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Improvement of the Destructive Interference Method in the Mitigation of PLC Radiation of Imbalanced Impedance Electrical Networks

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Abstract: Communication technology by power line carrier (PLC) marks its return with the advent of energy-mix. Although appreciated by power-grid operators and customers, this technology suffers from the emission of parasitic electromagnetic radiation. Suspected of causing heath problem, the future of this technology is linked to the level of its radiation reduction. This radiation, which is mainly due to the common mode current, can be attenuated by many ways such as the destructive interference method. The destructive interference method is a dynamic mitigation method mainly used on indoor PLC network. The mitigation of PLC radiation by this method gives reduction rates of more than 24 dB on a balanced impedance electrical network. Unfortunately, the effectiveness of this method decreases sharply depending on the level of network instability (impedance imbalance). This work focuses on improving the effectiveness of the destructive interference method on certain points of the network (point of weak mitigation or amplification of radiation) in an unstable environment. This improvement of the method is centered on the adaptation of the mitigation parameters (phase and amplitude) via a sequential mode of action. The positive impact of the improved method, although focused on a specific area, extended throughout the network. For a network with imbalanced impedance, the average rate of mitigation with this new method exceeds 11 dB.

Keywords: Power Line Carrier, Electromagnetic Radiation, Common Mode Current, Destructive Interference Method, Impedance Imbalance

1. Introduction

The advent of smart-grids has given new life to power line carrier or PLC. This communication technology allows the use of the electrical network as a communication network without removing its primary function, which is the transport of electrical energy. Although endowed with several advantages for subscribers and operators, one of the challenges of PLC technology is the potential for electromagnetic radiation to be emitted from the power lines. This parasitic electromagnetic radiation can interfere with other electronic devices, as well as pose health risks to humans. To address this issue which risk to compromise PLC large-scale deployment, most of researchers have proposed the use of destructive interference to mitigate the radiation emitted by PLC systems. Destructive interference involves the use of multiple signals that are out of phase with each other, which can cancel out the overall signal and reduce radiation levels [1-4].

Softening this parasitic radiation is a vital issue for PLC as it will help this technology to comply with EMC (Electro-Magnetic Compatibility) regulations [5, 6].

The destructive interference method is one of the best techniques for mitigating Indoor-PLC radiation. Studies as ASKARI & al [7] and MESCCO [8] have investigated the effectiveness of destructive interference in reducing PLC radiation levels, with promising results.

In a stable environment (impedance stability), this method gives satisfactory results (24 to 80 dB of radiation reduction rate compared to traditional PLC systems). Unfortunately, in a real environment, with the continuous variation of the network impedance due to the connection/disconnection of equipment, the effectiveness of this method is limited [5, 6]. This is due to the static mode of action of the method. In traditional destructive interference method, the destructive action is hold by a simple signal phase shift. In general, the method is satisfactory except at certain critical points where the radiation reduction rate is mediocre.

The static mode of action of the destructive interference method must be improved so that it can continue to be among the best methods for mitigating PLC radiation, regardless of the state of the network [7].

The improvement of this mode of action will take in addition in to the phase shift, the amplitude adaptation of the destructive signal.

2. Material and Methods

2.1. Classic PLC Communication

During a classic PLC communication, the electrical wires carry in addition to the electrical energy, information modulated at high frequency as illustrated in figure 1 below [6, 8].

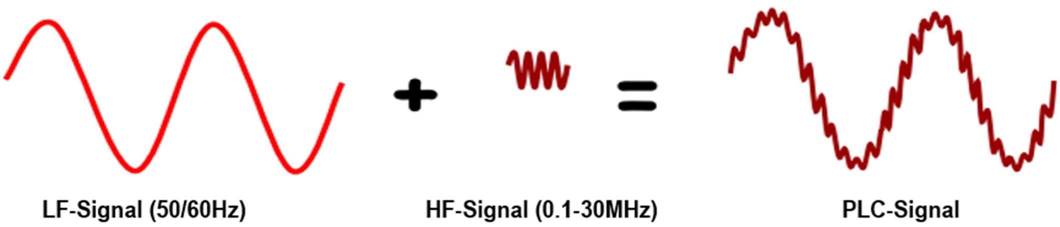

Figure 1. *Synoptic of PLC Signal.*

The signal containing the information is injected into the electrical network by a coupler (inductive or capacitive) [9, 10]. The passage of this high frequency (100 kHz-30 MHz) informative signal on wires designed for the transport of low frequency signals (50/60 Hz) causes the appearance of two types of current: the common mode current and the differential mode current shown in Figure 2.

These two currents are responsible for the electromagnetic radiation emitted by electrical wires in PLC mode [8, 11].

