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# Importance of denoising in dielectric response measurements of transformer insulation: An uncertainty analysis based approach

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ABSTRACT

In Data Acquisition denoising is an important issue. In the present work, importance of denoising in the case of real-time data acquisition for transformer condition monitoring using dielectric response measurements in time domain has been studied using uncertainty analysis approach. The uncertainty analysis of the recorded data is also very important for proper decision making in dielectric response analysis of transformers. Detailed descriptions of the real-time dielectric response measurement system (namely, Polarization–Depolarization current and Recovery Voltage measurements) as well as real-life experimentations are given. The paper establishes the fact that the uncertainty due to the noise is more significant than the traditional expanded uncertainty of the data acquisition setup. Experimental results and comparisons of performances of different filtering schemes show that a hybrid-filtering technique could reduce the uncertainty in the acquired data efficiently. A parameter called Uncertainty Envelope is observed to establish this fact. The procedure to calculate the uncertainty envelope for the data corrupted with non-stationary noise and also its importance are explained in detail. Results also show that without denoising and uncertainty analysis of the data one may arrive into a wrong interpretation about the insulation condition in dielectric response analysis.



## 1. Introduction

Real-Time Data Acquisition is one of the challenges in measurements and instrumentation. Devising an efficient experimental setup to acquire data in the form of electrical signal in real-time, is of immense importance in different fields of science and engineering research. Noise contamination being one of the important aspects of any data acquisition, it should be sensibly taken into account in real-time systems [1]. In the present work, importance of denoising in the case of real-time data acquisition for transformer condition monitoring using dielectric response measurements in time domain has been studied using uncertainty analysis approach.

In practice, real-life random noises may have stationary or non-stationary characteristics. Moreover, in many cases neither the actual values of the measured signal are known, nor is it possible to determine the noise level accurately. Hence there exists an uncertainty in the recorded data even if the uncertainties involved in the measurement procedures are small. Even with a denoising scheme, it is not possible to remove the noise from the output signal completely, though the noise level is definitely reduced. Therefore the filtered output is also associated with an uncertainty, however small it may be. The information of this uncertainty may help in avoiding wrong interpretation using the denoised data.

The real-time data acquisition application for condition monitoring of transformers using dielectric response analysis in time domain has been considered in this work. Inevitably the recorded data contain real-life noise. However, to assess the insulation condition from the measured signals, not only a denoised recording is desired, but also

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the wave shape of the signals should not be altered during denoising. A hybrid-filtering technique, employing weighted median (WM) filter and digital infinite impulse response (IIR) filter is used as a denoiser. The hybrid-filtering scheme, used in this experimentation, is carefully designed so that it meets the system requirements [2].

The real-time experimental set up, used in this work, is capable of acquiring data in a desired sequence without constant manual supervision. The uncertainties linked with the elements used in the set up, are negligible compared to the uncertainty due to the noise present in the data. So, the uncertainty in the recording due to the random noise present in the signal is analysed here. An estimate of this uncertainty is envisaged through a parameter called uncertainty envelope [3]. This uncertainty envelope is a measure of the range within which the actual signal value is expected to remain with a confidence level of 95%. This means, it can be stated with 95% surety that the actual noise free signal lies within this envelope. Results also show that due to the uncertainty involved in the data, it may lead to wrong interpretation about the insulation condition. So the uncertainty analysis of the noisy data is important because it makes one aware of this, so that the possible ambiguity in decision making can be avoided.

Therefore, the proposed method is an extension of ISO guidelines to take into account non-stationary noise which is common form of signal contaminant in dielectric response measurement for transformers. Two condition-monitoring signals in dielectric response analysis are Polarization–Depolarization Current (PDC) and Recovery Voltage (RV). The method is explained mathematically for PDC and RV measurements.

## 2. Overview of the uncertainty analysis and dielectric response based condition monitoring of transformers

### 2.1. About uncertainty analysis

According to the "Guide to the expression of Uncertainty in Measurement" (GUM), the standard uncertainty, $u(x)$ associated with parameter $x$, can be obtained from the standard deviation of the results of performed experiments. The expanded uncertainty, $U$, may therefore be estimated from the expression, $U = K \cdot u(x)$. $K$ is the coverage factor representing the confidence level of the estimate. For Gaussian Probability Distribution, a confidence level of 95.45% requires the value of $K = 2$. Coarsely this confidence level will be mentioned as 95% confidence later in the paper [4–6].

In this work a parameter called "Uncertainty Envelope" is used to reflect the uncertainty associated with the noisy signal. The uncertainty envelope is nothing but the range, within which the value of the measurand is expected to lie with a certain degree of confidence. The term "Uncertainty Envelope" is used in the context of this present application because of the non-stationary nature of noise. Hence, the uncertainty cannot be expressed as a single-valued parameter over the entire time span of the waveform. So, it is more meaningful to express the uncertainty of the recorded waveforms in time domain by an envelope rather than mere numerical values at different time instants.

### 2.2. About condition monitoring of transformers

Condition monitoring of transformers and other power equipment with noninvasive and nondestructive techniques such as Polarization–Depolarization Current (PDC) and Recovery Voltage (RV) measurements has become one of the important facets of power system maintenance strategy.

The phenomenon called dielectric polarization occurs in a dielectric material when it is placed in an external electric field and results in a polarization current that is dependent on the characteristics of the dielectric material. Following the withdrawal of this external field a depolarization or relaxation process starts which gives rise to another current in the reverse direction called depolarization current. Both the polarization and the depolarization currents (PDC) are dependent on nature and ageing of the dielectric material [9,10]. The nature of a typical PDC waveform recorded from real-life experimentation is shown in Fig. 1.

