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DESIGN OF BOOSTER SHED PARAMETERS FOR IMPROVING THE ELECTRICAL PERFORMANCE OF POST INSULATORS UNDER ICING CONDITIONS

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CONCEPTION DES PARAMÈTRES DES JUPES AUXILIAIRES
POUR AMÉLIORER LES PERFORMANCE ÉLECTRIQUES
DES ISOLATEURS DE POSTE DANS DES
CONDITIONS DE GIVRAGE

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ABSTRACT

The optimized design of outdoor insulators that consider heavy icing and pollution conditions is a significant concern for the reliability of power networks. Based on field observations, the probability of flashover of EHV post insulators is higher than line insulators under the same heavy icing conditions. The flashover along the insulators is caused mainly by the presence of a water film on the ice surfaces (melting period) and partial arcs in ice-free zones (air gaps).

One of the mitigation options is the use of booster sheds (BSs) to create air gaps along the iced insulator. A booster shed (BS) is a flexible c-shape device made of high-quality insulating materials. Since BSs are easy to use, they seem to be simpler alternatives to upgrading insulators to those designed for cold climate regions. Despite the promising results of BS applications, still an important work must be achieved to propose optimized design of BS configurations.

This project aims to provide a generic design approach to the use of BSs by optimizing their main parameters (number, diameter, inclination angle, position, and permittivity) on post insulators under heavy icing conditions. This approach is based on analyzing previous BS tests in CEGELE, an improved hypothesis of BS effects, numerical analysis using commercial software (e.g. Comsol Multiphysics™, Matlab, and Minitab), geometric modeling of ice-covered post insulator with BSs, and finally experimental validation tests.
The improved hypothesis states that the major effect of BSs is the creation of air gaps and their minor effect is the increase in dry arcing distance. Moreover, among total length of the air gaps, dry arcing distance, and total ice-free leakage distance ($IFLD_{tot}$), the $IFLD_{tot}$ is a good indicator to quantify the BS effects on standard post insulators. Simulation analyses of BS configurations during the melting period demonstrate that the optimized relative permittivity of BS is an arbitrary value in its feasible variation range (2-15). The proper positions of BSs close to the HV electrode should be determined based on the probability of electrical breakdown. In contrast, the positions close to the ground electrode are determined based on ice-bridging effect. The geometric model and Taguchi method analysis show that the optimized value of BS inclination angle is equal to the upper shed angle of the insulator. Also, it indicates that generally the maximum feasible values for diameter and number of BSs are the best options. The feasibility in this regard, depends mainly on the minimum required distances between BSs as well as the mechanical forces of heavy ice and strong wind that may deform BSs. PVC sheet was deemed an effective solution for fabricating BS prototypes to perform the final validation tests. The experimental tests completely confirmed the improved hypothesis, the effectiveness of the geometric model, and the simulation analysis.
RÉSUMÉ

La conception optimisée des isolateurs externes sous des conditions sévères de givrage et de pollution est une préoccupation importante, surtout pour la fiabilité des réseaux électriques dans les régions au climat froid. Basée sur la pratique des transporteurs d'énergie électriques, la probabilité de contournement des isolateurs de poste THT est plus élevée que celle des isolateurs de ligne dans les mêmes conditions de givrage. Le contournement le long des isolateurs est essentiellement dû à la présence d'un film d'eau sur les surfaces de glace (période de fonte) et d'arcs partiels le long de zones sans glace (intervalles d'air).

L'une des alternatives pour diminuer la probabilité de contournement des isolateurs recouverts de glace est l'utilisation des jupes auxiliaires (JAs), ce qui permet de créer de plus grands intervalles d'air le long des isolateurs. Une jupe auxiliaire (JA) est un dispositif en forme de C flexible fabriqué à partir de bons isolants. En plus d'être faciles à utiliser, les JAs semblent être une alternative relativement simple, puisqu'elles permettent d'éviter de concevoir des isolateurs spéciaux pour les régions froides. Même si les résultats des applications de JA sont prometteurs, il y a encore un important travail à faire pour proposer une conception optimisée de leur configuration.

Ce projet vise à optimiser les paramètres principaux (nombre, diamètre, l'angle d'inclinaison, la position et la permittivité) des jupes auxiliaires pour fin de leur utilisation sur les isolateurs de poste sous des conditions sévères de givrage. Cette approche est basée sur plusieurs éléments tels que l'analyse des tests précédents des JAs à la CEGELE, une
hypothèse améliorée des effets des JAs, des analyses numériques utilisant des logiciels commerciaux tels que Comsol, MATLAB, et Minitab, ainsi que la modélisation géométrique de l’isolateur glacé avec JAs et sur des tests de validation expérimentaux.

Selon l’hypothèse améliorée, l’effet majeur de JAs est la création d’intervalles d’air et leur effet mineur est l’augmentation de la distance de l’arc. De plus, parmi la longueur totale des intervalles d’air, la distance d’arc et la distance totale de fuite dans les intervalles libres de glace (IFLD_{tot}), le IFLD_{tot} est un bon indicateur pour quantifier les effets des JAs sur des isolateurs de poste standard. Les analyses de simulation de configurations des JAs en période de fonte montrent que la permittivité relative optimisée d’une JA est une valeur arbitraire dans sa gamme de variation possible (2-15). Les positions appropriées des JAs proches de l’électrode de haute tension devraient être déterminées à partir de la probabilité de décharge électrique. Par ailleurs, les positions proches de l’électrode reliée à la masse sont déterminées à partir de l’effet de pontage de la glace. Le modèle géométrique et la méthode Taguchi montrent que la valeur optimale de l’angle d’inclinaison des JAs est égale à l’angle de la jupe supérieure de l’isolateur. Ceci indique aussi que les valeurs réalisables maximales pour le diamètre et le nombre de JAs sont généralement les meilleures options. La faisabilité à cet égard, dépend principalement des distances minimales requises entre les JAs, ainsi que des forces mécaniques de la glace et du vent qui peut déformer les JAs. La feuille de PVC a été considérée comme une solution efficace pour fabriquer des prototypes de JA afin d’effectuer les tests de validation finale. Il s’est avéré que les tests ont complètement confirmé l’hypothèse améliorée, l’efficacité du modèle géométrique et les analyses de simulation.
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Glossary of Terms

Air Gap (AG): an ice-free zone along the insulator.

Applied water conductivity ($\sigma_{20}$): the electrical conductivity of water used to simulate ice, snow, or cold-fog accretion on insulators, corrected to 20 °C.

Booster Shed (BS): a flexible c-shape device usually made of high-quality insulating materials. It can improve the electrical performance of insulators under heavy wetting and icing conditions.

Dry Arcing Distance (DAD): is the shortest distance in air between the high voltage and the ground electrodes.

Dry ice: the ice without water film at its surface.

Flashover: a disruptive discharge through air around or over the surface of solid or liquid insulation, between parts of different potential or polarity, produced by the application of voltage wherein the breakdown path becomes sufficiently ionized to maintain an electric arc.

Glaze ice (clear ice): type of precipitation icing resulting in pure ice accretion of density 0.7 – 0.9 g/cm$^3$, sometimes with the presence of icicles underneath the wires. It very strongly adheres to objects and is difficult to knock off.

Ice thickness: the radial thickness of ice accumulation measured on a rotating monitoring cylinder.

Insulator: an insulating material designed to support a conductor physically and to electrically separate it from another conductor or object.

Leakage current: a component of the measured current that flows along the surface of the tool or equipment, due to the properties of the tool or equipment surface, including any surface
deposit, when the device is connected as intended to the energized power system at rated voltage.

**Leakage distance:** the shortest distance, or the sum of the shortest distances, along the insulating parts of the insulator between those parts that normally have the operating voltage between them.

**Maximum withstand voltage** ($V_{WS}$): is established using constant contamination exposure. The tests are complete when three withstands in four tests are observed at one voltage level, and two flashovers are observed at 5% higher voltage level. The $V_{WS}$ is the test level that gives three withstands out of four tests.

**Minimum flashover voltage** ($V_{MF}$): corresponds to a voltage level that is one step (5%) higher than $V_{WS}$ and gives two flashovers out of a maximum of three tests.

**Monitoring cylinder:** a cylinder for measuring reference ice accretion, typically 25 – 30 mm in diameter, either rotating at 1 rpm or fixed.

**Partial discharge:** a discharge that does not completely bridge the insulation between electrodes.

**Total air gap length** ($L_{AG\text{-}tot}$): the sum of the lengths of air gaps.

**Total Ice-Free Leakage Distance** ($IFLD_{tot}$): the total of the shortest distances along the insulating surface between the high voltage and ground electrodes that are free of ice.

**Uncertainty:** an estimated limit based on an evaluation of the various sources of error.

**Wet-grown ice (wet ice):** is characterised by the presence of a water film of low resistivity at the surface of ice and icicles during their growth.
CHAPTER 1

INTRODUCTION
CHAPTER 1
INTRODUCTION

1.1 Overview and description of the problem

Electrical insulation and improving the flashover performance of HV insulators are challenging problems for many utilities in cold climate regions. In addition, the electrical problems of station insulators, such as high fault currents and equipment stresses, are more severe than for faults on line insulators. Actually, more than fifty percent of electrical icing flashover problems in North America are related to station insulators [1]–[5]. Thus, this project concentrates principally on the icing problems on station post insulators.

Several investigations and methods have been used to improve the performance of insulators in ice, snow, and pollution conditions [6]–[8]. One of the effective methods is using accessories such as booster sheds (BSs) and creepage extenders to break up icing patterns and to increase the threshold of ice accretion necessary for insulator bridging. BSs are flexible c-shape devices (Figure 1.1) which were invented in England to improve the flashover performance of insulators under heavy rain and high-pressure washing under energized conditions [9]–[13]. Some designs of booster shed (BS) have hemispherical "nubs" (Figure 1.1-a) to set a space between BSs the insulator surface. This space allows natural rain washing [2]. Figure 1.2 shows typical BSs applied to transformer bushings.
The effectiveness of BSs in heavy rain conditions is due mainly to a combination of features such as water shedding, discharge inhibition, and arc suppression [9], [11]. BSs can be used in cold regions with heavy ice and snow conditions as well [14]–[20].

The key parameters and/or properties that can be considered in BS optimized design and BS applications are:

1. Electrical properties (e.g. dielectric strength, volume, and surface resistance, permittivity or dielectric constant, tracking and erosion resistance).
2. Mechanical properties (e.g. tensile strength, ultimate elongation, low temperature flexibility).

3. Chemical properties (e.g. ultra violet resistance, hydrophobicity).

4. Aging properties i.e. the variations of above mentioned properties over time.

5. Geometrical parameters (e.g. diameters, inclination angle, thickness).

6. Installation parameters (e.g. number of BSs, positions, and speed in installation procedure).

Commercial BSs are generally made of ethylene vinyl acetate (EVA), a copolymer with suitable characteristics for industrial purposes under electrical, environmental, and mechanical stresses [11]. Hence, among the mentioned parameters, this PhD project contributes mainly to the optimization of some geometrical and installation parameters of BSs. It can close some major gaps in the present state of knowledge of BS applications under heavy icing conditions. For example, in the Tyco Company’s manual for BSs, it is suggested to install BSs in equal distances. However, since the electrical field distribution along post insulators with BSs is not uniform, the ice accretion on BSs is not equal from top to bottom. In fact, the suggested method is not an optimum approach.

To solve the problems of the electrical performance of post insulators under heavy ice conditions, they can be substituted with new types of insulators. However, new insulators and their installation is much more expensive compared to the price of BSs. Thus, a more economical approach would be to add optimum BSs to the existing power network insulators.
1.2 Research objectives

The overall objective of this PhD project is to design booster shed parameters under heavy icing conditions through a generic approach in order to improve the electrical performance of EHV ceramic post insulators. The main BS parameters are as follows: number, diameter, inclination angle, position, and relative permittivity. Thus, a systematic study based on the combination of analytical analysis, simulations, and experimental tests should be performed. For this purpose, the specific objectives are as follows:

- To analyze different BS configurations by simulations of electrical field and potential distributions and parametric studies (water film effect, variation of BS parameters, flashover performance analyses, etc.);
- To establish an improved comprehensive hypothesis of BS effect under heavy icing conditions;
- To improve and develop effective geometric models in order to analyze the electrical performance of ice-covered post insulators equipped with BSs;
- To do optimality and post-optimality analyses of BS parameters using problem formulation process and modern techniques;
- To validate results by making proper BS prototypes and performing corresponding feasible experimental tests under heavy icing conditions.
1.3 General methodology

To achieve the main and specific objectives of the project, numerical modelling and calculations were done by Comsol Multiphysics™, Minitab and Matlab software, mainly based on previous BS tests in CIGELE. Finally, experimental validation tests were carried out. Figure 1.3 illustrates the general methodology by a flowchart. In the next chapters, the details of the methodology and the corresponding results are presented.
1. Study of ice accretions on booster sheds
2. Computer simulations and parametric studies
3. Improved hypothesis concerning the effects of BSs under heavy icing conditions
4. Geometric modeling of the ice-covered post insulator equipped with BSs
5. Taguchi method application to design and optimize BS parameters
6. Experimental validation tests

1.4 Originality of the research and contribution to knowledge

Based on exhaustive study and consultation, only a few research results can be found on the effect of using BSs for insulators in cold climate environments and no systematic studies that analyze the major BS parameters installed on insulators in heavy icing conditions. Thus, the originality of this PhD project is summarized mainly as follows:

- the first extensive study to optimize BS parameters under icing conditions,
- the first simulations for various BS configurations, BS parameters and partial arcs on BS,
- upgraded model of BS dimensioning,
- improved hypothesis of the BS effects under heavy icing conditions,
- novel geometric modeling of ice-covered post insulators equipped with BSs, considering the precipitation angle,
- innovative indicator to quantify electrical performance of insulators with BSs,
• new design approach to use Taguchi method for optimality and post-optimality analyses,

• unique design method and fabrication of feasible BS prototypes for application on EHV ice-covered insulators that not only opened a locked door toward the final experimental tests in this research but also for the future studies in this domain,

• original optimized BS configuration to carry out the final experimental validation tests under heavy icing conditions.

1.5 Thesis outline

The structure of this dissertation is as follows:

Chapter 1 introduces general information about the problem, the necessity and motivation for the present research. Moreover, it presents the general and specific objectives, the general methodology, and the statement of the originality of the research.

Chapter 2 reviews the literature as it relates mainly to ice-covered insulators, booster sheds as well as design and optimization methods.

Chapter 3 proposes an upgraded model of booster shed dimensioning. It deals mainly with the diameter and position of booster sheds.

Chapter 4 describes the parametric simulation studies and the improved hypothesis of BS effects under heavy icing condition. Since the design approach is based on this improved hypothesis, this stage is as important as a foundation of a building.
Chapter 5 elucidates the geometric modeling of ice-covered post insulators equipped with BSs taking into account the precipitation angle. Then the geometric model is used to apply the Taguchi technique in the optimality and sensitivity analyses of various BS configurations under heavy icing conditions.

Chapter 6 deals with the fabrication of BS prototypes and the final experimental validation tests.

Finally, Chapter 7 concludes this study and it also presents the recommendations for future work.
CHAPTER 2

LITERATURE REVIEW
CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Outdoor insulators are widely used in power networks, but ice accretion may cause a drastic reduction in their electrical insulating performance in high altitudes and cold climate regions in many countries, such as Canada [21], [22], the USA [23], China [5], [24]–[27], Norway [28], Japan [29], and Iran [30]. In fact, in many cold regions of the world, atmospheric icing is a severe problem in electrical power systems. It can cause power outages and often incurs major costs by insulator flashover at service voltage [2], [31].

Two famous ice storms which clearly illustrate the disastrous consequences of the problem were firstly in Eastern Canada and US in 1998 and secondly in Southern China in 2008. The cost to the economy in the first one was estimated at nearly US$6 billion. Almost 1.6 million customers in Quebec and Ontario were left without power for periods of 3-30 days [32]. During the second ice disaster frozen rain and snow lasted for more than three weeks, caused a large-scale outage in several provinces of China, and led to an economic loss of US$7.9 billion [26], [33], [34]. These ice storms caused mainly mechanical damage, but fast restoration of service was affected by lack of reliability at critical substations.
Since BSs are known to be efficient and easy to use on already installed insulators, this option seems to be a very interesting solution to this problem [2], [15], [20]. Using BSs is a mitigation option generally in demand for heavy icing conditions. Hence, a review of competing mitigation options under heavy icing conditions is given in the next section.

2.2 Mitigation options under heavy icing conditions

Over the past decades, a large number of studies have been carried out by many research institutions and experts. This includes icing test methods, icing flashover performance, mitigation options. Several parameters and factors affect the dielectric strength of ice-covered insulators, such as the type and density of ice, length of icicles, freezing water conductivity, altitude, profile and type of insulator, and the position and length of ice-free zones (often called air gaps) [1], [21], [23], [24], [28], [29].

The presence of ice on insulators may initiate corona discharge, partial arcs resulting sometimes in flashover, if the required conditions are present. The flashover phenomenon is caused mainly by the presence of a highly conductive water film on the surface of the ice and the reduction in insulator leakage distance caused by ice bridging [35]–[37].

Based on field observations, EHV post station insulators are more susceptible to flashover than line insulators. This is mainly due to their higher electric field strength, smaller shed spacing, larger diameter, and their parallel application concentrated in small areas [1]. One of the main reasons causing significant decrease in flashover voltage of these insulators is the ice-bridging of their shed spacings. It has been shown that some approaches such as using BSs, creepage extenders, use of profiles with greater shed-to-shed
distance, and semiconducting glaze insulators can reduce the probability of the bridging of the insulator sheds by icicles [15], [38], [39].

Reliability of insulators in icing conditions can be improved through several methods. The effectiveness of the solutions for improving their reliability and electrical performance varies in different ice severity. A rough distinction in icing severity for electrical performance includes very light (<1 mm), light (1-6 mm), moderate (6-10 mm) and heavy (>10-mm) ice accretion where the numbers represent radial ice accretion measured on a rotating reference cylinder. This classification is based on full bridging of station post insulators with uniform shed profile at 6 mm and full bridging of cap-and-pin insulator strings at 10 mm [2].

Insulators with close shed-to-shed spacing are more easily bridged by icicles. Once they are fully bridged, their electrical flashover performance will be compromised. For the heavy icing regime, countermeasures such as BSs and semiconducting glaze play roles that are somewhat different from the functions they perform in contaminated conditions [2]. The main mitigation options for heavy icing include:

- the increase in dry arc distance,
- semiconducting glaze,
- polymer insulators,
- the increase in leakage distance with the same dry arc distance,
- monitoring and washing,
- silicone coatings,
- accessories (e.g. corona rings, creepage extenders, and booster sheds).
One practical limit on increases in the dry arc distance of station post insulators relates to their cantilever strength requirements. A recommendation to increase dry arc distance by 25% may lead to an increase in post diameter by 33%, which, in turn, leads to additional ice accretion per unit length and a reduced leakage resistance [2]. This negative effect of increased diameter for the same strength requirements can negate the positive effect of additional dry arc distance.

The improved performance of semiconducting glaze insulators in heavy icing conditions is mainly a result of the improved voltage grading along the insulator surface. Moreover, in both laboratory tests and field exposure, these insulators develop larger ice-free zones than conventional glaze posts and develop these zones earlier in the melting phase [38], [40]. The larger the ice-free zones, the higher flashover strength.

Polymer insulators with typical 100 mm shed diameter perform better than IEEE standard disk insulators with 254 mm diameter. This improvement is essentially due to the effect of diameter, rather than any properties of the material [2]. Investigations on the effect of diameter on the electrical performance, supported by tests and modeling [41], also confirm that the flashover strength increases slowly with a reduction of insulator diameter.

One of the most important facets of electrical performance in icing conditions is associated with the partial or complete bridging of insulator leakage distance by icicle growth from shed to shed. The leakage distance of an insulator can be reduced nearly to its dry arcing distance in the worst conditions. More precisely, the effective leakage distance can be reduced to the dry arcing distance under fully bridged conditions. This extreme reduction in leakage distance (by a factor of about 2-3) can result in severe flashovers at
numerous affected utilities [8], [21]. For 15-mm ice accumulation, uniform and alternating profiles gave identical performance per meter of post length [42]. In other words, the performances of the various profiles (standard uniform profile, the alternating profiles, etc.) are indistinguishable in the heavy icing condition.

The possibility of using leakage current activity as a predictor of the probability of icing flashover was studied in [43]. Based on the results, icing rate measurement and the severity of ice accumulation can be achieved by leakage current analysis, e.g. the time evolution of the third and fifth harmonic, the phase angle difference between leakage current and applied voltage. In the continuation of this study, artificial neural network (ANN) models were used to analyze leakage current evolution [44]. The obtained results verify that it is possible to use the proposed ANN model as part of a monitoring system for post insulators during icing events for early warning of potential flashover hazards.

Silicone rubbers have been used as housing material for transmission, distribution, and post insulators [45]. The Room Temperature Vulcanizing (RTV) type is cured in room temperature. The use of RTV silicone coating is generally not recommended on post insulators with shallow shed depth, especially in areas of heavy accumulation of ice, which would lead to full bridging. The loss of electrical strength is partly attributed to the longer duration of ice retention on the rougher RTV surface [2]. However, micro/nano fillers can be added to silicone rubber to improve its properties, such as the surface hydrophobicity, electrical conductivity, relative permittivity and thermal conductivity [46]. Therefore, the final product, e.g. semiconducting RTV coatings in [47], can provide promising results under icing conditions.
Corona rings are metal toroids; their main function is to prevent corona discharges by providing more uniform electric field distributions. They can be applied to any type of high voltage equipment, but they are often associated with nonceramic insulators to ensure a long-term reliability [2], [45]. "Grading rings" is generally used as a synonym for "corona rings", and their main function is to reduce the potential gradient along an insulator, thereby preventing premature electrical breakdown [2], [45]. Since grading rings produce a more uniform electric field, they affect the ionization of bipolar molecules of water and icicle growth. Hence, the result is more uniform shapes of ice accumulations (Figure 2.1) [48]. This phenomenon can especially be observed in the vicinity of the HV electrode, where the electric field is high. Even though uniform icing indicates satisfactory field grading, they can cause unsatisfactory electrical performance under icing conditions, because ice bridges the sheds of the insulator more quickly.

Figure 2.1- Ice accretion on 500-kV polymer insulator with grading ring [48]

A modified grading ring is proposed in [49] that also improves electrical performance under heavy icing conditions (Figure 2.2). It is a standard grading ring that
includes a fine metallic mesh. The metallic mesh must be fine enough to prevent passing water drops through it under icing condition. This modification not only causes a better potential grading but it also creates a large air gap similar to the function of a BS.

Creepage extenders are applied to insulators to increase the creepage (or leakage) distance and shed diameter [2], [45]. They are bonded with an adhesive to the outside edge of the shed. The correct inner diameter of creepage extender must be selected to fit over the sheds. Figure 2.3 shows a common style of slip-on creepage extender with open small gaps. These open gaps face opposite directions in an alternating pattern. Hence, flashover arcs found their way through the open gaps rather than over the edges.
2.3 Booster sheds under icing conditions

In a Cooperative Research and Development (CRD) collaboration between a utility, manufacturers and UQAC/CIGELE, the improvement in flashover performance of single station post insulators with 655-mm diameter booster sheds was evaluated [18]–[20]. The tests were performed using insulators with a total dry arc distance of 2.7 m and a stress of $105\,\text{kV}_{\text{rms}}$ per meter of dry arc distance. The post station insulators and stress levels correspond to those used on 735-kV substations in Quebec, Canada. The ice was formed with an applied water conductivity of 30$\mu\text{S/cm}$ and an ice thickness of 15 or 30 mm on a rotating cylinder. The ice accretion, hardening, and melting sequences followed the IEEE Task Force recommendations defined in [50]. With a 30-mm ice accretion, as the number of BSs increased from four to six, the maximum withstand voltage increased by about 15kV per BS. When the BS positions were arranged to produce the largest air gaps and to prevent ice bridging, the best results for both icing thicknesses were obtained.

A multi-arc model for predicting flashover voltage of ice-covered insulators was introduced in [16]. This mathematical model is based on a previous model developed at
CIGELE [51] using Obenaus/Rizk model [52]. The number of air gaps depends mainly on the insulation profiles, voltage stress and insulator length. Overall results for the various insulators and configurations predicted with the model and experimentally determined are presented in Table 2.1 [16]. Two types of arc were defined— the arcs with one root and others with two roots on the ice surface. Their numbers are \( N' \) and \( N'' \), respectively, and the total number of arcs is \( N = N' + N'' \). Good agreement was achieved between the calculated and experimental results for the insulators without BSs. This result suggests that the multi-arc model can be applied to different types of insulators covered with ice, provided that the number and type of local arcs are properly considered.

