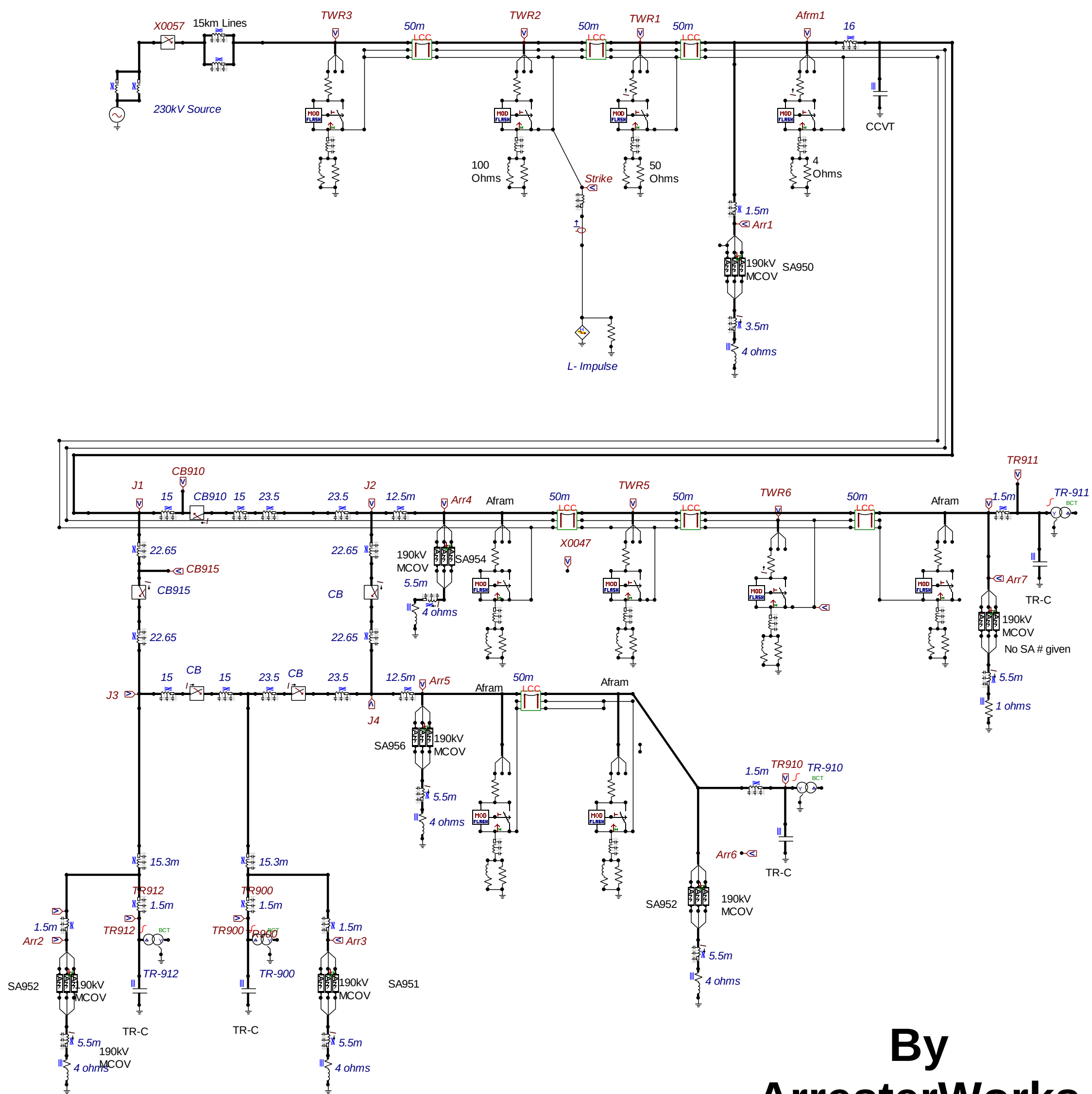
Substation Insulation Coordination Study



By
ArresterWorks
For
…………

June 28th, 2011

Contents

Substation Insulation Coordination Study
Phase 2B

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Analysis Summary

…….. is expanding a 260kV substation to accommodate increased production of bitumen at the --------------- as part of a 3 phase project. This expansion project is part of Phase B2. The substation will be expanded to include two more transformers and a 260kV ring bus. This insulation coordination study was commissioned by ----------------------------- to confirm that the proposed arrester locations will adequately protect the substation and transformers from flashover during a lightning strike. This analysis was done using methods as outlined in the application guides IEEE 1313.2 [2], IEEE C62.22 [3], Insulation Coordination of Power Systems by Andrew Hileman [1] and ATPDraw [6]. ATPDraw is the time domain based transient software used to determine the voltage stresses throughout the station during surge events.

Lightning Protection Analysis of Bus

The station was modeled in ATP using drawings supplied by -------------------------. The voltages throughout the station were determined with a surge entering the station from the incoming line. The resulting voltage values at specified junctions in the substation were used to calculate the protection margins based on equipment data also supplied by ---------.

The bus analysis was completed two ways, with arresters installed only at the transformers (scenario 1) and then including the line entrance arrester (scenario 2). As shown in Table 1, it can be seen that the bus insulation at location J1 is the most highly stress but still has >50% more BIL than needed. Even with arresters only installed at the transformers as shown in scenario 1, the insulation has <50% more BIL than minimum. **The 190kV MCOV arresters and their location do adequately protect the bus insulation in this substation.**

Table 1	**Scenario 1 Arresters mounted only at Transformers**			
	Minimum Required BIL (kV 1.2/50 µs Impulse) (kV)	**Installed Insulation Level (kV)**	**% apparatus BIL above Min BIL**	**IEEE Recommended level above Min**
TR900[1]	535.3	1300	142.9%	0.00%
TR910	539.9	1050	94.5%	0.00%
TR911	549.2	1050	91.2%	0.00%
TR912	539.9	1050	94.5%	0.00%
Voltage at J1	595.8	900	51.1%	0.00%
Voltage at J2	605.1	900	48.7%	0.00%
Voltage at J3	530.6	900	69.6%	0.00%
Voltage at J4	539.9	900	66.7%	0.00%
Scenario 2 Arresters mounted at Transformers and Line Entrance				
TR900	502.7	1300	158.6%	0.00%
TR910	349.1	1050	200.8%	0.00%
TR911	512.0	1050	105.1%	0.00%
TR912	512.0	1050	105.1%	0.00%
Voltage at J1	591.1	900	52.3%	0.00%
Voltage at J2	386.3	900	133.0%	0.00%
Voltage at J3	535.3	900	68.1%	0.00%
Voltage at J4	502.7	900	79.0%	0.00%

Note 1: For all 4 transformers in this table, the analysis in for the bushing only, not winding

Analysis of Transformer Winding Protection

For the protection analysis of the transformer windings, three scenarios were ran with arresters installed at 1) transformers only, 2) transformers and line entrance, and 3) at all 7 locations as proposed. As show in Table 2 the transformer windings have >20% margin of protection above that recommended by IEEE even if the only arresters in the station were at the transformers as in scenario 1. With arresters installed at all locations, the worst-case protection is 36% above that recommended by IEEE. **It can be concluded that the transformer windings are well protected in this station.**

The two arresters mounted in the center of the station however have very little effect on the transformer protection as can be seen by comparing scenario 2 and 3.

