Energy Based Correlation Method for Location of Partial Discharge in Transformer Winding

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***Abstract*—Partial discharge (PD) is the major source of insulation failure in power transformer. When transformers are subjected to electrical stress during operation, PD can occur. PD identification is an important diagnostic tool for the reliable operation of transformers. The PD signal detection and location is one of the main challenges for system utilities and equipment manufacturers. In this paper energy based correlation method is proposed for locating the source of PD for different pulse durations. Simulation and experiment are performed on lumped physical layer winding to prove the feasibility of the method and also verified with distributed model of 22kV prototype interleaved winding.**

***Index Terms*—Transformers, Insulation failure, Partial Discharge location, Energy, Correlation method, time domain correlation**

I. INTRODUCTION

A number of research works have been done on the sophistication of the PD signals and its location. Masayuki et al, have extensively analysed the similarities, differences and features of various PD measurement methods and also describe the noise removal, PD location and foreign particle identification [1]. Some of the authors have located PD based on zeros and poles of the transfer functions. For example Mohammad S. Naderi et al., has reported poles in the transfer functions always occur at fixed frequencies and are not affected by the location of the PD while various simulations show that zeros of the transfer functions might be considered as an indicator of the position of the PD [2]. S.N. Hettiwatte et.al., have also extensively analysed and reported that zeros are used to locate the source of the discharge. But zeros of the measured line-end signals are difficult to detect when the source of the discharge is near the line-end [3, 4]. The main limitations of these methods are influence of noise. In recent studies, correlation method has been used to locate the PD source for single PD pulse width [5]. In this work an attempt has been made to analyse the efficacy of the correlation methods to locate PD in transformer winding for different pulse widths.

II. EFFECTS OF PD PULSE AND ITS DURATION IN TRANSFORMER WINDING

PDs are small electrical sparks resulting from the electrical breakdown of a gas contained within a void. If the void is within an solid or liquid, the PD will degrade the material and may eventually cause the failure of the winding insulation [6]. The discharge in small void in insulation is extremely a rapid event.

The PD pulses in solid, liquid and gaseous insulations are different. Experiments are performed to analyse PD in idealized dielectric medium with PD pulses of very short duration of 200ns [7]. In literature analysis of the PD events it is found that PD events can occurs from 1ns to few µs [8]. S. N. Hettiwatte et al., has reported the propagation of PD pulse duration varies from 100ns-10µs [4] The experimental investigations are performed on transformer oil impregnated paper indicate durations as high as 5µs [9].Tanaka has reported one PD pulse can be discriminated within 100µs for a 50Hz voltage and extensively analysed on PD pulse pattern [10]. Hence in this work, PD is represented by voltage pulses of duration 1-10 µs with rise time of 10nsec.

III. PD IN TRANSFORMER WINDING

In order to locate the PD within transformer winding, a 10 section physical model of a uniform layer winding is constructed shown in Figure 1. The circuit parameters of the lumped parameter model with discrete elements are Ls = 2.5 mH, Rs = 18 Ω, Cs = 150 pF and C_g = 850 pF. The part of the windings between the nodes 'j-1' and 'j' is denoted as section 'i'. Simulation is performed using Orcad circuit simulation package (PSPICE).

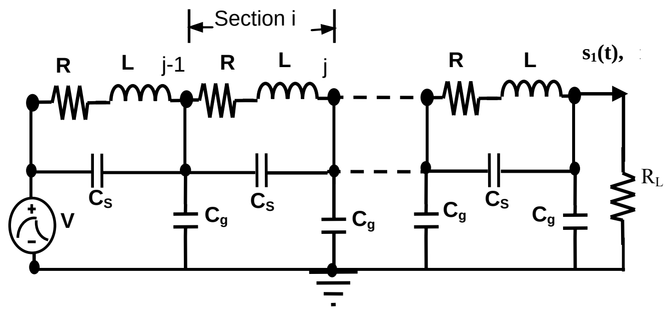

Figure 1. Lumped parameter model of transformer winding.