<table>
<thead>
<tr>
<th>Insulator type and configuration</th>
<th>Arcing distance (cm)</th>
<th>No. of arcs</th>
<th>Minimum flashover voltage (kV)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE standard</td>
<td>268</td>
<td>2</td>
<td>300</td>
<td>285</td>
</tr>
<tr>
<td>Post insulator</td>
<td>270</td>
<td>3</td>
<td>285</td>
<td>274</td>
</tr>
<tr>
<td>Post insulator with booster sheds</td>
<td>307</td>
<td>2 1</td>
<td>330</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 2</td>
<td></td>
<td>360</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 4</td>
<td></td>
<td>432</td>
</tr>
</tbody>
</table>

For the post insulator with BSs, the best results were obtained in the case of the 3-arc model (\( N' = 2 \) and \( N'' = 1 \)). This suggests that for the three tested types and configurations of insulator strings having an arcing distance longer than 2 m, normally there were three arcs: one at the top, one at the middle part and one at the bottom of insulator string, when the total arc length reaches its critical length.
In this investigation, adding six BSs to the two units of standard post insulators resulted in an increase in dry arcing distance from 2.70 m to 3.07 m, i.e., a 13.7 % increase. Correspondingly, the critical flashover voltage increased 15.7 % for the experimental results; it also corresponded to the critical flashover predictions using the 3-arc model. Then it was concluded that the increase in the critical flashover voltage of post insulators with BSs is mainly due to the increase in the dry arcing distance.

The multi-model can be used to predict the critical flashover voltage of ice-covered insulators provided that the number and type of local arcs are considered properly. On the other hand, in the case of 6 BSs, it seems hard to judge how many arcs formed at the critical point since the flashover process occurs very quickly. Thus, the multi-arc model is not suitable to attain a clear agreement between calculated and experimental results for the insulators with many BSs.

In [17] a method to determine the proper values only for two geometry parameters (i.e. positions and diameters) of three BSs along with one unit of a 735 kV standard ice-covered post insulator was presented. Figure 2.4 shows the considered BS set-up. "L" and "x" are considered as the length of the icicles and lengths of the air gaps, respectively. "e" is the ice thickness and "R_e" is clarified in Figure 2.4.

To calculate the diameter of BSs, \( D_{BS} \), based on Figure 2.4 the following equation can be used:

\[
D_{BS} \approx \frac{2R_e}{\cos 24.5^\circ}.
\]  (1.1)
Then, to ease the evaluation of the proposed method, the final diameters are summarized in Table 2.2. Position (cm) means the distances between two consecutive BSs.

<table>
<thead>
<tr>
<th>BS No.</th>
<th>Diameter (cm)</th>
<th>Position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.34</td>
<td>44.9</td>
</tr>
<tr>
<td>2</td>
<td>68.35</td>
<td>30.8</td>
</tr>
<tr>
<td>3</td>
<td>61.98</td>
<td>28.2</td>
</tr>
</tbody>
</table>

As it is clear from Table 2.2, the calculated diameter for the first BS is much bigger than what is commercially available. Moreover, the calculated positions are not suitable because they would lead to ice-bridging compared to the experimental test results in [2], [18]–[20]. The main problems of the proposed method are:
• using the simulation results of one unit of post insulator unequipped with BSs in the calculations,
• improper approximation of the length of the icicles along BSs,
• imprecise definitions regarding the radius of BS, diameter of insulator, etc.
• inaccurate estimation of the breakdown voltage as a function of the lengths of the air gaps.

Hence, the cited dimensioning method has been upgraded during this PhD project, and good agreements with the previous BS tests in [2] have been achieved. The upgraded model is presented in Chapter 3.

The flashover performance of 500kV porcelain post insulators with and without BSs was investigated in [53]. Test results showed the installation of BSs decelerated icicle growth, ice-bridging, and all of this led to a significant increase of 58% in the flashover voltage of the post insulator. Discharge path was mainly along the icicle and air gaps.

In [15] 0.6-m sections of a standard porcelain station post with 0, 1 or 2 BSs were tested. The maximum withstand voltage stress was reported to be 102 kV/m_{dry arc} untreated, 113 kV/m_{dry arc} with one and 147 kV/m_{dry arc} with two BSs in the icing regime tests.

In [14] strength improvements of 20% at 110 kV and 40% at 400 kV are stated. In addition, the tests in [39] show that the flashover voltage can increase about 50% for the post insulator after adding BSs. The differences in the reported improvements may be related to the test conditions and dimensions of the BSs and the insulators.
2.2.1 Problems of using BSs

One of the major problems of the application of BSs is the pollution issue. BSs can prevent natural washing of some parts of the insulators, and they may lead to glaze damage [1], [2], [21]. For example, under heavy icing conditions, there would be heavy ice on the top surfaces of BSs and none beneath. This situation could cause sufficient electrical stress so that the BSs would either puncture or confine flashover arcs between the neck of the BS and the insulator beneath, as shown in Figure 2.5 and Figure 2.6 [2]. This kind of damage is reported in the laboratory flashover tests, but should not occur in the field if there is no flashover under service voltage. However, if for any reason insulators face a flashover, the BSs should be checked for puncture and the insulators replaced if there is extensive damage beneath [2].

Figure 2.5- Typical puncture damage to BS after heavy, conductive ice test [2]

Figure 2.6- Insulator glaze damage under bottom surface of failed BS [2]
For good long-term performance more frequent cleaning or washing of insulators is required if they use BSs. Another proposed solution is to install the BSs during winter phase and remove them after winter [1]; however, that is an expensive approach. Moreover, some designs of BS have hemispherical "nubs" that set a small space between BSs and the insulator surface to allow for some natural rain washing (Figure 2.7).

![Figure 2.7- Typical booster shed applied to a post insulator (CIGELE Lab.)](image)

2.4 Air gap effects on iced-covered insulators

Since using BSs can cause the formation of the long air gaps on a post insulator, it is necessary to study the role of these air gaps on the electrical performance of the ice-covered insulators. Several Finite Element and Boundary Element Methods (FEM and BEM) have been used for the investigation of ice-covered insulators. A coordination between simulations and experimental tests is often necessary [27], [40], [54]–[61].
Little research has been done on the influence of the number and position of air
gaps on the electrical performance of insulators. A few papers have dealt with the influence
of air gaps on the potential and electric field distribution along an EHV ceramic post
insulator. The experimental and numerical results of voltage distributions of 1, 2, and 3 air
gaps along one unit of an ice-covered post insulator show that [35-36]:

- An ice accretion with two air gaps seems to be more dangerous than one with three
  air gaps.
- During the melting period, around 96% of the applied voltage distributes along the
  air gaps, regardless of the number, position, and the length of the air gaps.
- It is the total length of air gaps, rather than their number, which is really significant
  in the process of partial arc formation.

All of the mentioned results were obtained during ice melting conditions, which are
the most dangerous conditions for ice-covered insulators. These notes are used to propose
an improved hypothesis of the effects of BSs under heavy icing conditions in Chapter 4.
They were also used to conclude the minimum required number of BSs for installation on
post insulator in order to apply the Taguchi method in the design approach of Chapter 5.

In [61] the influence of the number and position of air gaps on the 50% AC
withstand voltage, \( V_{50} \), of 5 IEEE standard insulator units covered with ice was
experimentally investigated and numerically simulated. The results confirmed again that
the number and position of air gaps have significant effects on the flashover voltage of ice-
covered insulators. The results also showed that the presence of a partial arc along the air
gap close to the high voltage (HV) electrode leads to a redistribution of the voltage along the ice-covered insulator.

It may be concluded that the effects of the air gaps on post and line insulators under heavy icing conditions are principally similar. Considering this similarity, the results of this PhD research on ice-covered post insulators with BSs could be extended for the applications on line insulators as well.

2.5 Design and optimization methods

Since the objective of this PhD project is the design and optimization of an expensive power system component (i.e. BS), a survey of classical and modern optimization and design methods is necessary.

In a design process, a trial design is analyzed to determine whether it satisfies prescribed requirements. If it is satisfactory, the design process is terminated. In the optimization process, the trial design is analyzed to determine if it is the optimum. Depending on the specifications, “optimum” can have different connotations for different systems. In general, it implies cost-effective, efficient, reliable, and durable systems. Based on the engineering optimization and design books [62], [63], for most engineering projects, the formulation of a problem consists of 5 steps:

- Step 1: Project/problem statement
- Step 2: Data and information collection
- Step 3: Identification/definition of design variables
• Step 4: Identification of a criterion to be optimized

• Step 5: Identification of constraints

However, the order of the steps can be changed. It is generally accepted that the formulation of a problem takes roughly 50 percent of the total effort needed to solve it. Therefore, it is critical to follow well-defined procedures for formulating design optimization problems. However, the design and/or optimization of a system is a creative process that can be quite complex.

Many analytical formulations of optimization and various algorithmic issues arise in the application of different methods in power electric equipment. In fact, electric power equipment optimization problems are difficult to solve because power equipment can be large and complex. Moreover, they are exposed by environment stresses and are influenced by many unexpected events. Therefore, it is necessary to employ most efficient optimization methods to take full advantage in simplifying the formulation and implementing the problem.

In [64], [65] the optimization of locations and dimensions of a corona ring is presented for EHV transmission line composite insulators. In order to set the optimal goal, the finite element method is employed to calculate the electrical field distribution along the composite insulator with corona ring that has various dimensions and locations. Moreover, the neural network model is built to map the location as well as the dimensions of the corona ring and the optimal goal. In these works the optimization is based on finding the maximum field along the insulator surface, such that this maximum field is well below the corona inception level. In design of corona rings, the design parameters are usually the ring
diameter, the diameter of the ring tube, and the position of the ring in its vertical plane. Furthermore, the main criterion of the design is that the maximum field must not exceed the corona inception level.

Potential control inside a switch device using FEM and stochastic optimization algorithm is explained in [66], [67]. It describes the impact of selected insulation elements and the surrounding material, on the magnitude and distribution of electric potential in a switch device. The procedure is based on finite element method numerical analysis and stochastic optimization algorithm of differential evolution (DE). The optimal selection of mutually independent insulation materials has an impact on the control of potential and, consequently, on dielectric strengths, both inside the bushing and in other switchgear elements. The entire modeling procedure also includes optimization of the bushing's geometrical shape.

Optimization for high voltage composite insulators using experimental design theory is developed in [68]. This paper introduces a method for optimizing parameters of HV composite insulators. The optimal values of design parameters are determined by multivariable optimization procedure using theory of Design of Experiments (DOE). For repetitive calculation of the electric field strength the finite element method is used with domain decomposition. This method gives fast working software with accurate results to examine a very complex geometry without high computational effort.

2D and 3D simulations were used in [69] to analyze two stress grading options for 115 kV non-ceramic suspension insulators. The optimization criterion was to reduce the maximum electric field at the surface of the insulator. FEM was used to obtain the electric
field distributions, and different functions of the MATLAB optimization toolbox were used to optimize the design parameters.

In [70] real coded genetic algorithm with simulated binary crossover were used for contour optimization of suspension insulators. The optimization criterion was to reach a desired uniform and minimal tangential field to increase the onset voltage of surface flashover. More precisely, the criterion was to minimize the tangential electric field and make the tangential electric field uniform, respecting the design constraints.

Taguchi method is a generally accepted methodology for modern design of experiments [71]–[73]. It can be used for virtual experiments (e.g. FEM simulations) as well [74]. The problem of using global optimization techniques (e.g. genetic algorithm and particle swarm optimization methods) is that the parameters of the algorithm are hard to determine. On the other hand, the Taguchi method uses orthogonal arrays to survey a large number of variables with a small number of experiments. So, it is used for optimal designs. An optimal design requires a smaller number of experiments to estimate the parameters with the same precision as a non-optimal design. The results are valid over the whole experimental region covered by the control factors and their settings. Hence, this method reduces costs. Moreover, after the problem formulation process in this PhD project, Taguchi method can provide effectively the required optimality and post-optimality results. Considering these advantages, Taguchi method is used in this project.
2.6 Conclusion

The reviewed literature mainly includes booster shed, ice-covered insulators and air gap effects, and optimization and design methods. It was observed that BSs improve the electrical performance of insulators under icing conditions. The reason for this improvement was attributed to the increase in dry arcing distance and creation of the air gaps. Then, the effects of these air gaps on ice-covered insulators were reviewed briefly, and three main points were emphasized. Finally, the five steps of the classical optimization approach as well as the modern techniques and the selected Taguchi method were introduced. Actually, to propose some feasible solutions to this challenging problem, not only a sufficient background about these three issues is required but also the interactions of all of them should be considered. Figure 2.8 illustrates this concept.

Figure 2.8- The main parts of the literature review and their interactions
CHAPTER 3

UPGRADED MODEL OF BS DIMENSIONING
CHAPTER 3
UPGRADED MODEL OF BS DIMENSIONING

3.1 Introduction

To advance the previous studies on BSs, this chapter presents an innovative approach of BS dimensioning under heavy ice conditions based on previous laboratory results in [2] and FEM 2D axisymmetric simulations by Comsol Multiphysics™. In fact, it is the upgraded model and approach of [17] which was reviewed and critiqued in Chapter 2. It deals with the two BS parameters (position and diameter) in the installation of 4, 5, and 6 BSs along 2 units of an ice-covered EHV ceramic post station insulator.

3.2 Description and observations of previous BS tests

Two units (bottom and middle) of a three-unit station post insulator were tested with a stress of 105 kV per meter of dry arcing distance which is equivalent to the stress on 735 kV substations in Quebec, Canada (Figure 3.1) [2], [18]–[20]. Heavy ice tests were carried out with an applied water conductivity of 30 μS/cm and ice accumulation of 30-mm on a rotating cylinder. The ice accumulation duration was 140 min, and the applied voltage was set at 285 kV. Each section has a 3500-mm leakage distance and a dry arcing distance of 1390 mm. The BSs that were used have an external diameter of 655 mm. Figure 3.1 shows
4-, 5- and 6-BS configuration tests after the heavy ice accretion in CIGELE climate room [2]. The ice accretion, hardening, and melting sequences followed the IEEE Task Force recommendations defined in [50]. The results of maximum withstand voltages ($V_{ws}$) and minimum flashover voltages ($V_{MF}$) are shown in Figure 3.1.

![Image of insulators with ice accretion](image.png)

Figure 3.1- Test results for standard post insulators in heavy icing conditions (30-mm ice accretion on rotating cylinder)

with a) 4 BSs, b) 5 BSs and c) 6 BSs [2], [18]–[20]

BSs installed to a post insulator must have a satisfactory electrical performance under the most dangerous stresses. Based on the literature [35]–[37], a wet-grown ice is more dangerous than a dry-grown one. Thus, the ice formed under wet regime is selected to analyze the electrical performance of the insulator. A wet-grown ice is characterized by the presence of a water film with relatively low resistivity at the ice surface.
The test was repeated 5-6 times for the same configuration and test conditions [2], [50]. In the present study, the individual measured values of the corresponding 5-6 air gaps and icicle lengths of each BS from previous experimental results [2], [18]–[20] were averaged and summarized for those test conditions in Table 3.1 and Table 3.2.

Air gaps play an important role in the flashover process as they are where partial arcs appear and their formation directly depends on the electric field distribution [61]. The use of BSs allows the creation of "controlled" artificial air gaps along the ice-covered insulator.

Table 3.1- The average lengths of the air gaps (cm) during the BS tests

<table>
<thead>
<tr>
<th>BS No.</th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.2</td>
<td>23.2</td>
<td>21.8</td>
</tr>
<tr>
<td>2</td>
<td>16.2</td>
<td>16.2</td>
<td>13.8</td>
</tr>
<tr>
<td>3</td>
<td>9.6</td>
<td>9</td>
<td>8.4</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>9.6</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>11</td>
<td>2.6</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>9.2</td>
</tr>
<tr>
<td>Total</td>
<td>60.0</td>
<td>69.0</td>
<td>62.8</td>
</tr>
</tbody>
</table>

The length of icicles mainly depends on the accumulation time and the electrical field strength at the area of icicle growth. The average length of the icicles, \( L \), between insulator sheds as a function of the accretion time in the space of insulator sheds is [75]:

\[
L_t(cm) = 0.242t(min) \tag{3.1}
\]

Using (3.1) as a primarily approximation for the icicle length on BSs \((t=140 \text{ min})\) results in:

\[
L_0(cm) = 33.9 \text{ cm} \tag{3.2}
\]
Normalization of the lengths of the icicles based on \( L_0 \) (Normal), can also give us a good understanding of the effect of electric field on the icicle growth along BSs from top to bottom (Table 3.2). There is some tendency for longer icicle length on the BSs that are in regions of lower electrical stress, towards the bottom of the insulator.

<table>
<thead>
<tr>
<th>BS No.</th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( L(\text{cm}) )</td>
<td>( L(\text{PN}) )</td>
<td>( L(\text{cm}) )</td>
<td>( L(\text{PN}) )</td>
<td>( L(\text{cm}) )</td>
<td>( L(\text{PN}) )</td>
</tr>
<tr>
<td>1</td>
<td>17.4</td>
<td>51.3</td>
<td>17.4</td>
<td>51.3</td>
<td>19.8</td>
<td>58.4</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>59.0</td>
<td>20</td>
<td>59.0</td>
<td>24</td>
<td>70.8</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>88.5</td>
<td>32.2</td>
<td>95.0</td>
<td>29.8</td>
<td>87.9</td>
</tr>
<tr>
<td>4</td>
<td>37</td>
<td>109.1</td>
<td>29.6</td>
<td>87.3</td>
<td>33</td>
<td>97.3</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>26.8</td>
<td>79.1</td>
<td>37</td>
<td>109.1</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>44</td>
<td>129.8</td>
</tr>
<tr>
<td>Total</td>
<td>104.4</td>
<td>308</td>
<td>126</td>
<td>371.7</td>
<td>187.6</td>
<td>553.4</td>
</tr>
<tr>
<td>Average per BS</td>
<td>26.1</td>
<td>77.0</td>
<td>25.2</td>
<td>74.3</td>
<td>31.3</td>
<td>92.2</td>
</tr>
</tbody>
</table>

### Table 3.2 - The average lengths of the icicles during the BS tests (per cm and per-normal (PN) as percent)

#### 3.3 Numerical simulations

The simulations were done using the FEM commercial software COMSOL Multiphysics™. With this software surface conductivity and open boundary can be easily implemented. Moreover, to do the comparative calculations faster, 2D axisymmetric modeling was used instead of 3D modeling (Figure 3.2). The potential and the electric field distributions were calculated on the vertical and radial plane (\( zr \)-plane). The accuracy of this approach was verified in the previous studies [27], [76].
Figure 3.2- Equipotential line distributions of the post insulator with BSs under heavy wet-grown ice condition: a) 4 BSs b) 5 BSs c) 6 BSs in 2D axisymmetric view

The simulation parameters are summarized in Table 3.3.

<table>
<thead>
<tr>
<th>Table 3.3.- Simulation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porcelain</td>
</tr>
<tr>
<td>Relative permittivity</td>
</tr>
<tr>
<td>Conductivity ( \sigma ) (( \mu )S/cm) at 20°C</td>
</tr>
<tr>
<td>Thickness (mm)</td>
</tr>
</tbody>
</table>

Next, Table 3.4 demonstrates the comparison of the voltage drops (AV (%)) for 4-, 5- and 6-BS tests. The voltage drops were computed by using reference lines located along the air gaps. More explanations about the modeling method and potential field distributions of all of the BS tests can be found in our previous papers i.e. [77], [78].
Table 3.4. Comparison of the calculated voltage drops (ΔV (%)) for 4, 5 and 6 BS tests

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.5</td>
<td>51.2</td>
<td>50.3</td>
</tr>
<tr>
<td>2</td>
<td>23.1</td>
<td>20.0</td>
<td>20.8</td>
</tr>
<tr>
<td>3</td>
<td>9.8</td>
<td>7.9</td>
<td>6.9</td>
</tr>
<tr>
<td>4</td>
<td>14.0</td>
<td>8.1</td>
<td>6.7</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>12.2</td>
<td>3.1</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>11.8</td>
</tr>
<tr>
<td>Total</td>
<td>99.4</td>
<td>99.4</td>
<td>99.4</td>
</tr>
</tbody>
</table>

3.4 Procedure for BS dimensioning

Figure 3.3 illustrates the geometric model for dimensioning two parameters of BSs (i.e. diameter and position). Based on the experimental test results, it is assumed that the tips of hanging icicles and ice surfaces are not contacted.

In Figure 3.3 and the coming equations and tables:

- **D_{BSi} (cm)**: is the diameter of BS_i.
- **R_{BSi} (cm)**: is the radius of BS_i.
- **R_{ho,i} (cm)**: is the horizontal distance between the center axis of the insulator and the tip of the installed BS_i.
- **BS_{ij}**: signifies the zone between BS_i and BS_j.
- **e_{inj} (cm)**: is the thickness of ice on the insulator surface in BS_{ij}.
- **e_{bsj} (cm)**: is the thickness of ice accretion on the upper surface of BS_j (e_{bsj} ≈ 3cm).
- **d_{ext-i} (cm)**: is the average exterior diameter of the STD insulator shed under BS_i.
\( \beta \, (^\circ) \): is the inclination angle of \( BS_i \) (in CIGELE Lab: \( \beta = 24.5^\circ \), upper shed angle of the insulator shed).

\( \theta \, (^\circ) \): is the incidence angle of precipitation (\( 0 \leq \theta \), and in CIGELE Lab: \( \theta = 53\pm5^\circ \)).

\( \alpha \, (^\circ) \): is the slope angle of the icicles (\( \alpha \approx 8^\circ \), except \( \alpha_{BS_i} = -15^\circ \)).

\( L_i \, (cm) \): is the maximum length of the icicles on \( BS_i \) obtained from experimental results.

\( W_i \, (cm) \): is the total insulator length protected from precipitation by \( BS_i \).

\( P_i \, (cm) \): is the distance between the extremities of two \( BS \)s that determine the position (\( P \)) of the \( BS \)s.
\( x_i \) (cm): is the minimum required length of each air gap to prevent electrical breakdown (between the tip of the icicles and the opposite surface of ice).

The AC breakdown voltage in the air gap of \( BS_{ij} \) (\( V_{b-i} \)) as a function of \( x_i \) (cm) can be stated as (3.3) or (3.4) [2], [60], [78]–[81]:

\[
V_{b_i}(kV_{rms}) = ax_i + b \tag{3.3}
\]

\[
V_{b_i}(kV_{rms}) = cln(x_i) + d \tag{3.4}
\]

Where,

"a", "b", "c", and "d": are real constant values.

If we obtain the values of \( V_{b-i} \), "a", and "b", or \( V_{w-i} \), "c", and "d", then we can calculate \( x_i \) as (3.5) or (3.6):

\[
x_i = (V_{b_i} - b)/a \tag{3.5}
\]

\[
x_i = e^{(V_{b_i} - d)/c} \tag{3.6}
\]

According to the geometric model (Figure 3.3), the minimum required diameter of BS (\( D_{BS_i,\text{min}} \)) to prevent electrical breakdown is:

\[
D_{BS_i,\text{min}}(cm) = 2(R_{ho,i})/\cos \beta \tag{3.7}
\]

\[
D_{BS_i,\text{min}}(cm) = 2\left(\frac{d_{ext,i}}{2} + e_{ini,i} + x_i + L_i \sin \alpha\right)/\cos \beta \tag{3.8}
\]

Moreover, the minimum required distance between the tips of two consecutive BSs (\( P_{i,\text{min}} \)) is (Figure 3.3):

\[
P_{i,\text{min}}(cm) = L_i \cos \alpha + e_{bsj} + x_i \tag{3.9}
\]

To calculate \( D_{bs-i,\text{min}} \) and \( P_{i,\text{min}} \), all of the parameters are known in (3.8) and (3.9) except \( x_i \). In other words, the main challenge in this approach is the estimation of \( x_i \). Thus,
in this method, the estimation of the breakdown voltage equations in the BS air gaps is the key required point to calculate the proper diameters and positions of BSs. In the next section the estimation approaches are explained.

3.5 Estimation of the breakdown voltage equations in the BS air gaps

3.5.1 First approach

Air gaps formed during the ice accumulation in a wet regime can be assimilated to rod-plane configuration. The rod and the plane respectively represent the icicle on the booster shed and the ice surface on the upper surface of the next BS (Figure 3.4).

The high value of the freezing water conductivity ($\sigma=340\mu$S/cm) of the icicles used in the previous icicle-plane experimental tests were based on field experience [82]. In fact, during the freezing process impurities are rejected from the solid part toward the liquid portion of droplets [83]. Therefore, they increase the surface conductivity of ice and enable it to reach values as high as ten times those of the freezing water conductivity in the BS tests ($\sigma = 30\mu$S/cm). This is the reason that $\sigma = 340\mu$S/cm corresponds to the BS test conditions. In reality freezing water conductivity has a wide range of natural values but levels of 30 $\mu$S/cm are more typical in Quebec. Values in this high level are influenced by road salt [84].

By curve fitting of the obtained results in [80], we reach the AC breakdown voltage $V_b$ as a function of minimal air gap length $x$ (between the tip of icicle and the surface) for the corresponding temperature (temp) and $\sigma = 340\mu$S/cm and $1\text{ cm} \leq x \leq 4\text{ cm}$:
Moreover, the BS tests were performed at temperature (temp) of -1°C. Thus, using a linear estimation between (3.10) and (3.11), leads in:

\[ V_b(kV_{rms}) = 6.55x(cm) + 9 \quad \text{temp} = -1°C \quad (3.12) \]

The presence of a water film on the tip of icicle can result in around 27% reduction in the breakdown voltage [75]. Thus, multiplying (3.12) by 73% results in the final required breakdown voltage (\(\sigma=340\mu S/cm\) and \(1cm \leq x \leq 4\ cm\)):

\[ V_b(kV_{rms}) = 4.78x(cm) + 6.57 \quad \text{(temp}=-1°C \text{ with water film effect}) \quad (3.13) \]

Figure 3.4- Schematic diagrams: a) the icicle on BS b) the icicle-plane configuration c) the icicle dimensions
3.5.2 Second approach

The breakdown voltage \( V_b \) obtained from (3.6) can be compared with the values of the voltage drop at the air gap no. \( i \) (\( \Delta V_{ag-i} \)) in two conditions. Firstly, when the applied voltage equals the flashover voltage \( V_{MF} \), and secondly, when it equals the withstand voltage \( V_{WS} \). In short, the following inequality must be satisfied:

\[
\Delta V_{ag-i,WS} < V_{b,agi} < \Delta V_{ag-i,WF} \tag{3.14}
\]

Where

\( \Delta V_{ag-i,WS} \): is the voltage drop at the air gap no. \( i \) (\( \Delta V_{ag} \)) when the applied voltage equals the flashover voltage.

