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Design Validation and Field-Testing Experience of Linear Shore Line Grounding Electrodes for Reliable Operation of HVDC Links

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SUMMARY

This paper presents and discusses design consideration and validation methodology for a special grounding electrode, based on field testing at site versus simulated results obtained during planning stage. Measurement and calculated electrodes' main characteristics of two eighty–well (10X8) linear shore-line electrode sites are used as a case study. The considered study sites have been designed and constructed in a recently built HVDC project. Transmission link is located in Atlantic region of Canada which connects Mainland to Newfoundland via a LCC/VSC DC system as depicted in Figure 1.

The main topics covered here are (1) How to accurately predict and avoid non-uniform wells current distribution of grounding electrode in the design process; (2) How different attributes of grounding electrodes influence the grounding wells current distribution and how to accurately calculate effective ground resistance of site to remote earth; (3) Effectiveness of proper volumetric heterogeneous soil modelling concept in performance evaluation of coastal grounding sites; (4) How to mitigate non-uniform wells current distribution of grounding electrode; (5) How to estimate & measure electrode wells' self and mutual resistances for proper maintenance;

Measured and simulated results as related to case study have been presented in the paper and applied methodology can be used as a reference in designing HVDC shore line grounding sites. It is shown that the heterogeneous character of the earth as a conductor and an electrolyte must be considered in some instances.

KEYWORDS

Linear Shore Line Grounding Electrodes, LCC/VSC HVDC Link, Heterogeneous Soil modelling, Wells' current distribution

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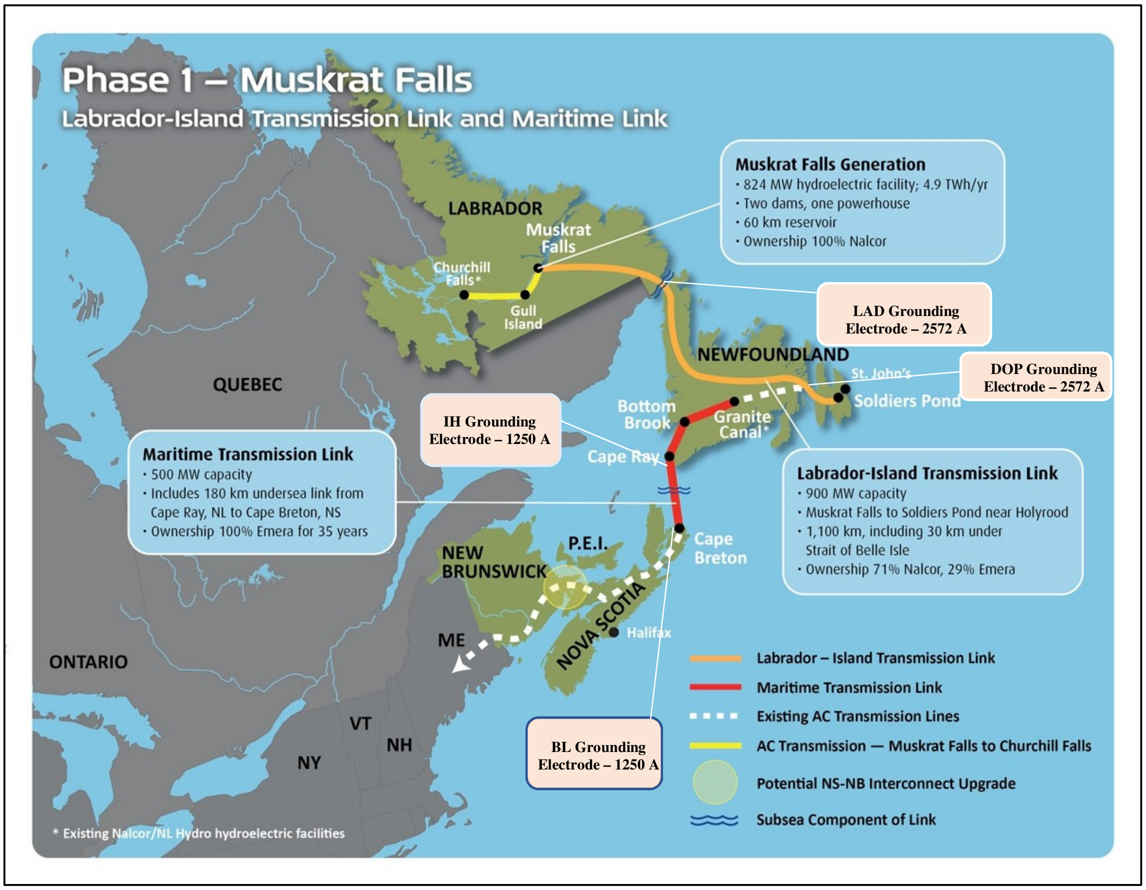