Table 2 Transformer Winding Margin of Protection Summary

	Voltage stress at windings per ATP (kV)	BIL Transformer	Margin of Protection of Transformer	IEEE Recommendation above Min	% above the IEEE Recommended
Scenario 1 Arresters at Transformers only					
Transformer 900 Winding	575	1050	83%	20%	63%
Transformer 910 Winding	580	825	42%	20%	22%
Transformer 911 Winding	590	825	40%	20%	20%
Transformer 912 Winding	580	825	42%	20%	22%
Scenario 2 Arresters at Transformers and Line Entrance					
Transformer 900 Winding	540	1050	94%	20%	74%
Transformer 910 Winding	375	825	120%	20%	100%
Transformer 911 Winding	550	825	50%	20%	30%
Transformer 912 Winding	550	825	50%	20%	30%
Scenario 3 with arresters at all proposed locations in Substation					
Transformer 900 Winding	500	1050	110%	20%	90%
Transformer 910 Winding	375	825	120%	20%	100%
Transformer 911 Winding	530	825	56%	20%	36%
Transformer 912 Winding	550	825	50%	20%	30%

Analysis of Open Breaker Protection
Because breakers are normally closed, the transformer mounted arrester can protect back through the breaker to other parts of the substation, However if lightning should flashover an insulator several spans from the station and cause a fault on the system, the breaker opens for 4-10 cycles. During this time, a second stroke of the lightning can enter the station and flashover the breaker bushing on the side away from the transformer arrester. This analysis determines the margin of protection of the breaker bushing in the open and most vulnerable state. Table 3 shows the margin of protection with and without an arrester at the line entrance.
With no arresters mounted on the line entrance, the post insulators with a 900kV BIL would be jeopardy if the breakers are caught in the open mode during a surge event. The other bushings are ok. **With line arresters installed as proposed in this station, the post insulators upstream from the breakers are adequately protected in an open breaker scenario.**

Table 3	Open Breaker Insulator Analysis		
		Worst Case Insulator Margin of Protection	**Min Recommended by IEEE**
Without Line Terminal Arrester		-8%	0.0 %
With Line Terminal Arrester		18%	0.0 %

Clearance Analysis
The clearance requirements in a substation are a function of the lightning impulse levels. For this analysis, the worst case voltage levels as calculated using ATP are compared to the lowest actual clearance in the station. **From table 4 can be seen that there is ample phase to phase and phase to ground clearance in this sub.**

Table 4	Substation Clearance Analysis		
	Minimum Required Clearance based on Bus Voltages and Elevation (meters)	**Actual (meters)**	**% above Actual**
Scenario 1 Arresters at Transformers only			
Clearance p-p	1.15	3.5	203.8%
and p-g	1.15	2.4	108.3%
Scenario 2 Arresters at Transformers and Line Entrance			
Clearance p-p	1.13	3.5	211.0%
and p-g	1.13	2.4	113.2%

Conclusions and Recommendations
1. Based on the bus voltage analysis, insulation levels selected are appropriate for this substation, as long as line entrance arresters are installed as planned to eliminate any potential flashover during an open breaker event.
2. The transformer windings are very well protected in all cases. The 1050 BIL winding rating of transformer 900 is more than needed, but since it is already there, it is ok as is.
3. The arresters installed near the center of the station are not necessary.

Recommendations
The only recommendation is that the station be built as specified and it will be adequately protected from lightning in all cases.

End of Summary

Bases for the Analysis
All insulation will flashover or puncture in the presence of surges with amplitudes and durations above the limit of the design. This study was commissioned to determine if the chosen insulation levels for the bus and transformer are adequate for surges that will enter the station from a backflashover on the incoming line within a few kilometers of the station. This analysis was done using simplified methods as outlined in the application guides IEEE 1313.2 [2], IEEE C62.22 [3] and Andrew Hileman's book [1]. The transient voltages in the substation were determined using ATPDraw [6].

Scope of Work
Station Insulation Protection

- Determine the margins of protection of the station bus with the installed protection.
- Determine the effect on the station from an open breaker and no line terminal arresters.

Transformer Insulation Protection

- Determine the margin of protection of the 260/13.8kV substation transformers with existing arrester protection.
- Determine the margin of protection of the 234/25kV substation transformers with existing arrester protection.

Methods of Analysis

Lightning Protection Analysis of Bus
The apparatus withstand levels were given by Rising Edge Engineering. These levels were then used in a margin analysis using ATPDraw and ATP to calculate voltages throughout the substation based on methods presented in IEEE 1313.2 and Insulation Coordination of Power Systems [1]. The surge arrester characteristics were obtained from Cooper Power Systems AZG catalog section I235-84.

Protective Margin Analysis of Transformer
Since transformer winding insulation is not self-restoring it is only evaluated using a deterministic analysis. With this method, conventional transformer BIL Withstand and Chopped Wave Withstand characteristics of the transformer are compared to the corresponding arrester protective levels and the protective margins. Fast front voltage and standard lighting impulse voltages are calculated using ATP, ATPDraw, and IEEE 1313.2 methods. The voltages calculated, include the effect of separation distance and arrester leads.

Equipment Characteristics
The equipment subjected to surges in these substations are:

1.	Post Insulators for bus support	900kV BIL	
2.	Insulators on disconnect switches	1050kV BIL	
3.	Breaker Bushings	1300kV BIL	
4.	Transformer 900	1300kV BIL Bushings	1050kV BIL Windings
5.	Transformers 910, 911, 912	1050kV BIL Bushings	850kV BIL Windings
6.	Incoming Line Insulation Level	1350kV CFO	

Lightning Analysis

Lightning surge withstand capability of the 230kV side of the substation is evaluated by calculating the voltage magnitudes at critical points and comparing them to the BIL of the insulation at those locations. ATP and ATPDraw were used to calculate the voltages. Voltage levels attained are a function of the incoming surge steepness which is assumed to be the worst case for this analysis (1000kV/us).

Lightning Analysis Assumptions

1. Transformer Capacitance of 3 nanofarads (nF) (typical per Hileman page 567)
2. The station is shielded and no lightning enters the station directly, only via the lines when a back flashover occurs within a few spans of the station.
3. Transformer Margin of protection of 20% is a minimum for lightning surges (IEEE Recommendation)
4. The steepness of the incoming surge is 1000kV/us. This is on the high side of typical surges on 230kV lines but used for most conservative results.

Elevation Coefficient

When determining the margin of protection of the insulation within a substation, the station elevation needs to be considered. The impulse withstand capability of air decreases inversely proportionally to the altitude. At 580m altitude, the flashover level of insulation is decreased by 7% as compared to sea level. This 7% reduction is used in these calculations.