\( \Delta V_{ag-i,WF} \): is the voltage drop at the air gap no. \( i \) (\( \Delta V_{ag} \)) when the applied voltage equals the withstand voltage.

\( V_{b,agi} \): is the breakdown voltage of the air gap no. \( i \).

Actually, the objective of this section is the estimation of the breakdown voltage equations in the BS air gaps considering their average air gap lengths and their variation \( (\Delta L_{ag} \text{ (cm)} \neq 0) \). To this end, it is sufficient to focus only on the first air gap (close to HV electrode), because:

1) It was shown that following the addition of 4, 5 or 6 BSs, the majority of the applied voltage (more than 50%) was dropped along the air gap closest to the HV electrode (Table 3.5).

2) In addition, based on the previous BS tests, partial arcs usually appear first in the first air gap closest to HV electrode.
In other words, the air gap no. 1 has the most determinant role in the electrical performance of the ice-covered insulator.

Table 3.5 shows the voltage drops along the first air gaps (obtained from simulations) for 4-, 5- & 6-BS tests when the applied voltage is equal to $V_{MF}$ or $V_{WS}$ during melting period (30-mm ice accretion on rotating cylinder). In addition, $L_{ag1-ave}$ is the average length of the air gap no. 1 during the previous BS tests.

<table>
<thead>
<tr>
<th></th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{WS}$</td>
<td>285</td>
<td>300</td>
<td>315</td>
</tr>
<tr>
<td>$V_{MF}$</td>
<td>300</td>
<td>315</td>
<td>330</td>
</tr>
<tr>
<td>$\Delta V_{ag1-WV}$</td>
<td>149.62</td>
<td>153.6</td>
<td>158.44</td>
</tr>
<tr>
<td>$\Delta V_{ag1-MF}$</td>
<td>157.50</td>
<td>161.28</td>
<td>165.99</td>
</tr>
<tr>
<td>$\Delta V_{ag1-MF} - \Delta V_{ag1-WV}$</td>
<td>7.88</td>
<td>7.68</td>
<td>7.55</td>
</tr>
<tr>
<td>$L_{ag1-ave}$(cm)</td>
<td>23.2</td>
<td>23.2</td>
<td>21.8</td>
</tr>
</tbody>
</table>

The breakdown voltage equations for icicle-plane configurations in [2], [60], [78], [80], [81] suggest that the typical values for $a$ and $b$ can be in the ranges below:

$$3.5 < a < 8 \text{ and } 6 < b < 13$$  \hspace{1cm} (3.15)

To begin, consider 6-BS tests.

**Note (1): Inequality (3.14) must not only be satisfied for the average length of the air gap 1 ($L_{ag1-ave}$) but it must also be satisfied for minimum and maximum length of the air gap no. 1 ($L_{ag1-min}\leq x \leq L_{ag1-max}$) measured during the BS tests.**

So the following relations can be obtained:
\[ V_b(x = \text{Lagl}_{\text{min}}) = a \times \text{Lagl}_{\text{min}} + b \] (3.16)

\[ V_b(x = \text{Lagl}_{\text{max}}) = a \times \text{Lagl}_{\text{max}} + b \] (3.17)

Suppose:
\[ \text{Lagl}_{\text{max}} - \text{Lagl}_{\text{min}} = \Delta \text{Lagl} \] (3.18)

\[ V_b(x = \text{Lagl}_{\text{min}}) = V_{b1} \] (3.19)

\[ V_b(x = \text{Lagl}_{\text{max}}) = V_{b2} \] (3.20)

From (3.16)-(3.20), we obtain:
\[ V_{b2} - V_{b1} = a \times \Delta \text{Lagl} \] (3.21)

Then, from (3.14) and note (1), we calculate:
\[ V_{b2} - V_{b1} < \Delta V_{\text{agl MF}} - \Delta V_{\text{agl WV}} \] (3.22)

So, from (3.21) and (3.22), we compute:
\[ a < (\Delta V_{\text{agl MF}} - \Delta V_{\text{agl WV}}) / \Delta \text{Lagl} \] (3.23)

Furthermore, the following relations can be written by using (3.14) and Table 3.5:

\[
\begin{align*}
149.62 & < 23.2a + b < 157.5 & \quad (4 \text{ BS tests}) \\
153.6 & < 23.2a + b < 161.28 & \quad (5 \text{ BS tests}) \\
158.44 & < 21.8a + b < 165.99 & \quad (6 \text{ BS tests})
\end{align*}
\] (3.24-3.26)

To isolate values of \( a \) and \( b \), equations (3.24), (3.25), and (3.26) can be rewritten as:

\[
\begin{align*}
6.62 - b/23.2 & < a < 6.79 - b/23.2 & \quad (4 \text{ & 5 BS tests}) \\
7.26 - b/21.8 & < a < 7.61 - b/21.8 & \quad (6 \text{ BS tests})
\end{align*}
\] (3.27-3.28)

From (3.15), suppose \( b = 9 \), then (3.27) and (3.28) result in:
\[ 6.23 < a < 6.40 \] (4 & 5 BS tests) (3.29)
6.84 < a < 7.20 \quad (6 \text{ BS tests}) \quad (3.30)

Suppose $\Delta L_{ag} \leq 1$ cm, then, from (3.23) and Table 3.5, we acquire:

- $a < 7.88 \quad (4 \text{ BS tests, } \Delta L_{ag} \leq 1 \text{ cm})$ \quad (3.31)
- $a < 7.71 \quad (5 \text{ BS tests, } \Delta L_{ag} \leq 1 \text{ cm})$ \quad (3.32)
- $a < 7.55 \quad (6 \text{ BS tests, } \Delta L_{ag} \leq 1 \text{ cm})$ \quad (3.33)

Therefore, considering $\Delta L_{ag} \leq 1$ cm, the following breakdown voltage equations can be proposed:

\[
V_b = 6.3x + 9 \quad (4&5\text{-BS-tests, } b=9, \Delta L_{ag} \leq 1 \text{ cm}) \quad (3.34)
\]
\[
V_b = 7.0x + 9 \quad (6 \text{ BS test, } b=9, \Delta L_{ag} \leq 1 \text{ cm}) \quad (3.35)
\]

### 3.5.3 Comparison of the approaches

The first approach, (3.13) can be used only as a primarily estimation to predict the breakdown voltage on the air gaps of ice-covered post insulator equipped with BSs; because:

1) The air gap lengths in the BS tests were around 0 to 27 cm. However, (3.13) is actually valid for $1 \text{ cm} \leq x \leq 4 \text{ cm}$. Thus, if (3.13) be used for the air gaps more than 4 cm, the error of the prediction can be high and unacceptable.

2) The slope of the icicles can affect the breakdown voltage as well. As stated in the previous study [78], based on the BS tests, the direction of the icicles on BS1 is directed away from the ice surface on the upper surface of BS2. This phenomenon is because of the effect of the direction of the high electric field (close to the HV
electrode) on bipolar water molecules during the freezing process. Thus, the maximum error for the $V_b$ estimations by (3.13) will be in the first air gap, which is the most important air gap as stated before.

The first approach is similar to the approach that was used in [17]. Application of (3.13) results in unsuitable dimensioning of BSs. In contrast, as it is shown in the next section, (3.34) and (3.35) lead to their suitable dimensioning.

### 3.6 The application of the geometric model to the BS configurations

This section presents the application of the geometric model to calculate the proper diameters and positions of the BSs for the mentioned 4-, 5-, and 6-BS configurations under 30-mm ice accretion.

From (3.34) and (3.35), $x_i$ can be expressed as:

\[
x_i = \frac{(V_{bsi} - 9)}{6.3} \quad \text{(4 & 5-BS tests)} \tag{3.36}
\]

\[
x_i = \frac{(V_{bsi} - 9)}{7} \quad \text{(6-BS test)} \tag{3.37}
\]

The $D_{BSi-min}$ and $P_{BSi-min}$ were calculated in Table 3.6, to Table 3.8 considering (3.14), i.e. the possible range of the breakdown voltage ($V_b$ (kV$_{rms}$)) and using the results of the BS tests and the voltage drops obtained in the simulations. $\Delta D_{BSi-min}$ and $\Delta P_{i-min}$ signify respectively the variation range of $D_{BSi-min}$ and $P_{i-min}$ taking into account the possible range of $V_b$ in the calculations already mentioned.

The diameters and positions of the BSs must satisfy the extreme possible states in the BS tests. Thus, the extreme states must be considered in the dimensioning of the BSs.
As stated before, the previous BS tests were repeated 5-6 times for each configuration and test condition. Hence, regarding to note (1), the maximum icicle lengths among the 5-6 measured values of the BS tests should be used in the calculations.

The minimum required diameter of BS\textsubscript{i} (D_{BSi-min}) and the minimum required distance between the extremities of BS\textsubscript{i} and BS\textsubscript{j} that determine the positions (P_{i-min}) of BSs are (Figure 3.3):

\[ D_{BSi-min} \approx 2(d_{ext,i}/2 + e_{inij} + x_i + L_{i-max} \sin \alpha)/\cos \beta \]  \hspace{2cm} (3.38)

\[ P_{i-min}(cm) \approx L_{i-max} \cos \alpha + e_{bsj} + x_i \] \hspace{2cm} (3.39)

The measured values in the BS tests [i.e. L_{i-max} (cm), e_{bs} (cm), e_{inij} (cm), d_{ext,i}/2 (cm), \alpha (°)], the simulation results [\Delta V (%)], and BS dimensioning equations [(3.36) to (3.39) and (3.14)] were used in MATLAB m-files to calculate the required values [V\textsubscript{b} (kV\textsubscript{rms}), x\textsubscript{i} (cm), D_{BSi-min} (cm), \Delta D_{BSi-min} (cm), P_{i-min} (cm), \Delta P_{i-min} (cm)] in Table 3.6, Table 3.7, and Table 3.8. Furthermore, Table 3.9 displays the distances between the installed BSs in the tests.

<table>
<thead>
<tr>
<th>BS\textsubscript{j}</th>
<th>BS\textsubscript{12}</th>
<th>BS\textsubscript{23}</th>
<th>BS\textsubscript{34}</th>
<th>BS\textsubscript{4G}</th>
</tr>
</thead>
<tbody>
<tr>
<td>L\textsubscript{i-max} (cm)</td>
<td>19</td>
<td>22</td>
<td>37</td>
<td>38</td>
</tr>
<tr>
<td>e_{bs} (cm)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>e_{inij} (cm)</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>d_{ext,i}/2 (cm)</td>
<td>12.5</td>
<td>12.8</td>
<td>13.8</td>
<td>14.2</td>
</tr>
<tr>
<td>\alpha (°)</td>
<td>-15</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>\Delta V (%)</td>
<td>52.5</td>
<td>23.1</td>
<td>9.8</td>
<td>14.0</td>
</tr>
<tr>
<td>V\textsubscript{b} (kV\textsubscript{rms})</td>
<td>149.6-157.5</td>
<td>65.8-69.3</td>
<td>27.9-29.4</td>
<td>39.9-42.0</td>
</tr>
<tr>
<td>x\textsubscript{i-min} (cm)</td>
<td>22.32-23.57</td>
<td>9.02-9.57</td>
<td>3.0-3.24</td>
<td>4.90-5.24</td>
</tr>
<tr>
<td>D_{BSi-min} (cm)</td>
<td>65.73-68.47</td>
<td>54.69-55.90</td>
<td>54.85-55.36</td>
<td>60.21-60.94</td>
</tr>
<tr>
<td>\Delta D_{BSi-min} (cm)</td>
<td>2.75</td>
<td>1.21</td>
<td>0.51</td>
<td>0.73</td>
</tr>
<tr>
<td>P_{i-min} (cm)</td>
<td>43.67-44.92</td>
<td>33.81-34.36</td>
<td>42.64-42.88</td>
<td>42.53-42.87</td>
</tr>
<tr>
<td>\Delta P_{i-min} (cm)</td>
<td>1.25</td>
<td>0.55</td>
<td>0.23</td>
<td>0.33</td>
</tr>
</tbody>
</table>
Table 3.7-. Calculation of the positions and diameters of 5 BSs for the standard post insulator ($V_{WS} = 300$ kV, $V_{MF} = 315$ kV)

<table>
<thead>
<tr>
<th>BS$_{ij}$</th>
<th>BS$_{12}$</th>
<th>BS$_{23}$</th>
<th>BS$_{34}$</th>
<th>BS$_{45}$</th>
<th>BS$_{5G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{i-max}$ (cm)</td>
<td>19</td>
<td>22</td>
<td>38</td>
<td>38</td>
<td>38</td>
</tr>
<tr>
<td>$e_{bs}$ (cm)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>$e_{inij}$ (cm)</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$d_{ext}/2$ (cm)</td>
<td>12.5</td>
<td>12.8</td>
<td>13.1</td>
<td>13.9</td>
<td>14.4</td>
</tr>
<tr>
<td>$a$ ($^\circ$)</td>
<td>-15</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>$\Delta V$ (%)</td>
<td>51.2</td>
<td>20.0</td>
<td>7.9</td>
<td>8.1</td>
<td>12.2</td>
</tr>
<tr>
<td>$V_b$ (kV$_{rms}$)</td>
<td>153.6-161.3</td>
<td>60.0-63.0</td>
<td>23.7-24.9</td>
<td>24.3-25.5</td>
<td>36.6-38.4</td>
</tr>
<tr>
<td>$x_{min}$ (cm)</td>
<td>22.95-24.17</td>
<td>8.10-8.57</td>
<td>2.52-2.71</td>
<td>2.62-2.81</td>
<td>4.38-4.67</td>
</tr>
<tr>
<td>$D_{BSi-min}$ (cm)</td>
<td>67.11-69.79</td>
<td>52.65-53.70</td>
<td>52.55-52.97</td>
<td>54.53-54.95</td>
<td>59.50-60.13</td>
</tr>
<tr>
<td>$\Delta D_{BSi-min}$ (cm)</td>
<td>2.68</td>
<td>1.05</td>
<td>0.41</td>
<td>0.43</td>
<td>0.63</td>
</tr>
<tr>
<td>$P_{i-min}$ (cm)</td>
<td>44.31-45.52</td>
<td>32.88-33.36</td>
<td>43.15-43.34</td>
<td>43.25-43.44</td>
<td>42.01-42.30</td>
</tr>
<tr>
<td>$\Delta P_{i-min}$ (cm)</td>
<td>1.21</td>
<td>0.52</td>
<td>0.19</td>
<td>0.19</td>
<td>0.29</td>
</tr>
</tbody>
</table>

Table 3.8-. Calculation of the positions and diameters of 6 BSs for the standard post insulator ($V_{WS} = 315$ kV, $V_{MF} = 330$ kV)

<table>
<thead>
<tr>
<th>BS$_{ij}$</th>
<th>BS$_{12}$</th>
<th>BS$_{23}$</th>
<th>BS$_{34}$</th>
<th>BS$_{45}$</th>
<th>BS$_{56}$</th>
<th>BS$_{6G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{i-max}$ (cm)</td>
<td>20</td>
<td>27</td>
<td>32</td>
<td>35</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>$e_{bs}$ (cm)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>$e_{inij}$ (cm)</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>$d_{ext}/2$ (cm)</td>
<td>12.4</td>
<td>12.8</td>
<td>13.1</td>
<td>13.8</td>
<td>14.2</td>
<td>14.7</td>
</tr>
<tr>
<td>$a$ ($^\circ$)</td>
<td>-15</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>$\Delta V$ (%)</td>
<td>50.32</td>
<td>20.77</td>
<td>6.88</td>
<td>6.66</td>
<td>3.09</td>
<td>11.79</td>
</tr>
<tr>
<td>$V_b$ (kV$_{rms}$)</td>
<td>158.5-166.1</td>
<td>65.4-68.5</td>
<td>21.7-22.7</td>
<td>20.8-21.8</td>
<td>9.7-10.2</td>
<td>37.1-38.9</td>
</tr>
<tr>
<td>$x_{ij}$ (cm)</td>
<td>21.36-22.44</td>
<td>8.06-8.51</td>
<td>1.81-1.96</td>
<td>1.71-1.85</td>
<td>0.10-0.17</td>
<td>4.02-4.27</td>
</tr>
<tr>
<td>$D_{BSi-min}$ (cm)</td>
<td>62.82-65.19</td>
<td>54.11-55.09</td>
<td>49.15-49.48</td>
<td>51.39-51.71</td>
<td>50.27-50.42</td>
<td>56.44-56.99</td>
</tr>
<tr>
<td>$\Delta D_{BSi-min}$ (cm)</td>
<td>2.37</td>
<td>0.98</td>
<td>0.32</td>
<td>0.31</td>
<td>0.15</td>
<td>0.56</td>
</tr>
<tr>
<td>$P_{i-min}$ (cm)</td>
<td>43.68-44.76</td>
<td>37.80-38.24</td>
<td>36.50-36.65</td>
<td>39.37-39.51</td>
<td>42.72-42.78</td>
<td>53.53-53.79</td>
</tr>
<tr>
<td>$\Delta P_{i-min}$ (cm)</td>
<td>1.08</td>
<td>0.45</td>
<td>0.15</td>
<td>0.14</td>
<td>0.07</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Table 3.9-. Distances (cm) between the installed BSs in the tests

<table>
<thead>
<tr>
<th>BS$_{ij}$</th>
<th>BS$_{12}$</th>
<th>BS$_{23}$</th>
<th>BS$_{34}$</th>
<th>BS$_{45}$</th>
<th>BS$_{4G}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 BS test</td>
<td>60.5</td>
<td>96</td>
<td>57.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5 BS test</td>
<td>60.5</td>
<td>54</td>
<td>56</td>
<td>62.5</td>
<td>-</td>
</tr>
<tr>
<td>6 BS test</td>
<td>56.5</td>
<td>48.5</td>
<td>51</td>
<td>52</td>
<td>50.5</td>
</tr>
</tbody>
</table>

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Comparison of the calculated values ($P_{i-min}$) of Table 3.6, Table 3.7, and Table 3.8 with Table 3.9 demonstrates that the values are in a good agreement with BS positions in the previous BS tests. Moreover, the obtained values of the diameters are in good agreement with the diameter used ($D_{BS} = 65.5$ cm) in the BS tests. As a result, the fitting BSs can be selected among the available commercial BSs, considering the minimum required diameter of BS$_1$ ($D_{BSi-min}$). As well, the minimum required distance between the BSs ($P_{i-min}$) must be respected during the installation.

### 3.7 Discussion

The relation of the AC breakdown voltage as a function of air gap length is the key required equation [i.e. equation (3.3)] in the proposed method. This equation depends on several factors such as the length of the air gaps, the radius or sharpness of the tip of icicles, and the presence of a water drop and conductivity at the tip of wet icicles.

The calculated values in Table 3.6 to Table 3.7, demonstrate that the breakdown equation [(3.36) and/or (3.37)] mainly affects the diameter of BS$_1$ and the distance between BS$_1$ and BS$_2$. For example, in Table 3.6 to Table 3.7 the variation range of $x_i$ for the first and second air gaps are $21.36-24.27$ cm and $8.06-9.57$ cm, respectively. Similarly, the variation ranges of voltage drops [$\Delta V$ (%)] for the first and second air gaps are $50.3-52.5\%$ and $20.2-23.1\%$, respectively. In other words, it can be concluded from (3.36) and (3.37) and Table 3.6 to Table 3.7 that variations of $x_i$ are directly proportional to the variation of the breakdown voltages and/or the voltage drops along the air gaps. In addition, the
ΔD_{BS_{min}} (cm) and ΔP_{i-min} (cm) values in Table 3.6 to Table 3.7 might be considered as the sensitivity of the D_{BS}\text{I} and P_{BS}\text{I} calculations to the voltage drops from top to bottom.

In fact, in (3.38) and (3.39) the variations of the maximum icicle length (L_{i-max}) and the minimum required air gap length (x_i) chiefly influence the calculated values of D_{BS}\text{I} and P_{BS}\text{I}. In the area close to HV electrode, electric field strength is high and consequently a large air gap length (x) is required to resist against the electrical breakdown. On the other hand, for the BSs close to ground, icicle length and/or ice bridging is the main factor that determines the proper position and diameter of the BSs. It is due to the lower electric field and the larger icicle length in this lower region.

Actually, the accurate estimation of the equation is essential only for the first air gap. Hence, to calculate the proper BS dimensions, a rough estimation of the equation is sufficient for all the air gaps except the first one. This is the reason that in the proposed method, the estimated breakdown equations of the first air gaps were used for the dimensioning of the other BSs as well.

As mentioned before, the BSs used in the previous BS tests have an outer diameter of 65.5 cm. Thus, in the proposed dimensioning method, the calculated values of the D_{BS}\text{I} should be less than or equal to 65.5 cm in order to have complete agreement with the previous BS tests. Regarding Table 3.6 to Table 3.8, the complete agreement was achieved for all of D_{BS}\text{I} values except D_{BS}\text{I} in 4- and 5-BS configurations. In these two cases, the obtained values are close to 65.5 cm and they are still in a rather good agreement compared to the previous experimental BS test results. This agreement is achieved in spite of the
simplifications and estimations in the simulations and the proposed equations. In any case, more investigations are required to attain complete agreement and industrial applications.

Diameters and positions of the BSs must resist against the most extreme possible states in the BS tests. Hence, the extreme states must be considered in the dimensioning of the BSs. Since the direction of the icicles on BS$_1$ is away from the insulator ($\alpha < 0^\circ$, Figure 3.3); based on (3.8), $D_{BS1-min}$ is a decreasing function of $L_1$. Thus, actually, the shortest $L_1$ on BS$_1$ corresponds to the extreme case and should be considered in the calculations indeed. The use of the shortest $L_1$ leads to a greater discrepancy. Therefore, again, the necessity of more research in this issue comes in mind. To this end, a suggestion for future work is presented in Chapter 7. Since the key equation to calculate $D_{BS1}$ is the breakdown voltage as a function of the air gap length, some experimental tests should be performed to achieve better estimations of the breakdown equation [i.e. equation (3.3)]. From the previous studies [2], [85], [86] it can be concluded that main parameters for the determination of breakdown voltage are as follows:

1) the length of the air gap
2) ambient and ice temperature
3) water and surface conductivity
4) appearance of water drops
5) the radius of the tip of the icicles
6) pressure
7) humidity
Hence, a systematic study should be undertaken, which is explained in the recommendation for future work in Chapter 7.

There is a hidden hypothesis concerning the BS effects in the presented model of BS dimensioning. Based on this hypothesis, the useful effects of BS under icing conditions are the prevention of the electrical breakdown and ice-bridging along the created air gaps. Moreover, it states that the length of the air gaps plays the main role in the prevention of flashover and/or the electrical performance of the BS configurations. In the upgraded model of BS dimensioning, it was supposed that this hypothesis is acceptable. Then, in order to achieve a good agreement with the previous experimental tests, several simplifications and assumptions were considered. However, in spite of the achieved agreement, some realities demonstrate that the mentioned hypothesis should be improved. Most importantly:

- In order to find a way for proposing suitable equations of the electrical breakdown [i.e. (3.34) and (3.35)], it was supposed that $\Delta L_{agl} \leq 1$ cm. However, based on the previous experimental test (see Table A. 6 in Appendix.), we have $\Delta L_{agl} \approx 3-5$ cm.
- Inequality (3.14) [i.e. $\Delta V_{ag,WS} < V_{b,agi} < \Delta V_{ag,MF}$] is only true if all of the experimental uncertainty is a result of the variability in the air gap size.
- In order to achieve a good agreement with the previous experimental tests, two separate breakdown equations [i.e. (3.34) and (3.35)] were proposed for the BS configurations. In other words, in spite of the similarity of the first air gap in 4-, 5-, and 6-BS configurations, it was not possible to propose only one breakdown equation for obtaining a good agreement.
Moreover, the following presented assumptions can be changed or improved. However, these changes/improvements will lead again to similar conclusions (i.e. separate breakdown equations and/or the reality that the mentioned hypothesis should be improved.).

- In view of physical interpretation of a and b in inequality (3.40) (i.e. $3.5 < a < 8$ and $6 < b < 13$); a is breakdown stress (usually 5 kV$_{\text{peak}}$ per cm for large dimension) and b is a threshold voltage. It is possible to consider a wider range for a and b, for example: $3.1 < a < 8$ and $-5 < b < 22$.

- To achieve the breakdown equation at -1°C [equation (3.12)], a linear estimation was used. However, the change is abrupt at -0.5 °C and nonlinear indeed [87]. Thus, it would be better to simply use the breakdown equation at 0 °C and then evaluate the error of the estimation.

- In addition to the two described approaches for estimation of the electrical breakdown equations [i.e. equations (3.34) and (3.35)], it is also possible to use rod-to-plane flashover strength in standard test (metal rod to ground plane).

