

Effects of Transient Recovery Voltages on Circuit Breaker Ratings

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1. Introduction

Transient is associated with every change of state of a circuit. Transient recovery voltage thus is the transient across a circuit breaker. Transient recovery voltages are contingent upon the circuit conditions and parameters of the circuit. Thus making it extremely essential to study them for application of circuit breakers. [1][2][3]

Generally, circuit breakers in a system are applied based on available short circuit capability at that point in the circuit. But, when circuit is interrupted it results in a TRV, this has deleterious effects on the circuit breaker. TRV manifests in different way depending on circuit configuration, hence the object of this report is to study the various parameters causing and affecting the TRV.

2. Transient Recovery Voltages on Systems

2.1. What is Transient Recovery Voltage?[1][2]

It is ascertained that TRV is resultant of the change in state of circuit. Thus TRV can be defined as voltage appearing across a circuit breaker after a switching action. Typical of every transient TRV also has high amplitude and high frequency. The figure below shows example of TRV, figure is taken from TRV explanation given by Dufornet et. al.[1][2]

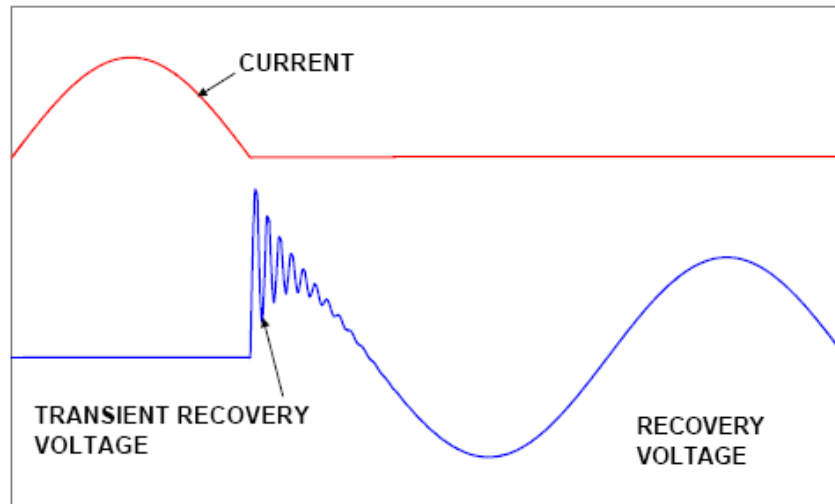


Figure-1:- Transient Recovery Voltage [2]

TRV is a point by point difference of voltage at the incoming side and at the outgoing side of a circuit breaker. When a circuit breaker interrupts, incoming side or the side to bus or supply is connected tries to return to power frequency voltage level and the outgoing side depending on what is connected also oscillates. The difference between these voltages is recovery voltage.

TRV is associated with every interruption, but the ones resulting because of interruption of fault current are the most ominous TRV. Thus the choice of circuit breakers or introduction of means and methods for safeguarding the circuit and circuit breaker has to be considered.

2.2. Factors affecting TRV [1][2][5]

Transient recovery voltage is affected by various parameters of the system. Prominent among them are listed below:-

1. Inductance and capacitance in the system
2. Fault current level of the system at point of study of TRV.
3. Bushing capacitance of circuit breakers, voltage transformers etc
4. Number of transmission lines terminating at a bus and their characteristics impedance.
5. Internal factors of the circuit breaker like the first pole to clear a fault etc.
6. System grounding.

2.3. Types of TRV wave shapes [2][5]

Transient recovery voltages manifesting across any circuit breaker in a system are seen to have some typical shapes. Waveshapes are classified into types[2]:

1. 1- Cosine: Observed in case of transformer fed or reactor fed faults.
2. Exponential cosine: Observed when transformer fed faults on breaker terminals with transmission lines connected on the incoming side of circuit breaker.
3. Triangular or Saw-tooth waveshape : Observed on line side when short transmission lines are connected.
4. Initial TRV: Observed when buswork of substation is involved.

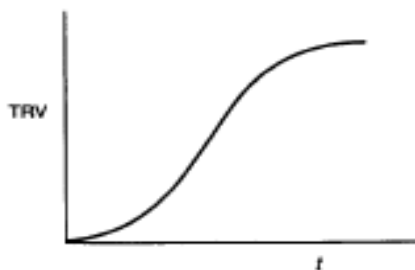


Figure 2a:-1-Cosine TRV [2]

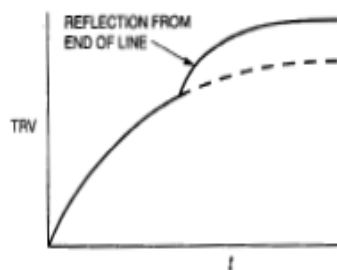


Figure 2 b. Exponential TRV [2]

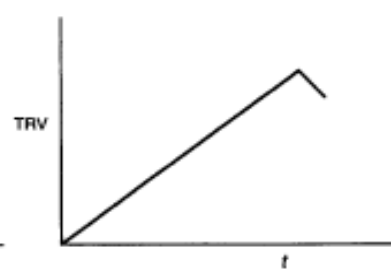


Figure 2c. Triangular TRV [2]

3. Calculation of different types of TRV wave shapes

3.1. System Reduction [1][2]

TRV can be analyzed by drawing detailed system diagram and then reducing it to obtain an equivalent circuit across the breaker terminals. It is generally observed that system can be reduced to a series or parallel R-L-C circuits. These equivalent RLC circuit can then be solved for TRV. An example of circuit reduction is shown below. The system is first drawn out as single line diagram and afterwards single phase RLC parallel equivalent is obtained at the breaker terminals. To obtain the resultant TRV it is assumed to inject short circuit current in the breaker terminals and solution for voltage across the elements is obtained which is TRV.