A reference PD (V_{ref} =1V) pulse width of t_{ref} = 5µs is applied across section 1(10% of the winding) and the corresponding winding response $s_1(t)$ is measured across the resistor (R_L). Similarly, the winding response $s_2(t)$ to $s_M(t)$ are observed when a V_{ref} signal is applied across section 2 to M. The Figure 2 shows the PD responses due to applied V_{ref} across section 1 to 8. The responses of the winding $s_i(t)$ are the reference signals for the correlation to locate the PD.

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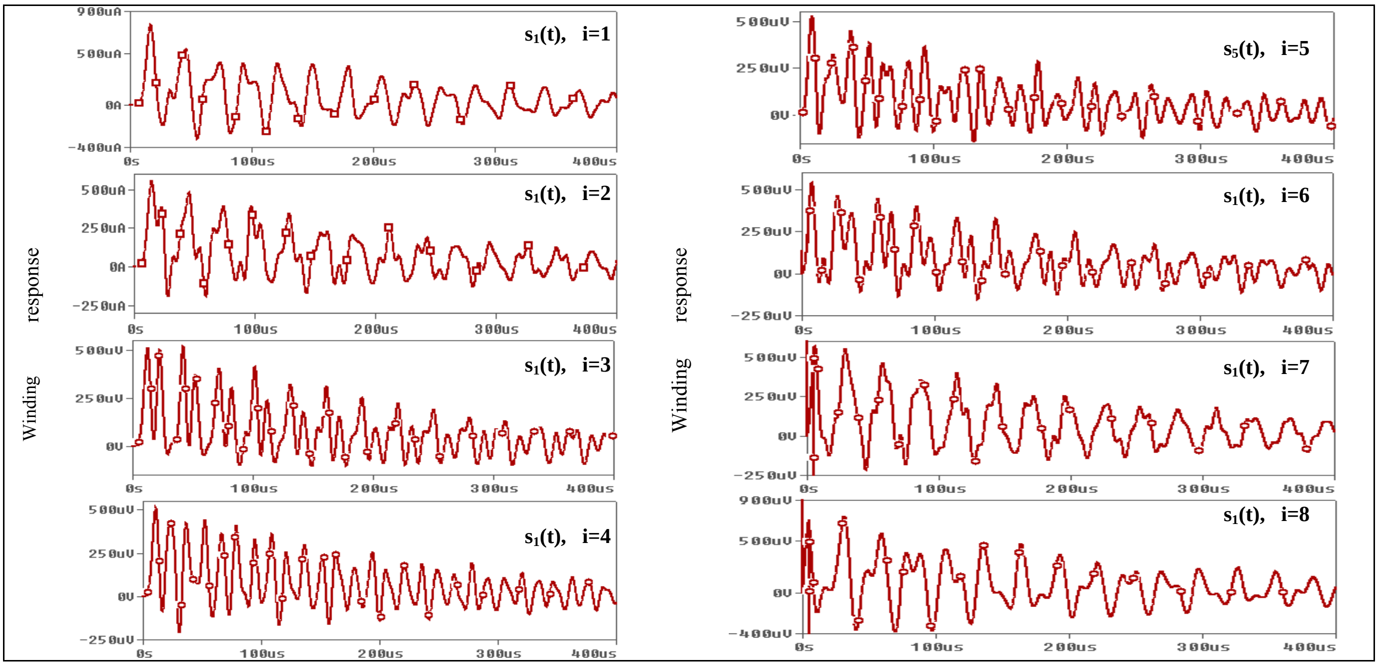

Figure 2. Responses of the layer winding for V_{ref} =5 µs.

PD may occur in any place where the insulation becomes weak, but normally it occurs in winding insulation. Knowing there is a PD, some where within the winding, PD location is performed by applying test PD pulse (t_{test}). t_{test} is applied across any section 'x' and the corresponding response $r_x(t)$ is measured across the resistor R_L. By an appropriate method, one has to identify the location 'x' using $s_i(t)$ and $r_x(t)$. The location 'x' can be anything between sections 1 to 8. The Figure 3 show the winding response when V_{test} of 10µs is applied across section x =1, 2,3, 4 and 7.