Hence, in the next chapter an improved hypothesis regarding the BS effects under heavy icing conditions will be presented.
3.8 Conclusion

This chapter presents an original method of BS dimensioning, based on previous experimental results, new numerical simulations, and analytical calculations. The method was applied for two units of a post station insulator under heavy icing conditions (30-mm ice accretion on a monitoring rotating cylinder) during the melting period. The stress levels equal those used at 735-kV Hydro-Quebec substations.

The FEM 2D axisymmetric simulation results are in good agreement with those of laboratory experiments in spite of the complexity of the insulator geometry and the simplifications made with the numerical model. Thus, the numerical simulation can be a good alternative to experimental measurements, which are time consuming and difficult to perform, especially for a full-scale station post insulator. However, practical care must be taken if the results presented here are to be carried out over a three-section post insulator due to the non-uniformity of the potential distribution along it. The presented dimensioning method also can be generalized to other types of insulators such as bushings and suspension insulators.

Moreover, the effects of the electric field and ice bridging in the dimensioning of the BSs were quantified from top to bottom along the post insulator. The analysis showed that to determine the proper diameters and positions of the BSs, the intensity of the electric field is the main factor for the BSs close to HV electrode. In contrast, ice bridging (icicle length) is the main factor for those close to the ground electrode.

It was assumed that the useful effects of BS on ice-covered insulators are the prevention of ice-bridging and electrical breakdown along the created air gaps. Also, the
length of the air gaps have the main function in the prevention of flashover. However, some realities demonstrate that this assumption/hypothesis should be improved.
CHAPTER 4

PARAMETRIC SIMULATIONS
AND IMPROVED HYPOTHESIS
CHAPTER 4
PARAMETRIC SIMULATIONS AND IMPROVED HYPOTHESIS

4.1 Introduction

BSs can increase the reliability of insulators in ice or snow conditions by the prevention of icicle or snow bridging and by protecting the leakage distance from ice accretion [1]. That is to say, BSs can make alternating diameters of sheds (as a kind of new shed profiles) on insulators by boosting some of the insulator-shed surfaces.

Chapters 4, 5, and 6 present an original approach to analyze systematically the effect of BSs on ice-covered post insulators. This process leads to the optimization of the BS parameters (i.e. diameter, inclination angle, number, permittivity, and position), thereby making it more beneficial for electrical industries in high voltage insulators.

Chapter 4, herein, explains the parametric studies and the improved hypothesis of the effect of BSs under heavy icing conditions. It is demonstrated that FEM 2D axisymmetric simulation is a valuable option as opposed to expensive experimental tests and time consuming 3D simulations in order to analyze the influence of BS in improving the electrical performance of post insulators under heavy icing conditions.
4.2 Study of ice accretions on BS tests

In Section 3.2, a brief description and some observations of the previous BS tests were presented. In the current section ice accretions on the mentioned BS tests are studied in more detail. Then some parametric simulation studies will be explained in the next section. The main objective of these studies is to propose an improved hypothesis of the effect of BSs that leads to an improvement in the electrical performance of the post insulators under heavy ice conditions. Figure 4.1 depicts 4-, 5- and 6-BS configuration tests in CIGELE climate room after heavy ice accumulation. As the number of BSs increases from 4 to 5 and/or 5 to 6, there was an increase in $V_{WS}$ of about 15 kV.

![Test results for standard post insulators in heavy icing conditions](image)

Figure 4.1- Test results for standard post insulators in heavy icing conditions (30-mm ice accretion on rotating cylinder) with a) 4 BSs, b) 5 BSs and c) 6 BSs [2], [18]-[20]
BS positions were selected to produce air gaps without ice bridging. The applied voltage was set at 285 kV. The levels of the withstand voltages ($V_{ws}$) were compared to the value of 270 kV, usually considered for the post insulators without BSs under heavy ice accretion of 15-30 mm.

The middle and bottom units have 26 and 25 sheds, respectively. Table 4.1 presents the installation positions of the BSs based on the shed numbers of the units from HV to ground electrodes.

<table>
<thead>
<tr>
<th>BS No.</th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>15</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>18</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>22</td>
</tr>
</tbody>
</table>

Next, Table 4.2 shows the average lengths of the air gaps (AGs) and icicles of the BS tests. Air gaps play an important role in the flashover process as it is where partial arcs appear, and their formation depends directly on the electric field distribution [61].

The icicle lengths of the BSs strongly depend on the position of the BS along the two insulator units. As the BS comes closer to the ground, the average icicle length becomes larger. This is due to the fact that the potential distribution along the insulators is not uniform. In fact, the icicles along the BSs closer to HV electrode are growing in a stronger electric field. The appearance of corona discharges at the tip of icicles in a strong electric field leads to the reduction of icicle growing rate. As BS approaches the ground
electrode, electric field strength decreases and consequently icicles grow with lower level restrictions.

Table 4.2-. Average lengths (cm) of the air gaps and icicles in BS tests

<table>
<thead>
<tr>
<th>BS No.</th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AG</td>
<td>Icicle</td>
<td>AG</td>
</tr>
<tr>
<td>1</td>
<td>23.2</td>
<td>17.4</td>
<td>23.2</td>
</tr>
<tr>
<td>2</td>
<td>16.2</td>
<td>20</td>
<td>16.2</td>
</tr>
<tr>
<td>3</td>
<td>9.6</td>
<td>30</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>37</td>
<td>9.6</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>11</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>60.0</td>
<td>104.4</td>
<td>69.0</td>
</tr>
</tbody>
</table>

However, it was a general observation that the icicles in a lower BS have longer lengths; in some cases it was observed that a lower BS has a shorter icicle length. This occurred for the icicles of installed BSs on the bottom unit of the standard insulator close to the ground electrode. Since the electric field is not strong in this area and the potential differences are lower, the electric field has a minor role in the icicle growth of the BSs on the bottom unit. Thus, a lower BS can have a shorter icicle length due to the random manner of the formation of the icicles.

Finally, Table 4.3 shows the Ice-Free Leakage Distances (IFLD) during the mentioned BS tests in Figure 4.1.
Table 4.3. Equivalent total ice-free sheds and ice-free leakage distances (IFLD) (cm), during the BS tests

<table>
<thead>
<tr>
<th></th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent total ice-free sheds</td>
<td>22.5</td>
<td>27</td>
<td>32</td>
</tr>
<tr>
<td>IFLD_{1,t} (along shed surfaces (cm))</td>
<td>283.3</td>
<td>339.9</td>
<td>402.9</td>
</tr>
<tr>
<td>IFLD_{2} (beneath of BSs (cm))</td>
<td>92</td>
<td>115</td>
<td>138</td>
</tr>
<tr>
<td>IFLD_{tot} (total ice-free leakage distance of the BS test (cm))</td>
<td>375.3</td>
<td>454.9</td>
<td>540.9</td>
</tr>
</tbody>
</table>

In Table 4.3, to calculate the equivalent total ice-free sheds, the relations (4.1) to (4.4) are used:

\[ N_{\text{equivalent total ice-free sheds}} = N_{\text{total ice-free sheds}} + 0.5 \times N_{\text{partially ice-bridged sheds}} \quad (4.1) \]

It means the number of equivalent total ice-free sheds equals the number of total ice-free sheds plus 50% of the number of partially ice-bridged sheds.

\[ IFLD_{1,t} (cm) \approx K \times N_{\text{equivalent total ice-free sheds}} \times d_{sh_{,sh}} (cm) \quad (4.2) \]

Where,

- \( IFLD_{1,t} \): is the sum of the equivalent IFLD on surfaces of insulator-sheds in the BS tests.
- \( K \): is the ratio of total leakage distance to the dry arcing distance of one section of the post insulator: 2.52 (3.5 meter / 1.39 meter).
- \( d_{sh_{,sh}} \): is the shed-to-shed distance of the post insulator: \( \approx 5 \) cm.

\[ IFLD_{2} (cm) = IFLD_{b,BSi} \times N_{BS} \quad (4.3) \]

Where,

- \( N_{BS} \): is the number of installed BSs.
- \( IFLD_{b,BSi} \): is the IFLD of bottom surface of BS\(_i\) (cm) \( \approx 23 \) cm.
- \( IFLD_{2} \): is the sum of the IFLD of bottom surfaces of BSs (cm).

At the end, we obtain the total IFLD (IFLD\(_{tot}\)) as follows:
IFLD_{tot}(cm) = IFLD_{1,t}(cm) + IFLD_{2}(cm) \hspace{1cm} (4.4)

Figure 4.2 clarifies schematically the definitions of IFLD\textsubscript{BSi}, ice-free sheds and partially ice-free sheds used in the above equations.

The correlations of IFLD\textsubscript{tot}, total dry arcing distance and total length of the air gaps with the maximum withstand voltage will be discussed in Section 4.4.

4.3 Parametric simulations

As stated in Section 3.3, the numerical simulations were done using the FEM commercial software COMSOL Multiphysics\textsuperscript{TM}. The current section presents comparative
studies of various BS configurations and situations. The 2D axisymmetric simulations are used here mainly to determine voltage drops along air gaps and to detect partial discharges.

4.3.1 The effect of water film

Figure 4.3 depicts the effect of water film on equipotential line distributions of an ice-covered post insulator equipped with 6 BS. Wet grown ice is characterized by the presence of a water film on the surface of ice.

Figure 4.3- Equipotential line distributions of the post insulator with 6 BSs considering water film effect under heavy icing conditions a) and b) without water film (dry ice); c) and d) with water film (thickness = 0.15 mm, conductivity = 30 μS/cm)
Table 4.4 shows the effect of water film on the voltage drops along the air gaps in the 6 BS configuration. The total voltage drops ($\Delta V$) along the air gaps are 43.3% and 99.4% for the dry-ice and wet-ice conditions, respectively. The higher $\Delta V$ leads to a higher probability of electric breakdown and appearance of flashover. It confirms the literature's statement that wet-grown ice is more dangerous than a dry-grown one [35]–[37].

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>$\Delta V$ (%) without water film</th>
<th>$\Delta V$ (%) with water film</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22.2</td>
<td>50.3</td>
</tr>
<tr>
<td></td>
<td>7.6</td>
<td>20.8</td>
</tr>
<tr>
<td></td>
<td>2.9</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>2.7</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>6.7</td>
<td>11.8</td>
</tr>
<tr>
<td>Total</td>
<td>43.3</td>
<td>99.4</td>
</tr>
</tbody>
</table>

A post insulator equipped with BSs must assure a proper electrical performance under the most severe conditions. Thus, in this research the wet-grown ice is commonly selected for following parametric studies.

4.3.2 The effect of number of BSs

In section 3.3, the numerical simulations of 4-, 5-, and 6-BS tests under heavy ice accretion were explained. The comparison of their calculated voltage drops (Table 4.5 and Figure 4.4) demonstrates that in all of the configurations:
1. The total voltage drops ($\Delta V_{\text{tot}}$) on the air gaps is around 99.4 %. It indicates that the air gaps have the main role in resisting the applied voltage and, consequently, to increase the flashover voltage.

2. The voltage drop distribution is non-uniform and the longest air gap close to the HV electrode has the highest voltage drop (more than 50% of the applied voltage).

3. There is a slight decrease ($\approx 1\%$) in the voltage drop of air gap 1 ($\Delta V_{AG1}$) as the number of BSs increase from 4 to 5 and 5 to 6.

Table 4.5.- Comparison of the calculated voltage drops ($\Delta V$ (%) ) for 4, 5 and 6 BS tests

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.5</td>
<td>51.2</td>
<td>50.3</td>
</tr>
<tr>
<td>2</td>
<td>23.1</td>
<td>20.0</td>
<td>20.8</td>
</tr>
<tr>
<td>3</td>
<td>9.8</td>
<td>7.9</td>
<td>6.9</td>
</tr>
<tr>
<td>4</td>
<td>14.0</td>
<td>8.1</td>
<td>6.7</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>12.2</td>
<td>3.1</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>11.8</td>
</tr>
<tr>
<td>$\Delta V_{\text{tot}}$</td>
<td>99.4</td>
<td>99.4</td>
<td>99.4</td>
</tr>
</tbody>
</table>

Figure 4.4- Potential distribution of the post insulator with 4, 5 and 6 BSs under heavy wet-grown ice condition
4.3.3 The effect of variations in the permittivity of ice and BS

The variation of ice relative permittivity in the range of ($\varepsilon_{r,\text{ice}} = 75-110$) has no major effect on the calculated potential and electric-field distributions along the EHV insulator in the wet-grown ice regime. The mentioned variation range was selected based on [2], [60]. The practical variation of relative permittivity of BSs ($\varepsilon_{r,\text{BS}} = 2-15$) [88] has no significant effect on the calculated electrical field distributions as well. Actually, the increase in $\varepsilon_{r,\text{BS}}$ may increase the portability of tracking and puncturing on BSs in practical applications.

In fact, melting period simulations show that the presence of a conductive water film at the ice surface has the most important role in the distribution of the potential along the insulator. It increases the voltage drop along the different air gaps and consequently enhances the electric field strength along them drastically.

4.3.4 The effect of air gap length variation on the voltage drops

The effect of the variation of air gap length on the voltage drops ($\Delta V$) of the air gaps was investigated in a sample simulation of 6 BSs configuration test. To this end, only the icicle length on BS$_3$ ($L_{\text{ice3}}$) was reduced by 50% (Figure 4.5). More precisely, it was changed from 26.8 cm to 13.4 cm in the simulation model. Therefore, the length of the air gap no. 3 ($L_{\text{ag3}}$) was approximately increased twice. It changed from 13.2 cm to 25.6 cm.
Figure 4.5- Equipotential line distributions of the 6-BS configuration with different air gap lengths:
a) and b) before the change in air gap no. 3; c) and d) after the change in air gap no. 3

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>Air gap length(cm) before the change</th>
<th>Air gap length(cm) after the change</th>
<th>ΔV (%) before the change</th>
<th>ΔV (%) after the change</th>
<th>ΔV (%) Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.8</td>
<td>32.8</td>
<td>53.65</td>
<td>52.8</td>
<td>-0.85</td>
</tr>
<tr>
<td>2</td>
<td>24.5</td>
<td>24.5</td>
<td>18.60</td>
<td>17.41</td>
<td>-1.19</td>
</tr>
<tr>
<td>3</td>
<td>13.4</td>
<td>25.6</td>
<td>6.42</td>
<td>8.8</td>
<td>2.35</td>
</tr>
<tr>
<td>4</td>
<td>14.6</td>
<td>14.6</td>
<td>6.28</td>
<td>5.9</td>
<td>-0.38</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>3.2</td>
<td>2.98</td>
<td>2.9</td>
<td>-0.08</td>
</tr>
<tr>
<td>6</td>
<td>22.3</td>
<td>22.3</td>
<td>11.51</td>
<td>11.2</td>
<td>-0.29</td>
</tr>
<tr>
<td>Total</td>
<td>110.6</td>
<td>122.8</td>
<td>99.44</td>
<td>99.01</td>
<td>-0.43</td>
</tr>
</tbody>
</table>

The results depicted in Table 4.6 shows that by 93% increase in the $L_{ag3}$ (i.e. 100% decrease in $L_{ice3}$):
1) The maximum of voltage drop variations occurs in air gap no. 3 (AG3) and it is an increase less than 2.5%.

2) Total voltage drop ($\Delta V_{\text{tot}}$) along AGs decreases less than 0.5%.

### 4.3.5 The effect of icicle direction of the first BS on the voltage drops

The inclination of icicles ($\alpha$, Figure 4.6) on the first BS is different from those on the other BSs because of the high electric-field strength in this area. Thus, the effect of the variation of the first icicle-direction on the voltage drops of the air gaps were investigated for 2 states in the simulation of 6 BSs configuration test (Figure 4.7 and Table 4.7).

![Figure 4.6- Schematic diagram of the icicles on BSs and the ice surfaces to estimate breakdown voltage equations](image)
Figure 4.7- Equipotential line distributions around BS₁ with different angles of icicles: 
   a) state 1: \( \alpha_{\text{BS1}} = 8^\circ \),  b) state 2: \( \alpha_{\text{BS1}} = -15^\circ \)

Table 4.7- Comparison of voltage drops in the 6 BS configuration by changing the icicle slope on BS₁

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>Air gap length (cm) before the change</th>
<th>( \Delta V ) (%) before the change (state 1: ( \alpha_{\text{BS1}} = 8^\circ ))</th>
<th>( \Delta V ) (%) after the change (state 2: ( \alpha_{\text{BS1}} = -15^\circ ))</th>
<th>( \Delta V ) (%) variation (state 2-state 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.8</td>
<td>50.3</td>
<td>49.9</td>
<td>-0.4</td>
</tr>
<tr>
<td>2</td>
<td>24.5</td>
<td>20.8</td>
<td>20.8</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>13.4</td>
<td>6.9</td>
<td>6.9</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>14.6</td>
<td>6.6</td>
<td>6.7</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>3.1</td>
<td>3.2</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>22.3</td>
<td>11.8</td>
<td>12.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Total</td>
<td>110.6</td>
<td>99.5</td>
<td>99.5</td>
<td>0.0</td>
</tr>
</tbody>
</table>

The results show that by changing the slope angle of the icicles (\( \alpha \), Figure 4.6) on the first BS from \( 8^\circ \) to \( -15^\circ \):

1) The maximum variation of \( \Delta V \) occurs along the first air gap (AG₁) and it is a decrease around of 0.4%.

2) Total voltage drop (\( \Delta V_{\text{tot}} \)) along the air gaps does not vary.

4.3.6 The effect of the diameter variation of the BSs

Figure 4.8 shows the equipotential line distributions of the 6-BS configuration with different diameters.
The comparison of voltage drops in the 6-BS configuration by changing the BS diameters is shown in Table 4.8. The results show that by changing the BS diameters from 65 cm to 55 cm in the three different states in Table 4.8:

1) The maximum of $\Delta V$ variations occurs in $AG_1$ or $AG_2$ and it is less than 1.5%.

2) The maximum of the total voltage-drop ($\Delta V_{\text{tot}}$) variations is less than 0.1%.

Figure 4.8- Equipotential line distributions of the 6-BS configuration with different diameters:
- a) state 1: $D_{BS} = 65$ cm
- b) and c) state 2: alternative diameters ($D_{BS} = 65$ cm & 55 cm)
- d) state 3: 55 cm
Table 4.8.-Comparison of voltage drops in a sample 6-BS configuration by changing the BS diameters

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>Air gap length (cm) before the change</th>
<th>( \Delta V ) (%) All BSs =65 cm (state 1)</th>
<th>( \Delta V ) (%) Alternative BSs BS135=65 cm, BS246=55 cm, (state 2)</th>
<th>( \Delta V ) (%) All BSs =55 cm (state 3)</th>
<th>( \Delta V ) (%) Variation (state2-state1)</th>
<th>( \Delta V ) (%) Variation (state3-state1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.8</td>
<td>53.40</td>
<td>52.04</td>
<td>54.14</td>
<td>-1.36</td>
<td>0.74</td>
</tr>
<tr>
<td>2</td>
<td>24.5</td>
<td>18.53</td>
<td>19.86</td>
<td>18.32</td>
<td>1.33</td>
<td>-0.21</td>
</tr>
<tr>
<td>3</td>
<td>13.4</td>
<td>6.42</td>
<td>6.32</td>
<td>6.67</td>
<td>-0.10</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>14.6</td>
<td>6.25</td>
<td>6.49</td>
<td>6.39</td>
<td>0.24</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>2.98</td>
<td>3.19</td>
<td>2.98</td>
<td>0.21</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>22.3</td>
<td>11.47</td>
<td>11.16</td>
<td>10.63</td>
<td>-0.31</td>
<td>-0.84</td>
</tr>
<tr>
<td>Total</td>
<td>110.6</td>
<td>99.05</td>
<td>99.05</td>
<td>99.12</td>
<td>0.00</td>
<td>0.07</td>
</tr>
</tbody>
</table>

4.3.7 The effect of the inclination angle variation of the BSs

Figure 4.9 shows the equipotential line distributions of the 6-BS configuration with different inclination angles (\( \beta \) in Figure 4.6) of BSs. Table 4.9 shows the comparison of voltage drops in the 6-BS configuration by changing the BS inclinations.

Table 4.9.-Comparison of voltage drops in the 6-BS configuration by changing the inclination angles of BSs

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>Air gap length (cm) before the change (state 1)</th>
<th>( \Delta V ) (%) All ( \beta ) =24.5° (state 1)</th>
<th>( \Delta V ) (%) All ( \beta ) =9.5° (state 2)</th>
<th>( \Delta V ) (%) Variation (state 2-state 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32.8</td>
<td>53.40</td>
<td>52.56</td>
<td>-0.84</td>
</tr>
<tr>
<td>2</td>
<td>24.5</td>
<td>18.53</td>
<td>18.60</td>
<td>0.07</td>
</tr>
<tr>
<td>3</td>
<td>13.4</td>
<td>6.42</td>
<td>6.32</td>
<td>0.07</td>
</tr>
<tr>
<td>4</td>
<td>14.6</td>
<td>6.25</td>
<td>6.32</td>
<td>0.07</td>
</tr>
<tr>
<td>5</td>
<td>3.2</td>
<td>2.98</td>
<td>3.23</td>
<td>0.25</td>
</tr>
<tr>
<td>6</td>
<td>22.3</td>
<td>11.47</td>
<td>11.82</td>
<td>0.35</td>
</tr>
<tr>
<td>Total</td>
<td>110.6</td>
<td>99.05</td>
<td>99.02</td>
<td>-0.03</td>
</tr>
</tbody>
</table>
The results show that by $15^\circ$ variation of the BS inclinations ($\beta$, Figure 4.6) from $24.5^\circ$ cm to $9.5^\circ$ in the different states:

1) The maximum of $\Delta V$ variations occurs in $AG_1$ or $AG_2$ and it is less than 1%.

2) The maximum of the total voltage drop ($\Delta V_{tot}$) variations is 0.1%.

Figure 4.9- Equipotential line distributions of the 6-BS configuration with different inclination angles of BSs:

- a) and b) $\beta = 24.5^\circ$;
- c) and d) $\beta = 9.5^\circ$.
4.3.8 The effect of the metal ring at the top of the insulator

As mentioned in Chapter 2 corona rings improve field grading, and they tend to promote accumulation of a uniform ice layer. Moreover, they reduce the production of ozone from the corona discharge activity. In the previous BS tests, a small metal ring was used at the top of HV electrode (Figure 4.1). According to the images, the metal ring was not much bigger than the metal hardware of the post insulator end fitting and would had a limited effect in the testing shown. Figure 4.10 shows the equipotential line distributions around the first BS with and without the small corona ring. The calculated voltage drops were approximately the same.

![Equipotential line distributions around BS, and small corona ring effect](image)

Figure 4.10- Equipotential line distributions around BS, and small corona ring effect
a) without corona ring  b) with corona ring

4.3.9 Comparison of the results for HVAC (f=50 or 60 Hz) and HVDC

The simulation results of potential and electric-field distributions along the EHV insulator for the wet-grown ice condition show that the values of voltage drops in the air gaps for HVAC (f=50 or 60 Hz) and HVDC are the same, ignoring space charge effects.
This is due to the size of an EHV post insulator (height ≈ 4.5 m) which is much smaller than the wavelength of the AC voltage (wavelength = wave velocity/frequency = 5 × 10^7 m). In other words, the system is in a quasi-static condition for both AC and DC. However, in order to attain a more accurate comparison regarding the frequency effect, the presence of the displacement (capacitive) currents in HVAC systems should be considered as well. There is no capacitive current in HVDC systems and this is due to frequency = 0 [89].

4.3.10 The effect of partial arc appearance on the voltage drops

The partial arc modeling method presented in [59] was used in this study. The model considers voltage drop along the partial arc during its propagation at the ice surface. To calculate the voltage drop, the equation for the voltage gradient along the partial arc can be expressed as:

\[
E_{\text{arc}} = 0.3464 I_m^{-0.3555} \quad \text{for } x < 7 \text{ cm} \tag{4.5}
\]

\[
E_{\text{arc}} = 0.2047 I_m^{-0.6607} \quad \text{for } x > 7 \text{ cm} \tag{4.6}
\]

where \(E_{\text{arc}}\) is in kV/cm and \(I_m\) in A represents the leakage current flowing on the ice surface. The voltage drop is obtained by multiplying (4.5) or (4.6) by the air gap length (cm):

\[
V_{\text{arc}} = E_{\text{arc}} x \tag{4.7}
\]

According to the previous BS tests, the transition between a breakdown streamer to a white arc corresponds to a leakage current of about 18-mA on the ice surface. By substituting this value in (4.1) and (4.2), we obtain the voltage drop (kV rms):
\[ V_{arc} = 1.44x \quad x < 7 \text{ cm} \quad (4.8) \]
\[ V_{arc} = 2.91x \quad x > 7 \text{ cm} \quad (4.9) \]

Firstly, as stated in our paper [77], since the voltage drops for the small air gaps (i.e. \( x < 7 \text{ cm} \)) are less than 4%, it might be concluded that the small air gaps have no significant effect on the total voltage drop. That is, in the vicinity of the HV electrode, a sufficiently large air gap in the ice layer is helpful, but a small air gap is not.

Secondly, according to the laboratory tests, partial arcs are mostly observed on the first BS closed to the HV electrode. When the applied voltage is increased to flashover voltage, it appears that the voltage drop (\( \Delta V \)) value of air gap 1 becomes higher than its breakdown voltage (\( V_b \)) value. It indicates that a partial arc can be initiated along this one. If this occurs, a redistribution of potential along the ice-covered insulator should occur, similar to the process explained in [59]. Redistribution can lead to appearance of partial arcs across the other air gaps that may develop to flashover. Whenever the number of remaining air gaps is higher, they can better resist the redistribution of the voltage drops after the formation of the partial arc. This may be a reason for the increase in \( V_{WS} \) as the number of BSs increase from 4 to 5 and 5 to 6.