A further investigation on the above phenomena, i.e. the "after effects" of the PDC measurement involves what is called recovery voltage measurement (RVM). The sample under RV measurement is charged for a definite period of time $(t_{ch})$ with a step voltage and then earthed for discharging through a period, half that of charging $(1/2t_{ch})$. After removing the earthed condition the voltage across the sample is recorded as the RV. This voltage arises due to active relaxation processes inside the dielectric material, which did not relax fully during the insufficient discharging period. So, this RV is a characteristic of the insulating property of the dielectric material. According to the RVM methodology the charging time is increased gradually with the corresponding increase in discharging time from a small initial value and a different peak value of recovery voltage, $V_{recovery}(\text{peak})$ is obtained each time. Peak values obtained for different charging times $(t_{ch})$ can be plotted to yield a $V_{recovery}(\text{peak})$ vs. $t_{ch}$ curve, which is called recovery voltage spectrum. From this recovery voltage spectrum the insulation condition is analysed.

## 3. Importance of proper denoising scheme for PDC and RV waveforms

Due to the low magnitude level of the condition-monitoring signals different types of noises can easily contaminate the actual signal, such as, random noise with some unknown distribution having stationary or non-stationary properties [7,8]. In Fig. 1 the PDC signal is buried in random high frequency noise and also contaminated with impulses (spikes).

In polarization–depolarization current measurement the slope of different curves (i.e. recorded PDC waveforms) may be utilized as a discriminating factor for diverse insulation conditions [9,10]. However the noise present in the recorded signal may adversely affect the precision with which this parameter (i.e. slope of the curve) can be

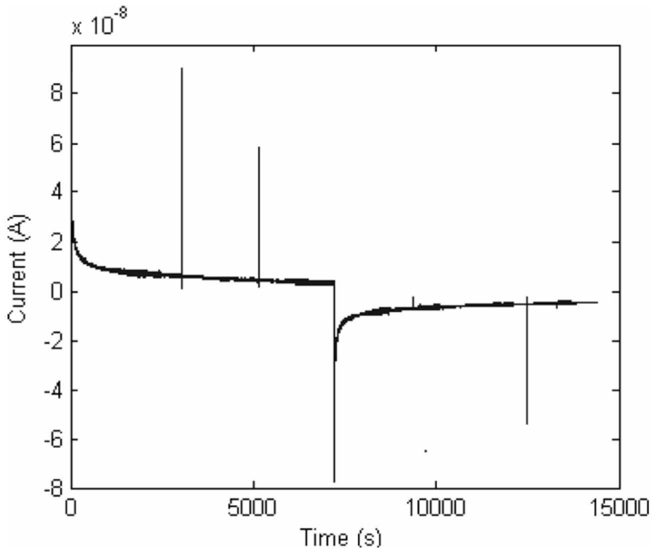


**Fig. 1.** Real-life noisy PDC waveform.

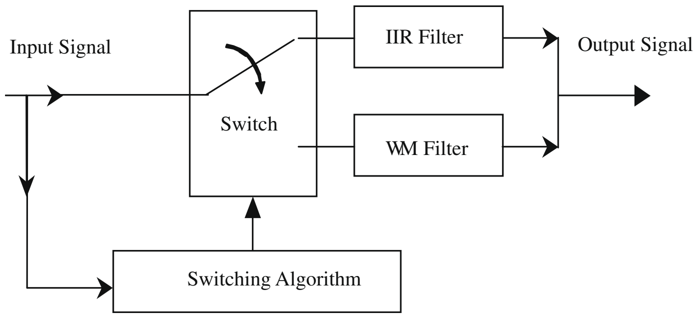


**Fig. 2.** Schematic representation of the hybrid filter.

detected. It is also evident from the above argument that any filtering technique that changes the slope of the curves of polarization–depolarization current must not be used for denoising. The typical PDC waveform, shown in Fig. 1, also establishes the fact that there occurs sudden change in the waveform while toggling from polarization process to depolarization. This sudden change is not a noise but is inherent in the measurement procedure. Hence this sort of jump-discontinuity in the waveform must be preserved while impulse noises need to be removed. No linear filtering technique is capable of performing this task; so non-linear filtering is a possible choice.

Similarly for RV measurement technique, properly denoised recordings of recovery voltage waveform and recovery voltage spectrum are necessary. So the determination of peak values of recovery voltage from periodic charging and discharging of the sample with gradually increased charging and discharging times is of great importance. Here a spike or any kind of spurious noise can lead to a wrong interpretation such as incorrect evaluation of the peak magnitude and the time of occurrence of the peak. If some denoising filter removes the noise, the shape of the waveform should not be changed, because any change in the wave shape will bring about a change in the slope of the curve. The initial slope of recovery voltage waveform bears important information about the condition of the insulation. Corrupting this data for the sake of denoising is highly discouraged. Therefore RV signals also demand a judiciously chosen filtering scheme.

In the present work a simple, fast and versatile hybrid-filtering scheme is proposed that is very effective for on-line denoising of different signals of dielectric spectroscopy, namely, for both PDC and RV [2].

The hybrid-filtering scheme incorporates weighted median (WM) filter, which belongs to the class of non-linear filters, along with a low pass digital infinite impulse response (IIR) filter.

The weighted median (WM) filter is a generalized form of the conventional median filter, and it has several applications in image and signal processing [11,12]. The basic idea of the filtering scheme is that the WM filters perform splendidly in removing impulse noises while preserving any step change in the signal, whereas lowpass digital IIR filter can eliminate the effect of high frequency noises present in the signal. If the system demands that any sharp change (edge) in the signal is to be preserved as well as any