Table 5

Elevation Coefficient	
Elevation in Feet	1900
Elevation in Km	.579
δ	.9341

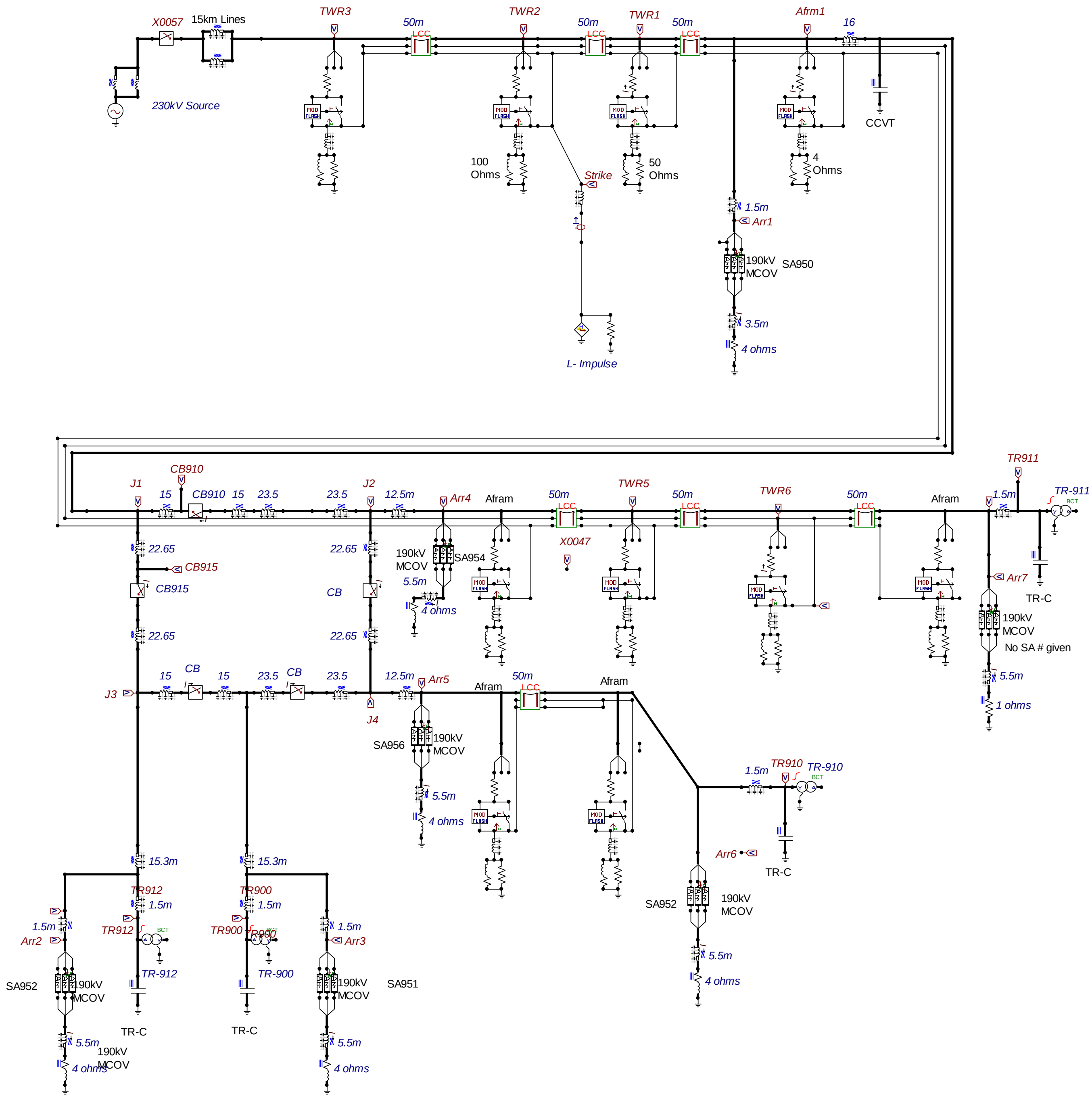


Figure 1 One line drawing of Substation

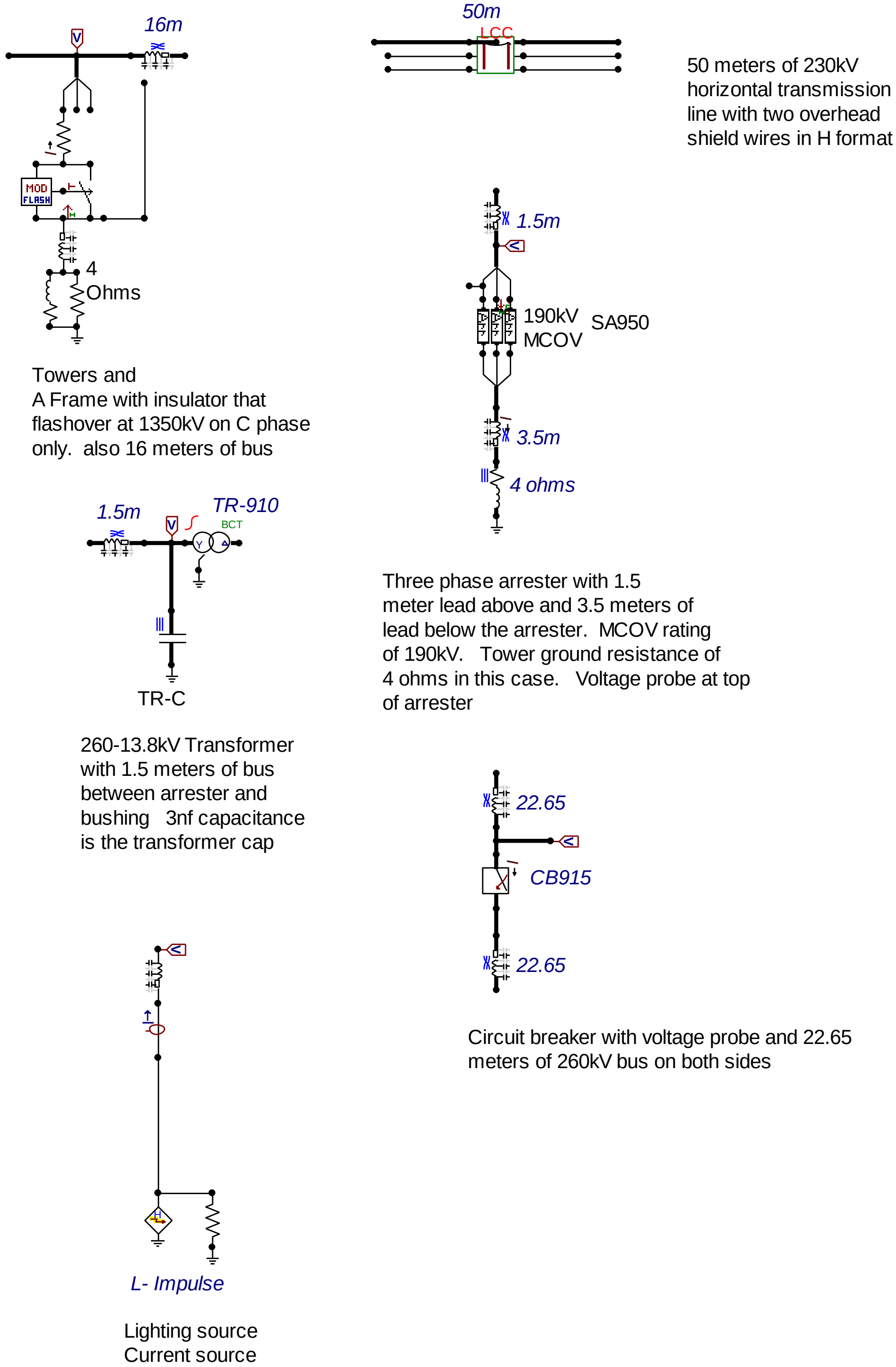


Figure 2 Key to one line drawing

Scenario Descriptions

Scenario 1: Analysis of Station with Arresters at the transformers only
This would be the minimum protection in a substation of this type. This scenario is ran for comparison purposes only.