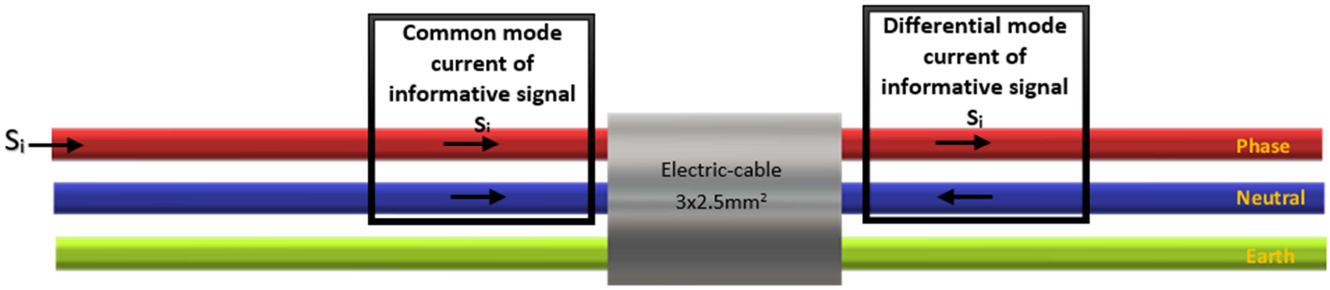

Figure 2. *Common and differential mode Current.*

Nevertheless, most of the radiation comes from the common mode because the common mode current is in the same direction both in the phase wire and in the neutral wire: the radiations emitted by these two wires are added.

On the other hand, for the differential mode, the current of the phase and that of the neutral are in opposite directions. Because of this opposition, the radiation emitted by the phase wire is almost canceled by that of the neutral wire.

2.2. Destructive Interference Method (DIM)

The A classic PLC transmission uses only two wires to convey the informative signal S_i. For electrical networks with three wires (phase, neutral and earth), only the phase and neutral wires are used, the earth wire is not used see figure 2.

The passage of high-frequency current on these two wires creates electromagnetic disturbances (conducted and radiated) in PLC mode.

The destructive interference method uses the neutral-earth pair of the electrical network to inject a second signal S_d identical to S_i but of opposite phase.

The radiation of the signal S_d (destructive) is supposed to cancel the parasitic radiation due to the signal S_i (informative) [8, 12]. The different currents (common and differential mode) generated by the signals S_i and S_d are represented in figure 3.

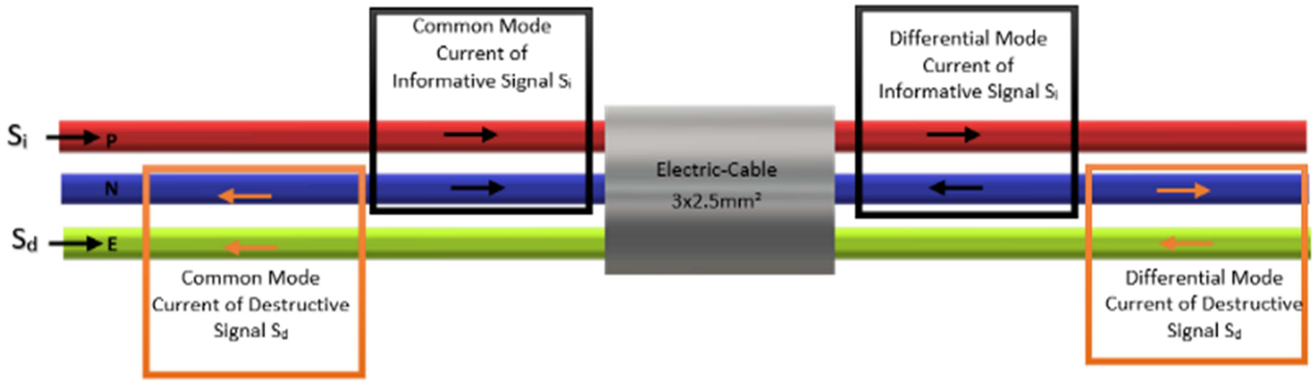

Figure 3. *Generated currents by S_i and S_d.*

In order for the S_d signal to generate electromagnetic radiation which will destroy that of S_i at a given frequency in the CPL band, the amplitudes of S_i and S_d must be equal and of opposite phases.

The implementation of the destructive interference method in a real indoor environment highlights the limits of this method on an unstable electrical network [7, 8].

Indeed, this electrical instability is due to traditional disturbances of the indoor-grid (micro-short-circuit, impedance variation, presence of harmonics, etc.) [7, 13, 14]. The presence of these disturbances requires the adaptation of the correction parameters (amplitude and phase) according to the state of the grid.

2.3. Improved Destructive Interference Method (IDIM)

Unlike the traditional destructive interference method where the informative signal S_i and the destructive signal S_d are just in phase opposition without amplitude variation, in the improved version of this method the amplitude and/or the phase will be dynamically adapted in order to reach a level of radiation close to zero. The results of the researchers [7, 8, 15, 16] show that if this new method is defined to reduce the radiation on any point near the wires, it also attenuates the radiation around the predefined point.

Consider a PLC transmission at frequency "f" on a three-wire cable in Figure 4:

1) S_i: The informative signal between the phase and neutral.
2) S_d: The corrective signal between neutral and earth.
3) Point *A*: A point near the cable where we want to mitigate the radiation of the informative signal S_i.