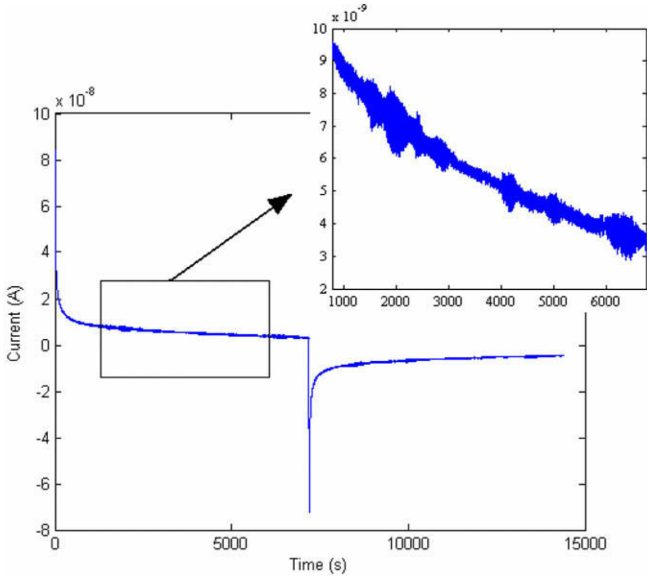


**Fig. 3.** WM filter output of a real-time noisy PDC waveform.

impulse noise should be removed, then the WM filter is a very good choice. Yet, its performance is poor when random high frequency noise is present in the slowly varying part of the signal. This fact is evident from Fig. 3. This figure shows the filtered output of the waveform shown in Fig. 1 using WM filter only [2]. The impulses present in the actual noisy data are removed completely by the WM filter and also the sudden change in the waveform during the toggling from polarization to depolarization is preserved but the random noises are not removed efficiently from the slow varying part of the waveform. In these portions of the input signal, standard lowpass filtering is done. However, being a linear system, the IIR filter distorts the output if any step change or impulse signal occurs in the actual input sequence. Fig. 4 shows that during initial stage of polarization and depolarization current waveforms the IIR filter output not only distorts the wave shape but also changes the slope of the curve, which is highly undesirable. The same kind of distortion occurs due to an impulse noise.

Thus to meet all the requirements of this measurement system a hybrid-filtering technique is adopted in the present scheme.

The hybrid filter works in conjunction with a switching algorithm. The algorithm dictates switching of the filtering technique between WM filter and lowpass digital IIR filter depending upon the nature of the input signal at that instant. It may be noted here that the switch is implemented in software and not in hardware. Switching a particular filter (either WM filter or IIR filter) implies that depending upon the input signal condition the output of the corresponding filter is considered. If a sudden step change or an impulse appears in the input then the switching algorithm selects WM filter to obtain the filtered output at that instant. When neither a step change nor an impulse

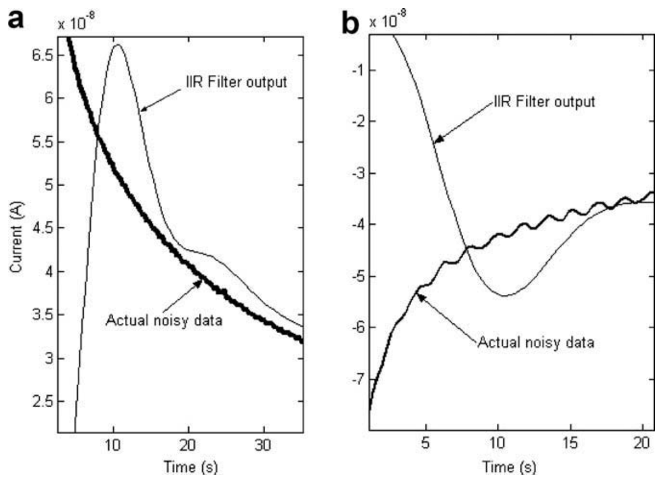


**Fig. 4.** Real-time noisy recorded data and lowpass IIR filter output in the initial stage of: (a) polarization current and (b) depolarization current.

appears in the input signal, lowpass digital IIR filter is selected through the switching algorithm.

The switching algorithm of the proposed scheme is shown below:

*Step 1.* Number of recent data samples taken into account is equal to the window length of the WM filter.
*Step 2.* Check whether any impulse signal or any step change occurs within this data sequence.
*Step 3.* If YES then output is tapped from WM filter. (i.e. switch to WM filter).
If NO then output is tapped from IIR filter. (i.e. switch to IIR filter).

The schematic diagram of the hybrid filter is shown in Fig. 2 [2].

As both IIR and WM filter are implemented in software, the problem of initialization during switching is tackled appropriately. If the IIR filter is switched on at an instant '$t$' then to obtain the output at that instant, $y_{t-1}, y_{t-2}, \ldots, y_{t-L}$ and $x_t, x_{t-1}, x_{t-2}, \ldots, x_{t-L}$ data samples are supplied to the IIR filter subroutine. So the output is obtained through the filter algorithm. Here $L$ is the filter order; $y_t$ and $x_t$ are the filter output and filter input data at $t$th instant, respectively. If the IIR filter is switched on at the very beginning of the data acquisition, the sample values of $y_{t-1}, y_{t-2}, \ldots, y_{t-L}$ and $x_{t-1}, x_{t-2}, \ldots, x_{t-L}$ are set as zero. However, if the filtering scheme is switched from WM filter to IIR filter then $y_{t-1}, y_{t-2}, \ldots, y_{t-L}$ and $x_{t-1}, x_{t-2}, \ldots, x_{t-L}$ are readily available from the output and input data samples of WM filter in the preceding instants. Similar things happen while the hybrid filter is switched to WM-mode.

## 4. Real-time data acquisition setup for condition monitoring of transformers

An important aspect other than noise corruption of dielectric response measurement is that the data acquisition for such condition monitoring goes on for several hours in a definite sequence of circuit rearrangement and in different measurement modes. Hence, a complete automated computer controlled system is necessary so that the tests could be carried out without manual supervision.

The complete experimental setup used in the present work for condition monitoring of transformers consists of:

(i) A continuously variable DC power supply unit having range 230 V to 3 kV, 50 mA with output regulation of 0.1%. The output from this source was kept at 1 kV throughout the experiment.
(ii) A two-way air-break contactor which could connect the power supply to the HV conductor during charging and could earth the same conductor during discharge.
(iii) Keithley 6514 Electrometer for measuring current and voltages. This instrument from Keithley Instruments Inc. has built in IEEE-488 (GPIB), RS-232 and Digital I/O Interface. Its measurement capabilities are given below:
- Voltage from ±10 μV to ±210 V
- Current from ±100 aA to ±21 mA

Data communication was through GPIB bus.
(iv) A GPIB driven Controller Module developed in the laboratory to control the contactor and operation of the electrometer from Personal Computer (PC) in a synchronous way.
(v) Labview software from National Instruments loaded in a PC was used for controlling the whole experimental sequence.
(vi) The hybrid-filtering scheme for denoising is also implemented in the software as a dynamic link library module and incorporated in the PC based main program.

