Partial discharge propagation studies in generator and transformer

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Partial Discharge Propagation Studies in Generator and Transformer

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School of Electrical and Electronic Engineering

A thesis submitted to the Nanyang Technological University
in fulfilment of the requirement for the degree of
Doctor of Philosophy

2006

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Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

19-06-2006

Date

Qin Shaozhen

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Abstract

Abstract

Partial discharge (PD) measurement on electrical equipment can be traced back to the beginning of the twentieth century. It is an effective tool to evaluate the quality and condition of the electrical insulation. The widespread application of PD tests, both as a quality control tool and a maintenance planning tool requires the understanding of what the PD test is measuring, and the significance of the measured signals.

It is not likely that these desires can be fulfilled easily, at least for testing on transformers and generators. PD in transformers and generators can occur at different locations due to weakening of insulation and the PD propagation from the origin to the test terminals will distort the original PD waveshape due to the complicated path. This is because the windings are not lumped capacitive elements, but are complex transmission lines with significant inductive and capacitive components. To detect incipient insulation faults, to prevent insulation failures of power transformers and generators and to locate the PD sites, PD propagation in those apparatus should be studied in depth.

In this limited 3 years of research work, three electrical apparatus namely experimental transformer (ET), potential transformer (PT) and generator (G) connected to power network are studied for the PD propagation characteristics. The study focuses on identifying the different propagation modes by varying the origin of the injected PD and monitored locations. A new method of transfer functions analysis for high and low frequency components using wavelet technique is proposed. This method is able to predict the different propagation modes clearly with the decomposed low and high frequency components of the signal. The results reveal clearly the existence of multi propagation modes for the same PD signal.

Based on experimental measurements and analysis, propagation models for PT and G connected to power network are developed to match the experimental results and explain the various PD propagation modes. The models are also used to predict the possible PD location and the type of PD occurring in the respective apparatus.

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List of Symbols and Abbreviations

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bot	Bottom
BW	Bandwidth
C	Capacitance
C1	Serial capacitance of generator winding in overhang section(Fig.7-8)
C2	Ground capacitance of generator winding in slot section(Fig.7-8)
C2s	Ground capacitance of generator winding in overhang section(Fig.7-8)
C3	Busbar ground capacitance (Fig.7-8)
C4	Transformer capacitance (Fig.7-8)
Cc	Coupling capacitance (Fig.7-8)
Cm	Measurement capacitance (Fig.7-8)
Cp1	Serial capacitance of of PT HV winding from 83.4% to 50% (Fig.7-1)
Cp2	Capacitance to ground of PT HV winding from 83.4% to 50% (Fig.7-1)
Cp3	Serial capacitance of PT HV winding from 50% to 0% (Fig.7-1)
Cp4	Capacitance to ground of PT HV winding from 50% to 0% (Fig.7-1)
Cpn	Serial capacitance of PT HV winding from 100% to 83.4%(Fig.7-1)
Cpn1	Capacitance to ground of PT HV winding from 100% to 83.4%(Fig.7-1)
Cpss1	Coupling capacitance couples 50% of HV winding to 50% of LV winding(Fig.7-1)
Cpss2	Coupling capacitance couples 83.4% of HV winding to 50% of LV winding (Fig.7-1)
Cpss3	Coupling capacitance couples 66.8% of HV winding to 50% of LV winding (Fig.7-1)
Cpss4	Coupling capacitance couples 33.3% of HV winding to 50% of LV winding (Fig.7-1)
Cpss5	Coupling capacitance couples 16.7% of HV winding to 50% of lv1-lv2 and lv3-lv4 (Fig.7-1)
Csg	Capacitance to ground of the LV winding (Fig.7-1)
Css	Coupling capacitance couples the 50% of lv1-lv2 to 50% of lv3-lv4 windings (Fig.7-1)
Css	Serial capacitance of the LV winding (Fig.7-1)
CT	Current transformer
ET	Experimental transformer
Exp	Exponential
Exp-osc	Exponential-oscillation
FFT	Fast fourier transform
g	Ground
G	Generator
HV	High voltage
L	Inductance
L1	Inductance of generator winding in slot section (Fig.7-8)
L1s	Inductance of generator winding in overhang section(Fig.7-8)
L2	Busbar inductance (Fig.7-8)
L3	Transformer inductance (Fig.7-8)
Lc	Inductance of coupling capacitance (Fig.7-8)
Lp1	Inductance of PT HV winding from 83.4% to 50% (Fig.7-1)

List of Symbols and Abbreviations

Lp2	Inductance of PT HV winding from 50% to 0% (Fig.7-1)
Lpn	Inductance of PT HV winding from 100% to 83.4% (Fig.7-1)
Ls	Inductance of LV winding (Fig.7-1)
LV	Low voltage
M	Mutual inductance from HV winding to LV winding (Fig.7-1)
M1	Mutual inductance between LV windings (Fig.7-1)
Mid	Middle
Osc	Oscillation
PD	Partial discharge
PSD	Power spectrum density
PT	Potential transformer
R	Resistance
R1	Resistance of generator winding (Fig.7-8)
R2	Busbar resistance (Fig.7-8)
R3	Transformer resistance (Fig.7-8)
Rc	Resistance of coupling capacitance (Fig.7-8)
RF	Radio frequency
Ri	Busbar insulation resistance (Fig.7-8)
RIV	Radio interference voltage
Rm	Measurement resistance (Fig.7-8)
Rn	Resistance of PT HV winding from 100% to 83.4%(Fig.7-1)
Rp1	Resistance of PT HV winding from 83.4% to 50% (Fig.7-1)
Rp2	Resistance of PT HV winding from 50% to 0% (Fig.7-1)
Rs	Resistance of the LV winding (Fig.7-1)
TEM	Transverse electromagnetic
t _f	Front time
TF	Transfer function
t _t	Tail time
Top	Top
UJT	Unijunction transistor
U _N	Rated phase voltage
Φ	Phase

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CHAPTER 1

Introduction

1.1 Motivation

With the increasing demand for reliable power supply in the competitive restructured energy market of 21st century, cost effective and reliable delivery of electric power is of prime concern to utilities throughout the world. The traditional individual power utilities are moving towards greater competition after restructuring. This means that consumers can buy electrical energy from any power company offering most favorable conditions like the cost, reliability and power quality. It results in a cost consciousness among utilities and drives to reduce maintenance costs. Avoiding or ignoring necessary maintenance outages have consequential costs. It results in asset management to work existing equipment harder and longer with the modern concept of condition-based maintenance [20].

On-line monitoring and on-site diagnostics of electrical equipment has attracted considerable attention for many years. The interest has recently accelerated, triggered by a restructured energy market and changes in the electricity business due to reduction in the work force.

Transformers and generators are the most important and costly equipments in power system. They are high current carrying elements and they are coupled permanently in many operating power stations. More attention should be paid to the operational state of these equipments. On-line partial discharge (PD) measurement is an effective and reliable method to appraise the state of the insulation of these equipments. Many utilities have permanently installed coupling capacitors to monitor PD activity in their power generation and distribution system.

Measurement of PD on the electrical equipments can be traced back to the beginnings of the twentieth century. It is an effective tool to evaluate the quality and condition of the electrical insulation as soon as it is fabricated. In a controlled laboratory environment and with one apparatus, an experienced researcher can locate the type and location of PD. In the twentieth century, the widespread application of PD testing as a maintenance planning tool has been appreciated and used. It requires the

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understanding of what the PD test is measuring, and the significance of the measured signals. Research related to understanding PD mechanisms, physical and chemical effects, detection sensitivity and measurement techniques are being carried out [1][2][3][9][10][20][36]. PD analysis in the form of apparent charge transfer, pulse repetition rate, energy loss, distribution of pulse height with phase and number, discharge epoch, pulse intervals, and pulse pattern recognition is constantly investigated to identify the deterioration level, the cause of PD, the possible location of PD, number and types of developing PDs[20].

PD in operating machines can occur at different locations due to weakening of insulation. The measured randomly occurring PD signal is distorted on the PD propagation path, by different couplers, instruments and analyzing methods [1] [2] [3]. PD propagation path in the windings is not lumped resistive, inductive and capacitive elements, but are complex transmission lines with significant inductive components [2] [3] [12]. In addition PD detection and location in transformer [5] [6] [7] [8] [20] becomes more complicated due to coupling and resonance effects between the windings. Furthermore, the transmission line aspects of windings yield attenuation and distortion effects which are highly dependent on frequency [2]. IEC 60270 cautions against the calibration of PD quantities into pC in inductive apparatus. To detect and locate the incipient insulation faults and prevent insulation failures of power transformers and generators, the high frequency PD propagation in different apparatus should be studied in depth. The different propagation modes and paths should be identified from origin of PD to the measuring node to predict the unknown PD observation. Currently PD measurement is used to assess the operational status of electrical equipments [1] [3] [5]. The PD signal contains a lot of information to identify the type, number and location of developing faults and no detailed research is done so far to extract the features for characterization. Since the local power station, Power Seraya is interested in identifying the location of PD from the recorded PD behavior at the high voltage (HV) coupler, this research work is supported and cooperated to understand the complicated PD propagation characteristics in the connected power apparatus in the network. No simple model is available to understand the different modes of possible PD propagation from origin to the

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measuring node. To understand the phenomenon and wave shape of PD at the measuring nodes, this research work is carried out.

1.2 Objectives

There are many unanswered questions on the PD propagation in an operating generator and the connected network. The *objectives* of this research project are:

- (a) To develop a powerful PD source to inject reproducible PD in a 250 MVA rated generator connected to step-up transformer and to develop computer controlled measurement system to record the randomly occurring simultaneous single PD pulses at 4 nodes;
- (b) To study the characteristics of PD propagation in an experimental laboratory transformer, HV potential transformer and HV power generator connected to power network in off-line and on-line configurations;
- (c) To develop signal acquiring programs for single PD with sufficient number of sampling points and processing programs for denoising, for transformation to transfer function analysis, for wavelet method of analysis and for PD propagation modes identification;
- (d) To come up with suitable PD propagation models incorporating PD propagation modes and the winding layout to match the simultaneous experimental observations and to identify the parameters of the model; and
- (e) To use the model for the identification of PD location and type of PD.

1.3 Major Contributions of the Thesis

The major contributions to this research project are:

- (a) Development of PD sources using unijunction transistor (UJT) and mercury switches to use with 250 MVA rating field generator and record PD propagation behavior in off-line mode from multi-nodes;
- (b) Acquired simultaneous single PD data from multi-nodes of an operating generator network using computer controlled measurement system;
- (c) Evaluated PD propagation behavior in HV power generator connected to power network, HV potential transformer and laboratory transformer by varying injection nodes in grounded and floating mode configuration, and measuring nodes;

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(d) Developed analyzing techniques in time and frequency domains to confirm the propagation modes through three different approaches. They are fast fourier transform (FFT) / power spectrum density (PSD) analysis, transfer function (TF) analysis and wavelet analysis [110];

(e) Came up with the new wavelet technique to decompose the low and high frequency content signals in time domain and came up with the separated transfer function analysis for high and low frequency content. It reveals clearly the existence of multi propagation modes for the same signal;

(f) Presented a model that can fit time and frequency response characteristics of simultaneous experimental observations at two locations. The model takes into account capacitive mode coupling, transmission mode propagation and electromagnetic coupling. The generator winding is modeled with alternate slot section coils and an over-hang section in each coil;

(g) Predicted using the model the role of generator winding, busbar and transformer in PD propagation, the role of PD location on monitored waveform and the role of type of PD on monitored waveform.

1.4 Organization of the Thesis

This thesis is organized in eight chapters with the contents described below:

Chapter 1: Introduction

The motivation for this research, the objectives, the major contributions of this project and the layout of this thesis are described.

Chapter 2: Literature survey on PD propagation in transformers and generators

Characteristics of PD, PD propagation mode, review of study of PD propagation in transformers and generators and PD/surge propagation model, topics to be researched and my program of research work are presented.

Chapter 3: Tools used for PD propagation studies

Chapter 1 Introduction

This chapter presents the developed experimental set up layout and used hardware and software tools. It also presents the procedures followed for the PD propagation studies.

Chapter 4: Measured responses and analysis on experimental transformer

This chapter presents the results obtained on experimental transformer by injecting PD and monitoring responses from multi-terminals. The same injected PD signal can appear as different waveforms at different terminals. Loading effect, analysis by transfer function and wavelet decomposed transfer function analysis are studied to identify the various propagation modes from the injected node to monitored node.

Chapter 5: Measured responses and analysis on 230 kV potential transformer

This chapter presents the measured PD responses on 230kV/110V SF₆ potential transformer (PT) and the analysis on PD propagation. The measured response and injected signals are analyzed for identifying the different propagation modes using transfer function and wavelet analysis.

Chapter 6: Measured responses and analysis on power network

This chapter presents the measured on and off-line responses from 250MVA generator connected to power network consisting of generator, busbar and HV step-up transformer. On-line PD propagation measurement is done simultaneously from the operating generator at 4 terminals. In off line measurement, 10 terminals are available for PD propagation study for PD injection and measurement. The simultaneous injected and response signals are recorded to identify the propagation modes from origin to the measuring nodes. Analyzes are done using the time mode signal, transfer function and wavelet analysis to identify the characteristic transmitted frequencies at the measuring nodes.

Chapter 7: Propagation model studies on 230 kV SF₆ potential transformer and 16 kV generator power network

Chapter 1 Introduction

This chapter presents the possible propagation model of SF₆ potential transformer and generator power network by matching the experimental results. Using model study, the parameters and layout of power network/apparatus are identified to predict the possible PD propagation path. The distortion can be related to the various values of predicted parameters. The possible location of PD origin and type of PD are predicted by matching the measured results.

Chapter 8: Discussion, conclusion and recommendations

This chapter discusses the analysed results and ends up with conclusion. It also presents the recommendations for future research work.

CHAPTER 2

Literature survey of PD propagation in transformers and generators

2.1 Introduction

Electrical discharge which does not completely bridge the space between energized electrodes is called partial discharge (PD). The winding insulation systems of generator and transformer experience thermal, electrical, mechanical, and environmental stresses during operation [7]. These stresses individually or in combination will age the insulation system and may lead to PDs which have the potential to cause deterioration to a greater or lesser extent and may ultimately result in an in-service failure [2]. PD testing is done either by off-line or on-line modes [3]. Sensors like coupling capacitors and RF current transformers yield PD signals from operating HV apparatus. The signals are measured on limited bandwidth oscilloscopes and “RIV” meters [3]. PD detected by the sensors is affected by the pulse characteristics of PD at the origin, applied voltage, location of the PD site like slot or end winding and distance of the PD site to the PD sensor. The trend of PD over time is frequently most valuable in the industry [3] [20]. In most types of HV apparatus, a PD acceptance test is required as PD magnitude is an indicator of the time to failure [3]. The effects of operating environmental conditions and test procedures must be considered. Also, the relation between PD and remaining lifetime of apparatus is to be researched [7].

Locating the PD and identifying the types of defect are to be explored. The PD pulse suffers distortion and attenuation as it travels from the site of origin to the measuring node. It may follow different paths depending on the apparatus winding and insulation layout structure. Not much research work is done about the different PD propagation paths and single PD wave shapes in power apparatus as most of the single node measurement uses the peak PD for interpretation. The literature survey to understand the existing knowledge on the characteristics of PD, the sources of PD, modes of PD propagation, existing theory of wave equation, transient analysis on transformer and generator, existing methods to study PD propagation and developed models for PD

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prediction is reported in this chapter. Since the objective of my thesis is to identify the PD propagation modes in transformer and power generator, it is concentrated on those two apparatus.

Transformer is a static apparatus to change the voltage level for power transfer and measurement. The winding may be cylindrical and disc types. Typical HV transformer insulation varies from solid, liquid, gas and a combination of them. PD is normally initiated in HV winding, hot-spot locations, weak insulation points, HV and high current connection terminals [6] [7]. PD detection, measurement and location in transformer [5] [6] [7] [8] [20] becomes more complicated as a result of more complex transmission line behavior of the coils as well as coupling and resonance effects between the windings. Switching and lightning surge propagation is extensively studied and many electromagnetic models have been proposed based on observations [103] [104]. PD is also a high frequency phenomena like HV transients but with small discharge magnitude. In PD measurements, the apparent charge quantity is still used as the most important factor to represent the severity of PD activity in insulation. The conventional unit for quantifying PD activity [12] is the pico Coulomb (pC). Accepted level in transformers is less than 300 pC at $1.3U_N$, less than 500pC at $1.6 U_N$ [10].

Power generator stator winding consists of a number of insulated stator bars kept in iron slots and overhang connections in air. Surge phenomena in rotating machines is also studied extensively [22] [103] [104] and analysis of the transients of voltage surges is studied with ladder network [5] [6] [7] [22] [103] [104]. PD in rotating machines can occur at different locations due to weakening of insulation and the propagation will be much more complicated [2] [3]. Some of the detected PD sources are due to delamination of the ground wall insulation, abrasion of the outer semi conducting shield, bar vibration, loosening of the wedging system, manufacturing defects, girth cracks, aging, overheating, sites of impact damage, insulation fracture, contamination in the end winding region, HV bushings, busbars and improperly installed sensors [1]. Normally, there is no PD at the neutral end of generator winding due to low electrical stress.

Most relevant PD standards IEC 60270 , IEEE Std 454 and ASTM D1868 specifically exclude, or caution against, the use of apparent charge when dealing with large

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inductive components, such as stator windings [1] [2] [3] [20]. The magnitude of the detected pulses may vary appreciably ranging from low levels due to intrinsic internal discharges within stator bar insulation to extremely high levels associated with slot discharges. Although there are many potential sources of PD, it is cautioned that no technology exists today that can uniquely and unambiguously take a PD pattern and back-calculate the exact source for each of those defects listed previously [1].

2.1.1 Existing theory of PD propagation

The existing theory of PD propagation [2,3] is based on transient analysis on power apparatus winding. The response of windings of transformers, coils and rotating machines to transient voltages is quite different from that under power frequencies. Transformers and rotating machines behave in a complex manner when impressed by a fast-rising transient voltage. It was verified by fabricated models that the voltage distribution along a winding under a steep-front transient was highly non uniform with a high electrical gradient near the lightning/transient occurring location [103][104]. Two theories were used to explain the observed transient phenomena. They are standing and travelling wave theories [103] [104].

A Standing wave consists of two waves travelling in opposite directions. If the reflected wave is equal in magnitude to the incident wave at the boundary, the wave is stationary in space. Standing wave is a function of time.

Travelling wave represents the fluctuating wave as a function of space and time.

Since the frequency ranges associated with a PD lie around the lightning voltage frequency band, the popular travelling wave theory is widely applied for the reported work [6] [22]. Following that theory, the winding for PD propagation is assumed to be a complex ladder network of LC elements. The wave equation for that network will be a series of partial differential equations and it can be used to analyse the transient behavior of a winding in such a distributed network. Another theory on PD propagation [11] proposes that PD will travel in multi-paths of surrounding winding conductors. The reported theories are included in this section to come up with analytical equations to predict the voltage and current with time and space. Real model of winding consists of other resistive losses and improved electromagnetic

models have been studied in detail [11] [108]. In the next section, equations on such electromagnetic models to predict the responses are presented.

2.1.1.1 Wave equation on transmission line model

Early work on PD location [5, 7] assumed the winding behaved like a capacitive and inductive network. Each section of the winding can be modeled as a lumped circuit that takes into account capacitive, inductive and resistive and dielectric losses of the winding. But further studies [8] indicated that this was only valid over a limited frequency range up to a few hundred kHz, but is inadequate in the MHz region [5, 7] to study the characteristics of PD propagation.

A lossless and uniform transmission line can be represented by a uniformly distributed inductance shunted by a uniformly distributed capacitance [22] as shown in Fig. 2-1.

L: self inductance of line per meter ; C: capacitance to ground of line per meter

Fig. 2-1 Schematic layout of a lossless transmission line [22]

The voltage drop across an elemental length Δx of the line is given by:

$$\Delta V = -L\Delta x \frac{\partial I}{\partial t} \quad (1)$$

$$\text{For } \Delta x \rightarrow 0, \frac{\partial V}{\partial x} = -L \frac{\partial I}{\partial t} \quad (2)$$

$$\text{Differentiating equation (2), } \frac{\partial^2 V}{\partial x^2} = -L \frac{\partial^2 I}{\partial x \partial t} \quad (3)$$

The current through the capacitance to ground for an electrical length Δx of the line is given by:

$$-\Delta I = C\Delta x \frac{\partial V}{\partial t} \quad (4)$$

$$\text{This gives: } \frac{\partial^2 I}{\partial x \partial t} = -C \frac{\partial^2 V}{\partial t^2} \quad (5)$$

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Combining (3) and (5): $\frac{\partial^2 V}{\partial t^2} = v^2 \frac{\partial^2 V}{\partial x^2}$ (6)

It can be similarly shown that:

$$\frac{\partial^2 I}{\partial t^2} = v^2 \frac{\partial^2 I}{\partial x^2} \quad (7)$$

Where $v^2 = \frac{1}{LC}$

Equations (6) and (7) are called the wave equations of voltage and current respectively as the solution of these second order differential equations may yield wave harmonics in terms of time and space.

This shows that the propagating PD waveform along the length of winding (space) will be different and the waveform will vary as a function of time.

The lossless transmission line model is very simple and it can be easily applied to study PD propagation in the winding as PD can be distorted and delayed from origin to the measured location along the galvanic path. It was used in very low frequency PD propagation studies in the range of few kHz [8]. This simple model may be improved by incorporating distributed parameters on the inter winding capacitance, mutual inductance between windings, resistance of the winding and dielectric losses to match with the real practical winding structure.

2.1.1.2 Wave propagation on multiconductor systems [22]

A recent paper [8] described a model based on multi-conductor transmission line theory which can be used to simulate a transformer winding over a frequency range from a few hundred kHz to a few tens of MHz. The PD propagation in the generator and transformer is more likely in multiconductor mode as there will be a number of adjacent parallel paths.

A lossless multiconductor model can be represented by its self-inductance, L_{rr} in H/m, capacitances to ground, C_{rg} in F/m, mutual inductances, L_{rs} in H/m and mutual capacitances, C_{rs} in F/m, where the subscripts r and s stand for the r th and the s th conductors. A 2-conductor line ($r = s = 2$) sectionalized into Δx segments is shown schematically in Fig. 2-2.

Fig. 2-2 Equivalent circuit of a two-conductor line [22]

The voltage drop ΔV is the voltage difference between two nodes across a section Δx of a multiconductor line and it can be determined by self and mutual inductive segments as shown below:

$$\Delta V_1 = -L_{11}\Delta x \frac{\partial I_1}{\partial t} - L_{12}\Delta x \frac{\partial I_2}{\partial t} - \dots - L_{1n}\Delta x \frac{\partial I_n}{\partial t}$$

.....

$$\Delta V_n = -L_{n1}\Delta x \frac{\partial I_1}{\partial t} - L_{n2}\Delta x \frac{\partial I_2}{\partial t} - \dots - L_{nn}\Delta x \frac{\partial I_n}{\partial t} \quad (8)$$

The partial differential equations in matrix form are given by

$$\frac{\partial[V]}{\partial x} = -[L] \frac{\partial[I]}{\partial t} \quad (9)$$

For the two conductor system shown in Fig. 2-2, $I_1 = I_{11} + I_{12}$. For an n-conductor system,

$$I_1 = I_{11} + I_{12} + \dots + I_{1n}; I_r = I_{r1} + I_{r2} + \dots + I_{rn}.$$

$$\begin{aligned} -\frac{\partial I_1}{\partial x} &= -\left[C_{1g} \frac{\partial V_1}{\partial t} + C_{1-2} \frac{\partial}{\partial t} (V_1 - V_2) + \dots + C_{1-n} \frac{\partial V}{\partial t} (V_1 - V_n) \right] \\ &= (C_{1g} + C_{1-2} + \dots + C_{1-n}) \frac{\partial V_1}{\partial t} - C_{1-2} \frac{\partial V_2}{\partial t} - \dots - C_{1-n} \frac{\partial V_n}{\partial t} \\ &= C_{11} \frac{\partial V_1}{\partial t} + C_{12} \frac{\partial V_2}{\partial t} + \dots + C_{1n} \frac{\partial V_n}{\partial t} \end{aligned} \quad (10)$$

where $C_{1r} = -C_{1-r}$, and $C_{11} = C_{1g} + C_{1-2} + \dots + C_{1-n}$. In matrix form:

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$$\frac{\partial[I]}{\partial x} = -[C] \frac{\partial[V]}{\partial t} \quad (11)$$

$$\text{Combining (9) and (11), } \frac{\partial^2[V]}{\partial x^2} = [L][C] \frac{\partial^2[V]}{\partial t^2} \quad (12)$$

This is called the wave equation with parameters of 2 conductor system.

Here the [L] and [C] are matrix of respective distributed parameters.

The advantages of this model is that the distributed magnetic and capacitive coupling is brought in and the drawbacks of this reported multiconductor model is that it does not consider the losses of the windings. It is planned to include the losses in my model.

2.1.1.3 Wave equation on real electromagnetic model

Real electromagnetic model has to take into account many factors such as inter winding capacitance, coil resistance and inductance, mutual inductance, dielectric losses and eddy current losses etc. so that the role of them in PD propagation can be predicted.

In detail, there are other areas in which different authors [22] [103] [104] have introduced variations on coupling modes and resistive losses. These are the approximations made regarding the physical parameters of the winding and in the method by which they are expressed. With the physical parameter of the winding, each turn of a winding possesses a self inductance attributable to the flux of its own current with which it is linked. It is also linked with the flux of neighboring coils and therefore has a mutual inductance with these coils kept in iron core and air. If the eddy currents in the core are considered, another mutual coupling is involved. All these parameters are a function of frequency. Regarding capacitance, the turn or coil will have capacitance to grounded core or tank. In addition, it will have some capacitive coupling with the other coils of the winding. This mutual capacitance will be more if the coils lie in closest proximity to it. Finally, there will be losses in the resistance of the winding, in the leakage of the insulation, and in the iron core due to different losses. All the above factors dissipate energy during PD propagation and may attenuate PD signal as it moved away from the location of occurrence.

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To take into account of all of these items in any apparatus would be a big task as this distributed parameters may vary and the length of winding is finite in length. It is extremely doubtful whether the experimental PD results at different monitored nodes in any operating power apparatus may be matched as the frequency response of these parameters are not known [103,104]. In the case of alternator windings where the conductors are almost buried in the steel, the only mutual capacitance considered is between the conductors in the same slot. Such simplifications can greatly reduce the analysis without seriously impairing its accuracy. The simplified reported equivalent circuit of the winding taking into account the distributed losses is presented in Fig. 2-3.

Fig. 2-3 Complete equivalent circuit [22]

If the leakage losses are neglected in Fig. 2-3, the winding can be represented by Fig. 2-4.