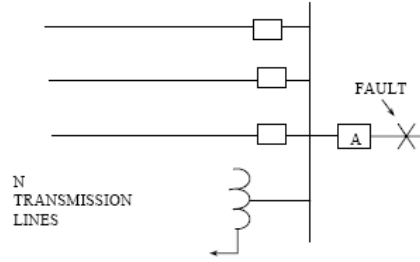


Figure 3a :-Single Line Diagram[2]

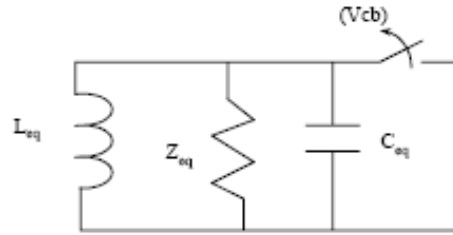


Figure 3c :-Equivalent RLC Network[2]

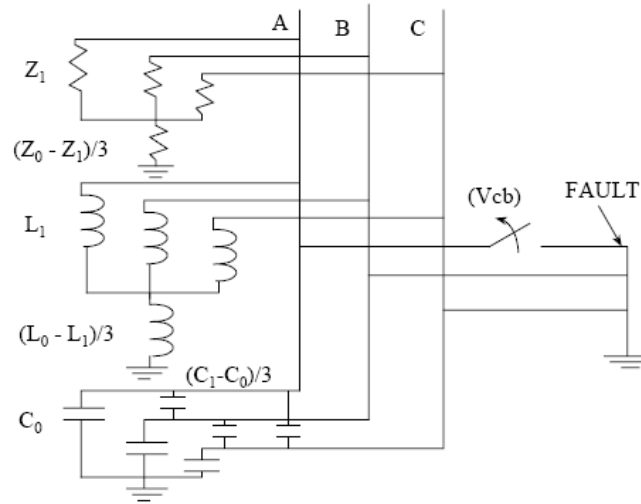


Figure 3b :-Three phase Diagram[2]

3.2. Calculation of different types Transient Recovery Voltage waveshapes

3.2.1. 1-Cosine or Oscillatory or Underdamped TRV [2]

This waveshape is generally obtained in case of transformer or reactor fed faults. This kind of TRV waveshape can also be obtained with transformer fed fault on a bus with with small number of transmission lines connected to it. System to be used for analysis of this kind is shown figure- 3. The resultant equations after analysis are shown below.[2]

$$V_{CB} = E_1 \left(1 - e^{-\alpha t} \left(\cosh \beta t + \frac{\alpha}{\beta} \sinh \beta t \right) \right) \text{KV} \text{ -----(1)}$$

If there are no lines, resistance of figure 3c is neglected, eq. 1 reduces to

$$V_{CB} = E_1 \left(1 - \cos \left(\frac{t}{\sqrt{L_{eq} C_{eq}}} \right) \right) \text{KV} \text{ -----(2)}$$

Condition for TRV to be oscillatory is

$$Z_{eq} \geq 0.5 \sqrt{\frac{L_{eq}}{C_{eq}}} \text{ -----(3)}$$

where

V_{CB} – Voltage across open circuit breaker

$E_1 - \sqrt{2} I \omega L_{eq}$

ω – System frequency

$\alpha - \frac{1}{2Z_{eq}C_{eq}}$

$\beta - \sqrt{\alpha^2 - \frac{1}{L_{eq}C_{eq}}}$

Z_{eq} equivalent impedance in ohms

L_{eq} equivalent inductance in Henrys

C_{eq} equivalent capacitance in farads

3.2.2. Exponential TRV [2]

This waveshape is obtained, when a circuit breaker at a bus with large number of transmission lines, interrupts a faults at its terminals. The waveshape obtained is seen on the bus side of the circuit breaker. . This is also referred to as overdamped TRV. The system used for analysis is the same as shown figure3a. [2]

For many systems resistance in equivalent circuit is surge impedance of the line, hence the capacitance of circuit is neglected and eq. (1) reduces to

$$V_{CB} = E_1 \left(1 - e^{-\frac{t}{\tau}} \right) \text{KV} \text{ -----(4)}$$

$$\tau = \frac{L_{eq}}{Z_{eq}} s$$

Condition for TRV to be exponential is

$$Z_{eq} \leq 0.5 \sqrt{\frac{L_{eq}}{C_{eq}}} \text{ -----(5)}$$

3.2.3. Triangular or Sawtooth Waveshape [2]

When a fault at a short distance from the circuit breaker on the transmission line is interrupted it results in triangular TRV on line side of circuit breaker. Sawtooth TRV is characterized by high rate of rise of recovery voltage (RRRV). These are seen to damage circuit breakers because of high RRRV even though the peak of TRV is less. The analysis of this TRV is based on the traveling wave on transmission lines.[2]

TRV across circuit breaker is given by

$$V_{CB} = V_L + V_S \text{ -----(6)}$$

$$V_L = d(1 - M) \sqrt{\frac{2}{3}} E_{\max} \text{ -----(7)}$$

$$V_S = 2M(T_L - t_d) \text{ -----(8)}$$

where

t_d – time delay of TRV on source side

$$T_L = \frac{V_L}{R_L} \text{ ---- time to peak}$$

$$R_L = \sqrt{2} \omega I_L Z$$

I_L Fault Current

Z Surge impedance of line

M ratio of fault current to rated short circuit current

E_{\max} rated maximum voltage (KV)

4. Circuit Breaker Ratings Structure

IEEE C37.04-1999 defines a general rating structure for high voltage circuit breakers 1000 V AC and above. The rating structure comprises of indoor and outdoor circuit breakers. ANSI/IEEE C37.06 states preferred rating for the circuit breakers. Ratings structure establishes the basis for ratings to be assigned to circuit breakers including electrical and mechanical characteristics.

