Characterization of partial discharge pulses of power generator

Yu, Ming

2005

Yu, M. (2005). Characterization of partial discharge pulses of power generator. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/3928>

<https://doi.org/10.32657/10356/3928>

Nanyang Technological University

Downloaded on 26 Apr 2023 20:36:47 SGT

CHARACTERIZATION OF PARTIAL DISCHARGE PULSES OF POWER GENERATOR

Yu Ming

SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

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

2005

Statement of Originality

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

March, 2005

.....
Date

.....
Yu Ming

ACKNOWLEDGMENT

I like to express my sincere appreciation and deep gratitude to my supervisor, Assoc.Prof. S. Birlasekaran, for his invaluable guidance in the form of stimulating suggestions and criticisms in pursuing the many phases of this work, understanding and patience and encouragement throughout my research. I have learnt many things of life and I regretfully missed to capitalize many valuable intellectual discussions.

I am grateful to Prof. Choi San Shing, Head of Power Engineering, Division of EEE for his support, intellectual discussion and encouragement.

The research would not be possible without the financial support provided by Nanyang Technological University in the form of a research scholarship. For that, I am very thankful.

I like to thank Mr. Lim Kim Peow, Mrs. Ng-Tan Jennifer, Mr. Benny Chia and Mr.Tsay Chi-Huang of System Protection Laboratory of EEE for their kind assistance and continued technical support in the course of my research.

I acknowledge the help given by Mr. Shih Chi Lai, Senior Manager and Mr. Lim Chwee Chuan, executive engineer of electrical maintenance section of PowerSeraya Ltd., Singapore in providing me the necessary field test facilities. I also thank them for active discussion during my tests at their sites.

Last but not least, I am deeply grateful to my sister, father and mother for their affectionate love, unfailing support, patience and encouragement that have made over these three years of my graduate program at NTU.

SUMMARY

Partial discharge (PD) detection, characterization and location in a connected power network of generator, bus bar and step-up transformer is an important area of research to identify the degradation status of various operating power apparatus. This research project investigates the methods to identify the phase of generator with maximum PD activity, to characterize the PDs for identifying the types of developing PD and to locate the possible origin of PD in an operating 250 MVA power generator. Known data for each type of PD is collected in the laboratory using developed PD models. An automated multi channel data acquisition system is developed to acquire data in the laboratory and in a local power generating station to the desired format and resolution. Analysis to characterize PDs becomes a major part of the investigation. PD signal contaminated with noises is extracted with minimum distortion on PD pulse shape and the time of occurrence using the developed wavelet denoising technique. Five signal processing methods are developed with the existing knowledge to characterize PD pulses. Two of those methods are based on the reported literature and the advantages, drawbacks and limitation of those methods are investigated. Classical method 1 analyses the random distribution of the occurrence of PDs in 360° phase (Φ) plane in terms of number (n) and magnitude (q) as used by International Standards. Method 2 analyses the the shape distribution in positive and negative half cycles using statistical operators like mean (μ), standard deviation (σ), skewness (Sk), Cross correlation (cc), kurtosis (Ku) and asymmetry ($asym$). It is found that the results by two methods are very sensitive to the window size used for calculation. Method 3 uses the sequential pulse analysis in terms of time (Δt) and magnitude (Δq) difference and it is found to get the characteristic pattern for each type of PD. Method 4 analyses the distribution of q with cumulative number of occurrence using exponential function known widely as Weibull scale (α) and shape (β) analysis. Both α and β have a definite range for each type of PD. Newly developed method 5 uses the single PD wave shape. It uses the correlation factor and characteristic frequency peaks to classify and identify the types of PD. Characterisation of the types of recorded PD in the laboratory and generating power station are done without difficulties. Location of PD in an operating generator is a challenge. Using the simultaneous recorded

single PD signal at two locations and apparatus modeling with Simulink, the possible location of PD is identified.

TABLE OF CONTENT

ACKNOWLEDGMENT	i
SUMMARY	ii
TABLE OF CONTENT	iv
LIST OF FIGURES	viii
LIST OF TABLES	x
LIST OF ABBREVIATIONS AND ACRONYMS	xi
Chapter 1 Introduction	1
1.1 Motivation.....	1
1.2 Objectives of my research.....	4
1.3 Major contribution	5
1.4 Organization of the thesis	7
Chapter 2 Partial Discharge Studies on Power Generator	9
2.1 Introduction.....	9
2.2 Existing condition monitoring methods in generator	10
2.3 Current theory of PD.....	11
2.3.1 Types of PD in insulating material	11
2.3.2 Physical basis for PD initiation.....	12
2.3.3 The physical model of PD	13
2.3.4 Stochastic character	13
2.4 PD measuring techniques for generator insulation	14
2.4.1 Reported methods	15
2.4.2 PD location methods	16
2.4.3 The conventional PD measuring circuit.....	16
2.4.4 PD sensors.....	17
2.4.5 PD detector	18
2.4.6 Difficulties	18
2.4.7 Display of PD activity.....	19
2.5 Identified PD defects in generator	20
2.6 Developed PD identification techniques.....	21
2.6.1 Derived parameters	21
2.6.2 PD distribution analysis in a period	22
2.6.3 PD identification using spectrum analysis.....	27
2.6.4 PD identification using neural network	27
2.6.5 PD identification using fuzzy techniques	28
2.6.6 PD identification using fractal geometry	28

2.6.7	PD identification using wavelet techniques.....	28
2.6.8	PD identification using single pulse technique.....	30
2.7	Types of PD	31
2.7.1	Internal discharge.....	31
2.7.2	Surface discharge.....	32
2.7.3	Corona discharge	33
2.7.4	The other types of discharge.....	33
2.8	Planned research work.....	34
Chapter 3 Experimental Set Up		35
3.1	Introduction.....	35
3.2	Laboratory Measurement System.....	36
3.2.1	Limitation.....	38
3.2.2	Effect of detector resistance.....	38
3.3	Fabricated laboratory samples	40
3.3.1	Corona PD model.....	40
3.3.2	Surface PD model	41
3.3.3	Cavity PD model.....	41
3.3.4	Generator coil	41
3.4	Field measurement system.....	42
3.5	Developed software	43
3.6	Conclusion	44
Chapter 4 PD Denoising and Analysis		45
4.1	Introduction.....	45
4.2	Recorded signal.....	47
4.2.1	Time domain PD signal in Laboratory	49
4.2.2	Time domain signal in generating station.....	49
4.2.3	Frequency domain responses in laboratory	50
4.2.4	Frequency domain responses in generating station	50
4.3	Denoising methods	52
	Introduction	52
4.3.1	Wavelet method	52
4.3.2	Choosing a Mother Wavelet	54
4.3.3	Effect of decomposition level on fitting	57
4.3.4	Extracted PD signals from laboratory data	57
4.3.5	Extracted PD signals and noise from field on-line data.....	58
4.3.7	Effect of differential field measurement to reduce noise.....	59
4.4	Signal Processing – 1	60
4.4.1	Analysis of different PD distribution.....	61
4.4.2	qm- ϕ and qave- ϕ distributions on laboratory samples.....	61
4.4.3	q- ϕ distribution of field data	64
4.4.4	q-n distribution on laboratory samples	66
4.4.5	q-n distribution of field data	67
4.4.6	q- Φ -n distribution of field data.....	67
4.5	Signal Processing - statistical analysis -2	68
4.5.1	μ and σ of the laboratory data.....	68

4.5.2	μ and σ of the field data.....	70
4.5.3	Sk of the laboratory data.....	71
4.5.4	Sk of the field data.....	72
4.5.5	cc of the laboratory data.....	72
4.5.6	cc of the field data.....	73
4.5.7	Ku of the laboratory data.....	73
4.5.8	Ku of the field data.....	74
4.5.9	Asym of the laboratory data.....	74
4.5.10	Asymmetry of the field data.....	74
4.5.11	Effect of window sizing.....	75
4.6	Signal Processing – 3.....	77
4.6.1	$(\Delta t) - (\Delta V)$ distribution of the laboratory data.....	77
4.6.2	$(\Delta t) - (\Delta V)$ distribution of the field data.....	79
4.7	Signal Processing –4.....	81
4.7.1	Mixed Weibull Parameter Estimation.....	81
4.7.2	Mixed weibull fitting on laboratory data.....	82
4.7.3	Mixed weibull fitting on field data.....	84
4.8	Signal processing – 5.....	86
4.8.1	PD identification using correlation coefficients.....	86
4.8.2	Single pulse analysis of laboratory data.....	87
4.8.3	Single pulse analysis of field data.....	91
4.8.4	Identified pulse groups in blue phase with correlation coefficient.....	91
4.8.5	Time and frequency domain characteristics of pulse groups in blue phase...	92
4.9	Summary.....	94
Chapter 5 Modelling.....		97
5.1	Introduction.....	98
5.1.1	Method.....	100
5.2	Modeling.....	100
5.2.1	Modeling of generator.....	100
5.2.2	Modeling of bus bar.....	102
5.2.3	Modeling of step-up transformer.....	102
5.3	Analysis of the ladder network.....	103
5.3.1	Effect of ‘N’ on network response characteristics.....	104
5.3.2	Effects of R_s , R_p , L_s and C_p on $G(s)$	106
5.3.3	Effect of Z on $G(s)$	107
5.3.4	Effect of termination.....	108
5.3.5	Effect of non-linearity in R_s and L_s	108
5.3.6	Effect of alternate Z_1 and Z_2	109
5.4	Simulation.....	110
5.4.1	Matching the responses at C and D.....	111
5.4.2	Predicted responses due to origin/location of PD.....	115
5.4.3	Predicted responses due to PD wave shape.....	117
5.5	Conclusion.....	118
Chapter 6 Conclusions and Recommendations.....		121
REFERENCES.....		128