Scenario 2: Analysis of Station with Arresters at the transformers and at the line entrance
This scenario generally offers very good transformer protection and improved bus protection. Often times it is the only way to insure no flashover during an open breaker situation.

Scenario 3: Analysis of Station with Arresters at the transformers, center and entrance
This scenario was completed to evaluate the added value of the two arresters sets installed in the center of the station.

Scenario 4: Open Breaker Scenario
This scenario is for an incoming surge where the breaker is open (generally during a fault clearing event). The only part of the station that is affected by this scenario is the line terminal and the bus up to the open breaker.

Incoming Wave Considerations
The steepness of the incoming surge into a substation is an important factor in how well the arresters are able to protect the equipment. For surges greater than 1000kV/us the inductance in the arrester leads start to become an issue in protection by causing voltages that add to the arrester residual voltage and in effect reduce the protection of the insulation installed in parallel with the arrester.
For this study, the rate of rise at the struck point was 3000kV/us but by the time it reached the station entrance, it was reduced to 1000kV/us by corona and capacitance of the lines. Per IEEE1313.2, a 1000kV/us surge rise is typical for 230kV stations. Figure 3 shows the surge at tower 2 and at the station entrance A-frame.

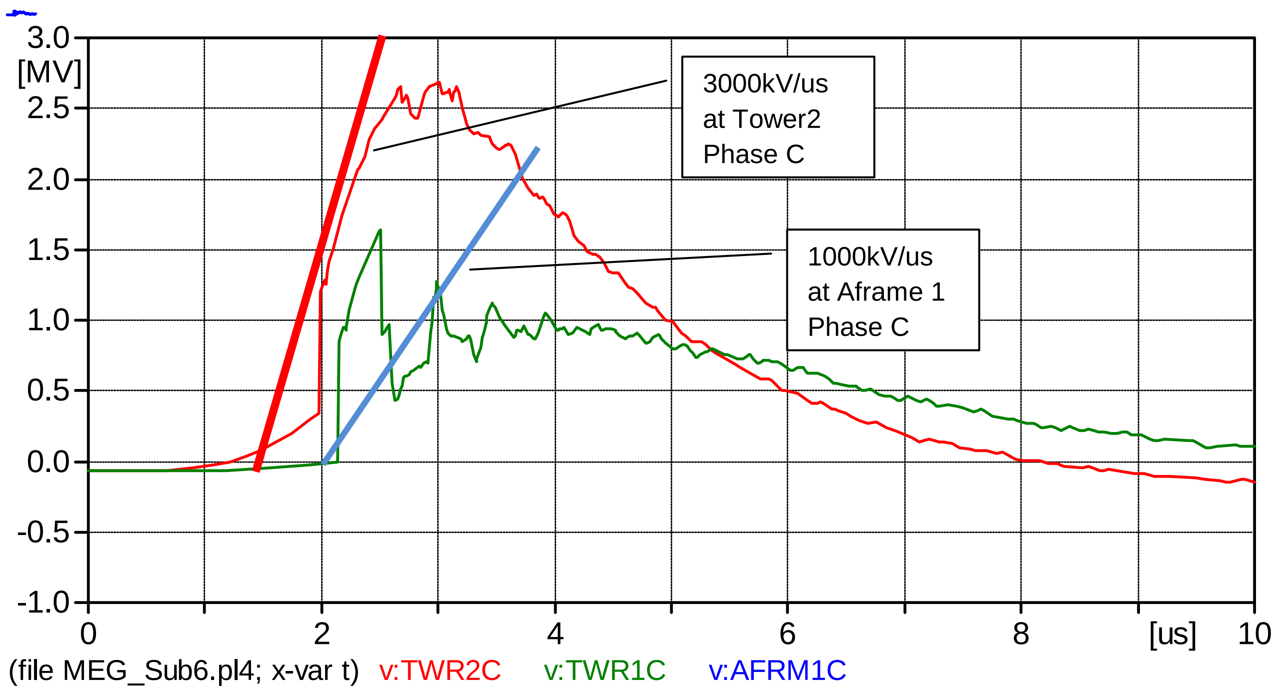
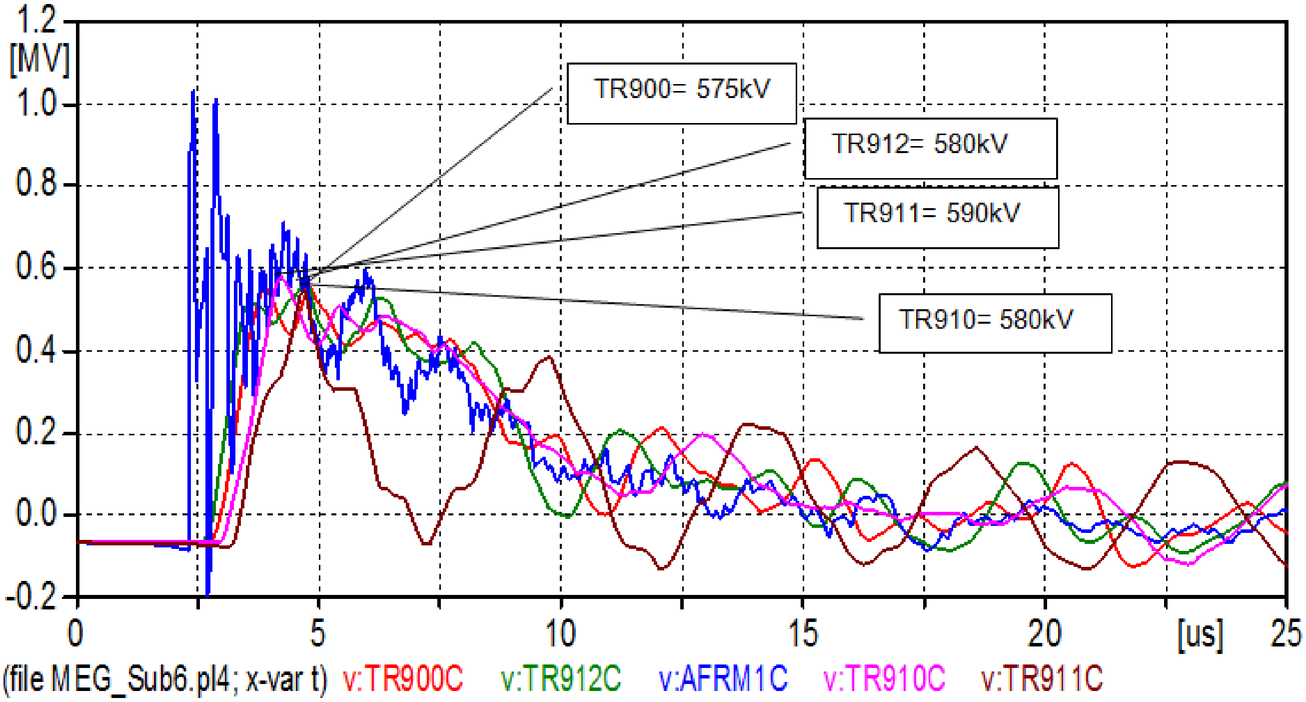


Figure 3 Waveshape of incoming surge from flashover on line at tower 2

Scenario 1: Analysis of Station with Arresters at installed at the Transformers Only
The purpose of this scenario was to determine the voltage levels at the transformers and juncions on the ring bus. Figures 4 and 5 show the output of ATP. The figures also show the level of the surge entering the substation at Aframe 1. The analysis is completed on phase C only because that is the phase that is flashed over at tower 2 and



experiences the worst stress in this case.

