The shift in system neutral results in a high amplitude TRV. It is a basis for rating a circuit breaker's TRV capability [4].

The procedure for TRV verification and the TRV capabilities are outlined in the IEEE standard C37.011-1994. For breakers of 72.5kV and below the TRV capability envelope is defined by a one – cosine curve as follows:

$$e_2 = \frac{E_2}{2} [1 - \cos(\pi / T_2)]$$

The plot of this function is shown in Figure 1

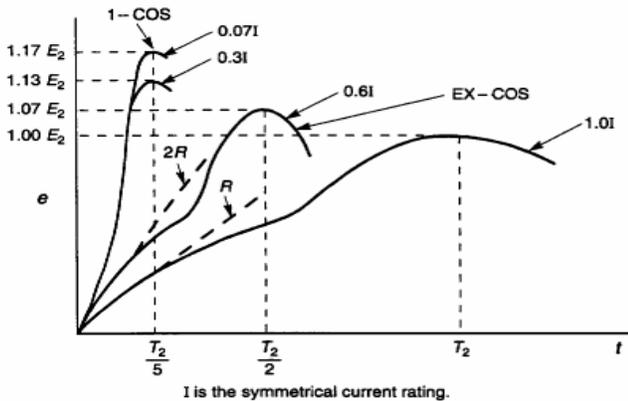


Fig. 1. TRV envelopes, 72.5 kV and below (referenced IEEE C37.011-1994)

Where E_2 is the crest value and the T_2 is the time reaching from zero to crest value. For different interruption currents, the breaker TRV capability envelopes have different crest values (E_2) and different times to reach the crest. Voltage E_2 multiplying factor K_1 and time T_2 multiplying factor K_t are used to calculate fraction of rated fault current interrupting capability. Both K_1 and K_t are functions of the interrupting current (IEEE ANSI C37.011-1994).

The actual interrupting current on the substation bus was around 10kA for the typical operating conditions during the past two failures, the breaker TRV capability envelope is then computed with $E_2=33\text{kV}$ and $T_2=14.4\mu\text{s}$. The actual TRV capability used in this study is listed in Table 1:

TABLE 1
COMPUTED TRV ENVELOPE USED IN THE SUBSTATION

Rating	Value
Rated Voltage	15.5kV
Interrupting Short Circuit Current	10kA
Rated Peak (E_2)	33 kV
Rated Time to Peak (T_2)	14.4 μs

During the simulation study the TRV capability envelopes are calculated automatically based on the actual interrupting current on the particular circuit of study.

The TRV curves of the power system under study will be compared with the corresponding TRV capability envelope. The system TRV should lag behind the TRV capability curve for all points.

The rate of rise of the recovery voltage, RRRV, is a method to quantify TRV and is an important factor in switchgear application [5]. It is a measure of circuit severity from a switchgear point of view. The mean RRRV is defined by peak TRV over the time of reaching it [5], or

$$RRRV = \frac{E_2}{T_2}$$

III. SUBSTATION POWER SYSTEM MODELING

To perform a TRV study in digital simulation, the first step is to build up the power system model of the study subject (The power plant substation in this case). The detailed representation of the substation and nearby power system is required. The time varying voltages at the breaker in question will be computed, displayed and examined.

The study model was carefully constructed from several sources. Several days were used to collect data of the substation. Onsite measurements were also carried out to get the data of the substation layout. Load flow and fault analysis raw and sequence data files in PTI's PSS/E data format were also obtained. These raw files were useful to determine the equivalent circuit of the external power network. With the data, the required parameters for digital simulation were calculated. The following sections give the details of data calculation and the study model set-up.

A. Power System Description

The power plant substation under study consists of 6 generators and provides electricity to the city and surrounding area by 18 distribution feeders. The nominal distribution voltage level in the substation is 12.47 kV. The substation is connected to the external network by two 138 kV transformers. The 12.47 kV bus-bars are divided in a North bus and South bus. Eight (8) feeders are connected to North bus and ten (10) feeders are connected to south bus. The 6 generators are normally not operating simultaneously due to dispatch and loading requirements. In this TRV study, only Generator No. 8 and generator CT4 are operating. Other generators are not in service. Figure.2 is a simplified schematic drawing of the substation.

