AC Interference Study on DESFA Natural Gas Pipeline due to the Operation of a 20.8 MW Wind Park

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Abstract

The paper thoroughly describes a case study that pertains in the AC Interference evaluation on 28.5km of DESFA natural gas pipeline routing near a 20.8MW Wind Park. The analysis and discussion of results account for the steady-state and fault energisation conditions that apply in the Wind Park. Moreover, the paper also includes a description of the mitigation steps that are necessary to ensure that the AC interference impact on the DESFA pipeline, remain within the limits dictated by EN 50443.

1. Introduction

AC interference in pipelines due to their proximity to high voltage overhead lines can result in electrical hazards to people and other adverse effects ranging from accelerated corrosion to pipeline failure. AC interference can be a threat during both normal operation and fault conditions. Predicting AC interference on pipelines is a complex problem, with multiple interacting variables affecting both the impact and consequences. In some cases, detailed modeling and field monitoring is used to estimate a collocated pipeline's susceptibility to AC interference, identify locations of possible AC current discharge, and design appropriate mitigation systems to reduce the effects of AC interference. Moreover, the electromagnetic interference resulting from underground HV cables should also be carefully studied as per the clauses dictated in [1]. This is because the interference principles resulting from the underground HV cables' operation is slightly more complex. To this extent, Table 1 marks the similarities and differences that arise when the electromagnetic interference on buried pipelines results from overhead lines and underground cables respectively [1].

Table 1: Similarities and differences that arise in the electromagnetic interference on buried pipelines: Overhead Lines Vs Underground Cables

Similarities	Differences
"*the magnetic field generated by the current flowing through the cable is relatively unaffected by the material surrounding the cable and the pipeline*" [1].	*"Distances of influence to the pipeline during steady-state operation are much smaller for underground cables than for overhead lines because underground cables are laid in a more compact configuration and significant magnetic field cancellation takes place"* [1]
	"Distances of influence to the pipeline during ground fault conditions are also much smaller for

	cables than for lines because the metallic sheath normally provides a return path for a substantial portion of the fault current, providing significant magnetic field cancellation" [1]

Thus, the calculation of induced voltages resulting from HV cables requires simulation tools that can take into account the geometry of the pipe, the cable with its concentric conductors, and the effect of different bonding schemes. This type of calculation can be handled with commercially available computer software. However, this detailed computer modeling generally requires extensive data collection, field work, and subject-matter expertise.

Moreover, the limits for permissible interference are given in the clauses of EN 50443 [2]: The limits provided apply for:

- to the total interference result, produced on a single pipeline, or pipeline system, by all the a.c. interfering systems acting together, when considering the operating conditions of the interfering sources;
- to the interference result, produced on a single pipeline, or pipeline system, by a single a.c. interfering system acting alone, when considering the fault conditions of the interfering system.

For normal operating conditions, the interference voltage (r.m.s. value) of the pipeline system versus earth or across the insulating joints at any point normally accessible to any person shall not exceed 60 V. For fault conditions, EN 50443 dictates that the interference voltage (r.m.s. value) of the pipeline system versus earth or across the insulating joints at any point normally accessible to (electrically) instructed persons shall not exceed the values given in Table 2 (Table 3 in EN 50443).

Table 2: Limits for interference voltage related to danger to (electrically) instructed persons

Fault duration	**Interference voltage**
Time (s)	**r.m.s. value(V)**
$t \leq 0,1$	2 000
$0,1 < t \leq 0,2$	1 500
$0,2 < t \leq 0,35$	1 000
$0,35 < t \leq 0,5$	650
$0,5 < t \leq 1,0$	430
$1 < t \leq 3$	150
$t > 3$	60

With regard to the limits related to damage of the pipeline systems, the clauses of EN50443 dictate the following remarks:

- The interference voltage (r.m.s. value) between the metallic pipeline system and the earth at any point of the pipeline system, or the interference voltage (r.m.s. value) between any element of the electric/electronic equipment connected between the metallic pipeline and the earth, shall not exceed 2 000 V;

- The voltage difference (r.m.s. value) across an insulating joint shall not exceed 2 000 V.
- Values greater than 2 000 V can be accepted if the plant is able to withstand such values and if there is an agreement on that.

Under fault conditions the coating stress voltage should also be examined. This is because the coating stress voltage includes not only the voltage transferred to the pipeline steel by magnetic field induction, but also the earth potential rise incurred by the nearby faulted tower injecting fault current into the earth. The coating stress voltage is defined as the voltage between the pipeline metal and the earth immediately outside the coating. Guidance on allowable coating stress voltage varies across references. NACE SP0177-2014 indicates, "Limiting the coating stress voltage should be a mitigation objective." Multiple references offer varying coating stress limits and are generally considered to be in the range of 1 to 1.2 kV for bitumen, as low as 3 kV for coal tar and asphalt, and 3 to 5 kV for fusion-bonded epoxy (FBE) and polyethylene, for a short-duration fault."[3]

2. Description of Case Study

2.1. Description of Software and Computational Methods

The work has required the development of a simulation model (using the HIFREQ module of CDEGS - Current Distribution Electromagnetic Interface Grounding and Soil Structure Analysis [4]) to enable the AC Interference evaluation on 28.5km DESFA Routing near a 28.5 MW Wind Park in Greece. In this particular case study, data entry into the HIFREQ computation software module of Multifields is achieved through a description of a network of conductors in 3D space through importing them from CAD files. HIFREQ module allows both aboveground conductors and buried conductors. It also considers not only conductive, through earth coupling between conductors, but also accounts for magnetic field inductive coupling and electric field capacitive coupling, thus providing a complete and accurate prediction of the interactions between the conductor systems modeled. The program relies on the numerical solution of Maxwell's equations. By solving Maxwell's electromagnetic field equations, the method allows the computation of the current distribution (as well as the charge or leakage current distribution) in the network consisting of both aboveground and buried conductors with topologically accurate orientations. The details of the solution methods used by the software are described in [5] and [6] and the references included therein.