Figure 4 Voltages at transformer bushings and windings with arresters mounted at transformers only

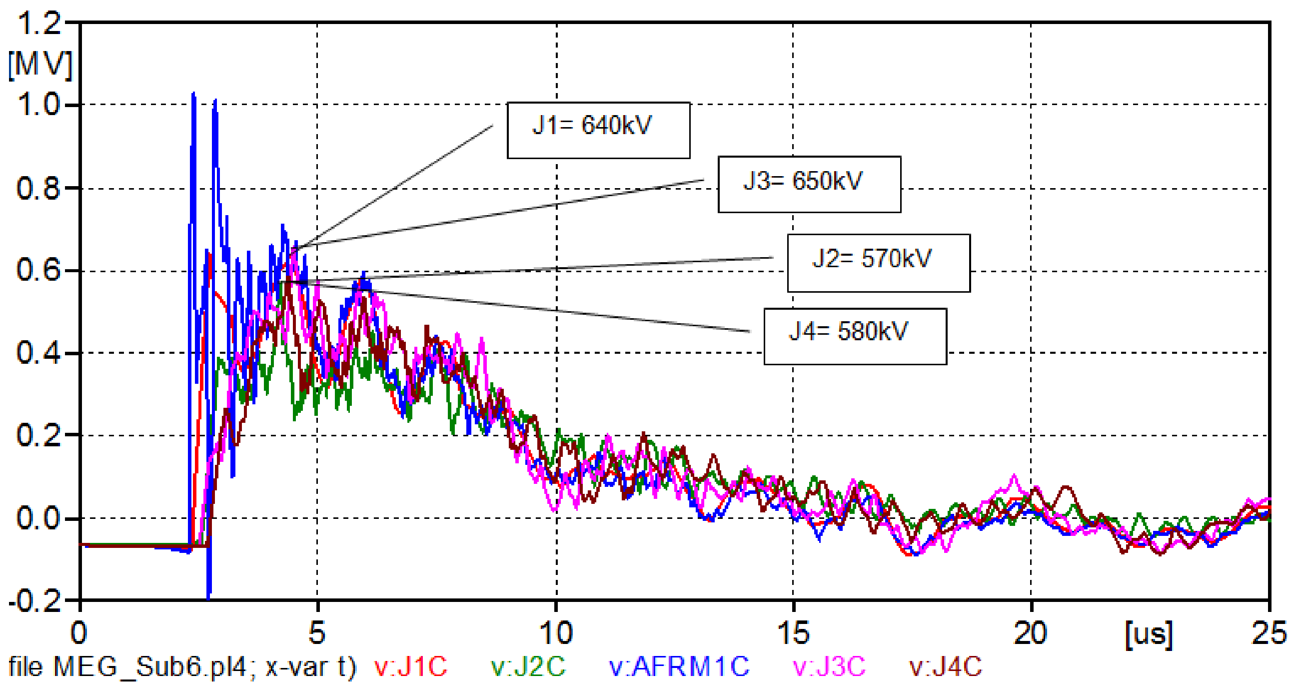


Figure 5 Voltages at J1 thru J4

Table 6 summarizes the substation protection at transformers and points on the bus if arresters are installed at the transformers only. The results show that protection in this case is all acceptable since all locations exceed that recommended by IEEE standards.

Table 6 **Scenario 1 Arresters at Transformers only**

External Insulation BIL Calculations

	Peak Fast Front Voltages from ATP (kV)	Minimum Required BIL (Note 1) (kV 1.2/50 µs Impulse)	Installed Insulation Level (kV) (Note 2)	% apparatus BIL above Min BIL (Note 3)	IEEE Recommended above Minimum
Transformer Winding 900	575	535.3	1300	142.9%	0.00%
Transformer Bushing (External) 910	580	539.9	1050	94.5%	0.00%
Transformer Bushing (External) 911	590	549.2	1050	91.2%	0.00%
Transformer Bushing (External) 912	580	539.9	1050	94.5%	0.00%
Voltage at J1	640	595.8	900	51.1%	0.00%
Voltage at J2	650	605.1	900	48.7%	0.00%
Voltage at J3	570	530.6	900	69.6%	0.00%
Voltage at J4	580	539.9	900	66.7%	0.00%
			Actual	% above Actual	
Require Clearance p-p (m)		1.15	3.5	203.8%	
(Note 4) and p-g		1.15	2.4	108.3%	
Delta (Elevation Factor)	0.9341				

1. **Minimum Required BIL:** Min BIL= (Peak ATP Voltage /1.15)/Delta
2. **Insulation Level** These are potential BIL levels of equipment in the substation.
3. **% above Min BIL** (Apparatus BIL/Min BIL) -1 in percent
4. **Clearance:** This is both phase to phase and phase to ground clearance. This is the minimum clearance needed to achieve the desired performance on the on the bus. Clearance = (Peak voltage from ATP)/605kV/m

Transformer Winding Margin of Protection Calculations

	Winding Voltages	BIL Transformer	Margin of Protection of Transformer	IEEE Recommendation	% above the IEEE Recommended
Transformer 900 Winding	575	1050	83%	20%	63%
Transformer 910 Winding	580	825	42%	20%	22%
Transformer 911 Winding	590	825	40%	20%	20%
Transformer 912 Winding	580	825	42%	20%	22%

Scenario 2: Analysis of Station with Arresters at the transformers and at the line entrance
This scenario was completed to show the protection levels with arresters installed at transformers and line entrance only which is most common for this size substation. Figures 6 and 7 and Table 7 show the output from ATP. The results show that there is good protection in this scenario.