Table of Contents

APPENDICES	140
APPENDIX A	140
APPENDIX B.....	141
VITA	142

LIST OF FIGURES

Figure 2-1 Circuit Layout for PD measurement	17
Figure 2-2 Methods of PD detection.....	19
Figure 2-3 PD phase distribution: (a) Corona in the air, (b) A cavity adjacent to a conductor creates an asymmetric pattern, (c) A cavity completely surrounded by a dielectric generates a symmetric pattern, and (d) bad contact noise in the leads occurs at the maximum current	20
Figure 2-4 Multi-resolution wavelet decomposition. h = low-pass decomposition filter; g = high-pass decomposition filter; 2 = down-sampling operation. $A_1(t)$, $A_2(t)$ are the approximated coefficient of the original signal at levels 1, 2 etc. $D_1(t)$, $D_2(t)$ are the detailed coefficient at levels 1,2.....	29
Figure 2-5 Multi-resolution wavelet reconstruction. h' = low pass reconstruction filter; g' = high-pass reconstruction filter; 2 = up-sampling operation. $A_1(t)'$, $A_2(t)'$ are the processed or non-processed approximated coefficient of the original signal at levels 1, 2 etc. $D_1(t)'$, $D_2(t)'$ are the processed or non-processed detailed coefficient at levels 1,2.....	30
Figure 2-6 PD model for cavity discharge.....	32
Figure 2-7 Model of surface discharge	33
Figure 3-1 The block diagram of measurement system.....	36
Figure 3-2 Layout of the developed computer-aided measurement system	37
Figure 3-3 50 Hz waveform of the laboratory power supply.....	38
Figure 3-4 Comparison of PD distribution with 50 Ω and 1M Ω	39
Figure 3-5 PD samples to generate three types of PD	40
Figure 3-6 7.5 kV rated generator coil.....	42
Figure 3-7 Layout of PD measurement system for operating generator.....	43
Figure 4-1 PD pattern with noise in 20 ms period for 3 PD samples	47
Figure 4-2 Simultaneously recorded PD and noise pattern at A,C,E and F	49
Figure 4-3 The spectral responses of corona, cavity and surface discharges in laboratory	50
Figure 4-4 The single and averaged spectrums of off and on-line data on generator.....	51
Figure 4-5 The decomposition tree of wavelet package with 4 levels.....	53
Figure 4-6 Decomposed corona signals at (4,0) and (4,15).....	54
Figure 4-7 The denoised corona discharge	54
Figure 4-8 Fitting of denoised PD with different wavelets on the original PD	55
Figure 4-9 Computed correlation coefficient with different wavelets.....	56
Figure 4-10 Fitted denoised signal from different decomposition levels	56
Figure 4-11 Computed correlation coefficient of extracted PD at different levels	57
Figure 4-12 The denoised cavity (LHS) and surface (RHS) PD distribution	58
Figure 4-13 Original data at E and extracted noises at red Φ of 250 MVA generator	58
Figure 4-14 Denoised PD distribution at E of 250 MVA generator	59
Figure 4-15 40 superimposed PDs at E and F. Top: E; Mid: F; Bot: (E-F).....	61
Figure 4-16 $qm-\phi$ patterns for the laboratory data.....	62
Figure 4-17 $qave-\phi$ patterns for laboratory data	63
Figure 4-18 The $q-\phi$ pattern for field data at A.....	65
Figure 4-19 The $q-\phi$ pattern for field data at E.....	65

Figure 4-20 The q - ϕ pattern for field data at A and E with $50\ \Omega$	66
Figure 4-21 The q - n pattern for laboratory data	66
Figure 4-22 The q - n patterns for field data at A and E	67
Figure 4-23 The q - Φ - n pattern of field data at A and E	68
Figure 4-24 Effect of horizontal window sizing on corona – qm - ϕ	76
Figure 4-25 Effect of vertical window sizing on field data on q - n distribution	76
Figure 4-26 (ΔV) - (Δt) distribution for corona discharge	78
Figure 4-27 (ΔV) - (Δt) distribution for cavity discharge. Top - +ve; Bot - negative	78
Figure 4-28 (ΔV) - (Δt) distribution for surface discharge	79
Figure 4-29 (ΔV) - (Δt) and (ΔV) - (Δt) - n distribution for the field data at A	80
Figure 4-30 (ΔV) - (Δt) and (ΔV) - (Δt) - n distribution for the field data at E	80
Figure 4-31 Weibull distribution of q and cumulative n on cavity and surface PDs	82
Figure 4-32 Mixed weibull distribution of q and cumulative n on corona PD	83
Figure 4-33 Mixed weibull distribution of q and cumulative n	85
Figure 4-34 Mixed PD pattern due to corona and surface PDs	88
Figure 4-35 Shapes of PD and variation of single surface and corona waveform	89
Figure 4-36. Variation of correlation coefficient in 20 ms. *: the reference single surface PD pulse is selected from positive half cycle, o: the reference single surface PD pulse is selected from negative half cycle	89
Figure 4-37 The distribution of number of pulses with correlation coefficient calculated using surface PD as reference	90
Figure 4-38 Identified PDs distribution from Figure 4-34 (b)	90
Figure 4-39 PD distribution in 1.6 ms window and the collected single PDs at A and E	91
Figure 4-40 Grouped 43 single pulses in blue ϕ and 45 pulses in red phase	92
Figure 4-41 Typical time and frequency domain responses of single PD from three large single PD sources in blue ϕ	93
Figure 4-42 Dominant frequency content distribution in each identified group	94
Figure 5-1 Model of a single turn of generator coil	101
Figure 5-2 Model of stator winding of a 3ϕ generator	102
Figure 5-3 Model of an air-insulated busbar	102
Figure 5-4 Model of the step-up transformer	103
Figure 5-5 Five sections of ladder network model	103
Figure 5-6 Effect of N on $G(s)$	105
Figure 5-7 Effect of R_s on resonance peaks	106
Figure 5-8 Effect of L_s on resonance peaks	107
Figure 5-9 Effect of Z on resonance peaks	107
Figure 5-10 Effect of inductance termination on resonance peaks	108
Figure 5-11 Effect of 10 sections of bar with alternate $Z_1=500\ \Omega$ and $Z_2 = 31\ \Omega$	110
Figure 5-12 Simulink layout for PD simulation study	112
Figure 5-13 Extracted low frequency profiles at C	112
Figure 5-14 Results of measured (dotted) and Simulink (solid)	113
Figure 5-15 Results of measured (dotted) and Simulink (solid)	114
Figure 5-16 Results from measured (dotted) and Simulink (solid)	114
Figure 5-17 Results from measured (dotted) and Simulink (solid):	115
Figure 5-18 Predicted frequency responses due to the injected PD	116
Figure 5-19 Predicted frequency responses due to the injected PD	116
Figure 5-20 Predicted frequency responses due to the injected PD shapes	118

LIST OF TABLES

Table 2-1 Tests on generator [2]	10
Table 4-1 Qualitative features of PD phase distribution.....	64
Table 4-2 Variation of μ and σ by taking $qm-\Phi$ of laboratory data	69
Table 4-3 Variation of μ and σ by taking $qave-\Phi$ of laboratory data.....	69
Table 4-4 Variation of μ and σ by taking $q-n$ of laboratory data	70
Table 4-5 Variation of μ and σ by taking $qm-\Phi$ of field data	70
Table 4-6 Variation of μ and σ by taking $qave-\Phi$ of field data.....	71
Table 4-7 Variation of μ and σ by taking $q-n$ of field data	71
Table 4-8 Variation of Sk with $qm-\Phi$, $qave-\Phi$ and $q-n$ of laboratory data	71
Table 4-9 Variation of Sk with $qm-\Phi$, $qave-\Phi$ and $q-n$ of field data	72
Table 4-10 Variation of 'cc' with laboratory data	72
Table 4-11 Variation of 'cc' of field data	73
Table 4-12 Variation of Ku of the laboratory data	73
Table 4-13 Variation of Ku using field data	74
Table 4-14 Variation of Asym of laboratory PD data	74
Table 4-15 Variation of Asym of field data.....	74
Table 4-16 Determined Weibull parameters in blue ϕ	85
Table 4-17 Determined Weibull parameters in red ϕ	86
Table 5-1 Simulated PD waves.....	117

LIST OF ABBREVIATIONS AND ACRONYMS

-ve	Negative half cycle
+ve	Positive half cycle
Φ	Phase
Φ -n	Phase to number
μ	Mean
σ	Standard deviation
α	Scale parameter of weibull distribution
β	Shape parameter of weibull distribution
$\Delta u, \Delta v$	Voltage difference between two consecutive peak pulses
dv (V)	
μ s	microseconds
ns	nanoseconds
ac, AC	Alternative current or voltage
cc	Cross correlation
dia	Diameter
dt(s)	Time difference between two consecutive peak pulses
q	Charge/ PD amplitude
$q_m-\phi$	Maximum PD amplitude to phase
$q_{ave}-\phi$	Average PD amplitude to phase
q-n	PD amplitude to number
Asym	Asymmetry of charge distribution
Bot	Bottom
ERA	Electrical Research Association
FT	Fourier Transform
FFT	Fast Fourier Transform
GIS	Gas insulated system
HFCT	High Frequency Current Transformer
HV	High voltage
Hz	Hertz
NTU	Nanyang Technological University

List of Abbreviations and Acronyms

LV	Low voltage
LHS	Left hand side
Mid/MID	Middle
PD	Partial discharge
PDs	Partial discharge Pulses
RHS	Right hand side
RTD	Resistance temperature detector
SCR	Silicon Controlled Rectifier
Sk	Skewness
SSC	Stator Slot Coupler
Ku	Kurtosis
SSC	Stator slot coupler
Top	Top
UHF	Ultra high frequency
WTC	Wavelet Coefficients

Chapter 1 Introduction

1.1 Motivation

With the development of high rating power system for the deregulated energy market, high voltage (HV) power apparatus plays a more important role in maintaining cost efficiency and reliability. An unscheduled outage of a machine in operation could result in a major instability in the system to which it is connected as well as in the loss of capital investment. Modern preventive maintenance programs [1] incorporate many intelligent diagnostic techniques. Condition parameters from diagnostic tests and information from operational history are used to assess the loading status of power apparatus. These condition monitoring methods provide information for expanding the operating life of different power apparatus and loading to minimize the risk of expensive breakdowns.

Large power generators are important elements of power generation. Power generator failures are associated with mechanical components failures and electrical breakdowns of the insulation system. It is found that about 40% of motor and generator problems [2] are due to the deterioration of the stator winding insulation. The insulation system provides electrical isolation, mechanical support, heat dissipation, and personnel safety. Insulation degrades locally as a ‘cancer’ in an electrical apparatus under various operational stresses [2] and it leads to a complete failure if not fixed. In particular, researchers’ [3] are constantly challenged to develop new on-line diagnostic and condition monitoring methods to uncover the character of the features of the measured signals in relation to developing faults. These programs are beneficial to both manufacturers and utilities in reducing the cost and enhancing the reliability of the power generator.

Many Technologies [4], such as vibration test, thermograph, high-potential test, power factor test, voltage surge comparison test, dissipation factor($\tan \delta$) test, leakage current versus time test, insulation resistance test of stator coil, corona probe test, DC over-potential test and partial discharge test are being used to predict the impending failure by measuring the insulation condition parameters. They all have many advantages and some disadvantages. Each of the method is always effective in one aspect to detect the developing faults in the insulation of the generator. The faults can be due to electrical

stress, the mechanical stress, and thermal damage or surface erosion by chemical reactions of moisture .

Degraded products may also cause some kind of faults. Among the many condition monitoring methods, partial discharge (PD) measurement is one of the sensitive indicators of localized damages[5], and has drawn people's attention for many years. Also, voluminous data on PD contain valuable information about mechanisms of the underlying aging process that leads to complete breakdown. Nowadays, the online PD measurement [6] is broadly implemented on generators. It costs less than other methods and it can be on-line and non-intrusive. Digital data under many different operating conditions can reveal the severity status from different analysis severity and for the management to predict the apparatus operational status.

From the statistical data on the failure of 200MW range power generators, short circuit faults initiate PD to lead to slow degradation in insulating materials. Various laboratory and on-site investigations have been initiated to understand the complex deterioration mechanisms of machine insulation.