2.2. Description of Physical Model

The topological arrangement of the wind turbines and the associated HV power cable routings of the 20.8MW Wind Park are displayed in Fig. 1. The wind turbines' earthing systems and their associated connections are also displayed. It is noted that the design shown in Fig. 1 is geometrically accurate and has been obtained from relevant AUTOCAD files. It is noted that the wind park benefits from 9 wind turbines (6 existing and 3 future additions). The geographically accurate routing description of DESFA pipeline is also displayed in Fig. 1

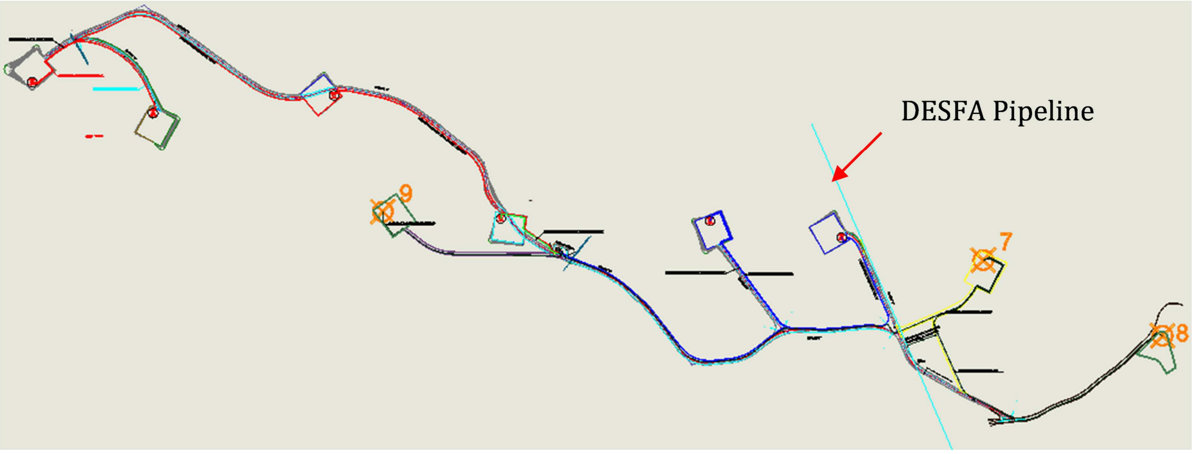

Fig. 1. CAD of 28MW Wind Park relative to DESFA pipeline routing

Using the physical model of Fig. 1, an equivalent geometrically accurate HIFREQ model has been developed. This was achieved thorough the object-based graphical environment (SESCAD) that allows for the development of arbitrary networks of conductors to be arranged in such a way to reflect the true topology of the infrastructures and cables involved in the study. Thus, the developed model includes the pipeline as well the Wind Park's earthing systems and the associated MV power cables. The HIFREQ model is shown in Figures 2 -3. Moreover, the model has accounted for the location and the design characteristics of the earthing wires that are currently installed on DESFA pipeline within the 28km considered (these are marked as 1 -13 in Fig. 2).