The experimentation is performed on different transformers with different insulation conditions and in diverse environmental situations. The complete setup for such experimentation is shown schematically in Fig. 5. All the

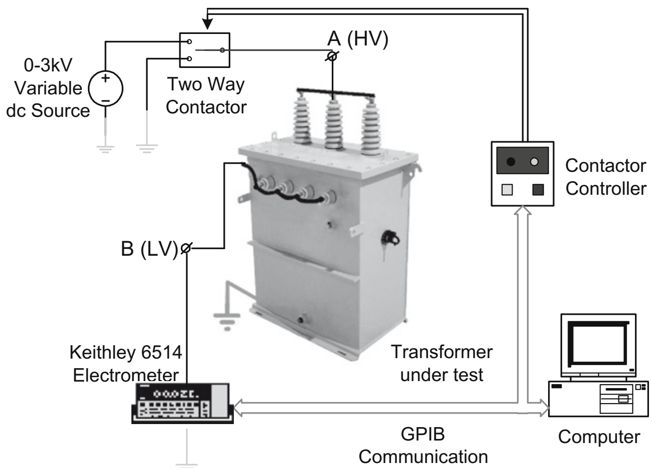


**Fig. 5.** Schematic diagram of experimental setup.

**Fig. 6.** On-site testing of a 33/11 kV, 6.3 MVA transformer using the developed setup.

HV terminals of the transformer under investigation were shorted to bring one terminal (A) and all the LV terminals are shorted to bring another terminal (B) so that the insulation between the HV and LV winding is stressed by the applied voltage between A and B, as in Fig. 5. The photograph of real-life experimentation on a 33/11 kV, 6.3 MVA transformer is shown in Fig. 6.

## 5. Uncertainty budget of the data acquisition setup

The usual way of uncertainty budget calculation is not very effective in the case of dielectric response based analysis of transformer insulation. The reason is explained below.

The overall sources of the uncertainties in the dielectric response measurement methodology may be classified into three categories.

*(1) Uncertainties that can be calculated with the usual approach.* This category mainly includes the uncertainties of the data acquisition setup and measuring instruments. Different components of the data acquisition are shown in Fig. 5. The uncertainties of two way contactor module and PC based contactor controller may be ignored. This is because of the fact that the contactor operates in 'binary' mode, i.e. 'ON' or 'OFF'. So, no uncertainty is introduced in the system during the proper operation of the contactor module. The controller module is GPIB driven and it is operated from a Personal Computer (PC) in a synchronous way with the electrometer. The protocols used in this communication are standard IEEE protocols. Moreover, the main software program is written in such a way that any loss of synchronism during the operational procedures gives error message and halts the operational sequence. So, there is very little chance of any significant contribution in the uncertainties due to these components during the measurement procedure. Therefore, contributions to the overall uncertainty that can be considered are the uncertainties of the DC power supply and Keithley 6514 Electrometer. Table 1 shows the uncertainty involved due to these components.

**Table 1**
The uncertainty contributions of different components.

| Components | Uncertainty (%) |
|---|---|
| DC Power supply | 0.1 |
| Keithley Electrometer | |
| (i) VOLTS | 0.025 |
| (ii) AMPS | 0.2 |

*(2) Uncertainties which are inherent to the dielectric response analysis.* As stated earlier, PDC and RV measurements go on for several hours (e.g. PDC measurement takes approximately 6 h to complete). So, there exists some sources of uncertainties that can not be measured directly but they have effects on the recorded waveforms of PDC and RV. These uncertainties may affect the wave shape but it is hard to measure or indicate their individual uncertainty contributions quantitatively. For example, the uncertainty due to variation of oil and paper conductivity with the changes in operating conditions or, the uncertainty because of the change in the dielectric polarization processes within the insulation due to the variation of ambient temperature during the measurement procedures etc. are such sources of uncertainties. These factors are inherent to the dielectric response measurement and these are known difficulties of this methodology. This may be considered as a drawback of the dielectric response measurement with PDC and RV. Researches are going on in this context [9,10,16].

*(3) Uncertainty due to the noise present in the recorded signal.* The uncertainty because of the noise present in the recorded data should be given due importance while making decisions about the insulation condition using dielectric response analysis (PDC and RV measurements). Non-stationary nature of the noise makes it difficult to measure this uncertainty. But it is the uncertainty due to the noise which has greater impact on the dielectric response analysis than the uncertainties due to the measurement procedure and data acquisition setup. In the next section it has been shown that the uncertainty due to the noise is greater than the uncertainties of the components, as given in Table 1. It is also described mathematically that how to calculate the uncertainty due to the non-stationary

noise present in the signal by uncertainty envelope for PDC and RV signals.

## 6. Experimental results and discussion

### 6.1. Mathematical background and calculations of results

Using the experimental setup, detailed in the previous section, uncertainty in the data acquisition as well as the performance of the hybrid filter to reduce this uncertainty, have been studied through real-time testing. A typical real-time noisy data of polarization–depolarization current (PDC) is already shown in Fig. 1. It is evident from the curve that the PDC signal is buried in random high frequency noise and also contaminated with impulses (spikes). Denoised output using the hybrid filter is shown in Fig. 7. Though it is practically impossible to remove the noise completely through filtering, it can be observed that the filtered output is close enough to the noiseless version of the signal. So, it can be assumed that the signal after filtering is noiseless. This is a fair assumption as the noise level in the input signal is much higher than that in the filtered output as evident from Figs. 1 and 7.

