Breaker Transient Recovery Voltages for the Series Compensated 500 kV Crystal Transmission System

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Abstract - **This paper describes the calculation of transient recovery voltage (TRV) and rate of rise of recovery voltages (RRRV) across the breakers on a series compensated transmission line.**

The studies included an investigation of the effect on breaker TRV and RRRV of series capacitor protection using triggered gap or metal oxide arresters across the series capacitors and gapped or gapless metal oxide phase-to-ground arresters. The maximum calculated values of TRV and RRRV of the breakers at Crystal Substation exceeded the maximum breaker capability defined in ANSI C37.06. The equipment that was specified and later purchased was designed to be suitable for the maximum calculated TRV and RRRV.

Keywords: Transient Recovery Voltages, Series Capacitor Compensation, Gapped Arresters, Metal Oxide Arresters, EMTP.

1 Introduction

Circuit breakers which are called upon to interrupt fault currents flowing through series capacitors are subjected to high transient recovery voltages (TRVs) due to capacitor trapped charge [1]. If the capacitors are protected by gapless metal oxide arresters the resulting TRV values will be higher compared to the case where the capacitors are protected by a triggered gap. The presence of series capacitors on both sides of the breaker results in further increase in breaker TRV value [2].

Circuit breakers are subjected to high rate of rise of recovery voltage (RRRV), especially if the breakers are subjected to faults through transformers.

This paper describes the calculation of TRV and RRRV across the breakers on the series compensated Navajo-Crystal-McCullough 500 kV line. The TRV and RRRV's were calculated with a combination of triggered gap and metal oxide arresters across the series capacitors and phase-to-ground arresters. The paper explores the influence of arrester protection on either side of the breakers on the calculated breaker TRV values and compares the calculated values with the breaker capability curves given in ANSI C37.06.

2 Pre-Crystal System

The original Navajo-McCullough 500 kV, 274 mile long line was provided with line end series capacitors of 35% at each end along with 70% shunt compensation consisting of 190 Mvar shunt reactor at each end of the line. The shunt reactors were connected on the bus side of the series capacitors.

The Navajo and McCullough series capacitors were protected by triggered gaps set to flash at 3.0 p.u. of the rated capacitor voltage calculated from the rated current (1630 A) and reactance of the capacitor. The shunt reactors at Navajo and McCullough were protected with 468 kV gapped silicon carbide arresters. A single line diagram of the initial system is shown in Figure 1.

3 Post Crystal System

The existing Navajo-McCullough 500 kV, 274 mile line was looped into the Crystal 500 kV substation thus forming the Crystal-Navajo 224 mile and Crystal-McCullough 52 mile transmission lines, as shown in Figure 2. The transmission re-configuration required that new series and shunt compensation and switchgear be provided. The design called for series compensation at Crystal to be added to provide approximately 70 percent compensation on the Crystal-Navajo line and for the existing capacitors at McCullough substation to be modified to provide approximately 70 per cent compensation for the Crystal-McCullough line.

The Crystal 500 kV bus is interconnected with Crystal 230 kV bus through two identical sets of auto and phase shifting transformers. The Crystal 230 kV substation will interconnect with the Harry Allen 230 kV substation via two 230 kV, 8 mile long transmission lines.

For study purposes the series capacitors at Crystal were assumed to be protected with 120 kV metal oxide arresters. The series capacitors at Navajo are at present protected with triggered gaps that bypass the capacitors at 3.0 p.u. voltage. The series capacitors at McCullough were represented with the existing triggered gap protection that bypasses the capacitors at 3.0 p.u. voltage. The TRV calculations were performed with triggered gap protection and also with 192 kV metal oxide arrester protection replacing the existing triggered gap protection at Navajo.

4 System Representation

An extensive portion of the 500 kV network around Navajo and Crystal buses was modelled for calculation of the transient recovery voltages. The system was represented explicitly up to more than two buses away from the study buses and equivalenced at the remote ends by equivalent impedances.

The Navajo-Crystal 500 kV transmission line was represented using a frequency dependent distributed parameter model with line transpositions as in the actual system. The other 500 kV lines were represented as frequency independent, distributed parameter, continuously transposed elements with parameters calculated at 250 Hz.