4.1 General Rating Structure

IEEE C37.04-1999 is based on symmetrical currents and specifies ratings for three and single phase, indoor and outdoor circuit breakers to be used above 1000V AC. Rating structure used for the circuit breakers is based on usual service conditions that prevail. The rating structure of the circuit breaker includes the following:[9]

Recloser Type	PVDR	PVDR
Rated Maximum Voltage	15.5kV	27.0kV
Nominal Voltage	15.5kV	27.0kV
Frequency	60Hz	60Hz
Low Frequency Withstand		
60Hz dry for 1 minute	50kV	60kV
60Hz wet for 10 seconds	45kV	50kV
Fullwave Withstand - B.I.L.	110kV	125kV
Continuous Current Rating @ 60Hz	200A thru 1120A	200A thru 1120A
Standard Duty Cycle	0 + 0 sec + CO + 5 sec + CO	0 + 0 sec + CO + 5 sec + CO
Interrupting Time	5 cycles (3 cycles optional)	5 cycles
Closing Time	4.5 cycles	4.5 cycles
Rated Short Circuit (RMS)	2kA thru 16kA	2kA thru 16kA
Close and Latch Rating		
RMS Asymmetrical	3kA thru 26kA	25.6kA
Peak 5kA thru	43kA	42.5kA
3 Second Short Time Current Rating (RMS)	2kA thru 16kA	16.0 kA
Reclosing Time	5 or 3 seconds	5 or 3 seconds
Permissible Tripping Delay	2 seconds	2 seconds
Capacitance Current Switching		
General Purpose Duty		
Line Charging Current	2A	2A
Isolated Cable Charging Current	250A	250A
Isolated Capacitor Bank Rating	250A	250A
Transient Recovery Voltage Peak	29kV	50.5kV
Time to Crest of Transient Recovery Voltage	36 microseconds	52 microseconds
Number of Operations		
Load Current Switching	2500 Before Servicing	2500 Before Servicing
Full Fault Unit Operations	18 Before Servicing	18 Before Servicing
Control Voltage	DC: 48V, 125V, 250V AC: 120V, 240V (60Hz)	DC: 48V, 125V, 250V AC: 120V, 240V (60Hz)

Figure 4:- Circuit Nameplate Catalogue GE Co. USA [9]

4.2 Ratings important for TRV[5][6]

The above is general rating structure and is provided on nameplate of every circuit breaker. Rating that are important from the point of view of Transient recovery voltages depend on the voltage level it is used at and application. IEEE C37.011 is a application guide for transient recovery voltage for AC high voltage circuit breakers. In addition the to the peak of the recovery voltage the following ratings are referred to

1. Peak TRV in KV
2. Time to Peak of TRV In μ s.
3. Rate of Rise of Recovery Voltage (RRRV)

These ratings of the circuit breaker are contingent upon application. To cater to various possible applications the standard specifies three different TRV characteristics envelopes

1. 1-Cosine waveform
2. Exponential Cosine TRV waveform
3. Triangular TRV waveform.

These waveforms are obtained for different applications and depend on the rated maximum operating voltage. TRV capability of the circuit breaker is required to increase as the short circuit current reduces as the TRV depends on the short circuit level of the system. System conditions and grounding of the system are important for TRV ratings to be evaluated.

5. Effects of Transient Recovery Voltages on Circuit Breaker[1][2][3][6]

Transient recovery voltages appear on the system for a very short duration of time and assume very high values. These rapid changes have deleterious effects on the devices in the system.

5.1 Insulation Failures

TRV is voltage which appears across the circuit breaker on the system when it interrupts current, and are especially dangerous when short circuits are interrupted. [2] . TRV causes the insulation of the circuit breaker to be stressed and can result in breakdown. The classical examples of the breakdown of insulation are external flashover between phase and ground, or between a phase and another. TRV causes the air around to be stressed to higher levels thus resulting in breakdown.

5.2 Re-ignition and Re-strikes[2][3]

When the circuit breaker is interrupting a fault, it results in arcing in the interrupting medium. During the process of interruption the arcing medium is trying to regain its insulation property. For the interruption to be successful the interrupting medium should withstand this fast rising recovery voltage.

Thus, there is a race in the interrupting medium to go from conducting state to insulating state, with the TRV, if the rate of rise of TRV is more than speed with which the medium returns to insulating state the arcing medium breakdown causing current to continue to flow in the circuit breaker, if speed of medium

is higher the interruption is successful. This process of establishment of current is called re-ignition and refers to re-ignition of arc in the circuit breaker.

Re-ignition generally occurs almost immediately after the current zero, is generally because the arc plasma containing conducting ions reestablishes current.

TRV, if it very high will result in the arcing medium which has returned to insulating state to stressed. If this field created across the contacts is very high a dielectric breakdown may take place causing the interrupting medium to become conducting and carry current. This process of establishing current is called restriking. This generally occurs about a half cycle later to the current interruption. This phenomenon occurring internally to the circuit breaker is akin to insulation failure external to the circuit breaker [3]

6. Calculation of Transient Recovery Voltages of Circuit Breaker

At the rated voltage circuit breakers are expected to interrupt rated short circuit current in a system where the TRV doesn't exceed the rated TRV envelope. System may be grounded or ungrounded. [5]

6.1 Envelope Specification and Calculation [5][6]

TRV rating of circuit breaker is defined by an envelope of rated withstand capability [5] Parameters that define the envelope are based on the characteristics of actual system. According to the standard various waveshapes are observed for circuit breakers on the system, illustrated in section 3. Applicable envelope of TRV depends on the application and voltage rating of the circuit breaker.

Two envelopes are defined, one for circuit breakers rated 100KV and below and other for above 100KV. Circuit breaker is generally used in conjunction with transformers and transmission lines. As noted earlier the transformer fed faults are known to produce 1-cosine wave, which is also characteristics of underdamped system. Transmission lines, depending upon number of lines in parallel, are known to add damping to the system and hence produce exponential waveform. Thus the two envelopes are :-

1. Two parameter envelope used for circuit breakers rated 100KV and below and for above 100KV, if fault current is less than 30% of rated short circuit current.
2. Four parameter envelope for circuit breakers used above 100KV.