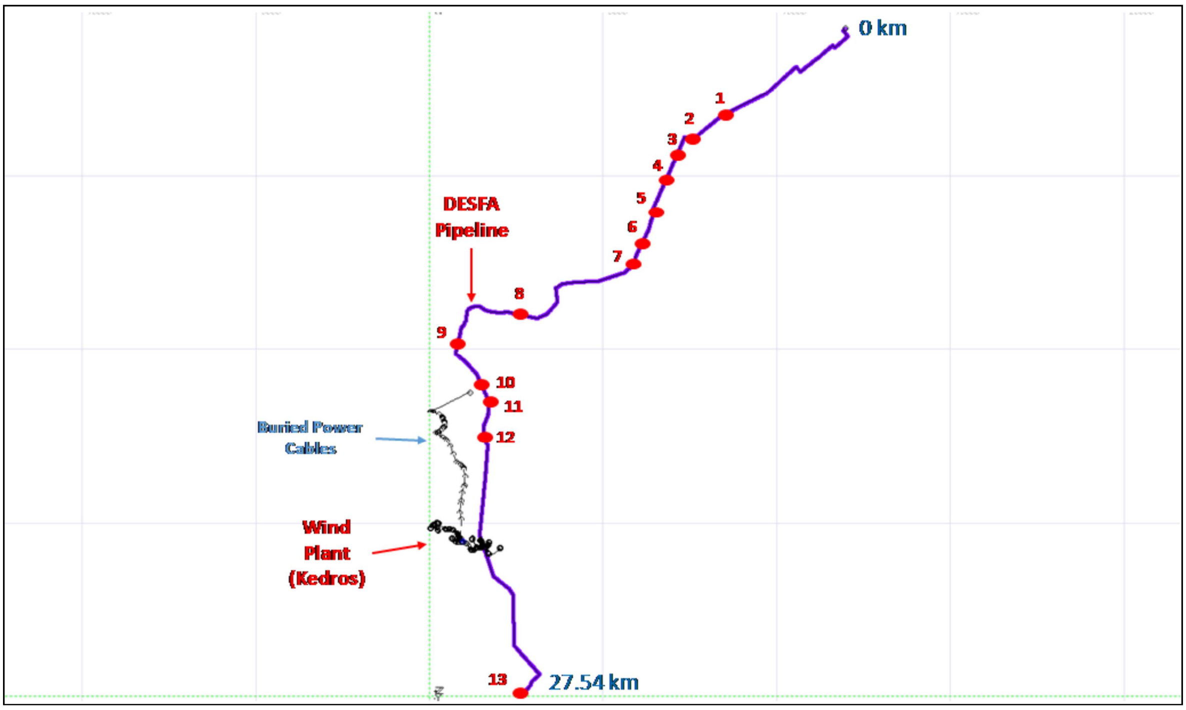

Fig. 2. Geometrically Accurate HIFREQ Template Model – Entire System

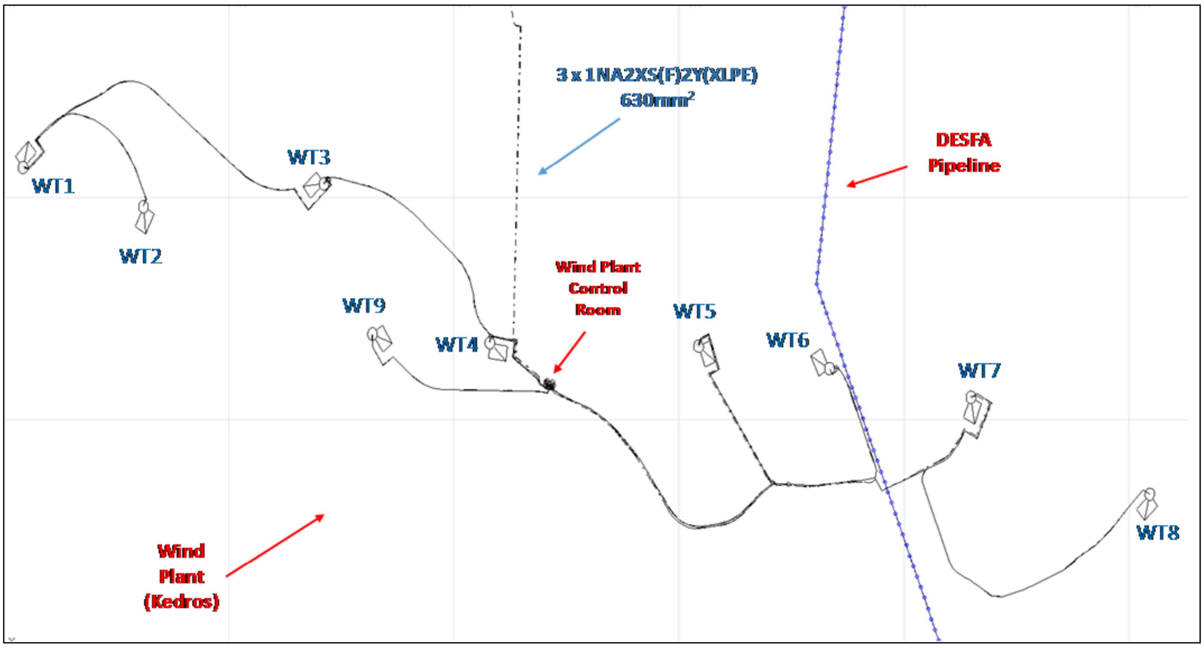

Fig. 3. Geometrically Accurate HIFREQ Template Model – Design Detail of Wind Turbines' Location

2.3 Description of Parameters used in the Simulation Process

2.3.1 Energisation under Steady State Balanced Conditions

The energisation of the MV power cables, under steady-state (balanced) conditions, is shown in Table 3.

Table 3: MV Cables' Energisation under Balanced Conditions

		Energization (per phase) – Balanced Conditions	
Connection	**Type**	**Current Source (A)**	**Phase Voltage (V_{rms})**
WT2 – WT1	NA2XS(F)2Y 3x240/25	66	6928
WT1 – WT3	NA2XS(F)2Y 3x240/25	132	6928
WT3 – C/R	NA2XS(F)2Y 3x240/25	198	6928
WT4 – C/R	NA2XS(F)2Y 3x240/25	66	6928
WT9 – C/R	NA2XS(F)2Y 3x240/25	66	6928
WT6 – WT5	NA2XS(F)2Y 3x240/25	66	6928
WT5 – C/R	NA2XS(F)2Y 3x240/25	132	6928
WT8 – WT7	NA2XS(F)2Y 3x240/25	66	6928
WT7 – C/R	NA2XS(F)2Y 3x240/25	132	6928
C/R – S/S	NA2XS(F)2Y 3x630/35	594	11547

2.3.2 Characteristics of DESFA Pipeline

The pipeline dimension, sizing and relative positioning within the ground as well as other parameters used in the computer model are provided in Table 4.

Table 4: Description of Parameters for Pipeline Model

Pipeline wall resistivity (relative to annealed copper)	20
Pipeline wall permeability (relative to free space)	250
Pipeline coating resistivity	10^8 Ω-m
Coating thickness	0.0015m
Internal Radius	0.2465 m
Outer Radius	0.254 m
Buried Depth (upper edge)	1.10 m

2.3.3 Soil Equivalent Model

The following soil resistivity model has been incorporated in the subsequent simulations:

- Two – Layer Horizontal Soil model: Top Layer 100 Ωm (2m) / Lower Layer 1000 Ωm (Infinite Depth). This is a conservative approach that acknowledges that: a) high soil resistivity values of lower in the earth layers may increase the need for mitigation, as these are the dominant layers and b) there was evidence that rocks are present at the depth of the pipeline's installation.

3. Simulation Results and Analysis

The simulations performed in this particular case study assume the following energisation conditions:

1. Steady-State Balanced Conditions at rated currents (See Table 2)
2. Steady-State Unbalanced Conditions, assuming -1.5% unbalance on Phase A.
3. Single- Phase to Ground Fault Conditions on the Wind Park's HV cables.
4. Symmetrical Three Phase Fault Conditions on the Wind Park's HV cables.

The results for both the steady state load and fault conditions are provided in this paper as:

- Touch Voltage (Worst Spherical – 1m Radius)
- Coating Stress Voltage (only for fault conditions)

It should be noted that the software provides the GPR of Conductor Metal, by drawing the pipeline conductor configuration and indicates the potentials with respect to remote earth (i.e. ground potential rise) at each conductor segment's observation point. Thus, the touch voltage (Worst Spherical – 1m Radius) is computed by the software with respect to the GPR values of all conductor segments which are wholly or partially within a 1m search radius of the observation point and the maximum value is retained.

- *Note 1:* Touch voltages are encountered by a person whose feet are touching the earth at some point and whose hands are touching an aboveground metallic structure. Most of the time, it is fair to assume that the potential of an aboveground metallic structure located electrically connected to the pipeline under study will be at a potential which is similar to that of the nearest buried pipeline conductor, since this conductor usually provides the most convenient grounding point.

- *Note 2:* The coating stress voltage is defined as the stress voltage across the coating of each conductor segment. The computed coating stress voltage includes not only the voltage transferred to the pipeline steel by magnetic field induction, but also the earth potential rise incurred by the nearby faulted section/earthing system that may be injecting fault current into the earth.