The Navajo shunt reactor was initially protected using 468 kV gapped silicon carbide arresters. Even though it was planned to replace these gapped arresters by 420 kV metal oxide arresters, the breaker TRV values were calculated for both silicon carbide gapped arresters as well as metal oxide arresters. It was not planned to replace the silicon carbide arresters (468 kV) on the bus side of breakers and they were modeled in these studies.

Metal oxide arresters (420 kV) at line entrance and transformer terminals were modelled at the Crystal end.

The magnitude of transient recovery voltage (TRV) and rate of rise recovery voltages (RRRV) across the breakers on the Navajo-Crystal-McCullough 500 kV line were calculated for the following conditions:

- triggered gap protection across the series capacitors at Navajo
- Metal oxide arresters protection across the series capacitors and at the line end at the Crystal
- triggered gap protection across the series capacitors at McCullough
- phase-to-ground gapped silicon carbide arresters on the bus side of breakers at Navajo
- phase-to-ground metal oxide arresters on the line side of breakers at Navajo
- phase-to-ground metal oxide arresters on bus side and line side of breaker at Crystal
- phase-to-ground gapped silicon carbide arresters on bus side and line side of breaker at McCullough

Several variations of the basic protection scheme were simulated to identify the impact of protection on breaker TRV duty.

The calculations were performed with three-phase representation of the network using the EMTP program.

The flashover characteristics of the gapped silicon carbide arresters were represented by a voltage sensitive switch connecting the arrester to the network. The switch closes once the voltage across it reaches the pre-specified flashover value and then the arrester starts conducting. The characteristics after flashover were represented by a non-linear element.

5 Methodology

TRV values were calculated by applying five cycle, three-phase ungrounded faults. The system was allowed to run in steady-state condition for about one cycle prior to the fault application. Three-phase ungrounded faults were simulated, even though they rarely occur, because the ANSI standard definition of breaker TRV capability is based upon this fault condition. The breaker at the near end of the fault was opened five cycles after fault inception. The far end breaker was opened 20 ms after the near end breaker is opened. The fault remained on the system during TRV calculations.

The calculations were performed with faults applied on the bus side of the series capacitors. For faults on the line side of series capacitors, the series capacitors would be bypassed and thus the condition would correspond to faults on the bus side.

The TRV curve calculated using EMTP was compared with the envelope given in ANSI C37.06-1987 to determine whether the capability of a standard breaker would be adequate. Calculated values of TRV, time to crest and RRRV for 100%, 60% and 7% fault currents are given in Table 1.

6 Analysis of Results

The results indicated that TRV values depend upon the type of series capacitor protection, the number of lines connected to the given bus and the type of line-to-ground arrester. A number of cases were performed to establish the impact of changing these variables. An analysis of the pertinent cases is given below. Case descriptions and the corresponding calculated TRV values are given in Tables 2 to 4.

6.1 Crystal Substation Breakers

The TRV value of breakers at Crystal on Crystal-Navajo and Crystal-McCullough lines were calculated. The TRV values with Crystal 500 kV bus connected with Navajo and McCullough 500 kV buses and Crystal 230 kV bus form the base case for comparison purposes.

For faults on the bus side of series capacitors at Crystal, the calculated TRV values were found to be about 1333 kV if the McCullough series capacitors are not bypassed (Case 1 in Table 2) see Figure 3. The type of Navajo series capacitor protection has very little effect on breaker TRV values at Crystal and the TRV would not be expected to change even for increased fault current through Navajo capacitors. For increased fault current through the Navajo breaker the Navajo series capacitors will be bypassed, through either the triggered gap or metal oxide arresters, depending on the protection scheme provided.

The high TRV values for this fault location are attributed mainly to the fact that the series capacitors on the Crystal-McCullough line will not bypass during this fault regardless of whether triggered gaps or metal oxide arresters are connected across the series capacitor.