Thus, to calculate the signal S_d whose radiation will destroy that of the signal S_i at point *A*, the procedure is as follows [7, 8, 14]:

Step 1:

1) The source of the signal S_d is turned off and the source of the signal S_i is turned on.
2) The electromagnetic field $\overrightarrow{C_1}$ is measured at point *A*.
3) The ratio between the measured field (C_1) and the signal (S_i) is defined as the transfer function (H_1) of the phase-neutral pair at point *A*.

$$H_1\ (f) = \frac{C_1}{S_i}\Big|S_d = 0 \qquad (1)$$

Step 2:

1) The source of the signal S_i is turned off and then that of the signal S_d is turned on.
2) The electromagnetic field $\overrightarrow{C_2}$ is measured at point *A*.
3) The ratio between the measured field (C_2) and the signal (S_d) is defined as the transfer function (H_2) of the neutral-earth pair at point *A*.

$$H_2\ (f) = \frac{C_2}{S_2}\Big|S_i = 0 \qquad (2)$$

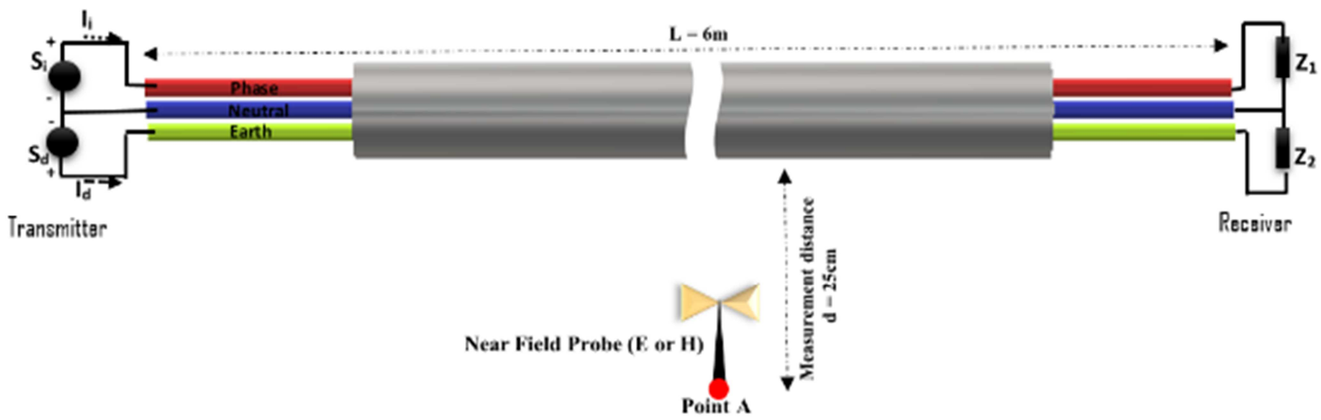

Figure 4. *Improved Destructive Interference Method (IDIM).*

For any configuration of the signals applied between the phase-neutral pair (S_i) and between the neutral-earth pair (S_d), the electromagnetic field $\vec{C}$ at the predefined point is equal to the sum of the products of the signals with their respective transfer functions. Mathematically, to calculate the electromagnetic field at point A (C_A) the relationship is defined by equation (3):

$$C_A = H_1(f).\ S_i + H_2(f).\ S_d \quad (3)$$

From equation (3), we can calculate the value of the destructive signal that can destroy the radiation of the informative signal at point A (with $C_A = 0$).

$$S_d = -\frac{H1(f).}{H2(f).}.\ S_i \ \Big|C_A{=}0 \quad (4)$$

2.4. Simulation

The high-end electromagnetism analysis software FEKO will serve as the simulation environment. A point-to-point PLC transmission will be implemented on a branch of the electrical network figure 4. Table 1 lists in a non-exhaustive way the different components of the new PLC branch:

Table 1. *Components.*

Equipment	Function
1 Function generator	Generation of Si et Sd signals
6 Meters of copper cable 3x2.5mm^2	Transmission channel
1 Near-field monopole antennas	measurement (CA, C1, C2)
3 Resistors	Network load resistors (Z1, Z2, Z3)

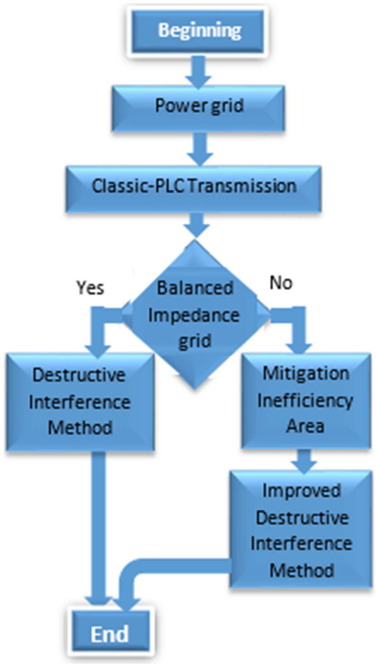

Figure 5. *Organigram.*

Figure 5 illustrates the steps of the approach used in the choice between the destructive interference method (DIM) and its improved version (IDIM) for quality mitigation.