So, from these two signals, as presented in Figs. 1 and 7, an estimate of the nature of time variation of the real-life noise can be obtained. One of such estimates is shown in Fig. 8. As the impulse noise (spike) rarely occurs during the data acquisition and it can be efficiently removed by the hybrid-filtering scheme, uncertainty due to the impulse noise is negligible. So during uncertainty analysis only real-life random noise is considered.

As the experimentation for PDC measurement goes on for several hours, the noise in this case is considered non-stationary. So with 20 such different noise estimates, recorded from different real-time experimentations in diverse environmental conditions, standard deviation of the noise across the ensemble is calculated at every instant of time according to Eq. (1). A coarse measure of the probability distribution of such noise across the ensemble of 20 measurements is shown in Fig. 9.

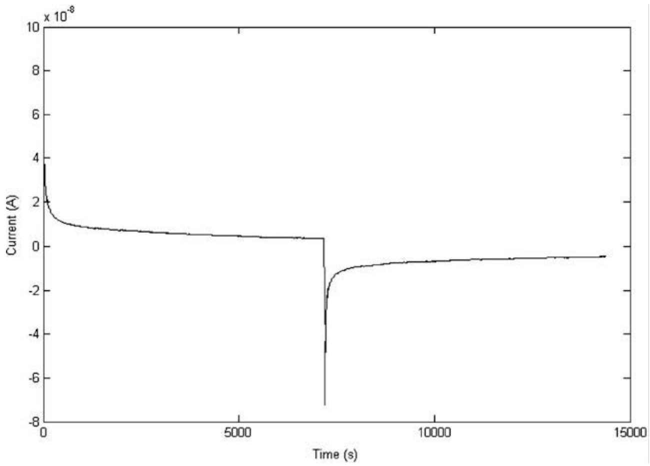


**Fig. 7.** Denoised output of the hybrid filter.

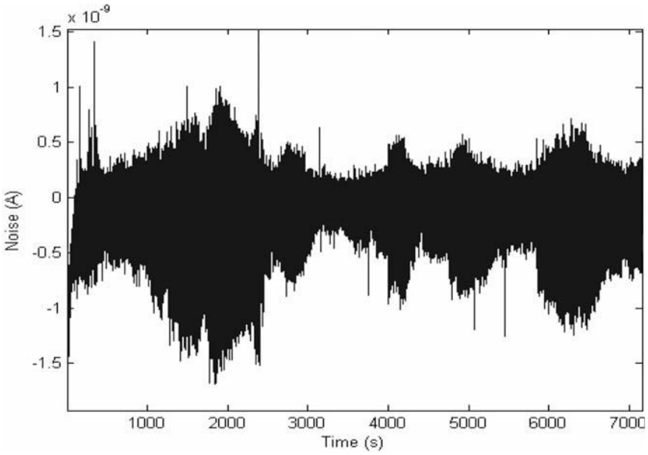


**Fig. 8.** Estimate of real-life noise.

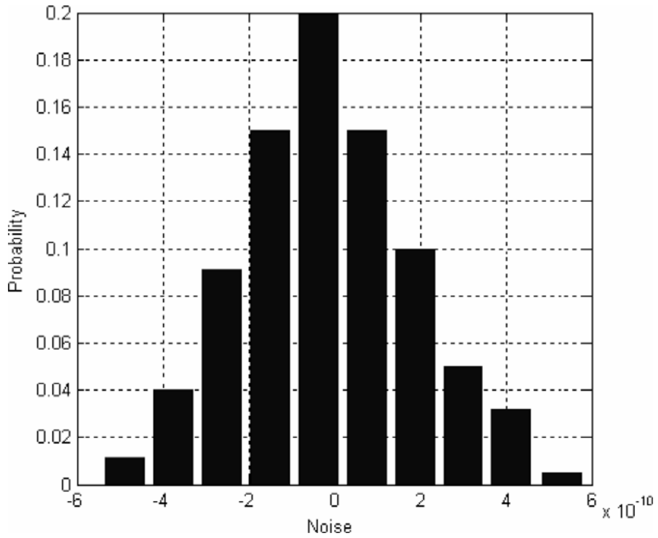


**Fig. 9.** Probability distribution function of the noise for PDC across the ensemble of 20 measurements.

$$\sigma_n(t) = \sqrt{\frac{\sum_{i=1}^{N}\{n_i(t)\}^2}{N}} \quad (1)$$

Here, $\sigma_n$ is the standard deviation of the real-life noise, $N$ is the number of different noise estimates, i.e. 20; $n_i$ is the $i$th estimate of real-life random noise and $t$ signifies the time instant. The estimate of the uncertainty envelope at any instant is obtained from the standard deviation of the real-life noise as follows: $UE = K \cdot \sigma_n$, where $K$ is a multiplication factor that expresses the confidence level of the uncertainty, as stated earlier. For 95% confidence level $K = 2$. The envelope for the noisy input is shown in Fig. 10. For clarity only the polarization current waveform is shown in the figure. But it is not practically feasible to denoise the signal completely in real-time because of the fact that the signal value at any instant is not known, neither is it possible to determine the actual noise level at that instant. So the denoised output from the filter also has some uncertainty associated with it due to the residual noise present.

If it is assumed that

$$y = s + n_r \quad (2)$$

where $y$ is the filter output, $s$ is the actual signal component in it and $n_r$ is the random residual noise present in the signal, then differentiating with respect to time,

$$\frac{dy}{dt} = \frac{ds}{dt} + \frac{d}{dt}(n_r)$$

But as the actual signal ($s$) is a slow-varying one in comparison with the real-life random noise ($n_r$), so,