Fig. 2-4 Simplified electromagnetic model of the winding [22]

At any distance x , the current equations are as follows:

$$i_1 = K \frac{\partial^2 e}{\partial x \partial t} \quad (13)$$

$$i_3 = C \frac{\partial e}{\partial t} = \frac{\partial}{\partial x} (i_1 + i_2) \quad (14)$$

$$\text{Voltage gradient per section} = \frac{\partial e}{\partial x} = L \frac{\partial i_2}{\partial t} + r i_2 \quad (15)$$

Differentiating (15) with respect to x ,

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$$\frac{\partial^2 e}{\partial x^2} = L \frac{\partial^2 i_2}{\partial x \partial t} + r \frac{\partial i_2}{\partial x} \quad (16)$$

Differentiating (14) with respect to t,

$$C \frac{\partial^2 e}{\partial t^2} = \frac{\partial^2 i_1}{\partial x \partial t} + \frac{\partial^2 i_2}{\partial x \partial t} \quad (17)$$

Rearranging (17),

$$\frac{\partial^2 i_2}{\partial x \partial t} = C \frac{\partial^2 e}{\partial t^2} - \frac{\partial^2 i_1}{\partial x \partial t} \quad (18)$$

Rearranging (14),

$$\frac{\partial i_2}{\partial x} = C \frac{\partial e}{\partial t} - \frac{\partial i_1}{\partial x} \quad (19)$$

Substituting (18) and (19) in (16),

$$rK \frac{\partial^3 e}{\partial x^2 \partial t} + LK \frac{\partial^4 e}{\partial x^2 \partial t^2} - LC \frac{\partial^2 e}{\partial t^2} - rC \frac{\partial e}{\partial t} + \frac{\partial^2 e}{\partial x^2} = 0 \quad (20)$$

To solve (20), substitute $\partial / \partial t = p$. (20) reduces to (21)

$$rKp \frac{\partial^2 e}{\partial x^2} + LKp^2 \frac{\partial^2 e}{\partial x^2} - LCp^2 - rCp + \frac{\partial^2 e}{\partial x^2} = 0 \quad (21)$$

$$(rKp + LKp^2 + 1) \frac{\partial^2 e}{\partial x^2} = rCp + LCp^2 \quad (22)$$

The solution to (22) is given by (23).

$$\text{Voltage at } x = e(x) = Ae^{\gamma x} + Be^{-\gamma x} \quad (23)$$

From (14) and (23), the equation for i(x) can be written as

$$i(x) = i_1 + i_2 = \int C \frac{\partial e}{\partial t} dx = \frac{Cp}{\gamma(p)} [Ae^{\gamma x} - Be^{-\gamma x}] \quad (24)$$

Rewriting (24) in terms of surge impedance (Z) as defined below

$$i(x) = \frac{1}{Z} [Ae^{\gamma x} - Be^{-\gamma x}] \quad (25)$$

Where

$$\gamma(p) = \sqrt{\frac{LCp^2 + rCp}{LKp^2 + rKp + 1}}$$

$$Z(p) = \frac{\gamma(p)}{Cp}$$

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Substituting $p = j2\pi f = j\omega$ and quality factor of winding $Q = \frac{\omega L}{r}$, the above terms become a function of frequency,

$$\begin{aligned}\gamma(f) &= \frac{j\sqrt{\frac{C}{K}}\sqrt{1+\frac{1}{jQ}}}{\sqrt{\frac{1}{LK\omega^2}-\frac{1}{jQ}}-1} \\ Z(f) &= \frac{\frac{1}{\omega\sqrt{CK}}\sqrt{1+\frac{1}{jQ}}}{\sqrt{\frac{1}{LK\omega^2}-\frac{1}{jQ}}-1}\end{aligned}\tag{26}$$

A and B are the constants determined by the terminal conditions. For a winding with open-circuited terminals, the transfer function $H(f)$ from one end to the other can be determined as follows:

$$H(f) = V_2(f)/V_1(f)\tag{27}$$

The terminal conditions are

$$i = 0 \text{ at } x = 0\tag{28}$$

substituting (28) in (25) results as $A = B$ and (27) reduces to (29).

$$H(f) = 1/\cosh(\gamma(p)l)\tag{29}$$

This electromagnetic model of winding considers more factors and the response may follow that of real winding. Using transfer function of the winding, the output response can be predicted for any input like PD signal input. The derived transfer function and surge impedance showed the frequency dependant characteristics of PD propagation.

With this amount of background theory gained from the literature, survey is focused on the reported characteristics of PD waveform. Improved electromagnetic PD models are developed to match experimental PD propagation from different nodes to the monitoring nodes of different electrical apparatus.

2.2 Characteristics of PD

The form of PD intrinsic to a given discharge site will depend on the geometrical size of defect, the gas and pressure within, the nature of the surface where the discharges

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take place, and the statistical time lag of initiating charges [1][2]. PDs may be detected as radio frequency (RF) electrical pulses, acoustic pulses, light, heat and chemical reactions. Some of these manifestations can be measured using different sensors to quantify the PD activity in power apparatus. Observed PD in solid dielectrics using HF electrical sensor has very sharp rise time in the range of 0.5ns to 5ns and short duration in the range 3 to 10 ns [2]. It is also unipolar and is essentially non-oscillatory. For corona PD in air, the rise time can be 0.1ns or less [11]. For PD in transformer oil, the rise time is 5 ns and the pulse duration is around 20ns [11]. Hence, the frequency bandwidth of PD can lie in the bandwidth from 50 MHz to 2.5 GHz [11]. The measured PD will be distorted in time and magnitude by R, L and C behavior of surrounding from origin to measuring node [11].

2.2.1 Distortion factors

The PD measurements are carried out at the HV winding terminals of the apparatus by some PD coupler. The undistorted PD pulse emerging at the discharge site must travel over a complex LC network prior to reaching the PD detector. As the PD pulse propagates along the windings and dielectrics, coupler and measuring detector, it will be distorted due to PD propagation path and cross-coupling. In addition, the occurrence of series and parallel resonances along the propagation path can introduce errors into the measured PD quantities [20]. The frequency response of the detection system will influence the characteristics of the signal detected at the terminals of the HV winding.

2.2.2 PD propagation to the measuring node

Wide-band pulse response tests on stator windings have shown that a fast rise-time pulse with frequency content > 100 MHz is capacitively coupled through the winding with attenuation, and that this is followed by a slower electromagnetic travelling wave. At such high frequencies, stray and interconductor capacitances become increasingly important. Concerning the slower electromagnetic travelling wave, the stator winding is treated as a transmission line with each coil or bar having an associated inductance or capacitance. Depending on the length of each coil or bar and the number in each parallel circuit, every winding will possess a unique set of resonant

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frequencies. In a wide bandwidth system, the magnitude of the measured PD at those resonant frequencies will be abnormally high.

Pulse propagation problems are further compounded as the consequence of the overhang region where the coils/bars make the transition from core iron to free space and back to core iron. The surge impedance of a typical stator bar has been found to be in the range of 20-30 Ω , whereas in the end arm area, the surge impedance is higher around 300 Ω . Thus, a PD pulse travelling along a stator bar will experience a reflection at the end of the slot, whereas in the end arm area, the transmitted pulse will be further reduced in magnitude because of cross-coupling with other circuits. Cross-coupling can be a source of errors in measurements on the other circuits [11].

2.3 Modes of PD propagation

Voltage and current waves propagate along a single conductor with a finite velocity. They get reflected and transmitted across a point of discontinuity. In multiconductor system like transformer and generator, the wave propagation differs from single conductor in the form of magnetic and capacitive couplings from each conductor and reflections at each discontinuity.

2.3.1 Transformer windings

Surge transfer through a transformer has been studied extensively [22] [103] [104]. It is reported that a transferred voltage from one winding to another winding due to the application of a step-voltage has four voltage components. The first component can be an electrostatic voltage component and its amplitude depends on the ratio of the capacitance between the two windings and that to ground. The second component can be due to space harmonics in the injected winding which will induce corresponding oscillations in the coupled winding. This induction process can be both electrostatic and magnetic, and will depend on the distributed constants and the turns ratio of the two windings. The third component is a free oscillation generated in the measuring winding and the magnitude depends on the distributed constants of the measuring winding. The fourth component is due to magnetic induction which gives rise to a voltage that rises exponentially to peak and subsequently decays exponentially. This

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rate may be controlled by the turns ratio of the coupled windings, the short-circuit inductance of the transformer and the surge impedances of the connected circuits. The reference [16] states that the measured PD signals can be categorized into three components: capacitive component (0.1 to 10 MHz), travelling wave component (0 to 0.01 MHz) caused by electromagnetic wave transmission, and oscillating component (0.01 to 0.1 MHz) caused by LC circuit of the insulating system which is excited by PD.

2.3.2 Generator windings

Stator windings are complex electrical systems. Reference [2] studies the winding characteristics and its influence to PD propagation. The result shows that a PD pulse occurring within the slot will see a transmission line structure [2] [11] and produce the fast rising unipolar pulse. This is followed by oscillations with frequencies that depend on the slot length and permittivity of the insulation. PD pulses in the end winding will also produce the initial fast unipolar pulse followed by oscillations that generally will contain different frequencies. The generator stator winding can be modeled as a ladder network of inductances (in the slot and in the end turn, with mutual inductances between the end turns) and capacitances (in the slot and in the end turn, as well as coil-to-coil capacitances in the end turns). The lower frequency components seem to be less attenuated than the high frequency components. The cause of this frequency dependent response is the L-C nature of a stator winding. The reported propagation modes for PD are the transmission line mode [5] [6] [7], fast mode electromagnetic coupling at the end windings [13], capacitive coupling between turns [13], oscillatory mode due LC path of the winding [16] and multiconductor transmission modes [8] [11].

Within the slot, the winding may have a surge impedance of about 30Ω as well as capacitance to ground (typically about 5 nF) [2]. Outside the slot near the end winding, there is no well-defined surge impedance, and instead a coil end winding seems to appear as an inductance with strong mutual capacitance to other coils [2]. Different models [11] are used to explain PD propagation. Within a certain frequency range, the generator winding is represented by a transmission line [9]. The PD signal manifests at the generator terminals after a transit time. The velocity of this slow

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mode is estimated as 9 m/ μ s. The fast mode signal due to electromagnetic couplings in the end-winding is present for higher frequencies > 400 kHz and it appears without appreciable time delay. The cross-talk due to electromagnetic coupling increases linearly with the bar number in the dominant signal area. The high-frequency components are highly attenuated [13]. The travelling wave speed increases with frequency and then reaches a constant value.

From a PD, electromagnetic and acoustic waves propagate along different paths through the insulating system of the apparatus. Acoustic waves propagate equally in all directions. The propagation of ultrasonic waves between a PD source and the detector is partly obstructed by solid insulating material. The propagation velocity depends on the properties of the medium [17] [52]. The PD pulse can propagate through a stator winding along various paths. It is found that pulse propagation path is frequency dependent. The windings acts as a low-pass filter, the cut-off frequency being dependent on the winding length, and normally it is below 1 MHz. In rotating machine stator windings [2], the initial pulses are significantly distorted and attenuated as they propagate through a winding. The attenuation at frequencies above 35 MHz is much stronger. The lower frequency components seem to be less attenuated than the high frequency components. The cause of this frequency dependent response is the L-C nature of a stator winding. Also, the winding can attenuate and distort the PD pulse pattern by resonance and reflections in the time domain. Also, depending on the frequency response of the detector, the data may be polluted. Reference [18] reconstructs the original magnitude from the distorted PD signals via transfer function techniques.

If the transfer functions from different PD locations in a winding are known, the location of the PD can be identified. The technique offers an empirical approach to minimize calibration errors [5] [7] [18] [26] [27].

2.4 Reported methods to study PD propagation

PDs are accompanied by several physical manifestations: electrical RF pulses, acoustic pulses, light and other chemical byproducts. PD and PD propagation can be evaluated by sensing the above. Noise reduction is a major issue on PD measurement

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and several denoising methods for on-line studies are reported to identify PD without noises [23] [24] [25].

Off-line testing is more time-consuming and expensive to perform. It needs a separate PD pulse source to simulate the actual PD. The machine has to be taken out of service to perform the measurements, and in some cases, depending on the testing to be performed, partial disassembly may be required. Because the machine is not operating, no electro mechanical forces are operating within the machine so that it may not be possible to detect all types of PD (slot discharge/loose winding). In addition, the temperature of the winding will usually be lower. In addition type of gas in cavity or discharge area, pressure and humidity may differ from the operating condition. Hence the propagation characteristics may be significantly different and a lot of research is to be done.

It is convenient to make the initial off-line tests when the machine winding is new. These measurements will provide a benchmark for future comparison. Noise level is comparatively low during off-line testing. If the rotor is removed, more nodes may be available for PD propagation studies. When off-line PD tests are being made at individual slots with an electromagnetic probe, the user should be aware that signals from a single source of PD can be transmitted to other bars/coils in the winding. Thus, it is possible to measure PD propagation from a single source to other slots of the machine. Many researchers try to study PD propagation under off-line modes. A few attempt to study PD propagation in on-line mode with simultaneous PD measurement from multi-locations [1] [9]. The objective of propagation analysis is to identify the location of discharge activity in distributed impedance structure of power plant.

Authors of reference [5] carried out on an experimental investigation on 110 kV continuous disc-type winding of a transformer. The author used the mercury-wetted switch to switch-on and switch-off the capacitance to simulate the PD source. PD with pulse width of 100 ns was injected into different discs along the winding, and the simultaneous current responses were measured at the bushing and neutral terminals. The time response measurements were recorded with 100 kHz bandwidth CT. The transfer function of the responses was determined to predict the poles and zeros of the transformer. The maximum number of fitted poles/zeros was 4 in a bandwidth of 500

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kHz. The frequencies of predicted poles did not vary with PD location. But the frequency of zeros varied significantly with tested 6 PD locations.

Authors of reference [10] used a 1 ns rise time pulse source to test the 500 MW generator, and 5 ns rise time pulse generator was used to test the stator model. The simultaneous input and output time domain waveforms were recorded on an oscilloscope of bandwidth 300 MHz. The spectrum analyzer with a bandwidth of 1 GHz was used to record the spectral response. In the model, the researcher used 6 locations to inject the PD and PD response was monitored at 2 locations. It was found that the propagated PD path behaved like a low pass filter with a bandwidth of 10 kHz, 400 kHz and 10 MHz depending on the injected location. High frequency signals were attenuated more and a number of resonance peaks above 10 MHz were observed. It was found that PD may have induced on a conductor with capacitive coupling and then it propagated as a travelling wave. During that travel, electromagnetic coupling may occur. He concluded the dominant mechanism of PD propagation was travelling wave.

Authors of reference [13] studied the complex propagation of PD signals in a stator winding of a 35 MW generator. Both on and off-line measurements were made. Simulated PD was injected at various places of the stator winding and the time domain responses in the range from 80 ns to 12 μ s at the HV terminals were measured. The response was found to have two modes of propagation and using 450 kHz filter, these modes were separated. The researcher concluded that the stator winding acts as a transmission line. The slow mode propagation velocity was determined as 9 m/ μ s. Depending on the injected location, the delay due to slow mode varied. The fast mode was attributed to electromagnetic coupling in the end-winding region and it arrived without any delay. The cross-coupling between phases varied depending on the injected location. In on-line measurement, the cross-talk between phases was used to locate PD origin. Using multi-sensors, PD location was identified on the operating unit.

Authors of reference [18] used spectrum analyzer with a built-in tracking generator of 9 kHz to 1.8 GHz bandwidth to study the frequency response characteristics of the generator winding transfer function. A specially designed BNC connector was used to match the winding impedance and to get a low output impedance. The tracking

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generator was used as a swept source and sweep time was 100 ms. Tracking generator output was injected into the stator winding at various locations to identify the various transfer functions connected with injected locations. Using the time domain measured responses of PD and the determined transfer functions, PD characteristic frequencies were predicted. Comparing with the data base, PD location was identified.

Authors of reference [26] used variable frequency sine wave generator up to a frequency range of 5 MHz and network analyzer to measure the transfer function of a single winding of specially prepared untanked 10 kV/380 V distribution transformer. The signal was injected at 7 locations and the measurement was done at neutral (N) and HV bushing. 14 transfer functions were determined and that data was used as a comparison data base. A time domain PD signal was injected to one of those 7 locations and the time domain responses at N and HV bushing were recorded. Using the two responses from N and HV bushing and 14 transfer functions, the input signal in time domain was predicted. The closest match with the known data base can reveal the location of PD.

Authors of reference [43] used pulse generators which can produce pulses with rise time of 5 ns, 50 ns and 100 ns with pulse width as twice the respective rise time. It was used to investigate the PD propagation in a 6.6 kV star-connected diamond-wound induction motor, with its rotor removed. It was injected at one location. Oscilloscope with 1 GHz bandwidth was used to investigate the responses at two locations for 1000 ns. Wavelet techniques are used up to 4 scales to analyse the responses in the time and frequency domain simultaneously. They proposed three modes of propagation based on the results. Low frequency component was propagated in transmission line mode defined as series-mode propagation. High frequency component was coupled capacitively. Another new mode known as coupling mode was proposed. In that, a narrow pulse was observed at the measuring nodes with almost instant transition time dependent on physical distance between the original site and measurement node divided by the velocity of light. Series travelling wave was observed with 100 ns pulse source and travelling wave and coupling wave were observed with 50 ns pulse source. While with 5 ns PD source, only coupling wave was dominant. They reported that the coupling wave or fast wave differed from

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the travelling wave in its arrival time and pulse shape, and different frequency components propagated differently[50].

To conclude the observation on propagation studies, it seems that PD propagation study is very complicated requiring simultaneous multi high frequency signals for interpretation and this study is currently researched mainly with laboratory test objects in off-line mode and by simulation tools.

2.5 PD/surge propagation models

When a step-function voltage is applied to the high-voltage winding of a transformer, the propagated voltage which appears across the low-voltage winding is composed of four voltage components [16] [22]. They are:

1. An electrostatic voltage component is transferred to the low-voltage winding. Its amplitude depends on the ratio of the capacitance between the two windings and that to ground.
2. The space harmonics in the high-voltage winding induces corresponding oscillations in the low-voltage winding. This induction process is both electrostatic and electromagnetic, and is dependent on the distributed constants and turns ratio of the two windings.
3. A free oscillation is also generated in the low-voltage winding and the magnitude depends upon the distributed constants of the low-voltage winding.
4. A voltage which exponentially rises to peak and subsequently decays exponentially is generated in the low-voltage winding by magnetic induction. This voltage component is directly proportional to the turns ratio, and is a simple function of the short-circuit inductance of the transformer and the surge impedances of the connected external circuits.

So far, precise analysis of the suggested 4 propagation modes is not reported on any single power apparatus. There may be other coupling related propagation through multipaths in a winding structure. More research work has to be done to understand the energy limited high frequency PD pulse propagation between occurring node and measuring nodes.

So far the influence of the elements on the propagation mode is not studied in the literature. Most of the models are based on transmission line mode.

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Surge models of different apparatus are reported in the literature published in early 1950's [22][103][104]. An extension of such models in various ways is tried for PD propagation studies. It is convenient to classify them into two categories.

The first one may be called as – detailed internal winding model in which large networks of capacitances and coupled inductances are used. They are obtained from the discretization of distributed self and mutual winding inductances and capacitances. The calculation of these parameters involves the solution of complex field problems and requires information on the physical layout and construction details of the transformer. These models have the advantage of allowing access to internal points along the winding, making it possible to assess internal winding stresses. These types of models are used for hot-spot calculation and winding electrical and mechanical stress calculation with 50 Hz signal.

The second category is known as terminal model. These models are developed using the frequency and/or time domain characteristics at the terminals of the transformer. From the determined transfer functions, complex equivalent circuits are developed. For PD propagation studies in power transformer and generator, terminal models are extensively used as the data connected with the apparatus is not normally available.

Reference [4] discusses the development of a simulation model of 500 kV transformer shown in Fig. 2-5 to study the propagation of PD occurring in transformers located in a 500 kV substation. The impedance matrix of a 500 kV single-phase transformer and its external coupling network are computed with the geometrical data. Using EMTP simulation, the propagation characteristics are predicted. Simulated PD is injected at 220 kV and 500 kV terminals and the responses are measured at the tank ground and 500 kV bushing tap. Simulated pulse width of 150 ns with a rise time of 5 ns and a bandwidth of 2 MHz are used for the analysis. The shape of responses in time and frequency domains is analysed. It is found that the coupling network impedance varies significantly with increase in frequency and that can be represented as a lumped coupling capacitor in the frequency range < 60 kHz.

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L: inductance, R: resistance, Cs: capacitance number: winding section number

Fig. 2-5 Diagram of the equivalent circuit of the 500kV transformer[4]

Reference [5] builds the simulation winding model based on the structural data of a transformer. Fig. 2-6 shows the lumped-element model for the transformer and the PD source. Each winding is divided into cells, and each cell normally includes two discs. The cell is represented as a lumped-element unit which consists of three parallel elements: an inductance L in series with a resistance R , a capacitance K which represents the end-to-end equivalent series capacitance and a conductance G representing dielectric losses. Between all the cells in different winding sections, there are mutual inductances that represent the magnetic coupling between them. Between cells in adjacent windings, there are cross-capacitances which represent the electric coupling between them, C_c . For the inner LV winding, there are parallel capacitances to the core. For the outer HV winding, there are parallel capacitances to the tank, C_g . The simulation study is carried out using the design data from a 110 kV continuous disc winding having 84 discs. PD is injected at different locations. The response at the bushing is measured up to 500 kHz bandwidth. The characteristic resonances are observed at 28 kHz, 102 kHz, 202 kHz and 342 kHz. The researcher finds that the zeros of transfer function changes as the location of the PD source moves along the winding, and the frequencies of poles of all the transfer function do not change with the location.

Fig. 2-6 The lumped-element model for the transformer and the PD source [5]

Reference [8] describes a PD propagation model shown in Fig. 2-7 based on multi-conductor transmission line theory (MTL). It can be used to simulate a continuous disc type 6.6 kV transformer winding over a frequency range from 1 kHz to 2 MHz. Wave equations for voltage and current vectors are written based on terminal conditions and Matlab programs are written to determine the transfer functions. They use a single input representing PD injection and multiple output representing the measured current signals. Simulation results from line-end current and neutral end current show that the 6 zeros in the predicted transfer functions contain information about the 8 locations of injected PD.

Fig. 2-7 is the simulation model of a continuous disc type 6.6 kV transformer winding modelled by multi-conductor transmission line model (MTL) to study the propagation behaviour of PD pulses. This model uses a single turn as a circuit element with its capacitance, inductance, and losses represented as distributed parameters. Using them, voltage (V) and current (I) vectors at any point x along a multi-conductor transmission line can be derived. With terminal conditions applied at the sending end 'Si' and the receiving end 'Ri', it is possible to express sending end and receiving end currents in terms of voltages. It assumes that the propagation behaviour is through the multi-paths.

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Fig. 2-7 Multi-conductor transmission line model [8]

The test and simulation results on a 200MW turbine generator stator windings show that multi-conductor transmission line model can illustrate the propagation characteristics of PD pulse effectively [61]. Based on the square pulse injection of width 5ns at one of the Φ , the time domain responses were measured at HV terminals of other Φ s with a 400 MHz bandwidth oscilloscope. They conclude that PD from slot and end windings travel in quasi-TEM mode. PD pulses in stator windings propagate in parallel with fast component and in series mode with slow component simultaneously. The effect of core on high frequency propagation is taken into account.

Reference [70] analyzes the very fast transients in transformers based on the multiconductor transmission line theory. Resonance characteristics and interturn voltage are predicted using the geometry data on 2-coil model and 500 kV autotransformer. Frequency response characteristics up to 5 MHz are used for determination.

Reference [11] points out that for electromagnetic transient analysis, a generator stator winding can be divided into two main parts: stator bars in the slot and overhang connections. Because of the surrounding steel core and the grounded semi-conductive paint, the bars have relatively large inductances at lower frequencies and larger capacitances to ground. The coupling capacitance between stator bars in different slots reduces significantly by the shielding of the grounded varnish and the core. In this situation, the bar is rather similar to a coaxial cable with grounding shield except

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the existence of the steel core, which can significantly increase its inductance and losses. In the overhang section, there exists coupling capacitance between the connection leads. Although the capacitances are quite small, at higher frequencies, they can have a significant effect on the pulses travelling in the winding. The reference suggests the use of Bewley's equivalent circuit shown in Fig. 2-8 for homogeneous windings to study travelling wave propagation at low frequency range from 60 to 120 kHz. It is anticipated that PD can propagate in various paths depending on the frequency content. Reference [58] suggests the existence of 4 propagation modes depending on the frequency range. From 10 to 300 kHz, it travels in the stator winding like a travelling wave. Between 200 to 500 MHz, travelling wave propagation occurs along the stator bars in the slots. Beyond 500 MHz, travelling wave propagation occurs along overhang sections. In addition to that, the fourth mode is the capacitive coupling between overhang sections.

Reference[18] points out that it is difficult to describe accurately the pulse propagation process and associated mechanisms in stator windings and to relate them to the detected pulse at the machine terminals. He uses the frequency response characteristics of the winding transfer function up to 1.8 GHz. However, if the PD pulse propagation is considered as a process of a signal transmission in a system, system analysis theory may be applied. The PD propagation passage in the measurement process, as a whole system, may be treated as a "black box" which can be divided into several subsystems in series with its defined transfer functions.

References [26][27] use differential equation and optimization method to identify the parameters of PD transfer function. No acceptable solution is found. They propose a new method based on travelling wave theory using genetic algorithms. It identifies the optimum parameters of partial differential equation that describes the transient behavior of the coil satisfactorily. Fig. 2-8 shows the used transformer model.

Fig. 2-8 shows the layout of disc coils used in a transformer and its discrete parameter (DP) model. It is an equivalent circuit containing series connected resistor, inductor, and capacitor (RLC) elements. The number of RLC elements is the same as the number of disk units of the transformer coil so that the circuit coefficients of each disk unit can be taken as the lumped parameters in each RLC unit, while the coupling between each unit with others is considered as the mutual inductances. The leakage

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inductances and losses are modeled by L and R . C_s and C_g represent the coil to coil and coil-to-ground capacitances, R_s represents the loss of the insulation between adjacent winding sections, and R_g is the loss of each section to ground. The mutual inductances, M , between each winding section and the others are modeled by a current controlled voltage source. For a time domain model, it is convenient to write the equations for the branch currents and node voltages as state variables using Kirchhoff's laws. To analyze the model in the frequency domain, the parallel branches (C_s and R_s as well as C_g and R_g) were replaced with the admittances Y_s and Y_g as depicted in Fig. 2-8. The PD propagation behaviour is modelled in transmission line mode with mutual current coupled magnetic coupling.

A detailed modeling approach based on discrete RLC circuit elements has been studied and different algorithms were used for parameter estimation and optimization. This model is applicable in practical cases for a limited frequency range if genetic algorithms (GAs) are used for parameter optimization. A new method based on travelling wave theory has been investigated using genetic algorithms to search for the optimum parameters of a partial differential equation that describes the transient behavior of the coil. This method has shown potential in solving SWTF (Sectional winding transfer function) calculation problems for different transformers.

Fig. 2-8 Transformer model based on the serial connection of RLC elements
Considering mutual inductances as interconnecting elements [26]

Reference [66] uses the modal analysis. The modal high frequency model of the four terminal transformer is built for EMTP analysis. Fig. 2-9 shows the modal model of the transformer with each resonating arm. Fast transient behavior is matched using the parameters of measured data from transformer.

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Every transformer possesses a number of resonance frequencies which in theory show up in both transfer and admittance functions if the corresponding mode shape function is not zero at the specified terminals. In practice resonances are not always visible in both functions. For Fig. 2-9, the values for R_0 , L_0 and C_0 are added to incorporate iron loss, no load inductance and input capacitance of transformer layout. For a complete model description of the transformer, three parameters for each resonance frequency have to be specified besides the values for R_0 , L_0 and C_0 . The PD propagation behaviour is controlled by a number of free oscillating/resonating LC elements.

Fig. 2-9 Modal model of the four terminal transformer [66]

Reference [69] develops the frequency response model based on two parts. The first part can be considered in the magnetic component from the measurements point of view: the ferromagnetic core and the windings. The core behavior prevails at very low frequencies while the windings effects could be neglected. On the other hand in the second part, the winding behavior prevails as soon as the frequency goes higher up to 10 MHz. Fig. 2-10 shows the transformer model with 4 cells for a winding of the transformer since he observes 4 peaks in the transfer function.

In Fig. 2-10, each cell is implemented with 3 basic elements which represent respectively the 3 electromagnetic effects that take place inside the magnetic component. L_i represents the magnetic field energy storage, R_i represents the power losses and C_i represent the electric field energy storage. Cell set 1 is composed of the lower order cells and represents the core effects. The behavior of these cells should prevail at low frequencies in the whole model response while the behavior of the rest of the cells should be negligible at these frequencies. Cell sets 2, 3 and 4 represent the

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middle and highest order cells which should prevail at middle and high frequencies in the whole model response. The behavior of the rest of the cells should be neglected at these frequencies. The PD propagation behaviour is controlled by 4 serially connected parallel LC elements.

