World's Lightest & Slimmest 380 kV Porcelain Long Rod Insulators for Ultra-High Pollution Levels

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2023 INMR WORLD CONGRESS

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ABSTRACT

The paper reviews and summarises the experimental tests for determination of pollution performance on different design variants of porcelain long rod insulators at high-voltage test laboratory under in-service environmental conditions. The authors investigate operational performance of two variants (termed as generation I for old design & generation II for new design) of porcelain long rod insulators that differ in terms of physical dimensions as actual designs. The driving motivation originates from no known service failure operations of generation I design of porcelain long rod insulators – to result in generation II design of porcelain long rod insulators with improved pollution performance under very high pollution conditions. The frequent sandstorms on seasonal occasions result in rapid accumulation of sand pollution on porcelain long rod insulators – especially along the deserted regions of the Middle East. To reduce and mitigate the adverse effects of severe contamination – experimental results on existing generation I design show that all transmission lines (up to 380 kVac) in the Kingdom of Saudi Arabia are over-dimensioned. The over-dimensioning to combat extreme pollution led to scaling up of unified specific creepage distances as high as 31 mm/kV to 50 mm/kV at 160 kN and 330 kN mechanical tensile loads. The primary target of this scientific project focuses to improve and optimise the existing design to develop new design of porcelain long rod insulators with optimised shed-profile, increased insulation length & arcing distance, decreased overall weight of porcelain units & surface area to result in improved pollution performance through higher values of withstand and flashover voltages. The re-engineered design of porcelain long rod insulators is artificially pollution tested to evaluate their di-electric strength including withstand and flashover voltages. The pollution tests include two main types of rapid tests (acc. IEC 60507): Quick Flashover (QF - to simulate wet salt-fog pollution) & Rapid Flashover (RFO - to simulate solid-layer pollution). The paper focuses on pollution performance of porcelain long rod insulators, especially as artificially polluted conditions. The summarised test results infer that pollution withstand and flashover voltage values of generation II design are higher than generation I design of porcelain long rod insulators.

KEYWORDS: High-voltage porcelain insulators, porcelain long rod insulators, pollution withstand, pollution flashover, pollution performance, creepage distance, contamination, salt-fog, solid-layer, quick flashover, rapid flashover, a.c. pollution, shed-profile, in-service lifetime.

1. INTRODUCTION

Porcelain long rod insulators are largely used for power transmission in Overhead Transmission Lines (OHTL). These insulators can widely cater a broad range of strength classes, close to 550 kN as mechanical tensile loads. The advancements in engineering and associated production methodologies have also resulted in improved designs of complete insulator string configurations that include integrated hardware accessories. Extra-high creepage values up to 50 mm/kV for all voltage classes (EHV-to-UHV as serial coupling of single units) remains possible in terms of technical feasibility. The recent growth in need for electric power has strongly emphasised the need for high-voltage transmission lines that demand porcelain long rod insulators with di-electrics integrity and increased mechanical strength requirements. Porcelain long rod insulators assembled as lead-antimony cemented alumina ceramic insulators offer very long and excellent operational in-service life.

Advantages of porcelain long rod insulators are numerous. Porcelain long rod insulators employ minimum metallic interconnections which in turn result in minimised (or no) problems associated with corrosion. Several single units when interconnected result in simpler mounting of string configurations, eventually to result in lower weight of complete insulator sets for a given class of system voltage. These insulators can be used for compression loads in addition to the regular tension loads. Amongst all offered advantages – porcelain long rod insulators are mainly solid-core in nature and are therefore theoretically puncture-proof which in actual conditions is almost equal to the dry arcing distance. In general, porcelain has several times the dielectric breakdown strength of air, which means in case of flashover (if) – the breakdown always occurs in the air outside of the porcelain body. Under-ribs sheds are not essential, as the core segments between the sheds contribute to the needed insulation deliverance. Because porcelain as a material shows no measurable aging and has high resistance to temperature variations – well designed and quality-controlled manufacturing of porcelain long rod insulators have enabled successful in-service operation of OHTL for several decades.

Figure 1: Illustration of porcelain long rod insulators as string configurations for OHTL.