Voltage (E_2) can also be calculated using formulae specified in standard [5] and stated as under

$$E_2 = k_a \times k_{pp} \times \frac{\sqrt{2}}{\sqrt{3}} \times V$$

$$E_1 = k_{pp} \times \frac{\sqrt{2}}{\sqrt{3}} \times V$$

k_a : transient amplitude factor

k_{pp} : first pole to clear factor

V : System rated voltage

Rated parameters as specified in ANSI/IEEE standard C37.06-2000 are used to define the envelope. Parameters are specified in Tables-1 through Table-3. [5] [6]

1. Two parameter envelope [2][5] [6]:- This envelope definition approximates the 1-cosine waveform. Rated values as given in Table-1 and Table-2, are used to construct the envelope. Envelope gives the withstand capability a circuit breaker should have in order to successfully interrupt rated short circuit current at rated values. The initial portion of the curve gives the voltage rise upto the peak value, thus this plotted as line joining the origin with the point (E_2, T_2) , the second portion of the envelope is horizontal line through point (E_2, T_2) . In case of circuit breakers rated above 100KV there is small delay time involved, hence the first sloping curve starts at $(0, T_d)$. Curves as obtained for 145KV circuit breakers are shown below.[2]

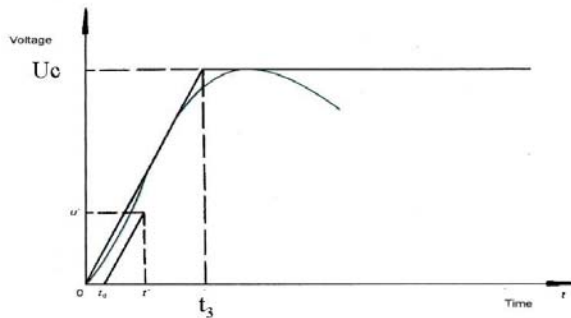


Figure 5: Two Parameter TRV Envelope [2]

2. Four parameter envelope [2][5] [6]: - Four parameter envelope is used to approximate the exponential-cosine waveform obtained on 100KV and above values. Rated values specified in ANSI/IEEE C37.06-2000 are used to define the envelope. Rated values defined in Table-3 are used. To construct the capability envelope the curve takes off after a delay of (T_d) and increases with a slope of Rate of Rise of Recovery Voltage to value $E_1=1.3*\sqrt{2}/3$, beyond this there is another straight line approximation from the point where first line ends to the point (E_2, T_2) . , beyond this point is horizontal line passing through (E_2, T_2) . Curves constructed for 550KV circuit breakers are shown above.

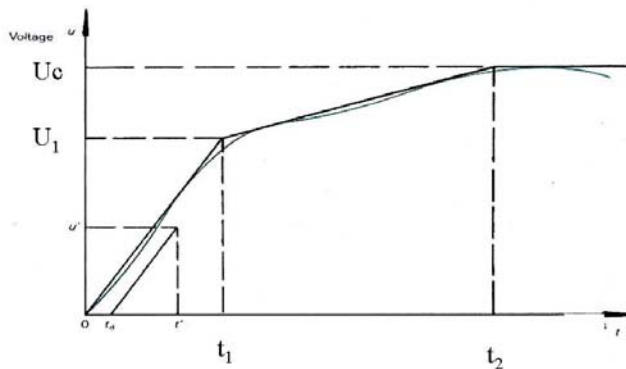


Figure 6: Four Parameter TRV Envelope [2]

6.2 Factors affecting Transient Recovery Voltage [2] [5] [6]

Transient recovery voltage appearing across a circuit breaker is affected by various factors like fault current, first pole to clear factor, out of phase switching, system inductance and capacitance etc...TRV may also be affected by the applications a breaker is used for.

6.2.1 Faults Current

Calculation of transient recovery voltage Eq.1,2,4 &6 [2] indicates that all forms of TRV are greatly dependent on the fault current. Short circuit at a point in system depends on the devices paralleled like the transmission lines, transformers etc. It is observed that TRV peak increases and time to peak reduces as short circuit reduces. This also causes the RRRV to increase [5]. Figure below shows the TRV envelopes. [5]

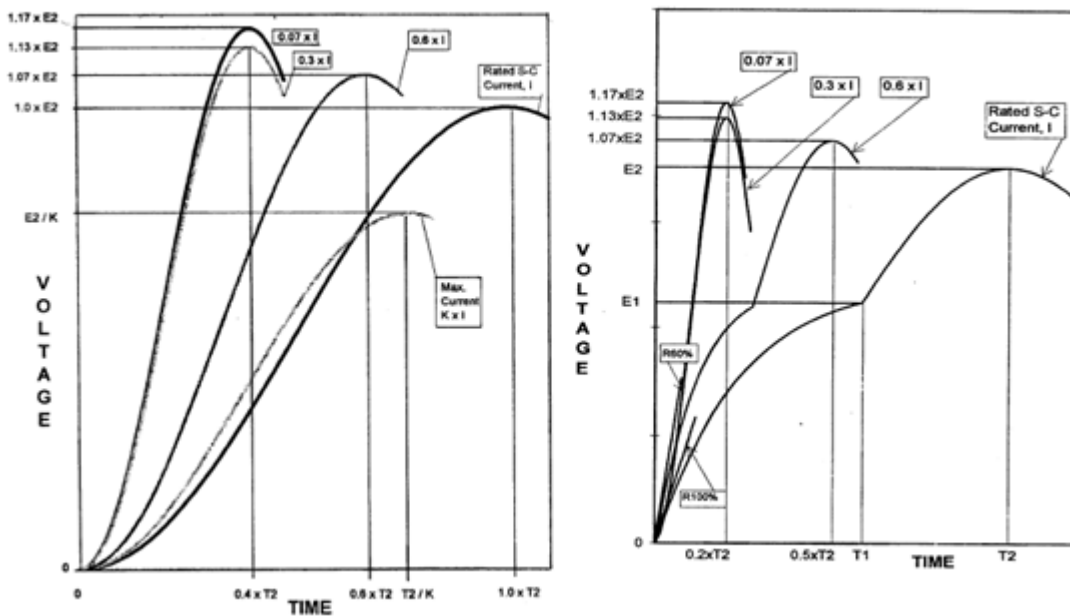


Figure 7: Parameter Envelopes varying as per fault current 1)100KV and below b) 100KV and above.[5]

6.2.2 Circuit Parameter [2]

Circuit inductance and capacitance plays a vital role in the TRV peak and time to peak. Eq.1, 2, 4&6 Thus the TRV values can be controlled and reduced using the inductance and circuit capacitance. Generally system capacitance is considerably less, hence TRV is controlled by addition of additional surge capacitance.