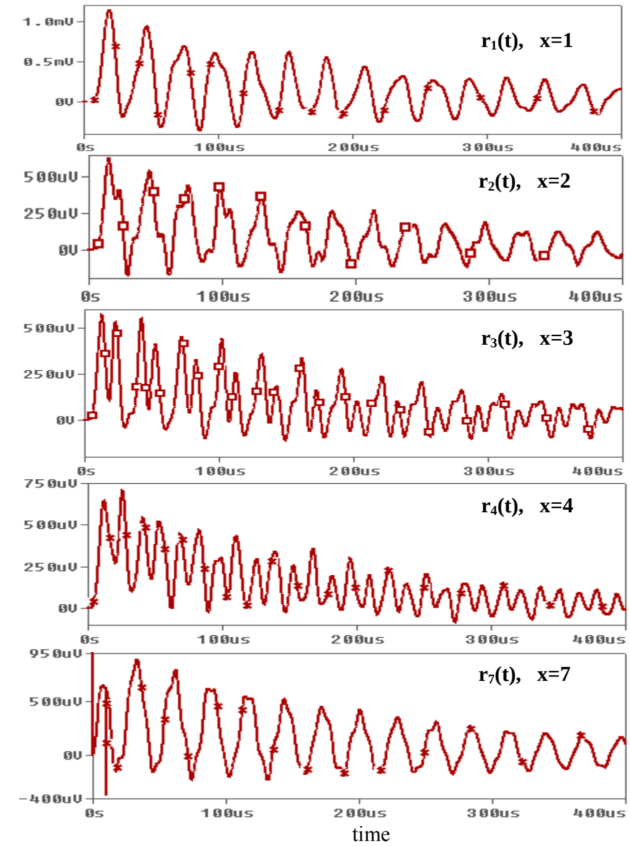

Figure 3. Responses of the layer winding due to applied V_{test} =10µs.

IV. PRINCIPLE OF CORRELATION METHOD

In general correlation method is a matching process which shows the strength of relationship between any pair of variables through appropriate mathematical formulation.

In this case, correlation analysis first checks whether there is any linear relationship between $s_i(t)$ and $r_x(t)$. We start by defining a time cross - correlation (reference cross correlation) coefficient (ρ_{ix}) as a measure of similarity between two signals vectors. The time cross - correlation coefficient is expressed as [11, 12]

$$\rho_{ix} = \frac{1}{\sqrt{s_i}\sqrt{r_x}}\int_0^T s_i(t)r_x(t)dt \qquad (1)$$

Where

$\sqrt{s_i}$ = magnitude of the signal $s_i(t)$

$\sqrt{r_x}$ = magnitude of the signal $r_x(t)$

The winding responses of $s_i(t)$ and $r_x(t)$ are perfectly correlated for ρ_{ix} =1, i.e. there is linear relationship between the two responses $s_i(t)$ and $r_x(t)$ over a time shown in Figure 4(a). In case of ρ_{ix}=0, corresponding signals are not correlated (zero correlation) over a time shown in Figure 4 (b). When ρ_{ix} >0, $s_i(t)$ and $r_x(t)$ increases or decreases together: there is a 'positive correlation' shown in Figure 4 (c). If ρ_{ix} < 0, large values of $r_x(t)$ are linked to small values of $s_i(t)$: indicating 'negative correlation' shown in Figure 4 (d). In case of ρ_{ix}=-1 the $s_i(t)$ and $r_x(t)$ being anti-correlated over a time shown in Figure 4(e). In such a case, the signals are called 'antipodal' (mirror images of one another or the signals are 180° apart, i.e., $s_i(t)$ =-$r_x(t)$. When the two signal vectors $s_i(t)$ and $r_x(t)$ are orthogonal, two signals cannot interfere with one another because they are disjoint in time. From the Figure 4(f), the vector representation of $s_i(t)$ and $r_x(t)$ illustrates the perpendicular(orthogonal) relationship.