The electrical diagram in Figure 6 represents the circuit for implementing PLC transmission on FEKO. Table 2 below gives the values of the electrical parameters according to the three transmission modes of the chosen approach:

Table 2. *Electrical parameters.*

Transmission mode	Voltage Vi (V)	Voltage Vd (V)	Resistor Z1 (Ω)	Resistor Z2 (Ω)	Resistor Z3 (Ω)
Classic-PLC	5	0	50	0	0
PLC with DIM	5	5	50	50	0
PLC with IDIM	5	1, 2 to 5	50	50	10

For the case of PLC transmission with IDIM, the values of the signal V_d are taken from equation (4).

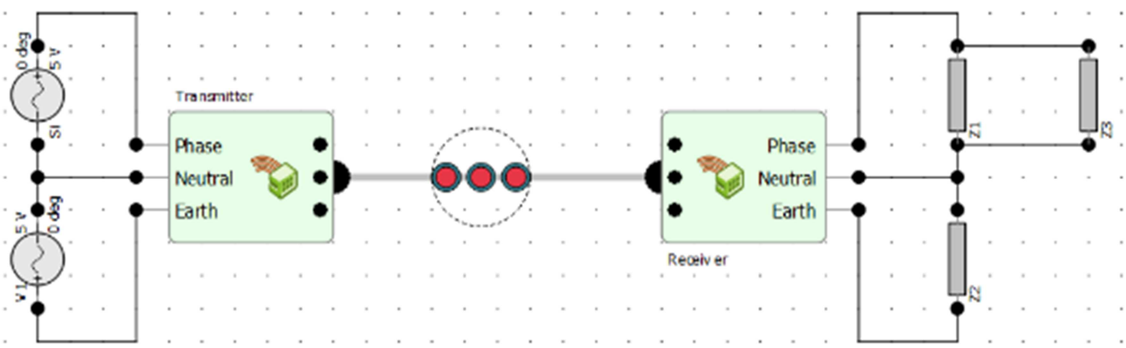

Figure 6. *Electrical Circuit of PLC Transmission.*

3. Experimental Results and Discussion

The simulation of the different scenarios on FEKO was done with:

1) Signal frequency f = 10 MHz;
2) Signals and loads: table 2.

For the graphical representations, (see figure 4):

1) The center of the cable is the origin of the land-marker;
2) Radiation measurement points: along the cable at a distance of 25 cm downwards.

3.1. Classic CPL Scenario (Without Mitigation Method)

Figure 7 represents the intensity of the electric field measured along the cable for a classic PLC transmission. The electrical-field emitted by the cable decreases as one moves away from the PLC transmitter.

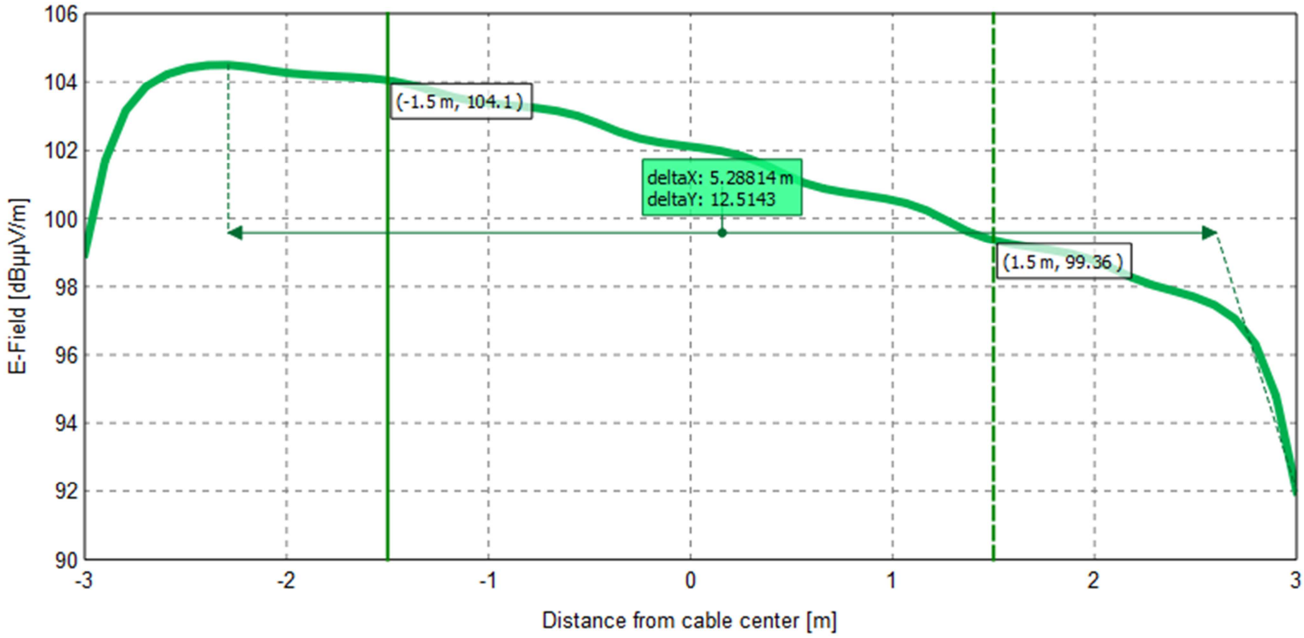

Figure 7. *Classic PLC radiated E-Field.*

3.2. PLC Scenario with Destructive Interference Method (DIM)

Figure 8 represents the intensity of the electric field measured along the cable for a PLC transmission with destructive interference method. Unlike classic transmission, the field increases as one moves away from the PLC signal transmitter.