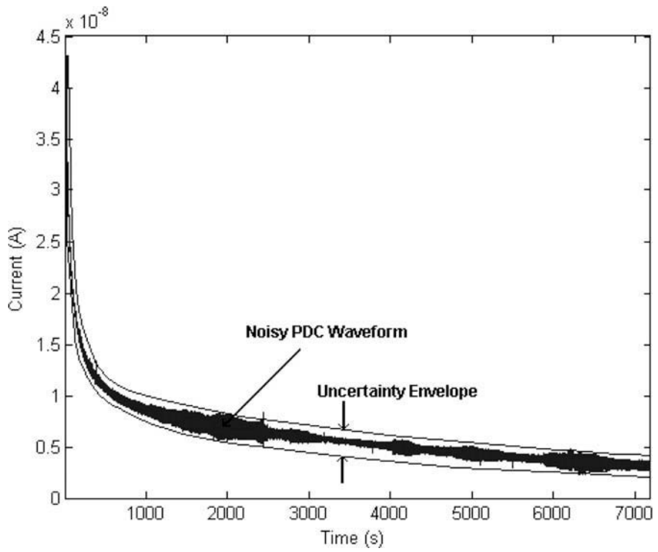


**Fig. 10.** Uncertainty envelope of noisy data, acquired during polarization current measurement.

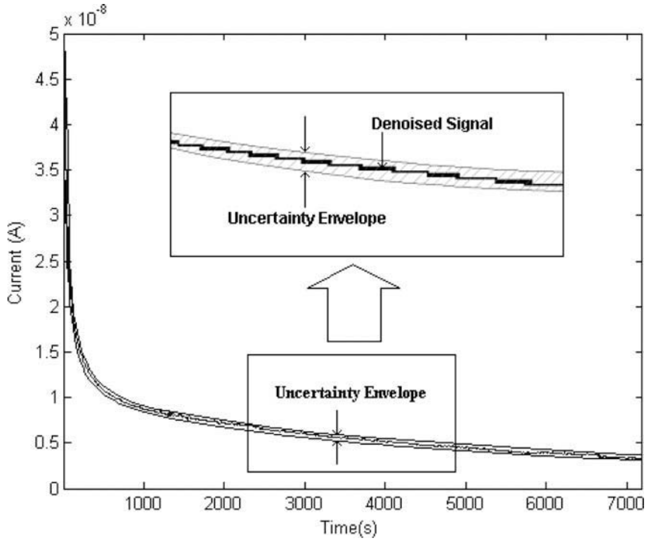


**Fig. 11.** Uncertainty envelope of the denoised signal employing hybrid filtering.

$$\frac{ds}{dt} \ll \frac{d}{dt}(n_r)$$

Therefore the standard deviation of the random, residual noise present in the filtered output may be calculated as, [3,13],

$$\sigma_{n_r} \approx \sqrt{\sigma^2_{diff\{y\}}} \quad (3)$$

where $\sigma_{n_r}$ is the standard deviation of the residual noise, $\sigma_x^2$ is the variance of any variable $x$ and *diff*{} is differentiation operator in discrete time. It is evident that differentiation for the digital data in this case is nothing but the difference operation. Therefore the standard deviation of the noise in the filtered output across the ensemble at every instant of time, i.e. $\sigma_{n_r}(t)$, is obtained with the help of 20 (i.e. $N = 20$) such noise estimates according to Eq. (4), which is similar to Eq. (1). It is assumed here that, due to the random nature of the residual noise the statistical property of the noise is unaffected by the differentiation

$$\sigma_{n_r}(t) = \sqrt{\frac{\sum_{i=1}^{N}[diff\{y_i(t)\}]^2}{N}} \quad (4)$$

From this standard deviation again the uncertainty envelope is calculated on the basis of 95% confidence level. The uncertainty envelope of the denoised output is shown in Fig. 11.

To compare the performance of the hybrid filter the noisy signal is also denoised with the help of WM filter only. The output of the WM filter and the corresponding uncertainty envelope is presented in Fig. 12. It is evident from Figs. 11 and 12 that the uncertainty envelope is

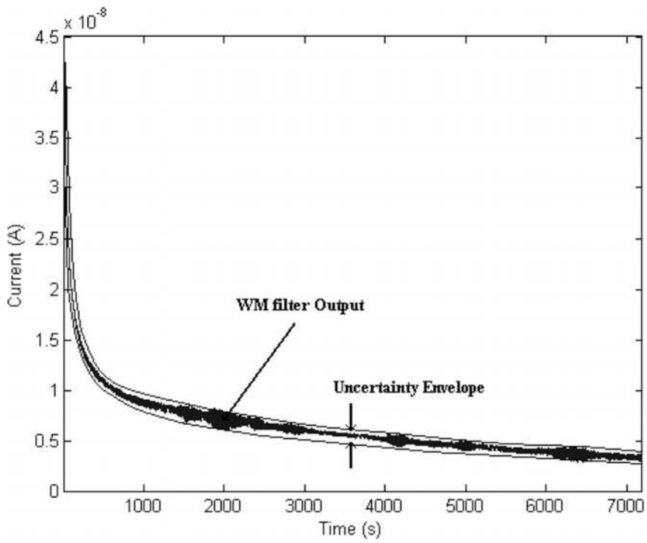


**Fig. 12.** Denoised signal employing WM filter only and the uncertainty envelope.

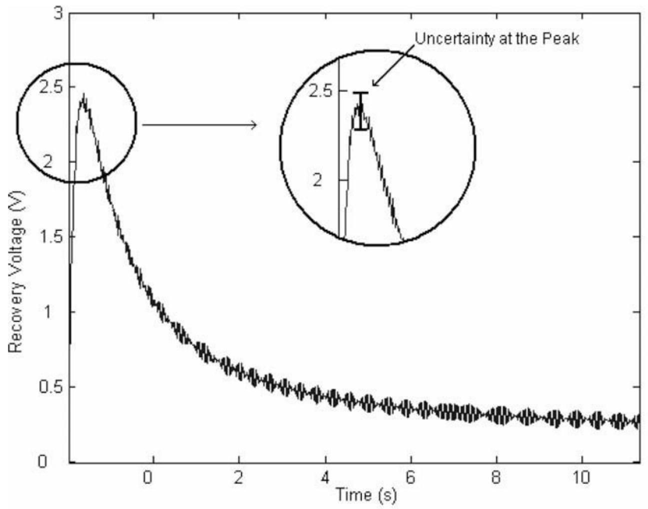


**Fig. 13.** Real-life noisy Recovery Voltage waveform.

thinner for the denoised output obtained from hybrid filtering than that of the WM filtering. So the uncertainty in the filtered output is quite less for the hybrid-filtering technique than the output of WM filter. Obviously the uncertainty of the output is quite low in comparison with the uncertainty of the original input signal.

