

Lightning incident at Saudi Arabia's first Aluminium Smelter at Ras Al Khair,

Authors:

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Overview of the project:

The industrial project is located at the Ras Al Khair complex within the north-eastern region of Saudi Arabia. It includes two aluminium smelter potlines, a 2.8 GW generating station including desalination plant and water distribution system operated by (Saline Water Conversion Corp. SWCC). An alumina refinery, a phosphate plant (Ma'aden Phosphate Company MPC) and a rolling mill with auto sheet plant, all fed by a local new power plant connected to the SEC grid (Saudi Electric Company 380 kV system).

The Ma'aden aluminium smelter project phase one is a 740'000 metric tons per year primary aluminium smelter. The plant includes two potlines, each consisting of 360 pots. Ma'aden's project planning is to extend the plant in the near future to six potlines delivering 2.2 million tons of primary aluminium annually and making it the world's largest single site smelter.

The smelter is connected to the SEC Ma'aden substation by three 380 kV overhead transmission lines in parallel, each of which is connected at the smelters 380/230 kV 1000 MVA stepdown transformers. The 230 kV switchgear at the Ma'aden smelter also supplies the alumina refinery and the rolling mill via 230 kV buried cables.

Sequence of Events

On the evening of March 23rd, 2013 there was significant lightning and storm activity in the RAK Smelter area. After the incidents it was then not possible to confirm if the lightning caused the events (1&2), but it was suspected that the lightning caused the tripping of the differential protection of the stepdown autotransformers.

Events:

1. Main 380kV/230kV **AutoTransformer # 3** tripped per phase differential protection at about 18:38:58
2. Main 380kV/230kV **AutoTransformer # 1** tripped per phase differential protection at about 18:39:28 (20 seconds after #3 tripped)



(Picture 1; Ras Al Khair Smelter 380kV Feeder, Lightning strike 23rd March 2013

Observations

There were multiple occurrences of lightning at 380/230kV Ras Al Khair, Aluminium Smelter plant.

During this incident, the transformer (TR) protection tripped on 23-03-2013 at 18.38.

There are three transformers connected in parallel feed from the SEC 380kV Ma'aden substation and on the secondary side feed the 230kV GIS. During this incident, TR2 was out of service. The protection function of TR3 had tripped first and few seconds, later the protection functions of TR1 also tripped.

Both the transformers tripped by transformer differential protection (PDIF -87T).

The following IEDs have recorded the DR file or event record.

- Transformer Bay Control Unit REC670
- Transformer Differential Protection P632
- Transformer Tertiary Protection P132
- Transformer Differential Protection P642
- Transformer Tertiary Protection P143

TR3 read 20kA and TR1 read 10kA of ground current on the delta tertiary ground. The surge counter on one phase on secondary side of breaker was increased. All other surge counters showed no count increase. Reading out the line PT's values, there were no indication of a primary lightning strike.

- I. In both incidents phase B was relatively less affected with respect to disturbance magnitude (Phase A and C were high)
- II. There was indeed per the report a difference in magnitude of currents (Primary vs. secondary) high enough to cause a differential trip
- III. There was lots of lightning in the area
- IV. On both transformers, phase B is the grounded point on the compensation winding (I know nothing about what this does but just an observation!)
- V. There is a distinct shift in the current phase angles per the waveform.
- VI. The transformer neutrals are both grounded



(Picture 2; Ras Al Khair Smelter 380kV Outdoor GIS Incomer from SEC Grid)

Analysis and possible cases leading to the differential tripping of the Main Step down Transformers

Case I

1) Tripping happened after a lightning strike i.e there was a current surge on the main conductor after the flashover at one of the string insulators on the transmission tower.

This may have caused:

- Ground Potential to rise
- Surge arrester at smelter end to show an increase of counter

Spurious tripping could have been the case if the protection panels and installation of the control and protection cables would not have been electromagnetic protection proof (EMC, Electromagnetic Compatibility)

Proposed reviews and actions:

- Review if the control cables were shielded
- Review the grounding of cables at cable gland
- Review the EMC of the panels
- Review the grounding system of protection panels and the main station grid.

Case II

The transformers have delta stabilising windings. One corner of delta is grounded with a CT connection. It is common practice to ground one end of delta for insulation co ordination considerations.

Proposed reviews and actions:

Was current on the grounded point of delta measured and how high was the value.

Case III

Relay settings and settings co ordination to be reviewed.

Proposed reviews and actions:

Event readout out of all protection relays event recorders,

Analysis of protection relay fault recorders

ABB then conducted analyses of all the protection relay fault recorders and concluded:

TRANSFORMER BAY CONTROL UNIT REC670 (TR3)

The below screen shot is taken from REC670, which is used as a control IED.