Figure 1 Overall Configuration of the HVDC Links with Grounding Sites Location

1. Introduction

Shore (Beach) line grounding electrode sites have relative advantages in comparison to land and sea-bed electrode counterparts, especially where long distance HVDC line is built in high resistivity coastal areas. Ease of access during construction & operation as well as relatively lower capital cost, makes shore line electrode grounding site more favourable.

Related IEC standard and CIGRE design guide lines [1,2] only cover general and less detailed soil models rather than more realistic cases as encountered in coastal area. Whereas rather higher design margin as considered in planning phase, can be avoided by appropriate and detailed modelling in design stage. The analysis of grounding systems buried in a combination of rock/sea water /native soil is conducted through proper representation of heterogeneous multi-volume soil model which covers electrode wells. Simulation is based on a low frequency moment approach combined with an application of Boundary Element Method [3-7]. The immersed grounding electrodes are assumed to be cylinders of length considerably larger than their radius as depicted in figure 2 .

Final design is established based on an evaluation of a cost function and selection of soft and hard design variable. Sensitivity analysis is used to identify the effectiveness of these variables upon cost and performances. Soft variables are defined based on design flexibility such as configuration of the electrode elements, burial depth & size, whereas current distribution and voltage gradient of the accessible area are among the hard ones as defined by real scenarios and requirements. As an input parameter, detailed characteristics of the multi-layer soil and sea water are measured and used for mathematical modelling. Three-dimensional model of the surrounding area is used for establishment of a finite-difference calculation method (FDM) as shown on the figures 4 and 5 for evaluation purpose.

Various soil structures considered include horizontally layered soils, vertically layered soils and finite volume soils. In all cases studied, grounding grid resistances, current distributions, earth surface potentials and touch/step voltages are computed and evaluated in search of a feasible and cost-effective solution.