Fig. 2-10 Model with 4 cells for a winding of the transformer [69]

Reference [105] studies the generator models for over voltage simulations. Simulation based on distributed parameter line model is simplified to a second order R, L, C network shown in Fig. 2-11. It is estimated from the above modeling that the surge impedance of turbo generator may be in the range of 10 to 30Ω.

Fig. 2-11 shows a simplified pi equivalent circuit for one phase of the generator using parameters R_e , L_e , and C_e . The step up transformer is modeled with leakage inductance L_t , series resistance R_t and lumped capacitance C_t . The PD distortion/propagation is studied by lumped parameter representation.

Fig. 2-11 Generator modeled by R, L, C equivalent [105]

A detailed model which has been solved using the Electromagnetic transients Program (EMTP) is presented for more accurate prediction of inter turn voltages in reference [106]. Fig. 2-12 shows the developed ladder network model for a group of cascaded coils.

Fig. 2-12 considers each coil modeled as a single pi-section for motor winding. The representation for a group of cascaded coils is a ladder network consisting of one pi-

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section per coil. The total coil capacitance to ground is split equally on each side of an inductance. Each inductor in the network represents the self and mutual inductances for individual coils. It is assumed that the coils forming the line-end group have no magnetic coupling to other coil groups in the same parallel, or to other parallels belonging to the same phase winding. The propagation behaviour is in the form of travelling wave with magnetic coupling.

Fig. 2-12 Network comprising pi-equivalent representation for cascaded coils in a group [106]

To summarize the existing models –

PD - PD may occur where the insulation is weak. PD is modeled as a current source.

Transformer - Transformer model often considers mutual inductance between different parts of the winding. Earlier research work [5] [6] [7] [8] on PD propagation and location use the structure and geometrical parameters to calculate the transformer model electrical parameters. The surge impedance of the winding can vary from 5 to 45 k Ω [103] [104]. It is seen that the surge impedances are much smaller with rotating machines than with transformers [103]. In transformer, the winding behaves more like a transmission line with relatively high surge impedance of the order of 1000 Ω [104].

Reference [5] assumes that the transformer behaves like a capacitive network. Further studies indicate that this is only valid over a limited frequency range and is inadequate for studying PD propagation. To study the propagation of PD pulses in core type transformers, simulation model with the frequency dependent characteristics of the parameters is used [5]. Using the above, the location of PD and its magnitude are predicted. The transformer winding is approximated by a uniform transmission line for the selected frequency range and PD is located by the frequency spectrum analysis measured at the transformer terminals. It is found that the

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transformer windings have different effect on PD pulses propagation in different frequency ranges. The frequency range from 400 kHz to 1 MHz is found to be capacitively transmitted when PD is injected in HV winding and a PD location method is developed based on ratio measurements. When PD is injected in the LV winding, the response is oscillatory suggesting that the path may be through interwinding inductances and other cross capacitances.

Generator –The generator model is due to the arrangement of the coils in individual slots since the influence of the mutual capacitance and also the mutual inductance between different parts of the winding is small. In generator, number of turns is fewer but longer and is deeply buried in the stator steel. The capacitance to ground is comparatively high, but series capacitance effects are only significant where the conductors occupy the same slot [103]. As the geometrical layout is different, the models parameter is different. The measured surge impedances of rotating electrical machines are from 60 to 1600 Ω [22]. In overhang area, coupling capacitor between turns will have significant role to transmit high frequency PD signals.

Power Network -A simulation model using geometry data and external coupling network [4] is developed to study the propagation of PD pulses of transformers in a 500 kV substation. Both time and frequency domain analysis are done. It shows that the resonant frequencies of the network can be used as characteristic intrinsic frequencies of the substation network.

2.6 Topics to be researched

On-line and off-line techniques to locate a PD source are of importance for transformer and generator connected power network. Accurate PD location is difficult due to the complex structure of the winding and the complicated propagation characteristics of PD in these serially connected electrical apparatus. More analysis with high frequency single PD pulses from different locations is to be researched.

The PD pulse suffers distortion and attenuation as it travels from the site of origin to the measuring terminals. Although the signal detected at the terminals is a highly distorted representation of the original PD pulse, it does contain the useful information about the location and nature of the discharge. Therefore, the knowledge

of the propagation of PD pulses in transformer and generator becomes very important in the PD measurement field.

2.7 Simple PD propagation modes model

The measured PD signals can be mainly categorized in four components: capacitive component caused by the transmission of the PD pulse through the capacitive ladder network of the winding, traveling wave component caused by the electromagnetic wave transmission which follows the galvanic path, inductive component caused by the self inductive and mutual inductive turns ratio of the respective windings, oscillating component determined by the resonant frequency of the LC circuit of the insulating system which was excited by the PD pulse. These signal components are strongly dependent on the design of the transformer and generator, the PD location and the PD measuring points.

The simple capacitive coupling model is shown as Fig. 2-13.

Fig. 2-13 Simple capacitive coupling model

For the Fig. 2-13, the relationship between V1 and V2 is shown as Equation 30.

$$V2 = \frac{V1 * C1}{C1 + C2} \tag{30}$$

The main characteristic of the capacitive coupling model is the amplitude of the response signal is decreased with comparing to the input signal.

For a pair of coupled coils each energized by an ideal voltage source, the model is shown as Fig. 2-14 [113].

Fig. 2-14 Simple inductive coupling model

For the Fig. 2-14, an application of KVL to each circuit produces the following set of system differential equations:

$$\begin{aligned} V_1(t) &= L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \\ V_2(t) &= M \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \end{aligned} \quad (31)$$

A situation of practical significance is where a source is connected to just one winding (the primary) and we wish to know the no-load voltage available across the other winding (the secondary). The current i_2 will be zero and the magnitude of V_2 will be that of the open-circuit (no load) voltage. In these circumstances equation (31) will become:

$$\begin{aligned} V_1(t) &= L_1 \frac{di_1}{dt} \\ V_2(t) &= M \frac{di_1}{dt} \end{aligned} \quad (32)$$

So that:

$$\frac{V_2(t)}{V_1(t)} = \frac{M}{L_1} \quad (33)$$

and for the case of a unity-coupled ($k = \frac{M}{\sqrt{L_1 L_2}} = 1$) transformer, the equation is:

$$\frac{V_2(t)}{V_1(t)} = \frac{N_2}{N_1} \quad (34)$$

For $N_2 > N_1$, the main characteristic of the inductive coupling model is the amplitude of the response signal is increased with comparing to the input signal.

For the series combinations of an inductor and a capacitor, the model is shown as Fig. 2-15.

Fig. 2-15 Simple LC series circuit

The impedance of L and C in series is written directly as:

$$\begin{aligned} Z &= j(X_L + X_C) \\ &= j(\omega L - 1/\omega C) \end{aligned} \quad (35)$$

Hence $|Z| = (\omega L - 1/\omega C)$

The impedance falls to zero when $\omega L = 1/\omega C$, that is when $\omega = 1/\sqrt{LC}$. The excitation of circuit at this frequency will generate the free oscillations.

For the transmission line model, it is discussed in detail in 2.1.1.1, the main characteristics of this mode is the time delay between the injected signal and the response signal.

Based on these simple models, the measurement response signal will be analyzed in later chapters.

2.8 My program of research work

A research program on PD propagation to complete in a limited period of 3 years is formulated after the literature survey with the available facilities. The local power utility is interested in identifying the location of PDs in their operating plant. With those objectives in mind, three test apparatus are taken for the PD propagation studies. The first one is a 3 kVA rated laboratory 3Φ transformer with multiterminals. Propagation characteristics with the injected PD are studied. The second test object is a 230 kV/110 V dismantled SF₆ potential transformer from that power utility and PD propagation characteristics with the limited terminals are studied in the laboratory.

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The last test object is a 250 MVA operating generator connected to power network of bus bar and HV step-up transformer. On-line and off-line studies are formulated. In addition to the above, propagation models to match the simultaneous multi-nodes observation are suggested to match the on-line and off-line test results using Matlab and PSpice programs. The experimental layout, the experimental results, analysis and identified PD propagation modes in 3 apparatus are reported in the subsequent chapters.

CHAPTER 3

Tools used for PD propagation studies

This chapter presents the developed and used experimental set ups based on the literature survey reported in chapter 2 and the available facilities at Singapore. It reports about the used signal processing tools to analyse the PD propagation in tested apparatus.

3.1 Introduction

PD is generated in operating power apparatus in many ways. It may be cavity discharges due to insulation material defects, surface discharge due to contamination on the external surface and corona discharge due to exposed sharp points of the HV apparatus. Laboratory studies suggest that the original PD waveform may be exponential in shape. PD propagation in operating apparatus can be studied with the internally generated PD signals. The measured PD waveform will depend on the characteristics of PD at origin and the path of propagation. Since the exact origin of PD is not predictable, simultaneous measurement of the same PD at two or more locations is made to understand the propagation in operating apparatus. In off-line condition simulated PD signals are injected at the known locations and the responses are monitored to identify the propagation paths. The drawback of the above off-line studies is the injected PD may not represent the original shape of PD. On the other hand in on-line mode, PD location and characteristics are not normally known. Both the experimental methods are researched. In addition theoretical methods are also developed by modeling the different power apparatus to understand the propagation of PD and locate PD from its terminal responses.

In this study, an operating 16.5 kV, 250 MVA rated generator (G) connected to a step-up transformer through a short length busbar is selected for on-line PD propagation study. In addition, off-line studies are also carried on the same power network. Laboratory propagation studies are also carried out on 3 Φ -3kVA-415V/380V rated transformer (ET) and single Φ - 230kV/110V –SF₆ filled potential

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transformer (PT) after letting out the gas. For off-line studies, fabricated and commercial PD calibrators are used to generate the desired PD wave shape. For model development and signal processing, PSPICE and MATLAB software tools are used. The details on 3 test objects- experimental layout, measuring instruments and used signal processing tools and the program of planned study are presented in this chapter.

3.2 Experimental items used for off and on-line measurements

As described earlier and from literature survey in section 2.4, the required items for propagation studies in off-line measurement can be sharp rising PD source/calibrator with a rise time of 100 ns or less and pulse width of 1000 ns, multi channel oscilloscope with a bandwidth in the range of 1 GHz and the apparatus with the necessary monitoring nodes. PD source is used for off-line measurements only. Three test objects are studied in off-line mode.

3.2.1 PD sources

At the start of the project, no PD source was available and two units are developed for testing. The first one uses unijunction transistor and the used circuit is shown in Fig. 3-1(a). The peak magnitude obtained is only 5V as shown in Fig. 3-2 (a) and this is mainly used for off-line PD propagation studies with 3Φ-3kVA-415V/380V rated transformer. The FFT analysis shown in Fig. 3-2 (b) indicates that the energy content may be up to 5 MHz only. Beyond which noise dominates. The second unit shown

Fig. 3-1 Developed PD sources

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in Fig. 3-1(b) uses mercury switch in combination with a stepper motor and its control to get PD peak magnitude of 16 V as shown in Fig. 3-2(a). It has a bandwidth of about 30 MHz. The frequency responses of the mercury switch impulse 1 and 2 are not identical. It is found that impulse 1 FFT energy content is more than impulse 2 up to 400 kHz. Both sources are powered by isolated power supplies or by batteries. The impedance in the loop is kept minimum to suppress the noise at the output. This PD source with mercury switch is used mainly to study off-line PD propagation in the high capacity 250 MVA/16 kV generator connected to network.

Fig. 3-2 Time and frequency domain waveforms of fabricated PD sources
The characteristics of the impulses are shown in Table 3-1.

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Table 3-1 The characteristics of PD from 3 PD sources

impulse	Peak (V)	Front time (ns)	Tail time (ns) (50% peak)	Pulse width (ns) (10% peak)
UJT impulse	5	500	1400	2700
mercury-switch impulse 1	16.5	180	2500	6000
mercury-switch impulse 2	15	120	800	1900

Commercial PD calibrator HAFELY Type 451 shown in Fig. 3-3 is used to investigate the PD propagation in SF₆ PT. The repetition frequency is 50 Hz to avoid ambient noise. The front time is 30 ns, tail time is 10,000 ns and pulse width is 35,000 ns with a maximum magnitude of 2 V as shown in Fig. 3-4 (a). The frequency analysis indicates that the bandwidth of PD source can be up to 25 MHz.

Fig. 3-3 Commercial PD source

Fig. 3-4 Time domain waveform of commercial PD source and its FFT content

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3.2.2 Oscilloscope

The used oscilloscope is Tektronix TDS 7104. It can record simultaneously data from 4 channels at a maximum sampling rate of 10 GS/s. The maximum bandwidth will be 1 GHz. The minimum recorded voltage signal can be 1 mV and the maximum can be 100 V. In all the measurements of off-line mode, the injected signal and the simultaneous responses at various available nodes are recorded with the settings shown in Table 3-2 for ET, PT and G.

Table 3-2 The settings used in digital oscilloscope for ET, PT and G

Test objects		Time duration	Sampling points
Experimental transformer (ET)		100ps/pt	2×10^5
SF ₆ potential transformer (PT)		2.0ns/pt	5×10^3
Power generator network (G)	Off-line	20.0ns/pt	500
	On-line	16ns/pt	10^5

Necessary Labview software routines are developed to control the GPIB controlled oscilloscope and to acquire the data with proper settings using computer.

Agilent 89410A Vector signal analyzer is used to investigate the frequency domain response characteristics of the signal. It is also used to check the developed transform technique for converting the time domain response to frequency domain.

3.3 Signal processing tools

Time and frequency domain responses are the two aspects of the signal characteristics. Fast Fourier Transform (FFT) is the most commonly used to extract the frequency contents of the signal. Power spectrum density (PSD) has more advantages like suppressing the noise and other leakage spectrums than FFT.

Transfer function can minimize the influence of the injected signal magnitude and the transfer function is used to analyze the PD propagation characteristics.

The weak point of FFT/PSD is that the FFT/PSD provides the result only in the frequency domain. The variation of frequency content with time will be lost. To overcome this limitation, wavelet transform is applied to perform time-frequency analysis.

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For the analysis in time and frequency domains, programs using Matlab – signal processing and wavelet toolboxes are developed. The Pspice and simulink under Matlab are used to develop the model of PD propagation path to match the experimental observations.

3.4 Test objects

3.4.1 ET

The laboratory transformer ET is rated for 3 Φ - 3 kVA-415V/380V operation. The structure of the 3 Φ , Y0/Y0, core type transformer with concentric windings is shown in Fig. 3-5(b) (RHS). The outer layer is the secondary winding. The 3 Φ primary windings ‘A-B-C-N’ have taps at 100% of the winding (R), 92% of the winding (L5) and 50% of the winding (L2) in all the phases. It has 10 terminals in primary winding for PD propagation studies. In secondary winding c Φ , 3 tapings are made and marked as bot, mid and top. With line end terminals a, b, c and neutral n, there are 7 terminals available in secondary winding. The approximate lengths of each Φ primary and secondary winding are 38m.

Fig. 3-5 (a) Photograph of ET and (b) its terminal layout

3.4.2 PT

This is a SF₆ gas insulated potential transformer removed from a local power generation plant. The gas is let out and then removing the metal enclosure, PT is used for PD propagation study. It is a 3 windings transformer of rating 230 kV/110 V/110

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V with the shield, HV connection and LV outputs as shown in Fig. 3-6(a). Part of the outer HV winding insulation is removed to get Tap1 and Tap2. RHS of figure shows the winding layout and 8 terminals are available for PD propagation studies. The approximate length of HV winding can be 16.7km. Tap1 is located 1.6% near the HV terminal hv1. Tap 2 is located 0.5% near the HV terminal hv1.

Fig. 3-6 (a) Photograph of PT and (b) its terminal layout

3.4.3 Generator (G) in power network

An operating 16.5 kV, 250 MVA rated generator (G) connected to a step-up transformer through a short length busbar is selected for PD propagation study. Installed 6 HV couplers are available for PD measurement as shown in Fig. 3-7. The HV bus couplers are 80 pF Epoxy-Mica capacitors with 25 kV rms withstand rating. In on-line measurement, simultaneous PDs are measured using the oscilloscope at any of the four of available 6 LV terminals of HV couplers. For off –line measurements, 3 HV terminals of generator/HV coupler, neutral (N) of generator and 6 LV terminals of HV coupler are used for PD propagation studies.

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Fig. 3-7 The HV coupler terminal box of network for measurement

3.5 Experimental layout for ET

The experimental layout for PD propagation study in ET is shown in Fig. 3-8. The generated periodic PD pulse is injected across one outer turn of transformer secondary $c\Phi$ winding at top location. The response of injected PD signal is measured at taps R, L5 and L2 of three Φ s of primary winding. Then the PD is injected at middle (mid) one turn of secondary $c\Phi$ winding and the corresponding responses are recorded. This sequence is repeated at bottom (bot) one turn of secondary $c\Phi$ winding.

M: oscilloscope probes

Fig. 3-8 Experimental layout for PD propagation in ET

3.6 Experimental layout for PT

The used experimental layout for PD propagation study in PT is shown in Fig. 3-9. The HAFELY PD calibrator type 451 is used as a PD source. The PD pulse is injected either between hv1 and hv2 or Tap1 and hv2 terminals or Tap1 and Tap2. The corresponding response signals are measured at lv1 and lv2 or at lv3 and lv4 simultaneously.

Fig. 3-9 Experimental layout for PD propagation in PT

3.7 Test layout for G connected to power network of Power Seraya

The layout for PD propagation study in 3 Φ generator (G) of rating 16.5 kV/250 MVA connected to step up transformer using a 25 m length busbar is shown in Fig. 3-10. Permanently installed 6 HV coupling capacitors Ca, Cb, Cc, Cd, Ce and Cf are used for on-line detection of PD from 3 ϕ s of generator and transformer ends of busbar. The LV terminals A, B, C, D, E and F of the coupling capacitors are terminated with 1 M Ω resistor to record PD voltages. Simultaneous measurement in the same ϕ at two corresponding terminals can evaluate the characteristics of PD in the transmission line mode. Similar measurement at different ϕ s can indicate the cross-coupled component of dominant PD. In off-line mode of testing, neutral terminal N of generator and HV terminals G, H and I are available for PD source injection and monitoring.

Fig. 3-10 The terminals layout of G connected to power network

3.8 Program of work

For the planned objectives of research project indicated in chapter 2, this research is concentrated on identifying the propagation modes of PD in HV transformer and generator. This phenomenon is investigated in the laboratory with two transformers indicated as ET and PT under various configurations with PD sources. While at the field, operating HV generator connected to busbar and HV step-up transformer is studied for on-line PD propagation study. Off-line PD propagation studies are also done by injecting PD at the HV and N terminals of generator. Model studies to match the experimental results are also carried out to understand the various PD propagation modes. Extensive time and frequency domain analysis are done to identify the dominant modes of PD propagation in ET, PT and HV generator connected in a power network. The results and the identified modes of PD propagation with each apparatus will be reported in the next few chapters.

CHAPTER 4

Measured responses and analysis on experimental transformer

4.1 Introduction

This chapter presents the measured PD responses on experimental transformer (ET) and analysis on its propagation. The original injected PD pulse shape gets distorted at the different injected terminals. The details on terminal connections are presented in section 3.4.1. The analysis in frequency domain is done by the transfer function and wavelet analyses. The first part of this chapter presents the experimental results and the second part of it briefs the analysis.

4.2 Loading effect

The PD pulse is injected across one turn of the secondary winding at top, mid and bot location. The length of one turn is around 36 cms. The loading effect varies depending on the injected location. Typical injected PD signals at top, mid and bot of $c\phi$ of secondary winding are shown in Fig. 4-1 (a). The peak is reduced by 5 times and the pulse width changes from $2.7\mu s$ to $5\mu s$ when PD is injected at top. This peak magnitude attenuation changes to around 25 times and the pulse duration reduces to $0.7\mu s$ with oscillation in the tail when PD is injected at mid and bot.

Fig. 4-1 Injected PD signals at top, mid and bot of $c\Phi$ and the corresponding FFT content

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The frequency spectrum is also an exponentially decaying function with significant energy in a bandwidth of 3 MHz for all the three input signals.

The time domain injected PD signal gets distorted due to loading as shown in Fig. 4-1 and the measured magnitude attenuation, front and tail times are listed in Table 4-1.

Table 4-1 Injected PD (5V peak) distortion due to loading at top, mid and bot of ET

injected PD at	Peak (V)	Front time (ns)	Tail time (ns) (50%)	Pulse width (ns) (10%)	Tail-osc- peak (V)
top	1	500	1400	5000	0
mid	0.16	300	450	700	-0.08
bot	0.18	300	400	700	-0.08

When injected at top, the loading is minimum and the original exponential waveform is maintained in terms of front and tail time but the pulse width is increased from 2700 ns to 5000 ns. When injected at mid and bot locations, the attenuation in magnitude is more and the exponential pulse is changed to decaying oscillatory pulse. Both front and tail times are reduced and the pulse width is reduced. This shows that the input impedance at top, mid and bot locations varies for the pulse source.

The transfer function (TF) of the measured PD signals with reference to original PD signal is determined and the estimated function is shown in Fig. 4-2. When it is injected at top, only magnitude attenuation is seen as a flat response at -14dB. The wave shape distortion is minimum. For mid and bot locations, the flat response is seen after about 1 MHz with an attenuation of -26 dB. At low frequency range, the attenuation is more up to -52 dB indicating definite frequency band attenuation which may distort the original PD pulse.

In Fig. 4-2, the frequency response of PD measured at the top position is flat. For PD injected at bot and mid of the winding, the frequency response between 0 to 50 kHz decreases with increase in frequency. This shows that the connected winding behaves like capacitor in that range. From 50 kHz to 500 kHz, TF ratio increases with increase in frequency. This shows that the winding behaves like an inductor in that frequency range. Beyond 500 kHz, the TF ratio is almost flat. This shows that the signal at this band has minimum frequency distortion.

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Fig. 4-2 Variation of injected PD w.r.t. unloaded PD at top, mid and bot

4.3 Comparison of time and frequency domain measurements

Usually the measurement is done in time domain as the bandwidth can be easily controlled by the number of digital sampling points. This time domain results can be converted to TF by mathematical operations described in section 3.3. In this ET, the maximum observed frequency response lies within 10 MHz and a verification is made on the time and frequency domain measurements. A good matching is observed in all the cases. A typical TF result by injecting PD at mid of the secondary $c\phi$ winding and by measuring the response at L2 of the primary $C\phi$ winding is shown in Fig. 4-3. Almost identical peak and trough frequencies with corresponding amplitudes are observed.

Fig. 4-3 Comparison of network analyzer response with mathematical analysis
for measurement at $c\phi / C\phi$

4.4 Responses due to PD injection

The PD pulse is injected across one turn of top or mid or bot sections of secondary $c\phi$ winding. For each injection, the responses are measured at the taps R, L5 and L2 of 3ϕ primary winding and HV end of the secondary winding. Since the responses in A ϕ and B ϕ s are the same, only A ϕ response is presented for further analysis.

4.4.1 Responses due to PD injection at top of $c\phi$

When PD impulse is injected at the top of the $c\phi$, the measured responses at three tap locations in primary winding of $C\phi$ and $A\phi$, and HV terminal of secondary winding $a\phi$, $b\phi$ and $c\phi$ are shown in Figs. 4-4 (a),(b) and (c) respectively.

Fig. 4-4 Time domain responses for the injected PD at top of $c\phi$

The distortion in terms of peak magnitude, time delay between injected and measured peaks (Peak delay), shape of measured response (Pulse shape), the duration of the

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measured response from starting to 10% of the peak magnitude at tail (Pulse duration), time delay between the initial appearance of injected and measured responses (Starting delay) are determined. The results are tabulated in Table 4-2.

Table 4-2 Time domain response characteristics (PD injected at top of c Φ)

PD location	Response location		Peak mag(V)	Peak delay(ns)	Pulse shape	Pulse duration(ns)	Starting delay(ns)
top	C ϕ	L2	-0.58	0	Osc	7200	0
		L5	0.08	0	Osc	4200	0
		R	5.1	0	Exp	5000	0
	A ϕ	L2	0.43	0	Exp- osc	15000	0
		L5	0.68	0	Exp- osc	15000	0
		R	0.62	0	Exp- osc	15000	0
	HV terminals abc	a	0.6	1700	Exp- osc	13000	1100
		b	0.55	1700	Exp- osc	13000	1100
		c	2.25	0	Exp- osc	14200	0

From the above, one can see the following:

The pulse duration is found to stretch in almost all the cases and the shape of the responses are either exponential (Exp) or oscillatory (Osc) or exponential pulse with modulated decaying oscillation in the tail (Exp-osc).

In the secondary winding, the starting and peak time delays are observed at a ϕ and b ϕ and it is due to propagation delay in transmission line in star network.

In the R tap of primary winding C ϕ , maximum peak is observed without much distortion and it is due to magnetic coupling. At the L2 tap of primary winding C ϕ , negative peak is observed with oscillatory response and it is due to phase reversal coupling. It appears that there is capacitive coupling at the beginning of the transient. A transfer function analysis shown in Fig. 4-5 is made to identify the characteristic frequencies at which amplification and attenuation are observed.

The distortion in terms of the characteristic frequencies at peaks or troughs are extracted from Fig. 4-5 and tabulated in Table 4-3.

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Fig. 4-5 Frequency domain responses for the injected PD at top of c ϕ

Table 4-3 Frequency domain response characteristics (PD injected at top of c ϕ)

PD location	Response location		Peaks		troughs	
			Freq(MHz)	Mag(dB)	Freq(MHz)	Mag(dB)
top	C ϕ	L2	0.15,0.25, 0.6,1.55	-16.6,-14.8, 0.59,17.8	0.2, 0.35, 0.85	-21,-20.88, -1.73
		L5	0.2, 1.15, 1.6	-33.1,-29.7, -6.9	0.4, 1.25, 2	-52.4,-40.2, -11
		R	Flat			
	A ϕ	L2	0.05, 0.15, 0.25, 0.35, 0.95, 1.65	-8.3,-6, -7.4,-1.8, -5.5,1.8	0.1, 0.2, 0.3,0.75, 1.35, 1.8	-15,-12, -9.9,-7.5, -10,-14
		L5	0.05, 0.15, 0.25, 0.35, 1.7, 2.55	-2.8, -2 -4, 2, 2.5,7	0.1, 0.2, 0.3, 1.35, 2	-11,-7.8, -6.5,-9, 1.1
		R	0.05, 0.15, 0.25, 0.35, 1.7, 2.55	-2.8, -2 -4, 2, 3.5,7.8	0.1, 0.2, 0.3, 1.35, 2	-11, -7.8, -6.5, -11 2
	HV terminals abc	a	0.05, 0.25, 0.45, 1.35, 1.6	1,4.1, 1,-9.2, -1.5	0.1,0.35, 1.2,1.45, 2.15	-5,-3, -13.2,-18, -6.8
		b	0.05, 0.25, 0.45, 1.35, 1.6,2.4,2.8	1,4.3, 1,-9.2, -0.5,-2.5,4.1	0.1,0.35, 1.2,1.5, 2.2,2.6	-7.5,-3, -13,-16, -7.5,-4.5
		c	0.25,2	14,12.5	0.4,1.2,2.3	7.5,6.7,8

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From the above, one can see the following:

At R tap of the primary winding of $C\phi$, no distortion is observed. The coupling at L2 tap is more than at L5 tap. Out of 4 peaks and troughs at L2 tap, 2 peaks and troughs match with L5 tap.

At all the taps of the primary winding of $A\phi$, below 1.5 MHz identical responses are obtained. At L2 tap, the coupling is reduced beyond 1.5 MHz.

At HV terminal of secondary winding, maximum coupling is observed at the injected $c\phi$. In other ϕ s, identical responses are obtained.

For $C\phi$ R tap, the frequency response is flat. This shows that the dominant transmission mode is capacitive component. For the above Fig. 4-5, the middle frequency band from 0.5 MHz to 1.5 MHz, the responses are almost flat. This frequency band is propagated in transmission line mode. In Fig. 4-5 (b), the different tap frequency responses are much the same than other two figures. This shows that the propagation characteristics are almost the same irrespective of tap locations.