B. Bus-Bar

The North and South bus-bar are divided into several sections; the length of the sections varies from 3.6 to 65 meters. It would not be beneficial to the simulation using the transmission line models to represent the bus-bar due to the

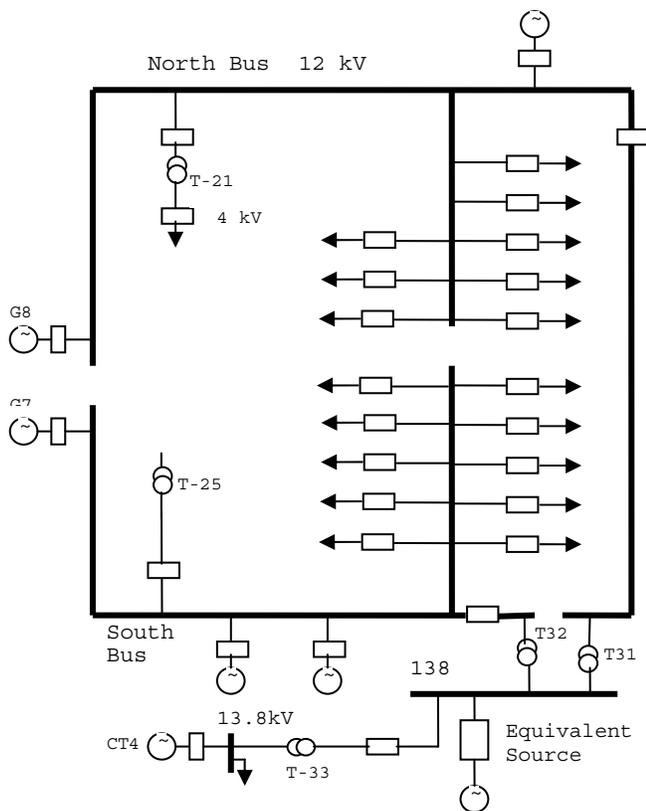


Fig. 2. Substation electric system simplified schematic short distance; it would result in tiny simulation time step. The bus-bars were represented by coupled PI sections. The parameters of the PI sections are calculated using the “Line Parameter Routine” based on the geometrical data of the bus-bar. The north and south bus-bars are constructed of 4 (0.1 meter) inch pipe. The measurement and layout of the bus-bar is shown in Fig.3.

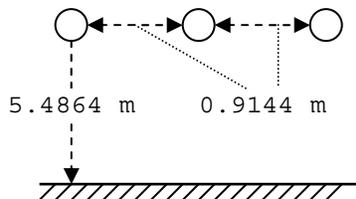


Fig. 3. North and South bus-bar layout

From the line-constant routine, the calculated resistance R , reactance X and susceptance B in p.u. /per meter are (Base MVA 100MVA, base kV=12.47 kV L-L RMS):

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SEQUENCE RESISTANCE Rsq [p.u./meter]:
+ Seq. Self: 0.228260516E-04
0 Seq. Self: 0.135853520E-03
SEQUENCE REACTANCE Xsq [p.u./meter]:
+ Seq. Self: 0.163312962E-03
0 Seq. Self: 0.113645918E-02
SEQUENCE SUSCEPTANCE Bsq [p.u./meter]:
+ Seq. Self: 0.107240994E-07
0 Seq. Self: 0.330836948E-08

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The above sequence data is entered in the Coupled PI section.

C. Feeder cables and feeder overhead lines

This is the bus-bar where the feeder breakers are directly connected to. The feeder bus-bars are also made of 4 inch

pipe. The measurement and layout of the bus-bar is shown in Table 2.

TABLE 2
FEEDER BUS-BAR MEASUREMENT

Feeder Bus-bar		
Height (m)	Spacing (m)	Diameter (m)
6.7056	0.9144	0.1016

Each bus section is represented by Coupled PI section model. The above sequence data were calculated using the same “Line Parameter Routine” and entered into the Coupled PI section. The feeder bus-bar connected to North bus is divided into 5 PI sections. The feeder bus-bars were divided into several sections of 4.57 meters each.