3.1. Simulation Results: Steady-State Balanced Conditions at rated MV cables' Currents

Figure 4 shows the simulated touch voltage along the length (28.5 km) of DESFA pipeline under steady-state balanced conditions.

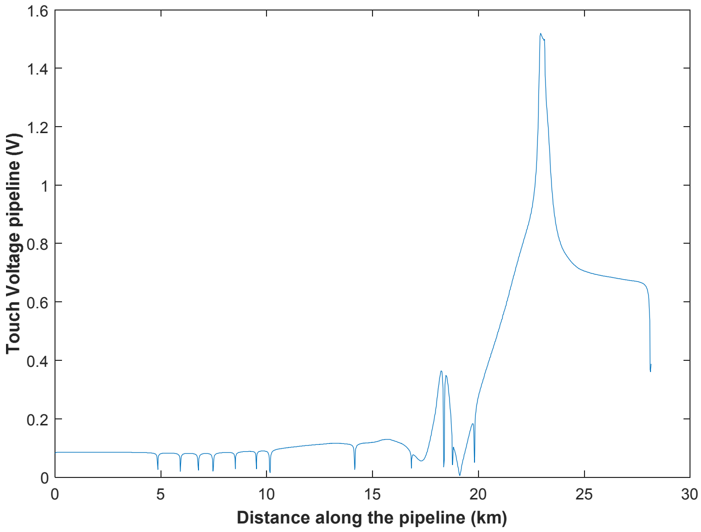

Fig. 4: Touch Voltage along the Length of Pipeline (km) – Steady State Balanced Conditions

3.2. Simulation Results: Steady-State Unbalanced Conditions

Figure 5 shows the touch voltage along the length of DESFA pipeline under steady-state unbalanced conditions. The unbalanced condition assumed in the simulations is 1.5% reduction in the current of Phase A.

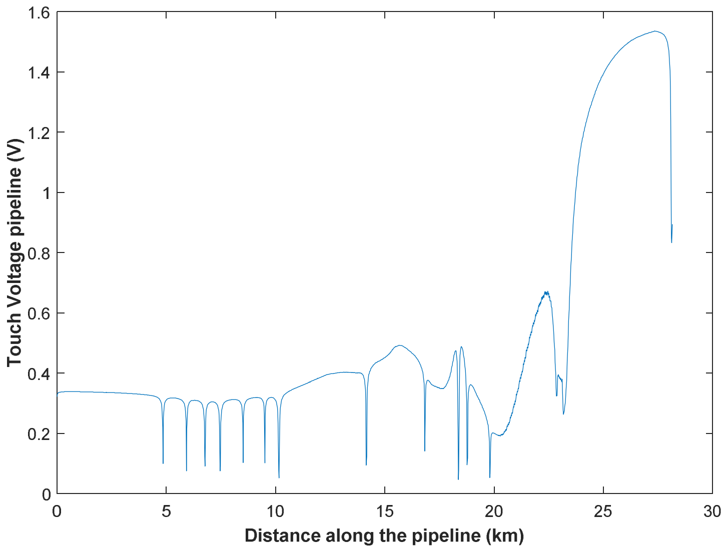

Fig. 5: Touch Voltage along the Length of Pipeline (km) – Steady State Unbalanced Conditions

3.3. Simulation Results: Fault Conditions

During fault conditions both inductive and conductive coupling should be given serious considerations in AC interference mitigation studies. However, in the case of power cables the following remarks should be taken into consideration:

- The metallic sheath of the cables provides a fault return path in the event of insulation failure, permitting rapid operation of the protection devices.
- In order to reduce circulating current and electric potential difference between the sheathings of single core three-phase cables, the sheathing is grounded and bonded at both ends of the cables.
- In HIFREQ, a fault is defined by creating a connection between the cable core and the sheath at the location of the fault. Thus, it is possible to study the effect of a multiple fault locations on the induced voltage on DESFA pipeline. However, this entails that at the fault location there is no current injected into the earth. The fault current flows through the sheath and it subsequently discharges where the sheaths are bonded: a) to the earthing system of the wind park and b) to the earthing system of the HV/MV substation.
- The latter suggests that irrespective of the fault location, inductive interference may be the dominant coupling where the cables' routing shares a parallel corridor with the DESFA pipeline. This is because no current is injected into the earth at the fault location.
- The HIFREQ model takes into account that the flow of sheath current may be in opposite direction than the flow in the core, thus any cancellation effects are taken into consideration.

The HIFREQ/ CDEGS model employed for this particular set of fault simulations is shown in Fig. 6. Fault conditions were simulated at two locations and these are explicitly marked in Fig. 6.

