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Online applicable techniques to evaluate field leakage current waveforms

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ABSTRACT

Leakage current monitoring is widely employed in order to investigate electrical surface activity and overall performance of high voltage insulators. Both activity and performance are closely linked with local conditions and experienced pollution. Therefore, field measurements are necessary to acquire an exact view of experienced activity and performance. However, field noise and the size of accumulated data are issues of concern in the case of field monitoring. In this paper, 75,887 leakage current waveforms obtained through more than six years of monitoring on 18 post insulators of different material, installed at two different 150 kV substations exposed to marine and industrial pollution, are investigated in order to evaluate the noise and data size problems. Three different types of noise are identified and their impact on raw data as well as their contribution to the data size is evaluated. Three different techniques are proposed to cope with the noise and data size problems. The techniques are selected so as to be online and hardware applicable in order to be incorporated in improved leakage current monitoring systems. Each technique is evaluated individually and in combination with the others. Combined use of all three, is proposed as a prerecording stage, able of coping with both noise and data size problems.

1. Introduction

The performance of outdoor insulation is strongly correlated to surface electrical activity, experienced in service conditions. Leakage current (LC) is a widely implemented tool to monitor surface electrical phenomena and overall performance of insulators. It is a method that can be employed on different types of insulators, providing simultaneous and continuous measurements both in laboratory and field conditions. Activity and performance are linked with local conditions, especially with the accumulation of pollutants on insulators' surface and wetting factors. Therefore, field measurements are required in order to acquire an actual view of the experienced activity and overall performance. However, the necessary long term monitoring results to the accumulation of vast amounts of data.

Extraction of several values from LC waveforms has been proposed in order to reduce the data amount gathered and to define criteria that could be used for diagnostic purposes. The most usual is the peak value of LC [1,2], followed by bin counting [3,4], the accumulated charge [3–5] and the frequency content [6,7]. More advanced techniques have also been employed by various researchers [8–19] and an extended review of measuring and analyzing leakage current for outdoor insulators and specimens can be found in [20]. However, a fully representative value is yet to be defined. In addition, in case of field measurements, the experienced noise can be rather significant, considering the service conditions and the required long term monitoring. As a result the reliability of any extracted value used as an indication can be compromised.

Therefore, both accumulated data size and noise are issues of concern in the case of field monitoring systems and should be evaluated. Techniques should be applied on LC measurements and be evaluated towards diminishing these problems. Those techniques should be fast and easily applied on hardware in order to be used on line in the field. In this paper, three techniques are evaluated on field leakage current measurements. The study objective is to incorporate the results in the development of an improved leakage current monitoring system, capable of operating in the field.

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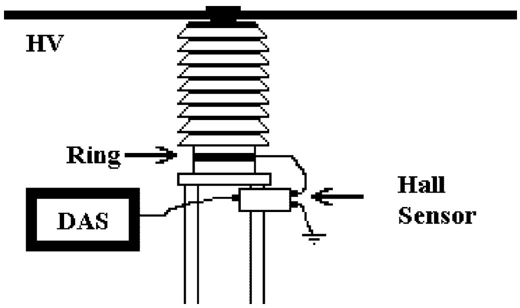

Fig. 1. A schematic representation of the measuring system.

2. Experimental setup

The monitoring sites are located in the Greek island of Crete. Due to the islands' coastal development, the power system in Crete suffers intense marine pollution and the Greek Public Power Corporation (PPC) has employed several techniques to cope with the problem [21,22]. The leakage current waveforms investigated in this paper have been recorded in two 150 kV substations of the Transmission System of Crete. The first substation is located right next to the coast suffering mainly from marine pollution, whereas the other is located in the city grid of Iraklion, next to the industrial area, suffering mainly from industrial pollution [23]. A group of nine 150 kV post insulators in each substation (including porcelain, RTV coated and composite ones), has been monitored for more than six years. A commercially available leakage current monitoring system was employed and a monitoring unit was installed at each substation. In order to measure the leakage current, a collection ring was installed at the bottom side of each insulator and the measured current was driven through a Hall current sensor. The acquired data were transmitted to a central data acquisition system (DAS). Nine channels were monitored by each unit, sampled continuously and simultaneously with a 2 kHz sampling rate. A schematic representation of the measurement system is illustrated in Fig. 1. Pictures and more information as well as a detailed table with the systems' specifications can be found in [24] and the custom-made software developed for managing the recorded leakage current waveforms is described in [25].