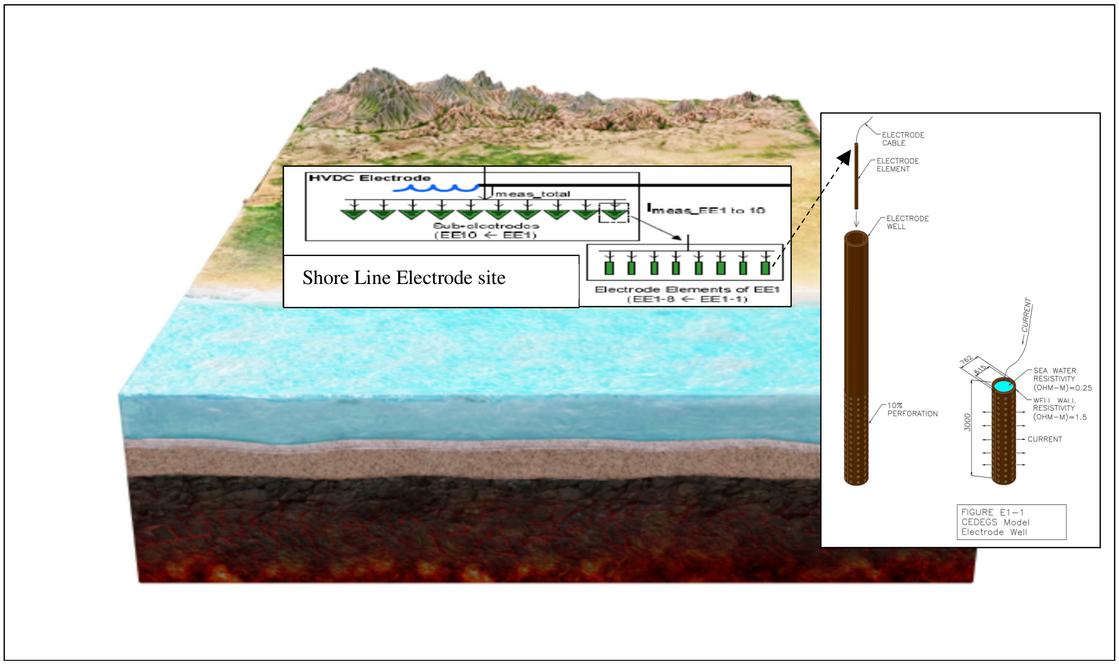

Figure 2 Shore Line Grounding Site General View

2.1. Case Study Description

As a case study design parameters and field measurement results of two different grounding sites both related to a recently built, Line Commuted Converter (LCC) based HVDC system, the Labrador-Island Transmission Link (LIL) is presented in following sections. With LIL constuction complete, it will soon be put into full operation by Nalcor Energy, a Newfoundland and Labrador Crown Corporation. There is another associated Voltage Source Converter VSC based system called the Maritime Link which connects the Newfoundland and Labrador grid to Nova Scotia network and Atlantic power grid. This link also includes two similar grounding stations but with lower capacity (Figure 1).
The LIL Project is called Lower Churchill Project, consists of a 1,100 km, ±350 kV High Voltage Direct Current (HVDC) electricity transmission system from Central Labrador to the Avalon Peninsula on the Island of Newfoundland. It includes two converter stations, (at Muskrat Falls - Labrador and Soldiers Pond - Avalon Peninsula) to convert electricity from alternating current to direct current and vice versa, two cable transition compounds (3x30 km, 350KV DC sub-marine cable for sea crossing) as well as two shore line grounding electrode sites as depicted in figure 1. These two grounding sites have different configuration (i.e. one is at shore (DOP) with rather symmetrical land/sea border while the other one (LAD) is situated between a pond & and open sea and rather in an unsymmetrical case. Figures 3 and 4 depict the case for these sites and their corresponding 3D model and volumetric soil model representation.

2.2. Implementation Challenges and Design Optimization

At the planning stage of the link, it was decided that the two electrodes at LAD and DOP Electrode Stations will be shore-line type electrode consisting of linear array of high silicon chromium iron electrodes elements arranged in tubes placed on the pond side on the slope of the breakwaters. The breakwaters comprise of porous bed of rocks required to conduct the electrode current through the breakwater and into the open sea and to maintain the salinity of the water in the pond.
Number of factors were considered as key for selection of these location:

- A range of technical, economic and environmental factors
- Proximity to the proposed converter station in Island
- Existing site access and suitability, including any previous development at site
- Local infrastructure presence requirements
- Public consultation

During detailed design stage, challenges were encountered in the design of the concrete structures required for providing mechanical protection against ice for the tubes placed on the slope of the breakwaters. The concrete structure design was becoming complex and costly, also it will require maintenance and renewal over its 50-year design life. It was decided to find a simpler and economical alternative to the method of placing electrodes elements in conduits on the slope of the breakwater. This led to the arrangement with tubular electrode elements placed inside perforated wells, with free flow of seawater, buried in porous rocks of the breakwater for protection against ice. The tubular electrode elements are placed in the tubes below the lowest tide levels found at the electrode sites to ensure that the elements are always in contact with seawater.
The new well design no longer require any complex concrete structures in the form of head blocks and protective slab for mechanical support and protection of the tubes or wells.
Other economical advantages that can be gained by using the well electrode concept include:
Smaller breakwaters as the breakwaters with the well concept can be placed closer to the shore. This was also resulted in smaller infrastructures such as access road and buried cable duct banks on the breakwater.
Elimination of the safety fence surrounding the electrode stations as electrode elements are now placed in wells buried in the breakwater that will provide a simple security barrier against electrical risk. In the previous design security fence was required to prevent the public from intruding inside the electrode station.

