A Feasibility Study for Bus-Tie Current Limiting Reactor Application in 230 kV Stations

Babak Ahmadzadeh-Shooshtari
Hydro One Networks Inc.
Toronto, Canada
Babak.AhmadzadehShooshtari@HydroOne.com

Lianxiang Tang
Hydro One Networks Inc.
Toronto, Canada
Lianxiang.Tang@HydroOne.com

***Abstract*—This study describes the considerations necessary for implementing bus-tie current limiting reactors (CLRs) in 230 kV stations. First, the impact of different bus-tie CLR values on the station fault level is investigated when the fault level is assumed to be around 80 kA without the CLR. Afterwards, the CLR's impact on the station voltage during the worst N-1-1 contingency in the station is studied when all lost power is passed through the bus-tie CLR. Finally, for a selected CLR value, transient recovery voltage (TRV) studies are conducted using simplified EMTP models, and the necessary surge capacitor arrangement to bring the tie breaker and diameter breakers' TRVs within the standard envelopes is discussed.**

***Index Terms*—Current limiting reactor (CLR), short-circuit, surge capacitor, tie breaker, transient recovery voltage (TRV).**

I. INTRODUCTION

With the increasing of the energy demand and consequent developments in transmission-level power plants and transmission systems, high-voltage stations are prone to experience short-circuit levels well beyond the limits defined by transmission system codes (TSCs) such as [1]. As the station short-circuit level exceeds the TSC limits, it can endanger the station equipment, specifically circuit breakers (CBs) and transformers, and ultimately, degrade the system resiliency.

One approach to reduce a station short-circuit level below the TSC limits is to insert current limiting reactors (CLRs) in series with the station bus-tie breakers [2], [3]. This approach can postpone the station upgrades and fundamental changes which can be costly. However, the implementation of CLRs may lead to challenges including station voltage drop, transient recovery voltage (TRV), and transient stability, as discussed in [3], [4], and [5]. This paper aims to comprehensively investigate the feasibility of using bus-tie CLRs to limit short-circuit currents in 230 kV stations. Such stations are usually supplied by transformers and/or transmission lines and employ two bus-tie CBs. The study cases of this work are listed below.

i) *Short-circuit studies*: using a simplified EMTP model of a 230 kV station, the effects of different CLR values on both single-phase and three-phase station fault currents are investigated.

ii) *Steady-state bus voltage calculations during contingencies*: the worst N-1-1 contingency in the station is determined to evaluate the CLR current rating and the bus voltage change due to the voltage drop across the bus-tie CLR as it transfers load from one bus to the other after the contingency.

iii) *TRV studies*: using the simplified station model, TRV studies are done for the tie breakers equipped with CLRs. IEEE standard-defined terminal fault (TF) TRV capability envelopes [6] are employed to evaluate the breaker TRV coordination. The station's extended EMTP model is also used to verify the TRV results obtained from the simplified model. Moreover, the extended model is employed to evaluate the impact of bus-tie CLRs on the TRVs of the station diameter breakers. Furthermore, the necessity of using surge capacitors for the TRV mitigation is discussed.

II. STATION TWO-BUS EQUIVALENT SYSTEM

Fig. 1(a) depicts the conceptual single-line diagram of a generic 230 kV station with two tie breakers in series with CLRs. Each arrow between two diameter breakers can represent either a transmission line or transformer terminal connected to the station. Fig. 1(b) shows the simplified two-bus equivalent system model of the station of Fig. 1(a). This model is utilized in the studies of this paper since (i) this work is intended to investigate the feasibility of implementing bus-tie CLRs for short-circuit level reduction in a generic station while maintaining acceptable TRVs upon fault current interruption and bus voltages during the contingencies, (ii) the study is not related to a specific station, which requires more detailed station modeling, (iii) the system of Fig. 1(b) can model the fault current through the bus-tie CLRs with the target of reducing the station fault current from 80 kA to 63 kA that is the TSC limit for 230 kV systems [1], (iv) it can also represent the power flow/lost power passing through the