2. DESIGN INPUT AND FEATURES

The input as parameters for designing of porcelain long rod insulators is primarily driven by the features of applications to serve in desert environmental conditions. The scientific work presented in this paper has reference to Transmission Material Standard Specification (TMSS) that specifies requirements as minimum technical requisites, especially for design and testing for performance evaluation of porcelain long rod insulators intended to be used in 380 kVac electric power transmission system of National Grid, Kingdom of Saudi Arabia [01]. The di-electric design of porcelain long rod insulators complies to IEC 60815-1, whereas the coupling conforms to IEC 60433 and IEC 60471. The base for scientific tests is derived from specific creepage distance of 50 mm/kV, focused for applications in coastal areas. The tests on specific creepage distance of 40 mm/kV and 31 mm/kV for applications in inland areas are under consideration, and therefore not presented at this stage as findings in this paper.

The climatic condition of Kingdom of Saudi Arabia is predominantly desert type climate. The temperatures during summer range from 27°C to 38°C in coastal regions and 27°C to 43°C in inland regions, whereas the temperatures during winter range from 19°C to 29°C in coastal areas and 08°C to 20°C in inland regions. The desert climatic conditions under harsh inland and coastal pollution are additionally complemented by low average annual rainfall (in major geographical sections of the kingdom) below 150 mm, except for southwestern province where the average annual rainfall ranges between 400 mm to 600 mm [02].

The high levels of in-service pollution and extreme in-service climatic conditions served as the design input for so-called 'old design insulators' (or generation I design). The decades of experience from past in-service operations catered as an input to draw upon the following shed profile.

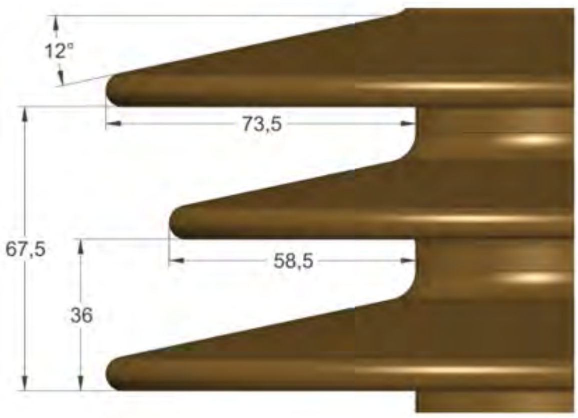


Figure 2: Illustration of shed profile for old design (generation I design) porcelain long rod insulators with specific creepage distance of 50 mm/kV.

The profile shape of porcelain long rod insulators refers to aerodynamic type (i.e., open profile) without under-ribs, designed in accordance with IEC 60815-2 [03]. The ratio of shed spacing to shed protrusion is greater than the minimum technical requisite, as a ratio of 0.65 according to TMSS.

3. OLD DESIGN (Generation I Design) vs. NEW DESIGN (Generation II Design)

The principle of re-designing porcelain long rod insulators for 380 kVac transmission lines in the kingdom of Saudi Arabia focuses to meet the in-service desert conditions at all values of specific creepage distances, i.e., ranging from 31 mm/kV up to 50 mm/kV – resulting in the drive to unify, in general, the shed profiles of all porcelain long rod insulators independent of the specific creepage distances. The insulator surface designs are shaped and inter-spaced to offer effective natural cleaning and result in effective usage of leakage distance for desert conditions. Figure 2 and figure 4 illustrates the shed profiles for old (generation I) and new (generation II) design of porcelain long rod insulators with specific creepage distance of 50 mm/kV. Figure 3 illustrates the self-cleaning efficiency under consideration of exposed creepage sections.

Figure 3: Comparative illustration of shed profiles:

LEFT illustration shows old design (generation I design) – porcelain long rod insulators with specific creepage distance of 50 mm/kV.
RIGHT illustration shows new design (generation II design) – for unified and optimised porcelain long rod insulators for all specific creepage distances ranging from 31 mm/kV up to 50 mm/kV.

The illustration as below outlines improved shed profile for new design (generation II design) porcelain long rod insulators with specific creepage distance of 50 mm/kV. The re-design principle aims to yield self-cleaning efficiency under consideration of exposed creepage segments of porcelain long rod insulators.

The re-design results in lower protected creepage distance for new design (generation II design) porcelain long rod insulators, thereby improves the effect of self-cleaning.