It is noted that the correlation between all the measured variables and the discharge processes is limited. It should also be noted that a single parameter [7] may not provide a reliable quantity to make a conclusive assessment of the state of the insulation. This is due to the random character of PDs and the large mount of data acquired. Instead, multiple analyzing methods are required to identify the type of defects that could lead to ultimate breakdown of the dielectric structure.

This is due to the random character of PDs and the large mount of acquired data. Instead, multiple analyzing methods are required to identify the type of defects that could lead to ultimate breakdown of the dielectric structure. The location of PD is another interesting research area and a few methods have been attempted to model the propagation path of PD in generator.

From the traditional phase distribution analysis [8], shape, symmetry and correlation distribution using statistical parameters analysis was introduced using automated discharge analyzers. It examines more than twenty statistical parameters associated with PD distribution. Using the PD wave shape, physical mechanism of PD growth is postulated [9]. After extracting the main features using known PD discharges, fractal parameters[10], neural network paradigms [11][12], fuzzy classification [13] and wavelet coefficients [14] are attempted to recognize the different types of PD.

Most of the above analyses were attempted with controlled experimental data. No clear approach was made to denoise the periodic and non-periodic noise signals modulated in industrial measurement. Traditional phase distribution analysis was not quantified beyond the statistical profile analysis. Severity indexes and diagnosis of the type of PD in mixed PD sources are yet to be developed. Techniques to identify the number of developing PDs and their location in operating apparatus are not developed. In addition, the role of measuring impedance, cross-coupling of PD signal between the phases, attenuation and propagation delay of PD signal with distance in the same phase are yet to be explored. Signal processing with individual PD wave shape is not reported. Many of the reported methods rely either on time-domain measurement or spectrum analyzer measurement on randomly occurring PD signals.

Few papers have reported the use of multiple sensors [15] to locate and identify the type of PD on generator. For transformer, GIS and cables, multiple sensors are used. Location of PD with sensors mounted at two or more locations and by online simultaneous measurements on generator has not been reported especially the PD location from the time domain waveform and frequency spectrum.

Most of the practical on-line PD measurement system involve network of connected generator, bus bar, cable and step-up transformer units. No systematic study is reported about the distortion introduced by the connected apparatus.

1.2 Objectives of my research

This research work intends to develop characterization methods for identifying the rate of PD growth, the type of developing PD, the number of developing PD sources and the possible location of those PD sources in an operating 250 MVA 16 kV generator that is connected to the power network. To do that, data acquisition system and analyzing software are to be developed. The extracted features are to be researched for identification.

A fast sampled digital PD data acquisition system is to be developed with phase voltage reference of repeated 20 ms cycles. It is aimed to characterize the PD random occurrence in 20ms of multiple ac cycles using the well known classical method [124] before developing other analyzing methods. To identify the type of random occurring PD in 20 ms repetitive cycle, PD occurrence in more cycles will be analysed with new techniques. To evaluate the characteristics of pure PD in controlled laboratory environment, new PD samples to generate one type of pure PD will be designed and tested.

The next objective of the research is to develop denoising techniques so that the original high frequency PD can be retrieved without magnitude, phase and shape distortions.

Classical PD identification pattern reported in international standards [16][124] need the phase of voltage reference signal. The reference time of PD occurrence in repeated ac cycles is needed to group the PDs in the corresponding phase location of the voltage cycle. Analysis and identification of the type of random occurring PD become meaningful by grouping PDs with the corresponding phase location in multiple 20 ms repetitive cycles. The technique should retrieve the reference phase information of energizing HV source. The reference phase is to be used in the q (discharge amplitude)- ϕ (discharge phase) analysis.

After extracting PD, techniques to evaluate the relative severity of PD in the laboratory samples and at three phases of the tested generator are to be developed. The character of

PD patterns is to be extracted. And the distribution of the scholastic PD amplitude is to be recognized of different PD patterns.

The characteristics of pure PD in a laboratory environment are to be investigated for type identification. This type of PD identification is to be applied to generator measurements as the status and location of developing PDs in the operating generator, bus bar or step-up transformer network are not known.

Grouping techniques are to be developed to identify the number of developing PDs. The method should be able to distinguish multi unknown PD sources existing at the same time.

After the identification of type and number of PDs, the possible origin in term of connected apparatus and the length of winding is to be predicted. The propagation model of PD inside the power network is to be setup. And the simultaneous PD response at different locations is to be simulated to find out the PD locations.

1.3 Major contribution

As a result of the research work, the following original contributions have been made.

- 1 Development of ultra-high frequency (UHF) PD measurement setup for NTU HV laboratory and for field studies at generating station of Power Seraya.

The new contribution is the automatic data acquisition system to capture PD activity in the desired multi 20 ms cycles from 4 channels simultaneously at a sampling rate up to 1 GS/s for PD distribution study in 20 ms and single pulse analysis.

- 2 Samples to generate only surface, corona and cavity discharges are designed and fabricated. They are tested at the controlled laboratory conditions in various combinations. The characteristics of pure PDs without any propagation distortion are investigated to understand the discharge mechanism. On-line simultaneous PD measurements at two ends of bus bar connected to generator and step-up transformer were made. With 4 channels, simultaneous PD activities in two phases of the bus bar were measured. It was done to identify (i) the origin of PD from generator, (ii) high

frequency noise or PD from connected step-up transformer, (iii) the cross-coupled high frequency picked signal between different phases and (iv) the propagation distortion from one end to other end of the bus bar.

- 3 New wavelet technique using Daubechies filters is developed for denoising laboratory and field data from the periodic 50 Hz and its corresponding harmonic noise, and commutation noise from power electronic devices. Correlation technique is developed to eliminate random and non-periodic high frequency noises too. The same technique is used to extract the 50 Hz phase reference voltage. The extracted PD retains the wave shape, magnitude and time/phase location after denoising.
- 4 Characterization methods for PD identification are developed. Five signal processing techniques are developed to match field PD in relation to laboratory data. Two of the techniques – (i) $q-\Phi$, $q-n$ and $q-n-\Phi$ distributions and (ii) statistical parameters are already reported in the literature and the problem of windowing on the above results is investigated. Three new techniques - (iii) $\Delta u-\Delta t$ and $\Delta u-\Delta t-n$ analysis, (iv) mixed weibull distribution and (v) *correlation technique* to identify the number of PDs are developed. The first four techniques are applied on traditional 20 ms period PD distribution known as *group PDs analysis*. The fifth technique compares the shapes of single PD known as *single PD analysis*. The first three techniques can identify the phase with severe PD activity. Techniques (ii), (iii) and (vi) can recognize the type of PD. Technique (iv) and (v) can determine the number of PD defects. For the first time, the characteristics of simultaneously extracted single PD population at different nodes are evaluated using time and frequency domain techniques. *Single PD analysis* identifies the number of PD defects and high frequency noises. In addition, it recognizes the direction of PD propagation in a network consisting of generator, bus bar and step-up transformer. It evaluates the velocity of propagation and distortion introduced in the same phase, and the cross-coupling between the three phases.
- 5 PD propagation model in network consisting of generator, bus-bar and transformer is developed. After identification of PDs, Power Seraya management is interested in knowing the approximate location of the identified PDs in their network. Investigation in the laboratory has produced the wave shape of original PD without the distortion due to propagation. Simultaneous on-line single PD responses on the

same phase but at two separate nodes, spaced at 25 m apart, enable the development of the model for PD propagation. Two serially connected ladder networks representing generator and bus bar, and a terminated lumped network for transformer are developed to match the time and frequency domain responses at the two nodes. For generator, a novel ladder network with alternate surge impedances and non-linear parameters is used to represent the conductor in the slot and overhang regions. The investigation shows that PD gets distorted due to propagation. My studies indicate that measured on-line simultaneous PD wave shape at different locations of field network can be matched with the ones simulated using the developed propagation model. The PD response matching is done in time and frequency planes at two measured nodes. The proposed method is able to identify the PD location in the generator winding.

1.4 Organization of the thesis

This thesis is organized into seven 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 presented.

Chapter 2: Partial Discharge Studies on Power Generator

An overview of various condition monitoring techniques, the theory of PD, principles of various measuring and location techniques for generator insulation, identify PD defects, developed PD identification techniques and types of PD from the reported literature are summarized. Based on the above, research work for the 3 year period is reported.

Chapter 3: Experiment Set Up

The details on wide bandwidth PD data logging system, the fabricated four samples to generate pure and mixed PDs, the layout of the power generating station under study and the software tools are briefed.

Chapter 4: PD Denoising and Analysis

The noise pattern on recorded PD signal, the developed denoising method and five signal processing methods to analyze PD data after denoising are presented. Using the above, the severity, type and number of developing PD sources in power generating station field data are characterized in comparison with the laboratory data.

Chapter 5: Modeling

A simulation method is proposed to identify the location of PD occurrence in a connected power network of a power station. Circuit models were built to represent the generator, transformer and bus-bar. The contribution of the equipment structure and its parameters to the model is studied. This type of analysis is able to predict the distortion introduced in the propagation path from the PD origin to any measuring node.

Chapter 6: Conclusions and Recommendations

This chapter summarizes the findings and presents new recommendations for future research works.

Chapter 2 Partial Discharge Studies on Power Generator

2.1 Introduction

Materials in the form of solids, liquids and gases capable of insulating two charged electrodes by preventing the transport of electrons between them are known as dielectrics. Over the decades, extensive studies have been carried out to understand the mechanism of electrical breakdown in dielectrics so as to design reliable HV apparatus [17] [18] [19].

Rotating power generator uses the following insulating dielectrics: shellac and bituminous mica, resin with vacuum pressure impregnation, epoxy mica [20]. Although the insulation of an electric machine generally is only 1-3% of the weight, it is the most vulnerable component of the machine. The insulation materials are exposed to moisture, dirt, chemical corrosion and radiation in addition to transient and constant thermal, electrical and mechanical stresses. The combined reactions of different force intensities and duration of such stresses set a limit to the useful life of the insulation. In addition to mechanical integrity of composite insulation at the interfaces due to magnetic forces on conductors, thermal expansion, water absorption and volume shrinkage of fillers due to aging create local imperfection at the insulator/conductor interfaces known as ground wall defects, delamination, micro voids, gas formation etc., [22]. In addition to that, surface contamination of solid insulation can cause surface PD to erode the surface with heating. As the discharge rate is intensified, it leads to the failure of dielectric insulation. In contaminated industrial environment under the action of high electrical, thermal and mechanical stresses, the solid dielectric of a machine stator bar may lose its electrical and mechanical integrity either globally or locally. This results in the development of a wide range of defects that further impair the dielectric strength of the insulation. Defective insulation created during manufacturing or under operational stresses exhibits a variety of dynamic electrical and non-electrical symptoms. Detection and monitoring of these signatures can, in turn, provide information about the mechanism and the extent of the aging process involved. Gradual deterioration and mechanical instability of the electrical insulation can initiate and produce different types of electrical PD which cause further degradation and could lead to a complete or partial disintegration of the insulation.