D. Transformers

Setting up a transformer in digital simulation is normally straightforward. The leakage inductance and rated MVA and voltage are readily available on the name plate. Transformers have strong influence on fast surges due to the dominant bushing and winding capacitance. However the transformer capacitances are often difficult to determine. Transformer capacitance is represented by CH, CL and CHL.

Where

CH = Capacitance of H winding to ground

CL = capacitance of L winding to ground

CHL = capacitance between H and L windings

These values can be obtained by measurement of the actual transformers. Normally the CL and CHL are greater than CH, simply because the fact of high voltage calls for more separation between windings and between windings and core [5]. Test results in Manitoba Hydro [8] and reference [9] show that roughly CL is three times larger than CH and CHL is four times larger than CH.

IEEE C37.011 1994 Table B.9 gives some reference values for transformer capacitance. From the table, the estimated single-phase, line to ground capacitances is assumed.

TABLE 3
Transformer Capacitance

Transformer size (MVA)	Capacitance (pf)
1 – 10	900 to 10000
10- 100	2000 to 12000

Reference [5] presents a more detailed method to determine transformer capacitance. Fig. 13.8 in [5] provides the value of the total capacitance to ground of the highest voltage windings on a per phase basis by IEEE working group. In this study, Fig. 13.8 of reference [5] is used to determine the total capacitance to ground of the highest voltage winding to find the value of CH, then CL and CHL are estimated based on CH.

The transformer data sheet gives the leakage reactance 9.1% at 30 MVA. Both windings are in Y-connection.

The per-phase MVA is 30/3=10MVA. From Fig.13.8 (b) of reference [5], the capacitance is around 0.0075 μ f. It should be noted that this capacitance reflects the winding to ground. If the winding is grounded at one end such as the Y-grounded windings, then the capacitance for such winding should be

multiplied by approximately 0.33 [5]. So the final capacitances in this transformer circuit are:
 $CH=0.0075 \times 0.33=0.0025\mu\text{f}$,

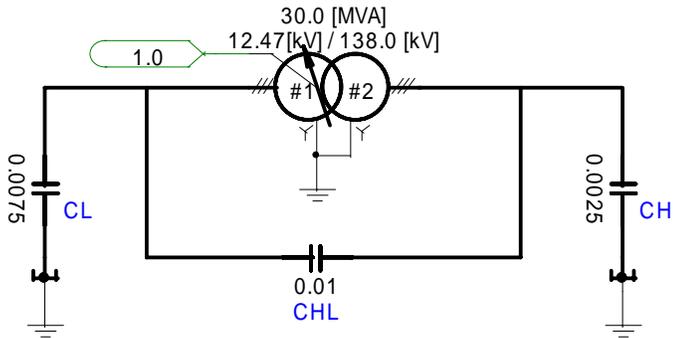


Fig. 4. Single line diagram of transformer model

$CL = 3 \times 0.0025 = 0.0075\mu\text{f}$, $CHL = 4 \times 0.0025 = 0.01\mu\text{f}$. The final parameters of the transformer are shown in Fig.4.

E. Generators

Due to the very fast transient of TRV, the detailed generator model with governor and exciter are not needed; the generators were represented by a voltage source. The parameters of generator CT4 are:

- Machine MVA base (3 Phase): 74 MVA
- Rated voltage (kV L-L RMS): 12.5 kV
- Sub-transient impedance: $0.00354 + j0.14677$ p.u.

From a power flow solution, the terminal conditions of CT4 are obtained. Based on the terminal conditions, the voltage source E behind machine impedance was calculated. Since there is a step-up transformer with Y- Δ connection, the Δ is lag Y 30 degree, so the final internal phase angle of the voltage source is -73.16 degree.

F. System equivalence

The power plant substation itself was modeled in detail. The external network viewing from the boundary bus, which is the 138kV bus of the substation, is represented by Thevenin equivalent circuit. The equivalent circuit is obtained based on the base case a PSS/E raw data file of a 5000-bus power system, using E-Tran data conversion program. E-Tran is a program to convert PSS/E power flow raw data file to PSCAD file. It also can do the system reduction and find the equivalent circuit for a specified part of the power system. The parameters of the equivalence are internal impedance of R and X and the terminal conditions such as terminal voltage and real and reactive power. Based on these parameters, the calculated voltage source E behind machine impedance is shown in the following Table.