979-8-3315-8138-1

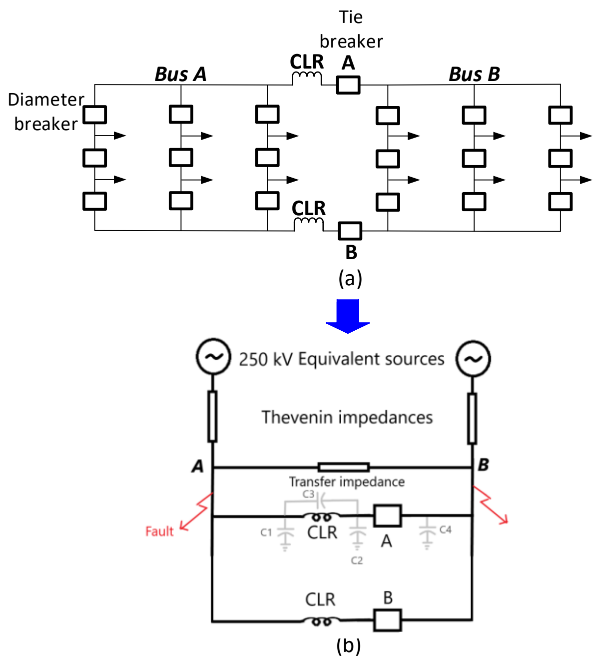

Figure 1. Single-line diagrams of a generic 230 kV station: (a) conceptual station diagram and (b) simplified station diagram.

TABLE I. STATION TWO-BUS EQUIVALENT MODEL PARAMETERS

	Positive sequence		**Zero sequence**	
	***R* (Ω)**	***X* (Ω)**	***R* (Ω)**	***X* (Ω)**
Equivalent source_A	0.194	4.206	0.706	4.538
Equivalent source_B	0.223	4.893	0.532	4.447
Transfer impedance	1.016	13.489	0	15.662

CLR during the worst contingency with one bus-tie breaker already open, and (v) the model represents reasonable accuracy for bus-tie breaker TRV investigations for the faults on both sides of the breaker.

In Fig. 1(b), a maximum operating voltage of 250 kV is used for two Thevenin equivalent sources representing the transmission lines and/or transformers connected to the station. The model parameters, which are derived from a station with a fault level of 63.7 kA, are represented in Table I.

III. Short-Circuit Results for Different CLR Values

In this section, the parameters of two-bus equivalent model in Table I are proportionally adjusted to reach a station fault current of 80 kA with the tie breakers closed without CLRs. The adjusted parameters of the station equivalent model are provided in Table II. The effects of different CLR values on station fault currents in different operation conditions of tie breakers are then investigated. Table III represents the three-phase and phase A to ground short-circuit results for different combinations of CLR values and tie breakers status in the station. The observations regarding the short-circuit investigations for stations with the bus-tie CLRs are: (i) if the desired station short-circuit level using the CLRs is assumed to be 63 kA when both tie breakers are closed, a CLR of 10 Ω for each tie breaker is enough, (ii) the results of Table III show the CLR's currents for three-phase and single-phase faults are almost similar since the positive-sequence and zero-sequence impedances are similar, and (iii) our studies reveal that the larger transfer impedance of a station's equivalent model, the more effective the bus-tie CLR is in short-circuit reduction. Accordingly, the stations mainly supplied by transformers are more sensitive to the bus-tie CLR for fault reduction, compared to those dominantly supplied by lines.

IV. Voltage Calcualtions during N-1-1 Contingencies

The station considered in this study includes two transmission lines, X and Y from a power plant, which are connected on the left and right sides of the station tie breakers, respectively. Line X has a maximum capacity of 825 MVA, while the capacity of line Y is 500 MVA. Accordingly, the

TABLE II. ADJUSTED PARAMETERS OF STATION TWO-BUS EQUIVALENT MODEL FOR STATION SHORT-CIRCUIT LEVEL OF 80 KA

	Positive sequence		**Zero sequence**	
	***R* (Ω)**	***X* (Ω)**	***R* (Ω)**	***X* (Ω)**
Equivalent source_A	0.154	3.338	0.560	3.602
Equivalent source_B	0.177	3.884	0.423	3.530
Transfer impedance	0.807	10.706	0	12.430