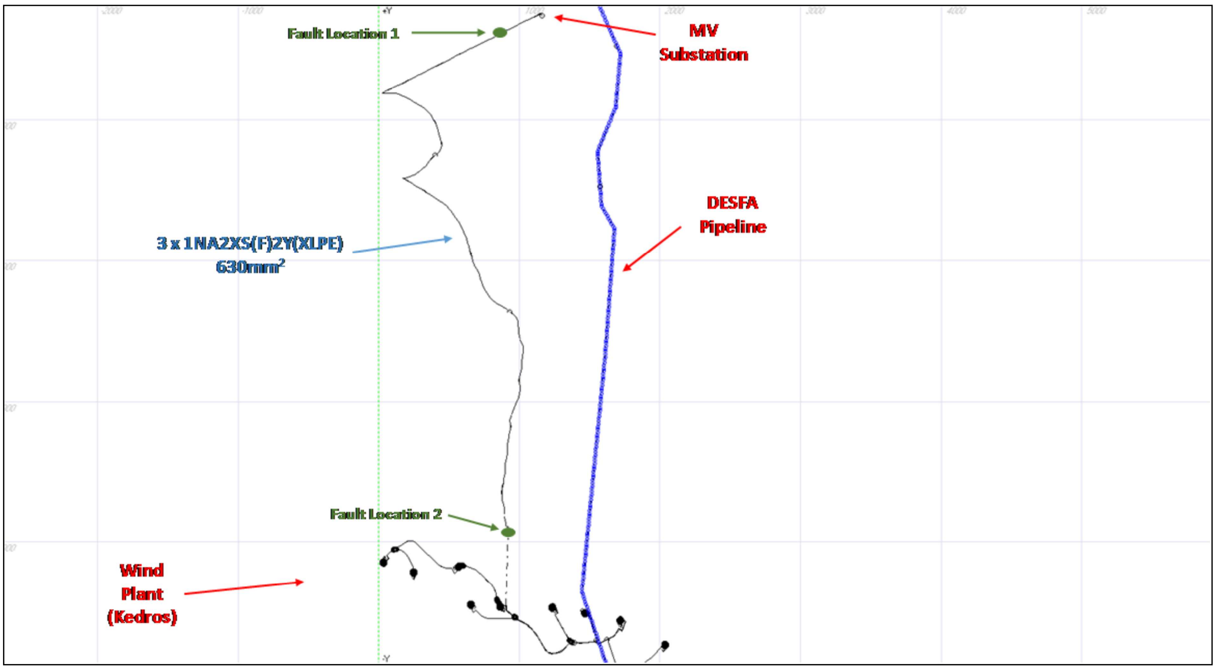

Fig. 6 HIFREQ/CDEGS model used for simulating fault –conditions

3.3.1 Simulation Results: Single-Phase to Ground Fault

The following results are assuming a fault contribution (at each fault location) of 1kA from the HV/MV substation and 2kA from the Wind Park. These are assumed values. It is noted that the results will change accordingly if different fault currents are used. Figure 7 shows the touch voltage along the length of DESFA pipeline under single-phase to ground fault conditions. The fault was simulated on Phase A at location 1 (see Fig. 6).

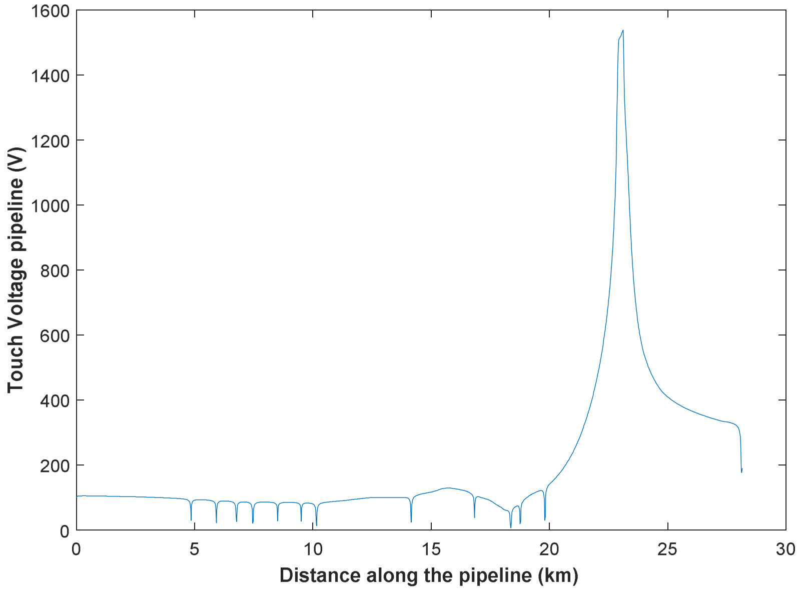

Fig. 7: Touch Voltage along the Length of Pipeline (km), Phase A to Ground Fault - Location 1

Figure 8 shows the coating stress voltage along the length of DESFA pipeline under Phase A to ground fault conditions at location 1.

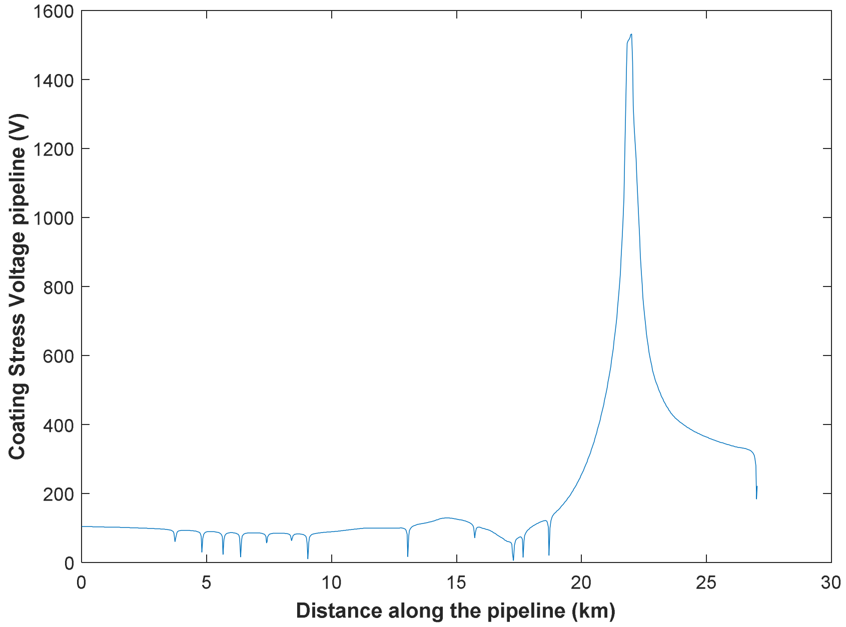

Fig. 8: Coating Stress Voltage along the Length of Pipeline (km), Phase A to Ground Fault - Location 1

Figure 9 shows the touch voltage along the length of DESFA pipeline under single-phase to ground fault conditions. The fault was simulated on Phase A at location 2 (see Fig. 6).