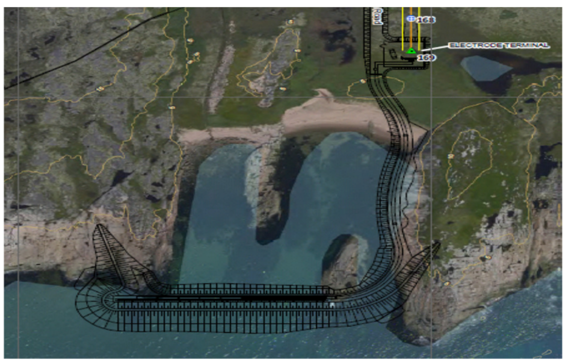

Fig.3 Aerial Photo of case study No.1 (LAD)

Fig.4 Aerial Photo of case study No.2 (DOP)

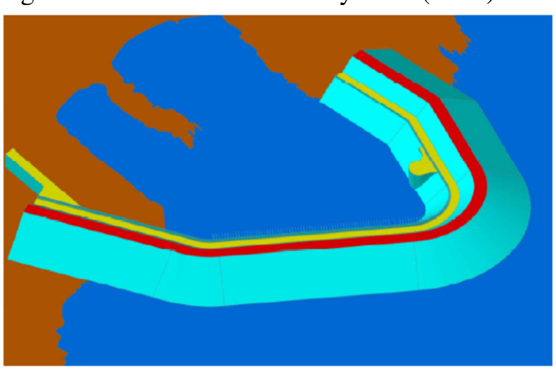

Fig.5 3D Volumetric Soil Model of case study No.1

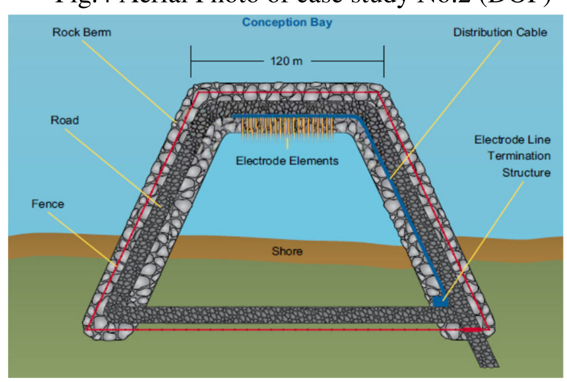

Fig.6 Volumetric Soil Model of case study No.2

3.1. Modelling Challenges in relation to Design Stage

It should be noted that design study and an accurate current distribution calculation of beach electrode elements require an intensive three-dimensional modeling of embedded electrode wells, surrounding soil, sea water, fresh water and electrode elements. This is because beach electrodes are generally high in term of number of elements and located on the beach inside of the waterline, and the active part of the electrodes contact the soil or with underground water but not direct with seawater as depicted in figures 4 and 5.

The analysis of grounding systems buried in a soil including heterogeneous / multi-volume is performed based on a low frequency moment method combined with an application of boundary element method as explained in the following section 4 [4-6]. The conductors of the grounding grid are assumed to be cylinders of length considerably larger than their radius.
The analysis reveals that for uniform linear array the element at the edge of the electrode discharges much more current than the middle elements as a result, the life span of the edge element could be substantially smaller than of the middle elements. One solution to this problem is to add more conductors to the edge elements. There are other solutions such as to increase the size of the conductors at the edge, use of non-uniform electrode array or inclusion of limiting resistor at certain feeders.

3.2. Sensitivity Analysis

The element arrangements described were modeled and the current distribution was analyzed from the outputs of the simulations. Three cases of uniform, semi-uniform and non-uniform electrode element spacing were investigated.