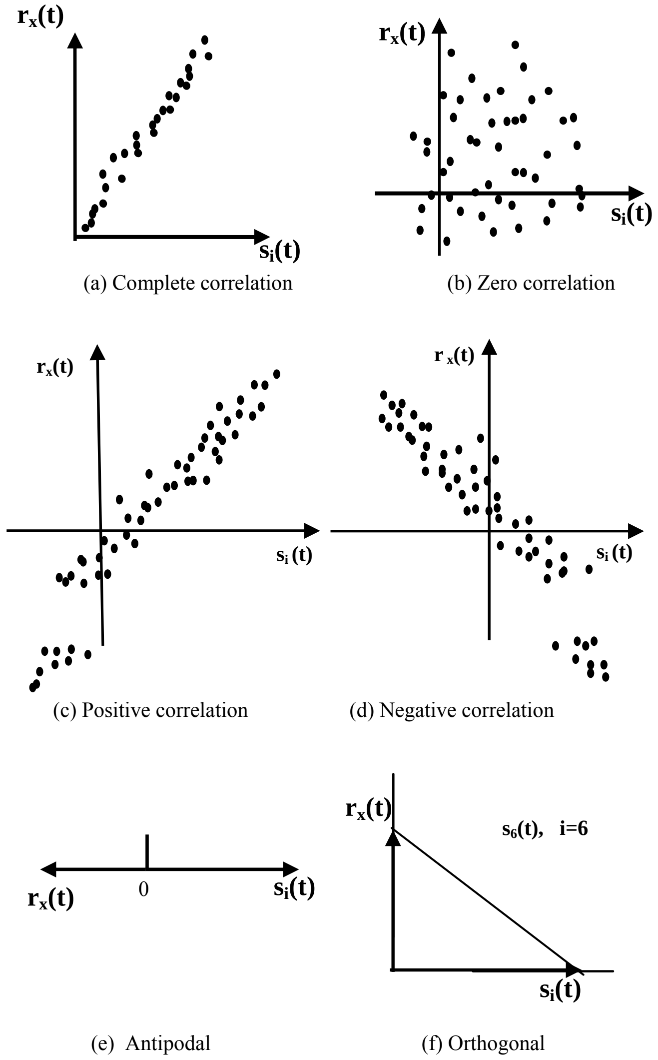

Figure 4. Basic principle of different correlation functions.

s7(t), i=7

s8(t), i=8

A. *Correlation based PD location*

In this case, correlation function consists of a bank of correlators supplied with a corresponding set of reference signals $s_i(t)$. This bank of correlators operate on the PD response $r_x(t)$ at $0 \le t \le T$, to locate section 'x'. The N elements of the location section 'x' of the vector $r_x(t)$ are first multiplied by corresponding N elements of each of the M reference signal vectors $s_i(t)=s_1(t),s_2(t),\ldots,s_M(t)$. The resulting products are successively summed $z_i(t)$. Finally, the largest in the resulting set of numbers is selected and a corresponding decision on the location is made i.e., the best matches or good matching (maximum value) is obtained when $r_x(t)$ has maximum correlation with $s_i(t)$.The maximum value occurs when i=x, thus determining the PD location 'x'. The Figure 5 shows the principle of correlation method for location of PD in identical PD pulse durations.

Simulation and experimental studies are performed to identify the PD location 'x' using correlation method [5]. In this method location of 'x' can be identified only when the duration of $t_{test} = t_{ref.}$ i.e., the PD can be located when the duration of pulse of t_{test} and t_{ref} are identical input. When the t_{test} is other than t_{ref}, the location of PD is wrongly estimated reported in [13].

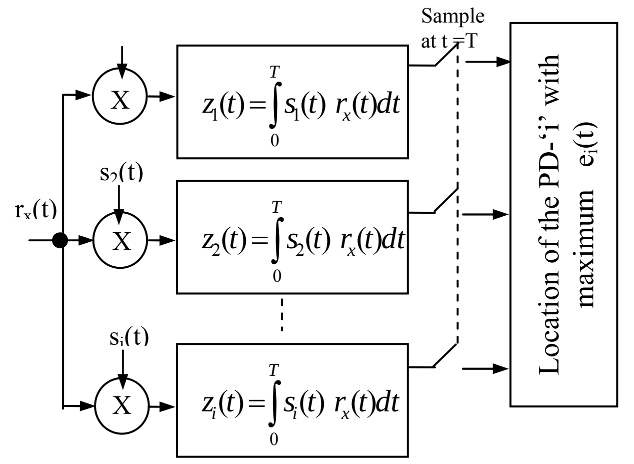

Figure 5. Principle correlation method for location of PD.

