Experiment Reproducibility and Electric Field Uniformity in GTEM

A Mukhtaruddin[a], M Isa[b], S M F S M Dardin[c], A M Ishak[d] and M N Mazlee[e]

[a ,c,d]Faculty of Engineering, National Defence University of Malaysia, Kem Perdana Sungai Besi, 57000 Kuala Lumpur, Malaysia
[b]Faculty of Electrical Technology Engineering, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia
[e]Faculty of Mechanical Technology Engineering, Universiti Malaysia Perlis, 02600 Arau, Perlis, Malaysia
Email: [d]azharudin@upnm.edu.my

Article History: Received: 10 January 2021; Revised: 12 February 2021; Accepted: 27 March 2021; Published online: 20 April 2021

Abstract: Giga-Hertz Transverse Electromagnetic (GTEM) cell is a simpler and cheaper alternative to the full-scale anechoic chamber. It is an equipment of choice in a lot of partial discharge (PD) research, especially for antenna validation. According to a good practice the cell must be validated, or also known as calibrated, for its usability. The calibration term means validating the uniformity of electrical field produced at the point of measurement. This paper introduced a verification technique to be used to validate the integrity of input and response signals. This step is essential so that the reproducibility of the experiment is warranted and also to support the calibration analysis result. It was found that the input and response signals were reproducible and consistent. The calibration analysis on the existing bespoke GTEM showed that electric field uniformity at the prescribed area of testing complied with an established practice. Therefore, the GTEM cell can be used to conduct related experiment.

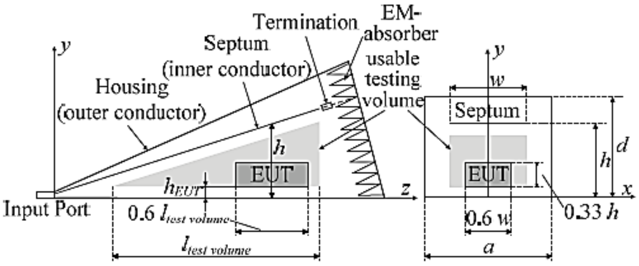
Keywords:

1. Introduction

Gigahertz Transverse Electromagnetic (GTEM) cell has commonly used in parametrising antennas used for partial discharge (PD) detection. It is a cheaper alternative compared to the full-scale anechoic chamber, but with the condition that its suitability and accuracy could be verified (1). Among the testing commonly conducted using GTEM are determining the effective height, h_e, of an antenna or antenna factor, AF, and also for the antenna gain, G (1),(2),(3). Although commonly GTEM cell is filled with air, some researchers have resorted to fill in the cell with other fluid such as dielectric oil (4),(5).

It is recommended that calibration on the GTEM cell to be carried out at least once a year, or before conducting an experiment (6). The word calibration here refers to the inspection on the uniformity of electric field at prescribed area of testing. According to (1), the axis of the antenna needs to be in parallel with the electric field, E, in order to avoid polarisation mismatch. The effect of this mismatch is losses. The type of GTEM used in the experiment was the one with the whole EUT can be placed inside through side door. Figure 1(a) below is the example of a commercial-produced GTEM. Due to the design, the whole equipment under test (EUT) can be placed inside the container. Figure 1(b) is the generic internal design of a GTEM.

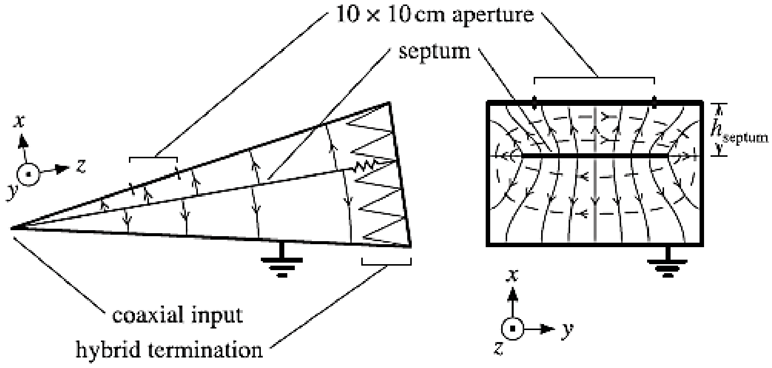
(a) (7)



(b) (4)

Figure 1: Side-door GTEM example

This EUT has the profile of E and magnetic field, H, as shown in the following Figure 2 (8). With reference to (1), the axis of EUT must be in parallel to vertical oriented E. This requirement is not difficult to achieve.