(Intelligent Electronic Device) This relay recorded the transformer feeder currents & voltages as well as the voltages of the Incoming power line.

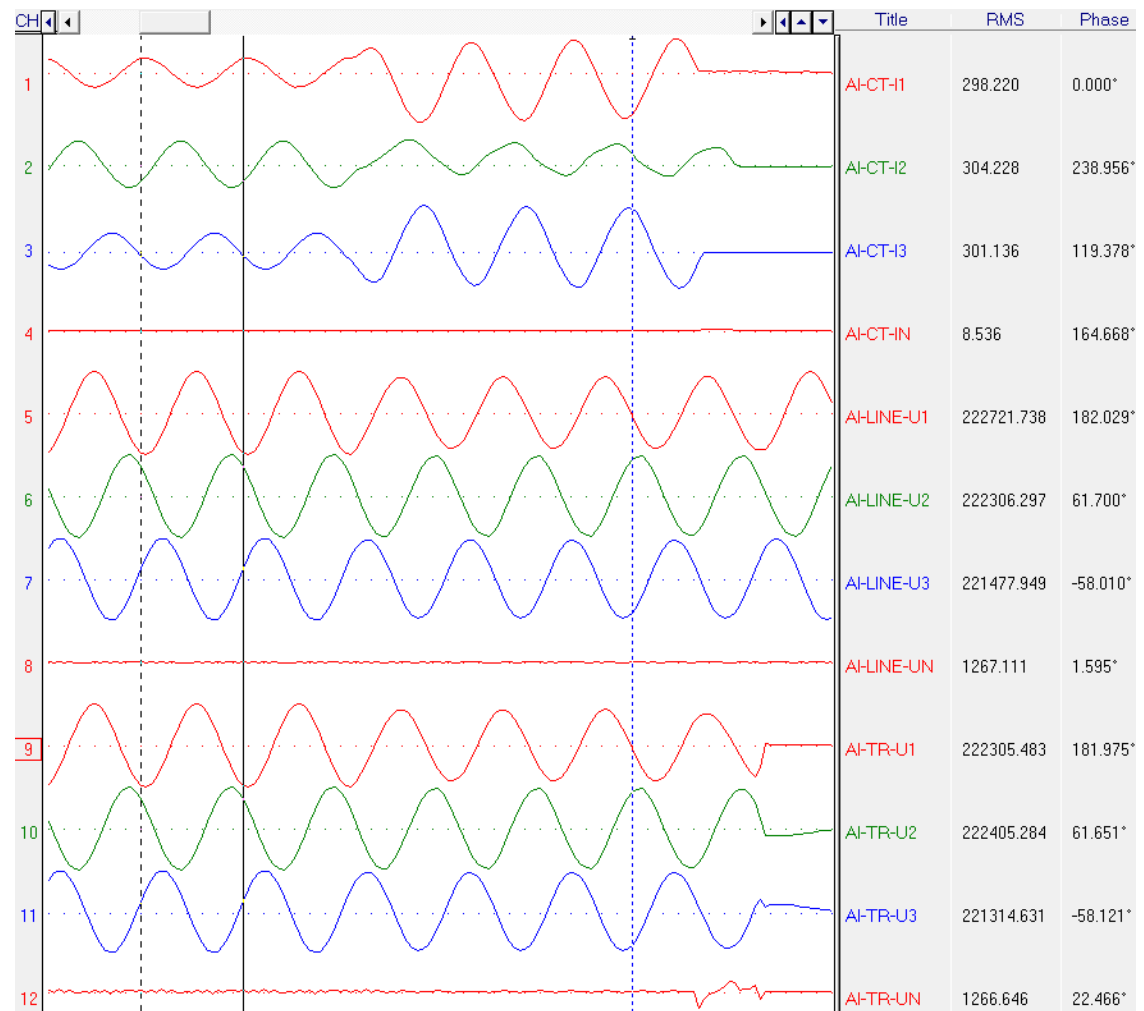


Figure 1 Differential current protection relays fault recorder read out and tertiary winding arrangement

DIFFERENTIAL PROTECTION

Differential Protection (PDIF, 87T), had operated and cleared the fault by tripped the breakers.

The differential current, I_{diff} , and the bias current I_{bias} are defined by the following expressions:

$$I_{diff} = |\bar{I}_1 + \bar{I}_2 + \bar{I}_3 + \bar{I}_4 + \bar{I}_5|$$

$$I_{bias} = \frac{|\bar{I}_1| + |\bar{I}_2| + |\bar{I}_3| + |\bar{I}_4| + |\bar{I}_5|}{2}$$

$$I_{bias(max)} = \text{Maximum}[I_{a_{bias}}, I_{b_{bias}}, I_{c_{bias}}]$$

RESTRICTED EARTH FAULT

Restricted earth fault (REFPDIF, 87N), which did not operated.