Electrode Element Spacing Case	Case characteristics
uniform	Linear array with uniform spacing of 1.6 m
semi-uniform	Inner elements uniformly spaced with the exception of the outer elements at half spacing (x /2 m)
non-uniform	Continuously decreasing spacing from middle toward outer electrodes

Table 1 Electrode elements array spacing characteristic

The trends observed in current distribution among elements for the different arrangements are similar for both electrode sites. As expected, the current imbalance was high at the ends of the electrode array. In all cases, the last electrode elements on each end dissipate more current than the target value.
The current dissipation of the end elements for "Uniform" and "semi Uniform, Non-Linear" arrangements are on the same order. Based on the above investigation outer elements are always prone to higher current however it can be concluded that based on site condition non-uniform spacing could be better solution.
A sensitivity analysis was carried out to examine the effect of different element arrangements in the shore on the element current density. It is known that equally spaced elements on the extremities of a linear array will carry higher currents than those in the middle. The analysis determined that a "quasi-uniform" arrangement would provide a fairly uniform current distribution among the elements and would be feasible from constructability standpoint.

Electrode Arrangement	Maximum Current (A)	Standard Deviation
Uniform Spacing	60.4	5.65
Quasi-Uniform Spacing	50.2	3.55
Uniform Spacing by subsection	52.7	4.97
Non-Uniform Spacing	48.1	2.41
Uniform, Non-Linear Spacing	61.9	5.93

Table 2 Sensitivity of electrode current distribution

4.1. Calculation Method for Parameters of Electrode Grounding Systems

In order to guarantee the safe operation of grounding site, it is extremely important to model the realistic physical circumstances. Calculation is generally based upon the following primary parameters:
The shape, dimensions and layout of the grounding system, and the soil characteristics (soil resistivity and layered circumstances). Calculations of grounding system parameters can be classified into two categories: (i) estimation using empirical formulas and (ii) precise calculation using numerical analysis methods.
Empirical formulas are obtained based upon an approximate treatment of the grounding system using theoretical analysis and assumption that current uniformly distributes on all grounding conductors in the grounding system. However, it should be noted that this is quite different from realistic physical

circumstances. For a large-scale grounding grid, inner conductors are shielded by external conductors, leading to inhomogeneous current distribution.

Various numerical analysis methods for grounding grids in the literature are generally based upon the theory of a static current field, that is, when a current flows through the grounding system, the potential of an arbitrary point satisfies Laplace's equation; by segmenting the conductors that form the grounding system, the complex integral of the potential can be changed to summation, then the leakage current distribution of the grounding grid is obtained by calculating the self-resistance and mutual resistance of different segments and, consequently, the potential of the arbitrary point can be obtained.

In this analysis as has been pointed out in references [5-6] a method of summation is used, where every segment is treated as a point source, rather than an integral method, which treated every segment as a line element [4]. Only when the grounding conductor is divided adequately will the result using the summation method be completely equal to the result using an integral method under the same conditions. Additionally, here a multi-step method is used to calculate the distribution of current through the grounding conductors and an average potential method to calculate the mutual resistance coefficient . The multi-step method can quickly resolve the non-uniform coefficient of current distribution, and the average potential method improves the accuracy of calculating the resistance coefficient.

4.2. Theoretical Foundation of the Numerical Analysis Method

When the leakage current distribution of the grounding system is known, the surface potential distribution of the grounding system can be analyzed; touch voltage, step voltage and mesh voltage can also be calculated. The basis of analyzing the potential distribution is to calculate the potential of any point generated by the leakage current.

Fundamental equations for finding grounding parameters based on green function [4] are as follow:

$V_P = \iint_S (P,Q) J(Q) dS$ (1), **$I = \iint_S J(Q) dS$** (2) **,** $E = -\nabla V$ (3)**,** $J = \sigma E$ (4)

Based on the constant current field theory, the applied feature of numerical calculation methods is to subdivide any segment of the conductor in the corresponding grounding system into point sources or linear sources, so the integral is changed into summation in calculation. Assuming the total length of the electrode is L and the total current discharging through L is I, L is divided into n segments where the length, the center and the leakage current of the j^{th} segment are L_j, O_j and I_j, respectively, then:

$L = \sum_{j=1}^{n} L_J$ (5) $I = \sum_{j=1}^{n} I_j$ (6)

According to the principle of superposition, the potential at point P generated by the current I flowing through L can be obtained: $V_P = \sum_{j=1}^{n} G(P, Qj\,)$ (7)