(a) lateral cross section (b) frontal cross section

Figure 2: GTEM with E profile (8)

Conducting radiated, radio frequency and electromagnetic field immunity testing is treated by the IEC standard 61000-4-3 (6). The article noted that the standard recognised GTEM as suitable alternative to conduct the testing and it also listed requirements as outlined by Annex D of the standard. However, the article further noted that the Annex has been taken over by IEC standard 61000-4-20.

To achieve a reliable measurement, IEC 61000-4-20 describes a test to gauge the field uniformity of a ‘defined area’ (DA). A defined area is ‘a hypothetical vertical plane [orthogonal] to the propagation direction of the field’. This means that is a GTEM, the area is perpendicular to the floor of the cell.

A method known as ‘constant field strength method’ (CFSM) has been devised in the standard to determine the uniformity of E within the defined area. In this method, the DA is divided into a number of points. Each point is located at an evenly spaced grid. For example, a X m x Y m DA may be divided into 3-by-3 grid with 0.5 m gap between them. This arrangement results in 9 points on the grid. Example of the arrangement is given in the following figure 3. Note that the EUT has the height of h/3. This is to fulfil the requirement that the arrangement of EUT must not exceed 1/3 of the dimension between the septum and the outer conductor.

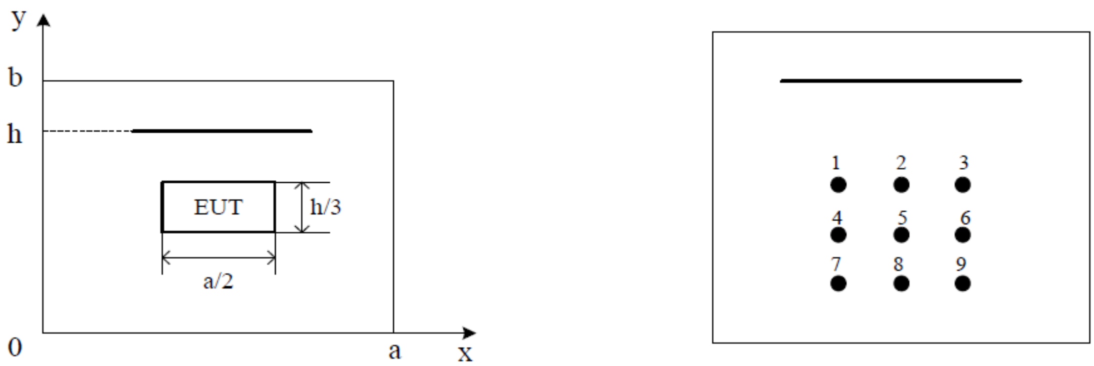


Figure 3: The placement of DA relative to septum – outer conductor distance (h) and its grids (9).

Measurement on differences of signals' input and output power is then carried out for each point and repeated and different frequency, f. According to the standard, 75% of the calibration points have to be within 6dB of the nominal field strength value (9). The formulation for the difference calculation is given as (9):

$$\Delta E_{max} = 20\, log \frac{E_{max}(f)}{E_{min}(f)} < 6dB. \tag{1}$$

2.Cross Correlation of Input and Response Data

The first data set of interest is the pulse that acts as the input to the EUT. For each cycle of test, the pulse has to have the same characteristics. This step is important so that the EUT is responding to identical input. Even though the presence of background noise inside GTEM is small, there is still a probability that it would influence on the pulse. The noise could also be originated from anywhere right from the source, the cables, and connectors. On top of that, delay might be took place.

The second set of data is the response of the EUT. The response is due to the input pulse. However it may also responded to noise as described previously. Hence even though the input pulse could be identical, noise might alter the way the EUT give out its response. And as for the input pulse, delay could be introduced due to the delay in the input or other reason.