Thus, failures of this kind can often be related to the occurrence and severity of PD which occur in inclusions of lower dielectric strength. The developing defects could be identified by different condition monitoring techniques [21]-[23] and the determined condition parameters are used to estimate the remaining life and loading schedule on the costly power apparatus.

2.2 Existing condition monitoring methods in generator

The condition parameters/signatures can be measured either by electrical [23][24][25][26], physical [27] and chemical techniques [28]. Each technique has some advantages and some limitations. Table 2-1 gives a summary of electrical tests. The physical tests can be mechanical strength and vibration, surface roughness and thermograph [125]. The chemical tests can be gas and other solid by-products analysis.

Table 2-1 Tests on generator [2]

	Test conditions	Advantages	Limitation
Power factor test [25]	100% line to ground (rated voltage)	-Abrupt change indicates the degradation status	-Off-line test; costly test equipment
AC Withstand voltage [29]	At 50 or 60 or 0.1Hz	-Less costly equipment can be used	-Could cause damage -off-line test
Voltage Surge Comparison test [30]	LV – Impulse test	-Efficient to detect localized mechanical damage like turn-to-turn, coil-to-coil and phase to phase short-circuit faults . Non-destructive.	- Weak signal
Dissipation factor($\tan \delta$) test [21]	HV test at 50 Hz; LV test by changing frequency from 1 mHz to 10 Hz	-Identifies the heating component or the degradation -Non-destructive test	- off-line test; costly test equipment
Leakage current versus time test [2][24]	Low DC voltage in the order of 1kV	-monitoring the leakage current to identify any impending failure	-Very low current and stray current can introduce errors
Voltage versus leakage current test [2][31]	10 voltage steps- until the rated voltage	- If secondary ionization occurs, fast growth in current will be noticed. If it occurs at less than rated voltage, it is serious	-Variable supply needed -off-line test
Partial Discharge [1]	Rated voltage	-On-line monitoring -Highly sensitive - Useful to locate the localized	-Interference affects sensitivity - interpretation is

Chapter 2 Partial Discharge Studies on Power Generator

		faults - Non-destructive	difficult - response varies with sensor
DC over-potential test [29]	maintenance test	-Assess the insulation dielectric strength of all parts in the generator - stress distribution different	-Simple routine DC test -Shut down and reconnection is required - stress distribution different
Corona probe test [32]	DC high voltage test	- Low cost test -Identifies the slot location precisely -mostly non-destructive	-the discharge pattern is not known 5MHz in bandwidth Each stator coil is individually tested Off-line test
Insulation resistance test of stator coil[33]	DC voltages from 500 to 10000V	- Low cost test - Polarization index (PI) gives the degradation level	-Not sensitive and precise -DC test -Needs skill to get PI

Although bulk properties such as dielectric loss per cycle, $\tan\delta$ and capacitance change are useful pointers to the condition of the insulation, their sensitivity to local defects is limited and will not identify the mechanism and location of developing fault. On the other hand, PD characterization can provide reliable measures of the insulation deterioration. Over the past four decades, considerable research was done to identify the type of PD using random PD occurrence plot in one cycle. In the subsequent sections of this chapter, a summary of the review of the existing theory of PD and current research work on generator insulation diagnostics is presented in order to explore new areas for further research.

2.3 Current theory of PD

2.3.1 Types of PD in insulating material

PD is a localized electrical discharge partially bridging the electrodes within an insulation system. The term “PD” includes a wide group of discharge phenomena: internal discharges may occur in voids of solid or liquid dielectrics, surface discharge appears at the boundary of different insulation materials, corona discharges occur in gaseous dielectrics if strong

inhomogeneous fields are present and the continuous impact of discharges in solid dielectrics forms discharge channels known as treeing.

The significance of discharge on reducing the life of insulation has long been recognized. Every discharge event deteriorates the material by the energy impact of high energy electrons or accelerated ions causing chemical transformation of many types. A PD within thermoplastic dielectrics, such as epoxy, may cause breakdown within a few days to years.

2.3.2 Physical basis for PD initiation

It is clearly recognized that there are certain requirements for initiation and occurrence of the PD pulses at active sites such as voids or cracks within the solid insulation, solid-gas interfaces or bubbles formed by vaporization of a liquid insulation, or in dielectric liquid. One of the important requirements for the formation of the PD is that the regions at which it occurs must be at least partially in the gas phase [34]. PD occurs also in liquids [35]. Two other conditions are required for PD to occur. First an electron avalanche must start from an initiating free electron [36] and second the local electric field must exceed the breakdown inception threshold field of the gap [20]. One source of the initiating electron is emission due to charges within the insulation wall from previous activity which can also influence the production rate of the initiating electron. The interaction of applied field with the ionic space charge at the site is a major factor in development and repetition of the discharges. When an existing free electron within a void gains enough acceleration from the electric voltage drop across the void, its kinetic energy will ionize the void via particle collision. PD current occurs as a consequence of exponential multiplication of the charge carriers in the region. Various criteria exist for the development and growth of avalanches and subsequent discharges among which the streamer type is considered as a major and more familiar discharge mechanism [10]. Influenced by the gas pressure and the size of the void, streamer criterion is a self-propagating phase of the electron avalanche, where the ionization charge produced via particle collision has grown large enough to become comparable with the external field. In the presence of the ionization electron, the PD pulse occurs as soon as the electric field reaches the streamer inception field. On the other hand, it is noted that PD exhibits a period without PD pulses either as a result of the reduction of the local electric field to a level that is not sufficient to support the continuous growth of the discharge or due

to the action of the surface or space charges produced during the activity that prevents the external field to sustain the discharge.

2.3.3 The physical model of PD

The physical model of the PD [36] is also complex due to the complex physical processes of electron generation. But different type of discharges is controlled by similar physical process to a large degree. This permits an efficient unified modeling approach[36]. In the process of establishing the model, the dimensional reasoning should be used, which consists of defect geometry, discharge structure and involved materials. The model should incorporate the inception voltage, inception delay, measurable charges, statistical characteristics and the distribution over the ac phase[37]. It provides the basis for a simulation of random sequences of PD pulses.

The discharge theories should be used in the modeling. The general character of the modeling procedure allows other types of gas discharges such as Townsend discharge, leader growth, or spark formation. The theories interpret the microsecond processes of discharges based on the collision ionization theory and influx discharge theory [38]. Based on the above theory and physical presumption, the electron current, the positive ion current of first ionization, the electron current resulting from positive ion impacting cathode and photo ionization during nanosecond discharge process can be predicted.

2.3.4 Stochastic character

The statistical variability in various properties of PD such as amplitude, shape and time interval of the pulsating PD for the same inception voltage is caused by statistical and formative time lags. It is also verified that ion densities, or surface charges generated during a previous PD event can influence both the local field strength and the release rate of the PD initiating electron [36]. The statistical time lag is influenced by the rate at which free electrons are released into the high-field region of a PD site. This statistical time lag depends also on the probability that an electron can initiate a PD event. It is now recognized that there are several electron release processes that can contribute to PD inception, in contrast to photo-ionization of the gas by external radiation [20]. The dependency of the rate of the

electron release to the local field strength is stronger when the predominant release mechanism is the detachment of negative ions. The statistical time lag modifies the initiation and growth of a discharge making it a probabilistic process in nature. Regardless of the physical mechanism of the electron generation and the cause for the polarity asymmetry of the charge, the amplitude and the frequency of the PD pulse varies depending on the number of available electrons.

2.4 PD measuring techniques for generator insulation

Various methods have been implemented in the measurement of PD in generator [39]. The frequency bandwidth of the discharge signal is very wide as the discharge signal is an impulse. While the effects of PD that inevitably takes place at the surface or inside the gaseous inclusions of the insulation are sources of concern and they have shown themselves to be reliable indicators of insulation degradation [40]. The detection of discharges is based on energy exchanges which take place during the discharge. These exchanges are manifested as (i) electrical impulse current, (ii) dielectric loss, (iii) magnetic radiation, (iv) light, (v) sound, (vi) increased gas pressure, and (vii) chemical reaction. Discharge detection and measuring techniques may be based on the observation of any of the above phenomena. PD measurements were primary used by manufacturers as nondestructive tests [41][121][123] for quality control or for type approval and proof tests [8] for customer specification. Nowadays, more efforts have been made to online measurement instead of off-line method [42]. During off-line tests with separate HV source, the thermal and mechanical stresses in the stator insulation are not the same as during operation. As a result, an off-line PD measurement does not show the PD processes of an operating generator. Also, the cost of such off-line tests is quite high as discharge free HV sources are needed. Oscillating voltage waves [43] is also used for PD detection in generator. In this nondestructive method, amplitude of the sine wave of the HV will decrease gradually. When the PD couplers are permanently installed on the generator terminals, an on-line test can be performed without any interruption of the generator operation under different loading conditions. Many electrical coupling methods have been applied for the on-line PD measurement on generators[44][45]. So it is becoming very popular in the last few years.

2.4.1 Reported methods

- Electrical [44][45]- The most frequently used and the most successful detection methods are the electrical ones. The appearance of PD within a closed apparatus can only be measured at its terminals. Localized transient current pulses (in the range of ns) induce apparent charge transport between the electrodes. In power generator, the HV coupling capacitors or HFCTs or stator slot coupler (SSC) or embedded RTD sensors are installed at the stator winding. After pre-amplification in the corresponding frequency bandwidth, the PD signal in time domain will be recorded in the data acquisition system [22]. Corona probe [32] is used in off-line mode. In addition meggering, loss-angle tests, over potential tests [49] and leakage current with respect voltage [24] are used to identify the defects in generator insulation. Spectrum analyzer [52] is also used in PD measurement on generator. The spectral analysis of the on-line test is more detailed because 3-phase PD activity can be monitored individually from each end of the corresponding phase winding. In higher band frequency (in tens of MHz), it will be possible to distinguish PD patterns in different phases.
- Electromagnetic radiation [21] - The bandwidth of the electromagnetic waves emitted from PD is very wide and ranges up to GHz. The GHz-band spatial difference method [53] has been developed to detect PD signal. The radiated microwave is received with antenna, and passed through preamplifier. Two antennas are used to distinguish the PD signal from noise signals by the time of receiving the signal at two monitored locations.
- Optical [55]-The use of optical techniques is limited to discharges within transparent media. It is also used to detect spark discharge in the generator and motor, especially in the explosion-proof motor. In this method of fundamental investigation, the attenuation of light intensity in different medium and different types of discharge are carried out. The discharge energy can be determined from the amplitude of the optical signal. The optical methods are always employed in equipment without a complex insulation structure[56].

- Sound [54][122]- The modern acoustical detection methods utilizing ultrasonic transducers can be used to localize the external discharges. The PD signal would damp quite fast in the air. The directional sensitiveness of this method depends on the placement of the sensor. The acoustic approach is merely used to locate the site of the PD.
- Chemical [43] – Ozone detector is used to identify external corona discharges. In off-line mode, localized discolored surfaces are analyzed for chemical degradation.
- Thermograph [125] – Temperature distribution on the surface of generator is scanned to identify the localized heating caused by PD.