It is expected that the McCullough series capacitors will be bypassed by the existing triggered gap protection, for faults at Crystal, and thus the TRV value will be less than 964 kV, which is within the breaker withstand value at 60% current. The effect on the Crystal breaker TRV of providing metal oxide arresters protection at the McCullough series capacitor (expected at a future date) is not known at this stage. However, it can safely be concluded that the TRV value will not exceed 1333 kV even if the McCullough capacitors are provided with metal oxide arresters protection.

Thus the maximum TRV value for any Crystal breaker, for faults at Crystal end on the Crystal-Navajo line, will not exceed 1333 kV, with Crystal 500 kV bus connected with Navajo, McCullough 500 kV buses and Crystal 230 kV bus. This TRV value is higher than the 60% current TRV value (1036 kV in Table 1) stated in ANSI C37.06-1987.

For faults on the bus side of Navajo series capacitors the highest TRV value on Crystal breakers was found to be 1319 kV (Case 7 in Table 2). For this fault the Navajo series capacitors are protected by 192 kV metal oxide arresters and the McCullough series capacitors are not bypassed, as their current is only 1.6 kA. This TRV magnitude is higher than the TRV value for 7% interrupting current (1133 kV in Table 1) in ANSI C37.06-1987. Thus it was recommended that the Crystal breakers be specified for a TRV of at least 1350 kV.

The calculated rate of rise of recovery voltage (RRRV) values were below the ANSI C37-06 values for all cases except when the Crystal 500 kV bus is transformer terminated (see Tables 2 and 3). The RRRV values were found to range from 6.25 to 8.32 kV/µs for cases 4, 5, 6, and 11. These high RRRV values are attributed to the transformer termination with low stray capacitance and line capacitance.

6.2 Navajo Substation Breakers

The maximum breaker TRV values at Navajo and McCullough for the pre Crystal configuration were calculated to be 1465 kV and 1522 kV respectively (see Table 4). These values are higher than the values in ANSI C37.06-1987. However, as these breakers have been in service for a long time, it is considered that these breakers were designed to withstand these high TRV values.

Similarly the calculated TRV values of Navajo breakers in the post Crystal configuration are higher than the ANSI C37.06-1987 values. They are, however, lower than the values under the present operating conditions. The RRRV values are below the ANSI C37.06-1987 stated values.

As the TRV values of the Navajo breakers in the post Crystal configuration are lower than the values under present operating conditions no additional TRV limiting measures were deemed necessary.

6.3 McCullough Substation Breakers

The calculated TRV values for McCullough breakers in the post Crystal configuration were also found to be lower than the values under the present operating conditions and similar to the Navajo values. Thus no additional TRV limiting measures were deemed necessary.

7 Specifications of New Equipment

The specification for the Crystal 500 kV breakers included two specific requirements: one representing the maximum TRV case and the other representing the maximum RRRV case. The actual values stated in the specification were 1333 kV, 3.2 kV/µs at 30.2 kA and 832 kV, 8.32 kV/µs at 4.7 kA. Two interrupters in series would have been expected to be sufficient for a typical 500 kV application. However, because of the high TRV requirements, breakers with three interrupters in series were proposed by manufacturers at bid time. This is typical of 800 kV breakers.

8 Summary and Conclusions

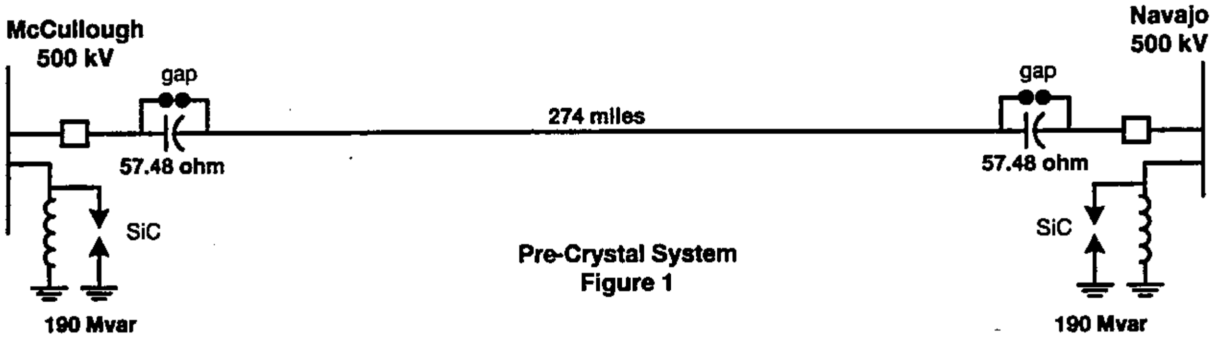
The re-configuration of the original series and shunt compensated Navajo-McCullough 500 kV line by looping it into Crystal Substation required an investigation into the Crystal 500 kV breaker requirements as well as the requirements of the breakers on either end of the original line