As explained before, the inputs and the responses could be affected by noise and delay. In order to determine whether different pulses or responses are identical, cross correlation analysis can be employed. The analysis can reveal the signal matching between. By confirming that any two signals (input pulses or responses) are identical, any footprint due to noise or delay can be eliminated. Hence, it is safe to assume that the input pulses will have consistent characteristics, or reproducible, at each run of experiment. As the result, the EUT can be confidently said to be responded to the identical input.

Cross correlation theorem the Fourier transform of the cross-correlation function of two signals with the Fourier transforms of the individual signals. Consider two signals *f(t)* and *g(t)*, with *g(t)* contains *f(t)* and unknown noise and delay, τ, is given by (10),

$$\mathrm{w(t) = f(t) \otimes g(t) = \int f^*(t-\tau)g(t)dt} \tag{2}$$

If $y(t) = f(t-t_o)$, for any fixed t_o, then $E_y = E_f$. Where,

$$E_y = \int |y(t)|^2\, dt = \int |f(t-t_o|^2 dt = \int |f(\tau)|^2\, d\tau = E_f \tag{3}$$

Following Cauchy-Schwarz inequality,

$$\left| \int y^*(\tau)g(\tau)d\tau \right|^2 \leq E_y E_f \tag{4}$$

So that,

$$|w(t_o)|^2 = \left|\int f^*(\tau - t_o)g(\tau)d\tau\right|^2 \le E_y E_f = E_f E_g \tag{5}$$

For normalized cross correlation,

$$z(t) = \frac{f(t)g(t)}{\sqrt{E_f E_g}} \tag{6}$$

With $z(t) \le 1$ for all t.

Auto correlation is the cross correlation of a function to itself. From (2),

$$w(t) = f(t) \otimes f(t) = \int f^*(t - \tau)f(t)dt \tag{7}$$

At zero lag,

$$w(0) = f(t) \otimes f(t) = \int f^*(t)f(t)dt = \int |f(t)|^2 dt = E_f \tag{8}$$

The normalized autocorrelation is given by,

$$z(t) = \frac{f(t) \otimes g(t)}{E_f} \tag{9}$$

With $z(t) \le 1$ for all t, and at zero lag $z(0) = 1$.

Cross correlation coefficient, r, takes the value up to 1. The maximum coefficient value means that the correlation between two signals is very high.

3.Research Methodology

In this study another design of GTEM has been used. This design doesn’t allow EUT to be inserted directly into the cell. Instead the EUT will be inserted through an opening, or coupler test port, normally located on the top of the cell. Another difference is the septum is installed orthogonal to the end of the cell. The septum in this design was a set of copper wire. Typical design of such GTEM is shown in figure 4. The same type of GTEM has been applied in (4),(3),(11). The EUT used in this study was an off-the-shelf wide-band, omnidirectional antenna. One advantage of this design is it replicated the actual insertion method in power transformer. This statement is also reflected in (12). However, the placement of larger EUT might pose some challenges.

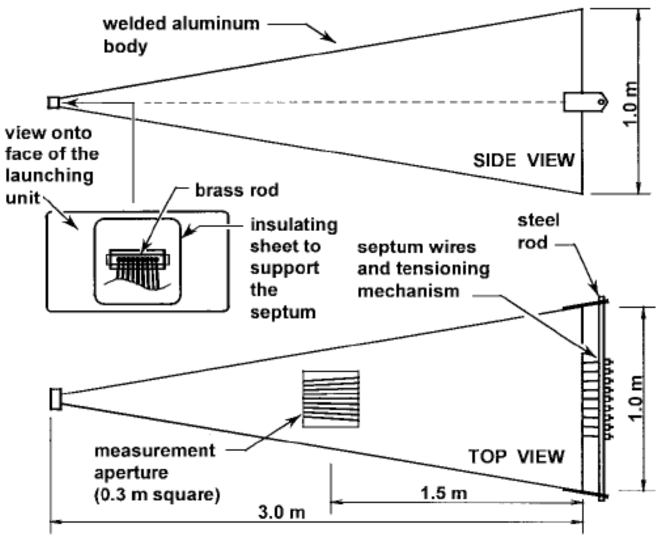


Figure 4: Structure and size of the wire septum GTEM cell (11).

The condition for doing the testing is as listed below (6).