TABLE III. STATION SHORT-CIRCUIT CURRENTS FOR DIFFERENT CLRS AND TIE BREAKERS STATUS

Bus-tie CBs	**CLR (Ω)**	**Bus**	**3-ph fault currents (kA)**		**1-ph fault currents (kA)**	
			Fault	***CLR***	***Fault***	***CLR***
Both open	N/A	A	53.1	N/A	51.5	N/A
		B	47.4	N/A	48.1	N/A
One close	5	A	63	13.5	61.9	13.8
		B	58.5	14.6	59.2	14.5
	10	A	59.1	8.2	57.9	8.4
		B	54.1	8.8	54.8	8.8
	15	A	57.4	5.9	56.1	6.1
		B	52.2	6.3	52.9	6.3
Both close	5	A	67.6	9.9	66.8	10.2
		B	64	10.9	64.7	10.8
	10	A	63	6.7	61.9	6.9
		B	58.5	7.3	59.2	7.3
	15	A	60.6	5.1	59.4	5.2
		B	55.7	5.5	56.5	5.5

979-8-3315-8138-1

worst N-1-1 contingency in the station, in terms of maximum current that can potentially pass through the tie breaker, would be when line X is out-of-service and either tie breaker A or B is open. In such a condition, the 825 MVA lost power is compensated through the closed tie breaker from the side with no outage. This contingency leads to maximum voltage change along the station's bus with the CLR. It also establishes a continuous rating of 2000 A for the CLR.

The voltage calculation results during the aforementioned contingency are summarized in Table IV for different CLR values when the lost power has a lagging or leading power factor (PF). It is assumed the tie breakers do not carry significant power in station's normal operating condition prior to the contingency. Considering the results of Table IV for a CLR of 10 Ω, it is observed that during a N-1-1 contingency, the station bus voltage can decrease to as low as 236.7 kV or increase to as high as 257.5 kV for a tie breaker current of 1.9 kA with a 0.95 lagging or leading PF, respectively. This is with the assumption that the bus voltage on the other side of the tie breaker and CLR is 245 kV. Note that the study assumes all the lost power will be re-supplied through the bus-tie reactor, which is a very conservative assumption since a part of the power will pass through the transfer impedance between the two station buses. Detailed power-flow studies determine if there is a need for reactive power compensation to regulate the bus voltages.

Table V summarizes the advantages and disadvantages of studied bus-tie CLR values in terms of short-circuit current reduction and imposed voltage changes on the buses during the worst N-1-1 contingency in a 230 kV station.

V. TRV Studies

A. Simplified Station Model

Using the simplified model of Fig. 1(b), tie breaker capability in interrupting fault currents during three-phase station faults, as studied in Section III, is investigated. Similar TRV results are expected for single-phase faults. The following assumptions are made in the studies of this section:

- To evaluate the tie breaker TRV capability, IEEE standard TF TRV capability curves/envelopes [6] with a k_{pp} of 1.5 (non-effectively grounded) are employed.
- The tie breaker rating and CLR are 63 kA and 10 Ω, respectively.
- The other station tie breaker is in maintenance prior to the fault.
- The potential surge capacitor(s) to mitigate the tie breaker TRV has a typical capacitance of 35 nF (see C1, C2, C3, and C4 in Fig. 1(b)).

For a fault at bus A, Fig. 2 depicts the TRV capability curve/envelope and TRVs of phase A for different surge capacitor arrangements. The breaker opens at 20 ms in the simulations of this section. The fault current is 59.1 kA and the current passing through the tie breaker is 8.2 kA (see the three-phase fault current in Table III with 10 Ω CLR and with one tie breaker closed). Therefore, the breaker TRVs are evaluated against T13 (i.e., $100 \times 8.2^{kA}/63^{kA}$) TRV envelope.