3. Problem description

3.1. Waveforms portraying activity

Laboratory and field researchers have successfully correlated certain types of leakage current waveforms with different stages of surface activity. The basic discrete stages are defined as: resistive sinusoid waveforms due to the presence of conductive film on the insulator surface [3,5–7,9,10,26], distorted sinusoid waveforms as an intermediate stage [3,6,7,10,11,15,16,26] and shoulder-like shaped waveforms due to dry band arcing that causes a time lag of current onset [1,3,5–9,12–15,18]. Pulses due to local discharges have been documented to be superposed on waveforms at the maximum absolute value of half cycles [5,7,8,14,15,26,27]. LC waveforms measured in the field, portraying the basic stages of activity, are illustrated in Fig. 2. It should be noted that beside the clearly recognizable basic types, a variety of more complex waveforms (combinations of the basic types) have been recorded in the field [20,24].

3.2. Field noise

Noise is a factor of great influence in the case of field measurements [24,28–30]. The monitored insulators and the measuring system are located in the field, subjected to various environmental factors, high voltage stress and several electrical events occurring during the operation of a HV substation (switching of heavy loads, opening and closing of switches etc.). Some dysfunctions (e.g. cable and sensor faults) occurred during the monitoring period, but noise related waveforms were recorded even on fault-free channels and were generally temporal [24]. Noise characteristics could not be strictly defined, as opposed to lab conditions [6], due to noise chaotic nature. However, examination of the recorded waveforms resulted to the identification of three different types of noise [24,29,30]: typical noise, dysfunction originated noise and single point noise. Typical noise (noise which is always present) consists of a random amount of minor peaks, as shown in Fig. 3a. Temporary dysfunctions lead to chaotic shaped waveforms, as the one shown in Fig. 3b. Single point noise results to a single point recorded far from the rest of the waveform. Such single points have been

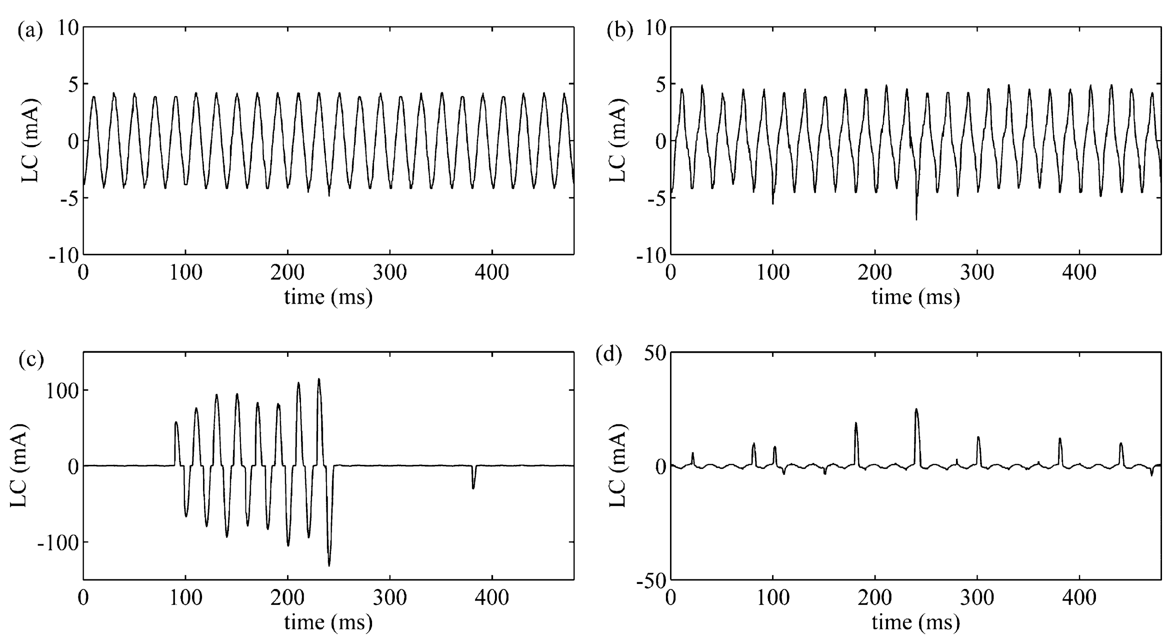

Fig. 2. Typical waveform shapes: (a) sinusoid, (b) distorted sinusoid, (c) dry band and (d) pulses superimposed at the waveform crest.