This protection calculates the difference in current between neutral & summation of all the 3 phases. The half of highest phase current with multiplication factor, has been taken as bias or restraint current.

$$I_{REF,diff} = \left| \left(\bar{I}_A + \bar{I}_B + \bar{I}_C \right) \times \text{scaling factor} + \bar{I}_N \right|$$

$$I_{REF,bias} = 0.5 \cdot \left[\left(\max \left[|\bar{I}_A|, |\bar{I}_B|, |\bar{I}_C| \right] \right) \times \text{scaling factor} + |\bar{I}_N| \right]$$

$$\text{scaling factor} = K = \text{CTn ratio} / \text{Neutral CT ratio}$$

Both occurrences or events were similar in nature but happened at different times.

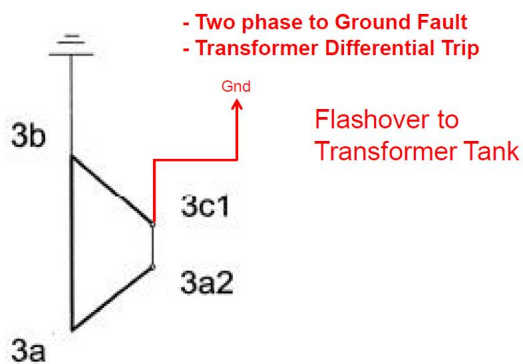
It appeared that there was no fault on primary or secondary side of transformer. However, it look like that the fault was on the tertiary winding of the transformer. The bushing of tertiary windings are exposed to the environment while almost all other terminals & devices are gas insulated or covered.

Conclusion was that there had to be a flashover on the tertiary bushings. Site personal were ask to conduct an inspection of the tertiary bushings which later confirmed ABB's study and analyses results.

Damage to the Transformer bushings due to flash over



Picture 3-4 Autotransformer tertiary bushings with flashover



Picture 5 Autotransformer tertiary winding arrangement

PROTECTED ZONES OF OVERHEAD EARTH WIRES THEN WERE ANALISED

The protected zone, which should cover all equipment, and also the transformers, is determined as per lightning sphere principle

The sectional plane of the protected zone is bounded by an arc along an overhead earth wire whose midpoint M_{2H} is equal to twice the height H of the earth wire both from ground level and from the overhead earth wire.

The sectional plane of the protected zone for two overhead earth wires, whose distance from each other is $C \cdot 2 \cdot H$. The outer boundary lines are the same as with one overhead earth wire. The sectional plane of the protected zone between the two overhead earth wires is bounded by an arc whose midpoint M_R is equal to twice the height $2H$ of the earth wire from ground level and is in the middle of the two overhead earth wires. The radius R is the distance between the overhead earth wire B and the midpoint M_R .

The overhead earth wires from the SEC 380kV towers were connected to the landing gantry of the smelter (see picture 2) the height of the gantry lightning poles was not sufficient to cover the transformer tanks completely