2.4.2 PD location methods

A high frequency calibration method [57] is used to investigate the degradation level and the location of developing PD. The spectrum of the current pulse at the site of a discharge contains a wide range of frequencies. The distorted transmitted signal at the measuring terminals may be considered as comprising of a series of components of different frequencies each of which is related to the form of the PD source, its location and electrical parameters of the winding. Based on the transmission line model, a set of equations relating the PD location to the ratio of the frequency spectra of the terminal transients has been derived [58]. International standards [16] [121][123] use a comparative measurement to locate PD using the calibration signal.

2.4.3 The conventional PD measuring circuit

Many commercial PD monitoring systems [21] are developed to suit the controlled laboratory conditions. PD type tests on sample stator bars after electrical and thermal aging stresses are carried out. The conventional PD measurement method is called ERA method as proposed by the Electrical Research Association, UK [2]. The layout of this method is shown in Figure 2-1.

Figure 2-1 Circuit Layout for PD measurement

A PD of magnitude q in a test object (C_t) generates a high-frequency pulse of height Δu in the detection circuit (Z_d) due to the discharge free coupling capacitor C_k . The resistor blocks the path of PD to the HV 50 Hz source. 50 Hz HV will be mostly dissipated across C_k and high frequency PD will be mostly dissipated across Z_d for measurement. The relationship between Δu and q can be easily derived. In the above layout of this off-line test, the test object is to be isolated from the connected power network. Also discharge free HV source and PD coupler are needed. That makes it difficult for industrial user.

Since the industry is primarily interested in measuring PD in the interconnected ring bus configuration of real machines, substantial development in hardware and software is being made. Nowadays, more efforts have been made to online measurement in the restructured energy market [42]. When PD couplers are permanently installed at the ends of the stator winding, on-line tests can be performed without any interruption of the generator operation under different loading conditions. After pre-amplification with a wide bandwidth amplifier, the PD signal will be recorded in the digital data acquisition system for further processing.

2.4.4 PD sensors

To measure PD during the operation of generators, different types of couplers can be utilized depending on the budget. The bandwidth of the electromagnetic waves emitted from PD is very wide and ranges up to GHz. The coupler acts as a HV isolator, and high pass filter allowing HF PDs to be detected by a suitable instrumentation at low voltage. Most widely used ones are: capacitive couplers [52], Rogowski coils, SSC and HFCT [59]. Permanent capacitive coupler is formed using HV capacitors with encapsulated epoxy resin insulation. It

is permanently connected to the HV termination of the stator winding in a corona free mode. The bandwidth of these sensors is wide and flat for sensitive detection [5]. The Rogowski coils are air-cored current transformer without saturation and it may not be cheap and reliable in some certain cases [60]. SSC is a waveguide installed in the slot and captured PD signal will be transmitted using carrier waves. HFCT with ferrite core may have a bandwidth of 100 MHz. The radiated PD microwave signal is sensed with antenna, and passed through preamplifier. Furthermore, a down-converter may be used in the system to shift the center frequency without changing the distribution of the frequency spectrum. The PD signal would damp quite fast in the air. The sensitive of this method depends on the placement of the sensor.

Optical method [56] uses the sensitive photo-multiplier tube to sense the light emission. The discharge energy can be determined from the amplitude of the optical signal.

Apart from that radiated or surface vibrations are sensed by ultrasonic sensors in the range of 40 to 150 kHz and other UHF piezo electric sensors.

2.4.5 PD detector

All PD detection circuits use detection impedance where the current impulses are converted to voltage pulses. The detection impedance [61] can be either R with stray capacitance C in parallel or RLC (resistor, capacitor, and inductor parallel connection) type. The shape of the original PD gets altered by the detector frequency response. In ERA units, this measuring impedance is followed by a step-up ferrite transformer to get an optimal signal-to noise ratio and isolation. It is then filtered and amplified for display. In old PD measuring units, the bandwidth of detectors [62] is usually in a few hundreds kHz. With modern digital system, higher frequency band width up to 1 GHz can be measured and then it can be denoised[63].

2.4.6 Difficulties

One of the major difficulties in PD measurement is the dominant role of ambient and internally generated periodic and non-periodic noises. In addition to that, cross-talking between three phases and noise picked in connected bus bar and step-up HV transformer makes the interpretation and identification difficult. The electrical noise is caused by arcing and sparking sources such as corona on outdoor transmission and distribution lines, power

tool operation, brush sparking, electrostatic precipitators, etc [64]. In an operating power plant, noise signals from rotor excitation circuit and other environmental interferences will also be picked. By suitable denoising techniques, periodic low, high and limited band pass noises can be eliminated. Also, the original PD signal gets distorted due to reflection and attenuation when traveling through the generator winding, bus bar, transformer and any other connected power apparatus. The online PD measurement is always associated with false indications like noise coming from outside or noise becoming dominant[65].

Also, the inconsistent placement of sensors, and use of different kinds of sensors with different frequency response characteristics show the individual PD shape and PD distribution differently. The limited bandwidth of PD detection system may distort the original PD. The response pattern may differ between identical types of machines, vary with loading and ambient temperature and humidity conditions.

2.4.7 Display of PD activity

Extracted PDs with phase information are displayed as shown in Figure 2-2 (a) in conventional ERA system. After amplification, the discharge pulses are modulated on the ellipse representing 20 ms ac cycle with the corresponding phase/time information. The repetitive ac cycle is divided into 360 degrees. Using calibrating markers, the peak pulse magnitude is measured.

Figure 2-2 Methods of PD detection

(a) Conventional display using elliptical time base (b) Zoomed single pulse

In modern PD instruments [66], after denoising PD information is plotted in straight line representing 20 ms period. The character of PD distribution will be different for different defects [67] as shown in Figure 2-3. The interval between horizontal dark dots is 5 ms or 90°.

Figure 2-3 PD phase distribution: (a) Corona in the air, (b) A cavity adjacent to a conductor creates an asymmetric pattern, (c) A cavity completely surrounded by a dielectric generates a symmetric pattern, and (d) bad contact noise in the leads occurs at the maximum current

2.5 Identified PD defects in generator

The winding is a very complex inductive-capacitive network which exhibits a rich variety of resonant frequencies at measuring nodes when triggered by PD. Since windings with different layout respond differently, it is often difficult to make conclusions about the winding condition based on detected pulse magnitudes from different machines. PD distribution can identify the units with loose stator bars or delaminated slot insulation. Discharges due to stress grading problems, void inclusions, mechanical impact to the coil, surface contamination, end winding, inter-turn and poor lap at turn give different PD patterns[67]. Imperfections in ground wall insulation layers and at the insulation/ conductor interface provide suitable sites and conditions for the initiation and occurrence of PD as surface or cavity discharges[68]. Large mica flakes have a better PD resistance compared to epoxy mica paper tape. Epoxy mica tape layers are difficult to bond and they can be delaminated. The breakdown voltage and stiffness of the composite insulation with mica gradually decreases with an increasing number of repeated load cycles [62].

The load cycling leads to rapid temperature changes within the stator winding. As the slot insulation surrounding the copper conductor operates at a lower temperature, differential thermally induced expansion can elongate copper conductors resulting in a considerable shear stress along the conductor-insulation interface. If the insulation system cannot resist the stress, the bond between the copper conductor and the insulation is broken. It decreases the dielectric strength of coil bars [40]. Thin micro-cracks [41] occasionally formed during the cooling process in manufacture affect mechanical properties like adhesive strength resulting in internal PD sites.

2.6 Developed PD identification techniques

The random nature and vast amount of PD data are characterized by different PD patterns [69]. The interpretation of online PD measurement [42] to identify the defects in the stator insulation system is always composed of three parts. They are pattern of PD distribution, trend analysis and difference in individual PD pulse shapes. Many PD characteristics such as discharge magnitude, energy and repetition rate are monitored to study the severity of the discharge [70] which can be related to the performance of the insulation. In addition to various derived parameters and stochastic properties, phase angle and time interval (Δt) distribution of the PD [71] are now widely used for the assessment and service performance in existing units.

2.6.1 Derived parameters

The various derived parameters are summarized in reference [72].

- **The Apparent charge [42]-** The apparent charge of PD is that charge which, if injected instantaneously between the terminals of the test object would momentarily change the voltage between its terminals by the same amount as the PD itself. When the PD occurs in the insulation, the pulse charge measured at the two electrode ends of the sample is called apparent charge. The apparent charge is not equal to the amount of local PD discharge which cannot be directly measured. Using calibrator, the measured apparent charge is calibrated in terms of pC [57]. By using simple capacitive model and if the voltage change in the void of capacitance C_c is ΔU_c , the discharge q_c from the void is given by (2-1).

$$q_c = \Delta U_c \left(C_c + \frac{C_a C_b}{C_a + C_b} \right) \quad (2-1)$$

Equation (2-2) indicates that the relationship between the apparent charge (q_a) and the actual discharge quantity (q_c).

$$q_a = \frac{C_b}{C_b + C_c} q_c \quad (2-2)$$

where: C_a : capacitor with the electrical field lines outside the cavity.

C_c : the cavity capacitance.

C_b : two capacitors with electrical field lines starting or ending at the cavity walls.

- **Repetition rate -**

The PD pulse repetition rate (n) is the average number of measured PDs per second over a selected period. In practice, only pulses above a specified magnitude or within a specified range of magnitudes may be considered. The results are sometimes expressed as cumulative frequency distribution curves of PD magnitudes to see the trend of PD activity.

- **PD inception voltage -**

The PD inception voltage is the lowest voltage at which pulses are observed in the test arrangement when the voltage is gradually increased from a lower value at which no such discharges are observed.

- **Other Characteristic Parameters -**

Besides the above three main parameters, other characteristic parameters [43], such as the average discharge current, the quadratic rate, the discharge power, and PD extinction voltage etc. are recommended for characterization.

q_a , n and PD inception voltage are the most basic characterizing parameters of the existence and severity of PD activity. They indicate only PD activity qualitatively but they cannot characterize the type of PD

2.6.2 PD distribution analysis in a period

The PD occurrence is studied with its peak or average magnitude (q) in a selected y -window size, the averaged phase angle of that x -window at which it occurs (Φ) and the number of its occurrence in a limited q window range [72].

Some of the analysed pulse height distributions are :

- **$qm-\phi$** : The $qm-\phi$ pattern is used to evaluate the PD maximum amplitude distribution. It is known as the maximum pulse height distribution. The maximum of peak PDs at the same phase window from a series of 20 ms data is extracted and the statistical distribution of q_m with ϕ is evaluated for PD identification.
- **$qave-\phi$** : The $qave-\phi$ pattern is used to evaluate the mean pulse height distribution. Instead of taking the peak in that ϕ window, the measured 'n' peak pulse heights are averaged and the statistical distribution of q_{ave} with ϕ is evaluated. The pattern $qave-\phi$ represents an accumulated result of the behavior of PD.
- **$\phi-n$ or $q-n$** : This distribution is known as pulse count distribution. The number of pulses with a certain magnitude range (q) is counted from 20 ms data distribution. This count in each discharge level window is also studied with ' ϕ '.