4.4.2 Responses due to PD injection at mid of $c\phi$

When PD impulse is injected at the mid of the $c\phi$, the measured responses at three tap locations in primary winding of $C\phi$ and $A\phi$, and HV terminal of secondary winding $a\phi$, $b\phi$ and $c\phi$ are shown in Figs. 4-6 (a), (b) and (c) respectively.

As done for section 4.4.1, the distortion factors are summarized in Table 4-4.

Table 4-4 Time domain response characteristics (PD injected at mid of $c\Phi$)

PD location	Response location		Peak mag(V)	Peak delay(ns)	Pulse shape	Pulse duration(ns)	Starting delay(ns)
mid	$C\phi$	L2	-1.2	2500	Exp-Osc	16700	500
		L5	-1.66	2100	Exp-Osc	16700	500
		R	-0.22	800	Exp-Osc	9000	500
	$A\phi$	L2	0.42	2900	Exp-Osc	19000	400
		L5	0.65	2900	Exp-Osc	19000	400
		R	0.57	2900	Exp-Osc	19000	400
	HV terminals abc	a	0.55	12000	Exp-Osc	19000	700
		b	0.65	12000	Exp-Osc	19000	700
		c	-1.1	1000	Exp-Osc	19000	200

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Fig. 4-6 Time domain responses for the injected PD at mid of c ϕ

From the above, one can see the following:

The pulse duration is found to stretch in almost all the cases and the shape of the responses is oscillatory modulated on decaying exponential pulse. There is start and peak delays in all the cases. In all the cases, the peak signal is amplified.

In the secondary winding cϕ, the minimum starting and peak time delays are observed. In all the taps of Cϕ, dominant negative peaks are observed.

In all the cases, increased magnitude and pulse duration with oscillation predict the injected PD propagated to the measuring nodes in the form of resonant frequency of the LC circuit which is excited by the PD pulse.

A transfer function analysis is made to identify the characteristic frequencies at which amplification and attenuation are observed. Fig. 4-7 shows the analyzed results. The distortion in terms of the characteristic frequencies at which peaks or troughs occur are extracted from Fig. 4-7 and tabulated in Table 4-5.

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Fig. 4-7 Frequency domain responses for the injected PD at mid of c ϕ

Characteristic resonant frequency peaks and troughs are observed in all the cases and they are tabulated in Table 4-5.

Table 4-5 Frequency domain response characteristics (PD injected at mid of c Φ)

PD location	Response location	Peaks		troughs	
		Freq(MHz)	Mag(dB)	Freq(MHz)	Mag(dB)
mid	C ϕ	L2	0.45,1.7	23,9.2	0.3,1.2,2.1
		L5	0.45,1.3 1.75,2.4	26,7.8, 13.5,14.7	0.3,0.9, 1.55,2.1,2.85
		R	1.3,1.75, 2.25	-6,-6, -5.3	1.15,1.6, 2.2,5
	A ϕ	L2	0.45,1.1	20,0.3	0.2,0.75,1.35
		L5	0.45,1.1	24,4	0.2,0.75,1.35
		R	0.45,1.1	24,4	0.2,0.75,1.35
	HV terminals abc	a	0.25,0.65	19,1.7	0.15,0.55,1.05
		b	0.25,0.65	19,4.9	0.15,0.55,1.05
		c	0.05,0.3,1.2,2.1	45,25,7,12	0.15,0.4,0.7,1.6

From the above, one can see the following:

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At $A\Phi$ taps and HV terminals of secondary winding, no significant change in response is observed with some amplification in low frequency range from 0 to 0.5 MHz and then in high frequency range above 2 MHz.

In $C\Phi$ taps, more signal is obtained at L2 and L5.

4.4.3 Responses due to PD injection at bot of c ϕ

When PD impulse is injected at the bot of the c ϕ , the measured responses at three tap locations in primary winding of $C\phi$ and $A\phi$, and HV terminal of secondary winding a ϕ , b ϕ and c ϕ are shown in Figs. 4-8 (a), (b) and (c) respectively.

Fig. 4-8 Time domain responses for the injected PD at bot of c ϕ

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As done for section 4.4.1, the distortion factors are summarized in Table 4-6.

Table 4-6 Time domain response characteristics (PD injected at bot of cΦ)

PD location	Response location		Peak magnitude(V)	Peak delay(ns)	Pulse shape	Pulse duration(ns)	Starting delay(ns)
bot	CΦ	L2	-0.94	3600	Osc	19000	0
		L5	-1.46	3600	Osc	19000	0
		R	-0.12	0	Exp	1400	0
	AΦ	L2	0.32	11700	Osc	19000	0
		L5	0.55	11700	Osc	19000	0
		R	0.57	11700	Osc	19000	0
	HV terminals abc	a	0.53	12400	Osc	19000	600
		b	0.64	12400	Osc	19000	600
		c	-1	600	Osc	19000	0

From the above, one can see the following:

The pulse duration is found to stretch in almost all the cases and the shape of the responses is oscillatory modulated on decaying exponential pulse. There is a starting delay for HV terminal aΦ and bΦ responses. There is peak delay in all the cases except for CΦ- R tap. In all the cases except CΦ- R tap, the peak signal is amplified. In all the taps of CΦ, dominant negative peaks are observed.

In most of the cases, increased magnitude and pulse duration with oscillation predict the injected PD was propagated to the measuring nodes in the form of resonant frequency of the LC circuit which is excited by the PD pulse.

A transfer function analysis is made to identify the characteristic frequencies at which amplification and attenuation are observed. Fig. 4-9 shows the analysed results. The distortion in terms of the characteristic frequencies at which peaks or troughs are seen are extracted from Fig. 4-9 and tabulated in Table 4-7.

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Fig. 4-9 Frequency domain responses for the injected PD at bot of c ϕ

From the above, one can see the following:

At A Φ taps and HV terminals of secondary winding, no significant change in response is observed with some amplification in low frequency range from 0 to 0.5 MHz and then in high frequency range above 2 MHz. In C Φ taps, more signals are obtained at L2 and L5. The frequency response at C Φ - R tap is almost flat and this shows that the dominant PD propagation mode is capacitive coupling.

Characteristic resonant frequency peaks and troughs are observed in all the cases and they are tabulated in Table 4-7.

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Table 4-7 Frequency domain response characteristics (PD injected at bot of cΦ)

PD location	Response location		Peaks		troughs	
			Freq(MHz)	Mag(dB)	Freq(MHz)	Mag(dB)
bot	CΦ	L2	0.45,0.9,1.4	18.7,11,-0.5	0.3,0.75,1.3,1.75	7.8.1,-7.9,-17
		L5	0.45,1.25,2	22,8,11.5	0.3,0.9,1.4,2.15	12,0,-13.5,6
		R	0.1	-0.9	0.25	-6.2
	AΦ	L2	0.15,0.45,1.25,1.6,2.2	17.5,17.8,2,4,4	0.1,0.25,0.75,1.35,1.75,2.3	10,-6.5,-8,-2,-1,1
		L5	0.15,0.45,1.2,2.2,2.6	21,21,5,9,13.5	0.1,0.25,0.75,1.35,2.35	15,-3,-3,-3,4
		R	0.15,0.45,1.2,2.2,2.6	21,21,5,9,13.5	0.1,0.25,0.75,1.4,2.35	15,-1.2,-5,-9,4
	HV terminals abc	a	1.15,1.4	-7,5	0.9,1.3,1.65	-12,-13,-7.5
		b	0.3,1.4	13,9	0.2,1.25,1.6	6,-9,4
		c	0.1,0.4,1.2	42,17,12	0.2,0.7,2	18,10,8

4.5 Analysis -1

Analysis is done to identify the PD propagation modes. For that, the typical experimental data presented in section 4.4 are analysed by keeping the monitoring node fixed and the injection node is varied. In the second case, the injection node is fixed and the monitoring nodes are varied. In the third case, the shape of PD pulse is varied but the injected and monitored locations are kept the same.

4.5.1 Variation of PD responses due to fixed monitoring node and varying injected PD nodes

The monitoring node is fixed at primary winding CΦ - L2 tap and PD is injected at secondary winding cΦ - top, mid and bot locations. Since there is loading effect due to the injected PD at different locations, transfer function analysis is taken to understand the propagation from node to node and the calculated responses are shown in Fig. 4-10 and Table 4-8.

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Fig. 4-10 Frequency domain responses at CΦ -L2 for the injected PD at top,mid & bot of c φ

Table 4-8 Frequency domain response characteristics

PD location	Response location		Peaks		troughs	
			Freq(MHz)	Mag(dB)	Freq(MHz)	Mag(dB)
top	Cϕ	L2	0.15,0.25, 0.6,1.55	-16.6, -14.8, 0.59,17.8	0.2, 0.35, 0.85	-21, -20.88, -1.73
mid		L2	0.45,1.7	23,9.2	0.3,1.2,2.1	7.2, -0.8,-3
bot		L2	0.45,0.9, 1.4	18.7,11, -0.5	0.3,0.75, 1.3,1.75	7.8,1, -7.9,-17

Taking the PD injection from top of secondary cΦ winding, the calculated transfer function is shown as solid line. The response appears like a high-pass filter with low frequency component attenuated more. The time domain response in Fig. 4-4(a) L2 tap is oscillatory. There is no start and peak time delays as per Table 4-2. This shows that the injected PD was coupled capacitively and then resonated at 1.55 MHz due to the inductance of CΦ winding at L2 tap. Other minor resonance peaks and troughs are also observed.

Taking the PD injection from mid of secondary cΦ winding, the calculated transfer function is shown as dashed line with + marker. The response appears like a low -pass filter with amplified input PD pulse. The injected PD in Fig. 4-6 (a) gets distorted due to loading and the sharp fall is due to reflection at cΦ HV terminal with large capacitance. The propagation delay in starting and peak time responses is due to inductive coupling component. The increased magnitude is due to series resonance in the propagation path. The propagation modes in this case are more likely inductive coupling with series resonance in low frequency range.

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Taking the PD injection from bot of secondary $c\Phi$ winding, the calculated transfer function is shown as dotted line with (o) marker. The response appears like a low - pass filter with amplified input PD pulse. The injected PD gets distorted due to loading and attenuated to 0.18 V peak. The sharp fall is due to reflection in $c\Phi$ HV terminal with large capacitance. Since there is no starting delay at $C\Phi$ -L2 tap, the injected PD signal must have been capacitively coupled. But there is delay in peak time domain response and the injected PD is magnified as per Table 4-6 suggesting the existence of another propagation mode. The increased magnitude in the low frequency range of Fig. 4-10 is due to series resonance in the propagation path. The propagation modes in this case are more likely inductive coupling with series resonance in low frequency range. There is characteristic high frequency parallel resonances at 1.3 and 1.75 MHz giving troughs in TF response.

The above reasoning indicates that the inductive and resonance coupling in low frequency component play a dominant role for mid and bot responses as shown in Fig. 4-10. The amplification of injected PD at the output is reflected in the low frequency range up to 1.3 MHz. For injection at top, attenuation due to capacitive coupling is noticed. The response appears like a low pass filter. The mid-band response from 1.3 to 1.7 MHz appears to be the same irrespective of the PD occurring location. This range is controlled by capacitive coupling. High frequency components are amplified by 4 dB when injected at mid and bot locations. There is almost no attenuation when injected from top location. This range is controlled by capacitance coupling.

4.5.2 Variation of PD responses due to fixed injected PD node and varying monitoring nodes

The injected PD node is fixed at secondary winding $c\Phi$ - mid and PD monitoring nodes at primary winding are $A\Phi$, $B\Phi$ and $C\Phi$ - L2 tap. Since there is loading effect due to the injected PD at mid locations, transfer function analysis is taken to understand the propagation from node to node and the calculated responses are shown in Fig. 4-11 and Table 4-9.

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Fig. 4-11 Frequency domain responses at Aφ, Bφ and Cφ-L2 tap for the injected PD at cφ -mid

Table 4-9 Frequency domain response characteristics

PD location	Response location		Peaks		troughs	
			Freq(MHz)	Mag(dB)	Freq(MHz)	Mag(dB)
mid	Aφ	L2	0.45,1.1	20,0.3	0.2,0.75,1.35	5,-4.5,-10.7
	Bφ	L2	0.45,1.1	20,0.3	0.2,0.75,1.35	5,-4.5,-10.7
	Cφ	L2	0.45,1.7	23,9.2	0.3,1.2,2.1	7.2, -0.8,-3

Injecting PD at cΦ - mid winding, the monitored responses at primary winding – L2 taps show the clear difference in AΦ and BΦ responses with reference to CΦ. This can be used to identify the Φ of PD occurrence. The trough frequencies 0.2 MHz and 0.75 MHz in AΦ and BΦ get shifted to 0.3 MHz and 1.2 MHz respectively in CΦ. The injected time domain PD gets distorted due to loading and the sharp fall is due to reflection in cΦ HV terminal with large capacitance. The propagation delay in starting and peak time responses is due to travelling wave component in secondary winding and inductive coupling component. Low frequency band up to 600 kHz is amplified in all the responses. The increased magnitude is due to series resonance in the propagation path. The propagation modes in all the cases are more likely inductive coupling with series resonance in low frequency range. Above 2 MHz, amplification is observed in all the phases.

4.5.3 Variation of PD responses due to different PD sources

Used PD sources have different rise and fall times. The role of PD sources in PD responses is explored. Both injecting and monitoring nodes are fixed and PD sources are varied. Typical measured responses at CΦ-L2 tap by injecting PD at cΦ-mid are shown in Fig. 4-12.

Fig. 4-12 Frequency domain responses at CΦ-L2 tap for the injected PD at cΦ-mid due to 3 PD sources

The determined TF in the low frequency range up to 2 MHz appears to be the same. Around 1.3 MHz, the trough due to mercury switch 2 is more. In the high frequency range above 2 MHz, the response due to mercury switch 1 is different from other two PD inputs. This shows that the high frequency component of PD with longer time width has different propagation characteristic compared to PDs with smaller time width. Table 4-10 lists the observed characteristic frequencies. Mercury switch 2 source is found to give shifted frequency peak at 1.95 MHz and trough at 1.8 MHz.

Table 4-10 Frequency domain response characteristics

PD type	Response location	Peaks		troughs	
		Freq(MHz)	Mag(dB)	Freq(MHz)	Mag(dB)
UJT impulse	CΦ	L2	0.45,1.7	23,9.2	0.3,1.2,2.1
Mercury switch 1		L2	0.45,1.75	23,10	7.2,-0.8,-3
Mercury switch 2		L2	0.45,1.75,1.95	23,11.2,9	0.3,1.35,2.3
					7,-2,-12
					2,-8.6,2

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To summarize this analysis of section 4.5 on ET with reference to PD injection and monitoring nodes and PD sources, one can understand that PD source can be loaded differently depending on the injecting location. The PD response depends on the propagation path from the injected node to the monitored node. The transfer function analysis to eliminate the role of injected PD magnitude and shape indicates in section 4.5.1 that if PD is injected from $c\Phi$ -top, the measured response at $C\Phi$ -L2 will have more capacitive coupling. If PD is injected from $c\Phi$ -mid, the measured response at $C\Phi$ -L2 will be in the form of inductive coupling with series resonance in the low frequency range to amplify the injected PD signal. If PD is injected from $c\Phi$ -bot, the measured response at $C\Phi$ -L2 will be a combination of capacitive and inductive coupling. In all the above cases in section 4.5.1, the coupling is more dominant in the low frequency range.

Section 4.5.2 indicates that the coupling between secondary and primary windings by keeping PD source at $c\Phi$ -mid. The measured responses at L2 tap of primary winding show the corresponding $C\Phi$ -L2 tap response is significantly different from other two Φ s especially phase reversal in time domain response. All the responses have start and peak delays indicating that the propagation modes can be a combination of transmission and inductive coupling.

Section 4.5.3 indicates that PD response is not affected much by the different PD sources in the frequency range up to 2 MHz. Beyond 2 MHz, the propagation path is frequency dependent.

4.6 Analysis-2

A wavelet, as its name implies, can be interpreted as a small wave that has a limited duration and a zero mean value. It oscillates in amplitude and decays to zero quickly on both sides of the central position of the waveform. Compared to sine and cosine waves, the basis functions of the Fourier transform, which extend from minus to plus infinity, wavelets usually tend to be irregular and asymmetric in terms of wave shape [19].

Wavelet method is used to separate the high and low frequency components of input and output signals in time plane. This will enable to identify the propagation characteristics of low and high frequency bands.

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Using db3 as mother wavelet and 10 level decomposition and reconstruction, the analysis can be made without introducing much distortion. Two cases are analysed. In the first case, the role of injected PD at $c\Phi$ -bot is analysed at two monitored locations $C\Phi$ - L2 and R taps to understand the PD propagation. In the second case, the propagation of PD at $C\Phi$ - L2 tap from two injected locations - $c\Phi$ -bot and top is analysed.

4.6.1 Variation of PD responses due to two monitored locations

Injected PD at $c\Phi$ -bot is separated in time plane with low and high frequency components using wavelet and Fig. 4-13 (a) shows the separated signals. It dominantly contains low frequency signal with a peak magnitude of 0.18 V and an oscillatory high frequency decaying component with a peak voltage of 0.022 V. There is no significant time delay at the start and peak. Right hand side shows the frequency content. The dominant low frequency component has a bandwidth of 1 MHz while the high frequency component has $1/20^{\text{th}}$ of the low frequency component in the frequency range from 1 to 10 MHz. The response time domain signal at $C\phi$ -R tap shown in Fig. 4- 13(b) shows phase inversion and attenuation. The high frequency peak signal is $1/10^{\text{th}}$ of low frequency peak signal. The peak of low and high frequency components appear with a delay time of 25 ns and 505 ns respectively with respect to injected PD. In frequency domain, the response low frequency component is spread to a wider bandwidth spread to low frequency band. In high frequency spectrum, more discrete frequency bands are obtained. From the delay time and attenuation level, low frequency component is capacitively coupled. More delay time with minor distortion in high frequency component indicates that the propagation mode is transmission line.

The response time domain signal at $C\phi$ -L2 tap shown in Fig. 4- 13(c) shows phase inversion, pulse amplification and stretching. The high frequency peak signal is $1/36^{\text{th}}$ of low frequency peak signal. The peak of low and high frequency components appear with a delay time of 3700 ns and 1434 ns respectively with respect to injected PD. In frequency domain, the response low frequency component is shifted to very low frequency band. In high frequency spectrum, more discrete frequency bands are obtained. From the amplification of low frequency signal, it appears that the low

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frequency component is propagated inductively. More delay time with minor distortion in high frequency component indicates that the propagation mode is transmission line.

(a) Components of injected PD signal at cΦ-bot

(b) Components of responses at CΦ- R tap

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(c) Components of responses at CΦ- L2 tap

Fig. 4-13 Wavelet separation of injected PD at cΦ-bot and response signals at CΦ- R and L2 taps

4.6.2 Variation of PD responses due to two injected locations

The propagation of PD at CΦ- L2 tap from two injected locations - cΦ-bot and top is analysed. The response due to injection from cΦ-bot is discussed in Fig. 4-13 (c). The injected PD signal gets loaded and hence the corresponding analysis is reported below.

Injected PD at cΦ-top is separated in time plane with low and high frequency components using wavelet and Fig. 4-14 (a) shows the separated signals. It dominantly contains low frequency signal with a peak magnitude of 1 V and an oscillatory high frequency decaying component with a peak voltage of 0.048 V. There is no significant time delay at the starting and peak. Right hand side shows the frequency content. The dominant low frequency component has a dropping frequency response with a bandwidth of 1 MHz while the high frequency component has $1/160^{\text{th}}$ of the low frequency component in the frequency range from 1 to 10 MHz. The response time domain signal at CΦ-L2 tap shown in Fig. 4- 14(b) shows attenuated and decaying oscillatory response. The high frequency peak signal is $1/4^{\text{th}}$ of low frequency peak signal. The peak of low and high frequency components appear with a delay time of 30 ns and 409 ns respectively with respect to injected PD. In

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frequency domain, the attenuated response of low frequency component is spread to high frequency band with its discrete peak responses. In high frequency spectrum, more discrete frequency bands are obtained with amplification. The minimum time delay and oscillatory response shows that the low frequency component is capacitively coupled with LC resonance to get more high frequency peaks in low frequency range. Delay time with discrete amplified high frequency component indicates that the propagation in high frequency mode is transmission line coupled with minor resonance.

(a) Components of injected PD signal at $c\Phi$ -top

(b) Components of responses at $C\Phi$ - L2 tap

Fig. 4-14 Wavelet separation of injected PD at $c\Phi$ -top and response signals at $C\Phi$ - L2 tap

4.7 Summary

Studies with ET suggest that PD propagation will be affected by a number of factors.

Loading - Section 4.2 indicates that the injected PD across one turn will be distorted depending on the injected location. When PD is injected in the 2 winding, 3 Φ star-star transformer at $c\Phi$ top, mid and bot locations, the distortion is minimum at top and maximum at other two locations. At top, the injected exponential peak waveform is attenuated by five times but the front and tail times are retained. The pulse width is increased from 2700 ns to 5000 ns. When PD is injected at mid and bot locations, the magnitude attenuation is more and the exponential pulse is changed to decaying oscillatory pulse. Front, tail times and pulse width are reduced. This is verified by frequency domain analysis also. This shows that the input impedance at top, mid and bot locations varies for the pulse source and it distorts the injected PD signal.

Technique of measurement - The work reported in section 4.3 is carried out to do the measurement either in frequency or time domains so that identical results can be obtained. Measured network analyzer measurement results and calculated TF from time domain measurement are found to match up to 2.5 MHz.

Section 4.4 suggests that the corresponding measured Φ of the injected PD is characteristically different from other two Φ s. The measured responses are distorted. The waveform is exponential, oscillatory or exponential with modulated decaying oscillation. The pulse is stretched up to 20 μ s. In some cases, there are starting delays and delay in peak occurrence. Frequency analysis suggests the existence of the characteristic peak and trough frequencies.

Identification of propagation modes using time and frequency domain results -

PD propagation modes can be in four ways [16] [22].

The first propagation mode is in the form of inductive coupling. The main characteristic of this mode is that the increased magnitude of the response signal due to inductive turns ratio of the respective windings.

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The second propagation mode is the capacitive coupling. The main characteristic of this mode is that the delay between the peaks of injected and response signals is very small.

The third mode is the transmission line mode. The characteristics of transmission line mode is that the shape of the injected and response signals is much same, but the time delay of its occurrence varies depending on the propagation distance.

The fourth mode is that the L-C resonance mode. The characteristic of this mode is the generation of oscillation in the response waveform.

Based on the above justifications, the response signals are analyzed to identify the different propagation modes.

In section 4.5, the obtained experimental results of section 4.4 are analysed to identify the PD propagation modes. For that, three cases are analyzed. The first case is analysed by keeping the monitoring node fixed and the injection node is varied. In this case, the loading and propagation distortions are brought in. In the second case, the injection node is fixed and the monitoring nodes are varied. With this, the loading effect is kept constant and the propagation paths are varied. In the third case, the shape of PD pulse is varied but the injected and monitored locations are kept the same. This can evaluate the influence of injected wave shape on the responses.

Section 4.5.1 discusses the effect of varying injected PD nodes on the monitored node C Φ - L2 tap. For injection at top, reduced time domain responses are oscillatory without any delay at the start and peak occurrence as per Table 4-2. Frequency domain response shown in Fig. 4-10 predicts that the injected PD at c Φ -top is coupled capacitively to C Φ winding and then it resonates at 1.55 MHz due to the inductance of C Φ winding at L2 tap.

For injection at mid, capacitively coupling is minimum as significant delay in start and peak occurrence times are observed. Increased magnitude of the attenuated

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injected signal in Table 4-4 shows that the propagation mode is inductive coupling with series resonance in the low frequency range. There is no direct relationship on the measured peak time domain response in relation to loaded injected signal peak level.

For injection at bot, there is no starting delay in measured time domain response. The loaded peak injected signal of 0.18V is capacitively coupled in the initial time domain response. But the measured peak response is around -0.94V with a peak delay shows the existence of the propagation mode of inductive coupling with series resonance in low frequency range. In this, two propagation modes are present.

Injected PD location is fixed at c Φ -L2 tap and the measured responses in section 4.5.2 and Fig. 4-6 indicate that C Φ response is clearly different from A and B Φ s. The propagation modes in all the cases is due to inductive coupling with series resonance in low frequency range. The characteristic changes in C Φ in comparison with other Φ s are the peak time domain signal shown in Table 4-4 is more and 3 trough frequencies 0.3, 1.2 and 2.1 MHz in Fig. 4-11 get shifted.

The last case described in section 4.5.3 with injected PD wave shapes predicts that PD response is not affected much by the different PD sources in the frequency range up to 2 MHz. Beyond 2 MHz, the propagation path is frequency dependent.

Identification of propagation modes using wavelet analysis - Wavelet analysis shown in Fig. 4-13 (a) predicts that the injected PD at c Φ -bot dominantly contains low frequency signal with a peak magnitude of 0.18 V and an oscillatory high frequency decaying component with a peak voltage of 0.022 V. There is no significant time delay at the starting and peak of both the components. The dominant low frequency component has a bandwidth of 1 MHz while the high frequency component has 1/20th of the low frequency component in the frequency range from 1 to 10 MHz.

The response time domain signal at C Φ -R tap shown in Fig. 4- 13(b) shows the delay and attenuation. It predicts that low frequency component is capacitively coupled.

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More delay time with minor distortion in high frequency component shows that the propagation mode is transmission line.

The response time domain signal at C ϕ -L2 tap shown in Fig. 4- 13(c) shows the amplification of low frequency component of signal and it predicts the existence of the propagation mode of inductive coupling with series resonance in low frequency range. No delay at the starting time of low frequency signal predicts the existence of capacitive coupling on low frequency component as seen by the TF analysis. More delay time with minor distortion in high frequency component predicts that the propagation mode is transmission line.

This predicts the existence of many propagation modes in low frequency component.

Loading effect of the injected PD at c Φ -top in Fig. 4-14 (a) shows the dominant low frequency signal with a peak magnitude of 1 V and an oscillatory high frequency decaying component with a peak voltage of 0.048 V. There is no significant time delay at the start and peak occurrence. Right hand side shows the frequency content. It follows the same frequency range. The minimum time delay and oscillatory response shows that the low frequency component is capacitively coupled with LC resonance to get more high frequency peaks in low frequency range. Delay time with discrete amplified high frequency component indicates that the propagation with high frequency component is transmission line mode coupled with minor resonance.

Wavelet method is able to identify PD propagation modes on high frequency component more clearly.

CHAPTER 5

Measured responses and analysis on 230 kV potential transformer

5.1 Introduction

This chapter presents the measured PD responses on 230kV/110V SF₆ potential transformer (PT) and the analysis on PD propagation. PT is removed from service. In the laboratory, after releasing the SF₆ gas and removing the pressurized outer cover the PT is used for measurement. The insulation of outer multilayered cylindrical HV winding is removed to get Tap1 and Tap2 in Fig. 3-6. The PD pulse from PD calibrator Hafeley Type 451 is used as PD source as this is purchased when we started this measurement and it is portable. The calibrator is a battery operated unit. The PT is a 3 winding transformer with 6 terminals brought out and another 2 taps are created for PD studies. PD is injected at the available terminals and the corresponding responses at other leftover terminals are recorded using the digital oscilloscope. The measured and injected signals are analysed for identifying the different propagation modes using transfer function and wavelet analysis. The first part of this chapter presents the measured results and the second part discusses the analysis and the possible PD propagation modes in PT.

5.2 Loading effect

Like section 4.2, it is planned to test the distortion introduced on PD source by connecting to the test object. Fig. 3-6 shows the PT with voltage rating 230 kV/110 V/110 V. The available terminals are hv1, hv2, lv1, lv2, lv3, lv4, Tap1 and Tap2. Tap1 and Tap2 are located near hv1 at 1.6% and 0.5% length of hv1 and hv2 winding respectively. Since PD is not going to be generated at 110 V winding, simulated PD is not injected at lv1, lv2, lv3 and lv4.