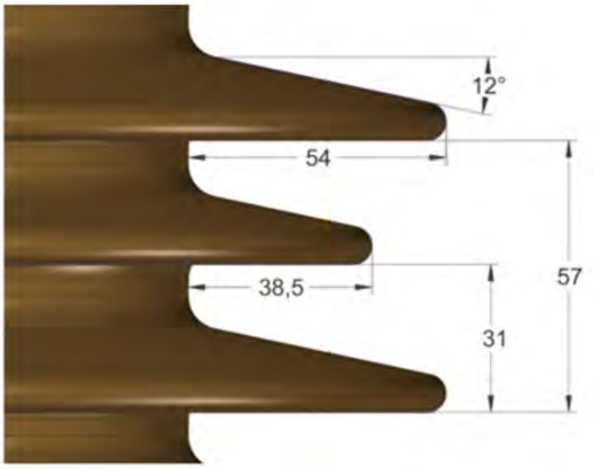


Figure 4: Illustration of shed profile for new design (generation II design) porcelain long rod insulators with specific creepage distance of 50 mm/kV.

The calculations for insulation characteristics and corresponding profile parameters for old (generation I) design porcelain long rod insulators in comparison to new (generation II) design porcelain long rod insulators for 380 kVac transmission lines differs according to tabulated parameters as follows:

Draw. No. / Mat. No.		**Insulator length (mm)**	**Mechanical failing tension load (kN)**	**Creepage distance (mm)**
50 mm/kV 160 kN				
7.012724.01.07.00		**1700**	**160**	**6340**
7.012776.00.07.00		**1840**	**160**	**6340**
Arcing distance (mm)	**Distance between sheds (mm)**	**Spacing versus shed overhang (s/p)**	**Creepage distance versus clearance (l/d)**	**Shed angle (α)**
1545	**58.5**	**0.92**	**5.23**	**12 °**
1655	**48.1**	**1.05**	**4.41**	**12 °**
Surface area (m²)	**Creepage Factor (CF)**	**Shed profile**	**Design remarks**	
2.81	**4.10**	**Alternate**	**Generation I**	
2.54	**3.83**	**Alternate**	**Generation II**	

Table 1: Calculations according to IEC 60815-2 for old (generation I) and new (generation II) design of porcelain long rod insulators with specific creepage distance of 50 mm/kV.

The re-engineered calculations according to IEC 60815-2, driven by factors to retain system requirements to maintain minimum insulation characteristics result in the following 3D models [Figure 5] as optimised shed profiles for old (generation I) and new (generation II) design porcelain long rod insulators for 380 kVac OHTL. The new (generation II) design retains minimum mechanical tension load as 160 kN with creepage distance as 6340 mm when compared to the old (generation I) design. The noticeable difference in the former compared to the latter design lies in increased length of insulation from 1700 mm to 1840 mm (8.23 in terms of percentage increase), along with an increased arcing distance from 1545 mm to 1655 mm (7.12 in terms of percentage increase). A full-scale 3D model as one-to-one comparison [with visually evident differences in physical dimensions] for old (generation I) and new (generation II) designs of porcelain long rod insulators for string configurations [as vertical I-suspension (single/double) or V-suspension and tension strings (single/double) – from 160 kN up to 330 kN mechanical strength class] for 380 kVac OHTL is depicted in Figure 8.

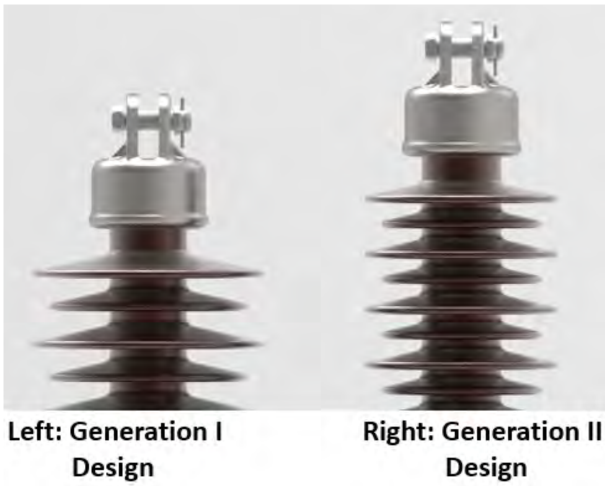


Figure 5: Illustration of 3D Models of the shed profiles for old [picture to the left] & new [picture to the right] designs (generation I & II) of porcelain long rod insulators with specific creepage distance of 50 mm/kV.