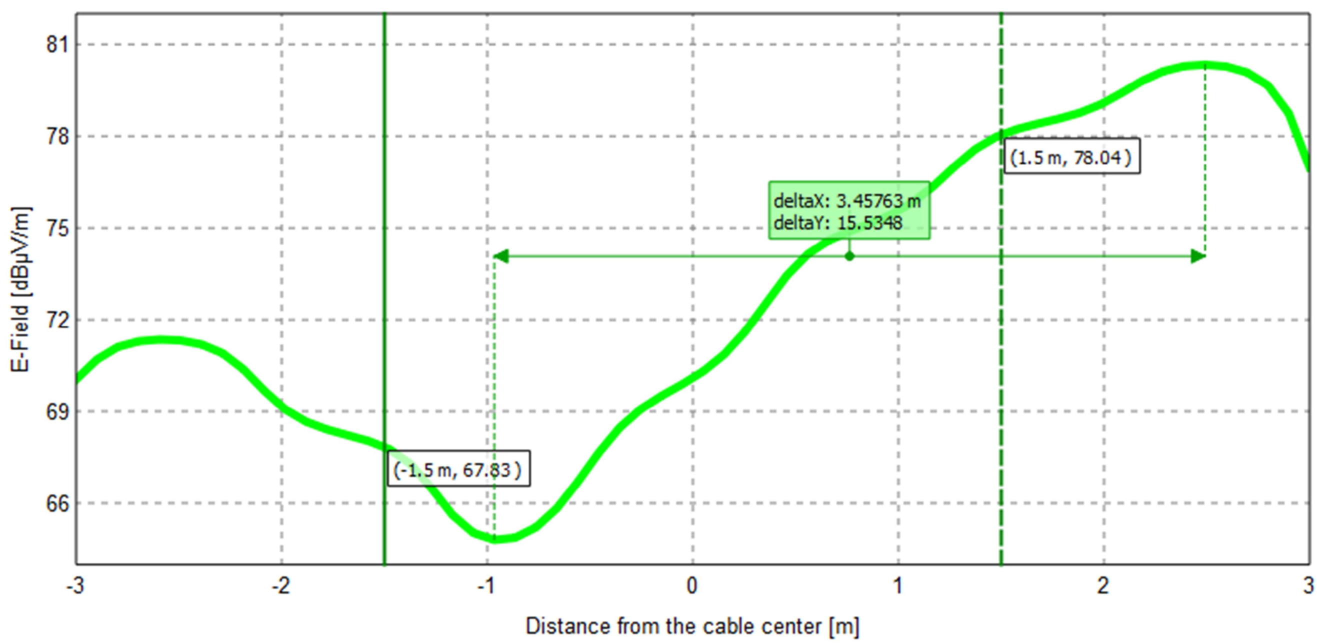

Figure 8. *Radiated E-Field of PLC with Destructive Interference Method.*

The method of destructive interference allowed us to have an average reduction in the intensity of the radiation of 29.06 dB. This result is close to the 24 dB of MESCCO [8] but far from the 50 dB of ASKARI & al. [7] and 80 dB of VUKICEVIC & al [15, 16] figure 9.