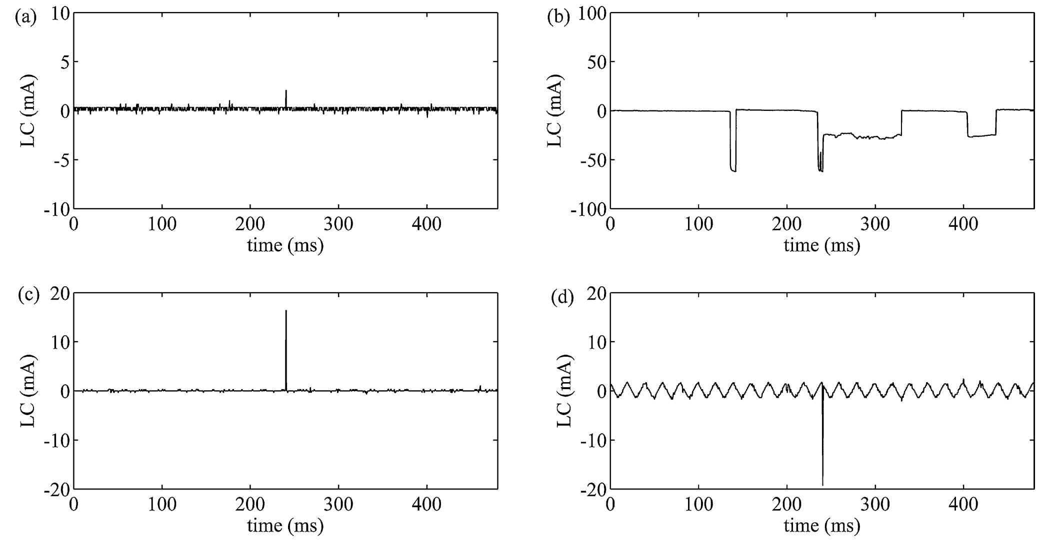

Fig. 3. (a) Typical noise, (b) dysfunction generated noise, (c) single point noise superimposed on typical noise waveform and (d) single point noise superimposed on sinusoid waveform.

recorded superimposed on all types of waveforms, even those portraying typical noise (Fig. 3c), and they do not necessarily follow the current trend (Fig. 3d).

3.3. Data size problem

In the case of LC waveform monitoring vast amounts of data are recorded. A pre-recording processing stage of LC measurement is required in order to cope with the problem. Two techniques have been proposed in this direction: the set of a negligible threshold [5,31] and the time-window technique [14].

Setting a negligible threshold will result to the recording of a waveform only if its peak value exceeds that threshold. This technique brings up the issue of defining the threshold value. Furthermore, it is impossible to predict the rate of waveform recording and thus the available monitoring period, which is essential in field monitoring. The time window technique uses a user-defined time window of certain length and records only one waveform during it. The waveform recorded is the one portraying the maximum peak value. The time window technique offers the advantage of a steady rate of waveform recording which allows the pre-calculation of the monitoring period in relation to the available memory. However since one waveform is always recorded during each time window and no distinction is made between meager and intense activity periods, applying the time-window technique will lead to a data set that is mainly consisted of waveforms portraying low activity.

Further, since both techniques use the LC peak value, their field effectiveness can be compromised by single point noise. Therefore, a processing stage prior to waveform recording is required, in order to maximize the efficiency of field monitoring. This stage should provide advanced evaluation features and at the same time remain simple enough to be implemented in a field data acquisition system. Considering the noise types, total removal of typical noise and dysfunction generated waveforms is required, while in the case of noise generated single point peaks, the peaks should be removed but the rest of the waveform should remain intact.