Figure 6 and figure 7 shows shed profile parameters for both designs according to IEC 60815-2, to explicitly highlight the differences in terms of:

- shed overhangs
- s/p ratios
- distance between sheds
- creepage distances vs. associated clearances
- shed angles
- corresponding creepage factors

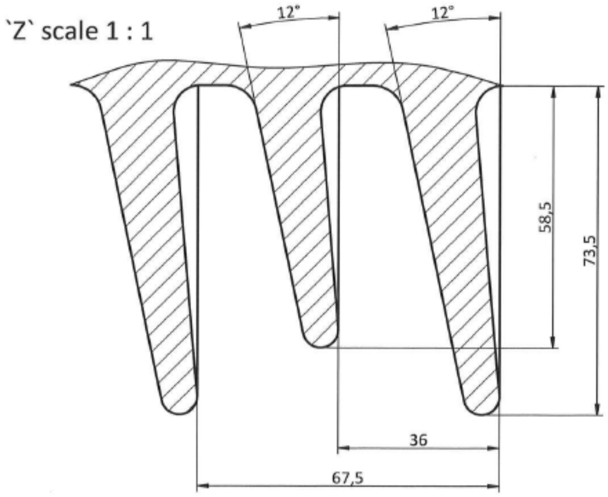


Figure 6: Sketch of shed profile parameters for old (generation I) design of porcelain long rod insulators for specific creepage distance of 50 mm/kV.

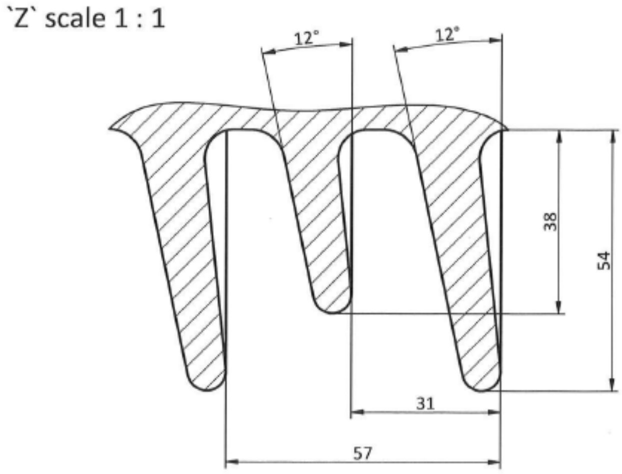


Figure 7: Sketch of shed profile parameters for new (generation II) design of porcelain long rod insulators for specific creepage distance of 50 mm/kV.

Additional noticeable difference that reflects in new (generation II) compared to old (generation I) design is the decrease in insulator surface area of assembled single short string porcelain long rod insulator – lowered to 2.54 m² from 2.81 m², i.e., 9.61 in terms of percentage decrease. In other terms, the decrease in insulator surface area indicates reduced exposure to wind (reduced area of porcelain surface) which results in lower wind load on porcelain long rod insulators including complete string configuration. As an extrapolated case of interpretation, in case of application of silicone coat on porcelain long rod insulators – the required volume of silicone also reduces in terms of minimum required quantity. In parallel, the difference in new (generation II) compared to old (generation I) design is the decrease in weight of assembled single short string porcelain long rod insulator – lowered to 56.8 kg (porcelain unit = 50.0 kg) from 62.9 kg (porcelain unit = 54.9 kg), i.e., 9.70 in terms of percentage decrease. The optimisation of insulator shed-profiles resulted in an increased length of insulation & arcing distance, complemented by decreased insulator surface area & weight of unassembled / assembled porcelain units – as targeted intentions to meet and technically comply all system requirements for in-service operations in 380 kVac power transmission network of National Grid, Kingdom of Saudi Arabia.

The aero-dynamic shed profile results in lesser accumulation of contamination under conditions of pollution, i.e., reduced deposition of pollutants including conditions under desert contamination. The tests on both designs (generation I & generation II) to determine pollution performance under contaminated conditions as pollution tests, including di-electric tests are discussed and presented in the following section of this paper.