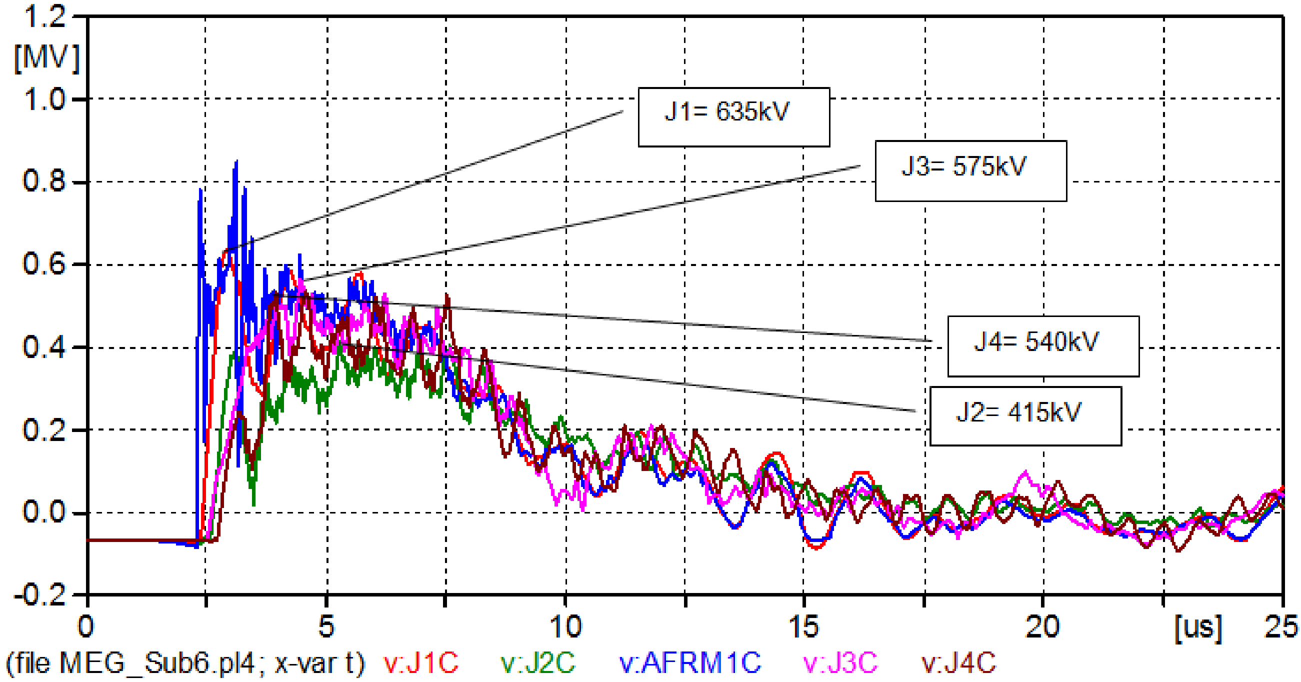


Figure 6 Voltages at bus junctions with arresters at transformers and line entrance

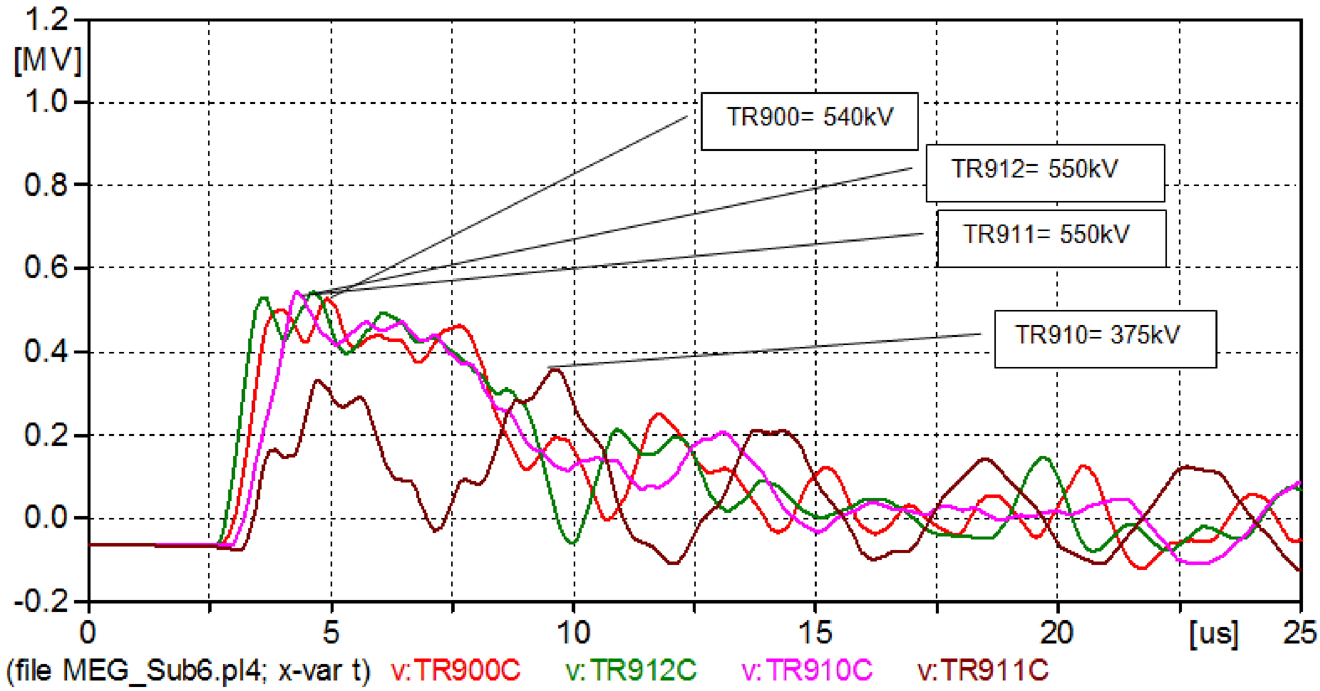


Figure 7 Voltages at transformer bushings and windings with arresters at transformers and line entrance

Table 7 **Scenario 2 Arresters at Transformers and at Station Entrance**

External Insulation BIL Calculations

	Peak Fast Front Voltages from ATP (kV)	Minimum Required BIL (Note 1) (kV 1.2/50 μs Impulse)	Installed Insulation Level (kV) (Note 2)	% apparatus BIL above Min BIL (Note 3)	IEEE Recommended above minimum
Transformer Winding 900	540	502.7	1300	158.6%	0.00%
Transformer Bushing (External) 910	375	349.1	1050	200.8%	0.00%
Transformer Bushing (External) 911	550	512.0	1050	105.1%	0.00%
Transformer Bushing (External) 912	550	512.0	1050	105.1%	0.00%
Voltage at J1	635	591.1	900	52.3%	0.00%
Voltage at J2	415	386.3	900	133.0%	0.00%
Voltage at J3	575	535.3	900	68.1%	0.00%
Voltage at J4	540	502.7	900	79.0%	0.00%
			Actual	% above Actual	
Require Clearance p-p (m)		1.13	3.5	211.0%	
(Note 4) and p-g		1.13	2.4	113.2%	
Delta (Elevation Factor)	0.9341				

1. **Minimum Required BIL:** Min BIL= (Peak ATP Voltage /1.15)/Delta
2. **Insulation Level** These are potential BIL levels of equipment in the substation.
3. **% above Min BIL** (Apparatus BIL/Min BIL) -1 in percent
4. **Clearance:** This is both phase to phase and phase to ground clearance. This is the minimum clearance needed to achieve the desired performance on the on the bus. Clearance = (Peak voltage from ATP)/605kV/m

Transformer Winding Margin of Protection Calculations

	Winding Voltages	BIL Transformer	Margin of Protection of Transformer	IEEE Recommendation	% above the IEEE Recommended
Transformer 900 Winding	540	1050	94%	20%	74%
Transformer 910 Winding	375	825	120%	20%	100%
Transformer 911 Winding	550	825	50%	20%	30%
Transformer 912 Winding	550	825	50%	20%	30%

Scenario 3: Analysis of Station with Arresters at the transformers, center and entrance
This scenario is for the substation as proposed. The only difference between this scenario and scenario 2 is the addition of the two sets of arresters in the center of the station. The voltage levels for this scenario are marginally better than without the center sets of arresters installed.