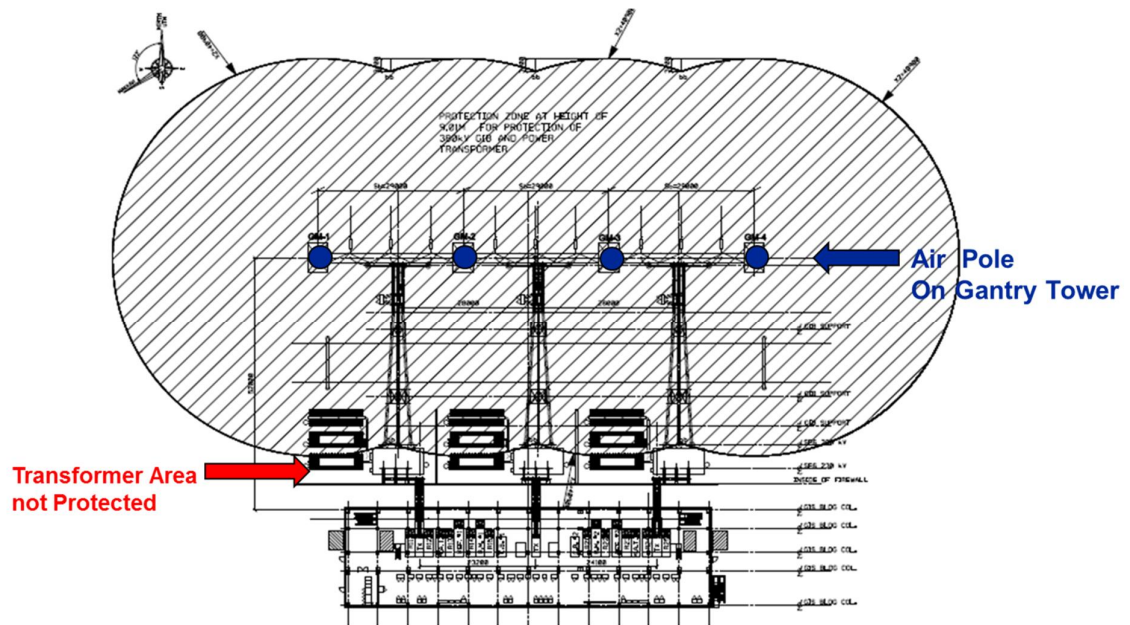


Figure 2 MAC 380/230kV Lightning pole arrangement

Recommendations to improve the Lightning protection:

The lightning sphere principle

In practice for the design of lightning protection systems to prevent direct strokes on buildings, industrial plants, outdoor switchgear installations or overhead lines different methods are available, which are all based on the lightning sphere principle. The principle is demonstrated in Fig. 5-11. When the lightning sphere is rolled around the model on a flat surface, all objects below the sphere are in the protected area, as long as the sphere is in touch with the lightning capture devices. The principle is based on the experience that every lightning main discharge is initiated by a partial flash-over across the final gap between ground potential and the end of the discharge channel growing forth from the atmosphere. The length of this flash-over gap, which is decisive for the spatial positioning of the main discharge channel, depends on the energy content of the developing main discharge. The lightning sphere radius chosen for the sphere method, is equal to the smallest length of the gap of a final flash-over, which corresponds to the smallest main discharge current to be taken into account at the relevant location.

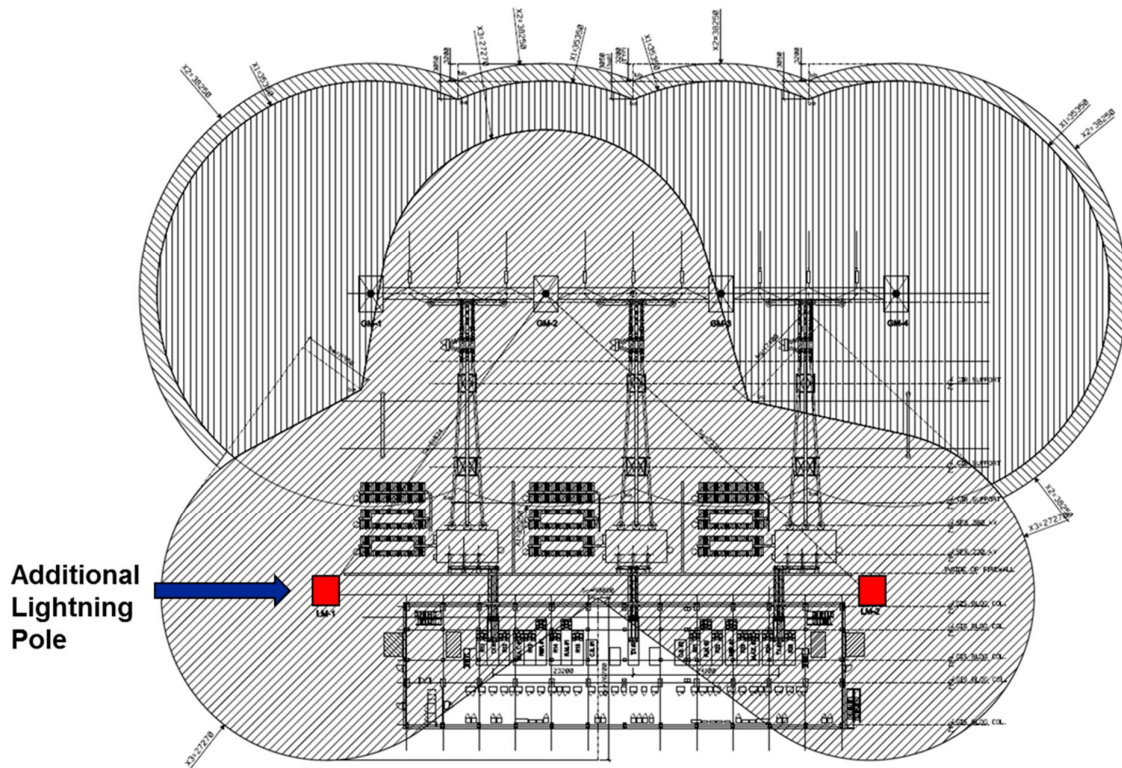


Figure 3 MAC 380/230kV Lightning pole arrangement after ABB conducted a detailed study