Thevenin Equivalence	
E magnitude (kV L-L RMS)	142.0572 kV (1.0294 pu)
E angle	-53.68535 degree
Impedance R	1.728377 ohms
Impedance X	6.914944 ohms

G. Effective equipment stray capacitance

In the calculation of TRV, circuit constants should be

supplied for each of the elements on the system. In general, only inductance and capacitance are needed; resistance can be neglected. Proper representation of the stray capacitances of the substation is important in some situations. Accurate information on the inductance of apparatus is given by the manufacturer, but little or no information is given on the effective capacitance of apparatus.

The effective capacitance values of various pieces of equipment are obtained from the recommended values in IEEE Standard C37.011-1994. These capacitances represent breakers, disconnect switches, transformers, surge arrestors, etc as shown in Table 4.

TABLE 4
SUBSTATION EQUIPMENT EFFECTIVE CAPACITANCE

Effective Capacitance	
Steam Generator	50nF (15-70MVA) 100nF(70-300MVA)
Outdoor potential transformers	125pF(15kV system voltage)
Circuit Breaker	100pF(open) 200pF(close)
Lighting Arrestor	80pF
Line reactor	200pF
Disconnect	20pF(open) 30pF(close)

The five PTs (PT243, PT244, PT245, PT246 and PT247) are represented by a combined capacitor of $5 \times 125 = 625\text{pF}$ capacitor.

H. Model Validation

After setting up the system, the model was validated with a load flow condition of the power plant Substation Summary on June 9, 2004. The load flow condition of the system under study matches the Daily Substation Summary. The load flow condition is also the initial operating point for the TRV analysis.

There was a fault on the distribution circuit in each case. Fault records show the fault current at a maximum of 10kA. The actual event records were used as reference to verify the fault current level. The actual event was re-produced in the simulation. The fault currents obtained by the simulation are 9.86kA at breaker 216 and 9.7kA at breaker 206 respectively for a near substation (150 feet away from the substation) three phase fault. The simulated fault currents match with the recorded fault current. Based on the load flow and fault current verifications, the digital simulation set-up is believed to be a good representation of power plant substation.

IV. TRV SIMULATION AND DISCUSSION

In order to obtain sufficient resolution in the output, a 0.5 μs time step was used for the TRV simulations. The TRV waveform is measured by voltage meters at both sides of the breaker, then the difference is plotted to get the instantaneous TRV voltage waveform.

To examine the worst TRV condition, three-phase

ungrounded faults were applied at two locations for each breaker. Location A is at the load side immediately adjacent to the feeder breaker. Location A simulates substation faults. Location B is on the feeder line or cable 150 feet away from the breaker. Location B is used for near substation faults (faults on distribution circuit)

For example, case 216A is the test case of breaker 216 in station fault at the start point of feeder of breaker 216. 216B is the test case of breaker 216 near station fault at 150 feet away on feeder from breaker 216.

At each simulation, when the system reaches steady-state (in about 0.1 seconds), a three phase ungrounded fault is applied at time $t=0.1$ seconds. The fault lasts 3 cycles, and is then cleared by the corresponding breaker. The TRV waveforms of the first open-pole contact are plotted against the rated breaker TRV capability envelope. In this study phase C is the first open-pole.

There are 18 15kV-breakers in the substation. Each breaker was tested with both in-station and near-station fault locations for a total of 36 test cases. Here we present the TRV waveforms for breaker 206 only.