So, the integral in Equation (1) can be changed into simple summation in Equation (7), where $G(P, O_j)$ is so called Green's function, which is the potential at point P generated by the unit point current source with equivalent center O_j. In order to obtain the current distributions of all segments, we position the target of point P in the i^{th} segment, so G(i, j) represents the potential generating on the i^{th} segment when a unit current source is applied on the j^{th} segment. We define G(i, j) as the mutual resistance represented by R_{ij}. When i=j, R_{ij} represents the self-resistance. Equation (1) can be changed into:

$V_P = \sum_{j=1}^{n} R_{ij} I_j$ (8)

Assuming that the potential of the grounding electrode is Vg, according to the boundary condition Equation (8) can be changed into: $\sum_{j=1}^{n} R_{ij}I_j - V_g = 0$ (9) , $I = \sum_{j=1}^{n} I_j$ (10)

The above two equations form an $(n+1)^{th}$ order equation which can be represented in the form of a matrix: $[R][I] - [A]V_g = [B]$ (11) , $Rg = \frac{Vg}{I}$

where; [R] is the resistance matrix with self (R_{ii}) and mutual (R_{ij}) as main entries,

$$[R] = \begin{bmatrix} R_{1,1} & R_{1,2} & R_{1,3} & R_{1,4} & \cdots & R_{1,n} \\ R_{2,1} & R_{2,2} & R_{2,3} & R_{2,4} & \cdots & R_{2,n} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdots & \cdot\cdot \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdots & \cdot\cdot \\ R_{n,1} & R_{n,2} & R_{n,3} & R_{n,4} & \cdot\cdot & R_{n,n} \\ 1 & 1 & 1 & 1 & \cdots & 1 \end{bmatrix}, \; I = [I_1, I_2, .. I_n]^T, \; A = [I, I, .. I, 0]^T, \; B = [0, 0, .. 0, I]^T$$

Therefore, having the resistance matrix and by solving the set of equations (8 to 11), one can obtain the distribution of the leakage current flowing through electrode I_j, (or R based on adequate set of field measurement) , the potential rise of grounding electrode Vg and the grounding resistance. In addition, the potential of any point P in soil can be obtained using above equations respectively.

5. Site Measurement Results

After completion of the design and installation, and during commissioning stage, off-line current injection tests as well as fall of potential tests were conducted. Test circuit configuration is depicted in figure 7. The following tests were performed to verify the design and performance of the stations.

- Current distribution between sub-electrode and sections (figure 8 and figure 9)
- Electrode grounding station resistance to remote earth (table 3)
- Electrode potential rise

It shall be noted that here a dc generator used as source for current injection purpose. On the other hand, a corresponding meshed test electrode was placed at sea shore at distance of 2km for current point interface between earth path and cable return circuit. Test current was set at 25 times lower than rated current ($I_{test} = 0.04I_{rated}$) to respect safety constraints and measurement limitation. The measured currents in the electrode elements were scaled to the corresponding electrode grounding station operational current values for comparison with the simulated results (Figs 10-11). All elements must carry portion of the I_{test} and the ideal situation is that the current is evenly distributed. However, some unbalance between the currents was expected in accordance with the design. As depicted in the figures (10-11), there are some discrepancies compared with simulated values which are due to tolerances in soil characteristics. As per presented equations (8 to 11) and measured element currents, associated self and mutual resistance matrix of electrode elements were calculated. The calculated resistance parameters were used as basis for the assessment of application of limiting resistor at outer elements as a mitigation option. It should be noted that larger current at some outer electrode elements and especially during N-1 contingency are not necessarily cause for an immediate required mitigation, however in long term it may cause greater consumption of electrode material in anodic operation., larger chlorine gas generation and larger thermal heating in the wells. The current in any element cable or feeder cable with all sub-electrodes in service or one sub-electrode out of service (N-1 contingency) should not exceed the rating of the cable.