Various combinational distribution plots like ' $n-q$ ' and ' $q-n-\Phi$ ' are also evaluated for identification.

The PD pulse distribution in 20 ms period is evaluated by superimposing a finite number of repetitive cycles PD data [26]. The shape of these distributions can be quantified by statistical operators. Thus there is the visual recognition of discharges by an automated computer-aided classification system [17]. With the acquired PD patterns (including the 3-D patterns), features can be extracted out by surface fitting method[73]. The statistical operator method [7] is used to identify different PD patterns.

The time based PD pulse distribution is a more direct and effect method to describe the PD character from raw data. They give the full view of all the details. The character of the different PD patterns may be described by the figures with the pulse profile and locations.

The understanding of them depends much on the experience. They give out the character by a visual method, which may be difficult to make a judgment in a quantitative way. Further quantificational analysis method is needed.

The PD pulse distribution in the form of $q-\Phi-n$ analysis is the classical method followed widely in all the International Standards [16][121][124] for identification of the types of PD. The understanding of PD distribution requires experience. They give out the features by a visual distribution method, which may be difficult to make a judgment in a quantitative way. An analysis to quantify the distribution is needed.

Statistical operators on the shape of PD distribution

A collection of sequential PD pulses that evolves in time according to probabilistic laws forms a time series. For pattern recognition purposes, the information contained in the discharge shape distributions is quantified using statistical operators.

Skewness (Sk) - describes the asymmetry of the distribution with respect to a normal distribution. It is defined as

$$Sk = \frac{\sum (x_i - \mu)^3 \times P_i}{\sigma^3} \quad (2-3)$$

where x_i is the recorded value, P_i is the probability of appearance for that value, μ is the mean value and σ is the variance as defined in (2-4).

$$\sigma^2 = \sum (x_i - \mu)^2 \times P_i \quad (2-4)$$

For a symmetric distribution, $Sk=0$, if it is asymmetric to the left, $Sk>0$, and if it is asymmetric to the right, $Sk<0$.

Kurtosis (Ku) - represents the sharpness of the distribution with respect to the normal distribution.

$$K_u = \frac{\sum (x_i - \mu)^4 \times P_i}{\sigma^4} \quad (2-5)$$

If the distribution has the same sharpness as a normal distribution, $Ku=0$. If it is sharper than normal, $Ku>0$, and if it is flatter, $Ku<0$.

Cross-correlation factor (cc) - describes the difference in shape between the pattern distributions of the positive and the negative half cycles. It is defined as

$$cc = \frac{\sum x_i y_i - \sum x_i \sum y_i / n}{\sqrt{[\sum x_i^2 - (\sum x_i)^2 / n][\sum y_i^2 - (\sum y_i)^2 / n]}} \quad (2-6)$$

A value of cc=1 means 100% shape symmetry, cc=0 means total asymmetry.

Asymmetry (Asym) - is the quotient of the mean level of PD in the negative and positive half cycles. It is calculated as:

$$Asym = \frac{Q_s^- / N^-}{Q_s^+ / N^+} \quad (2-7)$$

The asymmetry can vary between -1 and 1. A value of (-1) indicates that there is only a distribution in the positive half of the voltage cycle. A value of 0 shows that the distributions in the positive and negative half of voltage cycle are of equal size.

With the statistical parameters, the shape of PD occurrence distributions in 20 ms can be quantified by values. Different PD patterns have different characteristic values [17]. The recognition no longer relies on the operator's experience on visual justification.

It is difficult to use in situations with multi PD sources occur simultaneously. Also there are a number of statistical parameters to compare and make a decision. Additional tool like neural network [11] with these statistical parameters is needed for identification.

Weibull Distribution

Weibull distribution is used to predict the failure analysis and failure forecasts with small number of data samples. Recently PD sources are recognized using [74] Weibull processing. Using measured PD pulse height (q) cumulative distribution on laboratory test samples, discharge sources are identified from the scale and shape parameters of the Weibull distribution. The two parameter Weibull distribution of PD is expressed by (2-8).

$$F(q) = 1 - \exp\left[-\left(\frac{q}{\alpha}\right)^\beta\right] \quad (2-8)$$

$$F(q_i) = \frac{\sum_{j=1}^i n_j}{N_T} \quad (2-9)$$

The Weibull shape parameter, β , is also known as the slope. This is because the value of β is equal to the slope of the regressed line in a probability plot. Different values of the shape parameter can have marked effects on the behavior of the distribution. A change in the scale parameter α has the same effect on the distribution as a change of the abscissa scale. Increasing the value of β while holding α constant has the effect of stretching out the distribution with a reduced peak magnitude [75][76].

Different types of PD have different q-cumulative n distribution. Fitting the shape after scaling, type of PD can be identified. This method can be extended to identify multi PD sources. It is a complex statistical method of prediction and difficult to link with the physical mechanism of the type of PD.

ΔV distribution

Since the applied voltage is related to the PD activity, the PD repetition rate is a function of applied voltage. As the PD activity growth, the initial condition of the next discharge will be varied by the former discharge, according to the discharge mechanism. Therefore, there will be inter-relations between the neighbor pulses. Since different PD patterns have different discharge mechanism, different PD patterns may have different ΔV patterns. In a cavity of given size, increase in the applied voltage does not change the amplitude of the discharge but increases the frequency of the recurrence of PD. The deterioration in insulation life increases rapidly with increasing test voltage. Therefore, electrical failure can be accomplished by intensifying the field strength or ac frequency [19]. It is a good method to know inter-relationship between the pulses in sequence of different PD patterns. And it is related to the discharge theory. But it may be difficult to cope with multi source discharge.

This method analyses the distribution of difference in successive PD magnitude of the sequential pulses. Since ions are left in the dielectric, a PD can affect the subsequent discharge. Therefore, there will be inter-relations between the neighbourhood pulses. Each

type of PD has different discharge mechanism and it may have different ΔV patterns. It is a good method to know inter-relationship between the pulses in sequence of different PD patterns for characterization. With multi-sources, this method of analysis may not be valid.

2.6.3 PD identification using spectrum analysis

Spectrum analysis [77] is also applied in PD measurement on generator. The spectral analysis from the on-line test is more detailed because all 3 phases could be monitored individually from each end of the winding. In higher band frequency, it will be possible to distinguish PD patterns in different phase. FFT analysis [78] and PD distribution [79] are applied to PD identification. FFT has a special feature for extracting the average spectral intensities of recorded signal. Different PD patterns have different frequency components. However, the weak point of FFT is that the information of the time domain would be lost. And also in the frequency domain, statistical analysis need cope with the random character. To analyze the waveform, the features can also be extracted via auto regression model coefficient estimation[65].

Different PD patterns in 20 ms and single PD have different definite frequency components. If one uses spectrum analyzer, random sampling with limited sampled points may result in more error.

2.6.4 PD identification using neural network

With a well trained neural network configuration, the recognition of different PD patterns [80][81] is reported. The most widely used is the back propagation network. Other configuration of network and algorithm are also implemented. The network will be trained by some known data before putting into use. These data are acquired from some standard PD samples emitting the known types of discharge. The training will be continued until the result predicts the known group of PDs with a high percentage of trials. Ordinarily, the input data pattern for the network can be fed in 2 ways. One method [11] inputs the complete single PD waveform into the network. The other method inputs the derived parameters like from statistical distribution [12] into the network. The structure of the network is modified according to the requirements of input and output. The process of the recognition will be automatic after training. It may only be sensitive to the patterns that have been trained with.

A refined algorithm may be able to respond to an unknown pattern as unknown, instead of classifying it into known patterns [82].

By using neural network, it is possible to process a set of parallel data without knowing the internal rules for PD identification. But network is to be trained with known data which are difficult to obtain in the industrial testing. Any unknown data set like multi-sources PD can result in more difficulties in identification [83].

2.6.5 PD identification using fuzzy techniques

Fuzzy method [13] is also used to identify different PD patterns. It can be used to classify void size in terms of significant features. The rule base is modified accordingly to match the associated void feature on the size. It is mapped to the membership function describing the void size. Fuzzy method is used to judge the different aging status of PD [84]. With the development of the fuzzy algorithm, the type and level of degradation can be classified[85]. But the definition of the fuzzy boundary requires large amount of data.

2.6.6 PD identification using fractal geometry

Fractal geometry [86] is also used to describe the parameters associated with PD patterns. The most normally used image is the three dimensional pattern of $H(\phi, q, n)$, which provides the relationship between the phase, the discharge quantity and number of occurrence. It is also a method to study the tree shaped PD [86]. Only two fractal features- the fractal dimension and lacunarity are used in this method to identify the difference of various PD patterns. It can describe q - Φ - n distribution by only 2 parameters, but it is difficult to explain according to the discharge theory.

2.6.7 PD identification using wavelet techniques

Fourier transform based on spectral analysis is the dominant analytical tool for frequency domain analysis. However, Fourier transform cannot provide any information of the spectrum changes with respect to time. Fourier transform assumes that the signal is stationary, but PD signal is always a transient non-stationary nano-second period signal. To overcome this deficiency, a modified method-short time fourier transform allows representing the signal in both time and frequency domain through time windowing function

[87]. The window length determines a constant time and frequency resolution. The wavelet method [88] has broadened the study of PD into both time and frequency domain simultaneously. The advantage of wavelet method is the wavelet function matches the character of PD. PD signal rises sharply and appears in a localized region in the time domain. By decomposing the signal with different filters at various levels, the associated noise may be separated from the PD signal. De-noising on PD is implemented by this method.

The study on classification of multi-source PDs [14] is done by the decomposed coefficients from the three dimensional PD patterns. Various kinds of noise of random occurrence and shape may exist in the PD measurement. They can be narrow band sinusoidal or pulse-shaped, stochastic noise or, indeed, a combination of these in a harsh field environment. To extract the buried PD signal from the above noisy signal, wavelet techniques are applied. Wavelet analysis represents a windowing technique with variable-sized region. Wavelet analysis allows the use of long time intervals to extract more precise low frequency information and shorter regions to extract high frequency information. The ability to do local analysis with wavelet is ideal for PD analysis. The wavelet transformer provides substantial information for a signal to be processed with the property of localization in both the time and frequency domains.

Figure 2-4 Multi-resolution wavelet decomposition. h = low-pass decomposition filter; g = high-pass decomposition filter; 2 = down-sampling operation. $A_1(t)$, $A_2(t)$ are the approximated coefficient of the original signal at levels 1, 2 etc. $D_1(t)$, $D_2(t)$ are the detailed coefficient at levels 1,2.

Figure 2-5 Multi-resolution wavelet reconstruction. h' = low pass reconstruction filter; g' = high-pass reconstruction filter; 2 = up-sampling operation. $A_1(t)'$, $A_2(t)'$ are the processed or non-processed approximated coefficient of the original signal at levels 1, 2 etc. $D_1(t)'$, $D_2(t)'$ are the processed or non-processed detailed coefficient at levels 1,2.