6.2.3 Out-of-phase Switching

Out of phase switching results in higher values of TRV and are analyzed in a similar way as the generator circuit breaker analysis. [9] Rated values for out of phase switching are specified for 90° phase shift.

6.2.4 First Pole to Clear Factors [2][5]

First pole to clear factors are a function of the system grounding arrangements. It is defined as ratio, Eq.9.[2]

$$K_{pp} = \frac{V_{IP-60Hz}}{V_{3P-60Hz}} \text{ --- (9)}$$

$V_{IP-60Hz}$:- Voltage appearing across interrupting pole, when other poles have not interrupted

$V_{3P-60Hz}$:- Voltage appearing across all poles after interruption

K_{pp} is 1.5 for ungrounded systems and 1.3 for effectively grounded system. First pole to clear factor is seen to be dependent on the zero sequence and positive sequence impedance of the system and is given by [2]

$$K_{pp} = \frac{3X_0}{X_1 + 2X_0} \text{ --- (10)}$$

For effectively grounded system

$$X_0 = 3X_1 \text{ hence } K_{pp} = 1.3$$

For ungrounded system

$$X_0 \gg X_1 \text{ hence } K_{pp} = 1.5$$

6.2.5 Applications [2][7]

TRV depends on the application of circuit breaker. Some important applications are

1. Transformer fed faults [2][7]: - Standard capability curve is specified as two parameter curve. Severe TRV conditions may result if the fault is immediately after transformer, without appreciable capacitance in between transformer and circuit breaker. In such cases the TRV peak and RRRV may exceed the values specified in C37.06-2000, in such circumstances values specified in C37.06.1-2000 are used. These values correspond to fast time to peak values.
2. Series Reactor limited faults [2][7]: - Series reactors are used to limit short circuit current in a line. Use of series reactors on line side can cause high Rate of rise TRV values.
3. Shunt reactor switching [2][7]: When a shunt reactor is switched circuit breaker interrupts very small currents. This kind of circuit results in load side oscillating with frequency of $1/\sqrt{LC}$, L being shunt reactor and C being capacitance associated with it. This can result in very high frequencies sometimes in the range of 1 to 5 KHz.[2]
4. Generator Circuit breakers [2][7]: - These circuit breakers are required to have special characteristics as these are installed between the transformer and generators. Faults associated with this can result in TRV values higher than the values ones given in C37.04 and C37.06. For system-source faults these can be 3-5 times higher.[2]

7. Case Study for analysis of TRV and Circuit Breaker Ratings Selection

System provided in [3] is used here as benchmark for analysis and explanation of the concepts involved. System is modeled in ATP and results are obtained.

7.1 Modeling for ATP from single line diagram

System as given in [3] was modeled using ATP. ALL parameters associated with the system were not provided, hence these were obtained from the test case results. Z_{sc} , thevenin equivalent impedance of the system is obtained from the test case 2 .[3]. Parameters for other generators were also obtained in similar fashion from test casesm10 and 11 respectively. System required for analysis is greatly influenced by capacitances of various devices. These capacitances were obtained from standard [7] and specification related to capacitances in [1] .System as inputted to ATP is shown below.

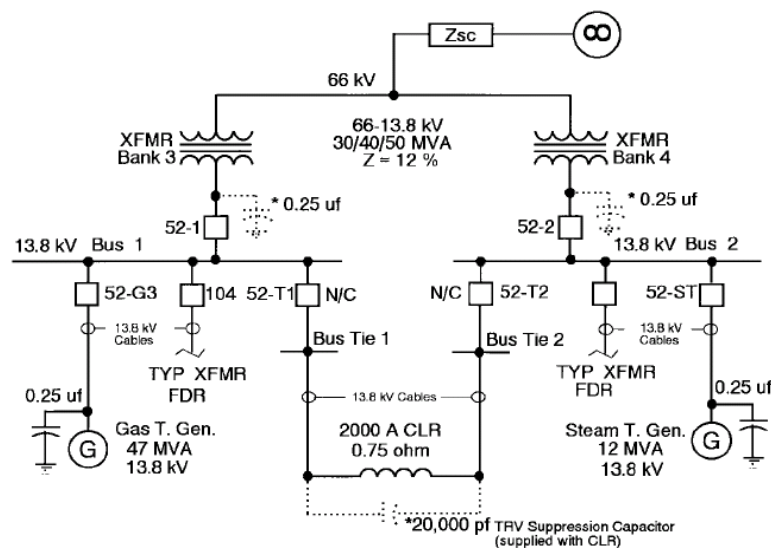


Figure 8: One-Line Diagram [3]

7.2 Simulation in ATP

System as shown above was modeled in ATP and test cases for simulation were chosen to be the same as in [3] .Various faults were initiated at locations as per the test cases and to validate the system short circuit currents at these locations were compared with those provided in [3] .After validation of system parameter three phase ungrounded and grounded faults were initiated and TRV obtained across the circuit breaker for interruption of these faults was noted.