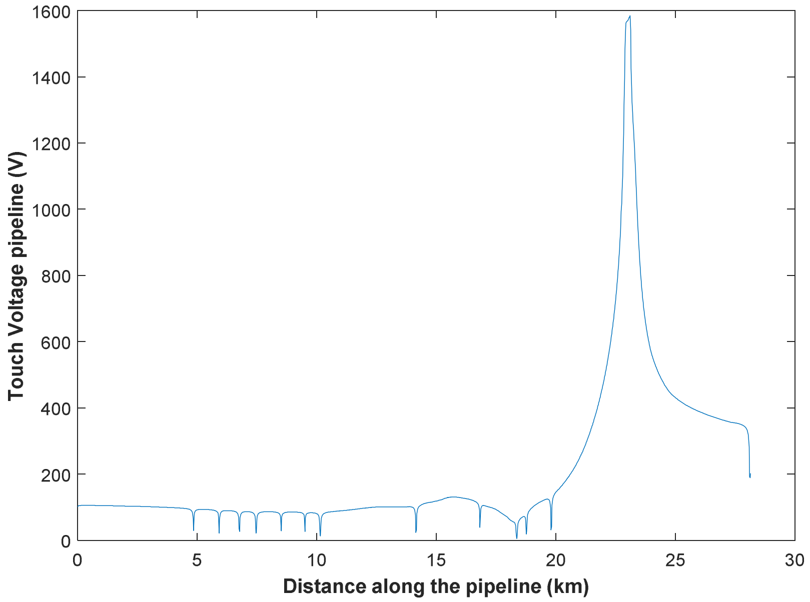

Fig. 9: Touch Voltage along the Length of Pipeline (km), Phase A to Ground Fault -Location 2

Figure 10 shows the coating stress voltage along the length of DESFA pipeline under Phase A to ground fault conditions at location 2.

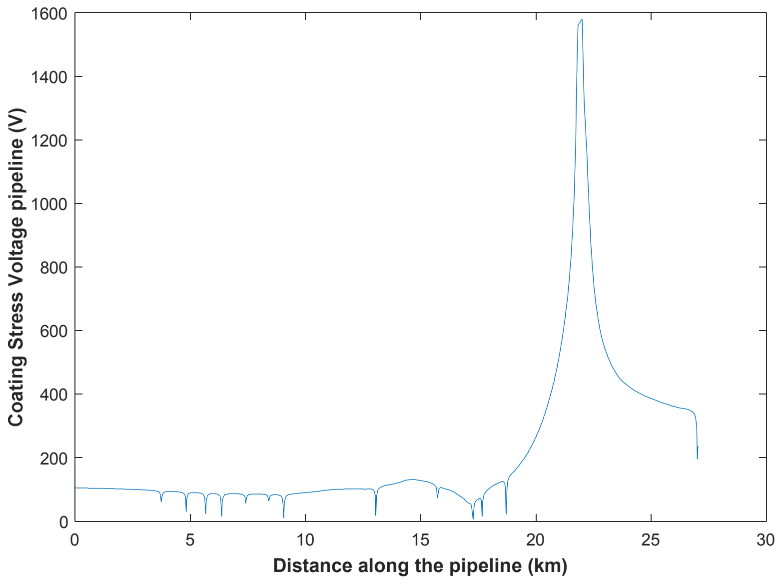

Fig. 10: Coating Stress Voltage along the Length of Pipeline (km), Phase A to Ground Fault - Location 2

Finally Fig. 11 shows the touch voltage along the length of DESFA pipeline under two different single-phase to ground fault conditions: a) Phase C to ground fault, at location 1 and b) Phase A to ground fault, at location 1 (see Fig. 6). This simulation was performed to investigate if there is any significant difference on the interference results, should the fault at location 1, occur on difference phase. As shown in Fig. 11, when the fault occurs on phase C, the induced voltage on the pipeline reduces. This is because Phase A of the cable rooting is the phase that is closest to the DESFA pipeline routing.

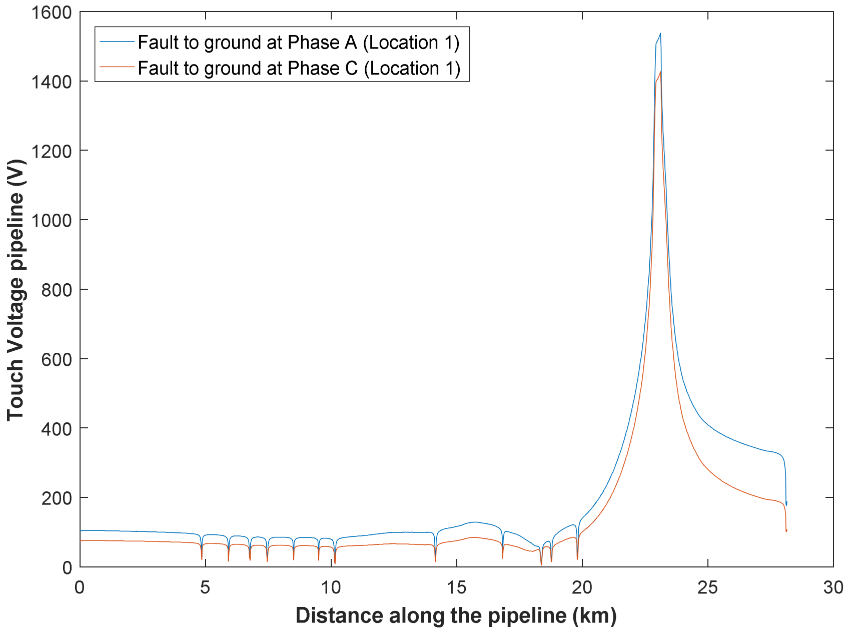

Fig. 11 Comparison of Touch Voltage along the Length of Pipeline (km), for Phase A to Ground and Phase C to Ground Faults -Location 1

3.3.2 Simulation Results: Three-Phase Symmetrical Fault

The following results are assuming a symmetrical three phase to ground fault of 7.2 kA from the HV/MV substation (Short-Circuit Level 250MVA). These are assumed values. Figure 12 shows the touch voltage along the length of DESFA pipeline under the symmetrical three-phase to ground fault conditions. The fault was simulated at location 2 (see Fig. 6).