TABLE IV. Station Voltage Results for Different Bus-Tie CLR Values during the Worst N-1-1 Contingency

Contingency	CLR's current (kA)	CLR (Ω)	Voltage across CLR (kV)	Voltage at receiving end of CLR (kV)*	
				0.95 lagging PF	*0.95 leading PF*
Line X is out and either breaker A or B opens	1.9**	5	9.7	240.3<-3.8°	250.8<-3.7°
		10	19.4	236.7<-7.8°	257.5<-7.1°
		15	29.2	234.2<-11.8°	265.1<-10.4°

* The CLR's sending end voltage is assumed to be 245<0° kV.
** This current corresponds to 825 MVA at 245 kV.

TABLE V. Pros and Cons of Different Bus-Tie CLR Values in terms of 230 kV Station Fault Current Redution and Voltage Change during N-1-1 Contingecies

CLR	Pros	Cons
5 Ω	Acceptable bus voltage change during N-1-1 contingencies	Insufficient station fault current reduction
10 Ω	Sufficient station fault current reduction (below 63 kA)	Voltage regulation needs to be studied for the worst N-1-1 contingency*
15 Ω	High station fault current reduction	Potentially unacceptable bus voltage during N-1-1 contingencies

* Assuming a conservative bus-tie CLR power flow leading to a CLR current of around 2 kA.

Fig. 3 illustrates the results for the fault of 54.1 kA at bus B and the tie breaker current of 8.8 kA (see Table III). The study results of this section show that using C2 and C4, the tie breakers' TRVs do not violate the corresponding TRV capability curves for the faults on both sides of the tie breakers

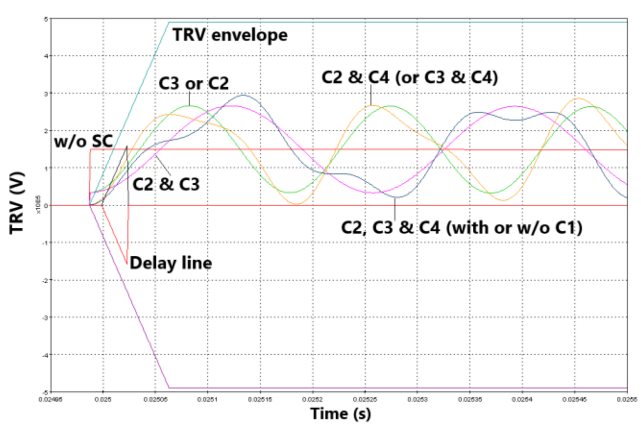

Figure 2. Phase-A T13 TF TRV envelope and TRVs of tie breaker with a 10 Ω CLR for different surge cap (SC) arrangements after interrupting a fault current of 8.2 kA during a station fault of 59.1 kA at bus A.

979-8-3315-8138-1

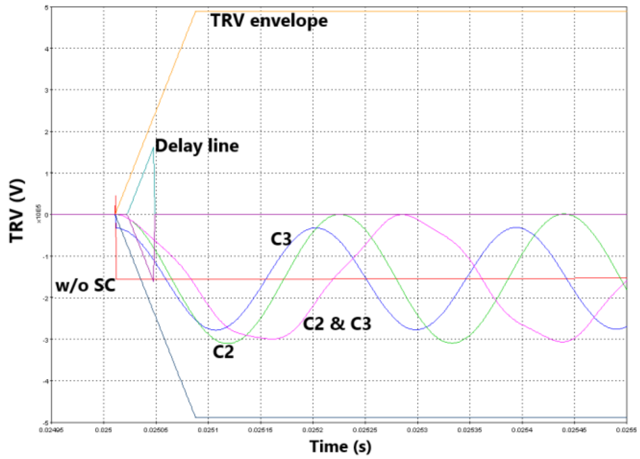

Figure 3. Phase-A T14 TF TRV envelope and TRVs of tie breaker with a 10 Ω CLR for different surge cap (SC) arrangements after interrupting a fault current of 8.8 kA during a station fault of 54.1 kA at bus B.