Figure 8: Illustration of full-scale 3D Models of single short string profiles for old [picture to the left - generation I] & new [picture to the right - generation II] designs of porcelain long rod insulators with specific creepage distance of 50 mm/kV at 160 kN as mechanical tensile load.

4. PERFORMANCE EVALUATION AS TEST RESULTS

The tests were set-up to benchmark individual performance of both (generation I & generation II) designs. And the derived a.c. pollution performance is presented in this section as test results. The considered level of contamination for pollution tests is based on known Site Pollution Severity (SPS) conditions as:

Equivalent Salt Deposit Density (ESDD): 0.55 mg/cm^2 for coastal applications and 0.3 mg/cm^2 for inland applications.

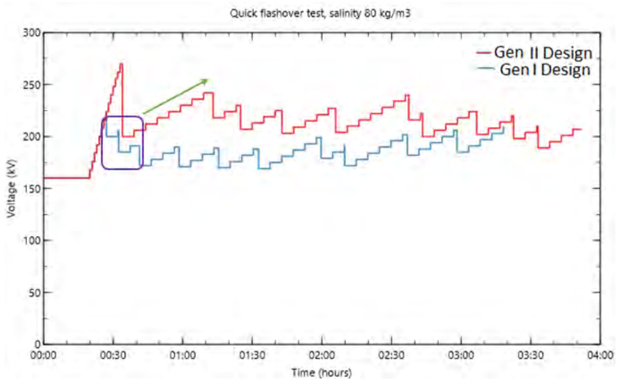
Non-Soluble Deposit Density (NSDD): 5.00 mg/cm^2 for both for coastal and inland applications.

Figure 9: General set-up as test arrangement for all a.c. pollution tests on porcelain long rod insulator (for generation I & generation II) designs with specific creepage distance as 50 mm/kV.

The performance analyses are based on special tests as variants of different types of pollution tests on both designs (generation I & generation II) of porcelain long rod insulators:

- Quick Flashover Method [04]
  [according to CIGRE TB 691]
  (for salt-fog pollution @ Salinity: 80 kg/m³)

The test voltage chosen for the start of salt-fog pollution test according to quick flashover method equals to 160 kVac. The first flashover voltage for generation I design equals 220 kVac, whereas for generation II design equals 280 kVac. Graph 1 shows the comparative plot for quick flashover tests (as salt-fog tests) with corresponding flashover values for generation I & generation II designs. The graph depicts the decrease in time-duration (as build-down) in case of generation I design for successive flashovers (reference to graph 1 - outlined block in purple). The graph also shows an increase in time-duration (as build-up) in case of generation II design for successive flashovers (reference to graph 1 - arrowed upward trend in green).



Graph 1: Comparison of quick flashover tests (as salt-fog tests) - recorded flashover values for generation I & generation II designs [acc. to CIGRE TB 691].

- Rapid Flashover Method [04]

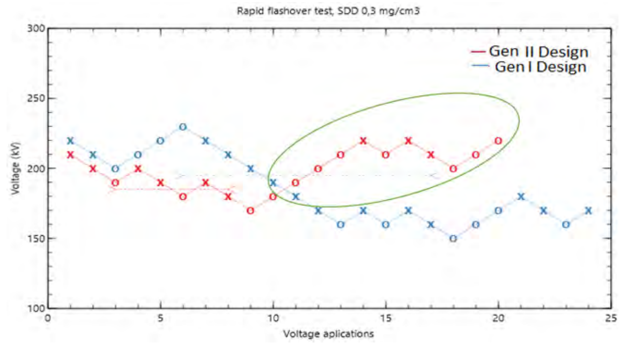
  [acc. to CIGRE TB 691]

  (for solid-layer pollution @ ESDD: 0.3 mg/cm²)

The test voltage chosen for the start of solid-layer pollution test according to rapid flashover method is greater than 205 kVac. The first flashover voltage for generation I design equals 220 kVac, whereas the last withstand voltage equals 160 kVac. And the first flashover voltage for generation II design equals 210 kVac, whereas the last withstand voltage equals 240 kVac. Graph 2 shows the comparative plot for rapid flashover tests (as solid-layer tests) with flashover values for generation I & generation II designs respectively.

The graph depicts the decrease in performance in case of generation I design for successive voltage applications (reference to graph 2 - voltage plots in blue). The graph also shows an increase in performance in case of generation II design for successive voltage applications (reference to graph 2 - voltage plots in red and ellipse-highlighted in green).