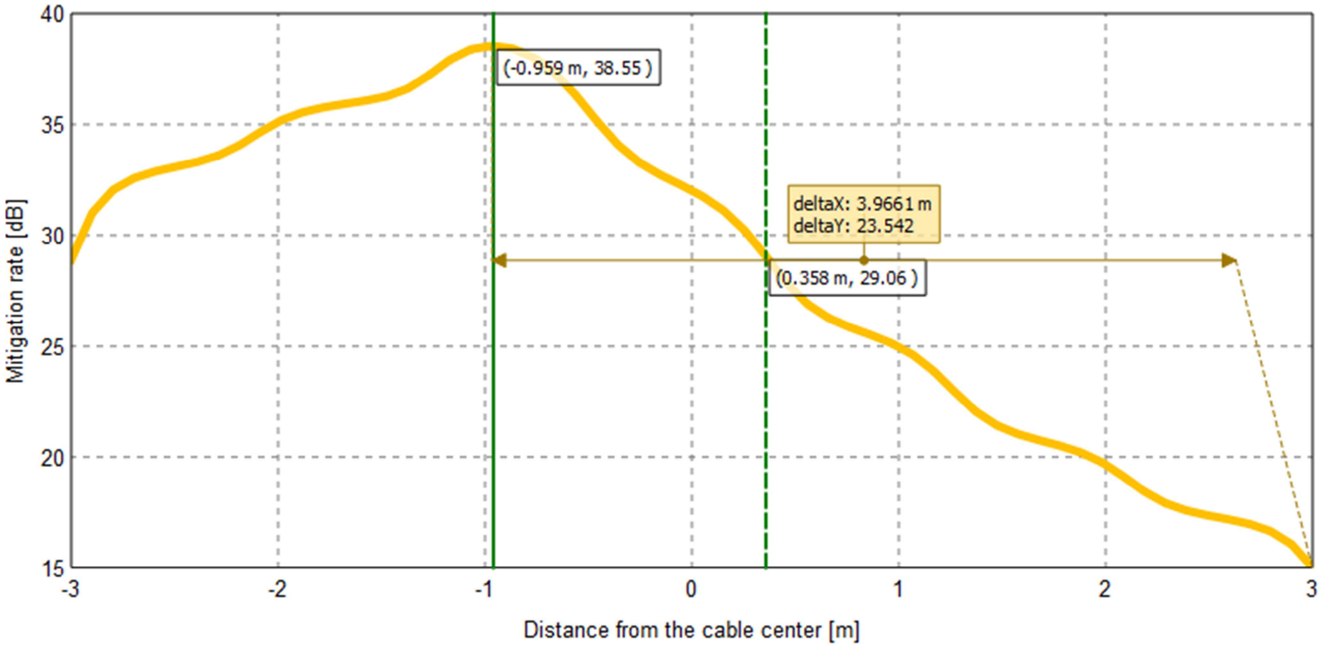

Figure 9. *Mitigation rate of balanced impedance network.*

This average reduction rate of 29.06 dB of the steady state decreases rapidly with the connection and/or disconnection of devices on the network, as shown in Figure 10.

Connecting the Z3 resistive load reduced the effectiveness of the method by almost 60%: The average reduction rate fell from 29.06 dB to 11.9 dB. Apart from the fall in the average rate, we also observe the presence of an area of inefficiency in the DIM (the last two meters of the cable). This zone is subdivided into two sub-zones on either side of point *A* (point where the reduction rate is zero):

1) A low radiation mitigation sub-zone (in green) where the reduction rate is less than 2.5 dB.
2) A radiation amplification sub-zone (in red) where the reduction rate is negative.

This reduction in the effectiveness of the method is drastic when approaching the load (source of the imbalance). At the level of the receiver, for example, the rate is less than -10 dB, which confirms the limitations of the destructive interference method within an imbalanced impedance electrical network.

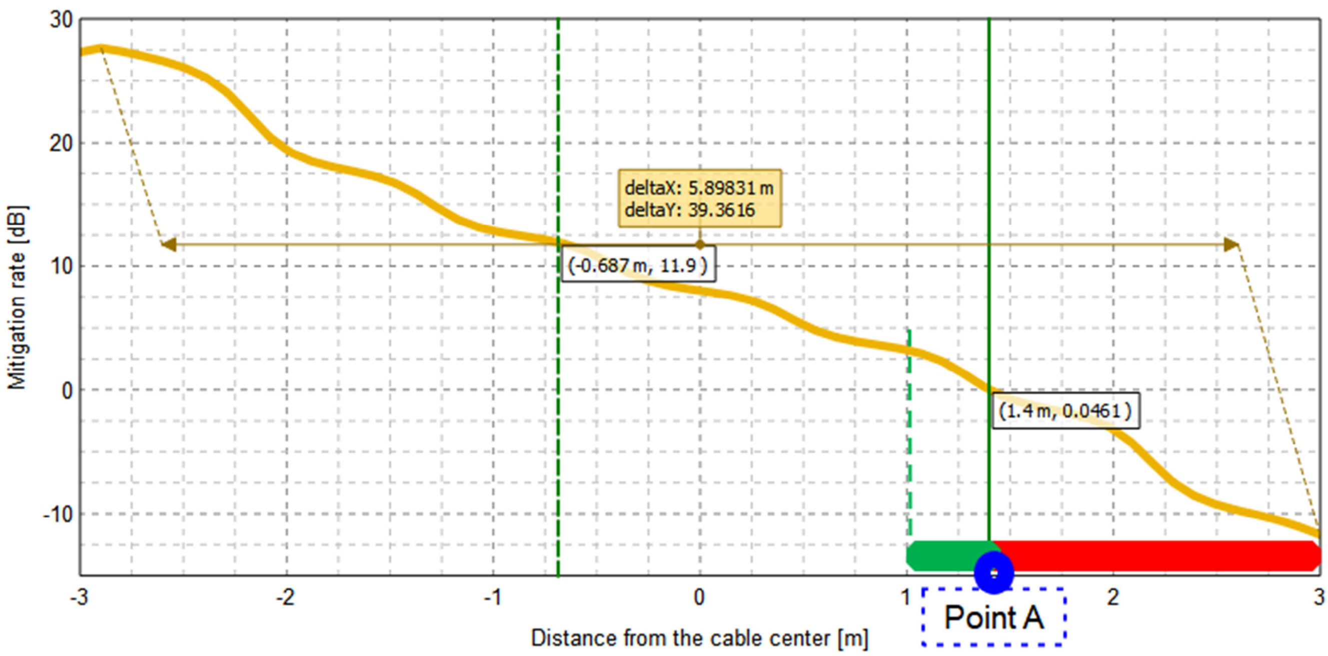

Figure 10. *Mitigation rate of imbalanced impedance network.*

The drop in efficiency of the destructive interference method is greater when the load Z3 is capacitive or inductive

[7, 17]. An improvement (adaptation of the destruction parameters) of this method of mitigation of PLC radiation is necessary for an efficiency, which will not be linked to the state of the network.