Figure 4.11 shows the appearance of partial arcs along air gaps during the evaluation period in a 6-BS test at CIGELE. Moreover, Figure 4.12 shows the simulation results of 4-, 5-, and 6-BS configurations with and without partial arc (PA).

Table 4.10, Table 4.11, Table 4.12 and their corresponding figures, i.e. Figure 4.13, Figure 4.14 and, Figure 4.15 compare the voltage drops (\( \Delta V \)) in the 4-, 5- and 6-BS configurations before and after partial arc appearance at the first air gap.
Based on the simulation results, around 58.5-64.6% of $\Delta V_{ba-1}$ (variation of the voltage drop along air gap 1 before and after the formation of the partial arc) shifts to air gap 2. This means that air gap 2 acts as a potential barrier, and it prevents the re-equilibrium of the potential distribution along air gaps 2 and the other air gaps.

These 2D axisymmetric simulation results are in good agreement with previous validated 3D simulations in [59] which indicate that for three air gap configuration on a post insulator, 77% of $\Delta V_{ba-1}$ shifts to air gap 2 (Table 4.13 and Figure 4.16).
Figure 4.12- Equipotential line distributions for different BS configurations with and without partial arc (PA)
   a) 4BS, b)4BS with :PA, c) 5BS, d)5BS with :PA, e) 6BS, f)6BS with :PA.

Table 4.10-. Comparison of voltage drops (AV (%)) along the air gaps of 4-BS tests, before and after the formation of a partial arc along air gap1

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>Before PA (ΔV₁)</th>
<th>After PA (ΔV₂)</th>
<th>Variation (ΔV₁₂)</th>
<th>Normalized Variation (ΔV₁₂n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>52.5</td>
<td>23.7</td>
<td>-28.8</td>
<td>-100</td>
</tr>
<tr>
<td>2</td>
<td>23.1</td>
<td>41.7</td>
<td>18.6</td>
<td>64.6</td>
</tr>
<tr>
<td>3</td>
<td>9.8</td>
<td>14.9</td>
<td>5.1</td>
<td>17.7</td>
</tr>
<tr>
<td>4</td>
<td>14.0</td>
<td>19.1</td>
<td>5.1</td>
<td>17.7</td>
</tr>
<tr>
<td>Total</td>
<td>99.4</td>
<td>99.4</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 4.13- Comparison of voltage drops (ΔV (%)) along the air gaps of 4-BS tests, before and after the formation of a partial arc along air gap1
Table 4.11 - Comparison of voltage drops (ΔV (%)\(^c\)) along the air gaps of 5-BS tests, before and after the formation of a partial arc along air gap 1

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>Before PA (ΔV_a)</th>
<th>After PA (ΔV_a)</th>
<th>Variation (ΔV_{ba})</th>
<th>Normalized Variation (ΔV_{ba,a})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51.4</td>
<td>23.7</td>
<td>-27.7</td>
<td>-100</td>
</tr>
<tr>
<td>2</td>
<td>20.2</td>
<td>36.4</td>
<td>16.2</td>
<td>58.5</td>
</tr>
<tr>
<td>3</td>
<td>8.1</td>
<td>12.6</td>
<td>4.5</td>
<td>16.2</td>
</tr>
<tr>
<td>4</td>
<td>9.2</td>
<td>13.0</td>
<td>3.8</td>
<td>13.7</td>
</tr>
<tr>
<td>5</td>
<td>10.5</td>
<td>13.6</td>
<td>3.1</td>
<td>11.2</td>
</tr>
<tr>
<td>Total</td>
<td>99.4</td>
<td>99.3</td>
<td>-0.1</td>
<td>-0.4</td>
</tr>
</tbody>
</table>

Figure 4.14 - Comparison of voltage drops (ΔV (%)) along the air gaps of 5-BS tests, before and after the formation of a partial arc along air gap 1

Table 4.12 - Comparison of voltage drops (ΔV (%)) along the air gaps of 6-BS tests, before and after the formation of a partial arc along air gap 1

<table>
<thead>
<tr>
<th>Air gap no.</th>
<th>Before PA (ΔV_a)</th>
<th>After PA (ΔV_a)</th>
<th>Variation (ΔV_{ba})</th>
<th>Normalized Variation (ΔV_{ba,a})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50.3</td>
<td>22.3</td>
<td>-28</td>
<td>-100</td>
</tr>
<tr>
<td>2</td>
<td>20.8</td>
<td>37.5</td>
<td>16.7</td>
<td>59.6</td>
</tr>
<tr>
<td>3</td>
<td>6.9</td>
<td>10.7</td>
<td>3.8</td>
<td>13.6</td>
</tr>
<tr>
<td>4</td>
<td>6.7</td>
<td>9.5</td>
<td>2.8</td>
<td>10.0</td>
</tr>
<tr>
<td>5</td>
<td>3.1</td>
<td>4.3</td>
<td>1.2</td>
<td>4.3</td>
</tr>
<tr>
<td>6</td>
<td>11.8</td>
<td>15.0</td>
<td>3.2</td>
<td>11.4</td>
</tr>
<tr>
<td>Total</td>
<td>99.4</td>
<td>99.3</td>
<td>-0.1</td>
<td>-1.1</td>
</tr>
</tbody>
</table>

Figure 4.15 - Comparison of voltage drops (ΔV (%)) along the air gaps of 6-BS tests, before and after the formation of a partial arc along air gap 1
4.4 Improved hypothesis of BS effects

One of the acceptable approaches to rank electrical performance of insulators under icing conditions is determination of maximum withstand voltage ($V_{WS}$) [50], [48]. The approach requires a minimum of five tests to determine the $V_{WS}$ for each insulator configuration, and it can give adequate data for design. The tests are complete when three withstands in four tests are observed at one voltage level, and two flashovers are observed at 5% higher voltage level. The $V_{WS}$ is the test level that gives three withstands out of four tests. Test severity must be held constant in a series of the five trials. This method was used in the previous test of 4-, 5- and 6- BS configurations to rank their electrical performance.

As stated in section 4.2, it was found out, as the number of BSs increases from 4 to 5 and/or 5 to 6, there was an increase in $V_{WS}$ of about 15 kV (Figure 4.1). Now, the key point of the optimization is responding to the following challenging question:
What are the effects of BSs on the ice-covered post insulator that lead to the increase in
the maximum withstand voltage and/or a better electrical performance ranking?

It is generally stated in the literature that this improvement is due to the increase in
dry arcing distance and to the delaying of ice bridging [2], [15], [16]. However, sometimes
the emphasis is on the increase of dry arcing distance and sometimes on the creation of the
air gaps (ice-free zones).

To continue replying precisely this key question, it is beneficial to review some
important definitions which are:

1. Dry Arcing Distance (DAD): is the shortest distance in air between the high voltage and
the ground electrodes.

2. Total air gap length (LAG$_{tot}$): is the sum of the lengths of the air gaps which are created
by BSs.

3. Total Ice-Free Leakage Distance (IFLD$_{tot}$): is the total of the shortest distances along the
insulating surface between the high voltage and ground electrodes that are free of ice.

Actually, the above parameters can help us to quantify the created ice-free zones by
BSs and to discover more precisely their effect in the heavy ice conditions. Thus, the average
values of DAD, L$_{AG-tot}$ and IFLD$_{tot}$ which were measured or estimated in this study from the
previous BS test results [2], [18]–[20] are shown in Table 4.14. In addition, Figure 4.17 is a
graphical illustration of Table 4.14 for the four normalized parameters (V$_{WS}$, DAD, L$_{AG-tot}$ and
IFLD$_{tot}$). As can be understood from Table 4.14, the four mentioned parameters have been
normalized based on their corresponding values in the 4-BS configuration.
There is a slight increase in the DAD as the number of BSs increases from four to five and five to six (Table 4.14, Table 4.15, and Figure 4.17). However, the following analyses in this study demonstrate that in spite of their positive effect in DAD, this effect cannot be their principal effect that leads to the increase in the $V_{WS}$. 

1. In fact, DAD depends only on the position of extreme (the top and bottom) BSs. In consequence, since the other BSs have no role in the increase of DAD, it can be concluded that they have no role in the increase of $V_{WS}$ as well. However, it is undeniable that the other BSs have an important role in $V_{WS}$ by creating some air gaps.

2. The level of $V_{WS}$ increased by about 15 kV (5.3%) per BS as the number of BSs increased from four to six. On the contrary, based on the measurement of DAD (Table 4.14), the levels of DAD increase only 0.7% and 1.3% as the number of BSs increased from four to five and five to six, respectively. Thus, when we compare the BS test results, there is not a firm correlation between the increase in the DAD and the $V_{WS}$.

When comparing the figures of the BS tests (Figure 4.1), perhaps a focus on the remaining total unbridged zones rather than increased DAD would be helpful. In addition, the numerical results showed that when there is a conductive water film on the ice surface, about 99% of the applied voltage distributes along the different air gaps, regardless of the number, length, position, or inclination angle of the BSs. Thus, these ice-free zones have the principal role to determine the $V_{WS}$. 
The levels of IFLD$_{tot}$ increase 21.3% (121.3-100) and 23.0% (144.3-121.3) as the number of BSs increases from 4 to 5 and 5 to 6, respectively (Table 4.14 and Figure 4.17). On the other hand, for the same transitions, the variations of L$_{AGtot}$ are +15% (115-100) and -10.3 % (104.7-115), respectively. Therefore, among these three parameters (DAD, L$_{AGtot}$ and IFLD$_{tot}$), IFLD$_{tot}$ has the best correlation with V$_{WS}$. 

---

Table 4.14: Comparative test results for post insulators with 4, 5 and 6 BSs under 30-mm ice accretion

<table>
<thead>
<tr>
<th>BS Config</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>V$_{WS}$ (kV)</td>
<td>285</td>
<td>300</td>
<td>315</td>
</tr>
<tr>
<td>DAD (m)</td>
<td>3.01</td>
<td>3.03</td>
<td>3.07</td>
</tr>
<tr>
<td>L$_{AGtot}$ (cm)</td>
<td>60.0</td>
<td>69.0</td>
<td>62.8</td>
</tr>
<tr>
<td>IFLD$_{tot}$ (m)</td>
<td>3.75</td>
<td>4.55</td>
<td>5.41</td>
</tr>
<tr>
<td>V$_{WS}$ (%)</td>
<td>100</td>
<td>105.3</td>
<td>110.5</td>
</tr>
<tr>
<td>DAD (%)</td>
<td>100</td>
<td>100.7</td>
<td>102.0</td>
</tr>
<tr>
<td>L$_{AGtot}$ (%)</td>
<td>100</td>
<td>115.0</td>
<td>104.7</td>
</tr>
<tr>
<td>IFLD$_{tot}$ (%)</td>
<td>100</td>
<td>121.3</td>
<td>144.3</td>
</tr>
</tbody>
</table>

Table 4.15: Variation of the parameters for post insulators with 4, 5 and 6 BSs under 30-mm ice accretion

<table>
<thead>
<tr>
<th>4 to 5 BS</th>
<th>5 to 6 BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>V$_{WS}$ (kV)</td>
<td>15 kV</td>
</tr>
<tr>
<td>DAD (m)</td>
<td>0.02</td>
</tr>
<tr>
<td>L$_{AGtot}$ (cm)</td>
<td>9.0</td>
</tr>
<tr>
<td>IFLD$_{tot}$ (m)</td>
<td>80</td>
</tr>
<tr>
<td>V$_{WS}$ (%)</td>
<td>5.3</td>
</tr>
<tr>
<td>DAD (%)</td>
<td>0.7</td>
</tr>
<tr>
<td>L$_{AGtot}$ (%)</td>
<td>15.0</td>
</tr>
<tr>
<td>IFLD$_{tot}$ (%)</td>
<td>21.3</td>
</tr>
</tbody>
</table>

Figure 4.17: Comparative test results for post insulators with 4, 5, and 6 BSs under 30mm ice accretion
Moreover, by increasing the number of BSs from 5 to 6, not only $L_{AG\text{-}tot}$ does not increase but also it decreases around 10.3%. In fact, the total length of the air gaps ($L_{AG\text{-}tot}$) depends mainly on the following parameters:

1. the number of BSs ($N_{BS}$)
2. the average distance between the BSs ($D_{BSij\text{-ave}}$).

In the previous tests, to increase $N_{BS}$ from 5 to 6, $D_{BSij\text{-ave}}$ decreases from 58.25 cm to 51.7 cm. Thus, however the number of AGs is increased, the mentioned decrease in the $D_{BSij\text{-ave}}$ is more determinant in the final variation of $L_{AG\text{-tot}}$.

In the previous 6-BS tests, it has been observed if two BSs (BS$_5$ and BS$_6$, Figure 4.1-c) are fully bridged, the $V_{WS} = 315$ kV cannot be achieved. Table 4.16, Table 4.17, and Figure 4.18 compare the parameters for ice-bridging during the 6 BS-test under 30-mm ice accretion.

As Table 4.17 shows the variations of the parameters in the ice-bridged and no-ice-bridged states, there is a large difference $\approx 23\%$ between their $IFLD_{tot}$ but no difference in their DADs and only a slight difference ($\approx 3\%$) between their $L_{AG\text{-tot}}$. Hence, the effect of ice-bridging on the $V_{WS}$ can be distinguished clearly by comparing the $IFLD_{tot}$ of the ice-bridged and unbridged states. However, it cannot be distinguished and explained by the other indicators (i.e. DAD and $L_{AG\text{-tot}}$).

According to the above analyses, the following "improved hypothesis about the effects of BSs on standard post insulators under heavy icing conditions" is proposed:

- **Qualification of BS effects:**
  
  *A) The major effect is the creation of ice-free zones (unbridged ice zones).*
B) The minor effect is the increase in dry arcing distance (DAD).

- Quantification of BS effects:

Among DAD, $L_{AGtot}$ and $IFLD_{tot}$, the best indicator to quantify the electrical performance ranking (variation of $V_{WS}$) is the total ice-free leakage distance ($IFLD_{tot}$).

<table>
<thead>
<tr>
<th>BS Config.</th>
<th>6-BS-ice-bridged</th>
<th>6-BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{WS}$ (kV)</td>
<td>300</td>
<td>315</td>
</tr>
<tr>
<td>DAD (m)</td>
<td>3.07</td>
<td>3.07</td>
</tr>
<tr>
<td>$L_{AGtot}$ (cm)</td>
<td>60.8</td>
<td>62.8</td>
</tr>
<tr>
<td>$IFLD_{tot}$ (m)</td>
<td>4.55</td>
<td>5.41</td>
</tr>
<tr>
<td>$V_{WS}$ (%)</td>
<td>105.3</td>
<td>110.5</td>
</tr>
<tr>
<td>DAD (%)</td>
<td>101.7</td>
<td>102</td>
</tr>
<tr>
<td>$L_{AGtot}$ (%)</td>
<td>101.3</td>
<td>104.7</td>
</tr>
<tr>
<td>$IFLD_{tot}$ (%)</td>
<td>121.3</td>
<td>144.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>&quot;6-BS-ice-bridged&quot; to 6-BS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{WS}$ (kV)</td>
</tr>
<tr>
<td>DAD (m)</td>
</tr>
<tr>
<td>$L_{AGtot}$ (cm)</td>
</tr>
<tr>
<td>$IFLD_{tot}$ (m)</td>
</tr>
<tr>
<td>$V_{WS}$ (%)</td>
</tr>
<tr>
<td>DAD (%)</td>
</tr>
<tr>
<td>$L_{AGtot}$ (%)</td>
</tr>
<tr>
<td>$IFLD_{tot}$ (%)</td>
</tr>
</tbody>
</table>

Figure 4.18- Comparison of the parameters in ice-bridging during the 6 BS-test under 30-mm ice accretion
4.5 Conclusions

The following conclusions and recommendations can serve to optimize the BS parameters and configurations:

1) Since the main objective of the BS installation is the improvement of the electrical performance under heaviest icing conditions, it is necessary to optimize BS parameters mainly under the heaviest anticipated icing situations. For example:
   A. Radial ice accretion of 30-mm on a rotating cylinder, corresponding to 60 mm on the ground or a fixed cylinder,
   B. Melting conditions,
   C. Horizontal incidence angle of precipitation (i.e. winter storm with strong winds).
2) The simulation results show that, the variation on the relative permittivity of BSs ($\varepsilon_{r,BS} = 2-15$), actually has no considerable effect on the electrical field distributions of the ice-covered insulator during the melting period. Therefore, from the viewpoint of the electrical field distributions or voltage drops along the air gaps, the optimized value of $\varepsilon_{r,BS}$ is an arbitrary value in the mentioned range.
3) The numerical results of the EHV ceramic ice-covered insulator equipped with BSs showed that when there is a conductive water film at the ice surface, the total voltage drops distributed along the air gaps ($\Delta V_{tot}$) is about 99% of the applied voltage. This reality ($\Delta V_{tot} \approx 99\%$) is regardless of the number, lengths, or positions of the air gaps. This value (99%) is also constant in spite of the variations in inclination angles, diameters of the BSs, and the inclination angle of the icicles on BSs. $\Delta V_{tot}$ does not vary during the transition from HVAC to HVDC and frequency variation from 60 Hz to 50 Hz as well. These 2D
axisymmetric simulation results are in good agreement with previous validated 3D simulations in [59], [60] which, indicate that the total voltage drop across the air gaps in a melting period is around 96% regardless of the number, length or position of the air gaps. In addition, the results of the 2D simulations were verified during the analysis of the effect of partial discharge appearance on the voltage drops.

4) The improved hypothesis concerning the positive effects of BSs on standard post insulators under heavy icing conditions is:

- Qualification of BS effects:
  A) The major effect is the creation of ice-free zones (unbridged ice zones).
  B) The minor effect is the increase in dry arcing distance (DAD).

- Quantification of BS effects:
  Among DAD, $L_{AG_{tot}}$ and $IFLD_{tot}$, the best indicator to quantify the electrical performance ranking (variation of $V_{WS}$) is the total ice-free leakage distance ($IFLD_{tot}$).

5) It was shown that following the addition of 4, 5 or 6 BSs, more than 50% of the applied voltage distributes along the closest air gap to the HV electrode, which was also the longest one. Hence, the air gap 1 (or ice-free zone 1) and consequently the BS$_1$ has the most determinant role in the electrical performance of the ice-covered insulator. Thus, it is recommended to select the largest possible diameter for BS$_1$ to create the largest ice-free zone. Also, the experimental test observations validated that the most electrical field stresses are on BS$_1$. Therefore, to prevent any damages (puncture, etc.) under the high electric field stresses close to HV electrode, using a modified grading ring or a creepage extender instead of a BS might be recommended. Another solution is the
installation of BS₁ on 2
nd or 3
rd insulator shed instead of 1
st shed, which is closest to HV electrode. However, this latter solution has a negative side – a slight decrease in DAD.
CHAPTER 5

GEOMETRIC MODELING AND DESIGN
CHAPTER 5
GEOMETRIC MODELING AND DESIGN APPROACH

5.1 Introduction

In the previous chapter, parametric studies and an improved hypothesis of the effect of BSs under heavy icing conditions were presented. The current chapter describes the geometric modeling of the post insulator equipped with BSs considering the precipitation angle. Then, optimality and post-optimality analyses of BS parameters using Taguchi Method is explained.

5.2 Geometric modeling of the precipitation on the insulator with BSs

Figure 5.1-a and Figure 5.1-b show two-unit post station insulator after heavy ice accretion for two situations; i.e. without BS and equipped with 6 BSs, respectively [16]. Figure 5.2-a and Figure 5.2-b illustrate the dimensions of these standard post insulator units and the geometric model of the ice-covered post insulator outfitted with BSs taking into account precipitation direction.
Figure 5.1 - Two-unit post station insulator after ice accretion:
(a) untreated state (b) equipped with 6 BSs [2], [18]-[20]

Figure 5.2 - Illustration of the standard post insulator and the geometric model
(a) Standard post insulator dimensions (mm) (b) Geometric model of the ice-covered post insulator with BSs considering precipitation direction
In the geometric model (Figure 5.2-b) and the consequent equations:

\( D_{BS_i} (\text{cm}) \): is the outer diameter of \( BS_i \).

\( R_{BS_i} (\text{cm}) \): is the radius of \( BS_i \).

\( R'_{BS_i} (\text{cm}) \): is the portion of \( BS_i \) that exceeds the insulator-shed length.

\( BS_{ij} \): signifies the zone between \( BS_i \) and \( BS_j \).

\( e_n_{ij} (\text{cm}) \): is the ice thickness on the insulator surface in \( BS_{ij} \).

\( e_{bsj} (\text{cm}) \): is the ice thickness on the upper surface of \( BS_j \).

\( d_{ext-i} (\text{cm}) \): is the average exterior diameter of the standard insulator shed under \( BS_i \).

\( d_{int-i} (\text{cm}) \): is the average interior diameter of the standard insulator shed under \( BS_i \).

\( \beta (\degree) \): is the inclination angle of \( BS_i \) (\( 0 \leq \beta \leq 24.5\degree \); 24.5\degree is the upper angle of the insulator shed.).

\( \theta (\degree) \): is the incidence angle of precipitation (\( \theta \geq 0 \)).

\( Y_i (\text{cm}) \): is the insulator length protected from precipitation by \( BS_i \) and it is independent to \( \theta \).

\( Z_i (\text{cm}) \): is the insulator length protected from precipitation by \( BS_i \) and it dependent to \( \theta \).

According to the geometric model (Figure 5.2-b) the following relations can be written:

\[ R'_{BS_i} = 0.5D_{BS_i} - \frac{0.5d_{ext-i}}{\cos \beta} \quad (5.1) \]

\[ Y_i = R'_{BS_i} \sin \beta \quad (5.2) \]

\[ Z_i = (R'_{BS_i} \cos \beta) \tan \theta \quad (5.3) \]

The sum of \( Y_i \) and \( Z_i \) is the total protected length (\( W_i \)) of insulator under \( BS_i \).

Therefore:
\[ W_i = Y_i + Z_i \quad (5.4) \]

\[ W_i = R_{BS}^i (\sin \beta + \cos \beta \times \tan \theta) \quad (5.5) \]

\[ W_i = 0.5(D_{BS} - \frac{d_{ext}}{\cos \beta})(\sin \beta + \cos \beta \times \tan \theta) \quad (5.6) \]

The incidence angle of precipitation (\( \theta \)) in the CIGELE Laboratory condition is 53° (+5°) [90], [91].

The previous BS tests were carried out on the middle and bottom units (unit 2 and 3 in Figure 5.2-a) of a three-unit station post insulator, typically used on 735 kV Hydro-Quebec network [36]. Thus, the average values in the equations should be calculated for these 2 units as well. Figure 5.2-a indicates that "di" is in the range of 24.8-29.4 cm. To ease the calculation of \( W_i \), the average of \( di \) (\( d_{ave} \approx 27.1 \) cm) can be used. Hence,

\[ R_{BS}^i \approx 0.5(D_{BS} - \frac{d_{ave}}{\cos \beta}) \quad (5.7) \]

\[ W_i \approx 0.5(D_{BS} - \frac{d_{ave}}{\cos \beta})(\sin \beta + \cos \beta \times \tan \theta) \quad (5.8) \]

To have a better sense of \( W_i \), it can be stated based on the total number of protected sheds (\( N_{wi} \)). So:

\[ N_{wi} = \frac{W_i}{d_{shsh}} \quad (5.9) \]

Where, \( d_{shsh} \) is the average shed-to-shed distance of the post insulator (\( d_{shsh} \approx 5 \) cm).

Finally, using (5.8) and (5.9), we obtain:
The above equations were implemented in a MATLAB m-file. Table 5.1 and Figure 5.3 show the calculated values of $N_{wi}$ based on the variations of $\theta$ for $D_{BS} = 65.5 \text{ cm}$ and $\beta = 24.5^\circ$.

Table 5.1: The effect of incidence angle of precipitation ($\theta$) on the $N_{wi}$ for $D_{BS} = 65.5 \text{ cm}$ and $\beta = 24.5^\circ$

<table>
<thead>
<tr>
<th>State no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta$</td>
<td>0</td>
<td>20</td>
<td>40</td>
<td>45</td>
<td>48</td>
<td>53</td>
<td>58</td>
<td>60</td>
</tr>
<tr>
<td>$N_{wi}$</td>
<td>1.49</td>
<td>2.67</td>
<td>4.22</td>
<td>4.75</td>
<td>5.11</td>
<td>5.82</td>
<td>6.71</td>
<td>7.14</td>
</tr>
</tbody>
</table>

Figure 5.3: The effect of incidence angle of precipitation ($\theta$) on the $N_{wi}$ for $D_{BS} = 65.5 \text{ cm}$ and $\beta = 24.5^\circ$.