In practice, the location of PD occurrence (x) in the winding and shape of PD pulse duration (t_{test}) is random in nature. Hence, a new methodology should be formulated to detect the PD location for any t_{test} other than t_{ref}. In this work, we propose an energy based correlation method to locate the PD in order to overcome the limitation of time domain correlation method.

B. *Energy based correlation for PD location*

In order to identify the location of section 'x', the energy of the difference signal is calculated as

$$E_{d_{ix}} = \int_0^T \left[s_i(t) - r_x(t) \right]^2 dt$$
$$= \int_0^T s_i(t)^2\, dt + \int_0^T r_x(t)^2 dt - 2\int_0^T s_i(t) r_x(t) dt \times \cos\theta_{ix} \quad (2)$$

Let us begin with some basic vectors concepts and then apply those concepts to signal for detection of PD. Because there is a perfect analogy between signals and vectors. For convenience, we define the dot product of two vector si and r_x as

$$s_i \cdot r_x = |s_i||r_x| \cos\theta_{ix}$$
$$\cos\theta_{ix} = \frac{s_i \cdot r_x}{|s_i||r_x|} \quad (3)$$

where θ_{ix} is the angle between vectors s_i and r_x

From the equation the amount of similarity between two signals can also be conveniently measured by $\cos\theta_{ix}$. Comparing the equation 1 and 3 it is evident that the area under the product of two signals corresponds to the inner product of two vectors. In fact, the area under the product of $s_i(t)$ and $r_x(t)$ is called the inner product of s_i and r_x [11].

To summarize the discussion, when the signals $s_i(t)$ and $r_x(t)$ are viewed as a vectors, then reference cross correlation coefficient (ρ_{ix}) is conventionally expressed as [12]

$$\rho_{ix} = \cos\theta_{ix} \quad (4)$$

In the literature [12] has given that, the cosine of this angle between two signal vectors gives the same normalized value of correlation as equation (4).

Substitute the equation 4 in 2

$$\rho_{ix} = \frac{\left(\int_0^T s_i(t)^2\,dt\right) + \left(\int_0^T r_x(t)^2\,dt\right) - E_{d_{ix}}}{2 \times \int_0^T s_i(t)dt \times \int_0^T r_x(t)dt} \quad (5)$$

The location criterion is the section ‘i’ that yields

Maximum of ρ_{ix} (6)

The total energy of the winding responses $s_i(t)$ is calculated upto 1ms with the interval of 0.2µs.The total energy of the signal $s_1(t)$ is 1.5472e-11 Joules. Figure 6 shows the energy of the signal set $s_1(t)$. From the Figures 90% of the total energy is reached within first 300µs.Similarly, total energy of the signal (i=2, M) is calculated. Hence, the response of the winding is considered upto 300µs in order to estimate the location of PD.

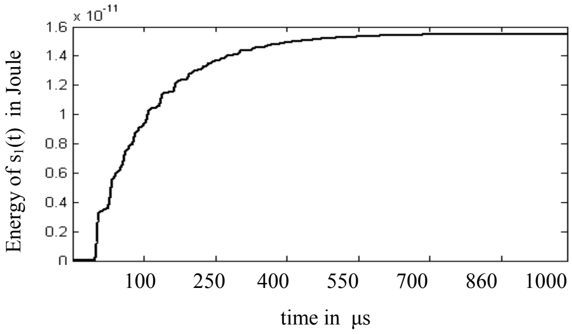

Figure 6. Energy of the signal $s_1(t)$

The above proposed energy based correlation method is tried for the cases with test PDs of 1-10 µs. For example, t_{test} =1, 6 and 10µs is applied across all the sections and the reference correlation coefficients ρ_{ix} are calculated using the equation (5). The maximum of ρ_{ix} gives the location PD (bold with underline data) and each value of ρ_{ix} gives the nature of signal between $s_i(t)$ and $r_x(t)$ shown in Table I. For example the result of output of signal set $s_1(t)$ and $r_1(t)$ is highly correlated i.e., ρ_{11} is highly correlated compared to other values of ρ_{12} to ρ_{18} in the first row. Similarly, ρ_{18} of the signal set $s_8(t)$ and $r_1(t)$ are antipodal. The Figure 7 shows the principle of energy based correlation method for PD detection.