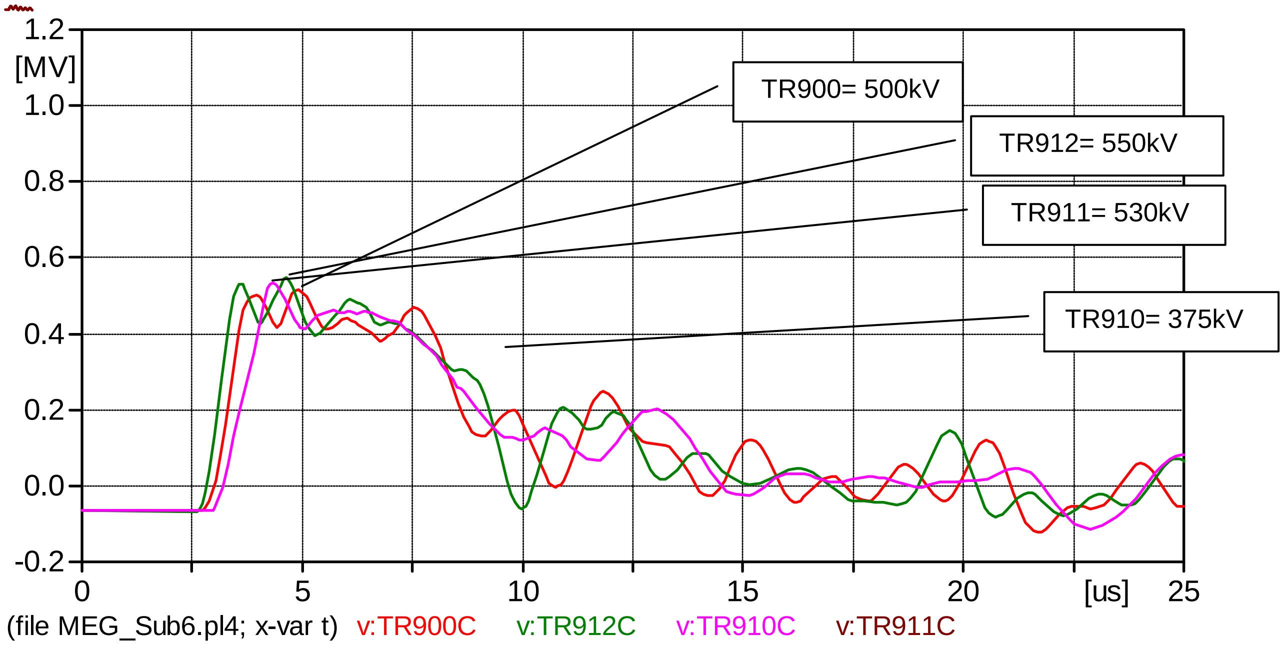


Figure 8 Transformer winding voltages with arresters installed at all proposed locations

Table 8

Scenario 3 Arresters at Transformers, Station Entrance, and Station Center

Transformer Winding Margin of Protection Calculations

	Winding Voltages	BIL Transformer	Margin of Protection of Transformer	IEEE Recommendation	% above the IEEE Recommended
Transformer 900 Winding	500	1050	110%	20%	90%
Transformer 910 Winding	375	825	120%	20%	100%
Transformer 911 Winding	530	825	56%	20%	36%
Transformer 912 Winding	550	825	50%	20%	30%

Scenario 4: Open Breaker Scenario
Because breakers are normally closed, the transformer mounted arrester can protect back through the breaker to other parts of the substation, However if lightning should flashover an insulator several spans from the station and cause a fault on the system, the breaker opens for 4-10 cycles. During this time, a second stroke of the lightning can enter the station and flashover the breaker bushing on the side away from the transformer arrester. This analysis determines the margin of protection of the breaker bushing in the open and most vulnerable state.

Figures 9, Figures 10 and Table 9 show the voltage stresses experienced during an open breaker event. With no arresters mounted on the line entrance, the post insulators with a 900kV BIL would be jeopardy if the breakers are caught in the open mode during a surge event. The other bushings are ok. With line arresters installed as proposed in this station, the post insulators upstream from the breakers are adequately protected in an open breaker scenario.

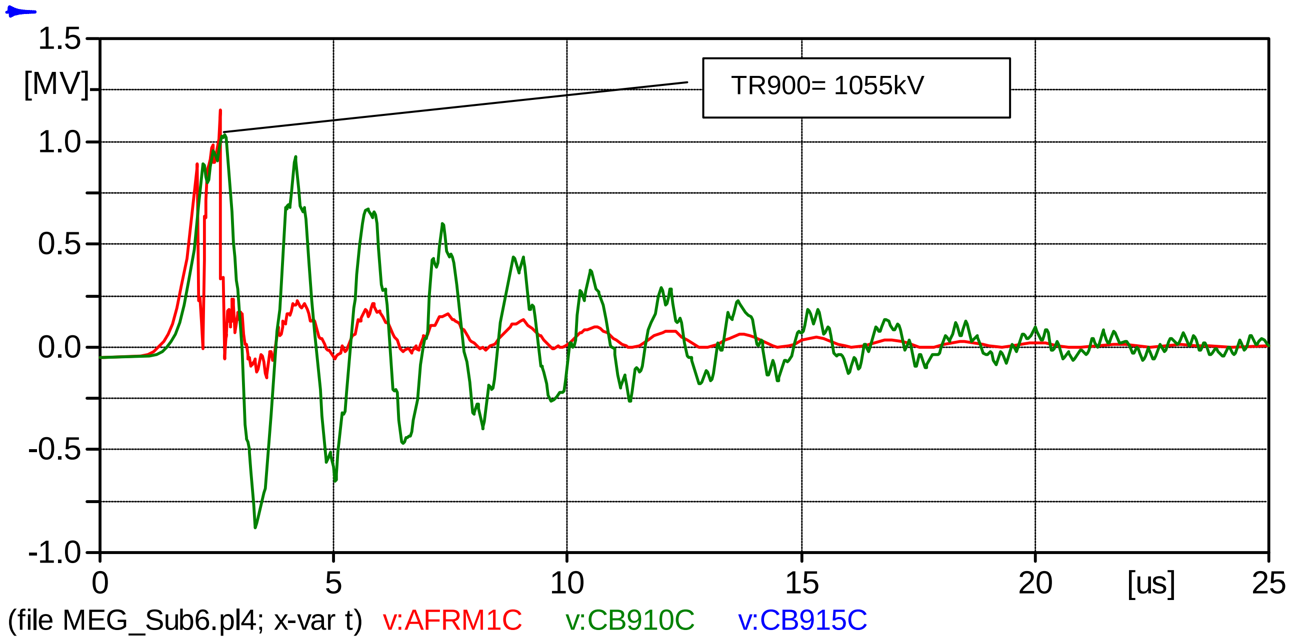


Figure 9   Voltage levels on bus with breakers open and not line entrance arresters