As a result of the studies TRV requirements beyond those allowed in ANSI Standard C37.06 were specified for the Crystal 500 kV breakers. Dead tank SF_6 breakers with three-interrupting heads per phase were supplied and have been in operation since 1998.

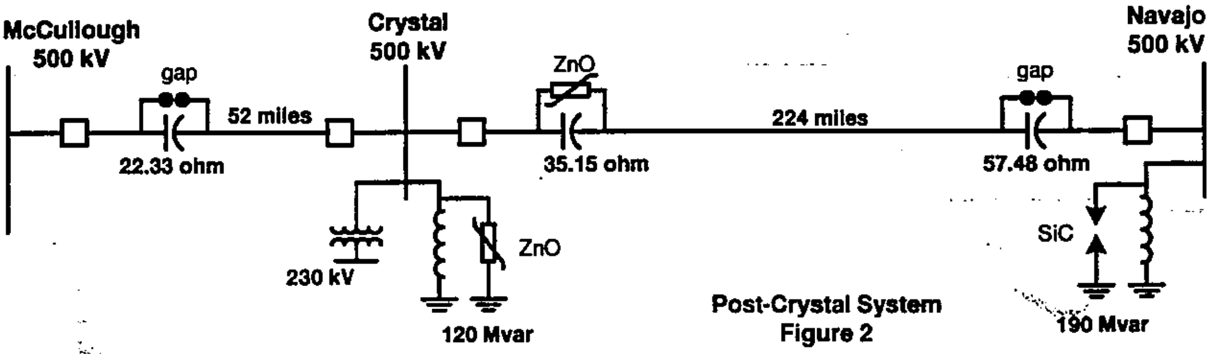
9 References

[1] D. D. Wilson, "Series compensated lines - Voltages across circuit breakers and terminals caused by switching", IEEE Trans. on Power Apparatus and Systems, Vol. PAS-73, pp. 1050-56, May - June 1973.

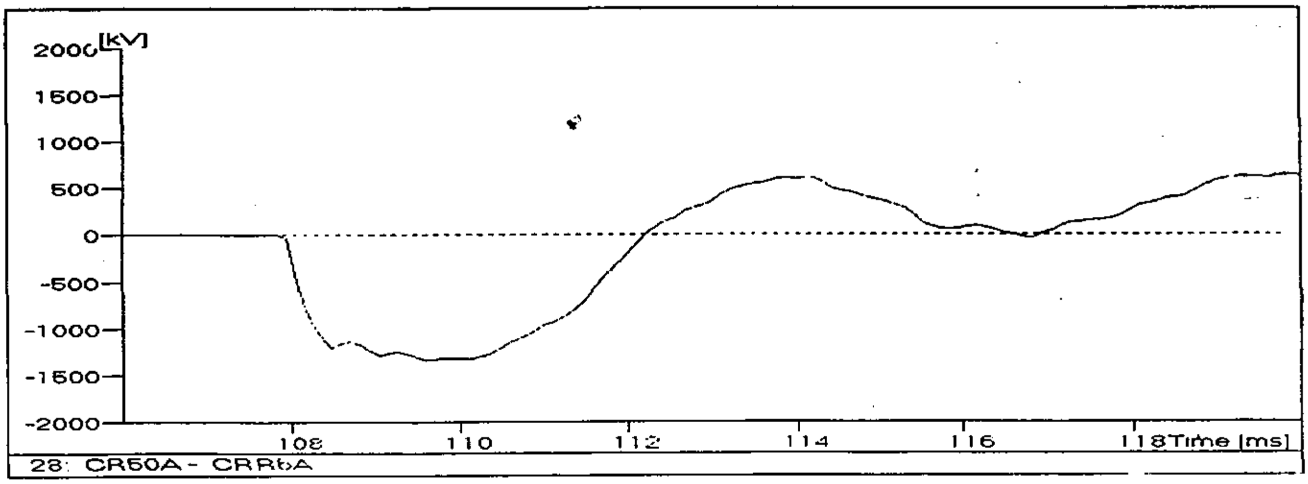
[2] F. Iliceto, F. M. Gatta, E. Cinieri and G. Asan, "TRVs across circuit breakers of series compensated lines, status with present technology and analysis for the Turkish 420 kV grid", IEEE Trans. on Power Delivery. Vol. 7, No. 2, pp. 757-766, April 1992.