In a similar manner the analysis is also extended to Recovery Voltage Measurement (RVM). The durations of periodic charging and discharging in RVM are not as long as the duration of PDC measurement. So here the contaminating noise is considered stationary. A typical Recovery Voltage (RV) waveform recorded in real-time experimentation is shown in Fig. 13. Effect of noise on the signal is evident from Fig. 13. The analysis of this signal is done in a similar manner, but as the noise is considered stationary, overall standard deviation across time is calculated rather than at every instant of time.

Moreover, due to the short durations of different charging and discharging cycles in RVM there may exist correlations between the noise estimates. So the standard deviation of real-life noise is obtained from Eq. (5), which is the general form of variance calculation. Twenty noise estimates is considered (i.e. $N = 20$) here. The probability distribution of one of such noise estimate across the time is shown in Fig. 14.

$$\sigma_n = \sqrt{\sum_{i=1}^{N} \sigma_{n_i}^2 + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \sigma_{n_i n_j}} \quad (5)$$

$\sigma_{xy}$ is the covariance of any two variables $x$ and $y$ and all other variables are in their usual meaning as explained earlier. From this standard deviation the uncertainty envelope is also calculated. As the peak value of a RV waveform is

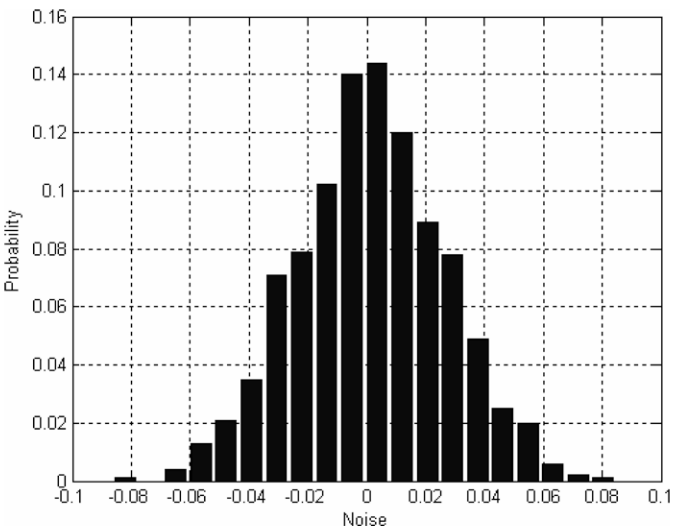


**Fig. 14.** Probability distribution function of the noise for RV across the time.

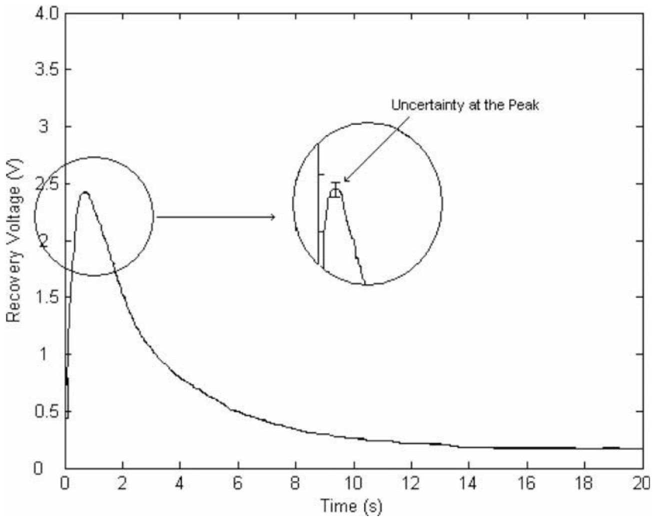


**Fig. 15.** Recovery Voltage waveform denoised with hybrid filter.

**Table 2**
Comparison of uncertainties for PDC waveform.

| Noisy waveform | WM filter output | IIR filter output | Hybrid filter output |
|---|---|---|---|
| *Overall uncertainty measure (%)* | | | |
| 7.3 | 4.8 | 1.2 | 1.2 |

**Table 3**
Comparison of uncertainties at the peak of RV waveform.

| Noisy waveform | WM filter output | IIR filter output | Hybrid filter output |
|---|---|---|---|
| *Overall uncertainty measure (%)* | | | |
| 6.25 | 3.1 | 0.7 | 0.72 |

the most important information, which is required to plot the recovery voltage spectrum, the uncertainty at the peak value of the waveform is shown in Fig. 13. The whole envelope is not shown, as the concept is already explained in the case of PDC measurements. The standard deviation of the noise present in the filtered output is also calculated according to Eq. (6), which is similar to Eq. (3). So the standard deviation of the residual noise, $\sigma_{n_r}$, is obtained from 20 (i.e. $N = 20$) residual noise estimates as,

$$\sigma_{n_r} = \sqrt{\sum_{i=1}^{N} \sigma^2_{diff\{y\}} + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N} \sigma_{diff\{y\}_i\ diff\{y\}_j}} \tag{6}$$

Meaning of all the variables is evident from the explanation of Eqs. (3) and (4). The denoised waveform with the uncertainty at the peak value is shown in Fig. 15. The uncertainty is decreased significantly due to filtering as before. So the filter actually reduces the uncertainty associated with the signal through denoising. This uncertainty should be considered during decision making from the waveforms.