The test procedures adopted for both variants of pollution tests, Quick Flashover Method and Rapid Flashover Method are performed acc. to test conditions and procedures (as guideline) outlined in CIGRE TB 691 [04].



Graph 2: Comparison of rapid flashover tests (as solid-layer tests) - recorded flashover values for generation I & generation II designs [acc. to CIGRE TB 691].

- a.c. Pollution Test Method [05]

  [according to IEC 60507 - cl. 5]

  (for salt-fog pollution @ Salinity: 80 kg/m³)

The test voltage chosen for a.c. pollution test according to salt-fog pollution method is 81 kVac. The test procedure adopts standard process as start of tests with pre-conditioning followed by three 01 hour of withstand tests at test voltage of 81 kVac.

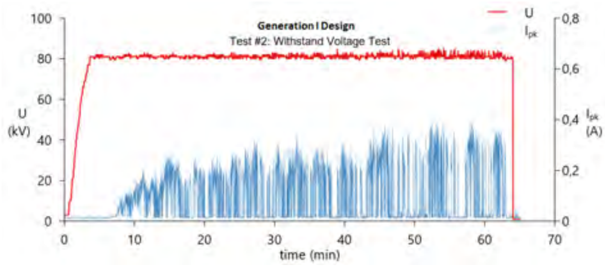


Figure 10: Record of test voltage and leakage currents during the salt-fog withstand voltage test @ salinity 80 kg/m³ on Generation I Design.

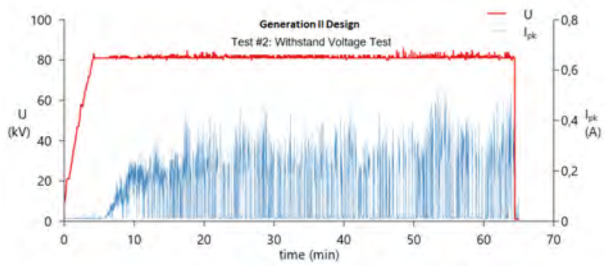


Figure 11: Record of test voltage and leakage current during the salt-fog withstand voltage test @ salinity 80 kg/m³ on Generation II Design.

The test results for both generation designs resulted identical – tests on generation I and generation II designs passed with no flashovers during all three 01 hour of withstand voltage tests. Also, the measured values of peak leakage currents during all three 01 hour withstand tests on both generation designs were close to an approx. average value of 400 mA.

As an additional procedure after three (of 01 hour each) withstand voltage tests performed at test voltage of 81 kVac, the test voltage was raised in defined steps of voltage (@ 16 kVac per 05 minutes) until respective flashovers occurred. The test results on generation I design shows flashover voltage values as 209 kVac - 209 kVac - 209 kVac (after each 01 hour withstand voltage test at 81 kVac). Similarly, test results on generation II design shows flashover voltage values as 209 kVac - 177 kVac - 209 kVac (after each 01 hour withstand voltage test at 81 kVac).

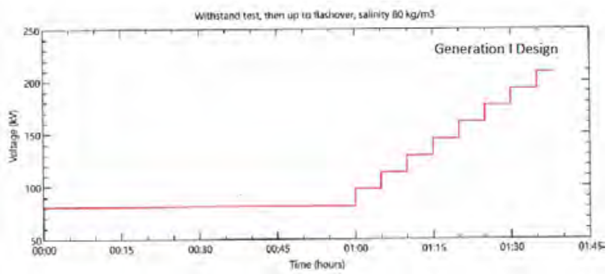


Figure 12: Graphical plot for withstand voltage test with increase in voltage steps (16 kVac / 05 minutes) until flashovers @ salinity 80 kg/m³ on Generation I Design.

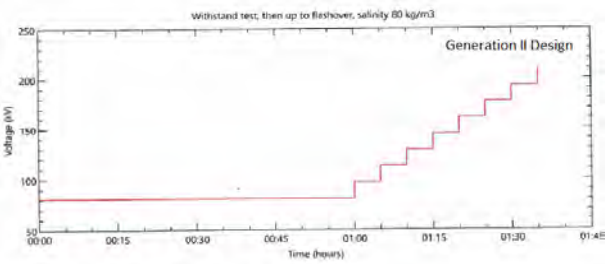


Figure 13: Graphical plot for withstand voltage test with increase in voltage steps (16 kVac / 05 minutes) until flashovers @ salinity 80 kg/m³ on Generation II Design.