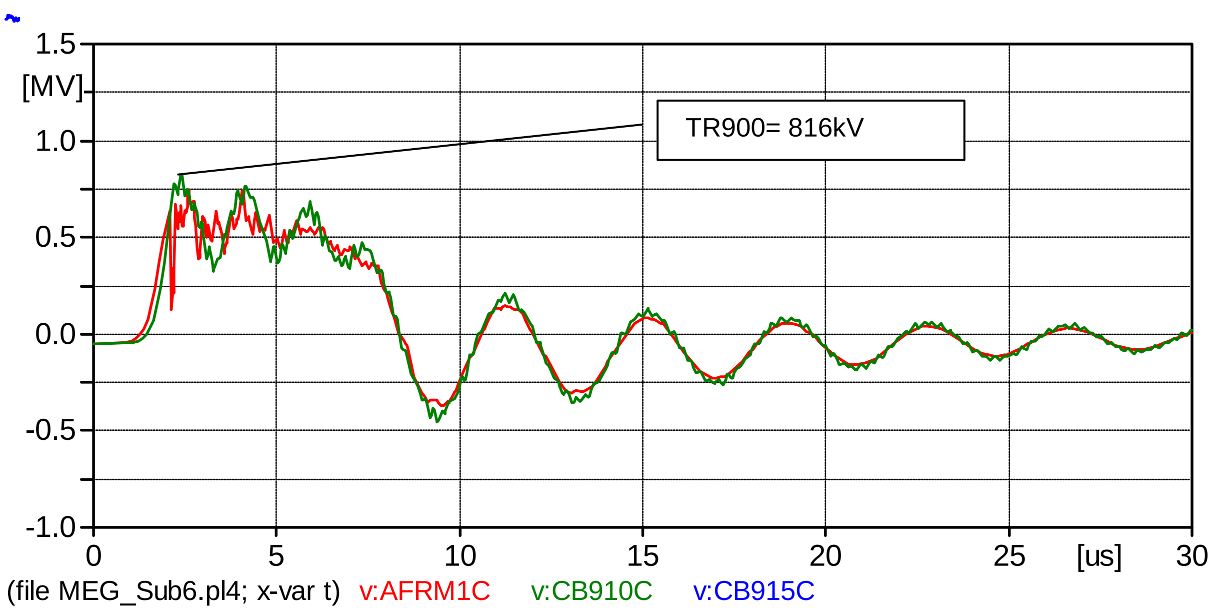


Figure 10   Voltage levels on the bus and breaker bushing with line entrance arresters installed

Table 9 **Scenario 4 Open Breaker Scenario**

	Peak Fast Front Voltages from ATP (kV)	Minimum Required BIL (Note 1) (kV 1.2/50 µs Impulse)	Installed Insulation Level (kV) (Note 2)	% apparatus BIL above Min BIL (Note 3)	IEEE Recommended level above minimum
No Arresters on the line entrance					
Line Post Insulators	1055	982.1	900	-8.4%	0.00%
Disconnect Switch Insulators	1055	982.1	1050	6.9%	0.00%
Breaker Bushings	1055	982.1	1300	32.4%	0.00%
Arresters Installed on the line entrance					
Line Post Insulators	816	759.6	900	18.5%	0.00%
Disconnect Switch Insulators	816	759.6	1050	38.2%	0.00%
Breaker Bushings	816	759.6	1300	71.1%	0.00%
Delta (Elevation Factor)	0.934				

1. **Minimum Required BIL:** Min BIL= (Peak ATP Voltage /1.15)/Delta
2. **Insulation Level** These are potential BIL levels of equipment in the substation.
3. **% above Min BIL** (Apparatus BIL/Min BIL) -1 in percent
4. **Clearance:** This is both phase to phase and phase to ground clearance. This is the minimum clearance needed to achieve the desired performance on the on the bus. Clearance = (Peak voltage from ATP)/605kV/m

Clearance Analysis
The clearance requirements in a substation are a function of the lightning impulse levels. For this analysis, the worst-case voltage levels as calculated using ATP are compared to the lowest actual clearance in the station.
From table 4 can be seen that there is ample phase to phase and phase to ground clearance in this sub.

Table 10 Substation Clearance Analysis

	Minimum Required Clearance based on Bus Voltages and Elevation (meters)	Actual (meters)	% above Actual
Scenario 1 Arresters at Transformers only			
Clearance p-p	1.15	3.5	203.8%
and p-g	1.15	2.4	108.3%
Scenario 2 Arresters at Transformers and Line Entrance			
Clearance p-p	1.13	3.5	211.0%
and p-g	1.13	2.4	113.2%

End of Main Body
See Summary at the Beginning of the report for the final Summary and Conclusions

References

[1] Hileman, A.R., *Insulation Coordination for Power Systems*, Marcel Dekker, Inc., New York, 1999, ISBN 0-8247-9957-7.

[2] IEEE Std 1313.2-1999 (R2005) *IEEE Guide for the Application of Insulation Coordination*, Institute of Electrical and Electronic Engineers, New York, 1999

[3] IEEE Std C62.22-2009 *IEEE Guide for the Application of Metal Oxide Surge Arresters for Alternating-Current Systems*, Institute of Electrical and Electronic Engineers, New York, 2009

[4] G.W. Brown, "Designing EHV Lines to a given outage rate - Simplified Techniques," IEEE Transactions on PA&S, March 1978 Pg 379-383.

[5] IEEE Std C57 12 00 - 2006 *IEEE Standard for Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers* Institute of Electrical and Electronic Engineers, New York, 2006

[6] ATP and ATPDraw Alternative Transients Program www.emtp.org the world's most widely used Electromagnetic Transients Program.

Annex A
Comments on the Relationship of CFO and BIL

Note on BSL, BIL and CFO

CFO of an insulator is the voltage at which flashover occurs 50% of the time. Also because the actual level has a normal distribution it also has an associated standard deviation. Experience indicates that one standard deviation for switching CFO is 7% and one standard deviation for a lightning CFO is 3%.
BSL (Statistical) is the voltage at which flashover only occurs 10% of the time. It also has a sigma associated with it.
BSL (Conventional) The voltage where there is no flashover with a switching surge.
BIL (Conventional) The voltage where there is no flashover with a standard 1.2/50 µs surge voltage..

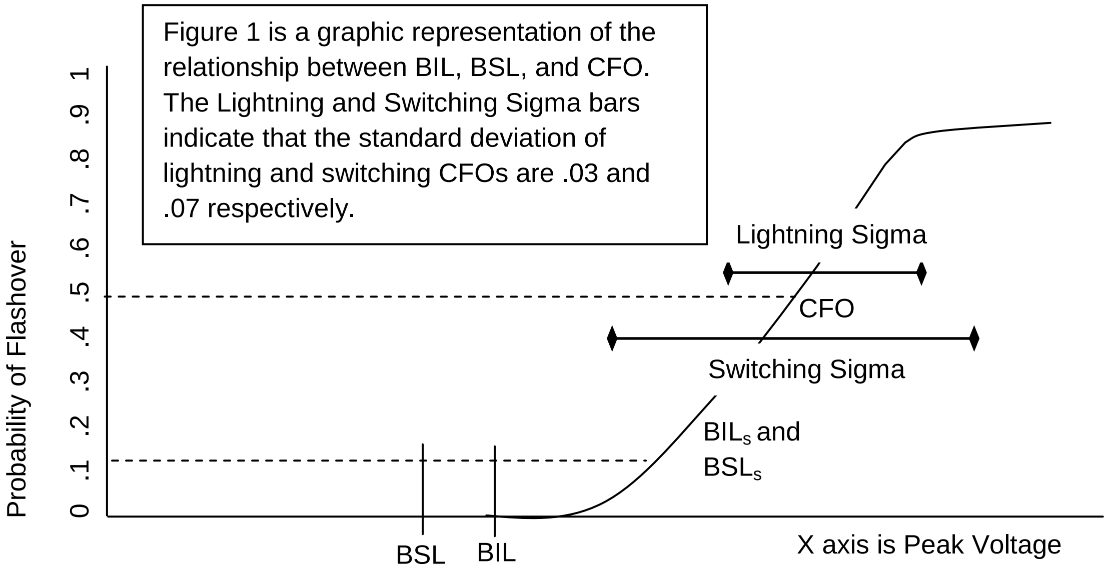


Figure 1 CFO-BIL-BSL Relationships (Probability vs. Peak Voltage of Surge)

Annex B Margin of Protection Definition