TABLE I. ENERGY BASED CORRELATION OUTPUTS OF LAYER WINDING

sections		V_{ref} (i), t_{ref}=5µs							
V_{test} (x)	i / x	1	2	3	4	5	6	7	8
t_{test}=1µs	1	***<u>0.85</u>***	0.44	0.24	0.15	0.23	0.28	0.07	-0.05
	3	0.21	0.52	***0.71***	0.47	0.45	0.20	0.08	-0.03
	6	0.01	0.08	0.15	0.30	0.42	***0.71***	0.58	0.01
, t_{test}=6µs	2	0.62	***0.99***	0.66	0.48	0.37	0.18	-0.15	-0.01
	4	0.28	0.50	0.64	***0.98***	0.86	0.48	0.30	0.02
	7	-0.02	-0.13	0.17	0.33	0.49	0.66	***0.81***	0.15
t_{test}=10µs	1	***0.83***	0.71	0.41	0.39	0.34	0.14	-0.13	-0.04
	5	0.39	0.59	0.68	0.75	***0.83***	0.71	0.43	0.02
	8	-0.11	-0.14	-0.12	-0.09	-0.05	0.10	0.40	***0.52***

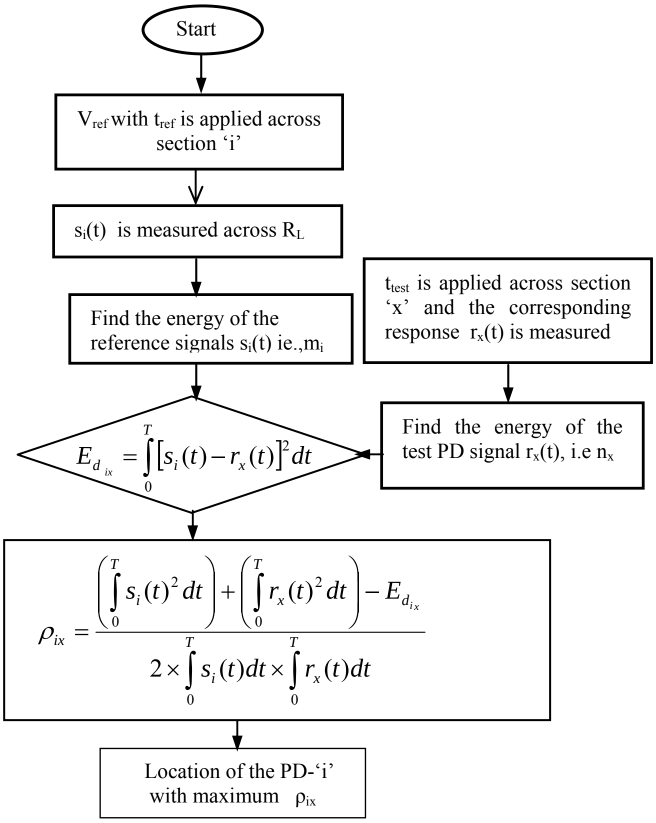

Figure 7. Principle of energy based correlation method for PD detection.

V. EXPERIMENTAL VALIDATION OF ENERGY BASED CORRELATION

The energy based correlation principle is validated on lumped physical layer winding and 22kV prototype interleaved winding (distributed model). Interleaved winding has 40 section and these sections in turn had 12 turns in it. Tapping were brought out at every 4 section (4 section is 10% of the winding) in order to be able to inject PD signals. The experimental setup for PD location is shown in Figure 8.