Table 3-Summary of Measured Resistance (based on Eq 11)

Grounding Site	R_g (m Ω) to Remote Erath Measured	Max R_{ii} (Ω) Self Resistance	Min R_{ii} (Ω) Self Resistance	Max R_{ij} (Ω) Mutual Resistance	Min R_{ij} (Ω) Mutual Resistance
LAD	130	0.72	0.57	2.06	1.3
DOP	70	0.49	0.36	0.96	0.68

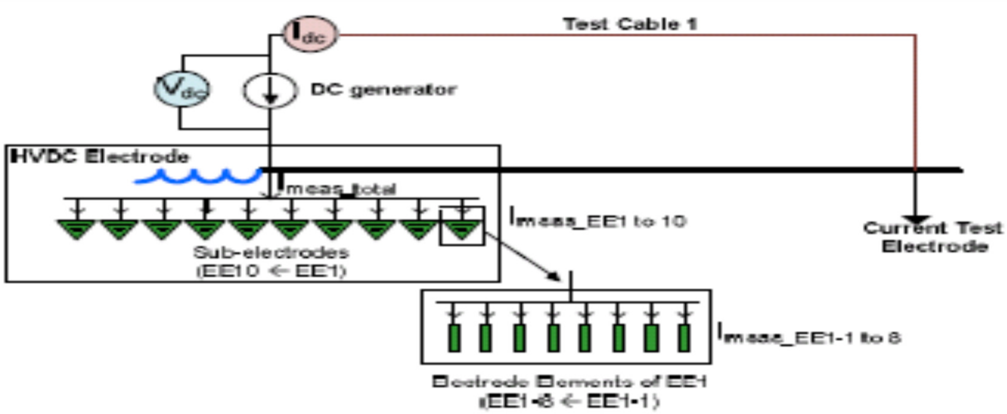

Figure 7 Test Circuit Configuration

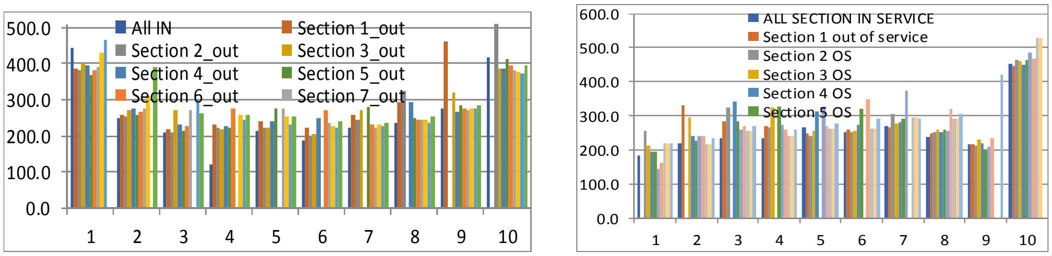

Figure 8 -DOP & LAD measured section currents (A)

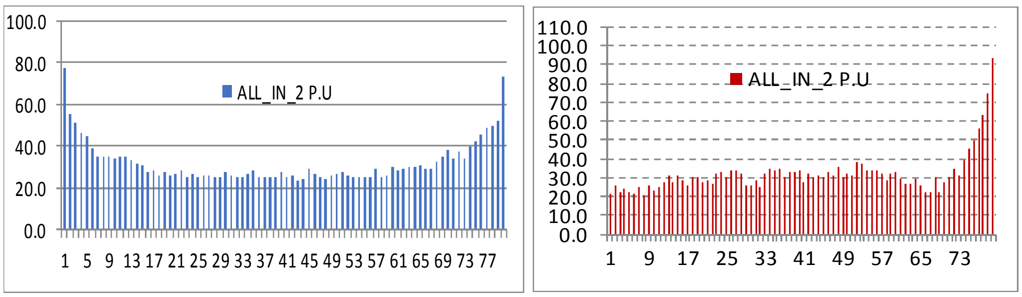

Fig 9 -DOP & LAD measured well currents (A)