The values ($D_{BS} = 65.5 \text{ cm}$ and $\beta = 24.5^\circ$) were selected based on the previous BS test conditions. The comparison of the states no. 5, 6, and 7 in Table 5.1 with the previous BS test results in [2] shows good agreement. Because in the BS tests, the total number of completely or partially ice-free sheds under each BS were between 5 to 7.
Figure 5.4 and Figure 5.5 show the effect of $\beta$ (BS angle) and $D_{BS}$ (Diameter of BS) variations on $N_{wi}$, respectively, for the 4 different incidence angles of precipitation. In fact, "$\theta = 53\pm5^\circ$" represents the CIGELE Laboratory condition and "$\theta = 0^\circ$" represents the worst possible state of $\theta$ (winter storms with strong winds). To better understand the BS configurations, much valuable information can be concluded from Figure 5.3 to Figure 5.5. For example:

Firstly, these three figures quantify the effect of wind or precipitation direction on the total number of protected sheds ($N_{wi}$). The following relation obtained from Figure 5.5 compares the effect of precipitation direction under laboratory ($\theta = 53^\circ$) and winter storm ($\theta = 0^\circ$) conditions.

$$N_{wi}(\theta=0^\circ) < N_{wi}(\theta=53^\circ) \quad (\beta=24.5^\circ, D_{BS}=65.5 \text{ cm})$$  \hspace{1cm} (5.11)

![Figure 5.4- The effect of $\beta$ (BS angle) variation on $N_{wi}$ for $D_{BS}=65.5 \text{ cm}$ for $\theta = 53\pm5^\circ$ and $\theta=0^\circ$]
Secondly, comparing the graphs that correspond to "θ = 0°" in Figure 5.4 and Figure 5.5, the graph slope in Figure 5.4 \([slope \approx 1.49 / 3 = 0.50]\) is about 2.4 times more than the slope graph in Figure 5.5 \([slope \approx (1.69-1.07) / 3 = 0.21]\). That is:

\[
\text{Slope of } N_{wi} (D_{BS} = 65.5 \text{cm}, \beta = 0°) \approx 2.4 \times \text{Slope of } N_{wi} (D_{BS} = 24.5°, \theta = 0°) \tag{5.12}
\]

This indicates that in the selected steps of variation for the diameter and the inclination angle of BSs, the angle has a more determinant role in the creation of the ice-free zones. This point is confirmed in the Taguchi Method and the importance ranking of the BS parameters as well (Figure 5.6 and Figure 5.7).

### 5.3 Calculation of the total ice-free leakage distance (IFLD\(_{tot}\))

To calculate the ice-free leakage distance along the surface of insulator using the model (IFLD\(_{1-m}\)), we can write:

\[
IFLD_{1-m} (cm) \approx N_{BS} \times K \times N_{wi} \times d_{sh-sh} (cm) \tag{5.13}
\]
Where,

\( N_{BS} \): is the number of installed BSs.

\( K \): is the ratio of total leakage distance (3.5 m) on the total dry arcing distance (1.39 m) of the post insulator unit: 2.52.

\( d_{shsh} \): is the shed-to-shed distance of the post insulator: \( \approx 5 \) cm.

Also, the ice-free leakage distance of the bottom surface of BS\(_i\) (IFLD\(_{b,BS_i}\)) can be calculated by:

\[
IFLD_{b,BS_i} = 0.5(D_{BS_i} - d_{BS_i})
\]  

(5.14)

Where, \( D_{BS_i} \) and \( d_{BS_i} \) are outer and inner diameter of BS\(_i\), respectively. In the previous BS tests (Figure 5.1-b), we have: \( IFLD_{b,BS_i} = 23.0 \) cm.

Then, we can obtain the total Ice-Free Leakage Distance of bottom surfaces of BSs (IFLD\(_2\)) as:

\[
IFLD_2 (cm) = IFLD_{b,BS_i} \times N_{BS}
\]  

(5.15)

A special attention is required for the calculation of IFLD under the last BS near the ground electrode to prevent over estimation. In fact, the calculated number of ice-free sheds under the last BS (\( N_{wi} \)) must not be more than the number of sheds located between the last BS and the ground electrode (\( N_G \)). Thus, \( IFLD_{G,m} \) is defined by equations (5.16) and (5.17):

\[
IFLD_{G,m} = 0 \quad \text{(if } N_{wi} \leq N_G \text{)}
\]  

(5.16)

\[
IFLD_{G,m} = (N_{wi} - N_G) \times K \quad \text{(if } N_G \leq N_{wi} \text{)}
\]  

(5.17)

At the end, we achieve the total ice-free leakage distance as follows:

\[
IFLD_{tot-model} = IFLD_{1,m} + IFLD_{2,m} - IFLD_{G,m}
\]  

(5.18)
The above equations were implemented in a Matlab m-file to calculate the $I_{FLD_{tot-model}}$ (total ice-free leakage distance obtained from the model). Table 5.2 shows the verification of the geometric model by comparing its results for the calculation of $I_{FLD_{tot}}$ with the results of the previous BS test in [2]. The maximum error is 1.6% which is for 5-BS configuration. More precisely, taking into account the effective precipitation angle equals to $51^\circ$ ($\theta = 51^\circ$) the model has its best agreement (i.e. minimum errors) to calculate the $I_{FLD_{tot}}$ of the previous BS tests.

<table>
<thead>
<tr>
<th></th>
<th>4 BSs</th>
<th>5 BSs</th>
<th>6 BSs</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{FLD_{tot}}$</td>
<td>375.3</td>
<td>454.9</td>
<td>540.9</td>
</tr>
<tr>
<td>(test)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_{FLD_{tot}}$</td>
<td>369.8</td>
<td>462.2</td>
<td>535.6</td>
</tr>
<tr>
<td>(model)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Error (%)</td>
<td>-1.5</td>
<td>1.6</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

### 5.4 Design approach using Taguchi method

Taguchi method was introduced in Chapter 2 at the end of Section 2.5. This method is used for the optimization of a single performance characteristic. Moreover, signal-to-noise (S/N) ratio is used to represent a response or quality characteristic. In other words, S/N ratio represents the magnitude of the mean of a process compared to its variation and the largest S/N is required. Calculation of the S/N ratio depends on the objective of real or virtual experiments [71]–[74]. Three types of quality characteristics for the Taguchi Method are introduced in Minitab software, i.e., larger-the-better, nominal-the-best, and smaller-the-better. They are defined as follows:

a) larger-the-better
\[ \frac{S}{N} = -10 \log\left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right) \]  
\[ \text{(5.19)} \]

b) nominal-the-best
\[ \frac{S}{N} = -10 \log\left( \frac{1}{nS} \sum_{i=1}^{n} y_i^2 \right) \]  
\[ \text{(5.20)} \]
c) smaller-the-better
\[ \frac{S}{N} = -10 \log\left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \]  
\[ \text{(5.21)} \]

where

S: is the standard deviation.

y_i: is the calculated index.

n: is the number of the real or virtual experiments.

S/N ratio of smaller-the-better is used in the current study. This S/N ratio is usually chosen for the characteristics that need the smallest possible ideal value.

In the following, it is clarified how to define a proper single index to compare the electrical performance of the various BS configurations. As stated in Chapters 3 and 4:

1. Air gaps have an important role in the electrical performance of ice-covered insulators. The numerical results of the EHV ceramic ice-covered insulator equipped with BSs show that when there is a conductive water film at the ice surface, about 99% (ΔV_{tot} = 99%) of the applied voltage distributes along the air gaps, regardless of the number, length, position, inclination angle, or diameter of the BSs. Also, ΔV_{tot} is independent of the inclination angle of the icicles.
2. In the previous BS tests, among DAD, LA_{AG-tot}, and IF LD_{tot}, the best indicator to quantify their electrical performance ranking (variation of V_{WS}) is the total ice-free leakage distance.

Thus, the following index (y_i) was proposed to use Taguchi design approach for the BS configurations:

\[ y_i = \frac{\Delta V_{tot \_i}}{IF LD_{tot \_i}} \] (5.22)

Minitab software was used to implement the Taguchi Method. Three controlling parameters of BS were selected, namely: the number, inclination angle, and diameter of BSs (Table 5.3). It aims to study the effect of these BS parameters in the improvement of the electrical performance of the two units of the standard post insulator.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of BSs</td>
<td>N_{BS}</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Angle (degree)</td>
<td>Angle_{BS}</td>
<td>0</td>
<td>8</td>
<td>16</td>
<td>24.5</td>
</tr>
<tr>
<td>Diameter (cm)</td>
<td>D_{BS}</td>
<td>55.5</td>
<td>60.5</td>
<td>65.5</td>
<td>70.5</td>
</tr>
</tbody>
</table>

Regarding the selected values for BS parameters in Table 5.3:

1. the range of the number of BSs was selected from 3 to 6. Because, firstly the literature recommends the creation of at least three air gaps [59]. In fact, the in-between air gap function as a potential barrier and it impedes the formation of partial arcs and flashover development. Secondly, based on the previous BS tests under 30-mm ice accretion, the maximum number of BSs to prevent ice bridging is six.

2. The selected inclination angles of BSs were 0, 8, 16, and 24.5 degree. They cover the 0-24.5 degree range in equal steps approximately. Moreover, "0°" and "24.5°"
were considered, respectively, as the minimum and maximum degrees which are feasible for the installation of BSs on the post insulator (Figure 5.2-b).

3. Next, the range of the diameter variations was selected between 55.5 and 70.5 cm by equal steps of 5 cm. The "65.5 cm" corresponds to the previous BS tests in CIGELE [2].

4. Finally, it was supposed that the different configurations have equal DADs roughly. So, the effect of the variation of DADs on the electrical performance of the BS configurations was neglected. Moreover, it was supposed that the distances between BSs are enough to prevent ice-bridging and electrical breakdown along the air gaps.

Taguchi method was used to analyze the virtual experiments (i.e. the configurations defined by the geometric model) under two incidence angles of precipitation i.e. $\theta = 51^\circ$ and $0^\circ$ (Figure 5.2-b). In fact:

1. $\theta = 51^\circ$ is the effective incidence angle which matches the conditions of the previous BS test in CIGELE Lab.

2. $\theta = 0^\circ$ represents the worst possible state of $\theta$ that is winter storms with strong winds.

Table 5.4 shows the selected design matrix based on Taguchi L16 orthogonal array consisting of 16 states of the virtual experiments. In addition, it depicts the results of the normalized $\text{IFLD}_{\text{tot}}$ and the corresponding index values. $\text{IFLD}_{\text{tot}}$ was calculated by a MATLAB programming for each virtual experiment using the geometric modeling and consequential mathematical equations of the insulator equipped with BSs (Figure 5.2-b).
In order to prevent being faced with very small values in Table 5.4, the index values were normalized based on the bolded state (i.e. state 8 of "θ = 51°"). Moreover, among the 32 virtual experiments in Table 5.4, the 8th is the only one with available experimental results. So, normalizing based on state 8 can provide a good benchmark for a general comparison of all virtual experiments. "Empty" in Table 5.4 means this column represents no design parameter in the calculations. This trick can be used in Taguchi method without occurring any problem in the analysis [72], [92].

<table>
<thead>
<tr>
<th>BS N</th>
<th>Inclination Angle (°)</th>
<th>Diameter (cm)</th>
<th>Empty</th>
<th>IFLD_{tot,i} (θ=51) (cm)</th>
<th>IFLD_{tot,i} (θ=0) (cm)</th>
<th>Normalized Index (θ=51)</th>
<th>Normalized Index (θ=0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>0</td>
<td>55.5</td>
<td>1</td>
<td>202.0</td>
<td>69.0</td>
<td>183.0</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>8</td>
<td>60.5</td>
<td>2</td>
<td>240.1</td>
<td>86.5</td>
<td>154.0</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>16</td>
<td>65.5</td>
<td>3</td>
<td>275.8</td>
<td>108.0</td>
<td>134.1</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>24.5</td>
<td>70.5</td>
<td>4</td>
<td>306.4</td>
<td>133.0</td>
<td>120.7</td>
</tr>
<tr>
<td>5</td>
<td>4</td>
<td>0</td>
<td>60.5</td>
<td>3</td>
<td>300.5</td>
<td>92.0</td>
<td>123.1</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>8</td>
<td>55.5</td>
<td>4</td>
<td>285.8</td>
<td>111.8</td>
<td>129.4</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>16</td>
<td>70.5</td>
<td>1</td>
<td>404.6</td>
<td>150.9</td>
<td>91.4</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>24.5</td>
<td>65.5</td>
<td>2</td>
<td>369.8</td>
<td>166.9</td>
<td>100.0</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>0</td>
<td>65.5</td>
<td>4</td>
<td>414.5</td>
<td>115.0</td>
<td>89.2</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>8</td>
<td>70.5</td>
<td>3</td>
<td>485.9</td>
<td>152.9</td>
<td>76.1</td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>16</td>
<td>55.5</td>
<td>2</td>
<td>367.6</td>
<td>162.6</td>
<td>100.6</td>
</tr>
<tr>
<td>12</td>
<td>5</td>
<td>24.5</td>
<td>60.5</td>
<td>1</td>
<td>413.8</td>
<td>195.5</td>
<td>89.4</td>
</tr>
<tr>
<td>13</td>
<td>6</td>
<td>0</td>
<td>70.5</td>
<td>2</td>
<td>526.7</td>
<td>138.0</td>
<td>70.2</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
<td>8</td>
<td>65.5</td>
<td>1</td>
<td>516.4</td>
<td>178.2</td>
<td>71.6</td>
</tr>
<tr>
<td>15</td>
<td>6</td>
<td>16</td>
<td>60.5</td>
<td>4</td>
<td>487.0</td>
<td>205.5</td>
<td>75.9</td>
</tr>
<tr>
<td>16</td>
<td>6</td>
<td>24.5</td>
<td>55.5</td>
<td>3</td>
<td>438.5</td>
<td>219.0</td>
<td>84.3</td>
</tr>
</tbody>
</table>

To determine which BS parameters significantly affect the electrical performance of the insulator, the S/N ratio based on smaller-the-better criterion for "θ = 51°" and "θ = 0°" were calculated in Table 5.5 and Table 5.6, respectively.
Table 5.5.- The response of the S/N ratios and their rank (in CIGELE Lab. condition, $\theta = 51^\circ$)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Max-Min</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers of BSs</td>
<td>-43.30</td>
<td>-40.81</td>
<td>-38.93</td>
<td>-37.54</td>
<td>5.76</td>
<td>1</td>
</tr>
<tr>
<td>Angle</td>
<td>-40.75</td>
<td>-40.18</td>
<td>-39.86</td>
<td>-39.79</td>
<td>0.95</td>
<td>3</td>
</tr>
<tr>
<td>Diameter</td>
<td>-41.51</td>
<td>-40.55</td>
<td>-39.66</td>
<td>-38.85</td>
<td>2.66</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 5.6.- The response of the S/N ratios and their rank (winter storm condition, $\theta = 0^\circ$)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
<th>Level 4</th>
<th>Max-Min</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Numbers of BSs</td>
<td>-51.69</td>
<td>-49.29</td>
<td>-47.62</td>
<td>-46.14</td>
<td>5.56</td>
<td>1</td>
</tr>
<tr>
<td>Angle</td>
<td>-51.34</td>
<td>-49.26</td>
<td>-47.68</td>
<td>-46.47</td>
<td>4.87</td>
<td>2</td>
</tr>
<tr>
<td>Diameter</td>
<td>-49.16</td>
<td>-48.83</td>
<td>-48.52</td>
<td>-48.22</td>
<td>0.94</td>
<td>3</td>
</tr>
</tbody>
</table>

The concept of the Max-Min values in Table 5.5 and Table 5.6 can be interpreted as the impact factor of the each BS parameter (Figure 5.6). For example, the impact factor of the inclination angle of BSs can be compared under laboratory and winter storm conditions (0.95 versus 4.87 in Figure 5.6). Moreover, in winter storm condition ($\theta = 0^\circ$), the inclination angle of BS has a much more important role in the formation of larger ice-free zones and increasing $V_{WS}$ than the BS diameter (4.87 versus 0.94 in Figure 5.6). Figure 5.6 concludes the importance order (rank) of the three BS parameters for the laboratory condition and the winter storm condition as follows:

1. $N_{BS}$, 2. $D_{BS}$, 3. $\text{Angle}_{BS}$ (in the laboratory condition, $\theta = 51^\circ$) \hspace{1cm} (5.23)

1. $N_{BS}$, 2. $\text{Angle}_{BS}$, 3. $D_{BS}$ (in winter storm condition, $\theta = 0^\circ$) \hspace{1cm} (5.24)

These orders or rankings of the parameters (sensitivity analysis) have been achieved based on the specific selected variation of the parameters. In other words, sensitivity analysis is completely dependent on the selected variation ranges of the inputs. Reasonable variations should be selected in order to obtain acceptable post-optimality (sensitivity) results.
Figure 5.7 shows graphically the S/N ratios of Table 5.5 and Table 5.6. The middle line represents the value of the total mean of the S/N ratios. Regardless of the category of the four controlling parameters, the larger S/N ratio corresponds to the better performance. Therefore, according to the S/N results (Figure 5.7), the optimal condition for the BS configurations is:

\[ N_{BS} = 6, \ \text{Angle}_{BS} = 24.5^\circ, \ \text{and} \ D_{BS} = 70.5 \text{ cm}. \]  \hspace{1cm} (5.25)

This conclusion is obtained for both the incidence angles of precipitation (\( \theta = 51^\circ \) and \( 0^\circ \)) and the defined ranges of the BS parameters.
5.5 Optimization of BS positions

According to the improved hypothesis, the optimum positions \( (P_{BS}) \) are those which:

1) Maximize \( IFLD_{tot} \) (i.e. creation of the largest ice-free zones) as the first priority.

2) Maximize dry arcing distance as the second priority.

Maximizing the \( IFLD_{tot} \) can be achieved using the described geometric model (Figure 5.2-b) for various possibilities. If only one case results in a maximum \( IFLD_{tot} \), then that case includes the optimum positions. However, it is also possible that several cases provide a same maximum \( IFLD_{tot} \). Then, it is recommended to select the case which includes the highest dry arcing distance. Figure 5.8 depicts a geometric model in order to evaluate the variation of dry
arcing distance for different BS positions. It graphically confirms that DAD depends only on the first and last BS. Table 5.7 shows the three cases to compare their DAD. According to Figure 5.8, we conclude:

\[ \text{HCBG} < \text{HABG} \]  \hspace{1cm} (5.26)

\[ \text{HADG} < \text{HABG} \]  \hspace{1cm} (5.27)

![Figure 5.8- Geometric model of dry arcing distance](image)

Table 5.7 - Comparison of dry arcing distance for different cases

<table>
<thead>
<tr>
<th>Case</th>
<th>First BS</th>
<th>Last BS</th>
<th>Dry Arcing Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case I</td>
<td>on shed 1</td>
<td>on shed 25</td>
<td>HABG</td>
</tr>
<tr>
<td>Case II</td>
<td>on shed 2</td>
<td>on shed 25</td>
<td>HCBG</td>
</tr>
<tr>
<td>Case III</td>
<td>on shed 1</td>
<td>on shed 24</td>
<td>HADG</td>
</tr>
</tbody>
</table>
It means that case I (Table 5.7) has the highest DAD. In fact, to achieve the maximum DAD, the first and the last BS should be installed on the first and the last shed of the insulator, respectively. Moreover, based on the geometric model of DAD (Figure 5.8), a closer BS position to the ends (i.e. HV or ground), leads to a higher DAD. However, the installation of the last BS on closer sheds to the ground electrode may reduce the IFLD. On the other hand, a closer BS to the HV electrode may damage sooner due to the higher electric field stress and partial arcs. In brief, for the 3 to 6-BS configurations with 30 mm radial ice accretion, it is advised to:

- Consider at least 48-50 cm (i.e. 9-11 shed-to-shed distance) between consecutive BSs.
- Install the first BS on the 1st or 2nd shed of the insulator-unit close to HV (middle unit) and the last BS on 19th up to 22nd shed of the unit close to the ground (bottom unit).

Figure 5.8 illustrates the flowchart of the described optimization procedure.
Project Statement: Optimization of booster shed parameters for improving the electrical performance of post insulators under icing conditions

Identification of the Design Parameters:
Number \(N_{BS} \), Inclination Angle \(\beta \), Diameter \(D_{BS} \), Positions \(P_{uni} \), Relative Permittivity \(\varepsilon_{r}\).

Identification of the Constraints:
Installation of BSs on 2 units of a standard EHV post insulator
0 \(\leq N_{BS} \leq 26\) (total shed number of the units),
0\(^\circ\) \(\leq \beta \leq 24.5^\circ\) (upper shed angle of the insulator),
2 \(\leq D_{BS} \leq 15\) (The possible range for \(\varepsilon_{r}\) of silicon rubber)
29.7 \(\leq D_{BoI} (cm) \leq 76.7\) (Viewpoint: commercial availability).
\(P_{uni}\): from the 1\(^{st}\) shed to the last shed of each unit (26 or 25).

Identification of a Criterion to be Optimized:
The increase of \(V_{WS}\) of the EHV Post Insulator with BSs under most severe icing conditions (i.e. 30 mm ice accretion on a rotating cylinder, glaze ice, melting regime, etc)

Information Collection, Modelling and Fundamental Analyses:
- Study of Ice Accretions on BSs & Geometric Modelling
- Electrical Field Calculations & Parametric Studies by Comsol Multiphysics™

Improvement of the BS Effect Hypothesis under Icing Conditions
(Major Effect: Increase in IFLD\(_{tot} \) & Minor Effect: Increase in DAD)

Optimality and Post-Optimality Analyses by Taguchi Method:
\[
\frac{S}{N} = -10 \log \left( \frac{1}{N} \sum_{i=1}^{N} y_i^2 \right)
\]
(smaller-the-better)
\[\Delta V_{WS} / \Delta \text{IFLD}_{tot} \mid \text{and } \text{FLD}_{tot} = 99\%\]

Determination of the Constraints & Assumptions:
Installation of BSs on 2 Units of Standard EHV Post Insulator
\(N_{BS} \in \{3, 4, 5, 6\}\)
\(\beta \in \{0, 8, 16, 24.5\}\)
\(D_{BoI} (cm) \in \{55.5, 60.5, 65.5, 70.5\}\)
Assumptions: Positions \(P_{uni}\) are proper to prevent ice-bridging & electrical breakdown, DAD variations are negligible
Two Conditions for the Precipitation Angle \(\theta\):
\(\theta = 51^\circ\) (Lab.), \(\theta = 0^\circ\) (Ice storm with strong winds)

1. Optimum \(\varepsilon_{r}\) arbitrary; 2. \(\Delta D_{BS} \leq 15\); because of its negligible effect on voltage drops along air gaps.
2. Attention: Around 50% of the applied voltage drops along the first air gap. Thus, a special attention may be required for the first BS that bears the highest electric field stress

The Optimum Positions \(P_{uni}\) are those which:
1\(^{st}\) Priority: prevent ice-bridging & electrical breakdown,
2\(^{nd}\) Priority: maximize dry arcing distance
So, for the 3 to 6 BS configurations, it is recommended to:
1. Consider at least 9-10 shed-to-shed distance (=48 cm) between BSs
2. Install the first BS on the shed no. 1 or 2 of the insulator unit close to HV and the last BS between shed no. 19 to 22 of the unit close to the ground.

Optimized Parameters:
\(N_{BS} = 6, \beta = 24.5^\circ, D_{BoI} = 70.5\) cm (Optimized \(D_{BoI}\) depends directly to its maximum defined constraint.)

Post-Optimality Results
(\(\theta = 51^\circ\): 1. \(N_{BS} = 2\), \(D_{BoI} = 3\), \(\varepsilon_{r} = 6\))
(\(\theta = 0^\circ\): 1. \(N_{BS} = 2\), \(\varepsilon_{r} = 3\), \(D_{BoI} = 6\))

Figure 5.9- Optimization flowchart 1 (analytical and simulation analyses)
5.6 Response surface analyses

Response surface methodology (RSM) is a set of mathematical and statistical procedures. Following the Taguchi method analyses, RSM is frequently used to achieve a deeper analysis. It investigates the relations between some explanatory variables and one or more response variables. It tracks a target response, which helps researchers to improve products and services. A low-order polynomial in some area of the explanatory variables is usually used. Almost all RSM use the first-, second-order, or both models. In RSM problems, generally the correlation between the independent variables and the response(s) can not be formulated, consequently it is approximated. In order to approximate the parameters in the polynomials, the least squares method is used. Then, based on the fitted surface, the response surface analysis can be achieved [72], [93].

Figure 5.10 shows The 3D response surface plot of the IFLD_{tot} as a function of inclination angle and diameter of BSs. As we can see, there is no local maximum in the response surfaces of IFLD_{tot}. Moreover, Figure 5.11 shows the 2D response surface plots of the IFLD_{tot} for some specific values. These graphs provide various selections of BS parameters to reach a specific IFLD_{tot}. Therefore, it can be used as an effective tool to provide a more reliable design of BSs under heavy icing conditions.
Figure 5.10- The 3D response surface plot of the IFLD\textsubscript{tot} as a function of inclination angle and diameter of BSs.

Figure 5.11- The 2D response surface plots of the IFLD\textsubscript{tot} as a function of inclination angle and diameter of BSs: a) spectrum of IFLD\textsubscript{tot}, b) IFLD\textsubscript{tot} = 371.7 cm, c) IFLD\textsubscript{tot} = 429.4 cm, d) IFLD\textsubscript{tot} = 487.2 cm.
5.7 Conclusions

This chapter investigated numerically various BS configurations on two units of an EHV standard post insulator under heavy icing conditions. The following conclusions and recommendations may be drawn:

1) A geometric model was proposed for a standard post insulator equipped with BSs considering the angle of precipitation. Its results were in a good agreement with previous BS tests in spite of the complexity of the insulator geometry and the simplifications made with the geometric model.