Similar to the pattern of observed leakage currents during the respective withstand voltage tests (as pollution tests) – the measured values of flashover voltages (after withstand voltage tests) were also comparable at 209 kVac. Table 2a & 2b shows comparative records of time to flashover (for both generation designs) and the respective values of flashover voltages.

Generation I Design		
Test No.	Time of Flashover	Flashover Voltage (kV)
1	1:38:00	209
2	1:35:59	209
3	1:41:12	209

Table 2a: Time to flashover in case of Generation I Design and corresponding values of flashover voltages.

Generation II Design		
Test No.	Time of Flashover	Flashover Voltage (kV)
1	1:35:10	209
2	1:29:10	177
3	1:35:01	209

Table 2b: Time to flashover in case of Generation II Design and corresponding values of flashover voltages.

Figure 14 refers to the graphical plot to express the pattern of flashover voltages vs. time on both generation designs (after standard salt-fog withstand voltage tests).

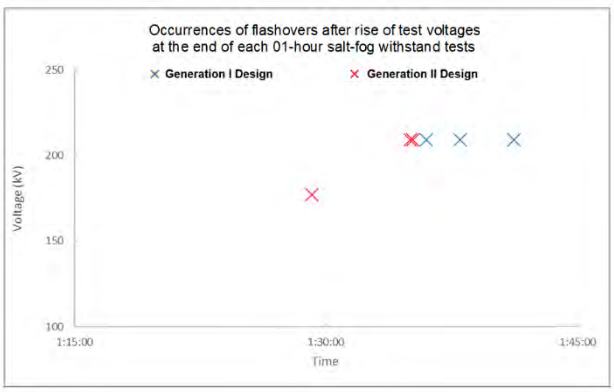


Figure 14: Graphical plot of flashover voltages vs. time on both generation designs (after salt-fog withstand voltage tests).

The test voltage in the test-methods were restricted to 209 kVac due to the limitation of test transformer used for tests at the high-voltage test laboratory.

- Di-electric tests to determine Wet Power-Frequency Flashover & Withstand Voltage Values
  [wet a.c. tests as flashover & withstand voltage tests on clean long-rod insulators - in absence of contamination]

The wet a.c. flashover voltage tests in actual service conditions were performed as di-electric tests to simulate the closest possible service conditions, as tests on clean insulator surface (under no pollution).

Tabulated Data: Wet a.c. flashover test results / unclean insulator surface (without pollution)

Generation I Design		Generation II Design	
Test No.	Flashover Voltage (kV)	Test No.	Flashover Voltage (kV)
1	436	1	570
2	408	2	554
3	424	3	551
4	464	4	564
5	435	5	562
Average	433.40	Average	560.20

Max. Withstand Voltage Values:
Generation I Design 420 kV (Arcing Distance 1.57m)
Generation II Design 500 kV (Arcing Distance 1.7m)

Table 3: Wet a.c. flashover test results on generation I & II designs of clean (without pollution) porcelain long rod insulators.

The average value of wet a.c. flashover voltage in case of generation I design is 433.40 kV, whereas in case of generation II design is 560.20 kV (reference to table 3). The generation II design shows a higher value of wet a.c. flashover voltage value compared to generation I design [under no pollution].

- [wet a.c. tests as flashover & withstand voltage tests on unclean long-rod insulators - in presence of contamination according to solid-layer pollution @ ESDD: 0.3 mg/cm²]

As an extrapolation to the above-mentioned test scenario – wet a.c. flashover voltage tests in actual operational conditions were also performed as di-electric tests to simulate the closest possible in-service conditions, as tests on unclean insulator surface (under solid-layer pollution @ ESDD: 0.3 mg/cm²).