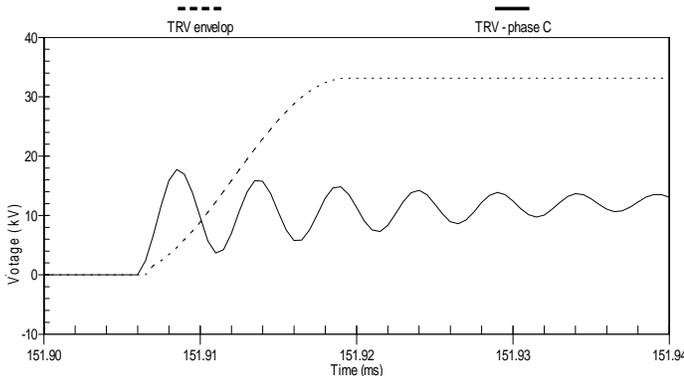


Fig. 5. The TRV characteristic waveform of breaker 206 in station fault

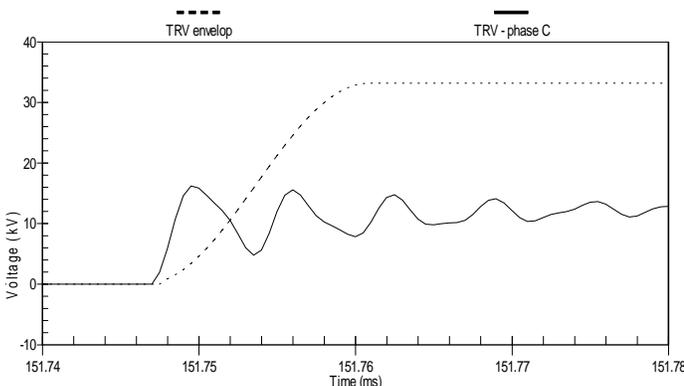


Fig. 6. The TRV characteristic waveform of breaker 206 near station fault

The peak voltage recorded in breaker 206 testing was 17.74 kV peak. The TRV oscillation is in a very high frequency with period of around 4 μ s. It is clearly seen that the system TRV waveform is exceeding the TRV capability envelope. This is an indication of TRV stress in the substation.

The results of all 18 feeder breakers are tabulated. The breakers are grouped in two tables – South bus and North bus respectively.

TRV tests were also done on the two bank breakers. The

faults were applied to breaker terminals at North bus and South bus side respectively. The Test results indicate that there is no TRV stress on these two breakers. The TRV waveform and RRRV are under the breaker TRV capability.

South Bus – TRV results								
Case Breaker	Fault Current		TRV			Breaker Capability		
	kA	% 40kA	Crest (kV)	T2 (μ s)	RRRV (kV/ μ s)	RRRV (kV/ μ s)	E2 (kV)	T2 (μ s)
201A	7.12	0.18	8.37	2.0	4.18	2.33	33.5	14
201B	6.96	0.17	9.54	2.0	4.77	2.33	33.5	14
202A	7.12	0.18	9.07	2.0	4.54	2.33	33.5	14
202B	6.96	0.17	9.43	2.0	4.72	2.33	33.5	14
203A	7.08	0.18	12.4	2.5	4.96	2.33	33.5	14
203B	6.92	0.17	11.1	2.5	4.44	2.33	33.5	14
204A	7.08	0.18	8.41	2.0	4.21	2.33	33.5	14
204B	6.92	0.17	9.49	2.0	4.75	2.33	33.5	14
205A	7.08	0.18	9.00	2.0	4.50	2.33	33.5	14
205B	6.92	0.17	9.64	2.0	4.82	2.33	33.5	14
211A	7.12	0.18	8.78	2.0	4.39	2.33	33.5	14
211B	7.04	0.18	8.63	2.0	4.32	2.33	33.5	14
212A	7.12	0.18	9.22	2.0	4.61	2.33	33.5	14
212B	7.04	0.18	8.97	2.0	4.49	2.33	33.5	14
213A	7.08	0.18	9.18	2.0	4.59	2.33	33.5	14
213B	7.04	0.18	9.13	2.0	4.57	2.33	33.5	14
214A	7.08	0.18	12.8	2.0	5.12	2.33	33.5	14
214B	7.00	0.18	9.08	2.0	4.54	2.33	33.5	14
215A	7.08	0.18	9.06	2.0	4.53	2.33	33.5	14
215B	7.00	0.18	9.17	2.0	4.59	2.33	33.5	14