2) To analyze various BS configurations by Taguchi Method, 128 virtual experiments were considered by the geometric model. Moreover, a novel index \( y_i = \frac{AV_{tot i}}{IFLD_{tot i}} \) was proposed to quantify the electrical performance of the virtual experiments as well as to apply Taguchi model for optimality and post-optimality analyses.

3) Based on the analyses by the Taguchi method (see the flowchart in Figure 5.8.), the optimal values of the BS parameters are:

\[ N_{BS} = 6, \quad \text{Angle}_{BS} = 24.5^\circ, \quad \text{and} \quad D_{BS} = 70.5 \text{ cm}. \]

These results were based on the analyses of two units of an EHV standard post insulator equipped with BSs under heavy icing conditions. Moreover, two angles of precipitation were considered; i.e. \( \theta = 51^\circ \) and \( 0^\circ \) correspond to normal laboratory and severe winter storm conditions, respectively.

4) Logical constraints for BS parameters and equal step variations in the parameters were considered in the Taguchi method. Then, the importance ranking of the controlling parameters in two different precipitation angles were concluded as:
1. N_{BS}, 2. D_{BS}, 3. \text{Angle}_{BS}; (in the laboratory condition, \theta = 51^\circ)

1. N_{BS}, 2. \text{Angle}_{BS}, 3. D_{BS}. (in winter storm condition, \theta = 0^\circ)

5) To optimize the positions of BSs different possibilities should be considered. Then, the IFLD_{tot} and dry arcing distance as the major and minor concern, respectively, should be compared. For analysis in this procedure, the presented geometric model of dry arcing distance can be used.

6) Response surface methodology is often used to obtain a deeper analysis after Taguchi method studies. There was no local maximum in the response surfaces of IFLD_{tot}. Moreover, in the design of BS parameters to reach a specific IFLD_{tot}, RMS provides various selections of BS parameters. The relationship between the BS parameters and the response(s) of IFLD_{tot} can be approximated by standard approaches such as least squares.
CHAPTER 6

VALIDATION TEST RESULTS
CHAPTER 6
VALIDATION TEST RESULTS

6.1 Introduction

In the previous chapters computer aided analyses (parametric simulations, geometric modeling, Taguchi method, etc.) were presented. The present chapter mainly explains an experimental validation of those computer aided analyses by a series of tests. The experimental tests includes two trial tests (i.e. flashover tests with the first fabricated BS prototype and previous 6-BS configuration), the main validation design test, and finally experimental study of the effect of electric field on icicle growth of BSs.

6.2 Validations based on previous researches

The simulation results are validated by comparing with the previous validated simulations in the literature and the results of the previous BS tests; most importantly:

1) The voltage drops along the air gaps should have a realistic trend from the HV electrode to the ground electrode resembling the calculated results of voltage drops in the previous studies [59], [60], [75]. For example, the voltage drops should have a U-shaped curve (Figure 4.4). Also, it was shown that following the addition of 4, 5, and 6 BSs, more that 50% of the applied voltage drops along the closest air gap to the HV
electrode. It parallels the results of the previous validated 3D simulations of one unit of an EHV ice-covered post insulator in [59], [60]. They indicate that the voltage drop along the first air gap (close to HV) is around 50% of the applied voltage. These similarities in the voltage drops along the first air gap are reasonable theoretically.

2) The numerical results showed that when there is a conductive water film on the ice surface, about 99% of the applied voltage distributes along the different air gaps, independent of the number, lengths, positions, or inclination angle of BSs. These results are in good agreement with the previous validated simulations in [59], [60]. They demonstrate that the total voltage drop along the air gaps during a melting period is around 96% of the applied voltage, independent of the number, lengths, or positions of the air gaps. Furthermore, the effect of partial discharge on the redistribution of voltage drops obtained by 2D-axisymmetric simulations. The results were logically similar to redistributions of voltage drops with the corresponding results in [59] (Table 4.13 and Figure 4.16).

3) The accuracy of 2D-axisymmetric simulation has been verified in the previous studies [27], [76].

4) As it was explained in Chapter 3, the simulation results had a good agreement with the previous BS test results [2] when comparing the voltage drops of the air gaps with the corresponding breakdown voltages.

Following the above verifications, the validation of the simulation results and the improved hypothesis were also finalized by the establishment of a series of experiments. The maximum withstand voltage ($V_{ws}$) was determined for an optimized BS configuration.
on an EHV standard post insulator under heavy ice conditions of 30-mm/140min. The subsequent sections explain the trial tests, the classifications and calculations for BS parameters, and finally the results of the experimental validation tests.

6.3 Trial tests

Before the validation tests, two series of trial tests were carried out:

- the tests with the first prototype of BS,
- the tests with the previous 6-BS test configuration in [2], [18]–[20].

6.3.1 Trial tests with the first prototype of BS

To build BS prototypes, a material with specific electrical and mechanical characteristics is required. As mentioned in section 4.3.3, the relative permittivity of BS should be in the range of "2-15". The material must be fire retardant to resist against partial arcs and flashover as well. For example, wood is not a proper material for this purpose. Moreover, it should be an electrical insulating material that is rather flexible. In addition, it should be readily available commercially and bear the weight of heavy ice accretion. After a comprehensive search and receiving various material samples from different companies, PVC ($\epsilon_{r_{PVC}} = 2.7-5$) [2], [94]–[96] was selected for this purpose. Figure 6.1 shows the stages of preparing the first prototype of BS.
Figure 6.1- The stages of preparing the first prototype of BS
a) material search, b) the selection of PVC sheet c) scheme and dimensions of the BS,
d) fabrication of the BS in CIGELE Lab. e) Final fabricated BS
Since some PVC characteristics (insulating strength, discharge inhibition and arc suppression) are not as good as the characteristics of commercial BS material (i.e. silicone rubber or EVA: Ethylene Vinyl Acetate), some problems (puncture, etc) may occur. Thus, before performing the main validation test, a trial flashover test under heavy icing condition was required. The results were rather satisfactory. Figure 6.2 shows the images of the trial flashover test with the first prototype of BS. Moreover, important technical points (to make BSs more effective, etc) were distinguished during this initial test. It provided beneficial insights and technical experience to go toward the main tests.

Figure 6.2- Trial flashover test with the first prototype of BS
a) ice-covered insulator with BS before flashover,
b) and c) the condition of BS after flashover period (upper side and underside of BS)
6.3.2 Trial tests with previous 6-BS configuration

This series of tests was carried out to master the facilities and to assure the correctness of the applied test procedure. The experimental procedure was the same as defined in [50], and considering the conditions of the previous BS tests in [2], [18]–[20]. Figure 6.3 illustrates the test procedure. Figure 6.4 shows the images of this test in the heavy ice conditions.

The flashover occurred after approximately 7 min application of 330kV. For the first time in the BS tests, arc propagation was recorded (Figure 6.5) by an ultra high-speed camera. The camera, Fastcam SA1, has the capacity of recording up to 675,000 frames per second. These observations can help to understand the formation of arcs when there are several air gaps in the flashover path.

![Diagram of different sequences during BS tests](image)

Figure 6.3- Different sequences during BS tests \( \Delta t_a = 140 \text{ min}, \Delta t_c = 20 \text{ min} \)
Figure 6.4- Trial test with 6-BS configuration under heavy ice condition:
a) before ice accretion, b), c), and d) after 30 mm/140min ice accretion from different views

Figure 6.5- Arc propagation pattern during the flashover along 6-BS configuration
stages (a) to (d)
6.4 Classification of the BS parameters

The main parameters of BSs in this study are as follows: number, inclination angle, permittivity, diameter, and position. These parameters were classified as fixed and variable parameters compare to the previous BS tests in [2].

6.1.1. Fixed parameters of BSs

1) Optimum Number of BSs \( (N_{opt}) \):

As explained in section 4.4 (Figure 4.18), the ice bridging may happen for 6-BS configuration. In fact, the previous BS test results with 30 mm ice accretion shows that to prevent ice bridging the maximum feasible number of BSs is six. In other words, as soon as another BS is added to the 6 BSs, ice bridging is unavoidable. In short: \( N_{opt} = 6 \)

2) Optimum inclination angle of BSs \( (\text{Angle}_{opt}) \):

The S/N ratio analysis (Figure 5.7) showed that the best inclination angle of BSs that can create the largest ice-free zones is 24.5° (24.5° is the upper angle of shed of the post insulator). So: \( \text{Angle}_{opt} = 24.5° \)

3) Optimum relative permittivity of BS \( (\varepsilon_{r,BS-opt}) \):

As explained in section 4.3.3, the variation in the relative permittivity of BS \( (\varepsilon_{r,BS} = 2-15) \) has no significant effect on the potential and electric-field distributions along the EHV insulator in the wet-grown ice regime. Thus: \( \varepsilon_{r,BS-opt} = \text{arbitrary} \ (2-15) \).
6.1.2. Variable parameters of BSs

The remaining parameters that can be changed to reach a $V_{ws}$ higher than $V_{WS}$ of the previous BS tests are the *diameter and position* of the BSs.

To make the prototypes of BSs, two PVC sheets (size: $121.9 \times 243.8$, thickness: 0.3 cm) were used. Figure 6.6 shows the drawing on the PVC sheets in order to extract 6 BSs with no sharp edges and fingers. The dimensions of the BSs are summarized in Table 6.1.

Table 6.1. Diameters (cm) of the BS prototypes

<table>
<thead>
<tr>
<th>BS</th>
<th>$d_{BS}$</th>
<th>$D_{BS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS_1</td>
<td>21</td>
<td>89</td>
</tr>
<tr>
<td>BS_2</td>
<td>21</td>
<td>89</td>
</tr>
<tr>
<td>BS_3</td>
<td>24</td>
<td>84</td>
</tr>
<tr>
<td>BS_4</td>
<td>24</td>
<td>84</td>
</tr>
<tr>
<td>BS_5</td>
<td>24</td>
<td>84</td>
</tr>
<tr>
<td>BS_6</td>
<td>24</td>
<td>84</td>
</tr>
</tbody>
</table>

Figure 6.6. Simplified drawing of BS prototypes on PVC sheets (size: $121.9 \times 243.8$, thickness: 0.3 cm)
The inner diameters of the BS prototypes were selected simply to fit the insulator core and nothing else. So, in this context, when BS diameter is mentioned, it means the outer diameter unless otherwise specified.

Considering the simulation results (Table 4.5), the majority of the voltage drops appears along the first and second air gaps. So, BS1 and BS2 have the most determinant role in the electrical performance of the ice-covered insulator. For this reason, the largest outer diameters were selected for the first and second BSs (Table 6.1.-Diameters (cm) of the BS prototypes) to create the largest ice-free zone beneath them. Table 6.2 shows the position (shed number) and diameters of the BSs on the post insulator in the optimized BS test versus the previous 6-BS test.

<table>
<thead>
<tr>
<th>BS No.</th>
<th>Previous 6-BS test</th>
<th>Optimized BS test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position</td>
<td>D_{BS} (cm)</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>65.5</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>65.5</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>65.5</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>65.5</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>65.5</td>
</tr>
<tr>
<td>6</td>
<td>22</td>
<td>65.5</td>
</tr>
</tbody>
</table>

Considering the improved hypothesis of the BS effect (section 4.4), IFLD_{tot} indicator was used to estimate the V_{WS} of the optimized configuration. More precisely, around 22.1% [i.e. the average value of 21.3 % and 23.0 % (IFLD_{tot} variations in Table 4.15] increase in IFLD_{tot} is considered as 15-kV increase in V_{WS}. That is:

\[ V_{WS} (kV) \approx 285 kV + \left( \frac{IFLD_{tot} \, \%}{22.1} - 100 \right) \times 15 kV \]  (6.1)
Equation (6.3) can be expressed in metric system as (6.4):

\[ V_{ws}(kV) \approx 285kV + 1.207(IFLD_{tot}(m) - 3.75) \times 15kV . \] (6.2)

Table 6.3 compares the previous 6-BS configuration and the optimized one from an electrical viewpoint. The positions of the BSs were optimized to prevent any ice bridging i.e. to maximize the IFLD\textsubscript{tot} as a first priority. Moreover, maximizing the DAD was the second main concern in selecting the BS positions.

<table>
<thead>
<tr>
<th>Table 6.3.- Comparison of the optimized BS test and the previous 6-BS test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Previous 6-BS test</td>
</tr>
<tr>
<td>IFLD\textsubscript{tot} (m)</td>
</tr>
<tr>
<td>DAD\textsubscript{tot} (m)</td>
</tr>
<tr>
<td>(V_{ws}) (kV\textsubscript{rms})</td>
</tr>
<tr>
<td>***IFLD\textsubscript{tot} (%)</td>
</tr>
<tr>
<td>DAD\textsubscript{tot} (%)</td>
</tr>
<tr>
<td>(V_{ws}) (%)</td>
</tr>
</tbody>
</table>

*From BS-geometric model (Figure 5.2-b)  
**The numbers in parentheses are the predicted values by equation (6.1).  
***Using the similar approach in the improved hypothesis section, all values are normalized based on the 4-BS test values. So, 100% means: IFLD\textsubscript{tot} = 3.75 m, DAD\textsubscript{tot} = 3.01 m and \(V_{ws}\) = 285 kV\textsubscript{rms}.

6.5 Validation test results

The maximum withstand voltage was determined using the same method explained briefly in the trial (Section 6.2.2). The tests are complete when three withstands in four tests are observed at one voltage level, and two flashovers are observed at 5% higher voltage level. The \(V_{ws}\) is the test level that gives three withstands out of four tests [97]. Figure 6.7 shows the test results of the optimized configuration. So, 345 kV < \(V_{ws}\) and it is in a good agreement with the predicted value obtained by the geometric model and the improved hypothesis of BS effect. In fact, 345 kV was the maximum possible voltage to
perform the tests in CIGELE laboratory considering the HV Transformer rating and the security circuit limitations. Figure 6.8 displays the physical appearance of the ice-covered post insulator with BSs after ice accretion sequence in the validation tests. Leakage current never reached more than 3 mA during the evaluation period.

![Graph showing the results of $V_{WS}$ of the optimized configuration.](image)

Figure 6.7- The results of $V_{WS}$ of the optimized configuration

![Image of physical appearance of the insulator with BSs after ice accretion sequence.](image)

Figure 6.8- Physical appearance of the insulator with BSs after ice accretion sequence
Figure 6.9 displays the corona discharges and violet arcs during the evaluation period.

Figure 6.9-. Corona discharge appearance in the vicinity of the first BS

As was predicted by the simulations, special attention was required to the first BS because it bears the highest electric field stress and voltage drop (around 50% of the applied voltage). Hence, the first BS was repaired after each test. Figure 6.10 and Figure 6.11 exhibit two conditions of the BS₁ during the tests. After finishing test no. 2, a commercial BS was added on top of BS₁ to prevent more severe damages on BS₁ caused by partial arcs (Figure 6.11).
Figure 6.10- The first BS condition after test no. 2.

Figure 6.11- The first BS repaired after test no. 3

Figure 6.12 presents the optimization and design procedure clearly by a flowchart.
Project Statement: Experimental validation of the proposed improved hypothesis and the optimized BS parameters

Identification of the Design Parameters:
- Number ($N_{BS}$), Inclination Angle ($\beta$), Diameter ($D_{BS}$), Positions ($P_{BS}$), Relative Permittivity ($\varepsilon_r$)

Information Collection 1: Review the optimization flowchart analyses and results

Identification of a Criterion to be Optimized: The increase of $V_{ws}$ of the EHV post insulator with BSs under most severe icing conditions (i.e. 30 mm ice accretion on a rotating cylinder, glaze ice, melting regime, etc) at least 15 kV more than the $V_{ws}$ of previous BS configurations (i.e. $330 \text{kV}_{ms} \leq V_{ws}$).

Identification and Classification of the Constraints to reach $330 \text{kV}_{ms} \leq V_{ws}$:
- Fixed optimized parameters: $N_{BS} = 6$, $\beta = 24.5^\circ$, $2 \leq \varepsilon_r \leq 15$
- Variable parameters: $D_{BS}$, $P_{BS}$

Information Collection 2: Performing trial tests with previous 6-BS configurations to master facilities

Information Collection 3: Search for and select a proper material with following main characteristics to make the BS prototypes: $2 \leq \varepsilon_r < 15$, fire retardant, electrical insulating, rather flexible but bears the heavy ice accretion weight, commercially easily available.

Novel Results: Record of flashover stages and path with the ultra high-speed camera (Fusium SA1)

Estimation of $V_{ws}$ using the proposed improved hypothesis & the geometric model:
$V_{ws} (\text{kV}_{rms}) = 285^\circ ([\text{IFLD}(\%)-100])/22.1) \cdot 15kV_{rms}$

Estimation Results: to achieve $345 \text{kV}_{rms} \leq V_{ws}$, it is required to have: $83.1 \text{cm} \leq D_{BS}$

Attention: Prevent any sharp edge in BS prototype, etc.

Two PVC sheets were selected to make the BS prototypes & BS dimensions were designed mainly based on:
1. The updated diameter constraints,
2. Extraction of maximum diameters using the 2 sheets,
3. Selection of larger diameters for BS1 & BS2 to create larger air gaps near HV that are more important than the other air gaps considering the simulation results.

Optimized Diameters:

<table>
<thead>
<tr>
<th>$D_{BS}$ (cm)</th>
<th>BS1</th>
<th>BS2</th>
<th>BS3</th>
<th>BS4</th>
<th>BS5</th>
<th>BS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BS2</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BS3</td>
<td>84</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>BS4</td>
<td>84</td>
<td></td>
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<td></td>
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<tr>
<td>BS5</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BS6</td>
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</tbody>
</table>

1. $V_{ws} \geq 345 \text{kV}_{rms}$
2. Since the BS1 repairman was required, the prediction of the simulations was verified.

Updating the Design Parameters & Constraints: $83.1 \text{ cm} \leq D_{BS} \leq 121.9 \text{ cm}$

<table>
<thead>
<tr>
<th>Positions</th>
<th>Shed. No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS1</td>
<td>1 or 2</td>
</tr>
<tr>
<td>BS2</td>
<td>12 or 13</td>
</tr>
<tr>
<td>BS3</td>
<td>22 or 23</td>
</tr>
<tr>
<td>BS4</td>
<td>1 or 2</td>
</tr>
<tr>
<td>BS5</td>
<td>11 or 12</td>
</tr>
<tr>
<td>BS6</td>
<td>21 or 22</td>
</tr>
</tbody>
</table>

Optimized Positions:

<table>
<thead>
<tr>
<th>Shed. No.</th>
<th>BS1</th>
<th>BS2</th>
<th>BS3</th>
<th>BS4</th>
<th>BS5</th>
<th>BS6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>12</td>
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<td>22</td>
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<tr>
<td>1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
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<td></td>
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<tr>
<td>22</td>
<td></td>
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</tbody>
</table>

Comparison of the possible states considering:
1st Priority: to prevent ice-bridging & electrical breakdown,
2nd Priority: to maximize DAD

Figure 6.12- Optimization flowchart 2 (validation tests)
6.6 Experimental tests on icicle growth of BSs

In addition, to the validation tests described in the previous section, two extra tests were carried out without application of voltage. The duration of ice accretion, curing and melting period were kept as same as the earlier validation tests. The main objective of these tests was analyzing the effect of applied voltage and electric field on the icicle growth of BSs from top to bottom. This study provides a better prediction of ice-bridging with BS configuration. Consequently, it will be helpful to select better positions for BSs in practical applications.

Figure 6.13 compares the icicle growth along the air gaps with and without applied voltage. In without-voltage state, ice-bridging along all of the air gaps is clearly observable at \( t = 105 \text{ min} \) (Figure 6.13-d'). Moreover, the inclination angles of the icicles are approximately identical. On the other hand, in the hot line condition (with-voltage), no ice-bridging appeared till \( t=140 \text{ min} \). Furthermore, the inclination angles are not identical, especially for the icicles on BSs no. 1 to 3 which were installed on the insulator unit close to the HV electrode.

Figure 6.14 compares dripping water conductivity for the two conditions. The high conductivity of the water film is due to the rejection of impurities onto the ice surface through the crystallization of water droplets during the accumulation period. As the impurities on the ice surface collected gradually, the conductivity decreased gradually as well. Higher conductivity of with-voltage condition is probably due to extra pollution of the ice surface from by-products of corona discharges and BS damages.
Figure 6.13- Comparison of the icicle growths along the air gaps to study the effect of applied voltage
(a)-(e) with voltage ($V_{app} = 285$ kV), (a')-(e') without voltage

Figure 6.14- Dripping water conductivity comparison for with- and without-voltage conditions

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6.7 Conclusions

This chapter reviewed the theoretical validation of the simulations of BS configurations. Moreover, it presented an experimental validation of the simulations and the improved hypothesis of BS effects under heavy icing conditions. The experimental results were in good agreement with the numerical analyses and the improved hypothesis.

Before the main validation tests, a series of trials was carried out. The first trial demonstrated that PVC sheets are good enough to fabricate the prototypes of BSs for research purposes under extra high voltage and heavy icing conditions. The second trial test obtained for the first time the electric arcing path by an ultra high speed camera and during the flashover period on the 6-BS configuration. To clarify the whole procedure of the validation tests, it was summarized in a flowchart (Figure 6.12).

Moreover, after the main validation tests, the icicle growth of BSs under the heavy icing conditions were analyzed experimentally. It was demonstrated that the electric field has a significant effect upon the growth of the icicles on BSs. The results are useful for better estimating ice-bridging of the air gaps as well as better positioning of BSs in practical applications.
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The present study concerns the optimized design of BS parameters (diameter, inclination angle, position, number, and relative permittivity) for icing protection of post insulators. The explained methodology consists of elaborating simulation analysis, geometric models, and their validation based on comparison with confirmed simulation results in the literature, experimental results previously obtained at CIGELE, as well as new test results on BS prototypes whose design is based on the models and computer aided analysis. According to the presented study, the following conclusions are drawn:

1) Since the main objective of the BS installation is the improvement of the electrical performance under heaviest icing conditions, it is necessary to optimize BS parameters mainly under the most severe anticipated conditions; for example: melting regime and 30-mm radial ice accretion on a rotating cylinder.

2) Based on the simulation studies of the electrical field distributions by Comsol Multiphysics™ regarding the standard post insulators with BSs under melting regime:
   a) the optimized value of relative permittivity of BS ($\varepsilon_{r, BS}$) is an arbitrary value in its feasible variation range ($\varepsilon_{r, BS} = 2-15$).
b) The total voltage drop distributed along the air gaps ($\Delta V_{\text{tot}}$) is almost 99% of the applied voltage. This value ($\Delta V_{\text{tot}} \approx 99\%$) is independent of the number, lengths, positions of the air gaps, inclination angles and diameters of the BSs, or the inclination angle of the icicles on BSs. The results of 2D-axisymmetric simulation are in good agreement with previous validated 3D simulations in [59], [60].

c) The closest air gap (AG$_i$) and BS (BS$_i$) to the HV electrode have the most important roles in the electrical performance of the ice-covered insulator. It is due to the largest value of the voltage drop (i.e. around 50% of the applied voltage) along AG$_i$. Hence, the installation of a larger BS to create a wider air gap close to HV electrode seems to be useful. However, to prevent any damage (puncture, etc.) under the high electric field stresses close to HV electrode on BS$_i$, using a modified grading ring [49] or a creepage extender instead of BS might be recommended. Another solution is the installation of BS$_i$ further from HV electrode, e.g. on 2$^{\text{nd}}$ or 3$^{\text{rd}}$ shed of the insulator instead of 1$^{\text{st}}$ shed. However, this latter solution leads to the negative result of a slight decrease in dry arcing distance.

3) The upgraded model of BS dimensioning concerns the proper calculation of diameter and position of BSs on two sections of a standard post insulator. It shows that in order to determine the proper diameters and positions of the BSs, the electric-field stress is the main factor for the BSs close to the HV electrode. Moreover, ice bridging (icicle length) is the main factor for the BSs close to the ground electrode. This guideline
would be used for the application of BSs on full-scale post station insulators on 735-kV Hydro-Quebec network as well.

4) The improved hypothesis regarding the positive effects of BSs on standard post insulators under heavy icing conditions consists of the following:

   a) Qualification of BS effects:
      • The major effect is the creation of ice-free zones (unbridged ice zones).
      • The minor effect is the increase in dry arcing distance.

   b) Quantification of BS effects:
      Among dry arcing distance, the total length of the air gaps, and the total ice-free leakage distance (IFLD$_{tot}$), the best indicator to quantify the electrical performance ranking (i.e. the variation of $V_{WS}$) is IFLD$_{tot}$.

5) A comprehensive computer aided study using Matlab and Minitab was carried out. Based on this study:

   a) A geometric model was proposed to calculate IFLD$_{tot}$ on a standard post insulator with BSs considering the precipitation angle. The results were in good agreement with the previous BS tests in [2], [18]–[20]. Moreover, its effectiveness was confirmed by its successful application in the required calculations of the final validation tests. Thus, it is a robust model that also can be used in other applications.

   b) A novel index ($y_i=\Delta V_{tot}/IFLD_{tot}$) was proposed to quantify the electrical performance of the virtual experiments in the Taguchi method. Then, after systematic analyses (summarized in a flowchart in Figure 5.8.), the optimal values of the BS parameters and their importance rankings were obtained as:
\( N_{BS} = 6, \ \text{Angle}_{BS} = 24.5^\circ, \ \text{and} \ D_{BS} = 70.5 \ \text{cm}, \ \text{(laboratory and wind storm conditions)} \)

1. \( N_{BS} \), 2. \( D_{BS} \), 3. \( \text{Angle}_{BS} \); (in the laboratory conditions, \( \theta = 51^\circ \))

1. \( N_{BS} \), 2. \( \text{Angle}_{BS} \), 3. \( D_{BS} \). (in winter storm conditions, \( \theta = 0^\circ \))

c) Optimization of the positions should be accomplished for various possibilities by comparison of the IFLD\(_{tot}\) and dry arcing distance as the major and minor concern, respectively. The presented geometric model of dry arcing distance can be used as an effective tool for analysis and quantifications in this regard.

d) Response surface methodology was used to provide various selections of BS parameters for a specific IFLD\(_{tot}\). It also was used to analyze the correlation between the design parameters of BSs and no local maximum was observed on the response surface of IFLD\(_{tot}\).