3.3. PLC Scenario with Improved Destructive Interference Method

The improvement of the PLC radiation mitigation method by destructive interference based on equation (4) consists in focusing this reduction on a predefined point near the grid. The value of the destructive signal S_d depends on the point where the reduction of the radiation is to be focused, as shown in figure 11.

Point A in figure 10 being the point where the reduction rate is zero with DIM, we will try to reduce the radiation on this point with the improved version of the method (IDIM). Figure 11 gives us the value of the destructive signal adapted for an improvement in the reduction rate centered at point *A* (S_d=*3.222 Volts*).

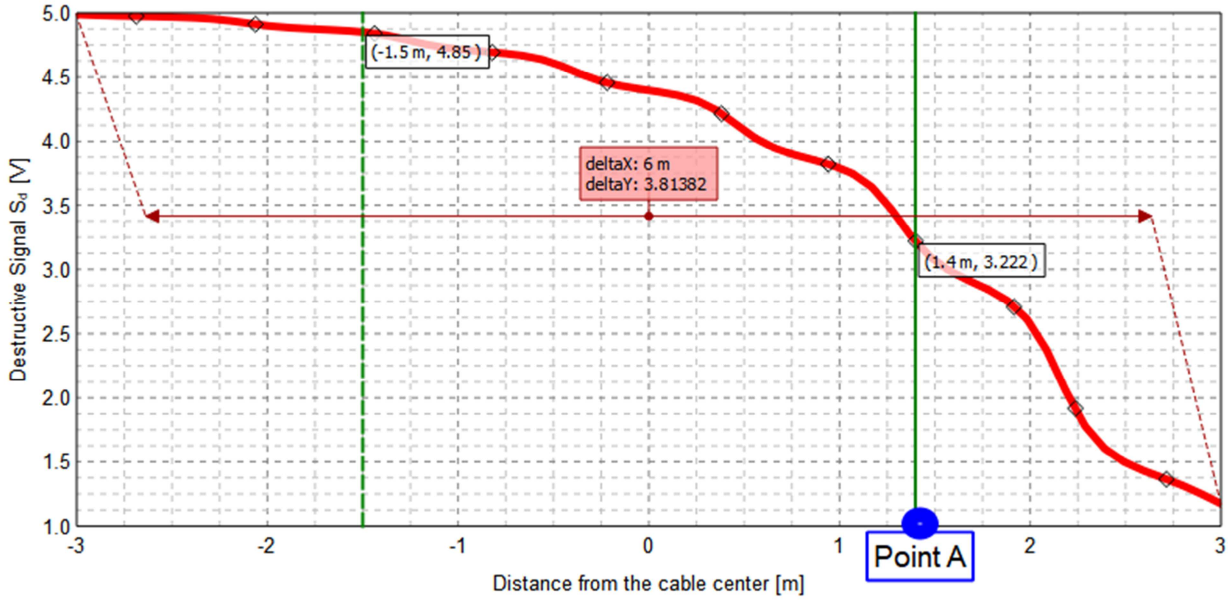

Figure 11. *Adapted value of destructive signal* S_d.

The implementation of the improved method at point A showed its positive impact on figure 12. The reduction rate which was 0 dB with DIM (figure 10) increased to 5.16 dB with IDIM (figure 13). Better, the average rate is always positive although the correction is centered on a predefined point (point A): By wanting to reduce the radiation on a predefined point, we also reduced the radiation in its vicinity as in those researches [8, 15, 18].

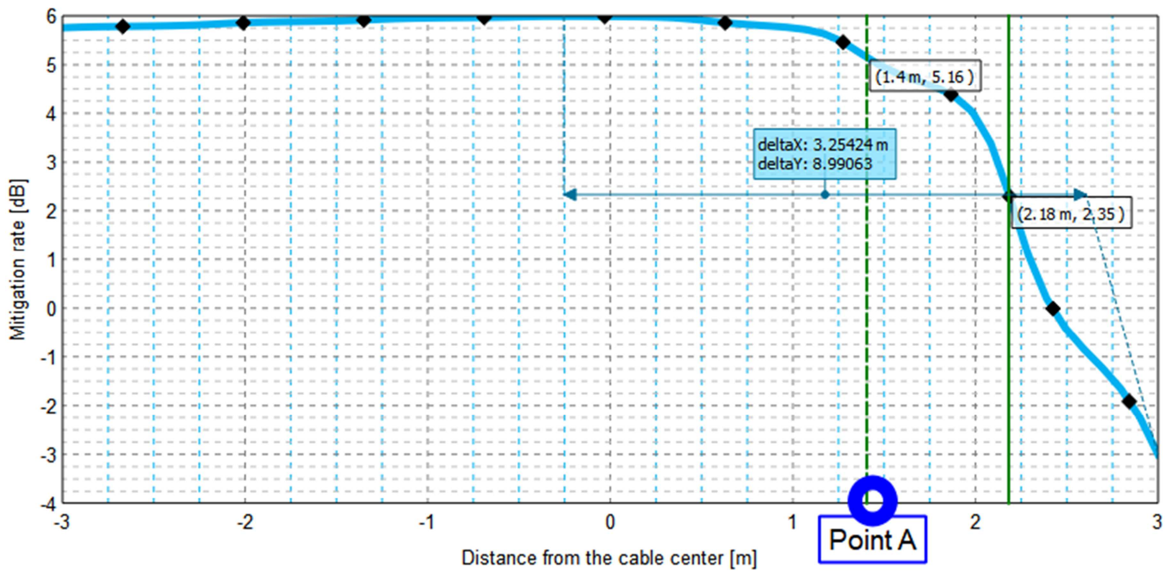

Figure 12. *Mitigation rate of the improved method at point A.*

Figure 13 is a superposition of the radiation curves (E-field) emitted by the three types of transmission of our approach:

1) The curve in red (Classic-PLC) represents the radiation of our cable under simple PLC transmission (without radiation mitigation method).
2) The curve in blue (DIM) represents the radiation of our cable under PLC transmission with the destructive interference method.
3) The green curve (IDIM) represents the radiation of our cable under PLC transmission with the improved destructive interference method focused at point A.

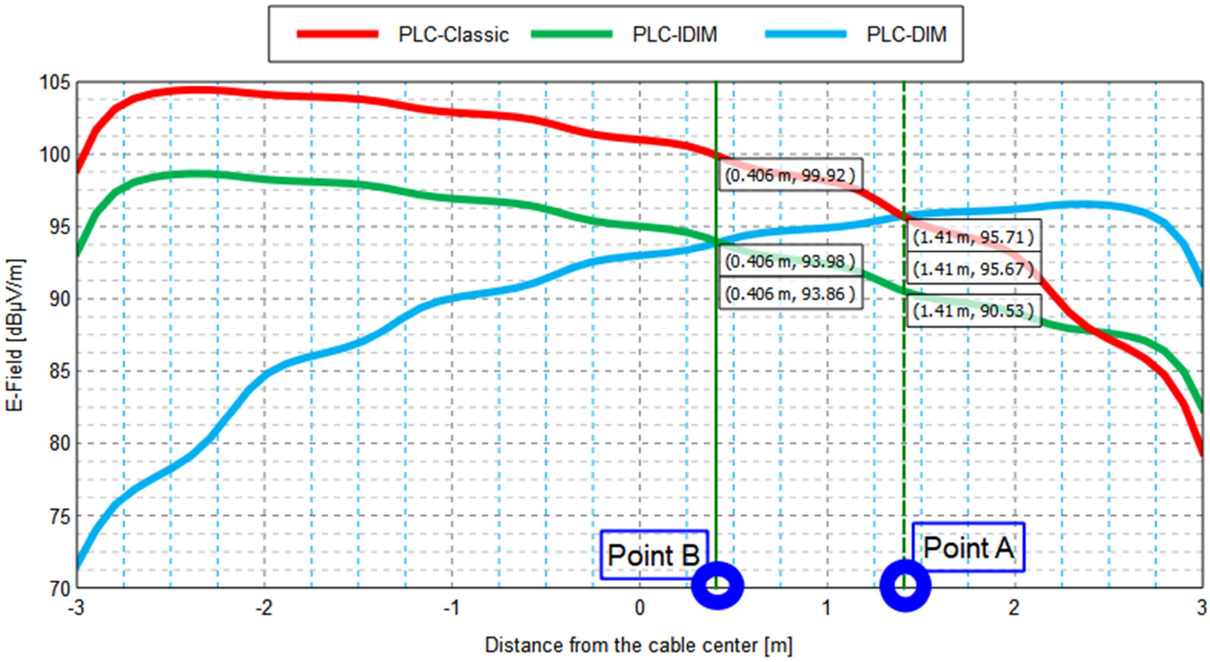

Figure 13. *Superposition of methods.*

For point **A**, the lowest level of radiation belongs to the IDIM curve with an intensity of the order of 90.5 dBμV/m and it is the same for the other points of its entourage: This confirms the efficiency of IDIM on a imbalanced impedance network.

Nevertheless, on the first half of the cable (from the transmitter to point *B*), the intensity of the radiation of the IDIM is higher than that of the DIM: This is due to the much-localized aspect of the IDIM, which does not guarantee a positive result at any point in space [8, 12].

Unlike IDIM, which is more effective around the predefined point A, DIM is more effective near the transmitter. The attenuation of the signals as one approaches the receiver is responsible for this phenomenon because this attenuation is more pronounced on the informative signal than on the destructive signal: the more powerful the destructive signal, the less effective is the mitigation in the vicinity of the receiver.

4. Conclusion

The destructive interference method is very effective in mitigating PLC radiation on networks with balanced impedance. Unfortunately, in an unstable environment (connection and disconnection of devices), we observe at certain points a weak mitigation or even an amplification of the radiation by this method.

In this work, we have adapted the operating mode of the destructive interference method in order to improve its performance on imbalanced impedance PLC networks. With the improved version of the method, an increase in the reduction rate of around 5 dB is observed. By focusing its action on a predefined point, the improved version of the method has extended its positive impact to other points in the vicinity.

The use of an impedance adapter bridge, which limits the creation of the common mode current, could significantly increase the efficiency of the method in an unstable environment.

Similarly, a more judicious choice of point **A** would have a positive impact on the average efficiency rate of IDIM.

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