Since in the simulation packages, the injected PD can be modeled with reference to ground, the PD pulse is injected in 2 ways with reference to grounded hv2 terminal and in one case, it is injected in floating mode. In way 1, PD is injected between hv1-

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lv2 (grounded) terminals, and the responses are measured simultaneously at lv1-lv2 (grounded) and lv3-lv4 (grounded). In the subsequent presentation ‘grounded’ is represented by ‘g’. In way 2, the effect of moving PD injected location to Tap1-hv2 (g) is studied and the responses are measured simultaneously at lv1-lv2 (g) and lv3-lv4 (g). In way 3, the floating PD outputs from PD source are connected to Tap1-Tap2 and the corresponding simultaneous responses are measured at hv1-hv2 (g), lv1-lv2 (g), and lv3 - lv4 (g). For this case, differential mode is used to record the injected PD signal at Tap1-Tap2. The shape of PD without connecting to any terminal is shown in Fig. 3-4. By connecting PD source to the terminals indicated in the above 3 ways, the injected PD source is found to be distorted in peak magnitude (-2 V), front time (30 ns), tail time (10000 ns) and pulse width (35000 ns) as shown in Table 5-1. There are no oscillations in the tail of injected PD for all the cases.

Table 5-1 Injected PD (-2V peak) distortion due to loading

Configuration	Peak (V)	Front time (ns)	Tail time (ns) (50%)	Pulse width (ns) (10%)
Way 1	-2	50	9500	34000
Way 2	-1.8	50	9500	34000
Way 3	-1.7	800	8000	40000

From the Table 5-1, it is seen that the significant loading effect is noticeable when injected across Tap1 – Tap2. Front time and pulse width increase with a reduction in peak value and increase in front time. This shows that Tap1-Tap2 appear like a capacitive load to increase the front time from 50 ns to 800 ns. The variation in tail time and pulse width is due to low frequency response characteristics of the connected network at Tap1-Tap2.

5.3 Responses due to PD injection

PD is injected in the HV winding in 3 ways described in section 5.2. The responses are generally measured at the LV windings.

5.3.1 Responses due to PD injection at hv1- hv2(g)

PD is injected across hv1 and hv2 (g). The responses are measured at lv1-lv2 (g) and

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lv3-lv4 (g) as shown in Fig. 5-1. The approximate turn's ratio at 50 Hz is 2000:1. The measured time domain responses are decaying oscillatory signal with its peak amplitude attenuated by 15 times at lv1-lv2 (g) and 20 times at lv3-lv4 (g) respectively. It shows that the coupling is not dominated by mutual induction. The oscillation indicates the presence of capacitance and the decay in response is due to resistive element. There is no time delay at the starting but the peak occurrence delays by 34 ns in the two LV windings. The duration of the response is around 8000 ns indicating the resistive damping effect.

Fig. 5-1 Time domain responses for the injected PD at hv1-hv2 (g)

5.3.2 Responses due to PD injection at Tap1- hv2(g)

PD is injected across Tap1 and hv2 (g). The responses are measured at lv1-lv2 (g) and lv3-lv4(g) as shown in Fig. 5-2. The measured time domain responses are decaying oscillatory signal with its loaded peak amplitude attenuated by 26 times at lv1-lv2 (g) and lv3-lv4 (g). It shows that the coupling is not dominated by mutual induction. The oscillation indicates the presence of capacitance and the decay in response is due to resistive element. There is no time delay at the starting as well as in peak occurrence in the two LV windings. The duration of the response is around 7000 ns indicating the resistive damping effect.

Fig. 5-2 Time domain responses for the injected PD at Tap1-hv2 (g)

5.3.3 Responses due to PD injection at Tap1- Tap2

PD from battery operated PD source is injected across Tap1 and Tap2. The measured time domain responses at the LV windings lv1-lv2 (g) and lv3-lv4 (g) are more or less same. The measured time domain responses at lv1-lv2(g) and hv1-hv2(g) are shown in Fig. 5-3. At lv1-lv2, the double exponential shape is distorted in peak magnitude, front and tail times and pulse width. At the tail, a minor decaying oscillation is observed. The attenuation of the loaded PD at lv1-lv2(g) is 56 and front time changes to 50 μ s, tail time increases to 60 μ s and pulse width stretches to 70 μ s. A significant time delay is observed. The time delays at the starting and peak occurrence are 270 μ s and 310 μ s respectively. This appears that the PD may have travelled in transmission line mode. At hv1-hv2(g), the double exponential shape is distorted with phase inversion. Both tail time and pulse width vary. At the tail, a minor decaying oscillation is observed. The attenuation in the peak of the loaded PD at hv1-hv2(g) is 0.7. No time delay is observed. Front time increases to 1800 ns. The tail time is 400 μ s and pulse width stretches to 600 μ s. This appears to be the PD may have coupled capacitively and then it is stretched more due to inductance.

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Fig. 5-3 Time domain responses for the injected PD at Tap1-Tap2

The measured time domain peak responses at the LV winding are attenuated with decaying oscillation when PD is injected from HV winding. When PD is injected at Tap1-Tap2 of HV winding, the response at LV winding is delayed in occurrence and distorted in front and tail times. While at HV winding hv1-hv2, the response is phase inverted with pulse stretching.

Analysis is done to identify the PD propagation modes in PT. Two types of analysis are undertaken for the identification in the frequency domain. Analysis -1 uses a transfer function analysis using PSD and analysis-2 uses the wavelet to separate the high and low frequency components and its characteristics.

5.4 Analysis -1

The measured response with PT signal is much attenuated. To avoid spectral leakage and degradation at spectral peaks, the analysis using power spectral density (PSD) is proposed [21]. PSD analysis can extract the signal from the noise interference environment and shows the dominant peaks of signal.

5.4.1 Transfer function analysis for PD injection at hv1- hv2(g)

Characteristic peaks are observed in the calculated transfer functions shown in Fig. 5-4. With the measured response at lv1-lv2(g), the dominant characteristic frequency is

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14 MHz and another minor characteristic frequency is observed at 98 MHz. While at lv3-lv4 (g), a reduced dominant frequency at 14 MHz is observed. While the minor frequency is shifted to 78 MHz.

It predicts that the dominant peak is due to structure capacitive coupling and resonance due to LV inductance. While the second minor peak is due to external stray capacitance which will vary with reference to lv1-lv2 (g) and lv3-lv4 (g).

Fig. 5-4 Transfer function analysis for the injected PD at hv1-hv2(g)

5.4.2 Transfer function analysis for PD injection at Tap1- hv2(g)

Reduced characteristic peaks are observed in the calculated transfer functions shown in Fig. 5-5. With the measured response at lv1-lv2(g), the dominant characteristic frequency is 13.6 MHz and another minor characteristic frequency is observed at 90 MHz. While at lv3-lv4(g), a reduced dominant frequency at 10 MHz is observed. While the minor frequency remains the same at 90 MHz.

The resonance dominant peaks are due to resonance across the outer high voltage winding (hv1&hv2) and inner low voltage windings (lv1 &lv2 and lv3 & lv4) self and mutual distributed inductance and capacitance parameters.

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Fig. 5-5 Transfer function analysis for the injected PD at Tap1-hv2 (g)

5.4.3 Transfer function analysis for PD injection at Tap1- Tap2

Characteristic peaks are observed in the calculated transfer functions shown in Fig. 5-6. It indicates that there is not a significant change in frequency response from 0 Hz to 100 kHz at lv1-lv2 (g) when PD was injected between Tap1 and Tap2. But attenuation was more across lv1 and lv2 both in time and frequency domain responses. While at hv1-hv2 (g), an exponentially decreasing response is obtained. This indicates that PD is transmitted in transmission line mode. The characteristic peak at 130 kHz of hv1-hv2 (g) response is due to the fluctuation in time domain tail response. The PSD predicts the existence of dominant low frequency signal which is due to the inductance of HV winding.

5.4.4 Summary of analysis-1

If PD is injected at hv1-hv2(g) or Tap1-hv2(g), the PD may propagate to lv1-lv2(g)/lv3-lv4(g) by structure capacitive coupling and PD signal is distorted by resonance with LV winding inductance. When PD is injected at Tap1-Tap2, the PD may propagate to LV winding with a delay and attenuation indicating the transmission line mode of propagation. Propagation to HV winding is in capacitive coupling mode and PD is stretched due to the high inductance of HV winding.

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Fig. 5-6 Transfer function analysis for the injected PD at Tap1-Tap2

5.5 Analysis - 2

Wavelet method as described in section 4.6 is used to separate the high and low frequency components of input and output signals in time plane. This will enable to identify the propagation characteristics of low and high frequency bands. Instead of 10 levels used for ET in section 4.6, 6 levels are found to decompose and reconstruct the signal for PT.

5.5.1 Wavelet analysis for PD injection at hv1- hv2(g)

Injected PD at hv1-hv2(g) is separated in time plane with low and high frequency components using wavelet. Left hand side of Fig. 5-7 (a) shows the separated signals. The shape is double exponential pulse in low frequency time domain signal with a peak magnitude of -1.89V and the high frequency domain signal is an oscillatory burst occurring only during the fall time with a peak voltage of 0.545 V . There is no significant time delay at the starting and peak occurrence. Right hand side shows the frequency content. The dominant low frequency component has a bandwidth of 5 MHz with decreasing magnitude with increase in frequency. While the high frequency component is distributed in bell shape with peak magnitude in the range of $1/10^{\text{th}}$ of the low frequency peak. The high frequency bandwidth is from $1\text{ to }12\text{ MHz}$.

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The response time domain signal at lv1-lv2(g) shown in left hand side of Fig. 5-7(b) presents the distortion and attenuation. The high frequency time domain peak signal is $1/2^{\text{th}}$ of low frequency peak signal. The starting delay in time domain low and high frequency components is 0 and 130 ns respectively. The peak of time domain low and high frequency components appear with a delay time of 0 ns and 384 ns respectively with respect to injected PD. In frequency domain, the low frequency component shows the characteristic peaks distributed in the range 2 to 5 MHz. In high frequency spectrum, more discrete frequency bands are obtained in the frequency range from 2 to 30 MHz. From the delay time and attenuation level, low frequency component is capacitively coupled.

The response at lv3-lv4(g) does not differ much except the high frequency peak delay reduces to 126 ns in comparison with lv1-lv2(g) value of 384 ns.

The transfer function analysis shown in Fig. 5-7 (c) indicates that the characteristic resonance peaks can be obtained. An attempt is made to determine the transfer function of separated high and low frequency components to evaluate the propagation characteristics in that two ranges. The combined one shown in top of Fig. 5-7(c) indicates two dominant peaks at 2 MHz and 8.1 MHz. While the transfer function shown in mid. of Fig. 5-7 (c) shows about 4 peaks at 2 MHz, 4.5 MHz, 6 MHz and 10 MHz respectively. No delay in time domain and the responses in the range of 1 predict that the low frequency component of signal is capacitively coupled with 4 characteristic series resonance responses across lv1-lv2(g). The transfer function shown in bot. of Fig. 5-7 (c) shows a number of resonance peaks of magnitude less than 1. The high frequency peaks are found to be sharp with high Q. The starting delay and peak delay in time domain predict that the high frequency component travelled in travelling wave mode of propagation. This predicts that PD propagates to lv1-lv2(g) in many paths.

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(a) Wavelet analysis of the injected PD signal at hv1-hv2(g)

(b) Wavelet analysis of the response signal at lv1-lv2(g) due to (a)

(c) Computed transfer function of (b) w.r.t (a)

Top- without wavelet; mid- low frequency; bot- high frequency

Fig. 5-7 Wavelet analysis of the responses at lv1-lv2(g)
for the injected PD at hv1-hv2(g)

5.5.2 Wavelet analysis for PD injection at Tap1- hv2(g)

Injected PD at Tap1 - hv2(g) is separated in time plane with low and high frequency components using wavelet and left hand side of Fig. 5-8 (a) shows the separated signals. The shape is double exponential pulse in low frequency time domain signal with a peak magnitude of -1.83 V and the high frequency time domain signal is an oscillatory with many bursts with a peak voltage of -0.08 V. There is no significant time delay at the starting and peak occurrence. Right hand side shows the frequency content. The decaying low frequency component with peaks of wide band has a bandwidth of 10 MHz. While the high frequency component is distributed in bell shape with peak magnitude in the range of $1/25^{\text{th}}$ of the low frequency peak. The high frequency bandwidth is from 3 to 30 MHz.

The response time domain signal at lv1-lv2 (g) shown in left hand side of Fig. 5-8(b) presents the distortion and attenuation. The high frequency time domain peak signal is $1/3.6^{\text{th}}$ of low frequency peak signal. The starting delay in time domain low and high frequency components is 126 and 194 ns respectively. Both the peak of time domain low and high frequency components appear with a delay time of 128 ns with

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respect to injected PD. In frequency domain, the low frequency component shows the characteristic peaks distributed in the range 2 to 6 MHz. In high frequency spectrum, more discrete frequency bands are obtained in the frequency range from 2 to 20 MHz. The response at lv3-lv4 (g) does not differ much except the high frequency peak delay increases to 512 ns in comparison with lv1-lv2 (g) value of 128 ns.

The transfer function analysis shown in Fig. 5-8 (c) indicates that the characteristic resonance peaks can be obtained. An attempt is made to determine the transfer function of separated high and low frequency components to evaluate the propagation characteristics in that two ranges. The combined one shown in top of Fig. 5-8 (c) indicates two dominant clear peaks at 9 MHz and 75 MHz with a number of other high frequency peaks. While the transfer function shown in mid. of Fig. 5-8 (c) shows about 4 peaks at 3 MHz, 4 MHz, 5 MHz and 10.2 MHz respectively. Starting and peak delay in time domain oscillatory responses and transfer function value in the range of 1 predict that the low frequency oscillatory signal is coupled in transmission line mode and then resulted in 4 characteristic series resonance responses across lv1-lv2(g) like the response shown in Fig. 5-7 (c). The transfer function shown in bot. of Fig. 5-8 (c) shows a number of resonance peaks of magnitude greater than 1. The high frequency peaks are found to be sharp with high Q. The starting delay and peak delay in time domain predicts that the high frequency component travelled in travelling wave mode of propagation. The pulse stretching in high frequency time domain signal and a number of high frequency resonance peaks predict the existence of other types of magnetic coupling. This predicts that PD propagates to lv1-lv2 (g) in many paths.

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(a)Wavelet analysis of the injected PD signal at Tap1-hv2 (g)

(b)Wavelet analysis of the response signal at lv1-lv2 (g) due to (a)

(c) Computed transfer function of (b) w.r.t (a)

Top- without wavelet; mid- low frequency; bot- high frequency

Fig. 5-8 Wavelet analysis of the responses at lv1-lv2 (g)
for the injected PD at Tap1-hv2 (g)

5.5.3 Wavelet analysis for PD injection at Tap1- Tap2

Injected PD at Tap1 – Tap2 is separated in time plane with low and high frequency components using wavelet and left hand side of Fig. 5-9 (a) shows the separated signals. The original sharp falling double exponential pulse is distorted in low frequency time domain signal with a peak magnitude of -0.8 V and the high frequency time domain signal is an oscillatory with many bursts with a peak voltage of -0.6 V . Right hand side shows the frequency content. The low frequency component is distributed in a bandwidth of 10 kHz . While the high frequency component is distributed in the frequency range of 10 kHz to 100 kHz in bell shape with peak FFT magnitude in the range of $1/2$ of the low frequency peak.

5.5.3.1 Response at lv1-lv2(g)

The response time domain signal at lv1-lv2(g) shown in left hand side of Fig. 5-9(b) presents the distortion in front time and attenuation. The loaded injected signal with front time of $0.8\text{ }\mu\text{s}$ gets lengthened in the response as $50\text{ }\mu\text{s}$ and the original pulse

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width of 40 μs gets extended to 70 μs . The magnitude of 1.8 V is attenuated by 56 times to 0.03 V. The high frequency time domain peak signal is $1/4^{\text{th}}$ of low frequency peak signal. The starting delay in time domain low and high frequency components is 282 μs and 295 μs respectively. The peak of time domain low and high frequency components appear with delay time of 281 μs and 308 μs respectively with respect to injected PD. In frequency domain, the low frequency component shows the spectrum is distributed in the range of 20 kHz like a bell shape. In high frequency spectrum, the spectrum is distributed from 10 kHz to 800 kHz. The peak of high frequency FFT signal is about $1/8^{\text{th}}$ of low frequency FFT signal.

The transfer function analysis shown in Fig. 5-9 (c) indicates that small numbers of characteristic resonance peaks are obtained. An attempt is made to determine the transfer function of separated high and low frequency components to evaluate the propagation characteristics in that two ranges. The combined one shown in top of Fig. 5-9 (c) indicates one dominant clear peak at 0.78 MHz with a number of other less dominant frequency peaks. While the transfer function shown in mid. of Fig. 5-9 (c) shows about 3 peaks at 2.5 kHz, 37 kHz, and 74 kHz respectively. Starting and peak delay in time domain double exponential responses and transfer function value in the range of < 1 predict that the low frequency signal is coupled in transmission line mode resulting with distortion of 3 characteristic frequency contents. The transfer function shown in bot. of Fig. 5-9 (c) shows two dominant frequency peaks at 89 kHz and 0.7 MHz with value in the range 0.15. The starting delay and peak delay in time domain predicts that the high frequency component may also have travelled in travelling wave mode of propagation. The attenuated high frequency signal without much distortion predicts the propagation mode for high frequency signal is also travelling wave.

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(a)Wavelet analysis of the injected PD signal at Tap1-Tap2

(b)Wavelet analysis of the response signal at lv1-lv2(g) due to (a)

(c) Computed transfer function of (b) w.r.t (a)

Top- without wavelet; mid- low frequency; bot- high frequency

Note - “(b) delayed by 250 μ s compared to (a);

(a) starts at 0 and (b) starts at 300 μ s”

Fig. 5-9 Wavelet analysis of the responses at lv1-lv2 (g)
for the injected PD at Tap1-Tap2

5.5.3.2 Response at hv1-hv2(g)

The response time domain signal at hv1-hv2(g) shown in left hand side of Fig. 5-10(a) presents the phase inversion and distortion in tail time. The loaded injected signal with front time of 0.8 μ s gets lengthened in the response as 1.8 μ s and the original pulse width of 40 μ s gets extended to 600 μ s. The peak magnitude of 1.8 V is attenuated to 1.2 V. The high frequency time domain peak signal is 1/1.5th of low frequency peak signal. There is no starting delay and peak delay in time domain low and high frequency components with respect to injected PD. In frequency domain, the low frequency component shows the spectrum is distributed like a decaying exponential shape in the range of 10 kHz. In high frequency spectrum, the spectrum is distributed like a bell shape from 10 kHz to 800 kHz. The peak of high frequency FFT signal is about 1/25th of low frequency FFT signal.

The transfer function analysis shown in Fig. 5-10 (b) indicates that numbers of characteristic resonance peaks are obtained in the range 100 kHz to 1 MHz. An

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attempt is made to determine the transfer function of separated high and low frequency components to evaluate the propagation characteristics in that two ranges. The combined one shown in top of Fig. 5-10 (b) indicates four dominant clear peaks at 0.35 MHz, 0.61 MHz, 0.75 MHz and 0.9 MHz with a number of other less dominant frequency peaks. While the transfer function shown in mid. of Fig. 5-10 (b) shows about 2 peaks at 40 kHz and 80 kHz respectively. Zero time delay and transfer function value in the range of 15 predicts that the low frequency signal is coupled in capacitive mode with multiple series resonance across the high voltage winding. The transfer function shown in bot. of Fig. 5-10 (b) shows one dominant frequency peak at 89 kHz with value in the range 3. The starting delay and peak delay in time domain predicts that the high frequency component may have travelled in travelling wave mode of propagation. The attenuated high frequency signal without much distortion predicts the propagation mode for high frequency signal is also travelling wave.

(a) Wavelet analysis of the response signal at hv1-hv2(g) due to 5.9 (a)

(b) Computed transfer function of (c) w.r.t Fig. 5-9(a)

Top- without wavelet; mid- low frequency; bot- high frequency

Fig. 5-10 Wavelet analysis of the responses at hv1-hv2 (g) for the injected PD at Tap1-Tap2

5.6 Summary

Studies with PT confirm that the PD propagation will be affected by a number of factors.

Loading - Table 5-1 lists the distortion introduced on the PD source due to the location of injected PD source in PT. The injected PD either at hv1-hv2 (g) or Tap1 – hv2 (g) does not get distorted much. When injected across one turn at Tap1-Tap2, the distortion is more in time plane. No oscillatory changes are observed. It shows that if the impedance is low, PD source signal gets distorted due to loading.

Identification of propagation modes using transfer function analysis - In section 5.4, the obtained experimental results of section 5.3 are analysed to identify the PD propagation modes. For that, PD propagation is studied by injecting PD in 3 ways. In the first way, PD is injected at hv1-hv2(g) and the simultaneous responses are measured at lv1-lv2(g) and lv3-lv4(g). Transfer function analysis indicates the presence of two characteristic frequency peaks at 14 MHz and 98 MHz for lv1-lv2(g), and 14 MHz and 78 MHz for lv3-lv4(g). No time delay at starting and peak delay of

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34 ns in Fig. 5-1 shows that the propagation mode is capacitive coupling with resonance due to LV winding.

When PD is injected at Tap1- hv2(g), the measured responses at LV windings show in Fig. 5-5 the existence of two characteristic frequencies at 13.6 MHz and 90 MHz for lv1-lv2(g) and 10 MHz and 90 MHz for lv3-lv4(g). No time delays at starting and peak occurrence in Fig. 5-2 predict the propagation modes as capacitive coupling combined with resonance due to LV winding.

When PD is injected at Tap1- Tap2, the measured response at LV winding in Fig. 5-6 is attenuated with almost uniform response independent of frequency. Definite time delay and the retention of wave shape in Fig. 5-3 show that PD propagation is by the transmission line mode. The measured response at hv1-hv2 (g) in Fig. 5-6 displays the existence of one characteristic frequency at 0.13 MHz. No time delay and pulse stretching in Fig. 5-3 characterize this PD propagation as capacitive coupling coupled with free oscillation of 0.13 MHz due to high inductance of HV winding.

Identification of propagation modes using wavelet analysis - Wavelet analysis is able to separate the content of injected and measured responses in two frequency domains. Using wavelet, they are split into two frequency domains in time plane. A new method is developed to determine the transfer function of each frequency component with a view of identifying the propagation characteristics of low and high frequency components. Since identical responses are obtained at lv1-lv2(g) and lv3-lv4(g) in all the studied cases, description is restricted to one of the LV windings.

In the first way, it is analysed by injecting PD at hv1-hv2(g) and measuring the responses at lv1-lv2(g). Wavelet analysis in Fig. 5-7(c) with the responses before split shows the presence of two characteristic frequency peaks at 2 MHz and 8.1 MHz for lv1-lv2(g). The transfer function analysis with the low frequency component shows the existence of 4 peaks at 2 MHz, 4.5 MHz, 6 MHz and 10 MHz respectively. No delay in time domain and the responses in the range of 1 show that the low frequency signal is capacitively coupled with free oscillation of 4 characteristic frequencies across lv1-lv2(g). The transfer function analysis with the high frequency component in bottom of Fig. 5-7 (c) shows a number of resonance peaks of magnitude less than 1. The starting and peak delays in time domain show that the

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high frequency components have travelled in travelling wave mode of propagation. Wavelet analysis shows that PD propagated to lv1- lv2 (g) in many paths resulting many free oscillation frequencies.

In the second way, it is analysed by injecting PD at Tap1- hv2(g) and measuring the responses at lv1-lv2(g). The combined one shown in top of Fig. 5-8 (c) shows two dominant clear peaks at 9 MHz and 75 MHz with a number of other high frequency peaks. While the transfer function with low frequency component shown in middle of Fig. 5-8 (c) shows 4 clear peaks at 3 MHz, 4 MHz, 5 MHz and 10.2 MHz respectively. Starting and peak delays in time domain oscillatory low frequency component responses, and transfer function value in the range of 1 are the features of transmission line mode of propagation coupled with free oscillation of 4 characteristic resonance responses due to low voltage winding. The transfer function of high frequency component shown in bottom of Fig. 5-8 (c) shows a number of resonance peaks of magnitude greater than 1. The starting delay and peak delay in time domain of the high frequency component indicate the travelling wave mode of propagation. The pulse stretching in high frequency time domain signal and a number of high frequency resonance peaks show the existence of other types of space harmonics magnetic coupling. This shows that PD propagates to lv1-lv2(g) in many paths.

In the third way, it is analysed by injecting PD at Tap1-Tap2 and measuring the responses at lv1-lv2(g) and hv1-hv2(g). The combined response at lv1-lv2(g) shown in top of Fig. 5-9 (c) shows one dominant clear peak at 0.78 MHz with a number of other less dominant frequency peaks. While the transfer function with the low frequency component shown in middle of Fig. 5-9 (c) shows 3 dominant peaks at 2.5 kHz, 37 kHz, and 74 kHz respectively. Starting and peak delays in time domain double exponential responses and transfer function value in the range of less than 1 show that the low frequency component signal to lv1-lv2(g) is coupled in transmission line mode resulting with distortion of 3 characteristic frequency contents due to free oscillation. The transfer function with the high frequency component shown in bottom of Fig. 5-9 (c) shows two dominant frequency peaks at 89 kHz and 0.7 MHz with transfer function value in the range 0.15. The starting delay, peak delay and retention of waveshape in time domain show that the high frequency component travelled in travelling wave mode of propagation.

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The combined one for response at hv1-hv2(g) shown in top of Fig. 5-10 (b) shows four dominant peaks at 0.35 MHz, 0.61 MHz, 0.75 MHz and 0.9 MHz with a number of other less dominant frequency peaks. While the transfer function for low frequency component shown in middle of Fig. 5-10 (b) shows about 2 peaks at 40 kHz and 80 kHz respectively. Zero time delay and transfer function value in the range of 15 show that the low frequency component of signal is coupled in capacitive mode with multiple series resonances across the high voltage winding due to free oscillation. The transfer function for high frequency component shown in bottom of Fig. 5-10 (b) shows one dominant frequency peak at 89 kHz with value in the range 3. The starting delay, peak delay and retention of response waveshape in high frequency component of time domain signal show that the high frequency component is transmitted in travelling wave mode of propagation.

Based on the experiments performed and the current limitation of the test equipment, it can be concluded that more simple laboratory models are to be built to identify each propagation mode especially connected with space harmonics and free oscillation, and to verify the accuracy of wavelet and transfer function analyses in various frequency ranges.

CHAPTER 6

Measured responses and analysis on power network

6.1 Introduction

This chapter presents the measured on-line and off-line PD responses from 250 MVA generator power network consisting of generator, busbar and HV step-up transformer. On-line PD propagation measurement is done simultaneously from an operating generator at 4 terminals of available 6 terminals. In off-line measurement, 10 terminals are available for PD propagation study for PD injection and measurement. The simultaneously injected and response signals are recorded to identify the propagation modes from origin to the measuring nodes in off-line mode. To identify the characteristic transmitted frequencies at the measuring nodes analyses are done using the time mode signal and by the transfer function and wavelet analysis.

6.2 Experiments

When the generator was operating, on-line time domain measurement was done. Randomly occurring single PD pulse behaviour was simultaneously recorded at 4 nodes and analysed. Off-line measurement was done on isolated power network consisting of generator, busbar and HV step-up transformer. In section 3.7, the details on the measuring layout of operating generator are presented. For the convenience, the Fig. 3-10 is put again in this chapter.