6) The results of the final validation tests (summarized in a flowchart in Figure 6.12) were in good agreement with the simulation analyses and the improved hypothesis. Moreover, another original experimental study was performed concerning the effect of the electric field on the icicle growth of BSs. It can improve the estimation of ice-bridging of the air gaps which is important for proper positioning of BSs.

7) The presented generic approach is not only Taguchi method. In fact, it is an innovative combination of the improved hypothesis, virtual experiments defined by the geometric modeling, and the Taguchi technique (Figure 7.1). Table 7.1 shows the different stages in the novel design approach which leads to considerable time saving. In this approach, 128 states \((2 \times 4 \times 4 \times 4)\) were analyzed. IEEE Task Force recommendations [50] call for at least 5 to 6 icing tests to determine the maximum withstand voltage of each of the
states. In addition, during every working day only one icing test can be performed. The orthogonal arrays in Taguchi method reduce the number of states to 32. Finally, the improved hypothesis and the geometric model helped to obtain only one optimized configuration for the final validation test. Moreover, much more time and cost have been saved indeed, because the required time should also considered for the repairs of equipment, fabrication of many BSs, the availability of a well-equipped laboratory, etc. Above all of these advantages, the proposed modern approach is a generic design approach that can be applied for many other insulators and configurations.

<table>
<thead>
<tr>
<th>Tests</th>
<th>Required time (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All states</td>
<td>$128 \times 5 \cdot 6$</td>
</tr>
<tr>
<td>Orthogonal selection (Taguchi method)</td>
<td>$32 \times 5 \cdot 6$</td>
</tr>
<tr>
<td>Geometric model calculations and final validation test</td>
<td>$1 \times 5$</td>
</tr>
</tbody>
</table>

Figure 7.1- Interaction of the scientific methods used in the novel design approach leading in time and cost saving
7.2 Recommendations for future work

The following technical and practical issues deserve further investigation:

1) Booster sheds prevent ice bridging by the creation of ice-free zones along ice-covered insulators. Moreover, regular/modified grading rings lead to significant improvements of the electric field stress on EHV insulators [49]. Thus, an effective design to make use of these mitigation options simultaneously can lead to a practical guideline in order to benefit their positive effects altogether. A primary simulation analysis concerning the combined effects of BSs and grading rings under heavy icing conditions can be found in our paper [98]. However, more numerical and experimental studies are required in this regard.

2) Design and optimization of the BSs considering other weather conditions (rain, fog, ice, pollution build-up, etc.). Most importantly:
   
   a) Experimental analysis of the effect of wind with strong speeds on IFLD$_{tot}$ and the $V_{WS}$ of the insulators equipped with BSs.
   
   b) Since pollution problems of BSs have reported more frequently, further research concerning this challenge is in greater demand than the other conditions. For example, using anti-contamination and self-cleaning coatings [99] as well as application of micro/nano fillers [46], [100] for BSs seems feasible solutions that deserve more investigations. Superhydrophobic surfaces are generally considered as self-cleaning, because water droplets roll-off on them easily and remove any contamination [101], [102].
3) Since PVC sheets were adequate to fabricate the prototypes of BSs for this study, their application for the future research regarding the design of BSs for other configurations and type of insulators is recommended. For example:

   a) Suspension, bushings, V-type, etc., and especially parallel post insulators on 0.5-m spacing that are often used for air-break disconnect switches.

   b) Alternating BS configurations. In each configuration, the IFLD$_{tot}$ can be calculated as an effective index to quantify the total ice-free zones. Then, based on the improved hypothesis, generally a higher IFLD$_{tot}$ indicates a better configuration. Their dry arcing distance should be considered in the analysis as well. Moreover, the possibility of the ice bridging between the BSs should be estimated. This estimation can be realized using the presented experimental test studies of icicle growth on BSs.

4) A comprehensive study of the effect of electric field on the icicle growth of BSs with a good support of mathematical models is recommended. This study can provide a better estimation of ice-bridging along the air gaps and thus, better positioning of BSs in practical applications.

5) In the following, a new test is suggested considering the criteria of R3 (representative, repeatable, and reproducible) and cost-effectiveness for future research, essentially in the area of BS applications under heavy icing conditions. The air gaps formed during the first minutes of ice accumulation in a wet regime can be assimilated to rod-plane configurations. The configuration in Figure 7.2 is proposed to make the modeling as representative as possible. The main objective of this test is to obtain a better
estimation of the breakdown voltage as a function of air gap length. Hence, its results can lead to a better understanding of BS effects under icing conditions.

In Figure 7.2, the vertical (semi-cylinder) and horizontal (semi-BS shape) ground electrodes represent the accumulated ice surface along the post insulator and along the upper surface of the next BS, respectively. Actually, Figure 7.2 shows the cross section of the proposed configuration (the mounting of the icicle, BS, and the ground electrodes). A comparison of the proposed configuration (Figure 7.2) and the post station insulator with BSs under heavy ice accretion (Figure 7.3) helps to better understanding of the representative characteristic of the proposed configuration.

The vertical ground electrode is a semi-cylinder with a diameter ($d_{cy}$) and a height ($H_{cy}$) matching the average dimensions of the iced-covered insulator and BSs in the icing tests of BSs. As well, the horizontal ground electrode is a semi-circular plane with a radius ($R_{s-BS}$) similar to the shape of BS in the BS tests. The electrodes can be made from a proper conductor, such as copper or aluminum. The electric field near a sharp edge or point is intensive, and it can cause a breakdown of the air and electric discharges. Thus, it is important to avoid sharp edges or points on ground electrodes used in the test (Figure 7.2).

The icicles used in the experiments can be formed by a freezing method at a temperature of -12 °C and using several aluminum or wooden molds particularly shaped to achieve the average form of the icicles. The conductivity of freezing water adjusts to a desired value by adding sodium chloride (NaCl) to de-ionized water. The high voltage is applied to the molded icicle through a metal copper electrode incorporated into the center of icicle during its freezing formation in the mold. The molded icicle must be changed after
each test, since breakdown alters its form. The breakdown voltage, $V_b$, can be obtained by recording the voltage signal and the breakdown time ($t_b$).

The cold room and facilities are described in the previous investigations [80]. Typical values and dimensions of the proposed test (Figure 7.2) correspond to the first air gap range during the previous BS tests in [2]. However, to achieve a better understanding of the breakdown voltage of the air gaps in the BS tests, these typical values may be
changed. Moreover, it is recommended to study the effect of inclination angle ($\alpha$) variation of the icicle. The proposed test can be used not only in the area of BS designs and applications under icing conditions but also for other designs of ice-covered insulators with similar large air gaps. For example, it may provide better estimation of the breakdown voltage along the large air gaps for modified grading rings in [49]. Using equation (3.35) as a primary approximation, a transformer in the range of 198 kV or higher is required to perform the proposed test for its typical values (Figure 7.2).

Any artificial test method for insulators must meet the criteria of R3 (representative, repeatable, and reproducible) and cost-effectiveness [2], [97]. This test is representative as it is carried out based on the study of ice accretion configurations on BSs. Moreover, the icicles are formed from the water conductivity of $\sigma_{20} = 340 \ \mu$S/cm, which is selected on the basis of field experiences in Quebec [80]. For simulating ice near the seacoast or industrial region, a higher value of $\sigma_{20}$ may be appropriate [2]. In addition, the proposed test can be repeated and reproduced in other conventional HV laboratories. Also, it is similar to finding the breakdown voltage of icicle-plane configuration for previous cost-effective investigations in [80].
REFERENCES


APPENDIX

STUDY OF ICE ACCRETION ON BOOSTER SHEDS
APPENDIX

STUDY OF ICE ACCRETION ON BOOSTER SHEDS

This appendix presents the detailed study of ice accretion on BSs. It is based mainly on the previous experimental tests in CIGELE [2], [18]–[20] to determine the characteristic of the artificial air gaps, the variation of Ice-Free Leakage Distance (IFLD), etc. under different configurations and conditions (Figure A. 1).

<table>
<thead>
<tr>
<th>30-mm/140 min ice accretion on rotating cylinder</th>
<th>15-mm/70 min ice accretion on rotating cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-BS test</td>
<td>4-BS test</td>
</tr>
<tr>
<td>5-BS test</td>
<td>6-BS test</td>
</tr>
<tr>
<td>6-BS test</td>
<td>0-BS test</td>
</tr>
<tr>
<td>$V_{ws} = 285$ kV Improvement over untreated:</td>
<td>$V_{ws} = 300$ kV Improvement over untreated:</td>
</tr>
<tr>
<td>5.6%</td>
<td>11.1%</td>
</tr>
<tr>
<td>$V_{ws} = 315$ kV Improvement over untreated:</td>
<td>$V_{ws} = 330$ kV Improvement over untreated:</td>
</tr>
<tr>
<td>16.7%</td>
<td>22.2%</td>
</tr>
<tr>
<td>$V_{ws} &gt; 350$ kV Improvement over untreated:</td>
<td>$V_{ws} = 270$ kV untreated</td>
</tr>
<tr>
<td>&gt;29.6%</td>
<td></td>
</tr>
</tbody>
</table>

Figure A. 1- Test results of various configurations of standard post insulators in heavy icing conditions with 30-mm ice accretion a) 4 BSs b) 5 BSs c) 6 BSs and with 15-mm ice accretion d) 4 BSs e) 6 BSs f) 0 BS (untreated) [2], [18]–[20]
In previous experimental tests, an untreated EHV ceramic post insulator under heavy ice condition usually has an ice-free zone at the 1\textsuperscript{st} and 2\textsuperscript{nd} sheds close to the HV electrode (Figure A. 1-f). This phenomenon is because of the high electric field and consequent discharge activity close to the HV electrode zone that can produce enough heat dissipations to prevent ice bridging on the 1\textsuperscript{st} and 2\textsuperscript{nd} sheds. A similar pattern is seen at the junction from insulator to metal fitting of junction and also at the ground electrode.

Table A. 1 shows the shed numbers of the EHV ceramic post insulator units which the BSs were installed on them. Also in Table A. 2 the distances between the installed BSs are presented. Two sets of tests were carried out for six BS configurations [2], [18]–[20]. In Table A. 1 and Table A. 2, 6p-BS test represents the primary series of six BS tests. The problem in 6p-BS test was the appearance of ice bridging between BS\textsubscript{5} and BS\textsubscript{6}. For this reason, BS\textsubscript{5} on shed 13 shifted to shed 12 (the bold numbers in Table A. 1 and Table A. 2).

<table>
<thead>
<tr>
<th>BS No.</th>
<th>4-BS test</th>
<th>5-BS test</th>
<th>6-BS test</th>
<th>6p-BS test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>15</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>26</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>6</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>18</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>22</td>
<td>22</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BS\textsubscript{ij}</th>
<th>4-BS test</th>
<th>5-BS test</th>
<th>6-BS test</th>
<th>6p-BS test</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS\textsubscript{12}</td>
<td>60.5</td>
<td>60.5</td>
<td>56.5</td>
<td>56.5</td>
</tr>
<tr>
<td>BS\textsubscript{33}</td>
<td>96</td>
<td>54</td>
<td>48.5</td>
<td>48.5</td>
</tr>
<tr>
<td>BS\textsubscript{34}</td>
<td>57.5</td>
<td>56</td>
<td>51</td>
<td>51</td>
</tr>
<tr>
<td>BS\textsubscript{45}</td>
<td>-</td>
<td>62.5</td>
<td>52</td>
<td>57</td>
</tr>
<tr>
<td>BS\textsubscript{56}</td>
<td>-</td>
<td>-</td>
<td>50.5</td>
<td>45.5</td>
</tr>
<tr>
<td>Total</td>
<td>214</td>
<td>233</td>
<td>258.5</td>
<td>258.5</td>
</tr>
<tr>
<td>Average</td>
<td>71.3</td>
<td>58.25</td>
<td>51.7</td>
<td>51.7</td>
</tr>
</tbody>
</table>

*BS\textsubscript{ij}: signifies the zone between BS\textsubscript{i} and BS\textsubscript{j}.
The number of ice-free, partly-bridged ice and fully-bridged ice sheds of the insulator under each BSs for an accretion of 30-mm and 15-mm on a rotating cylinder are presented in Table A. 3 and Table A. 4, respectively. These values are extracted from the images of the previous BS tests in [2], [18]–[20]. Since the area above the BS₁ close to the HV electrode cannot be seen in the images, the ice condition of the sheds in this area is estimated after comparing with the untreated insulator of 15-mm ice accretion (Figure A. 1-f) and validation test results of 30-mm ice accretion (Figure 6.8).

Table A. 5 shows the values of the equivalent number of total ice-free sheds and the values of IFLD for both 30-mm and 15-mm ice accretion on rotating cylinder. To calculate the values in Table A. 5, the following relations are developed:

\[ N_{\text{equivalent total ice free sheds}} = N_{\text{total ice-free sheds}} + 0.5 \times N_{\text{partly ice-bridged sheds}}. \]  \hspace{1cm} (A.1)

It means the number of equivalent total ice-free sheds is equal to the number of total ice-free sheds plus the 50% of the number of partly ice-bridged sheds.

\[ IFLD_{1,1} \text{ (cm)} \approx K \times N_{\text{equivalent total ice free sheds}} \times d_{\text{shsh}} \text{ (cm)} \] \hspace{1cm} (A.2)

Where,

- \( IFLD_{1,1} \) : is the sum of the equivalent IFLD along surfaces of the sheds of insulator in the BS tests.
- \( K \) : is the ratio of total leakage distance of one unit of the post insulator to its dry arcing distance (DAD): 2.52 \((3.5 \text{ m} /1.39 \text{ m}) \)
- \( d_{\text{shsh}} \) : is the shed-to-shed distance of the post insulator \((d_{\text{shsh}} \approx 5\text{ cm})\)

\[ IFLD_{2} \text{(cm)} \approx IFLD_{\text{BSi}} \times N_{\text{BS}} \] \hspace{1cm} (A.3)
Where,

$IFLD_2$ : is sum of the IFLD of bottom surfaces of BSs (cm)

$IFLD_{bBSi}$ : is the IFLD of bottom surface of BS$_i$ (cm) = 23.0 cm.

$N_{BS}$ : is the number of installed BSs.

At the end, we obtain the total ice-free leakage distance ($IFLD_{tot}$) as follows:

$$IFLD_{tot} (\text{cm}) = IFLD_{1-t} (\text{cm}) + IFLD_2 (\text{cm}) + IFLD_3 (\text{cm}) .$$  \hspace{1cm} (A.4)

Where $IFLD_3$ is the ice-free distance of top surfaces of BSs.
Table A. 3- The ice condition of the insulator sheds under booster sheds
(30 mm ice accretion on rotating cylinder)

<table>
<thead>
<tr>
<th>Region</th>
<th>Shed Conditions</th>
<th>4-BS test</th>
<th>5-BS test</th>
<th>6-BS test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ice-free sheds</td>
<td>partly bridged sheds</td>
<td>fully bridged sheds</td>
</tr>
<tr>
<td>HV-BS1</td>
<td></td>
<td>(0)*</td>
<td>(0)</td>
<td>(2)</td>
</tr>
<tr>
<td>BS_{12}</td>
<td></td>
<td>5</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>BS_{23}</td>
<td></td>
<td>5</td>
<td>1</td>
<td>8+Conj**</td>
</tr>
<tr>
<td>BS_{44}</td>
<td></td>
<td>6</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>BS_{45}/BS_{46}</td>
<td></td>
<td>5</td>
<td>1</td>
<td>6+G**</td>
</tr>
<tr>
<td>BS_{55}/BS_{56}</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BS_{66}</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>21</td>
<td>3</td>
<td>27+Conj+G</td>
</tr>
<tr>
<td>Equivalent total sheds</td>
<td></td>
<td>21</td>
<td>3</td>
<td>31***</td>
</tr>
</tbody>
</table>

* The numbers in the parentheses are the estimated values.
** “Conj” signifies the conjunction floating electrode between the two units of the insulator. Also, “G” is the Ground electrode.
*** To calculate the equivalent total sheds, the effective length of Conj and G is considered equal to around 4 and 0 sheds of the insulator, respectively.

Table A. 4- The ice condition of the insulator sheds under BSs (15 mm ice accretion on rotating cylinder)

<table>
<thead>
<tr>
<th>Region</th>
<th>Shed Conditions</th>
<th>4-BS test</th>
<th>5-BS test</th>
<th>6-BS test (untreated insulator)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>ice-free sheds</td>
<td>partly bridged sheds</td>
<td>fully bridged sheds</td>
</tr>
<tr>
<td>HV-BS1</td>
<td></td>
<td>(1)</td>
<td>(1)</td>
<td>(0)</td>
</tr>
<tr>
<td>BS_{12}</td>
<td></td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>BS_{23}</td>
<td></td>
<td>5</td>
<td>2</td>
<td>7+Conj*</td>
</tr>
<tr>
<td>BS_{44}</td>
<td></td>
<td>6</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>BS_{45}/BS_{46}</td>
<td></td>
<td>5</td>
<td>1</td>
<td>6+G*</td>
</tr>
<tr>
<td>BS_{55}/BS_{56}</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BS_{66}</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>22</td>
<td>6</td>
<td>23+Conj+G</td>
</tr>
<tr>
<td>Equivalent* total Sheds</td>
<td></td>
<td>22</td>
<td>6</td>
<td>27</td>
</tr>
</tbody>
</table>

* Refer to the explanations below Table 1 please. (Also, it is considered: 0.6Conj=2.5 shed, 0.5Conj=2 shed, 1Conj=4 shed)
Table A. 5- Equivalent total ice-free sheds and ice-free leakage distances (IFLD) in BS configurations

<table>
<thead>
<tr>
<th>IFLD Configurations</th>
<th>30 mm ice accretion on rotating cylinder</th>
<th>15 mm ice accretion on rotating cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4-BS test</td>
<td>5-BS test</td>
</tr>
<tr>
<td>Equivalent total ice-free sheds</td>
<td>22.5</td>
<td>27</td>
</tr>
<tr>
<td>IFLD&lt;sub&gt;1&lt;/sub&gt; (equivalent ice-free leakage distance along insulator sheds (cm))</td>
<td>283.3</td>
<td>339.9</td>
</tr>
<tr>
<td>IFLD&lt;sub&gt;2&lt;/sub&gt; (ice-free leakage distance of bottom surfaces of BSs (cm))</td>
<td>92.0</td>
<td>115.0</td>
</tr>
<tr>
<td>IFLD&lt;sub&gt;3&lt;/sub&gt; (ice-free distance of top surfaces of BSs (cm))</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>IFLD&lt;sub&gt;tot&lt;/sub&gt; (total ice-free leakage distance (test))</td>
<td>375.3</td>
<td>454.9</td>
</tr>
</tbody>
</table>

* The numbers in the parentheses are the estimated values.

Table A. 6 and Table A. 7 show the length of the air gaps and icicles for the different configurations of the post insulator equipped with BSs.

Table A. 6- The lengths of the air gaps (cm) in BS configurations

<table>
<thead>
<tr>
<th>BS No.</th>
<th>Configs</th>
<th>30 mm ice accretion on rotating cylinder</th>
<th>15 mm ice accretion on rotating cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4-BS</td>
<td>5-BS test</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ave</td>
<td>range</td>
</tr>
<tr>
<td>1</td>
<td>(23.2)*</td>
<td>22-27</td>
<td>23.2</td>
</tr>
<tr>
<td>2</td>
<td>(16.2)</td>
<td>14-19</td>
<td>16.2</td>
</tr>
<tr>
<td>3</td>
<td>((9.6)*</td>
<td>7-11</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>((111))</td>
<td>7-11</td>
<td>9.6</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
<td>10-12</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>(L&lt;sub&gt;gap&lt;/sub&gt;)</td>
<td>(60.0)</td>
<td>60-80</td>
</tr>
</tbody>
</table>

* The numbers in the parentheses are the estimated values.
Table A. 7- The lengths of the *icicles* (cm) in BS configurations

<table>
<thead>
<tr>
<th>BS No.</th>
<th>Configs</th>
<th>30 mm ice accretion on rotating cylinder</th>
<th>15 mm ice accretion on rotating cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4-BS</td>
<td>5-BS test</td>
<td>6-BS test</td>
</tr>
<tr>
<td></td>
<td>ave</td>
<td>range</td>
<td>ave</td>
</tr>
<tr>
<td>1</td>
<td>(17.4)*</td>
<td>15-19</td>
<td>17.4</td>
</tr>
<tr>
<td>2</td>
<td>(20)</td>
<td>16-22</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>((30))</td>
<td>27-38</td>
<td>32.2</td>
</tr>
<tr>
<td>4</td>
<td>((37))</td>
<td>27-33</td>
<td>29.6</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>24-29</td>
<td>26.8</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>((104.4))</td>
<td>109-141</td>
<td>126</td>
</tr>
</tbody>
</table>

* The numbers in the parenthesis are the estimated values.
It can be also observed from the experimental test images (Figure A. 1) that:

1. A small ring was installed in the top of the insulators during the BS test.

2. There is a possibility of the appearance of a small air gap between the mentioned top small ring and BSj.

The icicle lengths of the BSs closely depend on the position of the BS along the two insulator units. As the BS comes close to the ground, icicle length increases. This is due to the fact that the potential distribution along the insulators is not uniform. In other words, the icicles along the BSs closer to HV electrode are growing in a stronger electric field. The appearance of corona discharges at the tip of icicles in a strong electric field lead to the reduction of icicle growing rate. As BS approaches the ground electrode, electric field strength decreases and icicles can grow without restriction.

In general, the icicles on a lower BS, have longer lengths. However, in some cases it was observed that a lower BS had a shorter icicle length. This occurred for the BSs installed on the bottom unit (close to ground) of the standard insulator. Since the electric field along the bottom unit is not strong and the potential differences are low, the electric field has a minor role in the icicle growth of the BSs on the bottom unit. Thus, a lower BS can have a shorter icicle length according to the random manner of the creation of the icicles.

The average length of the icicles between sheds of insulator, L, as a function of the accumulation time in the space of sheds of insulator is [75]:

\[ L_t (\text{cm}) = 0.242 \times t \text{ (min)} \]  \hspace{1cm} (A.5)
Using (A.5) as a primary approximation for the icicle length on BSs results in:

\[ L_{0.15}(\text{cm}) = 16.9\text{cm} \]  
(15-mm ice accretion on rotating cylinder, \( t = 70 \text{ min} \)) \hspace{1cm} (A.6)

\[ L_{0.30}(\text{cm}) = 33.9\text{cm} \]  
(30-mm ice accretion on rotating cylinder, \( t = 140 \text{ min} \)) \hspace{1cm} (A.7)

Normalization of the lengths of the icicles in Table A. 8 based on the above values, can give us a good understanding of the effect of the electric field in the icicle growth from top to bottom. Actually, the values of each icicle length on \( BS_{i=k} \) in 30-mm ice accretion test is normalized by its corresponding icicle length on \( BS_{i=k} \) in 15-mm ice accretion test.

For example, the value of icicle length on \( BS_1 \) in 30-mm ice accretion 6-BS test ("19.8" in Table A. 7) is divided by its corresponding icicle length on \( BS_1 \) in 15-mm ice accretion 6-BS test ("11.7" in Table A. 7) and it led to "1.69" (Table A. 8). Two interesting points are as follows:

1. Although the accumulation times of 30-mm versus 15-mm ice accretion are twice as duration (140 min vs 70 min), their corresponding icicle lengths are usually less than twice as long.

2. The average icicle length of \( BS_1 \) in 4-BS test of 30-mm ice accretion is even more than twice its corresponding icicle length in 4-BS test of 15 mm ice accretion test. This can be explained by referring to the random manner of the creation of icicles. In other words, it is the variation range of the icicle length (\( \Delta L_{\text{ice}}, \text{Table A. 7} \)) that can cause this phenomenon.
Table A. 8- Normalization of the average lengths of the icicles of BSs in 30-mm ice accretion tests based on 15-mm ice accretion tests

<table>
<thead>
<tr>
<th>BS No.</th>
<th>4 BS test</th>
<th>6 BS test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(2.56) *</td>
<td>1.69</td>
</tr>
<tr>
<td>2</td>
<td>(1.89)</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>(1.43)</td>
<td>1.35</td>
</tr>
<tr>
<td>4</td>
<td>(1.65)</td>
<td>1.36</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>1.18</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>1.42</td>
</tr>
</tbody>
</table>

* The numbers in the parentheses are the estimated values.

Apart from the average length of the icicle, it is necessary to know its geometrical characteristics, for example the inclination of the icicles forming on the different BSs. According the images of the experimental tests, the inclination of icicles on the first BS is different from the other BSs. It is due to the fact that these icicles are growing in the strong electric field strength and water molecules are bipolar. So, the icicles grow in the direction of the equipotential line distributions of the insulator.