### 6.2. Discussions on the importance of the uncertainty analysis

For the relative assessment of the uncertainties from different sources and various filtering techniques, the overall RMS value of the uncertainties at every instant of PDC waveform is calculated over the entire time range and termed as '*overall uncertainty measure*'. Comparisons are shown in Tables 2 and 3 for PDC and RV waveforms, respectively. These tables show that uncertainty values even for the denoised waveforms are much higher than the uncertainties of the individual components of the data acquisition setup as shown in Table 1. It is also observed

**Table 4**
The effect of uncertainty in the condition assessment of the insulation from noisy and denoised waveforms.

| | Noisy waveform | | | | Denoised waveform | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Hybrid Filter | | | | WM filter | | | | IIR filter | | | |
| | Paper moisture (%) | | Oil moisture (ppm) | | Paper moisture (%) | | Oil moisture (ppm) | | Paper moisture (%) | | Oil moisture (ppm) | | Paper moisture (%) | | Oil moisture (ppm) | |
| | A | B | A | B | A | B | A | B | A | B | A | B | A | B | A | B |
| Curve 2 | 3.3 | 3–3.9 | 35 | 30–40 | 3.2 | 3–3.3 | 33 | 31–35 | 3.3 | 3.0–3.7 | 35 | 30–39 | 4.6 | 4.4–4.7 | 51 | 49–53 |
| Curve 3 | 3.3 | 3–3.9 | 25 | 21–30 | 3.0 | 2.8–3.2 | 25 | 23–26 | 3.2 | 2.9–3.7 | 25 | 21–29 | 4.0 | 3.9–4.2 | 43 | 40–44.5 |

A = result from the recorded waveform; B = uncertainty limit obtained from uncertainty envelope.

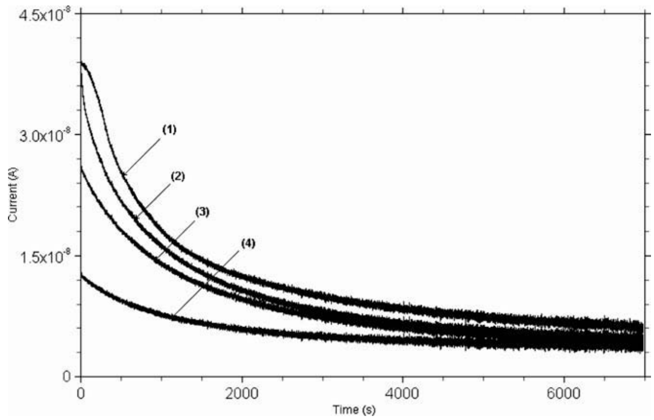


**Fig. 16.** Real-life noisy recordings of four polarization curves.

that uncertainty in the output waveform of IIR filter is very close to the uncertainty of the hybrid filter output. But IIR filter distorts the wave shape, i.e. changes the slope of the curves as shown in Fig. 4(a) and (b). So, it gives erroneous results in the analysis. It can be verified from the data shown in Table 4.

The importance of the uncertainty analysis in dielectric response measurement can also be emphasized with the help of Figs. 16 and 17. Fig. 16 shows four different polarization curves for four different insulation conditions. The noise present in the data makes the curves overlapped in certain portions. Fig. 17 shows the denoised version of these polarization curves. Four distinct curves clearly establish four different insulation conditions. But analysis shows that, due to the uncertainty involved, the curves may not be that distinct as they appear.

In Fig. 17 two magnified views are given, the view (a) is chosen when polarization processes are very much active, i.e. the current has not settled down, and view (b) shows the situation where active polarization processes have almost stabilized [14]. In both the cases the uncertainty envelopes of Curve-2 and Curve-3 show that due to the uncertainty involved the envelopes overlap, even though the denoised curves are distinct, particularly in the case of view (a).

As within the uncertainty envelope a curve may actually lie anywhere, overlapping of two uncertainty envelopes means that they hardly reflect two different insulation conditions. It means that if the data acquisition is repeated, these two curves may actually overlap. So ignoring this uncertainty information may lead to significant error in the judgment of the insulation condition. For this reason the uncertainty of Curve-2 and Curve-3 should be kept in mind while making inferences about the insulation from the analysis of the waveforms. Thus the concept of uncertainty envelope is a parameter that could be used for judicious analysis of signals in dielectric response measurements. Recently many researchers such as Zalis [15] and Saha and Purkait [16] have reported expert systems for the assessment of insulation condition of different power apparatus. The effect of the uncertainty in the assessment of the insulation condition is shown in Table 4 which is obtained from one of such expert systems. It is seen from Table 4 that the noise has significant effect on the determination of paper moisture. The uncertainty measure in the readings also gives the idea about the closeness of the conditions of insulation for two different dielectric response curves.

So, it is evident that the uncertainty information is important for the knowledge-base and the inference-engine

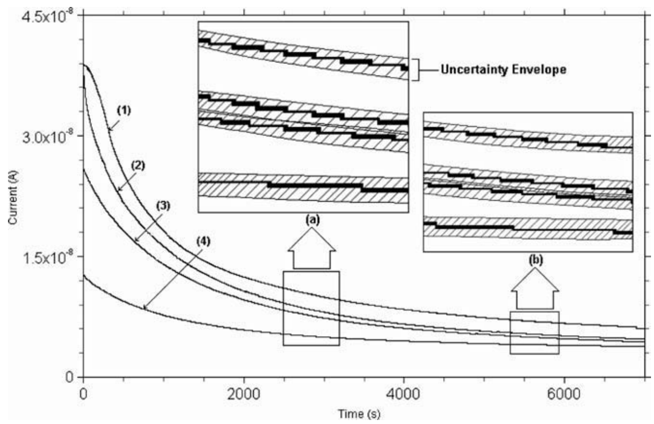


**Fig. 17.** Denoised version of four polarization curves.

of the expert system, to decide the condition of the insulation system with enhanced certainty.

## 7. Conclusions

Importance of denoising in the case of real-time data acquisition for transformer condition monitoring using dielectric response measurements has been studied using uncertainty analysis. It has also been shown that the uncertainty analysis of the recorded data is also important for proper decision making. Suitable denoising scheme can reduce the uncertainty in the recorded data. The present work establishes that the aim of denoising and the uncertainty analysis is to increase the certainty of the results obtained from the dielectric response analysis. Results of real-life experimentation show the justification of this approach.

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