4. Evaluated techniques

Three applicable techniques are proposed and evaluated in this paper. These techniques have been applied by the authors, along with more advanced techniques, not as hardware applicable, like wavelet analysis and STD_MRA, on a data set consisted of 26,089 LC waveforms which were recorded on four neighboring insulators of different materials installed at the same substation, in order to evaluate the impact of noise, and results were investigated per insulator and material [29]. In this paper, the techniques are applied on 75,887 LC waveforms, recorded on 18 different insulators installed at two substations (nine insulators in each one), using two different LC monitoring units, with no distinction being made regarding the material/type of insulators, the location or the pollution type, in order to acquire a general view of the problem and the results. Further, whereas past research was mostly focused on evaluating the impact of each noise type by using each technique [29], in this paper their combined use is also investigated and research is targeted on evaluating their efficiency towards coping with both noise and data size problems. All waveforms are considered as a single data set, since what interests is the incorporation of the results in improved field LC monitoring systems capable of monitoring different insulators in different locations.

The considered waveforms have been recorded using the time window technique, described in Section 3.3, for a monitoring period that exceeds six years, with the use of several different time windows. Hence, a critical amount of data has been gathered, portraying the electrical phenomena experienced in field service. It is worth mentioning that although the time window technique has been applied, the monitoring of the considered test sites for more than six years, provides sufficient information to establish a clear view of the expected leakage current waveforms in case of continuous online recording.

4.1. Technique-A: setting a negligible threshold

The first technique applied, is the set of a negligible threshold. Using this technique, any waveform that illustrates LC peak value below the threshold is discarded. The definition of the threshold value is an issue of major importance. Since surface activity depends strongly on local conditions, field noise and the experienced level of activity have to be considered in order to define the threshold value. As the threshold value increases, the data amount problem will diminish, but the probability of discarding waveforms that portray significant activity increases. The value of 1 mA has been employed in a site suffering from severe marine pollution [31]. In this paper, various threshold values have been employed, in order to choose the most efficient. The lower threshold limit was

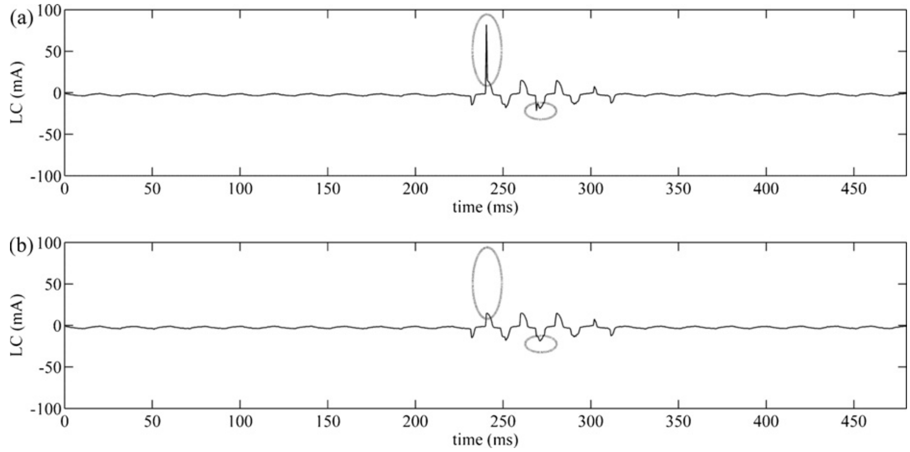

Fig. 4. A waveform suffering from single point noise (a) before and (b) after the application of Technique-B.

set to 0.5 mA, just over the typical noise amplitude area. The upper limit was set to 2.5 mA, less than half the amplitude of the smallest recorded discharge [30], in order to minimize the possibility of discarding discharge waveforms, which are far more important than sinusoid waveforms since they are correlated with an advanced stage of activity and inflict localized stress which can cause degradation of insulating performance and ageing especially in the case of polymer materials [20].