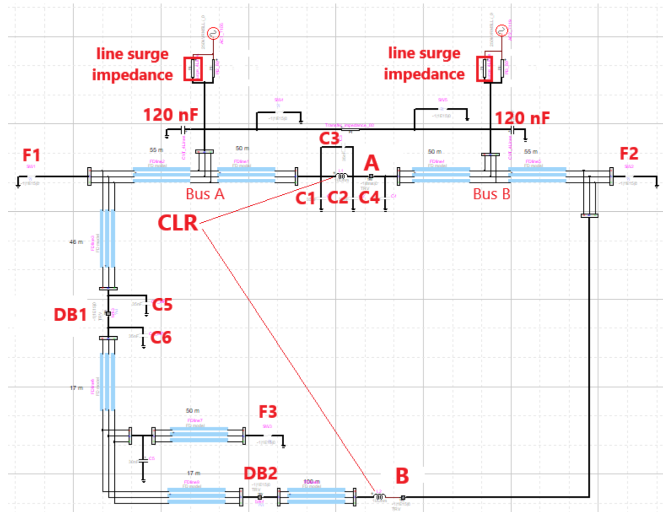

Figure 4. Station extended model in EMTP.

in Fig. 1. Note that for the fault at bus B, C2 alone can prevent the TRV violation (see the green curve in Fig. 3 that is within the TRV envelope and succeeds the delay line).

B. Extended Station Model

Fig. 4 shows an extended EMTP model of the station under study. In this model, only one main bus and one diameter bus of the station are represented by the frequency dependent (FD) line models, each with a surge impedance of 260 Ω. The impedances of equivalent sources on both sides of tie breakers A and B (related to buses A and B) are paralleled with equivalent line surge impedances which are represented by positive- and zero-sequence resistances of 90 Ω and 140 Ω, respectively. The station short-circuit current is 80 kA when the tie breakers are closed and no CLR is employed.

Fig. 5 depicts the phase-A TRV envelope and TRVs of tie breaker A with a CLR of 10 Ω for three-phase fault F1 (see Fig. 4) and different surge capacitor arrangements. The fault current is 58.8 kA and the breaker A current during the fault is 8.2 kA. The breaker A opens to clear the fault at 8 ms and the diameter breaker DB1 is assumed open during the entire simulation in this fault scenario.

The TRV results for fault F2 are shown in Fig. 6 where tie breaker A operates for the fault and tie breaker B is assumed open during the entire simulation. In this fault scenario, the fault and breaker A currents are 53.9 kA and 8.7 kA, respectively. Figs. 5 and 6 suggest that using either C2 (on the right-side terminal of CLR in Fig. 4) or C3 (in parallel with the CLR) is enough for the tie breaker with a CLR of 10 Ω to interrupt the currents during the bus faults F1 and F2.

Note that unlike the simplified model of Fig. 1(b), by modeling the line surge impedances in parallel with the equivalent sources' impedances in the extended model, the TRV stress across the tie breaker is alleviated; hence, the surge capacitor of C4 (on breaker A's right-side terminal) is no longer required to confine the breaker's TRV within the specified TRV envelopes for the station faults in this model.

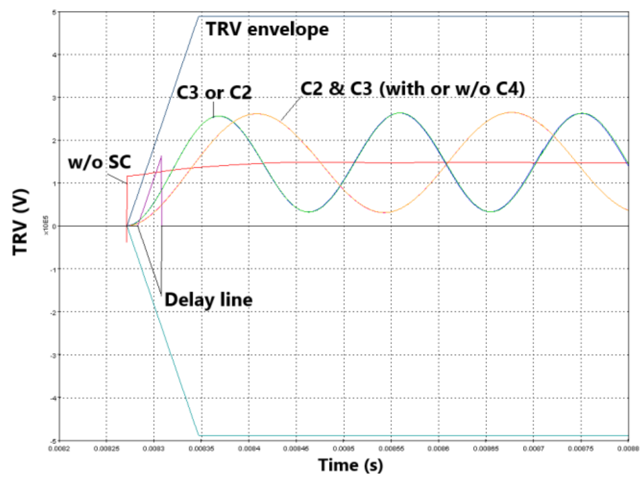

Figure 5. Phase-A T13 TF TRV envelope and TRVs of the tie breaker A with a 10 Ω CLR in the extended model for different surge cap (SC) arrangements after interrupting a fault current of 8.2 kA during a bus fault (F1) of 58.8 kA.