- The field homogeneity requirements are met,
- The arrangement of the EUT and associated wiring cannot exceed one-third of the dimension between the septum and outer conductor,
- The EUT should be rotated in the TEM cell in order to test both horizontal and vertical positions.

The uniformity determination of E in (11) has been given a small twists. First, the DA is now located in parallel to the propagation of E. However with reference to (1), the axis of EUT is still in parallel to E. Hence no loss due to mismatch should be taken place. Secondly, the measurement of interest is field strength, instead of power. This second point is actually an alternative way for uniformity test.

Originally, according to IEC 61000-4-20, 75% of the calibration points have to be within 6dB of the nominal field strength value. The standard does not specify the nominal field strength value. Hence, the maximum difference between the calibration points was calculated for each frequency (6). The latter method has been cited in (3),(13),(14). This study took the approach of maintaining the location of DA so that it is parallel to the propagation of E. However instead of reading the power, the measurement will be done on the E at the input and at the antenna.

The distance from the septum and outer conductor is 24 cm, while the width of the cell is 60 cm. Therefore, the size of the DA has been measured to be 30 cm x 8 cm. According to IEC 61000-4-20 (6), the number of testing points should be 4 + 1 (centre point): it was numbered as point 1, 3, 5 (centre point), 7 and 9. It is also required to have uniform grid spacing between the points.

Ten measurements were made for each point. The measurements include the input pulses as well as the response signals. Noise signals for outside and inside the GTEM were also measured. However, the noise signals inside the cell were relatively small.

4.Results and Discussion

4.1.Input Pulses

As explained in the preceding section, several measurements were taken at each testing point. In order to confirm that the antenna produced a reproducible response the source signal must be uniform. The generic pulses feed into the planar of the GTEM is given in figure 5. The pulses are triggered at different time and seem to be identical. However, all the pulses must be verified for their identically.

The voltage source used in this study was pulse produced using a signal generator. The specification of each of the pulse is as shown in figure 5. Each pulse has a magnitude of 5 V and time duration of

0.127 ns (between 10% to 90%). Figure 5 shows the sample of four cycles of pulses as produced by the signal generator. Generally, each of the pulses looked identical of each other. No sign of delay can be detected too.

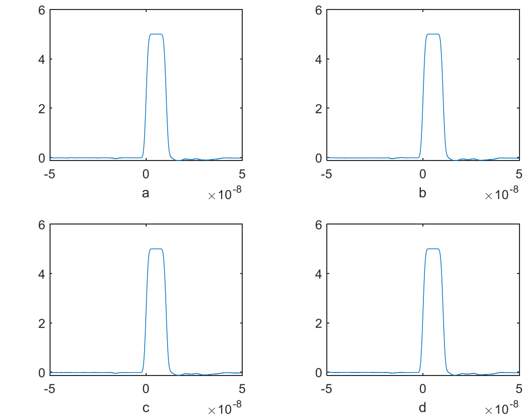


Figure 5. Four cycles of pulses produced by the signal generator.

The following figure 6 shows the cross correlation of all 10 pulses. It is very clear that all pulses are having similarities between each other. No significant differences are expected for any of the pulses. It is safe to conclude that the pulse was reproducible and consistent in term of its shape or waveform.

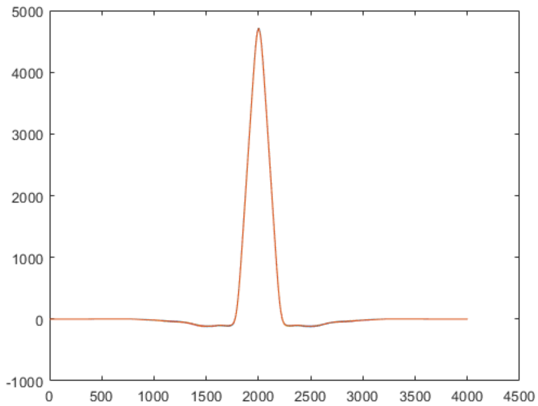


Figure 6. Four cycles of pulses produced by the signal generator.