4.2. Technique-B: smoothing of max/min points

In the second technique evaluated, a minor smoothing is applied on the waveform. The points of the waveform having the maximum and minimum value are located. Then, for each one, its value is set equal to the value of one of its two neighboring points. The neighboring point chosen is the one portraying the largest absolute value of the two. The absolute value is used because the minimum point and its neighboring points are negative. As a result, single point peaks are removed while the shape of the waveform remains intact. A typical example of single point noise removal using Technique-B is shown in Fig. 4, where the dotted ellipses indicate the area of the waveform that has been smoothed. It is worth mentioning that Technique-B has a minor effect to a waveform, if the waveform does not suffer from single point noise. The smoothing does not affect the shape of the waveform and the peak value is insignificantly altered. For example, in the case of the smallest recorded discharge (peak value in the range of 6 mA) the peak value has been decreased by 0.35 mA (a 5.8% reduction in respect of the initial value), while in the case of the largest recorded discharge (peak value over 160 mA) the peak value has been decreased by 1.4 mA (a 0.9% reduction in respect of the initial value).

4.3. Technique-C: fundamental frequency criterion

Technique-C utilizes a fundamental frequency criterion. In this case the current fundamental frequency is calculated and if it is found different that the fundamental voltage frequency (in this case 50 Hz), the waveform is considered as dysfunction originated and is discarded. A simply schematic of Technique-C application on a waveform caused by a dysfunction is shown in Fig. 5.

5. Results and discussion

The efficiency of each method is evaluated regarding the number of waveforms that have been discarded and the change of the peak LC values distribution. Combined application of more than one of the evaluated techniques has also been investigated.

5.1. Defining a threshold value – Technique-A

Technique-A has been implemented using different thresholds in the area of [0.5 mA, 2.5 mA]. The combined application of Techniques B and C, was also considered. The results are illustrated in

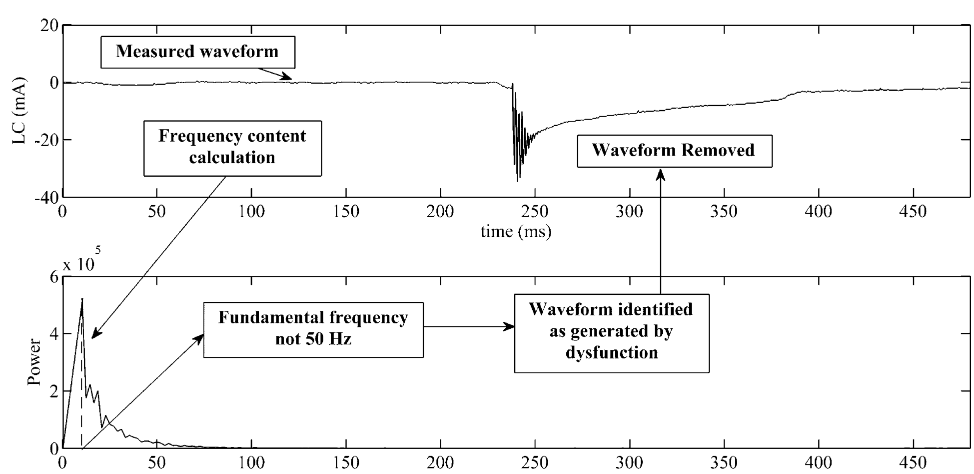

Fig. 5. Example of Technique-C application.

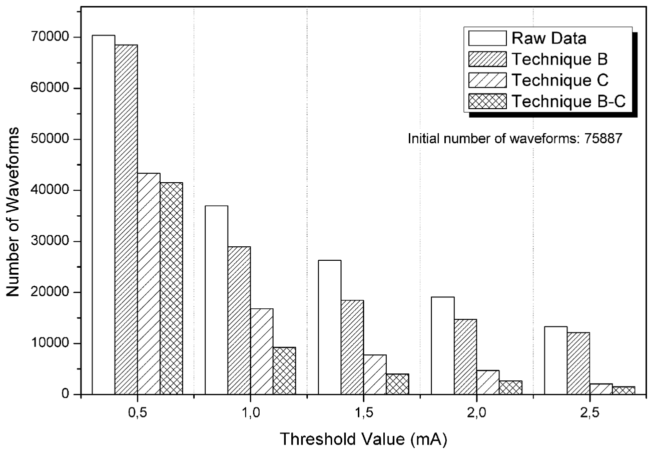

Fig. 6. Number of waveforms of raw data and data processed with Techniques B, C and a combination of both vs. different threshold values (Technique-A).