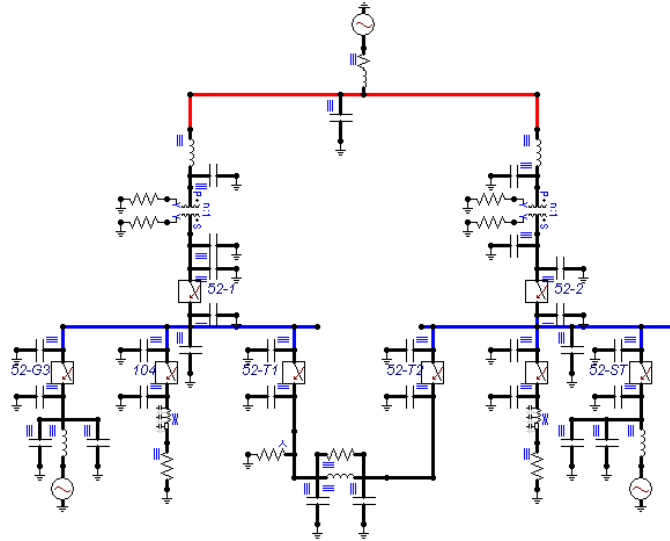


Figure 9: System Model in ATP

Waveshapes obtained are mostly 1-cosine type (Appendix). Values of peak voltage and time to peak are noted. Refer Table-1 for values of TRV.

7.3 Interpretation of results of simulation

7.3.1 TRV values obtained by simulation

Table 1 and Table 2 are respectively the TRV values and short circuit currents obtained on the system from simulation and as given in [3]. Grounded and Ungrounded faults were studied. It can be seen that ungrounded faults result in higher TRV values.

Table-1[Grounded and Ungrounded Faults]

	Fault	Fault Current KA	Grounded Faults		Ungrounded Faults	
			TRV Peak	Time to Peak	TRV Peak	Time to
			KV	μ S	KV	μ S
Case 1	Bus-1	9.9	22.188	12	33	12
Case 2	66KV Bus	--	--	--	--	--
Case 3	Bank-3	23.3	18.4	90	21.2	90
Case 4	Bank-3	23.3	18.4	90	21	80
Case 5	Bus Tie-2	5.2	15.9/16.86	14/38	23.3/24.55	16/40
Case 6	Bus Tie-1	21.2	22.8	58	33.17	58
Case 7	Bus tie-2	7.1	14.9	60	22.4	60
Case 8	Bus-2	5.2	15.1/16.9	14/46	22.9/24.5	15/48
Case 9	Bus-2	7.1	14.9	57	22.41	58
Case 10	Bus-1	11.4	22.5	79	33.8	79
Case 11	Bus-2	3.5	22.5	142	33.8	143
Case 12	Bus-1	9.99	21.975	91	32.94	94
Case 13	Bus tie-2	5.5	16.7	79	25	78
Case 14	Bus tie-2	5.2	16.9	92	25.36	93

Table-2 [3]

Summary of TRV Results								
Case	Operating Breaker	Short Circuit Current		TRV		Fault Location	Closed Breakers	Open Breakers
		kA	% of 37 kA	Crest (kV)	μ s			
1	52-1	9.9	26.9	24.1	12	Bus 1	none	all other @ 15 kV
2	52-1	3.6	9.6	9.8, 19.4	15, 36	66 kV bus	52-T1, 52-T2, 52-2	all other @ 15 kV
3	52-1	16.7	45.1	27.9	89	Bank 3	52-T1, 52-T2 52-2, 52-G3, 104	all other @ 15 kV 66 kV feed
4	52-1	16.2	43.8	27.1	89	Bank 3	52-T1, 52-T2 52-2, 52-G3, 104	all other @ 15 kV
5	52-T1	5.3	14.3	18.0, 24.2	21, 45	Bus tie 2	52-1	all other @ 15 kV
6	52-T1	21.4	57.8	30.4	78	Bus tie 1	52-1, 52-G3, 104	all other @ 15 kV
7	52-T1	7.3	19.8	22.4	40	Bus tie 2	52-1, 52-G3, 104	all other @ 15 kV
8	52-T2	5.3	14.3	27.6	36	Bus 2	52-1, 52-T1	all other @ 15 kV
9	52-T2	7.3	19.8	20.2, 24.1	30, 83	Bus 2	52-1, 52-T1, 52-G3, 104	all other @ 15 kV
10	52-G3	11.4	30.9	32.4	105	Bus 1	none	all other @ 15 kV
11	52-ST	3.5	9.4	31.5	143	Bus 2	none	all other @ 15 kV
12	52-1	9.9	26.9	29.1	71	Bus 1	none, *	all other @ 15 kV
13	52-T1	5.6	15.2	18.0, 27.0	42, 108	Bus tie 2	52-G3, 104	all other @ 15 kV
14	52-T1	5.3	14.3	21.0, 23.6	43, 86	Bus tie 2	52-1, *	all other @ 15 kV

* 0.25 μ F cap added to the 13.8 kV transformer bus

Waveshapes obtained in most of the cases is 1-cosine and in some cases a double frequency. The TRV values obtained in few cases exceed the capabilities of the circuit breakers used at those locations. These cases were handled with addition of surge capacitance across the incoming side of circuit breakers, these helped to reduce the TRV obtained at those locations.

7.3.2 Ratings of circuit breakers as per standards

Standards C37.04 and C37.06 specify the values of TRV envelope and parameters required to establish the capability of the circuit breaker. Ratings are given tables 1 through table 3 of C37.06-2000.

Only the values pertaining to TRV are listed and presented below.

Table 3:- TRV C37.06-2000 [6]

Ratings for circuit breaker 72.5KV and below

Rated Maximum Voltage KV, rms	Rated Peak Voltage E_2 KV peak	Rated Time to peak T_2 μ S
4.76	8.9	50
8.25	15.5	60
15	28	75
27	51	105
38	71	125
15.5	29	36
25.8	48.5	52
38	71	63
48.3	91	80
72.5	136	106

Rated Values for 123KV and above

Rated Maximum Voltage KV, rms	Rated Time to peak T_2 μ S	Rated Rate R KV/ μ S	Rated Delay Time T_1 μ S
123	260	2	2
145	310	2	2
170	360	2	2
245	520	2	2
362	775	2	2
550	1325	2	2
800	1530	2	2

Fast recovery Transients are specified in ANSI C37.06-1. This standard specifies TRV ratings for circuit breakers as per the variation of short circuit current.