Figure 7 is the tabulation of correlation coefficients for all 10 samples. All coefficients have the value ‘1’. The correlation is high that there is no reason to support statement that there are differences between the shapes of pulses. This is a supporting fact apart from conclusion that was made from figure 6 above

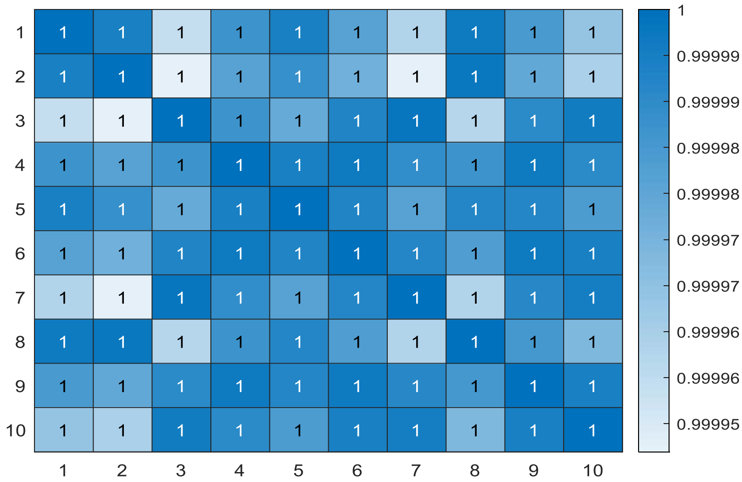


Figure 7. Four cycles of pulses produced by the signal generator.

The cross correlation coefficient, r, is as in figure 8. Figure 8 is the overall r between all the tested pulses against lags. It can be seen that the highest r resides at lag ‘0’. It is an indicator that no evidence of lag between pulses can be supported.

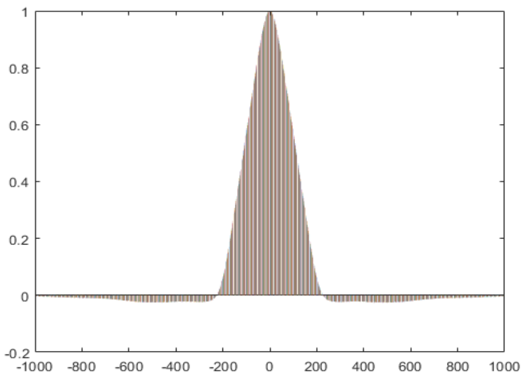


Figure 8. Four cycles of pulses produced by the signal generator.

As the conclusion, all input pulses showed no differences when compared to each other. There is also no evidence of lag in time for any of the pulses. Thus, it is highly possible to reproduce pulse with identical characteristics. Hence for each time the pulse is launched into GTEM, there is a high probability that the EUT will detect and eventually produce its response due to the similar input.

4.2.EUT responses

It is now paramount to determine whether EUT could produce identical and consistent response. There are 7 testing points. At each point 10 cycles of attempts were conducted.

Figure 9 is examples of the responses of EUT as measure at point 1. At this point, no concrete comparison can be made.