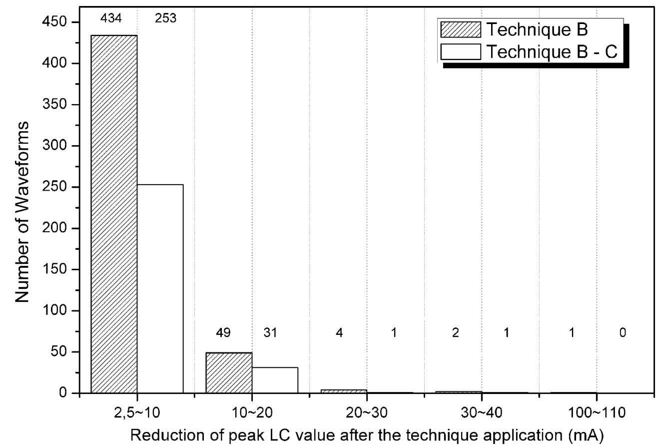

Fig. 8. Number of waveforms vs. reduction of peak value after the application of Technique B on raw data and on data processed with Technique-C.

Fig. 6. It is evident that threshold values near the typical noise area are insufficient. It is shown that thresholds slightly higher than the typical noise, can be sufficient only if Technique-A is combined with Technique-B or Technique-C or both of them. For example, when applying a threshold value of 1 mA, the discard percentage is 51.3%, but in case the threshold is combined with Techniques B and C the discard percentage increases to 79.58%. In the case of the considered test site, however, it is evident that the 2.5 mA threshold is sufficient to reliably distinguish waveforms that portray surface activity phenomena and still high enough to offer a partial solution to the data size problem, considering that the amount of waveforms is decreased by 82.5% of the raw data. The discard percentage is further increased to 96.59%, with the combined application of Techniques B and C.

5.2. Evaluating Technique-B

Technique-B cannot address the data size problem, but it can be used as an enhancement to Technique-A, as shown in Fig. 7. The improvement is considerable, especially in the range of threshold values from 1 mA to 2 mA. The number of waveforms that exceed 1.5 mA was decreased, as a result of the technique application and in the same time, the number of the waveforms below 1.5 mA was increased. In the same time however the change is significantly smaller for waveforms that exceed 2.5 mA. Further, single point noise can demonstrate false LC peak values that are significantly larger than the actual. The impact of single point noise is better

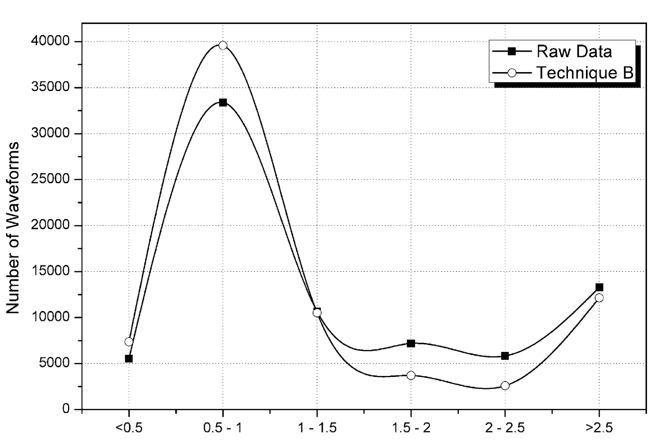

Fig. 7. Technique-B enhances the effectiveness of the negligible threshold.

illustrated in Fig. 8. The reduction of the peak leakage current value as a result of Technique-B application was more than 2.5 mA for a number of 489 waveforms. The reduction was greater than 10 mA for 56 of them and more than 100 mA for one. It should be noted that some of these waveforms are credited to dysfunctions, but even after the application of Technique-C, a number of 286 waveforms suffered from single point noise that generated peaks with amplitude larger than 2.5 mA while 33 of them illustrated a single point noise peak with amplitude larger than 10 mA.