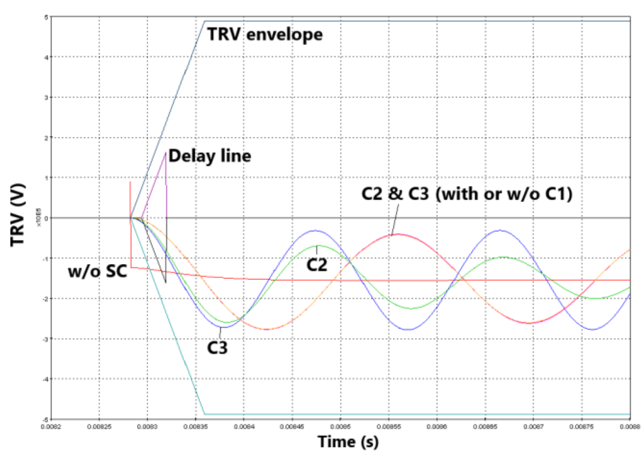

Figure 6. Phase-A T14 TF TRV envelope and TRVs of the tie breaker A with a 10 Ω CLR in the extended model for different surge cap (SC) arrangements after interrupting a fault current of 8.7 kA during a bus fault (F2) of 53.9 kA.

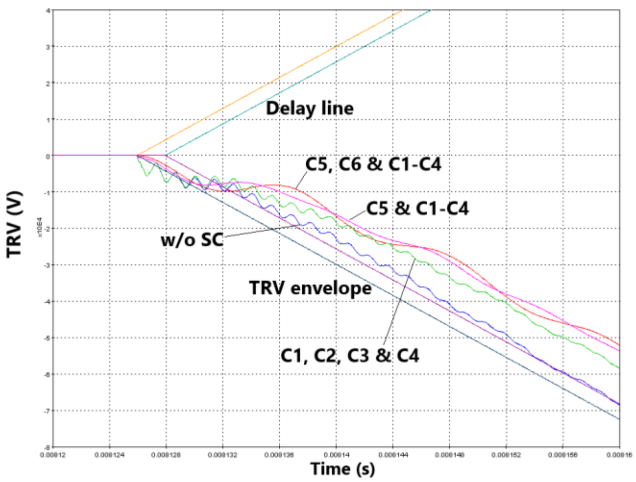

Figure 7. T92 TF TRV envelope and TRVs of diameter breaker DB1 in the extended model after interrupting a line fault (F3) of 58.1 kA.

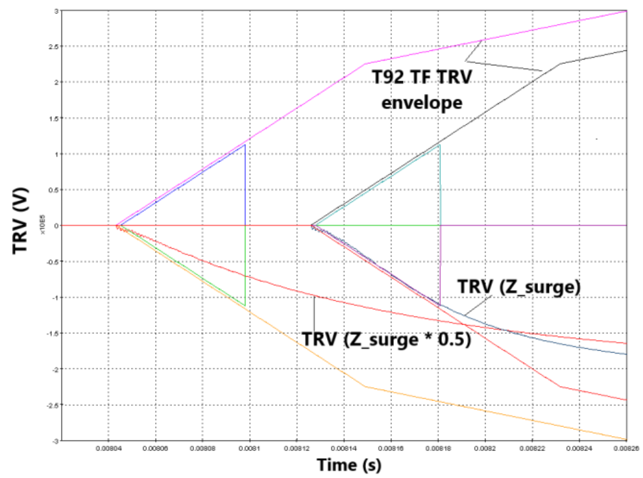

Figure 8. Impact of equivalent station surge impedance on diameter breaker DB1's TRV.