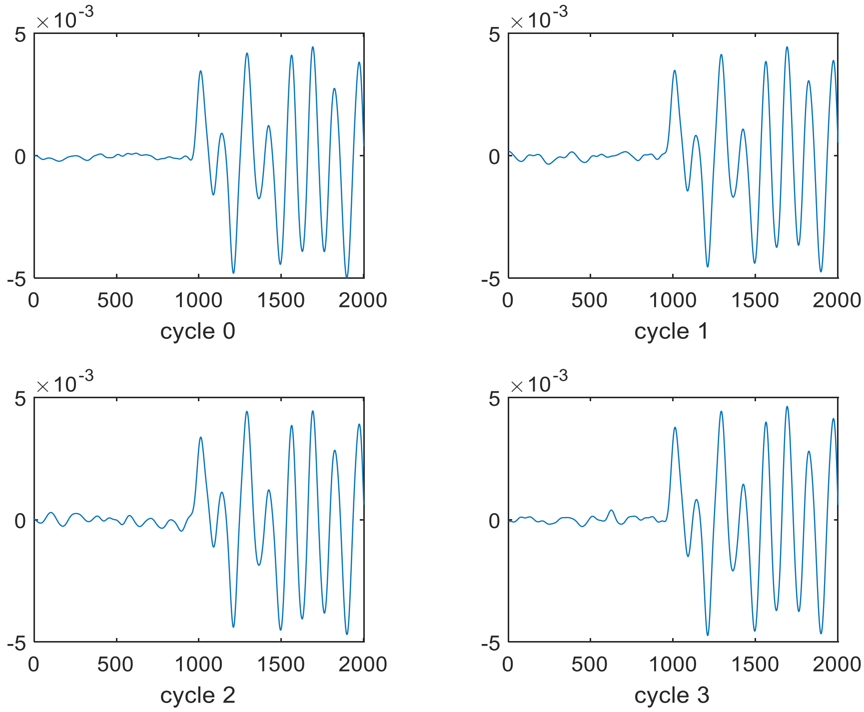


Figure 9. Four cycles of pulses produced by the signal generator.

However figure 10(a) can be interpreted that cross correlation of all ten responses indicates not evidence of significant dissimilarities. The fact is further backed up by figure 10(b) that shows a high cross correlation between each of the ten responses. The lowest coefficient is 0.988.

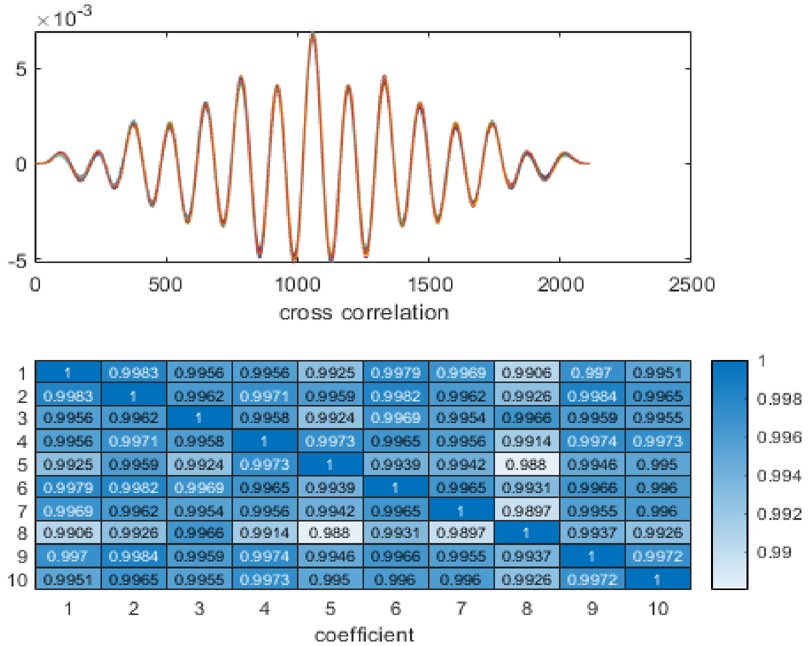


Figure 10. Four cycles of pulses produced by the signal generator.

Figure 11 is the normalized cross correlation coefficient and lags. Figure 11(a) is the tabulation of such data over the whole lag values. Figure 11(b) is the same data but for lags between -5 and 5. Detail observation shows that the highest coefficient is at 0 lag. Therefore no lags can be seen for any of the responses.

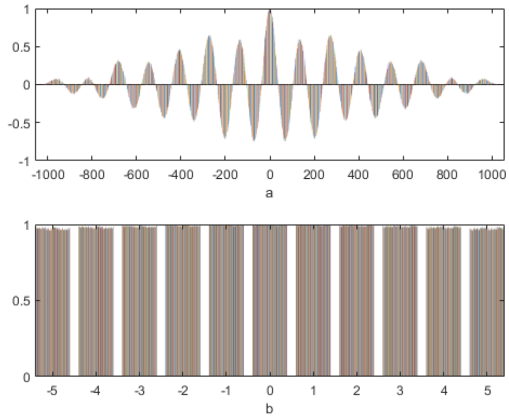


Figure 11. Four cycles of pulses produced by the signal generator.

Based on all findings above, it can be concluded that all ten responses are having a high degree of similarities. On top of that, there is no lag is detected in any of the responses. As the conclusion, the responses are reproducible and consistent.

Further analysis on point 3, 5, 7, and 9 are tabulated in Table 1. From the table all the responses for each of the testing point exhibit very high correlation and no lag.