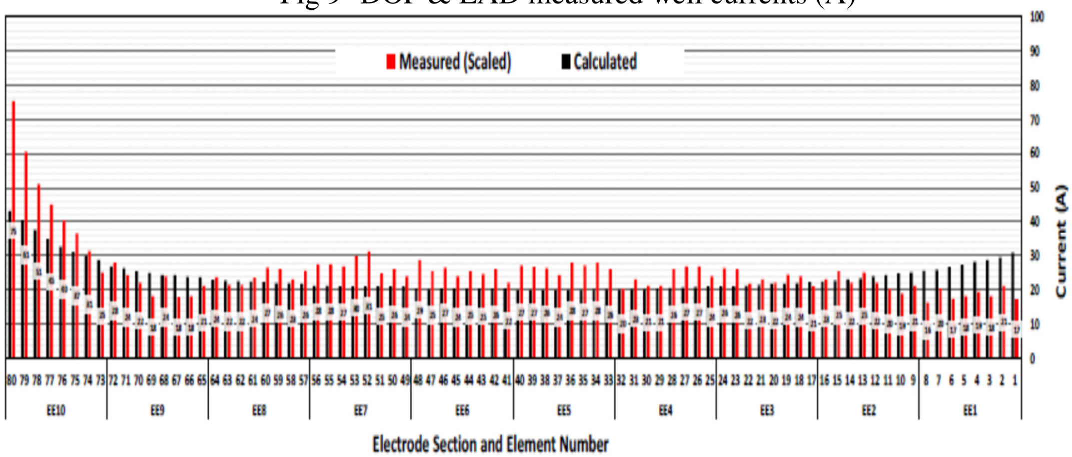

Figure 10 Comparison of Electrode Current Distribution (Measured VS calculated)

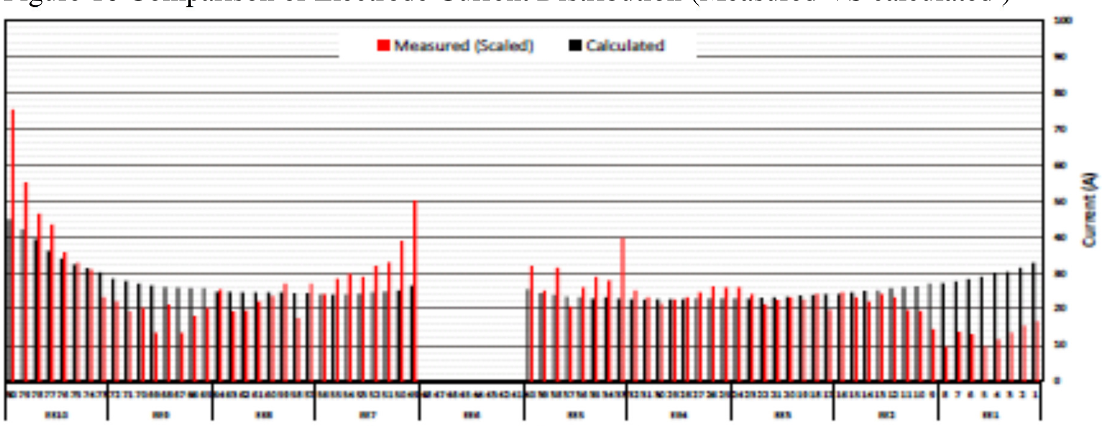

Figure 11 Comparison of Electrode Current Distribution (Measured VS calculated-N-1 case)

6. Conclusion

Design challenges and validation methodology for a special grounding electrode system, based on field testing at site versus simulated results obtained during planning stage were discussed.

Measurement and calculated electrodes' main characteristics of two eighty–well (10X8) linear shore-line electrode sites are used as a case study. The considered study sites have been designed and constructed in a recently built HVDC project.

Selection of optimum number and configuration of electrode elements requires current distribution calculations in the elements in order to examine the effect of different electrode arrangements on the element current densities.

Design study and an accurate current distribution calculation of shore line electrode elements require an intensive three-dimensional modeling of embedded electrode wells, surrounding soil, sea water, fresh water and electrode elements. This is because beach electrodes are generally high in term of number of elements and located on the beach inside of the waterline, and the active part of the electrodes contact the soil or with underground water but not direct with sea water.

To guarantee the safe operation of grounding site, it is extremely important to model the realistic physical circumstances in design stage.

Methodology for calculation of resistance matrix of an array of grounding electrodes is discussed. This approach can be adapted for design of current limiting resistor, in case of required mitigation option for outer electrodes current distribution.

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