Tabulated Data: Wet a.c. flashover test results / unclean insulator surface (with pollution)

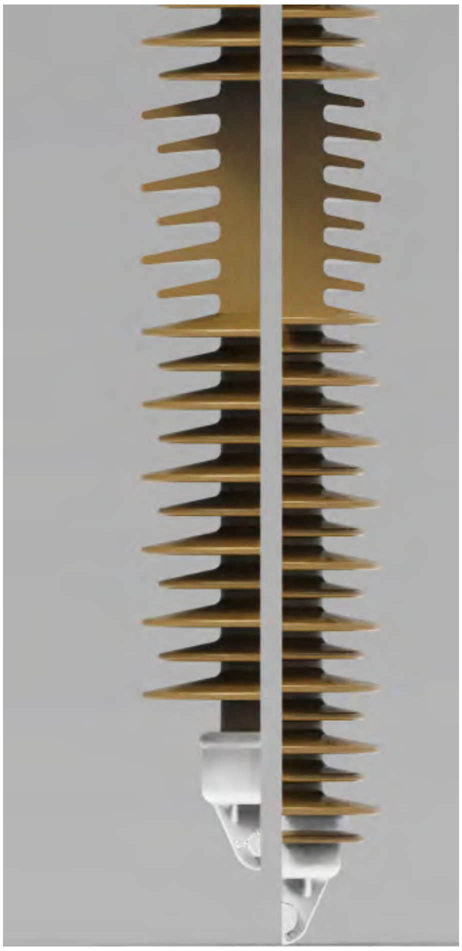
Generation I Design		Generation II Design	
Test No.	Flashover Voltage (kV)	Test No.	Flashover Voltage (kV)
1	215	1	301
2	205	2	305
3	212	3	337
Average	210.70	Average	314.30

Table 4: Wet a.c. flashover test results on generation I & II designs of unclean (with pollution [according to solid-layer pollution @ ESDD: 0.3 mg/cm²]) porcelain long rod insulators.

The average value of wet a.c. flashover voltage in case of generation I design is 210.70 kV, whereas in case of generation II design is 314.30 kV (reference to table 4). The generation II design shows a higher value of wet a.c. flashover voltage value compared to generation I design [under pollution].

5. CONCLUSIONS

The design standardisation through optimisation of 380 kVac porcelain long rod insulators for very heavy polluted environmental conditions were designed, developed and tested to evaluate improved performance against existing in-service design of porcelain long rod insulators for transmission lines (up to 380 kVac) in the Kingdom of Saudi Arabia. The performance evaluation is based on the analyses of positive results through special tests as variants of pollution tests on porcelain long rod insulators for applications in coastal- & inland-installations at National Grid - Saudi Arabia. The design standardisation through optimisation of 380 kVac porcelain long rod



insulators for very heavy polluted conditions were tested to evaluate improved pollution performance against the existing design of porcelain long rod insulators. The results as an outcome of tests on generation II design of porcelain long rod insulators, according to Quick Flashover Method, Rapid Flashover Method, a.c. Pollution Tests (followed by increase of test-voltage after standard three 01 hour withstand tests), Di-electric tests to determine Wet Power-Frequency Withstand & Flashover Voltage values on polluted and unpolluted variants of porcelain long rod insulators show superior test values in terms of improved performance under actual artificial pollution conditions. In parallel, the design optimisation is additionally complemented by an overall reduction in physical parameters of insulation design for generation II design of porcelain long rod insulators. Principally, the design standardisation through optimisation of 380 kVac porcelain long rod insulators also improves the overall carbon footprint. Slimmer single unit designs of porcelain long insulators could further aid in designing more economical string configurations. The new generation of porcelain long rod insulators confirm better design of shed-profile through – an increased length of insulation & arcing distance, followed by decreased insulator surface area & porcelain weight to result in lightest and slimmest possible variants of 380 kVac porcelain long rod insulators for very heavy polluted conditions of the Middle East, especially the regions that encompasses the OHTL of Arabian Peninsula.

Porcelain long rod insulators deliver failure-proof mechanical performance and in parallel are also known to eliminate commonly known mechanical failure modes when compared to other types of insulators for OHTL. The insulators of porcelain long rod type when well-engineered in terms of design and well-manufactured under stringent quality control are known to serve as the robust and reliable solution for electric power transmission.

6. ACKNOWLEDGMENTS

The authors would like to thank LAPP Insulators - Germany for the financial support received to conduct scientific tests related to the project: standardisation of design of porcelain long rod insulators for 380 kVac transmission lines in the Kingdom of Saudi Arabia. The authors would also like to thank the test engineers at EGU - HV Laboratory a.s. - Czech Republic for the test opportunities and technical discussions evolved during the test-phases.

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