Fig. 3-10 The terminals layout of G connected to power network

6.2.1 On-line data

Typical simultaneously recorded PD signals in 1.6 ms window at 4 terminals A, B, E and F are shown in Fig. 6-1. Two simultaneously occurring PD pulses with different magnitudes at 4 terminals are recorded. From the above, it is more likely that PD may have originated near to E and it is attenuated when travelling to F. There is simultaneous cross coupling at A and B with a reduced magnitude. It clearly suggests that PD at F and B are attenuated in relation to E and A respectively. The cross-coupled peak PD signals at A and B is less than signal at E and F. The peak to peak amplitudes of 2 PDs are 3.1 V and 2.6 V respectively at E. The corresponding attenuated peak amplitudes at F are 1.5 V and 1.34 V respectively. The cross-coupled two peak amplitudes at A and B are 1.34 V and 1.28 V, and 0.62 V and 0.52 V respectively. From the above time domain responses, one can understand the attenuation of PD to travel from E to F. There is some significant cross-coupling in other phases for this data.

Fig. 6-1 Simultaneously recorded signals at E, F, A and B in 1.6 ms interval

6.2.2 Off-line data

When the generator is not energized during the maintenance cycle, off-line measurement is carried out in 2 separate tests. In test 1, the grounding resistor at N is removed. PD from mercury-switch impulse 2 described in section 3.2.1 is injected at N with respect to grounded terminal of grounding resistor. The PD peak voltage level is raised from 15 V to 25 V to get responses at all the measured nodes. The simultaneous response signals at E and F of coupling capacitors are

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recorded with reference to ground. In test 2, a direct connection at the HV terminal of generator winding of R Φ is made and PD is injected at I. The simultaneous response signals at E, F, N, A, B, C and D are recorded with reference to ground.

6.2.2.1 Test 1 – Injection of PD at N – Responses at E and F

The injected impulse peak voltage of 25 V with t_f of 120 ns and t_t of 800 ns at N and the measured responses at E and F are shown in Fig. 6-2. The responses are oscillatory. The measured peak responses at E and F are attenuated by 69 and 62 times respectively. It indicates that most of the signal is dissipated in the generator windings. The attenuation along the busbar is not much. Peak delay at E and F are 430 ns and 960 ns respectively. Starting delay at E and F are 300 ns and 350 ns respectively. Both delays suggest that PD is propagated in transmission line mode. Pulse width at E and F are increased to 3700 ns and 2730 ns respectively.

Fig. 6-2 Measured time domain responses at E and F for the injected PD at N (magnitude of R phase response is shown magnified by 50 times)

6.2.2.2 Test 2 – Injection of PD at I

In test 2, PD is injected at I and the responses are measured at E and F, or A and B, or C and D or N. Significant increase in peak magnitudes at E and F are observed in comparison to Test1.

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6.2.2.2.1 Responses at E and F

The measured responses at E and F shown in Fig. 6-3 are oscillatory. The measured response at E has oscillation to a significant period of 3700 ns and at F, it is only 2710 ns. The measured peak responses at E and F are attenuated by 31 and 14 times of injected PD respectively. Peak delay at E and F are 80 ns and 35 ns respectively. Starting delay at E and F are same as 290 ns. Reduced delays suggest that PD propagates in capacitive mode to E and F from I with inductive-capacitive resonances at those nodes.

Fig. 6-3 Measured time domain responses at E and F for the injected PD at I
(magnitude of R phase response is shown magnified by 50 times)

6.2.2.2.2 Response at N

For the injected PD at I, the oscillatory response shown in Fig. 6-4 is observed at N. The pulse width at N is increased to 4000 ns. Attenuation is more in the range of 210. There is no starting delay. It suggests that the fast rising signal is capacitively coupled and resonated to give oscillatory output.

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Fig. 6-4 Measured time domain responses at N for the injected PD at I (magnitude of N terminal response is shown magnified by 200 times)

6.2.2.2.3 Responses at A and B, and C and D

The measured responses at A & B , and C & D are shown in left hand side and right hand side of Fig. 6-5 respectively. The measured responses at all the terminals have oscillation to a significant period of 3700 ns. The measured peak responses vary from 0.34 to 0.55 V. The starting delay varies from 250 ns to 300 ns. The peak delay varies from 80 ns to 130 ns. Reduced delay and reduced peak magnitude suggest that PD is propagated both in capacitive and magnetic coupling modes.

Fig. 6-5 Measured time domain responses at A, B, C and D for the injected PD at I

6.3 Analysis

The analysis is carried out both on and off-line data. The on-line data are analysed

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with an objective of characterizing the randomly occurring individual PD pulses at E and F. While the off-line data is analysed with reference to injected PD at the different measuring nodes.

6.3.1 Using on-line data

In on-line measurement, the occurrence of PD is random. Since the objective of research is in identifying the PD propagation modes, the relative simultaneous characteristics of responses at E and F are statistically analysed. The analysis is done both in time and frequency domains after extracting the simultaneously occurring single PD responses.

6.3.1.1 Time domain analysis

The extracted single PD is a decaying oscillatory response with time at E and F as shown in Fig. 6-6. The pulse width is around 1500 ns.

Fig. 6-6 Simultaneously recorded single PD pulse (17th in Fig. 6-7) at E (top) and F (bot)

Since the occurrence of PD is a random phenomenon, 20 samples of data are analyzed to understand the statistical nature of its individual PD characteristics. 20 samples of random occurring single pulse data from recorded frames are extracted. In all the recorded traces, simultaneous occurrence of PD with some delay is observed at E and F. The time domain peak response at E is more than F response. Since it is oscillatory, both positive and negative peaks are taken into account to extract the feature of single

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PD. Time ordered analysis did not show any logical variation with time. The sorted positive peak magnitude of individual PD at E with the corresponding positive peak magnitude at F and respective negative peak magnitudes at E and F are plotted in Fig. 6-7. The absolute magnitude of the peak varies from 0.25 V to 2.2 V at E and the corresponding magnitude of the peak at F varies from 0.25 V to 0.9 V.

Fig. 6-7 +ve and -ve peak magnitudes at E and F (Sorted w.r.t. E terminal +ve peak on 20 PD pulses)

Using the peak occurrence time as time delay indicator, it is found that in 17 cases, peak at F is found to occur with a delay in comparison peak at E as shown in Fig. 6-8. The sorted pulse sequence in Fig. 6-7 is kept the same for Fig. 6-8. This time delay varies from 10 ns to 380 ns and its delay depends on original waveshape of PD at origin and associated distortion in waveshape of single pulse to reach E.. The duration of the single PD pulse varies from 1.5 μ s to 3.2 μ s.

Fig. 6-8 The time delay of peak occurrence at E & F terminals for 20 single PDs

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The observation on the time domain responses indicates that peak response at E is greater than the peak response at F in all the 20 cases. In most of the cases, single PD at F occurs with some delay with reference to E occurrence. The PD transfer mode is in the transmission line mode.

6.3.1.2 Frequency domain analysis

For the on-line data, the frequency content of each individual single PD is analyzed using PSD analysis. For the time domain data in Fig. 6-6, the determined frequency content for the signals at E and F are shown in Fig. 6-9. Resonant frequencies of 7.9 MHz and 25 MHz at E, and 25 MHz at F occur. The power spectral magnitude at F terminal is comparatively less.

Fig. 6-9 Frequency response of the simultaneously recorded single PD pulse (17th in Fig. 6-7) at E (top) and F (bot)

A statistical evaluation of the distribution of the resonant frequencies is made for the 20-sorted pulses. The plot in Fig. 6-10 shows the distribution of resonant frequencies at E and F. More high frequency resonant peaks upto 30 MHz are observed at F. The characteristic observed resonance frequencies at E are 3.9, 8 and 15 MHz. At F, observed resonant frequencies are 3.5, 5, 20 and 25 MHz. There are more resonance frequencies in F than in E. It suggests that PD undergoes more reflection before propagating to F than to E.

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Fig. 6-10 Calculated resonant frequencies at E and F

6.3.2 Using off-line data

Since the simultaneous injected PD and responses are recorded, transfer function and wavelet analysis are done to identify the injected PD propagation modes from injected node to measuring node.

6.3.2.1 Transfer function analysis

The injected exponential time domain PD signal gets attenuated at the measuring nodes and modulated with the characteristic decaying resonance frequencies. The transfer function analysis identifies those resonance frequencies.

6.3.2.1.1 Test 1 – Injection of PD at N

This analysis as described in section 5.4 is carried out. PD is injected at N and the responses are measured at E and F. The calculated transfer function shown in Fig. 6-11 is found to have resonant frequencies of 3.3 MHz and 8.4 MHz for the PD propagated from N to E while for the PD propagated from N to F, it occurs only at 3.3 MHz. Transfer function at F is significantly increased at 3.3 MHz due to resonance in busbar/transformer surge impedances. The same resonance frequency of 3.3 MHz at E and F suggest the propagation mode is transmission line mode. It seems that busbar filters out 8.4 MHz signal generated at E.

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Fig. 6-11 Calculated transfer function responses at E and F for the injected PD at N

6.3.2.1.2 Test 2 – Injection of PD at I

PD is injected at I and the responses are measured at E and F. The calculated transfer function shown in Fig. 6-12 is found to have resonant frequencies of 4.1 MHz, 7.7 MHz and 8.2 MHz for the PD propagated from I to E while for the PD propagated from I to F, it occurs only at 3.3 MHz, 7.7 MHz, 8.2 MHz and 10.3 MHz. PSD ratios at F are either equal or more than at E. The observed common characteristic frequencies at E and F are 7.7 MHz and 8.2 MHz. 4.1 MHz at E gets shifted to 3.3 MHz at F. An additional peak at F is observed around 10.3 MHz. The existence of different multi resonance frequencies at E and F suggest the propagation mode is different from transmission line mode.

Fig. 6-12 Calculated transfer function responses at E and F for the injected PD at I

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PD is injected at I and the response at N also is measured. The calculated transfer function shown in Fig. 6-13 is found to have resonant frequencies of 5.1 MHz and 9.2 MHz. PSD ratios are comparatively very low indicating this path as a very high impedance one. Most of the signal is transmitted through busbar.

Fig. 6-13 Calculated transfer function responses at N for the injected PD at I

Grounding of N does not alter the responses at A, B, C and D. With a view to evaluate the cross-coupling from $R\Phi$ to $B\Phi$ and $Y\Phi$, this analysis is taken. PD is injected at I with grounded N and the responses are measured at A, B, C and D. The calculated transfer function with reference to injected PD is shown in Fig. 6-14. The maximum ratio of transfer function reduces from 1.6 at 4.1 MHz of E to 0.5 at 4.3 MHz of D. It indicates that there can be cross-coupling in the range of 1/3. In addition the peak responses are more at transformer ends B and D than at generator ends A and C. The observed characteristic frequencies at A, C and D are 4.3 MHz, 7.6 MHz and 8.4 MHz. This change only at B as 3.3 MHz and 8 MHz. Similar characteristic frequencies as in E and F are observed with a reduced magnitude indicating the coupling between phases is capacitive and magnetic.

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Fig. 6-14 Calculated transfer function responses at A, B, C and D For the injected PD at I

6.3.2.2 Wavelet analysis

Wavelet analysis is a better analysis than transfer function method because it can give the variation of decomposed frequency components in time plane. Transfer function analysis can show the dominant response only. In our analysis, all low frequency components are grouped as low frequency signal and the hidden variation of high frequency component with time is extracted as high frequency signal. Mother wavelet db3 is used with 12 levels of decomposition.

6.3.2.2.1 Test 1 – Injection of PD at N

As an initial step, the injected PD components are extracted as shown in Fig. 6-15 (a). left hand side of figure shows the decomposed signals in time plane. It indicates the presence of high frequency peaks in time plane in the range of 1/3rd of original peak signal. FFT analysis shown in right hand side suggests that low frequency bandwidth is up to 3 MHz and the high frequency bandwidth is up to 12 MHz with peak ratio of 12% of low frequency signal.

The measured responses at E and F are analysed as shown in Figs. 6-15 (b) and (c) respectively. The decomposed time domain signals in Fig. 6-15 (b) show that oscillatory peak magnitudes of high frequency signal is more than low frequency signal. The calculated FFT for E shows the characteristic low frequencies are 0.1 MHz and 0.5 MHz for the exponential input. While high frequency characteristic frequencies are 2.5 MHz and 9 MHz. The highest peak FFT magnitudes of low and high frequency spectrums are more or less same. Very similar responses are observed

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at F. The observed changes in FFT of low frequency spectrum at F are 1 MHz in addition to other peaks.

The calculated transfer function with reference to injected PD and its decomposed signals shown in Fig. 6-15 (a) and decomposed responses at E and F are shown in Fig. 6-15 (d). Top Fig. of Fig. 6-15(d) shows the characteristic frequencies as 3.3 MHz and 8.4 MHz with FFT analysis at both E and F. Same results are obtained with transfer function analysis shown in Fig. 6-11. The low frequency component analysis at E and F show similar characteristic frequencies at 3 MHz, 7 MHz and 9 MHz. While high frequency components at E are also at 3 MHz, 7 MHz and 9 MHz. At F, 7 MHz is not reflected in the high frequency analysis.

The time domain observation with low frequency component shows that there is delay in peak occurrence between injected, and E and F responses. Their response magnitude also reduces significantly. With the high frequency component, the starting delay is clearly observed at E and more delay is seen at F. Less distortion between E and F suggest that the propagation is transmission line mode from E to F. While from N to E also, it is in transmission line mode for high frequency component with higher attenuation. While attenuated low frequency component responses with few characteristic frequencies suggest that the PD propagation is a combination of transmission line mode and some magnetic coupling resulting in some resonance frequencies.

(a) Injected PD

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(b) E terminal

(c) F terminal

(d) Wavelet transfer function

Fig. 6-15 Wavelet analysis of the decomposed signals at E and F for the injected PD at N

6.3.2.2.2 Test 2 – Injection of PD at I

The injected signal's decomposed signals appear to be same as Fig. 6-15(a) and it is not presented. The measured oscillatory decaying responses at E and F are analysed as shown in Figs. 6-16 (a) and (b) respectively. The decomposed time domain signal in (a) shows that oscillatory peak to peak magnitudes of high frequency signal is more than low frequency peak signal.

The calculated FFT for low frequency spectrum at E shows an exponential response to a bandwidth of 2 MHz. While at high frequency spectrum, observed characteristic frequencies are 2.2 MHz and 9 MHz. The low frequency highest peak FFT magnitude is about 5 times more than high frequency peak response magnitude. Increased amplitude of peak responses of low and high frequency signals at F are noticed but the pattern is the same.

The calculated transfer function with reference to injected PD and its decomposed signals are shown in Figs. 6-16 (c) for E and F responses. Before decomposing, it shows the characteristic frequencies as 4.1 MHz and 8 MHz with FFT analysis at E. At F, in addition to the above, characteristic resonance at 10.5 MHz is observed. Same results are obtained with transfer function analysis shown in Fig. 6-12. A flat response is obtained with the low frequency component analysis at E and F. Similar flat response is obtained with the high frequency component analysis at E. High frequency components at F have the characteristic frequencies at 3 MHz, 7 MHz and 9 MHz.

No starting delays with the low and high frequency components suggest that the coupling is capacitive. The peak delay is observed with decomposed high frequency signal. The shape of low and high frequency responses of the decomposed signal remain the same as the injected signal. Hence PD travelled to E and F in transmission line mode after attenuated by the capacitive coupling.

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(a) E terminal

(b) F terminal

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(c) Wavelet transfer function

Fig. 6-16 Wavelet analysis of the decomposed signals at E and F for the injected PD at I

Next the measured response at N is analysed. The injected signal’s decomposed signals appear to be same as Fig. 6-15(a) and it is not presented. The measured oscillatory decaying response at N is attenuated more and it is decomposed as shown in Figs. 6-17 (a). The decomposed time domain signal in (a) shows that oscillatory peak to peak magnitudes of high frequency signal is more than low frequency peak signal.

The calculated FFT for response at N shows a characteristic resonance frequency at 5 MHz and 10 MHz. The low frequency spectrum is an exponentially decaying response to a bandwidth of 2 MHz. While high frequency characteristic frequencies are 3 MHz and 9 MHz. The low frequency highest peak FFT magnitude is about 4 times more than high frequency peak response magnitude.

The calculated transfer function with reference to injected PD and its decomposed signals shown in Fig. 6-15 (a) and decomposed responses are shown in Fig. 6-17 (b). Top Fig. of 6-17(b) show the characteristic frequencies as 5.1 MHz and 9.3 MHz with FFT analysis at N. Same results are obtained with transfer function analysis shown in Fig. 6- 13. A flat response is obtained with the low frequency component analysis at N. High frequency components at N have the characteristic frequency at 6.8 MHz only.

No starting delays with the low and high frequency components suggest that the coupling is capacitive. The shape of low frequency response is retained with peak delay. While the high frequency component is distorted by reflections and resonances.

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Hence PD travelled from I to N by some capacitive coupling. Then attenuated low frequency component travelled in transmission line mode while attenuated high frequency component is gone through reflections and resonances to get distorted.

(a) N terminal

(b) Wavelet transfer function

Fig. 6-17 Wavelet analysis of the decomposed signals at N for the injected PD at I

6.4 Summary

This chapter reports about the possible PD propagation modes from on-line and off-line measurements on 250 MVA rated generator connected to busbar and 16 kV/220 kV rated HV transformer.

On-line single PD responses suggest that single PD is always a decaying oscillatory signal at both E and F and the pulse width varies from 1.5 μ s to 3.2 μ s. The peak to peak magnitude at E is always more than the magnitude at F. The peak time delay varies from 10 ns to 380 ns. The recorded peak to peak PD voltage across 1 M Ω resistor in series with 80 pF capacitor varies from 0.5 V to 3.2 V. It suggests that PD is travelled in transmission line mode to E and F from PD origin sites in generator.

In off-line data analysis, transfer function analysis can be done as the source wave shape is known. Off-line double exponential PD injection of peak magnitude of 25 V at I is attenuated to about 0.8 V peak at E and 1.7 V peak at F. The response signal is always a decaying oscillatory signal. The original pulse width of 1900 ns is increased to 3700 ns at E and it changes to 2710 ns at F. Starting delay with reference to injected PD origin at E and F is same as 290 ns. While peak delay at E and F with reference to injected peak is 80 ns and 35 ns respectively. Reduced peak delay suggests that PD propagates from I to E and F capacitively. Attenuation at E and magnification at F is due to change in surge impedances of the respective nodes. The characteristic frequencies in Fig. 6-12 suggest the existence of resonances in the path. The propagation mode is capacitively coupled to E and F from I with inductive-capacitive resonances at those nodes. Measured response at N is attenuated more due to generator winding layout and there is no starting delay. The fast rising signal in Fig. 6-4 is capacitively coupled and resonated to give oscillatory output. Cross-coupled responses at A,B, C and D in section 6.2.2.2.3 suggests that reduced delay and reduced oscillatory peak magnitude is due to the PD propagation in capacitive and magnetic coupling modes. This shows that comparatively cross-coupling is low to other phases.

When injected from N as described in section 6.2.2.1, it is found that PD propagate in transmission line mode from N to E and F. But the occurrence of PD at N is rare.

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Transfer function analysis can show the dominant response only. Wavelet analysis can decompose low and high frequency components in time plane and the propagation study of weak high frequency signal can be evaluated.

The analysis in Fig. 6-16 shows that there is no starting delay with the low and high frequency components. The peak delay is observed with decomposed high frequency signal. The shape of low and high frequency responses of the decomposed signal remain the same as the injected signal. Hence PD travelled from I to E and F in transmission line mode after attenuated by the capacitive coupling. PD travelled from I to N by some capacitive coupling as per section 6.3.2.2.2. Then attenuated low frequency component was travelled in transmission line mode while attenuated high frequency component go through reflections and resonances to get distorted.

PD propagation from N to E and F as described in section 6.3.2.2.1 suggests that the propagation is a combination of transmission line mode and some magnetic coupling resulting in some resonance frequencies.

The two transmission modes can be identified by the use of wavelet analysis.

CHAPTER 7

Propagation model studies on 230 kV PT and 16 kV generator of power network

7.1 Introduction

This chapter presents the possible PD propagation models of potential transformer with 230 kV/ 110V rating, 1 Φ and generator of rating 250 MVA, 16.5 kV, 3 Φ connected to power network by matching the measured PD responses. Model study is an effective tool to vary the parameters and layout of power network/apparatus to identify the possible PD propagation path, to quantify the distortion in terms of parameters, to identify the possible location of PD origin and to predict the type of PD from the measured results and to understand the dynamic behavior of the complicated power apparatus.

7.2 Existing methods

Reported PD propagation models are summarized in section 2.5. Due to the limited time of research, development of PD propagation model is carried only on two major apparatus namely potential transformer with 230 kV/ 110V rating, 1 Φ and generator of rating 250 MVA, 16.5 kV, 3 Φ connected to power network. PT is a small insulation volume unit in comparison with generator. But the windings are closely packed. Chapter 5 identifies the possible propagation modes as capacitive coupling and transmission line mode for PT. While generator connected with power network is a very complicated network. Identified propagation modes for generator in chapter 6 are capacitive coupling, transmission line mode and magnetic coupling with resonance. A great number of transformer models have been proposed to date either by matching the laboratory measurements or by some simulation reasoning [22][103][104]. Following the transmission line theory on lightning, distributed network is proposed in many cases. Classical mathematical expressions also are derived for distributed network and predicted output is matched with the observations. In modern days, researchers use discrete lumped network model or

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known as parameter model valid for a definite frequency range and analyse using standard software packages like Simulink, PSpice, EMTP etc. In literature, the parameters are determined from the solution of complex field network analysis and by calculation using the physical layout data and construction details of the apparatus [4][5][22][103][104]. Very few experimental data are available about the high frequency behaviour of winding and insulation either as material property or as a machine.

In this thesis, with the limited number of components to represent in the processing software, equivalent circuits are developed to identify the propagation paths by matching the recorded responses. The initial guessing of the parameters is done using the available reported data and then they are optimized in term of minimizing the error to fit our simultaneous experimental observations at few nodes.

7.3 230 kV rated SF₆ filled PT

After releasing the SF₆ gas, this 3 winding PT is experimentally studied for PD propagation in off-line mode and the experimental results are reported in chapter 5. Since the windings are laid in concentric form, both distributed magnetic and capacitive coupling are taken into account. A simple transmission line model with feedback capacitors and inductors is found to fit the experimental results. The injected shape of PD is double exponential with a time front of 30 ns and tail time of 10 μ s.

7.3.1 Fitted model of PT for PD propagation

The available terminals for PD studies in PT are hv1,hv2, lv1,lv2,lv3,lv4, Tap1 and Tap2. Tap1 is located at 98.3% of hv1-hv2 winding. Fig. 7-1 shows the lumped parameter representation of PT and the fitted parameter values are listed below. The top 10 sections with $L_{pn} = 18\text{nH}$, $R_n=25\text{ m}\Omega$, $C_{pn}=1.2\text{ nF}$ and $C_{pn1}=20\text{ nF}$ represent 1/6 of 220 kV rated HV winding from 100% to 83.4%. The next serially connected 2 sections represent the HV winding from 83.4% to 50% of the winding. It is represented by $L_{p1}=1.8\text{nH}$, $R_{p1}=250\text{ m}\Omega$, $C_{p1}=0.12\text{ nF}$ and $C_{p2}=2\text{ nF}$. The last 3 sections of the HV winding represent from 50% to 0% of the winding. It is represented by $L_{p2}=80\text{ nH}$, $R_{p2}=250\text{ m}\Omega$, $C_{p3}=0.12\text{ nF}$ and

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$C_{p4} = 2 \text{ nF}$. The 110 V rated low voltage windings lv1 and lv2 and lv3 and lv4 are represented as separate 2 sections at the bottom of Fig. 7-1. They are represented by $L_s = 30 \text{ } \mu\text{H}$, $R_s = 50 \text{ m}\Omega$, $C_{ss} = 12 \text{ pF}$ and $C_{sg} = 40 \text{ pF}$. Coupling capacitors to represent capacitive coupling between HV winding to LV windings are used in the model. In this model, C_{pss2} of 21 pF couples 83.4% of HV winding to 50% of lv1-lv2 and lv3-lv4. C_{pss3} of 30 pF couples 66.8% of HV winding to 50% of lv1-lv2 and lv3-lv4. C_{pss1} of 415 pF couples 50% of HV winding to 50% of lv1-lv2 and lv3-lv4. C_{pss4} of 11 pF couples 33.3% of HV winding to 50% of lv1-lv2 and lv3-lv4. C_{pss5} of 1.5 pF couples 16.7% of HV winding to 50% of lv1-lv2 and lv3-lv4. In addition the coupling capacitor $C_{ss} = 415 \text{ pF}$ links the 50% of lv1-lv2 to 50% of lv3-lv4 windings. Magnetic coupling is provided in the form of mutual inductance between the windings. HV winding from 66.8% to 50% is coupled magnetically with $M = 41 \text{ nH}$ to 0 to 50% of lv1-lv2 winding. While HV winding from 50% to 33.3% is coupled magnetically with $M = 41 \text{ nH}$ to 0 to 50% of lv3-lv4 winding. In addition, magnetic coupling is provided between 50%-100% of lv1-lv2 to 50%-100% of lv3-lv4 through $M1$ of 31 nH. This model is entirely developed by me with scientific reasoning.

Fig. 7-1 Developed PT model with 3 windings

7.3.2 Predicted results with the model

Simulink [110] is a convenient tool to model the above and change the required parameters. The injected PD can be mathematically modeled as a double exponential wave and is injected at the desired location with reference to ground. There is no provision to inject PD across any two nodes in floating mode. Hence, the standard apparent charge model is used to represent the injected PD.

7.3.2.1 Predicted responses due to PD injection at hv1- hv2(g)

The recorded time domain responses at lv1-lv2(g) and lv3-lv4(g) for the injected PD at hv1-hv2(g) are shown in Fig. 5-1. The response at lv1-lv2(g) is plotted in Fig. 7-2 as a thick line along with the simulated output shown for comparison in

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thin line with the marker. A close match can be observed in time and frequency domains. Under steady state, a DC offset is obtained in the simulated output suggesting the need to improve low frequency coupling. In the frequency domain experimentally measured 2 characteristic frequencies 14 MHz and 98 MHz are matched as 14 MHz and 100 MHz respectively.

Fig. 7-2 Simulated and measured results at lv1- lv2(g) for the injected PD at hv1-hv2(g)

Fig. 7-3 Simulated and measured results at lv3- lv4(g) for the injected PD at hv1-hv2(g)

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The response at lv3-lv4(g) is plotted in Fig. 7-3 as a thick line along with the simulated output shown in thin line with the marker. A close match can be observed in time and frequency domains. Under steady state, a DC offset is obtained in the simulated output in this output also suggesting the need to improve low frequency coupling. In the frequency domain experimentally measured 2 characteristic frequencies 14 MHz and 78 MHz are matched as 14 MHz and 75 MHz respectively.

7.3.2.2 Predicted responses due to PD injection at Tap1- hv2(g)

The recorded time domain responses at lv1-lv2(g) and lv3-lv4(g) for the injected PD at Tap1-hv2(g) is shown in Fig. 5-2. The response at lv1-lv2(g) is replotted after correcting to the original level in Fig. 7-4 as a thick line along with the simulated output shown in thin line with the marker. A close match can be observed in time and frequency domains. Under steady state, a DC offset is obtained in the simulated output suggesting the need to improve low frequency coupling. In the frequency domain experimentally measured 2 characteristic frequencies 14 MHz and 90 MHz are matched as 10 MHz and 113 MHz respectively. The shift may be due to improper tuning of the parameter values.

Fig. 7-4 Simulated and measured results at lv1- lv2(g) for the injected PD at Tap1-hv2(g)

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For the measured response at lv3-lv4(g) the experimentally measured characteristic frequency lies at 90 MHz. In the matched response, it is around 94 MHz. The shift from lv1-lv2(g) response may be due to magnetic coupling from the HV winding of 50% to 33.3% section. The magnetic coupling for lv1-lv2(g) is from 66.8% to 50% of HV winding.