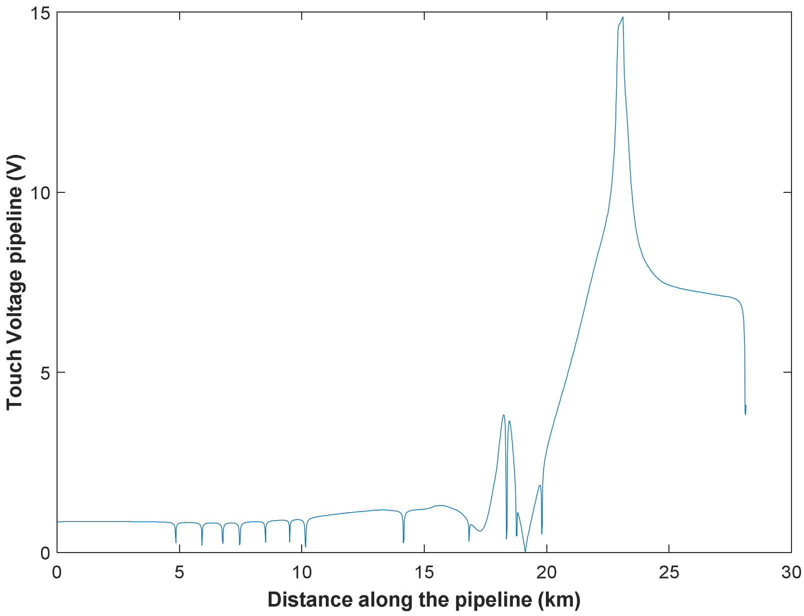

Fig. 12 Touch Voltage along the Length of Pipeline (km), 3-Phase to Ground Fault -Location 2

Figure 13 shows the coating stress voltage along the length of DESFA pipeline under three-phase to ground fault conditions at location2.

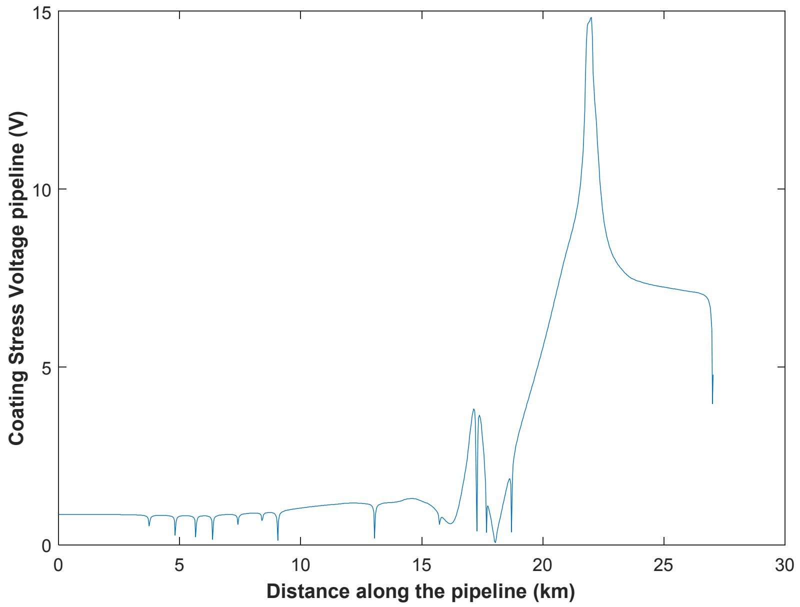

Fig. 13: Coating Stress Voltage along the Length of Pipeline (km), 3-Phase to Ground Fault - Location 2

3.4. Analysis of Simulation Results and Suggested Mitigation Solution

In all simulation results (steady-state balanced, unbalanced and fault conditions), the voltage induced on the DESFA pipeline peaks in the region between 21.76-23.01km of its routing. The reason for this peak can be explained through Fig. 14. This figure shows that the cables' routing is in close proximity (i.e. parallel for 212m and 188.5m respectively) with the DESFA gas pipeline. This exacerbates the inductive interference coupling on the pipeline in this particular region, under both steady state and fault conditions. The distances between the gas pipeline and cables at these parallel routings are at 7 and 58 m respectively, thus one routing is within, while the other is outside the interference distance of 50m dictated by EN 50443.

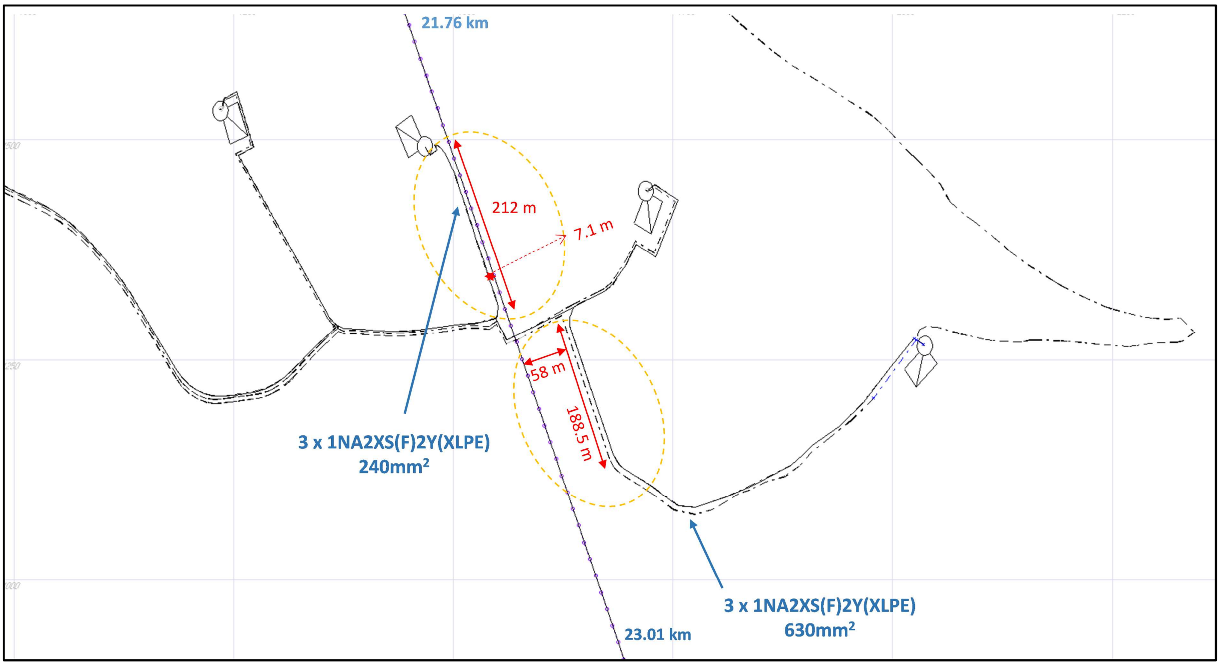

Fig. 14: HIFREQ model illustrating System topology to explain the region where inductive interference is dominant.