7.3.3 Comparison of ratings and values from simulation

When the waveforms obtained from simulation and circuit breaker TRV ratings in Table-3 [6] are compared, we find that in most of the cases the TRV capability of circuit breakers are exceeded in this application. The simulation case 12 and 14 were rerun with surge capacitor of 0.4μF capacitor on incoming side of breaker # 52-1. Resultant TRV are within the ratings of the circuit breaker capability as specified in C37.06-2000.[6]

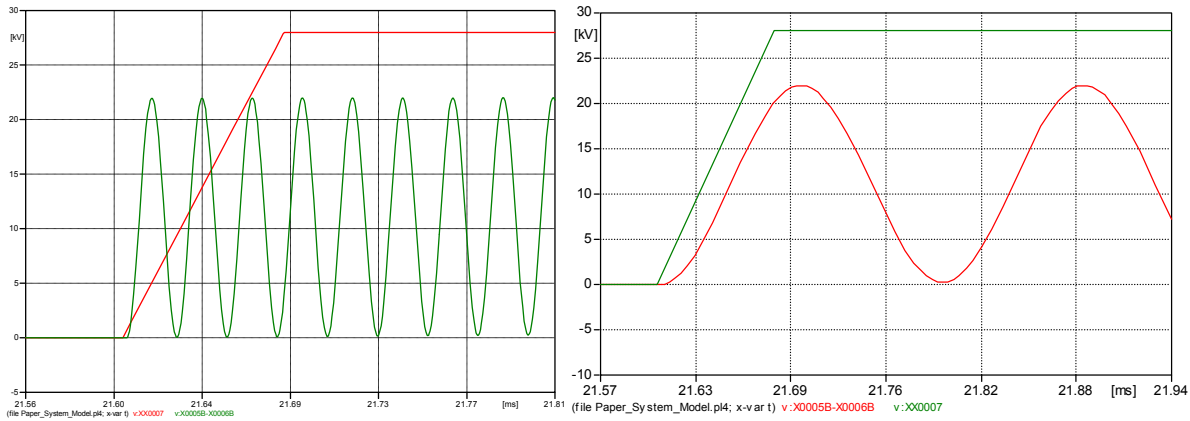


Figure 10:- Comparison Capability of Circuit Breaker TRV with System TRV a) Before addition of surge capacitor b) after addition of surge capacitor. Fault at Bus 1 Case 1 and Case 12.

Consideration of VT capacitance is extremely important; this is demonstrated through additional simulation run where resultant TRVs with and without addition of VT capacitance at 66KV bus is shown. It can be seen from the figure below that addition of capacitance has important bearing on the frequency, hence T_2 time to peak and peak of TRV.

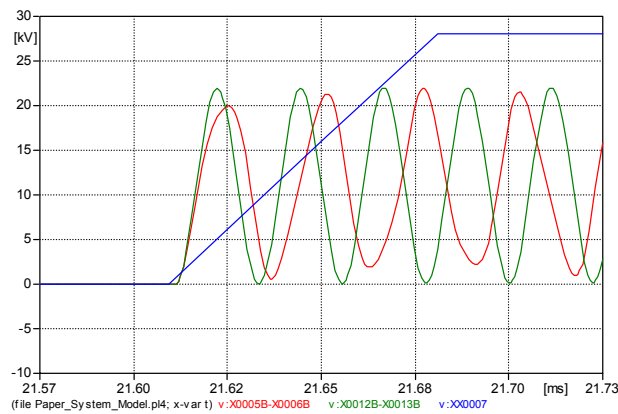


Figure 11:- Effect of VT capacitance on TRV of System.

8. Conclusions

1. Frequency and Peak values are greatly dependent on circuit inductance and capacitance.
2. Ungrounded faults result in high TRV across circuit breakers.
3. Surge Capacitors reduce TRV across circuit breakers.
4. Capacitance of the voltage transformers has effect on TRV values and times to peak.
5. Capacitance across the current limiting reactors has effect on TRV.
6. Results obtained from simulation and results provided in [3], don't match because of missing detailed parameters of cables and resistance in the circuit.

9. Recommendations

1. Capacitances of various devices have to be considered.
2. Ungrounded faults should be used for analysis as they result in higher TRV values.
3. Transient Analysis should be performed on a installation to prevent failure due to TRV issues.
4. To eliminate TRV surge capacitors should be employed on the incoming side of circuit breakers.
5. Modeling of all associated inductance and capacitance, with correct values is extremely essential for proper analysis.

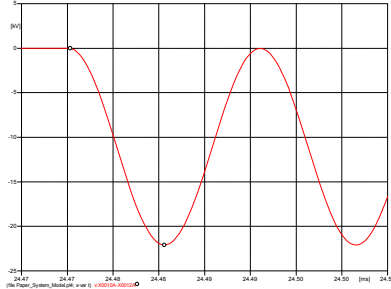
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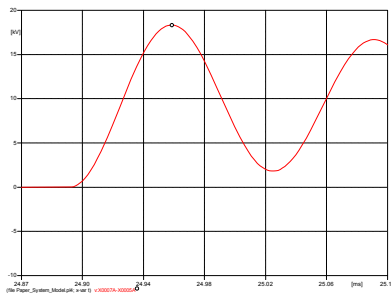
Appendix