Fig. 7-5 Simulated and measured results at lv3- lv4(g) for the injected PD at Tap1-hv2(g)

7.3.2.3 Predicted PD responses with the location using the model

Model studies will be useful in predicting the characteristics of same PD when it occurs in different locations of HV winding. An attempt is made by injecting PD at 100% (hv1), 98.4% (Tap1), 83.3%, and 66.8% of the HV winding. The response is measured at lv1-lv2 (g). The model predicts the shift in characteristic frequency to 14 MHz, 10 MHz, 25.4 MHz and 25.4 MHz with location of PD. This is verified at 100% (hv1) and 98.4% (Tap1) locations of HV winding experimentally.

Fig. 7-6 Variation of predicted characteristic frequency with PD location

7.3.2.4 Predicted PD responses with PD wave shape using the model

Injected PD wave shape reported in chapter 5 is used for the simulation. For the experimental measured response at lv1-lv2(g) with the injected node as hv1, the peak is observed at 14 MHz. In the simulation, only the front time is changed to 80 ns to understand more about high frequency PD component and the response peak is found to shift to 9 MHz. This is shown in Fig. 7-7 (a). But when only the tail time is changed to 50 μ s in simulation by keeping the front at 30 ns, the peak is found to shift to 12 MHz and another peak at 9 MHz appears. This is shown in Fig. 7-7 (b). This supports that the propagation path is a function of frequency content of PD resulting the change in characteristic resonance frequency. Such experimental behaviour is observed in Fig. 6-10.

(a) Variation of the front time from 30 ns to 80 ns

(b) Variation of the tail time from 10 μ s to 50 μ s

Fig. 7-7 Variation of predicted characteristic frequency with PD wave shape

7.4 Summary of model studies on PT

It can be summarized that model studies can be effectively used to predict the responses at various nodes by varying the PD origin, PD location and PD wave shape. To arrive at this model with the possible PD propagation modes, the trial and error method may be the first starting point as many layouts with a range of parameters can be visualized and it may be improved more by using some automated optimization method on the parameter values. The procedure takes much longer time to optimize the fitting and the parameter values. Once this stage is reached, the method may be automated by optimization programs and by introducing some constraints on the parameters. The model layout and interconnection have to be researched a lot with good experimental observations. But the method suggests that the high frequency behaviour of PD propagation can be represented by models. Having made some progress in PT model, an attempt is made to develop the PD propagation model for generator connected to power network.

7.5 16 kV Generator connected to 220 kV power network

The off-line measurements are presented in chapter 6 and based on the above, a transmission line model is developed with three connected apparatus in series. Since the experimentally observed coupling between the phases is minimum, only single Φ PD propagation to two terminals from PD origin is modeled. The surge

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impedance of the respective apparatus is varied. No detailed distributed model for transformer is used as the main interest is to study the PD propagation from generator and to locate the origin of developing PDs in generator. Hence a lumped model termination is used for 16kV/220 kV rated HV transformer. The shape of the injected PD is double exponential with a front time of 120 ns and tail time of 800 ns. PSpice software is used to develop the model.

7.5.1 Fitted model of power network

The available terminals for off-line PD studies in power network are N, I, E and F. PD from PD source is injected either at N or I. The simultaneous responses are measured at E and F. Fig. 7-8 shows the distributed parameter representation of generator winding with 3 sections and the fitted parameter values are listed below. Each section consists of a serially connected model of slot component and overhang component. Since the interturn capacitance is minimum in slot section, it is represented by $L1=0.065 \mu\text{H}$, $R1= 80 \text{ m}\Omega$ and $C2 = 4.1 \text{ nF}$. The overhang will have interturn capacitance. That component is represented by $L1s=0.055 \mu\text{H}$, $R1 = 80 \text{ m}\Omega$, $C1= 0.75 \text{ nF}$ and $C2s= 3.8 \text{ nF}$. It is found that the coupling capacitor does not behave like an ideal capacitor for the injected PD and it is modeled as a series resonance circuit with $Cc= 80 \text{ pF}$, $Lc= 83 \mu\text{H}$ and $Rc= 90 \Omega$. The determined resonance frequency is around 2 MHz. The terminating measuring impedance at E and F is represented by a parallel combination of $Rm = 1\text{M}\Omega$ and $Cm= 25 \text{ pF}$. Since the busbar is kept in an aluminum enclosure, the coupling capacitor between sections of busbar is minimum. 25 m length bus bar is represented by 8 sections of $L2= 3 \mu\text{H}$, $R2= 300 \text{ m}\Omega$, $C3= 33.3 \text{ pF}$, $Ri = 100\text{M}\Omega$. The terminating HV transformer at the bus bar end is represented by a parallel combination of $C4= 5\text{nF}$, $L3= 450 \text{ nH}$ and $R3= 60 \text{ M}\Omega$.

Fig. 7-8 Developed model of generator, bus bar and transformer in power network

7.5.2 Predicted results with the model

PSpice [107] is a convenient tool to model the above and change the required parameters. The simulated PD has also like the experimentally used PD with time front of 120 ns and tail time of 800 ns. The same type of PD is used in sections 7.5.2.1 and 7.5.2.2.

It is injected at I and N with respect to ground and the simultaneous responses are measured at E and F terminals. More attention is paid on the matching of resonance measured frequencies with the developed model.

7.5.2.1 Predicted responses due to PD injection at N

The recorded time domain responses at E and F for the injected PD at N of generator is shown in Fig. 6-2. The responses at E and F are replotted after correcting to the original level in Fig. 7-9 as a thick line along with the simulated output shown in dotted line. A close match can be observed in time and frequency domains both in x and y axes. In the frequency domain experimentally measured

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2 characteristic frequencies 3.3 MHz and 8.4 MHz at E are matched as 3.2 MHz and 8.5 MHz respectively. While at F, experimentally measured characteristic frequency of 3.3 MHz is matched to 3.3 MHz.

Fig. 7-9 Simulated and measured time domain results at E and F for the injected PD at N

Fig. 7-10 Simulated and measured frequency domain results at E and F for the injected PD at N

7.5.2.2 Predicted responses due to PD injection at I

The same model used to predict the responses at E and F for the injected PD at N is used for PD injection at I. The recorded time domain responses at E and F for the injected PD at I of generator are shown in Fig. 6-3. The measured responses in frequency domain at E and F are replotted after normalizing in Fig. 7-11 as a

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thick line along with the simulated output shown in dotted line. A close match can be observed in frequency domain. In the frequency domain experimentally measured 3 characteristic frequencies 4.1 MHz, 7.8 MHz and 8.2 MHz at E are matched only at 4.1 MHz. While at F, experimentally measured 4 characteristic frequencies of 3.3 MHz, 7.8 MHz, 8.2 MHz, and 10.2 MHz are matched only at 3.3 MHz.

Fig. 7-11 Simulated and measured frequency domain results at E and F for the injected PD at I

After validating the model for predicting the responses at E and F for the injected PD at N and I, analysis is extended to predict the responses due to the injected PD from different locations.

7.5.2.3 Predicted PD responses with the location using the model

Model studies will be useful in predicting the PD responses by varying the injected location. Using the developed model, the effect of varying PD injected location is predicted. In the developed model, the generator winding is represented as 3 sections and the possible model nodes are located at 33%, 67% and 100% length of winding for PD injection. Fig. 7-12 shows the predicted responses by injecting PD at 33% and 68% of the generator winding and at transformer end of busbar. The characteristic frequency peak occurs around 4.1 MHz at E and 3.3 MHz at F for the injected PD at I. This shifts to 4 MHz and 4.7 MHz at E for the injected PD at 33% and 68% of the generator winding, and 4 MHz and 4 MHz at F for the injected PD

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at 33% and 68% of the generator winding respectively. There is an additional 6.2 MHz appears at F for PD injected at 68% of the generator winding. When PD is injected at busbar end located near transformer, PD characteristic response at E is found to shift to 220 kHz with PSD ratio of 1.5. The attenuation is small to travel along the busbar. While at F, the characteristic frequency occurs at 3.3 MHz with a PSD ratio of 1.8. It clearly indicates that the model can be used to predict the possible location of PD from the responses measured at E and F. Nearer node normally gives a high PSD ratio and high characteristic frequency.

(a) Predicted frequency responses at E

(b) Predicted frequency responses at F

Fig. 7-12 Variation of predicted characteristic frequency with PD location

7.5.2.4 Predicted PD responses with the wave shape using the model

For the injected PD at I with $t_f = 120\text{ns}$ and $t_i = 800\text{ns}$, it is found to give characteristic frequency 4.1 MHz at E and 3.3 MHz at F. Only time front is varied in simulation. By varying t_f to 10 ns and keeping $t_i = 800\text{ ns}$ (impulse1), and by keeping t_f as 120 ns and varying t_i to 5000 ns (impulse2), the predicted PD responses are shown in Fig. 7-13.

Fig. 7-13 Variation of predicted characteristic frequencies by changing t_f and t_i

At E, the characteristic frequency does not change by varying t_f and t_i except for the PSD ratios. At F, the additional characteristic frequency peak of 6.2 MHz appears for the change in t_f to 10 ns (impulse1).

7.6 Summary of model studies on generator of power network

It can be summarized that model studies can be effectively used to predict the time and frequency responses at various nodes by varying the PD origin, PD location and PD waveshape. To arrive at this model with the possible PD propagation modes, the trial and error method may be the first starting point as many layouts with a range of parameters can be visualized and it may be improved more by using some automated optimization method on the parameter values. Further experimental data may be needed to validate the developed model.

CHAPTER 8

Discussion, conclusion and recommendation

This chapter discusses the findings of this project in relation to other reported research work and presents the conclusion of this PD propagation studies on three apparatus. It recommends the possible future areas of research.

8.1 Discussion

The PD propagation study in ET, PT and G connected to power network show that the PD propagates in these electrical equipments in a very complicated path from origin to monitoring node. Surge transfer between HV and LV windings is studied extensively and it is concluded that a step voltage in HV winding can give rise to four voltage components in LV winding [16] [22] [103] [104]. The first component is due to capacitive coupling and the second component is due to the coupling of magnetic and electrostatic induction of space harmonics in HV winding. The third component is the free oscillation generated in the LV winding and the fourth component is due to magnetic induction process due to turns ratio. Many of the above coupling phenomena can be applied to PD propagation studies. In addition in a closely packed conductors system, PD propagation and coupling because of multiconductor transmission phenomena, cross-coupling between Φ s, PD energy dissipation in the resistance of conductors, reflection at the mismatched surge impedances and resonance in LC path distort the original PD to a different attenuated pulse of different waveshape. In addition the frequency response characteristics of PD coupler, connecting leads, instrumentation and signal processing methods can distort the PD pulse at the final display of PD activity. In this thesis, an investigation is made to identify the propagation modes of PD in ET and PT by injecting PD from a PD source in floating and one end grounded modes. This method is applied on a power station generator connected to bus bar and step-up transformer in off-line mode. On-line PD data are also characterized to identify PD propagation modes. Model studies reported in chapter 7 are done to emulate the experimental observations on PT and G connected to power network. The study indicated that PD propagated in different apparatus in different ways resulting in a very distorted and attenuated waveform at

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the measuring node. The reported traditional modeling used only transmission line model without the detailed information on the values of parameters. More defined simple geometrical models should be built in the laboratory and the distributed parameters must be evaluated both by theory and experiment. PD propagation in such geometry should be modeled incorporating all PD propagation modes. The simultaneous responses at multi-locations must be measured by injecting simulated floating mode PD of different waveshapes and rise time from different locations. Models to match input and output responses should be developed. After understanding the basic principles of propagation and coupling, this study may be extended to complicated real practical apparatus.

8.1.1 Studied power apparatus

ET - More details on it can be seen in section 3.4.1, section 3.5 and chapter 4. It is a 3 Φ star-star connected transformer with 6 windings, 10 terminals at the primary and 7 terminals at the secondary. Using this, loading effect of PD source, propagation studies by varying PD injected locations for a constant monitoring node, and by varying the monitored nodes for a constant PD injection node are made.

PT - More details on it can be seen in section 3.4.2, section 3.6 and chapter 5. It is a potential transformer with 3 windings. HV winding is rated for 230 kV with SF₆ insulation and two LV windings are rated for 110 V. It has 8 terminals. PD propagation from HV winding to LV windings is studied in floating and grounded modes.

G connected to power network - More details on it can be seen in section 3.4.3, section 3.7 and chapter 6. It is a 3 Φ generator with grounded neutral through resistor. In on-line measurement, available 6 terminals at the HV coupler are used. For off-line measurement, 10 terminals are available for PD propagation study. PD from PD source is injected with respect to ground.

8.1.2 Time domain analysis

Time domain analysis of the responses show the peak attenuation, distortion in injected exponential wave shape, delays at the start and peak.

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ET - Injected PD gets loaded by connecting to ET. PD peak attenuates to 5 times when injected at top and 25 times when injected at bot and mid in Fig. 3-5(b). Pulse width changes from 2.7 μs to 5 μs at top and 0.7 μs at mid and bot apart from wave shape distortion shown in Fig. 4-1. The response signals shown in Fig. 4-4 had exponential, oscillatory and exponential pulse with modulated decaying oscillation at the tail. Table 4-2 indicates that PD peak increases by 5 times at the same LV Φ . No delay is observed. In the same Φ of HV winding, the peak amplitude increases by 2.25 times, and peak and start delay with increased pulse duration are observed. For mid and bot locations, it is tabulated in Tables 4-4 and 4-6. By monitoring at C Φ -L2 tap, PD pulse width for top injection is 7200 ns, for mid injection is 16700 ns and for bot injection is 19000 ns. By injecting at c Φ -mid, measured PD pulse width A Φ , B Φ and C Φ , -L2 taps are almost same but reduced peak magnitude at A and B Φ s.

PT - Injected PD gets loaded when connected to Tap1 and Tap2. When injected at hv1-hv2(g), PD peak attenuates to 15 times at lv1-lv2(g) and pulse width reduces from 34000 ns to 8000 ns. The wave shape changes from exponential to decaying oscillatory signal.

G connected to power network - Injected PD at I does not load PD source but the injected PD magnitude is increased to 25 V to get good signal to noise ratio in the power station. The measured peak response attenuates by 31 times and 14 times respectively at E and F. The exponential pulse width of 1900 ns increases to 3700 ns at E and 2710 ns at F in Fig. 6-3. The wave shape changes from exponential to decaying oscillatory signal. There is starting delay of 290 ns at E and F. Peak delay at E and F are 80 ns and 35 ns respectively.

8.1.3 Frequency domain/ Transfer function analysis

Frequency domain analysis of the injected PD sources has the following bandwidth (BW) as shown in Figs. 3-2 and 3-4. UJT source's BW is about 5 MHz, mercury switch bandwidth is about 30 MHz and the commercial unit BW is about 1 MHz. The frequency responses can show the characteristic resonance frequencies.

ET - Very complicated frequency responses are obtained as shown in Figs. 4-5, 4-7 and 4-9. By monitoring at C Φ -L2 tap, the characteristic peak frequencies are 0.15 MHz, 0.25 MHz, 0.6 MHz and 1.55 MHz and trough frequencies are 0.2 MHz, 0.35

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MHz and 0.85 MHz for top injection. For mid injection, the characteristic peak frequencies are 0.45 MHz and 1.7 MHz and trough frequencies are 0.3 MHz, 1.2 MHz and 2.1 MHz. For bot injection, the characteristic peak frequencies are 0.45 MHz, 0.9 MHz and 1.4 MHz and trough frequencies are 0.3 MHz, 0.75 MHz, 1.3 MHz and 1.75 MHz. From both time and frequency domain responses, one can conclude that the measured response at C Φ -L2 tap for c Φ -top PD injection, the propagation mode is more capacitive coupling; for c Φ -mid PD injection, it will be inductive coupling with series resonance in the low frequency range to amplify the injected PD signal; and for c Φ -bot PD injection, it will be a combination of capacitive and inductive coupling. By injecting at c Φ -mid, the characteristic peak frequencies at C Φ - L2 tap are 0.45 MHz and 1.7 MHz and trough frequencies are 0.3 MHz, 1.2 MHz and 2.1 MHz and the characteristic peak frequencies at A Φ - L2 tap are 0.45 MHz and 1.1 MHz and trough frequencies are 0.2 MHz, 0.75 MHz and 1.35 MHz. From both time and frequency domain responses, one can conclude that the measured response at C Φ and A Φ -L2 taps for c Φ -mid PD injection, it will be inductive coupling with series resonance in the low frequency range to amplify the injected PD signal. Starting delay suggests that they travelled in transmission line mode to both C Φ and A Φ -L2 taps.

PT - Transfer function analysis for the injected PD at hv1-hv2(g) shows that the characteristic frequencies can be 14 MHz and 98 MHz at lv1-lv2(g) and 14 MHz and 78 MHz at lv3-lv4(g). If PD is injected at Tap1-hv2(g), this changes to 13.6 MHz and 90 MHz at lv1-lv2(g) and to 10 MHz and 90 MHz at lv3-lv4(g). From time and frequency domain analysis, one can conclude PD propagated to lv1-lv2(g) and lv3-lv4(g) by structure capacitive coupling and PD signal is distorted by resonance with LV winding inductance.

G connected to power network - Transfer function analysis for the injected PD at I w.r.t. ground shows that the characteristic frequencies are 4.1 MHz, 7.7 MHz and 8.2 MHz at E, while at F, it will be 3.3 MHz, 7.7 MHz, 8.2 MHz and 10.3 MHz. Injected PD at I does not load PD source but the injected PD magnitude is increased to 25 V to get good signal to noise ratio in the power station. The measured peak response attenuates by 31 times and 14 times respectively at E and F. The exponential pulse width of 1900 ns increases to 3700 ns at E and 2710 ns at F in Fig. 6-3. The

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wave shape changes from exponential to decaying oscillatory signal. There is starting delay of 290 ns at E and F. Peak delay at E and F are 80 ns and 35 ns respectively. Reduced delays suggest that PD propagated in capacitive mode to E and F from I with inductive –capacitive resonances at those nodes.

8.1.4 Wavelet analysis

The wavelet method can decompose PD signal into high and low frequency components. It is found that wavelet method is able to identify PD propagation mode on high frequency component more clearly.

ET - Chapter 4- section 4.6 presents the wavelet analysis. The response time domain signal at C ϕ -L2 tap for injected PD at c ϕ - bot shown in left hand side of Fig. 4- 13(c) shows the amplification of low frequency signal and it suggests the existence of the propagation mode of inductive coupling with series resonance in low frequency range. No delay at the starting time of low frequency signal suggests the existence of capacitive coupling on low frequency component as seen by the TF analysis. More delay time with minor distortion in high frequency component indicates that the propagation mode is transmission line. This suggests the existence of many propagation modes in low frequency component.

The response time domain signal at C ϕ -L2 tap for injected PD at c ϕ - top is shown in Fig. 4-14. The minimum time delay and oscillatory response shows that the low frequency component is capacitively coupled with LC resonance to get more high frequency peaks in low frequency range. Delay time with discrete amplified high frequency component indicates that the propagation in high frequency mode is transmission line coupled with minor resonance.

PT - Transfer function analysis for the injected PD at hv1-hv2(g) shows that the characteristic frequencies can be 14 MHz and 98 MHz at lv1-lv2(g) and 14 MHz and 78 MHz at lv3-lv4(g). If PD is injected at Tap1-hv2(g), this changes to 13.6 MHz and 90 MHz at lv1-lv2(g) and to 10 MHz and 90 MHz at lv3-lv4(g). From time and frequency domain analysis, one can conclude PD propagated to lv1-lv2(g) and lv3-lv4(g) by structure capacitive coupling and PD signal is distorted by resonance with LV winding inductance.

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The transfer function analysis shown in Fig. 5-7 (c) indicates that the characteristic resonance peaks can be obtained. An attempt is made to determine the transfer function of separated high and low frequency components to evaluate the propagation characteristics in that two ranges. The combined one shown in top of Fig. 5-7(c) indicates two dominant peaks at 2 MHz and 8.1 MHz. While the transfer function shown in mid. of Fig. 5-7 (c) shows about 4 peaks at 2 MHz, 4.5 MHz, 6 MHz and 10 MHz respectively. No delay in time domain and the responses in the range of 1 suggest that the low frequency signal is capacitively coupled with 4 characteristic series resonance responses across lv1-lv2(g). The transfer function shown in bot. of Fig. 5-7 (c) shows a number of resonance peaks of magnitude less than 1. The high frequency peaks are found to be sharp with high Q. The starting delay and peak delay in time domain suggests that the high frequency component travelled in travelling wave mode of propagation. This suggests that PD propagate to lv1-lv2 (g) in many paths.

G connected to power network - The calculated transfer function with reference to injected PD at I and its decomposed signals are shown in Figs. 6-16 (c) for E and F responses. Before decomposing, it shows the characteristic frequencies as 4.1 MHz and 8 MHz with FFT analysis at E. At F, in addition to the above, characteristic resonance at 10.5 MHz is observed. Same results are obtained with transfer function analysis shown in Fig. 6-12. A flat response is obtained with the low frequency component analysis at E and F. Similar flat response is obtained with the high frequency component analysis at E. High frequency components at F have the characteristic frequencies at 3 MHz, 7 MHz and 9 MHz.

No starting delays with the low and high frequency components suggest that the coupling is capacitive. The peak delay is observed with decomposed high frequency signal. The shape of low and high frequency responses of the decomposed signal remain the same as the injected signal. Hence PD travelled to E and F in transmission line mode after attenuated by the capacitive coupling.

From the above, we can conclude the discussion that PD will follow different propagation paths depending on the frequency content. Wavelet is a better tool to identify the propagation characteristics of fast and slow components of PD signal.

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Model studies indicate that the location of PD and the type of PD can be identified if proper models representing all the coupling and transmission modes are incorporated to match the experimental observations.

On-line studies indicate the existence of multi characteristic frequencies in operating G of power network.

8.2 Conclusion

In this limited 3 years research period, this research study explored the propagation of PD in generator and transformers by off-line and on-line measurements and model studies. The new contributions are listed below:

Addressed new issues or problems are the loading effect of PD source, PD propagation from injected winding to monitored winding with magnetic and capacitive couplings, use of wavelet, and model simulation for the analysis and matching time and frequency domain responses at multinodes.

Regarding the new model development, simulation model for PT is developed by taking into account magnetic and capacitive couplings on 3 windings. For the network of connected generator, busbar and transformer, a model is presented by taking into account for the generator slot and overhang windings.

The reported models in Chapter 7 are an improved version of the transmission line model. It considers the different equipments PD propagation characteristics and magnetic and capacitive coupling in a distributed network model with optimized parameters. The simulated results can achieve the good matching with the measured results in time and frequency planes by varying injection or measuring nodes. The developed model can be used to predict the responses by varying the PD occurring location, PD measuring location, PD source characteristics and connected type of equipments.

Many new methods are employed to understand PD propagation due to the limited number of reported publication on practical difficulties.

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In the experimental methods, injected PD was not applied with one end to the studied node and other end to system ground. Floating PD source was injected across one turn simulating the actual PD occurrence. Studies were done on 3 different types of apparatus windings by changing the injection location and measuring simultaneous responses at multi-nodes. Simultaneous on-line measurements of PD occurrence at many nodes were recorded to understand PD propagation.

In the analysis method, for the first time wavelet analysis of both time and frequency domain recordings were analysed by splitting low and high frequency components of input and output. Different PD propagation modes in the equipments were identified using the time domain responses (sections 4.4, 5.3, 6.2), wavelet analysis method (sections 4.6, 5.5, and 6.2.2), transfer function analysis using separated high frequency and low frequency components (sections 5.5.2, 5.5.3 and 6.3.2.2). The above type of combined analysis techniques provided the features to identify the different attenuated PD transmission line propagation modes with and without capacitive and inductive couplings, and resonances.

The new results are:

- (i) The PD propagation in the windings is not just only by one propagation mode.
- (ii) Again wavelet analysis shows that the high and low frequency components of the same PD may have different propagation modes in the winding.
- (iii) PD propagation in transformers and generators will distort the original PD waveshape. Different propagation modes were caused by the different frequency components of the generated / distorted travelling PD from injection to measuring nodes. Different coupling modes also can contribute cross coupling in different time domains and wavelet analysis can separate the different components.
- (iv) By modeling the PD propagation paths of different equipment, the reasonable location of PD source can be predicted as shown in sections 7.3.2 and 7.5.2. Application of PD propagation model with reported parameter values are my new contribution to predict the characteristics of PD of different waveshapes injected from different locations of winding.

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Short descriptions of the results are:

- PD propagation in transformers and generators takes place by different propagation modes. These were caused by the different equipment layout path between PD origin to the measuring node, different time and frequency resolved PD components.
- Different propagation modes were initiated by the different frequency components of the generated / distorted travelling PD and the propagation paths.
- Different coupling modes result in the following time domain or wavelet transmission behaviour.
- PD will be changed from the origin to the measuring node by the structure, propagation path, reflection, transmission, cross-coupling, resonances and absorption of the selected frequency band spectrum and propagation velocity.
- By modeling the components a reasonable location of PD source will be possible in complicated power network as shown in section 7.5.2.3.

8.3 Recommendations

As clearly reported that the PD propagation in transformer and generator is an interesting area of research and very complicated. The following research area may be explored further.

- (1) PD source model for loading can be researched. In addition the effect of PDs with very fast to slow rise and fall times on the PD propagation behavior can be investigated on the studied power apparatus.
- (2) The high frequency parameters of the tested apparatus may be determined by suitable technique to incorporate into the model.
- (3) Since the PD propagation behavior is very complicated, studies by taking simple geometry may be initiated to identify the factors controlling the propagation.
- (4) In model and experimental studies, the relation between floating and grounded PD sources should be investigated.
- (5) Further research is required to improve the quality and accuracy of the model to fit with the experimental observations. This linear model should be

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improved to non-linear model to cover PD frequency range. After the identification of layout, matching parameters should be determined by automated optimization programs. The possibility of locating PD using model studies and the characteristic frequencies should be investigated further.

- (6) Frequency dependent parameters may be introduced in the model to understand the responses and propagation.
- (7) PD location and PD wave shape in distorting the responses should be investigated by more experiments.
- (8) Different models should be developed for different frequency range to explain the different propagation modes observed in wavelet decomposition technique.

References

References

- [1] IEEE Std 1434-2000, IEEE Trial-use Guide to the Measurement of Partial Discharges in Rotating Machinery, 2000, pp. 8-24.
- [2] G. Stone, "Importance of bandwidth in PD measurement in operating motors and generators", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 7, No. 1, February 2000, pp. 6-11.
- [3] G. C. Stone, "Partial Discharge Part XXV: Calibration of PD Measurements for Motor and Generator Windings-Why it can't be done", IEEE Electrical Insulation Magazine, Vol. 14, No. 1, January/February 1998, pp. 9-12.
- [4] X. Dong, D. Zhu, C. Wang and K. Tan, "Simulation of transformer PD pulse propagation and monitoring for a 500kV substation", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 6, No. 6, December 1999, pp. 803-813.
- [5] Z. D. Wang, P. A. Crossley, K. J. Cornick, D. H. Zhu, "An algorithm for Partial Discharge location in distribution power transformers", Power Engineering Society Winter Meeting, 2000. IEEE, Vol. 3, 2000, pp. 2217-2222.
- [6] Z. D. Wang, D. H. Zhu, "Simulation on propagation of partial discharge pulses in transformer windings", Proceedings of 1998 International symposium on Electrical Insulating Material, in conjunction with 1998 Asian International Conference on Dielectrics and Electrical Insulation and the 30th Symposium on Electrical Insulating Materials, Toyohashi, Japan, Sept. 1998, pp. 643-646.
- [7] Z. D. Wang, P. A. Crossley, K. J. Cornick, "A simulation Model for propagation of Partial Discharge Pulses in Transformers", Proceedings of International Conference on Power System Technology, 1998, Vol. 1, 1998, pp. 151-155.
- [8] S. N. Hettiwatte, P. A. Crossley, Z. D. Wang, A. Darwin, G. Edwards, "Simulation of a transformer winding for partial discharge propagation studies", Power Engineering Society Winter Meeting, 2002. IEEE, Vol. 2, 2002, pp. 1394-1399.
- [9] H. J. van Breen, E. Gulski, J. J. Smit, H. F. A. Verhaat etc. "Standardization of On-line VHF PD Measurements on Turbo Generators", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 9, No. 1, February 2002. pp. 140-149.
- [10] J. W. Wood, H. G. Sedding, W. K. Hogg, I. J. Kemp, H. Zhu, "Partial discharges in HV machines; Initial consideration for a PD specification", Sixth International Conference on Dielectric Materials, Measurements and Applications, 1992, pp. 154 –157.