In DIN V VDE V 0185-3 (IEC 62305-3 is under consideration) four different classes are specified for designing a lightning protection system. This offers the chance to evaluate the importance of complete safety in relation to the expenditure needed. Different lightning parameters are coordinated to the four lightning protection classes. With respect to the protection performance of the capture electrodes this are: smallest main discharge current taken into account and lightning sphere radius h_B . Selecting these parameters could be based on long lightning statistics experience. The lightning sphere radius is assumed in a fixed relation to the peak value of the main discharge current as per

$$h_B = 10 \cdot I_{0,65} \quad h_B \text{ in m, } I \text{ in kA}$$

Minimum values of the lightning main discharge current and the relevant lightning sphere radius of lightning protection classes I to IV according DIN V VDE V 0185-3

Lightning capture parameters	Lightning protection class				
	I	II	III	IV	
Symbols					
Units					
Lowest main discharge current					
I	kA	3	5	10	16
Lightning sphere radius h_B m		20	30	45	60

This table demonstrates how a nearly complete protection may be achieved, when a peak value of 3 kA is chosen for the lowest main discharge current to be taken into account. This requires a lightning sphere radius of 20m only and as a consequence a considerable more of capture electrodes and conductors than in case of a protection class IV system. All lightning strokes with a peak current value higher than the lowest current parameter value of the relevant lightning protection class will be caught by the capture electrodes and conductors and discharged to earth.

As further lightning parameters also the highest discharge energies to be expected have been coordinated to the lightning protection classes. These parameters are dimensioning for the protection system with respect to thermal and mechanical withstand. Here again we find the most challenging peak current value of 200kA in class I.

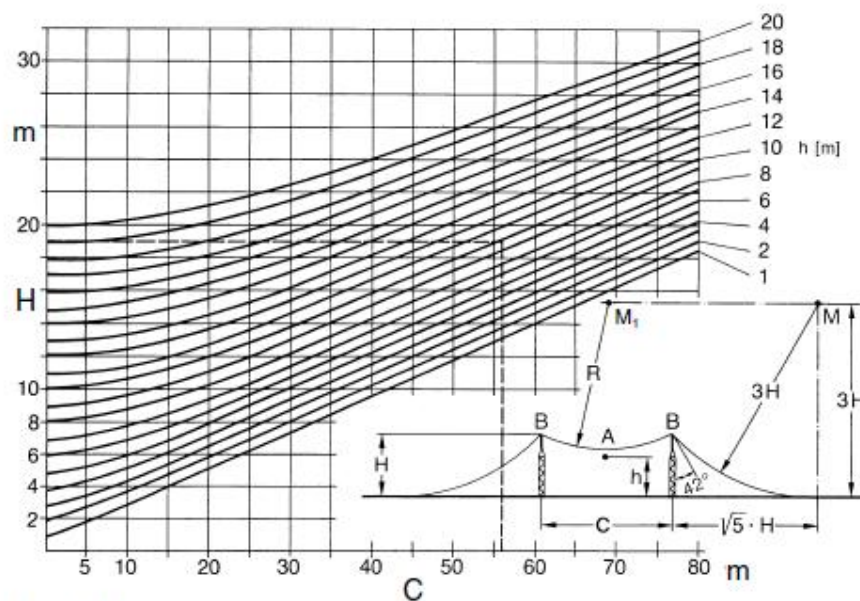


Fig. 5-16

Sectional plane of the protected zone for two lightning rods

Figure 4 Lightning pole dimensioning (ABB Switchgear Manual Section 5)

Summary

Damage caused by lightning cannot be completely prevented either technically or economically. For this reason, lightning protection facilities cannot be specified as obligatory. However it is generally agreed practice to provide lightning protection systems for outdoor switchgear installations and for the buildings of indoor switchboards.

The probability of direct lightning strikes can be greatly reduced on the basis of model experiments, measurements and years of observation with the methods described above.

Statement by Karl Cunningham:

ABB provided a report of recommended corrective actions after analysing the protection relay fault records and reviewing the overall design and installation. Our project team learned that a more detailed lightning protection design and design review must be carried out even when all conductive components are enclosed by grounded metal housings (such as GIS bus). Lightning protection in Saudi Arabia is a significant consideration due to the intense lightning storms with high frequency lightning strikes on very high resistive earth conditions.