Table 1: Cross correlation coefficient and lag for point 3, 5, 7, and 9.

Point	Lowest cross correlation coefficient	Lag
3	0.9489	No exhibit
5	0.9819	No exhibit
7	0.9861	No exhibit
9	0.9850	No exhibit

4.3.Electric field uniformity

Figure 12 is the magnitude of all EUT's responses in frequency domain. Following (1), it is found that 2045 from 2048 points at different frequencies are having the ratio of less or equal to 6 dB. This is well better than the 75% as required by the standard.

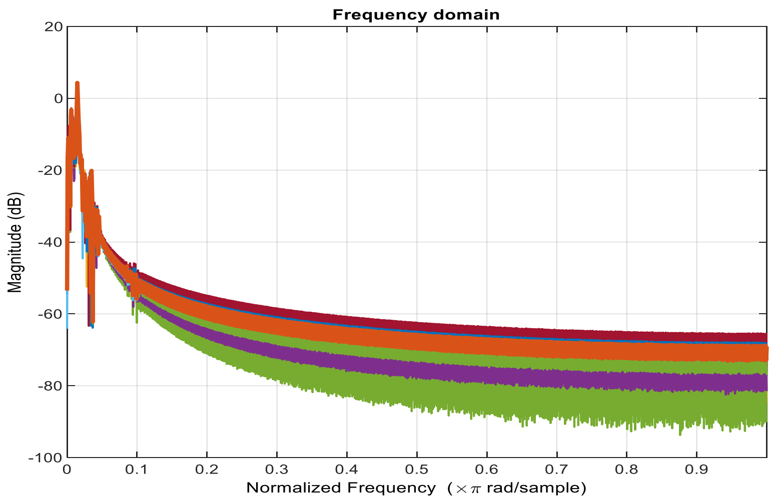


Figure 12. Four cycles of pulses produced by the signal generator.

Further analysis on point 3, 5, 7, and 9 is as in Table 2. All points have a very good uniform electric field at each point on the defined area. All of them are exceeding the 75% as required by the standard.

Table 2: ΔE_{max} for point 3, 5, 7, and 9.

Point	ΔE_{max}
3	99.85%
5	99.85%
7	99.90%
9	99.85%

6.Conclusion

The method of verifying measured data has been demonstrated for input pulse and responses signal. Verification result proved that the reproducibility and consistency of the data. The small noise existed in the GTEM cell did not affect the footprint of the data either in term of waveforms' consistency or introduction of lag in time.

As the integrity of data is rest assured, the outcome of the calibration of GTEM laid on a strong foundation. As shown in the result of the calibration, the GTEM has a uniform electric distribution. Hence the cell is ready to be used as a testing platform.

References

1. Živkovi Z, Šaroli, J Commun Softw Syst., 6, 4, 2010.
2. Siegel M, Beltle M, Tenbohlen S, Coenen S, IEEE Trans Dielectr Electr Insul., 24, 1, 2017.
3. Judd M, Siegel M, Coenen S, VDE High Voltage Technology 2018, ETG-Symposium, 2018.
4. Siegel M, Beltle M, Tenbohlen S, IEEE Trans Dielectr Electr Insul., 23, 3, 2016.
5. Coenen S, Siegel M, Luna G, Tenbohlen S, Monitoring and Acceptance Tests of Power Transformers. In: CIGRE, 2016.
6. Nothofer A, Alexander M, Bozec D, Marvin A, National Physical Laboratory, 2003.
7. Teseq AG., 2016.
8. Land SOT, Perdriau R, Ramdani M, IEEE Trans Electromagn Compat. 59, 6, 2017.
9. Zhang W, Zhou W, Xu D, Xu G, Li X, Lin Y, IOP Conf Ser Earth Environ Sci., 223, 1 2019.
10. Menke W, Menke J, 2016.
11. Judd MD, Farish O, Member S, IEEE Trans Instrum Meas., 47, 4, 1998.
12. Hampton B, Springer US, 1998.
13. Cleary GP, Judd MD, IEE Proceedings-Science, Meas Technol. 153, 2, 2006.
14. Sarathi R, Archana M, IEEE Trans Dielectr Electr Insul., 19, 5, 2012.