Table 5 summarises the maximum touch and coating stress voltages obtained for all case studies/ conditions examined in this case study.

Table 5: Summary of Results

Condition Examined	Maximum Touch Voltage	Maximum Coating Stress Voltage	Touch Voltage Limit as per EN 50443	Coating Stress Voltage Limit as per EN 50443
Steady State Balanced Conditions	1.52 V	-	60 V	-
Steady State Unbalanced Conditions	1.54 V	-	60 V	-
Single Phase to Ground Conditions	1537.79 V	1532.23 V	650 V (fault duration 0.5 s)	2000 V
Three-Phase Symmetrical Fault Conditions	14.87 V	14.82 V	650 V (fault duration 0.5 s)	2000 V

The results in Table 5 suggest that in the case of a single-phase to ground fault , the maximum voltage safety limit suggested by EN 50443 (i.e. 650 V for a 0.5 seconds fault duration) is violated. To mitigate this violation, it is proposed to add two additional earthing electrodes as suggested in Table 6.

Table 6: Suggested Mitigation Action

No.	Connection @ Pipeline (km)	Length of Electrode (m) / km
1	22.590 km	50m / 22.540 km -22.590 km
2	22.630km	100 m/ 22.630km -22.730 km

The effect of adding these two additional electrodes is shown in Fig. 15. That is, the touch voltage under single phase to ground fault conditions is about 620V and thus the 650V threshold limit is not violated. As for the step voltage, it will hardly be violated as the safety limit is even lower than the touch voltage.

4. Future work

The effect of higher resistivity and thickness of the gas pipeline coating would be interesting to be examined using the same methodology.

Furthermore, the effect of lightning strike on a nearby wind turbine tower has not been taken into consideration in the present work. The effect of such a nearby lightning strike on both pipeline integrity and safety is worth being analysed in a future project.

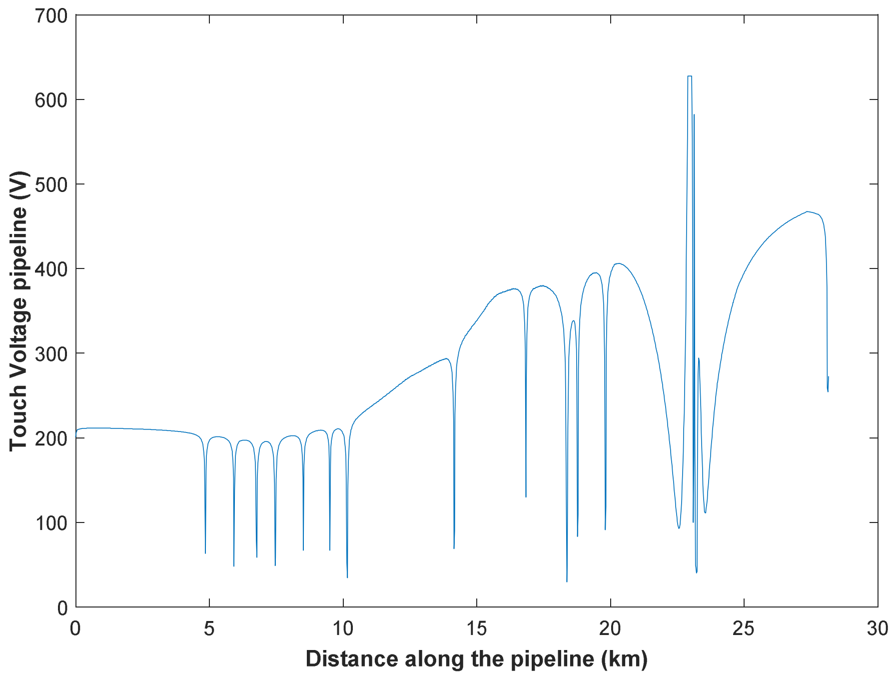

Fig. 15: Touch Voltage along the Length of Pipeline (km), for Phase A to Ground Fault - Location 1 under the proposed mitigation action.

5. Conclusions

This article presents a case study that pertains in the AC Interference evaluation on 28.5km of DESFA natural gas pipeline routing near a 20.8MW Wind Park. It is well established that AC interference is dominated by a number of factors and any simplification during the calculation process may underestimate or overestimate the severity of the impact. Detailed modelling is required and this should be exhaustive both in terms of steady state and fault conditions. This is necessary to approach any mitigation design conservatively but at the same time, sensibly and cost-effectively; acknowledging what influencing parameters should be considered and what can be safely neglected. As final note, we wish to note that the mitigation design's competence under fault conditions is crucial for the resilience of the pipeline system. That is, the ability of the pipeline system to sustain low probability but high impact events.

References

[1] Principles and Practices of Electrical Coordination Between Pipelines and Electric Supply Lines, CAN/CSA Standard C22.3 No. 6-13, 2013.

[2] EN 50443: “Effects of electromagnetic interference on pipelines caused by high voltage a.c. electric traction systems and/or high voltage a.c. power supply systems”, 2012.

[3] R. A. Gummow, “Cathodic protection considerations for pipelines with AC mitigation facilities”, Report for PRCI and AGA. PR-262-9809, 1999.

[4] CDEGS Software V15.6, Safe Engineering Services & Technologies Ltd Montreal, Quebec, Canada Est. 1978.

[5] F. P. Dawalibi and A. Selby, “Electromagnetic Fields of Energized Conductors”, IEEE Transactions on Power Delivery, Vol. 8, No. 3, July 1993, pp. 1275-1284.

[6] A. Selby and F. P. Dawalibi, “Determination of Current Distribution in Energized Conductors for the Computation of Electromagnetic Fields", IEEE Transactions on Power Delivery, Vol. 9, No. 2, April 1994, pp. 1069-1078.