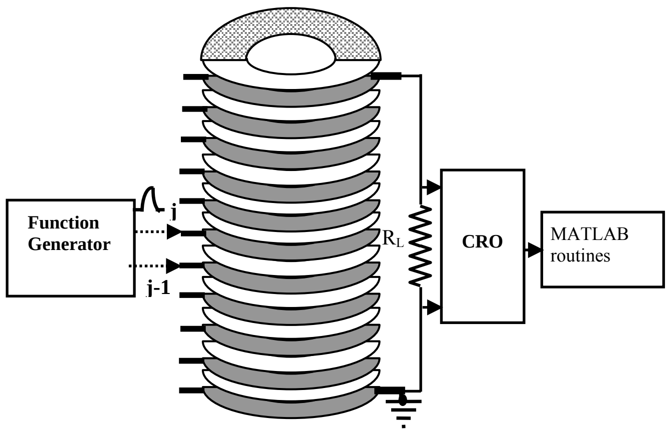

Figure 8. Schematic diagram of test setup.

A reference PD pulse width of t_{ref} = 5µs is created by using 80 MHz, Arbitrary function generator (Agilent 33250A) and applied across each sections of the winding. The corresponding winding response $s_i(t)$ is measured across the resistor (R_L). The measurement is done using a 60MHz, 1 GHz/s, digital storage oscilloscope (TDS 2004B). The

90% of the total energy in the winding response $s_i(t)$ is reached within first 150µs with the interval of 0.2µs. So, the response of the winding is considered upto 150µs. The Figure 9 shows the responses of the layer winding due to applied V_{ref} across the section i. The measured winding responses are then fed into a PC where MATLAB software routines are used to calculate correlation coefficients of the signal in order to detect the PD signal.