Fig. 7 depicts DB1's TRVs and corresponding TF TRV envelope for a three-phase line fault F3 (see Fig. 4) and different surge capacitor arrangements. In this fault scenario, both tie breakers A and B remain closed and the other diameter breaker DB2 is assumed open during the entire simulation. The fault current (also DB1 current) is 58.1 kA in this case. In Fig. 7, without DB1's surge capacitors C5 and C6, there is an Initial TRV (ITRV) issue within around 4 µs after the breaker interrupts the fault. In order for the diameter breaker TRV to coordinate with the associated T92 TF TRV capability curve, both C5 and C6 are required in the model. Note that only C5 and C6 are enough to prevent the DB1 ITRV violation, and C1 to C4 can help alleviate the TRV around 7 µs after the breaker opens. It should be noted that this ITRV issue does not stem from the bus-tie CLR, and a more detailed study is required to address the issue.

One important factor to take into consideration is that the bus-tie CLR separates the two station buses (buses A and B in Fig. 4), and hence, doubling the equivalent station surge impedance that is present for diameter breaker fault clearing. As shown in Fig. 8, the increase of the equivalent station surge impedance increases the TRV slope, and therefore, the stress on the diameter breaker while interrupting fault F3.

VI. Other Implemntation Considerations

With the bus-tie CLR, higher decaying DC component appears in the fault current owing to the higher X/R ratio. We found that the fault current's higher DC component decreases the TRV stress on the tie breaker, and therefore, it leads to a higher breaker fault interrupting capability if a current zero-crossing exists in the effective interrupting window.

However, for the stations close to synchronous generation units, current zero-crossing could be delayed due to the fast-decaying AC component and the presence of a large DC component. In that case, breaker arc thermal models are necessary to investigate the breaker interrupting capability. Delayed current zero-crossing may happen when the fault occurs around the voltage zero-crossing, such as reclosing onto a pre-existing fault. Although this is a rare case for a bus-tie CLR application since the tie breaker does not auto-reclose, system planners must assess the risk and determine if breaker-failure protection can be relied on for fault clearing.

VII. Conclusion

Using a simplified two-bus equivalent model of a 230 kV station, the impacts of different bus-tie CLR values on the station short-circuit level are investigated. It is revealed that a CLR of 10 Ω, in series with each tie breaker, can reduce the short-circuit level below 63 kA from an initial level of 80 kA. However, voltage calculations show that a CLR of 10 Ω might degrade the bus voltages after the worst N-1-1 contingency. Therefore, detailed power flow studies should determine whether additional reactive power compensation is required for the worst contingency. TRV studies are conducted for both station tie and diameter breakers. The studies suggest that a mitigating surge capacitor in parallel with the CLR or between the CLR and tie breaker is necessary to confine the tie breaker TRVs within the corresponding TRV envelopes. It is also shown that due to the bus tie separation caused by the CLR, the station diameter breakers can experience higher TRVs.

References

[1] *Transmission System Code*, Ontario Energy Board, Jul. 2000.

[2] "Reducing fault currents in power systems with air core series reactors," GE Vernova, pp. 1-5, 2024. [Online]. Available: https://www.gevernova.com/grid-solutions

[3] J. Amon F., P. C. Fernandez, E. H. Rose, A. D´ Ajuz, and A. Castanheira, "Brazilian successful experience in the usage of current limiting reactors for short-circuit limitation," in *Proc. 2005 International Conf. on Power Systems Transients (IPST'05)*, pp. 1-6.

[4] A. Shah, "Impact of current limiting reactor on bulk power network – A case study," in *Proc. 2023 IEEE Texas Power and Energy Conf. (TPEC)*, pp. 1-6.

[5] G. Zhen-xin, L. Xin, X. Jian-yuan, and T. Chi, "Effects of series reactor on short-circuit current and transient recovery voltage," in *Proc. 2008 International Conf. on High Voltage Engineering and Application*, pp. 524-526.

[6] *IEEE Standard for Ratings and Requirements for AC High-Voltage Circuit Breakers with Rated Maximum Voltage above 1000 V*, IEEE Std. C37.04-2018 (Revision of IEEE Std. C37.04-1999), May 2019.

979-8-3315-8138-1