Waveforms for 3-Phase grounded Faults

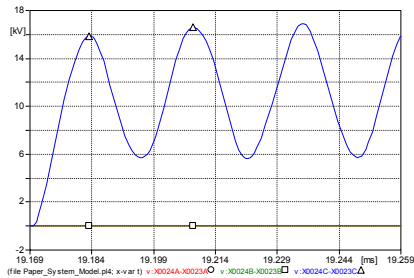
Case 1



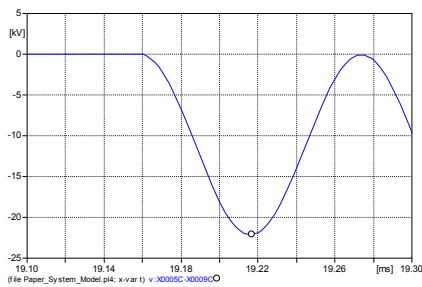
Case 3 and Case 4



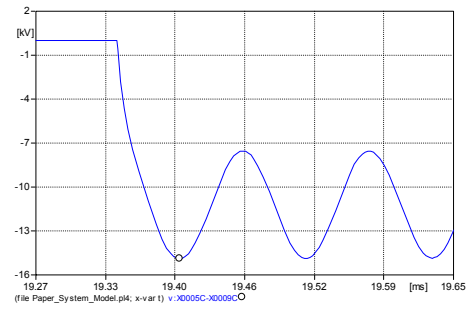
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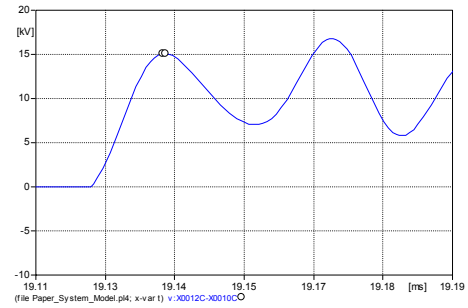
Case 6



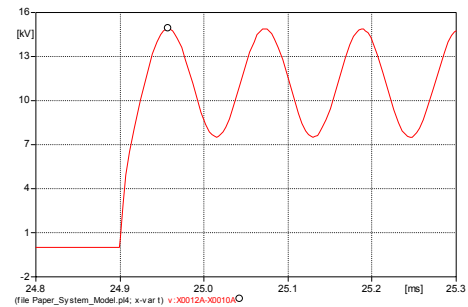
Case 7



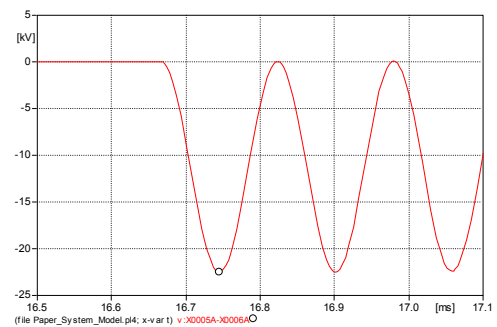
Case 8



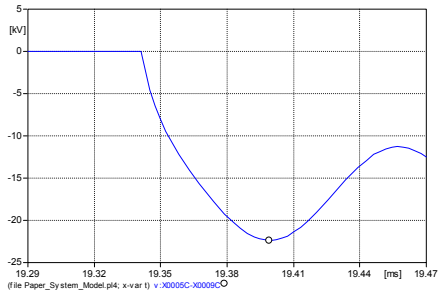
Case 9



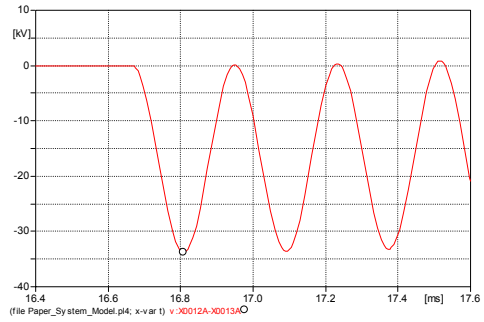
Case 10



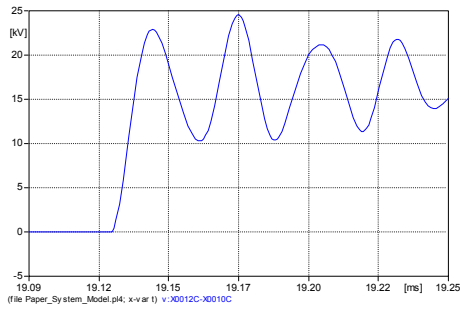
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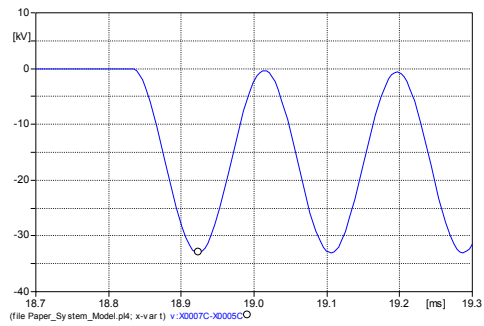
Case 11



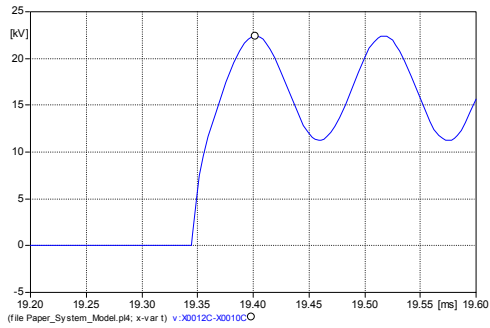
Case 8



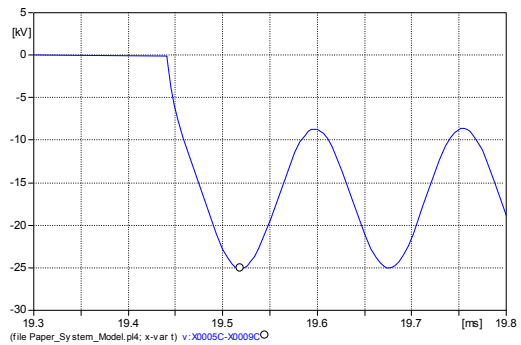
Case 12



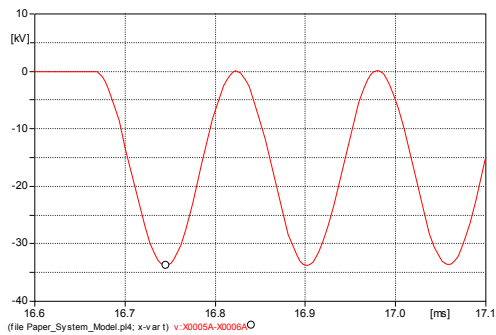
Case 9



Case 13



Case 10



Case 14