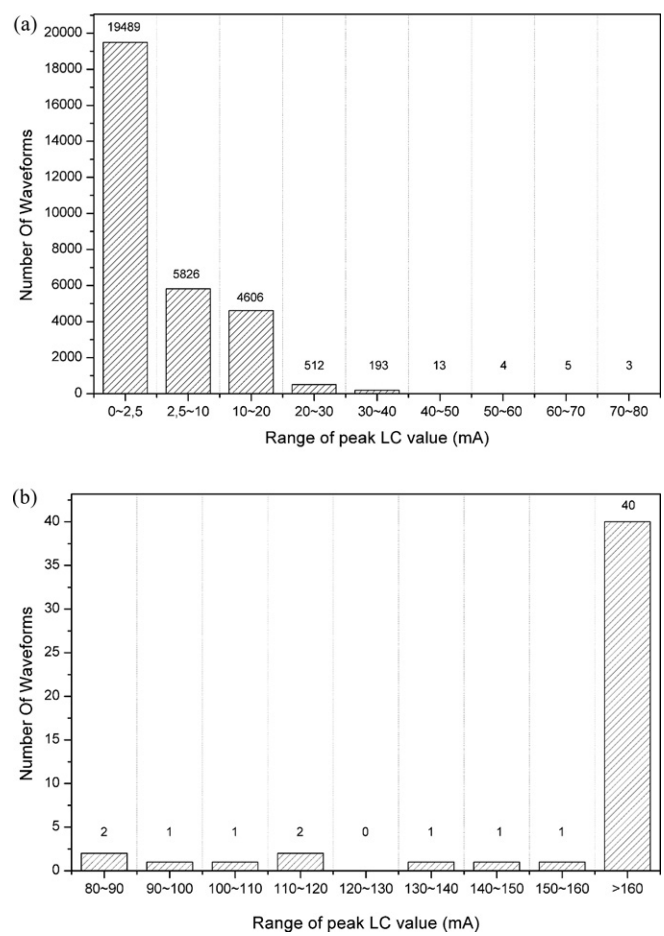

Fig. 9. (a) and (b) Peak value range of waveforms discarded by the application of Technique-C to raw data.

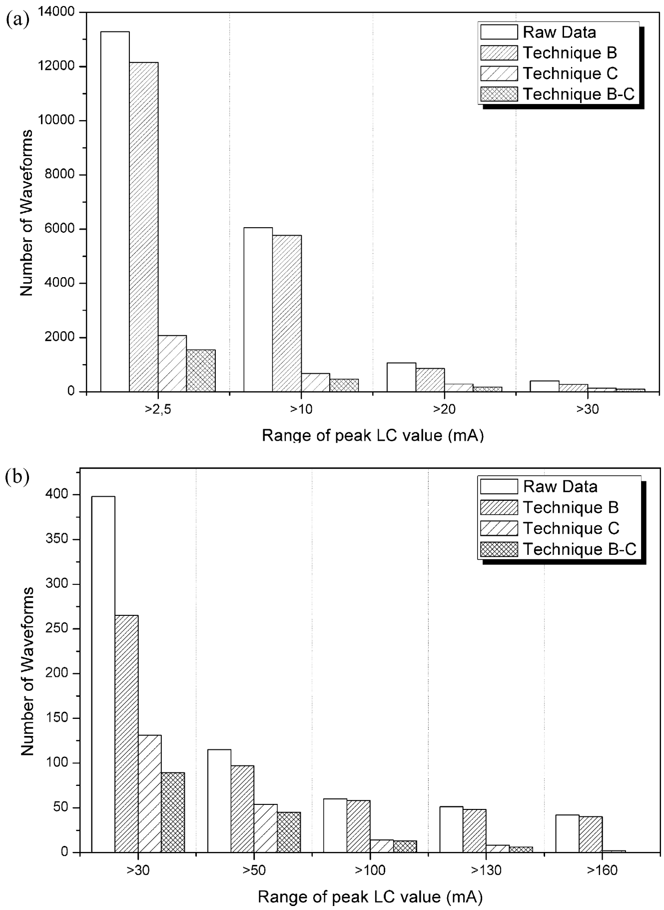

Fig. 10. (a) and (b) Number of waveforms vs. peak value range of raw data and data processed with Techniques A, B and C.