Pre-Crystal System
Figure 1



Post-Crystal System
Figure 2



Breaker Voltage at Crystal for Fault at Bus Side of Crystal Series Capacitor
Figure 3

TABLE 1
TRV Capability of 500 kV Breakers as per ANSI C37.06

Percent of Interrupting Rating	TRV max (kV)	Time to Crest (us)	RRRV (kV/us)
100	968	1325	1.6
75	1016	782	2.7
60	1036	663	3.2
30	1094	265	4.1
7	1133	265	4.3

TABLE 2
TRV Values of Breakers on the Navajo-Crystal Line

Case	Fault Location	Series Capacitor Bypass			Navajo Breaker		Crystal Breaker		Breaker Current (kA rms)		
		Navajo Gap	Crystal ZnO	McC. Gap	TRV (kV)	RRRV (kV/us)	TRV (kV)	RRRV (kV/us)	Navajo	Crystal	McC.
1	Crystal	No	No	No	1257	1.19	**1333**	**3.2**	4.5	**30.2**	19.2
2	Crystal	No	No	Yes	1238	0.94	951	1.6	4.5	30.2	19.2
3	Crystal	Yes	No	Yes	1152	0.73	899	1.6	4.5	30.2	19.2
4**	Crystal	Yes	No	N/A	1036	0.68	840	7.45	4.5	4.4	N/A
5**	Crystal	ZnO*	No	N/A	1460	0.68	806	7.23	4.5	4.4	N/A
6**	Crystal	No	No	N/A	1438	1.19	813	6.25	4.5	4.4	N/A
7	Navajo	ZnO*	No	No	1042	1.19	1319	0.83	22.3	2.7	1.6
8**	Navajo	Yes	No	N/A	1037	1.11	865	2.13	21.6	2.7	N/A
9**	Navajo	ZnO*	No	N/A	1022	1.11	1167	3.27	21.6	2.7	N/A

* In these cases ZnO arresters were modelled rather than a gap. N/A – not modelled

** Weak system and Crystal 500 kV disconnected from McCullough.

Breaker specified values are shown in **bold**.

TABLE 3
TRV Values of Breakers on the Crystal-McCullough Line

Case	Fault Location	Series Capacitor Bypass			McCullough Breaker		Crystal Breaker		Breaker Current (kA rms)	
		Navajo Gap	Crystal ZnO	McC. Gap	TRV (kV)	RRRV (kV/us)	TRV (kV)	RRRV (kV/us)	McC.	Crystal
10	Crystal	No	No	Yes	834	1.2	1027	1.33	19.2	8.8
11**	Crystal	N/A	N/A	Yes	854	1.54	**832**	**8.32**	19.8	**4.7**

N/A – not modelled

** Weak system and Crystal 500 kV disconnected from Navajo.

Breaker specified values are shown in **bold**.

TABLE 4
TRV Values of Breakers on the Navajo-McCullough Line

Case	Fault Location	Series Capacitor Bypass		Navajo Breaker		McCullough Breakers		Breaker Current (kA rms)	
		Navajo Gap	McC. Gap	TRV (kV)	RRRV (kV/us)	TRV (kV)	RRRV (kV/us)	Navajo	McC.
12	McC.	No	No	1465	1.19	1040	0.71	2.9	34.5
13	Navajo	No	No	967	1.19	1522	0.86	21.8	3.8