North Bus – TRV results								
Case Breaker	Fault Current		TRV			Breaker Capability		
	kA	% 40kA	Crest (kV)	T2 (μ s)	RRRV (kV/ μ s)	RRRV (kV/ μ s)	E2 (kV)	T2 (μ s)
206A	9.96	0.25	17.7	2.5	7.09	2.30	33.1	14
206B	9.68	0.24	16.2	2.5	6.48	2.30	33.2	14
207A	10.0	0.25	12.1	2.0	6.06	2.30	33.1	14
207B	9.72	0.24	13.3	2.0	6.67	2.30	33.2	14
208A	10.0	0.25	12.7	2.5	6.33	2.30	33.1	14
208B	9.84	0.25	12.5	2.5	6.24	2.30	33.2	14
209A	10.0	0.25	12.3	2.0	6.13	2.30	33.1	14
209B	9.88	0.25	11.8	2.0	5.92	2.30	33.2	14
210A	10.0	0.25	12.7	2.0	6.36	2.30	33.1	14
210B	9.72	0.24	13.7	2.0	6.84	2.30	33.2	14
216A	9.96	0.25	12.6	2.0	6.32	2.30	33.1	14
216B	9.80	0.25	12.6	2.0	6.30	2.30	33.2	14
217A	9.96	0.25	12.2	2.0	6.12	2.30	33.1	14
217B	9.84	0.25	12.0	2.0	6.01	2.30	33.2	14
218A	10.0	0.25	12.5	2.0	6.27	2.30	33.2	14
218B	9.82	0.25	12.4	2.0	6.21	2.30	33.2	14

From the simulation results, we observed the followings

1. The peak allowable TRV value from the IEEE defined TRV capability curves is 33 kV for the breakers when interrupting a 10kA fault current. Our maximum TRV voltage recorded was 17.74kV peak. This is well below the peak TRV capability value.
2. Regarding the rate of rise of the recovery voltage (RRRV), the TRV stresses do exist in the substation. The actual TRV RRRV at all 15kV breakers exceeds the breaker TRV RRRV capability. The rated mean RRRV of breaker capability is around 2.3 kV/ μ s. The actual RRRV of the 18 breakers in the substation are in the range of 4.18~7.09 kV/ μ s.

3. Breakers connected to North Bus have higher RRRV than the ones connected to South Bus. In other words, breakers at North Bus have more severe TRV stress than the breakers at South Bus.
4. The most severely TRV stressed breaker was breaker 206 (7.09kV/μs). This is the breaker that failed to interrupt the fault current and resulted in catastrophic failure.
5. Other highly TRV stressed breakers are breaker 216 (6.32kV/μs), 210 (6.36kV/μs) and 208 (6.33kV/μs). Breaker 216 was the second breaker that failed to interrupt a fault.
6. The test results show that actual TRV conditions for all 18 feeder breakers exceed the rated breaker TRV capability defined by IEEE STD C37. Other bank breakers and local plant supply breakers have no TRV problems, as their TRV performances are well within the rated TRV capability.
7. Preliminary investigations on breaker 206 have shown that the source of the excessive TRV during fault clearing is the feeder line reactor in combination with stray line capacitance on the feeder side of the substation breaker.

As an example, our simulations without the current limiting reactor show the TRV stress greatly reduced. However, as we would expect the fault current increased to about 30kA. When the reactor is re-located to the load bus side of Transformer T-31, the TRV stress on Breaker 206 was also greatly reduced, but fault current remained around 24 kA. More study is necessary to document the effects at all feeder positions.

V. CONCLUSIONS

Our studies indicate that breaker TRV risk exists in the Substation. One of the failed breakers (206) had the most severe TRV stress condition of all locations studied. Fault clearing for all substation breakers exceed the breaker TRV capability with high rate of rise of the recovery voltage (RRRV). However, the TRV peak is well below the TRV capability envelopes for the 40kA breakers used.

Fault duties less than rated maximum clearing duty allow for higher rates of rise for RRRV. Unfortunately, in this case the gain is insufficient for the TRV RRRV present at the substation.

Preliminary investigation as to the source of the high frequency TRV during fault clearing appears to be the feeder line reactors in combination with stray line capacitance on the feeder side of the substation breakers.

In order to ensure reliable breaker operation at the Substation, corrective measures should be considered to reduce the rate of rise of TRV.

The Manitoba HVDC Research Centre recommended further study to identify the source of the high frequency TVR for each feeder breaker, and examine options for a suitable mitigation strategy involving reactor relocation, additional bus capacitance, feeder capacitance, or some combination to limit the RRRV experienced during fault clearing.

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