5.3. *Evaluating Technique-C*

Application of Technique-C to the original data set results to the rejection of more than 30,000 waveforms, i.e. 40% of the recorded data. The majority of those waveforms consists of typical noise waveforms and illustrates peak values lower than 2.5 mA, as shown in Fig. 9a and b. However a significant amount of waveforms, which are discarded through the application of Technique-C, portray higher peak LC values. The waveforms of this kind cannot be detected by the application of Techniques A and B. Therefore, Technique-C not only diminishes the data size problem, but it is also able to discard a large amount of dysfunction generated waveforms that portray high peak values. Extended monitoring time and field service conditions resulted to a significant number of dysfunction generated waveforms. Similar problems are expected to occur on similar conditions and therefore Technique-C is proved valuable for the effectiveness of any long term field monitoring system. However, it should be mentioned that Technique-C is not able to remove all typical noise waveforms, since it is possible for typical noise to portray a 50 Hz fundamental [28].

5.4. *Addressing the data size and noise problem*

The application of a negligible threshold (Technique-A) is effective as far as the typical noise is concerned. However, single point noise and dysfunction originated noise demonstrate peak LC values that can exceed any threshold set. As illustrated in Fig. 10a and b, noise generated waveforms that are removed using Techniques B and C, are the majority in any LC peak value range.

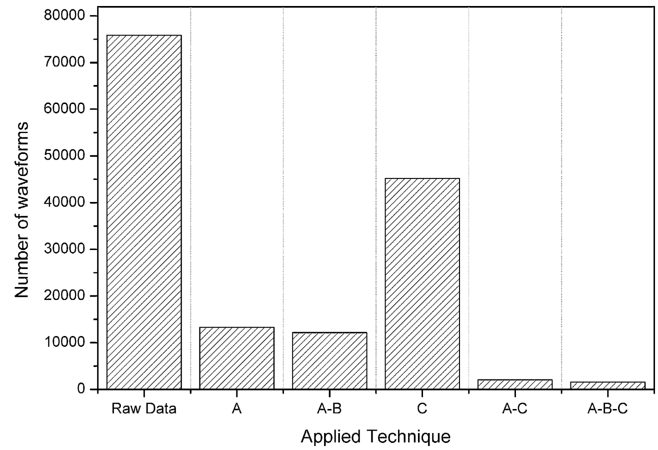

Fig. 11. Number of waveforms of raw data and final number of waveforms of data processed with Techniques A, B and C.

Regarding the data size problem, overall results are presented in Fig. 11. It is evident that combined application of the proposed techniques offers a significant solution to the data size problem. Technique-A is the first and obvious choice towards that direction and has the most effective results towards addressing the data size problem. Its effectiveness is enhanced through the use of Technique-B. Techniques-A and B are easily implemented on hardware, since they are consisted of basic logical and numeric functions, and should be incorporated in any field LC measuring system. However, it is shown that they cannot entirely cope with the data size problem due to the existence of dysfunction generated waveforms. Applying solely Technique-C, discards a large amount of waveforms. However, if it is combined with Technique-A the results are significantly better. Technique-C is slightly more complex but still hardware applicable and is proved necessary in the case of long term field monitoring, due to the occurrence of dysfunctions. It should be noted that Technique-C is not sufficient enough to be applied alone, as illustrated in Fig. 11. Techniques-A and C combined are able to cope with the data size problem. Their effectiveness is further enhanced when Technique-B is also applied. Combination of all three evaluated techniques is most effective discarding 96.59% of raw data waveforms.

6. Conclusion

In this paper, a number of 75,887 leakage current waveforms measured in the field for a period exceeding six years, are examined in order to obtain an exact image of expected data and problems during long term field monitoring. Two problems emerged concerning the effectiveness of any field LC measuring system: the data size and the impact of noise. Three hardware applicable techniques were applied on the data set and evaluated towards coping with these problems. It is shown that the proposed techniques are supplementary, each technique addresses certain issues and therefore is partially successful, and that their simultaneous application can offer an effective solution to both noise and data size problem. Combined use of all three is proposed to be incorporated as a prerecording stage in field LC monitoring systems.

Acknowledgement

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