The wavelet decomposition results in levels of approximated and detailed coefficients. The algorithm of wavelet signal decomposition is illustrated in Figure 2-4. The algorithm for the reconstruction of the signal from the wavelet transform and post processing is shown in Figure 2-5.

It is a good denoising tool and extracts the weak PD signals. It requires significant computation time depending on the sampled points. Optimization in selection of wavelet, scaling and noise thresholding has to be checked.

2.6.8 PD identification using single pulse technique

Nowadays, there is a great increase in number of papers [89] concerning the characterization of individual waveform of PD. The PD waveform exhibits the feature of transient wide-band signals in few hundred nanoseconds time duration. Unlike the narrow-band detection, the wide-band detection records nearly the true shape of the wave for characterization. It will discover the mechanism and internal details of the PD waveform. But it needs high revolution and large storage.

Single pulse analysis using the cross-correlation method

The single pulse waveform contains the information on the mechanism of the discharge [9]. Identical discharges with the same mechanism can be identified by calculating the cross-correlation of the respective time domain signals [86]. (2-8) is used to calculate the cross-correlation of two digital data with i and j defining the selected two single PD and n as the total number of sampled points of the single pulse. After collecting the random occurring single pulses, this method can be used to group the pulses with high correlation value. This method is verified by the laboratory measurements.

$$\rho_{ij} = \frac{\left| \sum_{m=1}^n f_i(m) f_j(m) \right|^2}{\sum_{m=1}^n f_i(m)^2 \sum_{m=1}^n f_j(m)^2} \quad (2-10)$$

An extension of this method is the determination of correlation coefficient of linearly related variables. A simple calculation can indicate that the results will be the same as (2-8) even if the scaling factor differs between the selected variables.

With the correlation method, auto classification can be achieved by grouping the identical pulses. But it requires more sampled points on single PD.

2.7 Types of PD

2.7.1 Internal discharge

In Figure 2-6, insulation with a cavity is sketched. Since mostly insulation is non-ohmic, it is shown as a capacitive network of a , b and c . ‘ a ’ is the capacitance of area without cavity. ‘ b ’ is the capacitance of insulation in the area of cavity. ‘ c ’ is the capacitance of cavity. This void will become the source of PD, as the field gradients in the void are strongly enhanced by the difference in permittivity as well as the shape of the cavity. For an increasing ac voltage, the first discharge will appear at the inception voltage, causing the cavity

capacitance C_c to discharge through R_c . The charges of opposite polarity produced by the discharge will drift to the walls in field direction, thus canceling the original electric field. If ac voltage continues to increase or decrease, new field lines are built up and hence the discharges are repeated during each cycle. Due to the dimension involved, $C_a \gg C_c \gg C_b$. R_a , R_b and R_c are the equivalent PD resistive parameters of the dielectric.

Figure 2-6 PD model for cavity discharge

Since the discharge takes place in a uniform cavity, the discharge pattern in positive and negative half cycles will be the same. Therefore, the discharge will appear symmetrically in the positive and negative half cycles [2] [124]. And the discharge amplitude will increase with the increase in AC voltage. Therefore, the value of the parameters will follow the case of symmetrical and normal distribution profile in both half cycles.

2.7.2 Surface discharge

Surface discharge occurs along the dielectric interface where substantial tangential field strength is present. The interface is either gas or liquid bounded. The location of the surface discharge is shown in Figure 2-7.

Figure 2-7 Model of surface discharge

In surface discharge model, C_C is the capacitance between the electrode and the dielectric surface where the surface discharge occurs. C_b is the capacitance of the dielectric in series with the surface discharge area, C_a is the capacitance of the remaining dielectric. The difference is that the dielectric is only in one side of the gas void and the other side is conductor. The surface charges occurred by discharge only can be accumulated at the dielectric side.

Since the discharge behaviour in the positive half cycle and negative half cycle is different, the discharge is also asymmetrical according to the discharge theory [4]. Normally, the discharge amplitude in positive half cycle will be lower and the discharge number will be more. Meanwhile the discharge amplitude in negative half cycle will be higher and the discharge number will be less. The statistical parameter values will also vary sharing this pattern.

2.7.3 Corona discharge

Corona discharge occurs at sharp metallic point in an electric field. As the high voltage conductor is surrounded by air, corona will occur if the local electric stress is greater than the breakdown strength of the surrounding air.

According to the theory[4], the discharge will only happen in negative half cycle and the amplitude will almost be the same. Therefore, the magnitude profile in the negative half cycle will be flat.

2.7.4 The other types of discharge

Besides three kinds of discharge, there are other types of discharges: (a) floating discharge which occurs at an electrically not connected or loosely connected metal conductor, therefore only happens when the AC wave change polarities, and (b) electrical treeing which occurs inside the dielectric, which will keep increase its effecting at a low speed [17][89]. The electrical tree looks like a branch shaped tunnel in between the electrodes. It often appears in

organic insulation materials[90]. If there is water present, the mechanism is partly changed and it is called water treeing. These phenomena are observed mostly in cables.

2.8 Planned research work

The objective of this research is the characterization of PD pulses in an operating generator. It is planned to develop a computer controlled digital data acquisition system with simultaneous multichannel record it. Since PD is a random phenomenon, it is planned to record it in multiple cycles with a fast sampling rate so that the statistical behaviour of its occurrence can be analyzed. Simultaneous recording in 3 phases can predict the cross-coupling of the dominant PD in other phases. Recording in the same phase at 2 nodes can reveal the mode of PD propagation and the external noise. In addition, it is planned to record random occurring single PDs with sufficient number of data points to evaluate its shape at different nodes.

As a second stage of research, it is planned to test the data acquisition in the laboratory with known samples and then test it in a power generating plant generator. Using the above, enough good and original data will be collected for the characterization.

In the third stage of exploration, it is aimed to develop modern denoising methods to extract PD without distortion and to retain original data for other analysis.

In the fourth stage of analysis, it is planned to develop and apply techniques to identify the characteristics of pure undistorted type of PD and apply them to unknown recorded data. The statistical operators like mean, standard deviation, skewness, kurtosis, cross-correlation factor and asymmetry will be extracted from different PD patterns. Cross-correlation method will be developed to classify different kinds of single PD pulses. Identification of the phase with high PD activity, the type and number of developing PDs will be made.

In the fifth stage of analysis, model studies will be taken to estimate the propagation path of PD and predict the possible location of PD in the operating generator.

Chapter 3 Experimental Set Up

3.1 Introduction

The main objectives of my research are to detect and characterize the types of PDs and to estimate the origin of PD in an operating generator. Section 2.4 described the various PD measuring techniques. In the laboratory, it is found that electrical method using directly coupled HV coupling capacitors can measure PD buried in HV power supply with harmonics. Also at the power generating station, permanently installed HV coupling capacitors are available for field on-line measurements. Electronic interfaces for amplification and recording with maximum sampling points are developed. In this chapter, the technical details related to the selected measurement method are detailed in brief.

The electrical method was selected for the measurement, since it can directly give the information, the discharge quantity, of the discharge activities. The quantity of the discharge can be used for further analysis. An ultra high frequency bandwidth was selected. Firstly, it can retain the high frequency information, which will contribute in analyzing the PD propagations. A high revolution rate was achieved to acquire the integrate PD pulse without losing any details. A pure resistor coupler and a HV capacitor were respectively used for coupler in lab and online measurements. They are both will high frequency response. In the online measurement multi-sensors will be used to locate the PD locations.

The PD detection system consists of four parts: the wide bandwidth sensor, the wide bandwidth preamplifier with transient protection, the filter, and the data acquisition and processing system. PD can be measured by different types of couplers. Since capacitive couplers give a wide bandwidth response, it is used both in laboratory and field studies. The block diagram in Figure 3-1 illustrates the functionality of each part. Hence the original PD signal may be distorted at various blocks and care must be taken to extract the original features for analysis. The newly developed digital diagnostic system combines the last two blocks of filter and data acquisition and analysis to extract the features of PD signals.

Figure 3-1 The block diagram of measurement system

3.2 Laboratory Measurement System

The detailed layout for laboratory studies is shown in Figure 3-2. A single stage HV transformer 230 V /100 kV controlled from LV winding with a controller and HV indicator is used as PD energizing source. A water resistor of 3 M Ω is used to limit the 50 Hz current from HV transformer and the PD current from sample to flow to HV transformer. A standard HV coupling capacitor of 105.2 pF/100 kV is used as a coupler. 1 M resistor with 90 V spark gap is used as the PD detector. Using 50 Ω coaxial cable and high frequency probes with low capacitance and high impedance, necessary interfacing is done to the oscilloscope or spectrum analyzer. A 4 channel digital Tektronix oscilloscope of model TDS7104 [91] with maximum sampling rate of 10 Gigapoints/s and bandwidth of 1 GHz is used for time domain recording. A spectrum analyzer of model HP8595E[92], with a maximum bandwidth from 9 kHz to 6.5 GHz is used for frequency domain recording. Necessary Labview software [93] routines are developed to control the GPIB controlled instruments and to acquire the data with proper settings. The Labview display and control panels on computer for the control of the spectrum analyzer and oscilloscope are shown in appendix B. Mostly, all the measurements are executed automatically after setting the system according to the requirements. The collected data are stored and analyzed using developed Matlab software [94].

Figure 3-2 Layout of the developed computer-aided measurement system

The harmonic content in laboratory power supply distorts the 50 Hz waveform as shown in Figure 3-3. The harmonic content also varies with time due to the variation of heavy industrial load surrounding University. Since PD analysis requires a proper phase reference, a calibrated phase shifter output is recorded with PD measurement. The phase shifter is energized from the same 230 V power supply. It generates a pure 50 Hz sinusoidal waveform. To calibrate the phase, 1 M Ω resistor in Figure 3-2 is replaced by a 0.1 μ F capacitor to get a capacitive divider with a ratio of 1000. The voltage across the 0.1 μ F capacitor is inputted into channel 1 of oscilloscope. LV reference pure sine wave from the phase shifter is inputted into channel 2 of oscilloscope. The phase of phase shifter is adjusted until the waveforms peaks got matched. The pure sine wave signal in channel 2 is used as the standard reference phase signal. By simple alteration of the coupling capacitor and PD sample, grounded and ungrounded test samples can be tested with maximum sensitivity.

Figure 3-3 50 Hz waveform of the laboratory power supply

3.2.1 Limitation

The maximum HV rated current and voltage of transformer are 100 mA(rms) and 100 kV(rms) respectively. The 50 Hz phase shift in charging current introduced by the 1M Ω resistor and coupler will be in the range of 1.8°. For PD signal, the cut-off frequency in the lower bandwidth will be about 3 kHz.

For group PD analysis in time domain, 20 ms data window is recorded with 5 Mega points/s with a resolution of 0.2 μ s/point. For single pulse analysis, 1.6 ms data window is recorded with 0.6 Gigapoints/s with a resolution of 1.67 ns/point. This resolution enables to record single PD with at least 256 points. Normally, 40 data file are collected continuously and automatically in sequence. The developed program names the files automatically in sequence and writes them into the hard disk. Two channels are used in the laboratory measurement to record simultaneously PD signal from coupler and reference signals.