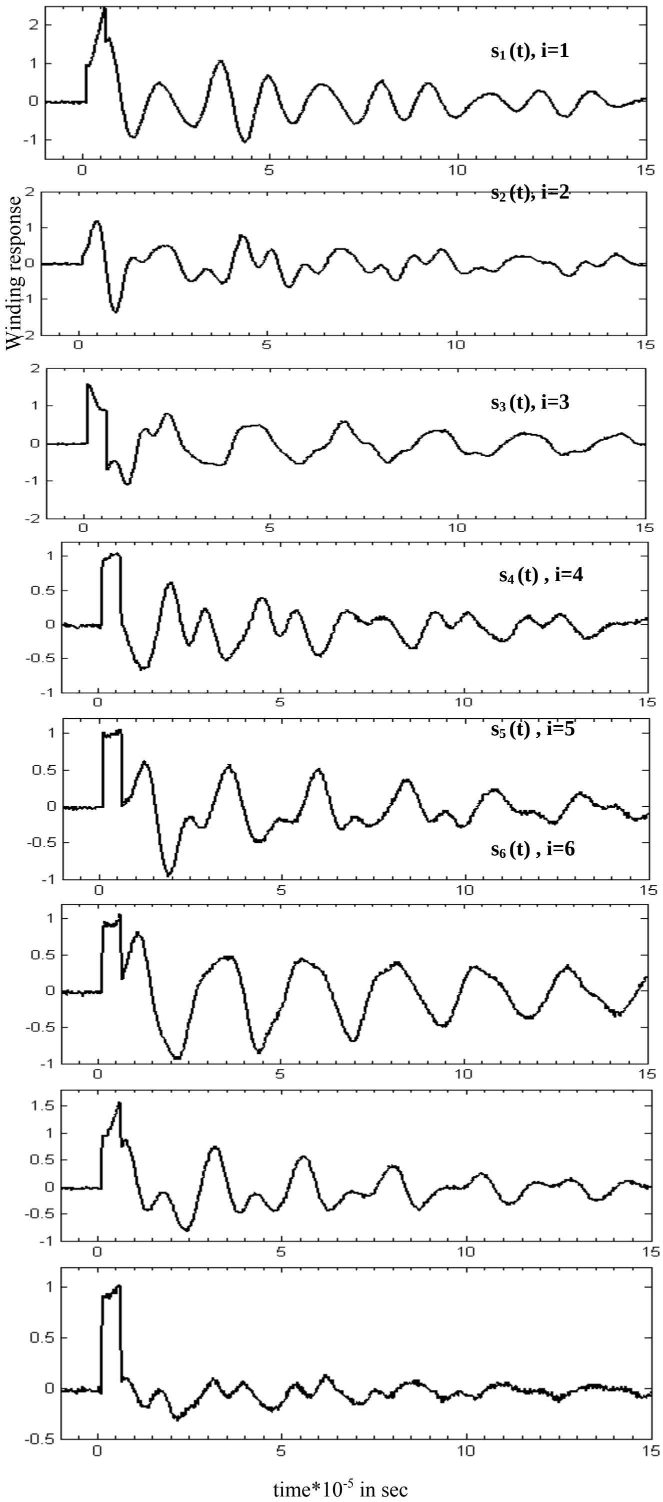

Figure 9. Responses of the layer winding due to applied V_{ref} =5 µs across section 'i'.

The energy based correlation outputs from the experimental results for test PD pulse width t_{test} =1, 6, 10µs across x=1 to 8 are shown in Table II and the location of PD is done successfully. Similar analyses are performed on continuous disc and interleaved winding. The results are correlation outputs of the interleaved winding are given in Table III.

TABLE II. ENERGY BASED CORRELATION OUTPUTS OF LAYER WINDING

sections		V_{ref} (i), t_{ref}=5µs							
V_{test} (x)	i / x	1	2	3	4	5	6	7	8
t_{test}=1µs	1	***0.64***	0.26	0.31	0.36	0.53	0.35	0.21	0.35
	3	-0.01	0.38	***0.51***	0.29	0.08	-0.13	-0.35	-0.19
	5	0.12	0.05	0.06	0.11	***0.32***	0.16	0.14	0.16
, t_{test}=6µs	2	0.21	***0.95***	0.84	0.61	0.22	-0.23	-0.52	-0.02
	4	0.30	0.55	0.65	***0.95***	0.39	-0.19	-0.15	0.47
	8	0.36	-0.10	-0.14	0.35	0.56	0.47	0.63	***0.97***
t_{test}=10µs	4	0.40	0.27	0.39	***0.62***	0.34	0.03	0.11	0.52
	6	0.36	-0.26	-0.29	-0.25	0.55	***0.69***	0.55	0.30
	7	0.27	-0.49	-0.56	-0.28	0.48	0.73	***0.80***	0.47

TABLE III. ENERGY BASED CORRELATION OUTPUTS OF INTERLEAVED WINDING

sections		V_{ref} (i), t_{ref}=5µs							
V_{test} (x),	i / x	1	2	3	4	5	6	7	8
t_{test}=6µs	2	0.22	***0.99***	0.82	0.16	-0.59	-0.76	-0.81	-0.15
	4	-0.42	0.07	0.49	***0.98***	0.54	0.37	0.49	0.80
	5	-0.25	-0.57	-0.45	0.46	***0.99***	0.76	0.84	0.59
	7	-0.40	-0.83	-0.49	0.39	0.87	0.72	***0.99***	0.57
t_{test}=10µs	1	***0.96***	0.42	0.09	-0.30	-0.35	-0.36	-0.55	-0.79
	3	-0.20	0.62	***0.96***	0.60	-0.36	-0.52	-0.27	0.28
	4	-0.50	-0.08	0.34	***0.94***	0.65	0.51	0.62	0.86
	8	-0.81	-0.36	-0.02	0.64	0.69	0.62	0.71	***0.94***

Comparing simulation and experimental responses of the winding is different which can improve by enhancing the transformer winding model. Though, the responses of the winding is different, there is no error in the estimation of PD location.

VI. CONCLUSION

For estimating the location of PD within transformer windings correlation method has been proposed earlier [13]. The main limitation of the correlation method is that it will work successfully only if the reference PD pulse duration exactly matches the test PD pulse duration. To overcome this limitation, the energy based correlation method is suggested for identification of PD in transformer windings. The proposed methodology has been checked by both simulation and experimental for layer and interleaved windings and the method locates the PD successfully.

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