References

-
- [11] Q. Su, "Analysis of partial discharge pulse propagation along generator stator windings", Power Engineering Society Winter Meeting, 2000. IEEE, Vol. 1, 2000, pp. 269–272.
 - [12] G. C. Stone, P. Kantardziski, "Partial discharge testing of motor and generator windings: an absolute or a comparison test", Proceedings of 1998 International Symposium on Electrical Insulating Materials, 1998, pp. 63–66.
 - [13] A. J. M. Pemen, P. C. T. van der Laan, W. de Leeuw, "Analysis and localization of spurious partial discharge activity in generator units", 2001 IEEE 7th International Conference on solid Dielectrics, June 2001, Eindhoven, the Netherlands, pp. 489-492.
 - [14] C. Hudon, P. Guuinic, A. Audoli, "Investigation of partial discharge signal propagation, attenuation and pattern recognition in a stator winding", Conference Record of the 1996 IEEE International Symposium on Electrical Insulation, Vol. 1, pp. 201-205.
 - [15] J. T. Holböll, M. Henriksen, "Frequency dependent PD-pulse distortion in rotating machines", Conference Record of the 1996 IEEE International Symposium on Electrical Insulation, Vol. 1, 1996. pp. 192-196.
 - [16] J. Fuhr, M. Haessig, P. Boss, D. Tschudi, R. A. King, "Detection and Location of Internal Defects in the Insulation of Power Transformers", IEEE Trans. on Electrical Insulation, Vol. 28, No. 6, December 1993, pp. 1057-1067.
 - [17] M. Ekberg, etc. "Recent Results in HV Measurement Techniques", IEEE Trans. on Dielectrics and Electrical Insulation", Vol. 2, No. 5, October 1995, pp. 906-914.
 - [18] I. J. Kemp, H. Zhu, H. G. Sedding, J. W. Wood, W. K. Hogg, "Towards a new partial discharge calibration strategy based on the transfer function of machine stator windings", IEE Proceedings of Measurement and Technology, Vol. 143, No. 1, Jan.1996, pp. 57-62.
 - [19] X. Ma, C. zhou, I. J. Kemp, "Interpretation of Wavelet Analysis and Its Application in Partial Discharge Detection", IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 9, No. 3, June 2002, pp. 446-457.
 - [20] R. Bartnikas, "Partial Discharges Their Mechanism, Detection and Measurement", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 9, No.5, October 2002, pp. 763-808.
 - [21] G. G. Karady, M. R. Hernandez, F. Amarh and G. McCulla, "Improved Technique for fault detection sensitivity in transformer impulse test", IEEE Power Engineering Society Summer Meeting, Vol. 4, 2000, pp. 2412-2416.
 - [22] P. Chowdhuri, "Electromagnetic transients in power systems" (book), Research Studies Press Ltd., England, 1996, pp. 261-276.

References

-
- [23] S. M. Tetrault, G. C. Stone and H. G. Sedding, "Monitoring Partial Discharges on 4-kV Motor Windings", IEEE Trans. on Industry Applications, Vol. 35, No. 3, May/June 1999, pp. 682-688.
 - [24] G. Stone and J. Kapler, "Stator Winding Monitoring", IEEE Industry Applications Magazine, September/October 1998, pp. 15-20.
 - [25] B. A. Lioyd, S. R. Campbell and G. C. Stone, "Continuous on-line partial discharge monitoring of generator windings", IEEE Trans. on Energy Conversion, Vol. 14, No. 4, December 1999, pp. 1131-1138.
 - [26] A. Akbari, P. Werle, H. Borsi and E. Gockenbach, "Transfer Function-Based Partial Discharge Localization in Power Transformers: A Feasibility Study", IEEE Electrical Insulation Magazine, Vol. 18, No. 5, September/October 2002, pp. 22-32.
 - [27] A. Akbari, P. Werle, H. Borsi and E. Gockenbach, "A Continuous Parameter High frequency Model based on Travelling Waves for transformer Diagnostic Purposes", Conference Record of the 2002 IEEE International Symposium on Electrical insulation, Boston, USA, 7-10, April 2002, pp. 154-157.
 - [28] P. Werle, A. Akbari, H. Borsi and E. Gockenbach, "Partial Discharge Localizations on Power transformers using Neural Networks combined with Sectional Winding transfer Functions as Knowledge Base", Proceedings of 2001 International Symposium on Electrical Insulating Materials, Nov. 2001, pp. 579-582.
 - [29] M. Hajiaghajani, H. A. Toliyat and I. M. S. Panahi, "Advanced Fault Diagnosis of a DC Motor", IEEE Trans. on Energy Conversion, Vol. 19, No. 1, March 2004, pp. 60-65.
 - [30] A. Kheirmand, M. Leijon and S. M. Gubanski, "Advances in Online Monitoring and Localization of Partial Discharges in Large rotating Machines", IEEE Trans. on Energy Conversion, Vol. 19, No. 1, March 2004, pp. 53 -59.
 - [31] P. Werle, A. Akbari, H. Borsi, E. Gockenbach, "Enhanced online PD Evaluation on Power Transformers using Wavelet Techniques and Frequency Rejection Filter for Noise Suppression", Conference record of the 2002 IEEE International Symposium on Electrical Insulation, Boston, USA, 7-10, April 2002, pp. 195-198.
 - [32] A. Keyhari, H. Tsai and S. Sebo, "Modelling and Parameter Estimation of Power Transformers for the Study of High Frequency System Transients", Proceedings of the 32nd Midwest Symposium on Circuits and Systems, Aug. 1989, Vol. 1, pp. 258 – 264.
 - [33] A. Morched, L. Marti and J. Ottevangers, "A High Frequency Transformer Model for the EMTP", IEEE Trans. on Power Delivery, Vol. 8, No. 3, July 1993, pp. 1615-1625.
 - [34] S. A. Ryder, "Diagnosing Transformer Faults Using Frequency Response Analysis", IEEE Electrical Insulation Magazine, Vol. 19, No. 2, March/April 2003, pp. 16-22.

References

- [35] R. Kurrer, K. Feser, "The Application of Ultra-High-Frequency Partial Discharge Measurements to Gas-Insulated Substation", IEEE Trans on Power Delivery, Vol. 13, No. 3, July 1998, pp. 777-782.
- [36] T. Sakakibara, H. Murase, E. Haginomori, S. Wakabayashi, K. Emoto and A. Ogawa, "Study of Propagation Phenomena of Partial Discharge Pulses in Gas Insulated Substation", IEEE Trans. on Power Delivery, Vol. 13, No. 3, July 1998, pp. 768-776.
- [37] IEEE Std C57. 124-1991, IEEE Recommended Practice for the Detection of Partial Discharge and the Measurement of Apparent Charge in Dry-Type Transformers, 1991, pp. 5-15.
- [38] IEEE Std C57. 113-1991, IEEE Guide for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors, 1991, pp.35-40.
- [39] H. Imagawa, K. Emoto, H. Murase, H. Koyama, R. Tsuge, S. Maruyama and T. Sakakibara, "PD Signal Propagation Characteristics in GIS and Its Location System by Frequency Components Comparison", IEEE Trans. on Power Delivery, Vol. 16, No. 4, October 2001, pp. 564-570.
- [40] I. Shim, J. J. Soraghan and W. H. Siew, "Digital Signal Processing Applied to the Detection of Partial Discharge: An Overview", IEEE Electrical Insulation Magazine, Vol. 16, No. 3, May/June 2000, pp. 6-12.
- [41] B. Cogitore, J. P. Keradec and J. Barbaroux, "The Two-Winding Transformer: An experimental Method to Obtain a Wide frequency range Equivalent Circuit", IEEE Trans. on Instrumentation and Measurement, Vol. 43, No. 2, April 1994, pp. 364-371.
- [42] A. Oguz Soysal and A. Semlyen, "Practical Transfer Function Estimation and Its Application to Wide Frequency Range Representation of Transformers", IEEE Trans. on Power Delivery, Vol. 8, No. 3, July 1993, pp. 1627-1637.
- [43] X. D. Ma, C. Zhou and I. J. Kemp, "PD Pulse Propagation Studies using the Wavelet Transform", 2000 Conference on Electrical Insulation and Dielectric Phenomena, pp. 626-629.
- [44] P. Kang and D. Birtwhistle, "Condition Assessment of Power Transformer On-Load Tap-changers Using Wavelet Analysis", IEEE Trans. on Power Delivery, Vol. 16, No. 3, July 2001, pp.394-400.
- [45] O. Poisson, P. Rioual and M. Meunier, "New Signal Processing Tools Applied to Power Quality Analysis", IEEE Trans. on Power Delivery, Vol. 14, No. 2, April 1999, pp. 561-566.

References

-
- [46] G. C. STONE, "Practical Techniques for Measuring Partial Discharges in Operating Equipment", Proceedings of the 3rd International Conference on Properties and Application of Dielectric Materials, Tokyo, Japan, 8-12, July 1991, pp. 12-17.
 - [47] R. J. Van Brunt, E. W. Cernyar and P. von Glahn, "Importance of Unraveling Memory Propagation Effects in Interpreting Data on Partial Discharge Statistics", IEEE Trans. on Electrical Insulation, Vol. 28, No.6, December 1993, pp. 905-916.
 - [48] Z. Du, M. S. Mashikian and F. Palmieri, "Partial Discharge Propagation Model and Location Estimate", Conference Record of the 1994 IEEE International Symposium on Electrical Insulation, Pittsburgh, USA, 5-8, June 1994, pp. 99-102.
 - [49] A. J. M. Pemen, P. C. T. van der laan and P. T. M. Vaessen, "Partial Discharge Monitoring of Turbine Generators: Laboratory and Live Measurements", Conference on Electrical Insulation and Dielectric Phenomena, 1994. IEEE 1994 Annual Report, Oct. 1994, pp. 118 – 124.
 - [50] C. Zhou, I. J. Kemp and M. Allan, "The PD Pulse Behaviour in Rotating Machine Stator Windings", Conference on Electrical Insulation and Dielectric Phenomena, 1995. Annual Report, Oct. 1995. pp. 372 – 375.
 - [51] M. Kawada, Z. Kawasaki, K. Matsu-ura, A. Nishimura, H. Tokura and I. Okada, "Verification of the detection of Partial Discharges by Microwave", International Symposium on Electrical Insulating Materials, Sept. 1995, pp. 311 – 314.
 - [52] R. Meunier, G. H. Vaillancourt, "Propagation behaviour of acoustic partial discharge signals in oil-filled transformers", Conference record of the 12th International Conference on Conduction and Breakdown in Dielectric Liquids, Roma, Italy, July 1996, pp. 401-404.
 - [53] A. J. M. Pemen, P. C. T. van der laan, "Pitfalls of Partial Discharge Measurements on Stator Windings of Turbine Generators", Seventh International conference on Dielectric Materials Measurements & Applications, September 1996, pp. 394-397.
 - [54] A. O. Akumu, N. Kawaguchi, R. Ozaki, H. Ihori, M. Fujii and K. Arii, "A Study of Partial Discharge Acoustic Signal Propagation in a Model Transformer", Proceedings of 2001 International Symposium on Electrical Insulating Materials, Nov. 2001, pp. 583 – 586.
 - [55] W. Gao and K. Tan, "Effect of Pulse Propagation Characteristics in Power Transformer on Partial Discharge Recognition", Proceedings of 2001 International Symposium on Electrical Insulating Materials, Nov. 2001, pp. 817 – 820.

References

-
- [56] R. Ozaki, A. O. Akumu, H. Ihori, "Simulation of ultrasonic wave propagation of partial discharge in transformer model", Proceedings of 2001 International Symposium on Electrical Insulating Materials, Nov. 2001, pp. 880 – 883.
 - [57] S. N. Hettiwatte, Z. D. Wang, P. A. Crossley, A. Darwin, G. Edwards, "Experimental Investigation into the Propagation of Partial Discharge Pulses in Transformers", 2002 IEEE Power Engineering Society Winter Meeting, Jan. 2002, Vol. 2 , pp. 1372 - 1377.
 - [58] Q. Su, C. Chang and R. C. Tychsen, "Travelling Wave Propagation of Partial discharges Along Generator Stator Windings", Proceedings of the 5th International conference on Properties and Applications of Dielectric Materials, May 1997, pp. 1132-1135.
 - [59] B. Quak, F. J. Wester, E. Gulski, J. J. Smit and Paul N. Seitz, "Advanced Partial Discharge Site Location in Power Cables Using Numeric Data Processing", 2001 IEEE 7th International Conference on Solid Dielectrics, June 2001, Eindhoven, the Netherlands, pp. 416-419.
 - [60] R. Geary, I. J. Kemp, A. Wilson and J. W. Wood, "Towards Improved Calibration in the Measurement of Partial Discharges in Rotating Machinery", Conference Record of the 1990 IEEE International Symposium on Electrical Insulation, Toronto, Canada, June 1990, pp. 141-144.
 - [61] J. G. Jiang, D. H. Liu, H. Deng, H. X. Cao, Z. M. Zhao, "Propagation Mode and Speed of Partial Discharge Pulse through the Stator Windings of Turbine Generator", 2000 IEEE Power Engineering Society Winter Meeting, Vol. 1, Jan. 2000, pp. 192 – 196.
 - [62] D. Pommerenke and S. Sakaguchi, "Application of Maxwell Solvers to PD propagation – Part I: Concepts and codes", IEEE Electrical Insulation Magazine, September/October 2002, Vol. 18, No. 5, pp. 15-21.
 - [63] S. Sakaguchi and M. Oyama, "Application of Maxwell Solvers to PD Propagation-Part III: PD Propagation in GIS", IEEE Electrical Insulation Magazine, January/February 2003, Vol. 19, No. 1, pp. 6-12.
 - [64] P. C. J. M. van der Wielen, E. F. Steennis and P. A. A. F. Wouters, "Fundamental Aspects of Excitation and Propagation of On-line Partial Discharge Signals in three-phase Medium Voltage Cable Systems", IEEE Trans on Dielectrics and Electrical Insulation, Vol. 10, NO. 4, August 2003, pp. 678-688.
 - [65] A. Keyhani, H. Tsai and S. Sebo, "Modelling and Parameter Estimation of Power Transformers for the study of High Frequency System transients", Proceedings of the 32nd Midwest Symposium on Circuits and Systems, Vol. 1, Aug. 1989, pp. 258 – 264.
 - [66] P. T. M. Vaessen, "Transformer Model for High Frequencies", IEEE Trans. on Power Delivery, Vol. 3, No. 4, October 1988, pp. 1761-1768.

References

-
- [67] D. A. Tziouvaras, P. McLaren, G. Alexander, D. Dawson, J. Esztergalyos, C. Fromen, M. Glinkowski, I. Hasenwinkle, M. Kezunovic, L. Kojovic, B. Kotheimer, R. Kuffel, J. Nordstrom, S. Zocholl, "Mathematical Models for Current, Voltage, and Coupling Capacitor Voltage transformers", IEEE Trans. on Power Delivery, Vol. 15, No.1, January 2000, pp. 62-72.
 - [68] T. Funabashi, N. Takeuchi, T. Sugimoto, T. Ueda, L. Dube, A. Ametani, "Generator Modeling for Transformer Transfer Voltage Study", IEEE Trans. on Energy Conversion, Vol. 14, No. 4, December 1999, pp. 1193-1198.
 - [69] J. Pleite, E. Olias, A. Barrado, A. Lazaro, R. Vazquez, "Frequency Response Modeling for Advanced Maintenance techniques of transformers", Proceedings of the 2002 IEEE International Symposium on Industrial Electronics, 2002. Vol. 2, July 2002, pp. 524-528.
 - [70] Y. Shibuya, S. Fujita and E. Tamaki, "Analysis of very fast transients in transformers", IEE Proc.-Gener. Distrib. Vol. 148, No. 5, September 2001, pp. 377-383.
 - [71] H. Tatizawa, G. F. Burani, "Analysis and Location of Partial Discharges in Power Transformers by Means of Electrical Methods", CIRED2001, June 2001, pp.355-357.
 - [72] A. P. Sakis Meliopoulos, "State estimation methods Applied to Transformer Monitoring", 2001 IEEE Power Engineering Society Summer Meeting, Vol. 1, July 2001, pp. 419 - 423
 - [73] D. Kehr, W. Simburger, H. Wohlmuth and A. L. Scholtz, "Modeling of Monolithic Lumped Planar Transformers up to 20GHz", IEEE 2001 CUSTOM INTEGRATED CIRCUITS CONFERENCE, pp. 401-404.
 - [74] E. Dallago and G. Venchi, "Analytical and Experimental Approach to High-Frequency Transformer Simulation", IEEE Trans. on Power Electronics, Vol. 14, No. 3, May 1999. pp. 415-421.
 - [75] X. Mao and W. Chen, "More Precise Model for Parasitic Capacitances in High-frequency Transformer", IEEE 33rd Power Electronics Specialists Conference, 2002, Vol. 2, June 2002, pp. 1054 - 1057.
 - [76] A. S. AlFuhaid, "Frequency Characteristics of Single-Phase Two-winding Transformers using Distributed-Parameter Modeling", IEEE Trans. on Power delivery, Vol. 16, No. 4, October 2001, pp. 637-642.
 - [77] S. Fujita, N. Hosokawa and Y. Shibuya, "Experimental Investigation of High frequency Voltage Oscillation in transformer Windings", IEEE Trans. on Power Delivery, Vol. 13, No. 4, October 1998, pp. 1202-1207.
-

References

-
- [78] S. K. Pandey and L. Satish, "Multiresolution Signal Decomposition: A New Tool For fault Detection In Power Transformers During Impulse Tests", IEEE Trans. on Power Delivery, Vol. 13, No. 4, October 1998, pp. 1194-1200.
 - [79] F. de Leon and A. Semlyen, "Reduced Order Model for Transformer Transients", IEEE Trans. on Power Delivery, Vol. 7, No. 1, January 1992, pp. 361-369.
 - [80] F. de Leon and A. Semlyen, "Complete Transformer Model for Electromagnetic Transients", IEEE Trans. on Power Delivery, Vol. 9, No. 1, January 1994, pp. 231-239.
 - [81] S. Major and Q. Su, "A High Frequency Model for the Analysis of Partial Discharge Propagation along Generator Stator Windings", Conference Record of the 1998 IEEE International Symposium on Electrical Insulation, Arlington, Virginia, USA, June 1998, pp. 292-295.
 - [82] H. Wang and K. L. Butler, "Modeling Transformers With Internal Incipient Faults", IEEE Trans. on Power Delivery, Vol. 17, No. 2, April 2002, pp. 500-509.
 - [83] Saleh A. Saleh and M.A. Rahman, "Transient Model of Power Transformer Using Wavelet Filter Bank", Proceedings of the 2002 Large Engineering Systems Conference on Power Engineering, pp. 47-54.
 - [84] H. B. Elrefaie and A. I. Megahed, "Modeling Transformer Internal Faults Using Matlab", IEEE MELECON 2002, 7-9, May 2002, Cairo, Egypt, pp. 226-230.
 - [85] Robert M. Del Vecchio, Rajendra Ahuja and Robert Dean Frenette, "Determining Ideal Impulse Generator Settings From a Generator-Transformer Circuit Model", IEEE Trans. on Power Delivery, Vol. 17, No. 1, January 2002, pp. 142-148.
 - [86] A. Oguz Soysal and Adam Semlyen, "Practical Transfer Function Estimation and Its Application to Wide Frequency Range Representation of Transformers", IEEE Trans. on Power Delivery, Vol. 8, No. 3, July 1993, pp.1627-1637.
 - [87] J. Bak-Jensen, B. Bak-Jensen, S. D. Mikkelsen and C. G. Jensen, "Parametric Identification in Potential Transformer Modeling", IEEE Trans. on Power delivery, Vol. 7, No. 1, January 1992, pp. 70-76.
 - [88] S. Mofizul Islam, K. M. Coates and G. Ledwich, "Identification of High frequency transformer Equivalent Circuit Using Matlab from Frequency Domain Data", IEEE Industry Application Society Annual Meeting, New Orleans, Louisiana, October 1997, pp. 357-364.
 - [89] J. Biernacki and D. Czarkowski, "High Frequency Transformer Modeling", 2001 IEEE International Symposium on Circuits and Systems, 2001, Vol. 3, May 2001, pp. 676 -679.
 - [90] H. Rodrigo and H. Q. S. Dang, "Behaviour of Transformer Windings under Surge Voltages", High Voltage Engineering Symposium, 22-27, August 1999, pp. 287-290.

References

- [91] A. De and N. Chatterjee, "Impulse fault diagnosis in power transformers using self-organising map and learning vector quantisation", *IEE Proc.-Gener. Transm. Distrib.* Vol. 148, No. 5, September 2001, pp. 397-405.
- [92] R. Vanaja and K. Udayakumar, "Fault Location in Power Transformers During Impulse Tests", 2000 IEEE Power Engineering Society Winter Meeting, Vol. 3, Jan. 2000, pp. 2199-2204.
- [93] T. Hasman, V. Kvasnicka and J. Totev, "Sensitivity of Methods for Diagnostics of Power Transformer Windings", *High Voltage Engineering Symposium*, August 1999, pp. 244-247.
- [94] S. A. Saleh and M. A. Rahman, "Transient Model of Power transformer Using Wavelet Filter Bank", *Proceedings of the 2002 Large Engineering Systems Conference on Power Engineering*, pp. 47-54.
- [95] M. Popov, L. van der Sluis and G. C. Paap, "A Simplified Transformer Model for the Simulation of Fast Surges and Adequate Protection Measures", 2001 IEEE Power Engineering Society Winter Meeting, Vol. 1, 28 Jan.-1 Feb. 2001, pp. 323-328.
- [96] S. M. Islam, "Detection of shorted Turns and Winding Movements in Large Power Transformers using Frequency Response Analysis", 2000 IEEE Power Engineering Society Winter Meeting, Vol. 3, Jan. 2000, pp. 2233-2238.
- [97] P. Purkait and S. Chakravorti, "Pattern Classification of Impulse Faults in Transformers by Wavelet Analysis", *IEEE Trans. on Dielectrics and Electrical Insulation*, Vol. 9, No.4, August 2002, pp. 555-561.
- [98] M. C. Liew and P. S. Bodger, "Partial-core transformer design using reverse modeling techniques", *IEE Proc.-Electr. Power Appl.*, Vol. 148, No. 6, November 2001, pp. 513-519.
- [99] Peter G. Blanken, "A lumped Winding Model for Use in Transformer Models for Circuit Simulation", *IEEE Trans. on Power Electronics*, Vol. 16, No. 3, May 2001, pp. 445-460.
- [100] E. E. Mombello and K. Moller, "New Power transformer Model for the Calculation of Electromagnetic Resonant Transient Phenomena Including Frequency-Dependent Losses", *IEEE Trans. on Power Delivery*, Vol. 15, No. 1, January 2000, pp. 167-174.
- [101] H. Wang and K. L. Butler, "Modeling Transformers With Internal Incipient Faults", *IEEE Trans. on Power Delivery*, Vol. 17, No. 2, April 2002, pp. 500-509.
- [102] E. E. Mombello, "Impedance for the Calculation of Electromagnetic Transients within Transformers", *IEEE Trans. on Power Delivery*, Vol. 17, No. 2, April 2002, pp. 479-488.
- [103] B. Heller and A. Veverka, "Surge phenomena in electrical machines" (Book), London Ilife books Ltd., 1968, pp. 364-387.

References

- [104] Allan Greenwood, "Electrical transients in power systems" (Book), John Wiley & Sons, Inc., 1991, pp. 251-280.
- [105] E. P. Dick, R. W. Cheung, J. W. Porter, "Generator models for overvoltage simulations", IEEE Trans. on Power Delivery, Vol. 6, No. 2, April 1991, pp. 728-735.
- [106] A. Narang, B. K. Gupta, E. P. Dick, D. K. Sharma, "Measurement and analysis of surge distribution in motor stator windings", IEEE Trans. on Energy Conversion, Vol. 4, No. 1, March 1989, pp. 126-134.
- [107] PSpice, Student Version, Cadence, USA.
- [108] M. Yu, S. Birlasekaran, S. S. Choi, "Simulation of partial discharge propagation in power network", IEEE Trans. on Energy Conversion, Vol. 20, No. 3, Sept. 2005, pp. 644-653.
- [109] S. Z. Qin, S. Birlasekaran, "The study of propagation characteristics of partial discharge in transformer", 2002 IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, Oct. 2002, pp. 446-449.
- [110] Matlab version 6.5 and Toolboxes, The Mathworks Inc., Natick, MA, 2003.
- [111] V. Brandwajn, Y. Liu, Electromagnetic Transients Program Version 2.0: Revised Application Guide, Nov. 1991.
- [112] J. S. Wang, Y. C. Qiu, X. H. Wu, X. B. Sun, "Propagation characteristics of UHF electromagnetic waves induced by partial discharge in GIS", 2000 IEEE International Symposium on Electrical Insulation, April 2000, pp. 308-310.
- [113] John. E. Whitehouse, "Circuit Analysis" (Book), HORWOOD PUBLISHING LIMITED, 1997, pp. 58-60.

Author's CV and list of publications

Curriculum Vita

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Author's publication

Paper related with this research

1. Qin Shaozhen and S. Birlasekaran, "The Study of Propagation Characteristics of Partial Discharge in Transformer", 2002 Annual Report Conference on Electrical Insulation and dielectrical Phenomenon, Oct. 2002, pp. 446-449.
2. S. Z. Qin, S. Birlasekaran and C. L. Shih, "Study of partial discharge and attenuation from an operating 250MVA Generator", IEEE Research Bulletin, School of EEE, NTU, 2003, pp. 85-86.
3. Qin Shaozhen and S. Birlasekaran, "The study of Partial Discharge Propagation Phenomenon in Power Network", (TPWRD-00256-2005) accepted in IEEE Transactions on Power Delivery for publication.
4. Qin Shaozhen and S. Birlasekaran, "The study of Partial Discharge Propagation Characteristics in SF₆ Potential Transformer", to be submitted to IEEE Transactions on Power Delivery.

Paper not related with this research

1. Shaozhen Qin and Yanming Li, "The Development of A New Opto-electrical Device Used in Measurement of DC Leakage Current", High Voltage Apparatus (China), No. 6, December 1996, pp. 45-47.

Author's CV and list of publications

2. Shaozhen Qin and Yanming Li, "A Study of the Low Voltage Impulse Method for Detection the Transformer Winding Deformation", *Transformer (China)*, No. 7, July 1997, pp. 24-29.
3. Shaozhen Qin and Haiyan Li, "The Development of A New Kind High Voltage Impulse Peak Value Voltage Meter", *High Voltage Engineering (China)*, Vol. 23, No. 4, December 1997, pp. 75-77.
4. Yu Wang, Shaozhen Qin and Yanming Li, "The FRA Method of Detection the Transformer Winding Deformation Using Wavelet Analysis", *High Voltage Engineering (China)*, Vol. 23, No. 3, Sep. 1997, pp. 23-26.
5. Pengxiang Bi, Shaozhen Qin and Wenyuan zhang, "Methods for Monitoring the Condition of Insulation in Power Transformers", *High Voltage Engineering (China)*, Vol. 26, No. 3, Jun. 2000, pp. 47-49.
6. Shaozhen Qin, and Yanming Li, "A New Opto-electrical Device Used in Measurement of DC Leakage Current of Motor", *ICEE98*, Seoul, South Korea, 1998, pp. 351-354.
7. Pengxiang Bi, Shaozhen Qin, Jian Liu, Wenyuan Zhang, "Interfacial polarization spectra and its application for monitoring insulation condition in power transformers", *High Voltage Engineering (China)*, Vol. 26, No. 6, 2000, pp. 63-64.