For the spectrum analysis, with center frequency set at 150MHz, 300 MHz bandwidth signal is analyzed with 400/2000 points. The resolution will be 750kHz /point.

3.2.2 Effect of detector resistance

Instead of 1 M Ω resistor in Figure 3-2, 50 Ω resistor is also used to match the connected 50 Ω coaxial cable. There is no significant change in PD distribution in 20 ms time plane. The

peak magnitude decreases in LHS of Figure 3-4 but not linearly with resistor value. The shape of single PD varies. With $1\text{M}\Omega$, it may collect more information for single pulse as shown in RHS of Figure 3-4. Since it will behave like a high pass filter, and the starting frequency will be much lower. With $1\text{M}\Omega$, 50 Hz charging current is modulated on PD enabling the extraction of the phase reference.

Figure 3-4 Comparison of PD distribution with 50 Ω and 1 $\text{M}\Omega$

It is planned to continue PD measurement with 1 $\text{M}\Omega$ resistor due to increased bandwidth, the feasibility of extracting 50 Hz phase reference and the retention of PD distribution irrespective of resistor value.

3.3 Fabricated laboratory samples

For the analysis of the partial discharge phenomena in generators, PD samples to generate one type of PD are made. Three PD discharge sources shown in Figure 3-5 are fabricated using epoxy compound, metal electrodes and one-sided printed circuit board (PCB).

Figure 3-5 PD samples to generate three types of PD
 (a) corona PD, (b) surface PD, and (c) cavity PD

The dimension of the three samples will not affect the PD pattern, since the time or phase distribution and the waveform shape are determined by the mechanism of the type of discharge. As the sample changes, the PD amplitude will change. Some random change of the data may occur. The physics of PD generation will not result in different pattern or parameters for analysis.

3.3.1 Corona PD model

The corona studies have been undertaken with point/plane system [47][48]. The left side of Figure 3-5 shows a needle HV electrode with an air gap facing an earthed plane electrode. This model is used to generate corona PD from the sharp needle due to increased electrical gradient. In operating generator, the corona would always appear at the sharp exposed bars of generator with the damage of corona-proof painting near the end of the bar [46]. This discharge would erode the end insulation by repeated discharges.

3.3.2 Surface PD model

In the surface treatment of polymers, ceramics, and metals, discharges are intentionally created and controlled to produce the desired surface modification of surface PD model [95]. To build a standard surface discharge sample, a metal to epoxy board structure was used.

The middle Figure 3-5 shows a uniform metal electrode with a small air gap touching the epoxy insulation. The other side of epoxy insulation of PCB is grounded metal layer. This set up enables us to create the required surface discharge on epoxy insulation. In the stator of the generators, surface discharges generally appear in the leading-out terminals due to environmental contamination [23]. Occasionally, they may also appear in the slot due to loose contact [20]. Surface models were created using polymer or ceramic in contact with metal [23][63]. In my model VDE electrode in contact with epoxy board structure is used.

3.3.3 Cavity PD model

Cavity models are created by injecting air bubbles in epoxy or by making air space between electrode and XLPE [96][97].

The right side of Figure 3-5 shows a cavity bead of size 0.1 mm dia. buried in the thermosetting epoxy compound in between two plane metal electrodes spaced 10 mm apart. This model is used to create a cavity discharge. They are always cavities inside the insulation of the stator due to manufacturing defects or due to formation of delaminated coils during operation [98]. A healthy stator insulation system may produce negligible internal cavity PD.

3.3.4 Generator coil

To generate defects associated with generator coil, a sample coil shown in Figure 3-6 from a damaged 13 kV rated alternator is removed. The aluminum foil is wrapped around the coil at different places to simulate different kinds of slot and surface discharge.

Figure 3-6 7.5 kV rated generator coil

International standards [16][124] use PD distribution with phase angle for universal representation of different well known discharges. Fabricated three samples can generate those pure discharge patterns when connected to HV 50Hz source. The generated reference PD as shown in Figure 4-1 of Chapter 4 can be taken as universal representation of these three discharges.

3.4 Field measurement system

The PD on-line measurement system for the generator rated 16.5kV, 250 MW is shown in Figure 3-7. Installed six 80pF epoxy-mica HV coupling capacitors are available for the measurement. Couplers facilitated the passage of PD to the connected detector and isolated the 50 Hz /16.5 kV HV. Each phase consists of two tapping points. One is at the generator side and the other is located near the bus-bar. A $1\text{M}\Omega$ resistor is connected across the LV terminal of the capacitor and the ground. The two or four monitoring points are simultaneously monitored to evaluate cross-coupling and to study PD propagation. The spectrum analyzer and the digital oscilloscope are in turn connected to record the frequency domain and time domain responses of PD from generator, bus bar and transformer. The two instruments are controlled by the IEEE-488 bus which is linked to the computer for data storage.

Figure 3-7 Layout of PD measurement system for operating generator

With spectrum analyzer, the signals at LV terminals of Ca to Cf are measured. Both on and off-line measurements are made to evaluate the background noise. At each setting, 40 measurements are taken to evaluate the statistical behaviour.

In time domain, the procedure used in the laboratory is used for group and single pulse recordings. Simultaneous recording at 4 nodes is done to evaluate the cross-coupling and PD propagation.

3.5 Developed software

Using the above experimental arrangements, required PD data are collected. Software using Matlab wavelet tools are developed to extract the PD signal and recognize the patterns using various methods reported in the next chapter. The analysis at the same phase with data from 2 different nodes results in different responses. This information is very useful for PD location based on PD propagation analysis. The analysis of simultaneous PD responses at 3 phase terminals demonstrate the cross infection of original PD between the phases.

3.6 Conclusion

Two PD measurement systems are developed for laboratory and field studies on operating generator. Three kinds of discharge samples to generate pure cavity, surface and corona discharges have been fabricated and the characteristics of pure PD are evaluated. For mixed PDs, the 7.5 kV rated generator coil is used.

The measurements have been implemented for group and single PD analysis to study various PD distributions in time and frequency planes.

In the online measurements, the multi channel facility in oscilloscope is used to record the simultaneous PD signals from 4 couplers. Generally, each channel is connected to one phase of the generator. The additional fourth channel is connected to any of the 3 phases to study PD propagation in the same phase.

Chapter 4 PD Denoising and Analysis

4.1 Introduction

Following the development of experimental set up, PD signals are collected in the laboratory and power generating station. In most of the recorded signals, it is found that the largest signal is 50 Hz and other noises. This chapter reports the developed technique by wavelet to denoise the modulated noises in group PD distribution and to get the waveform of single PD without time and magnitude distortion. After denoising, the statistical occurrence of PD in 20 ms with 20 or 40 waveforms is analyzed for group PD distribution after phase referencing. The characteristics of pure PD in laboratory environment are investigated. For field measurements, the technique to identify the phase with more PD activities in 3 phase generator is reported. To identify the type and number of PDs, five signal processing methods are used. The first one is based on the classical PD distribution. The second one uses the statistical operators of PD shape distribution in 20 ms and the third one is developed based the nature of PD formation in terms of ΔV and Δt distribution. The fourth method is developed based on mixed weibull distribution of pulse counts. The fifth one is developed from the single PD similarity with other PDs using the cross-correlation method. In chapter 5, technique to predict the possible location of PD using the propagation model is reported.

There are many processing and analysis method. But in this work, only 5 techniques were selected. The standard for selection is that the expected method firstly should be able to quantify the discharge directly. Therefore the electrical method was selected rather than optical or ultra-sonic method. Since optical or ultra-sonic are difficult in accurate calibration of the discharge value. Also some methods measuring the indirect parameters, such as dielectric loss or chemical reaction rather than the discharge quantity, have not been selected. And basic parameters of partial discharge is discharge amplitude and time phase. Therefore these methods should be able to deal with the random amplitude and phase distribution. The 3 difficulties in PD research are pattern recognition, denoising and location. These 5 methods are developed especially for them. The part of denoising and location are specially giving out in chapter 4.3 and chapter 5 individually. And another challenge is to recognize the multi source discharge.

The first method, statistical analysis, is to provide a basis for further analysis. Also it gives out the relation ships in every aspect of discharge quantity, discharge number and discharge phase. It is the most direct method and all the details can be investigated. With different discharge patterns, such as q_{max} , q_{mean} and q_n , the character can be fully described.

In the second method, PD pattern recognition, it extracted the pattern character from the phase distribution. Based on method one, therefore this method uses the most directly PD data and is able to extract the character from a large volume of data. With many statistical parameters, the character of different pattern can be fully described out of the random nature. The advantage is it can uniform the data; the changes in PD amplitude do not have effect on it. And since it is method based on large volume of data, the random character will not effect on the results.

The third method, the $(\Delta t) - (\Delta V)$ method, is intended to discover the internal relation ship between the pulses. It is used to go for further analysis to the direction of the details of individual pulses. And it focuses on more for neighbor pulses. And it is more close to the initial discharge condition in discharge mechanism.

.As we have obtained the detail information, we also need to know the overall distribution by few key parameters. Therefore the fourth method, the Weibull distribution was used. The advantage is come out with the Weibull distribution which can cope with multi source discharge.

Finally come to the single pulse analysis, which is the trend for PD analysis, since it can give out the detail information from the PD pulse waveform, which contain more information of character and discharge mechanism. The advantage is there is no need for knowledge of the number of PD source. Therefore it can cope with several unknown discharge type at the same time.

4.2 Recorded signal

Figure 4-1 PD pattern with noise in 20 ms period for 3 PD samples

In case of corona discharge, as the ac voltage is raised from zero in the negative half cycle, corona current pulses appear intermittently and they become more regular at higher voltages. This is due to the fact that the emission of electrons is dependent on the condition of the surface. As the voltage is increased, the field becomes high enough for the spontaneous electron emission from the surface and hence the regular nature of pulses with time. This intermittence also depends upon the availability of electrons initiating ionization at or near the point. Unlike with electrodes of large area where the probability of availability of initiating electrons is high, this probability is very small in case of point electrodes. The corona discharge at inception therefore occurs as and when the electrons become available, making the discharge intermittent. At higher voltages, the depth of the electric field in the gap increases and hence the intermittence decreases because electrons somewhat away from the point, but still in its vicinity can initiate the discharge.

As the AC voltage is applied to the surface model, the voltage then was held at a value which is considered in the region of burning voltage, which is characterized by either noticing hissing or a glow, also heating was observed as the electric fields is intensified. The leakage current will be caused by the burning voltage. Under such condition the dielectric material chemically charged and more ionization between the vertical and the surface took place, such changes of the dielectric material occurred are responsible for the glow or hissing which all took place during the abnormal glow region. A breakdown occurred through or over the contaminant surface. The electric field distribution on polluted insulator surface depends on

the leakage current flow in the polluted film; and the resistance of each segment on the surface that is randomly distributed.

Many reasons will influence surface charge density and its distribution on a dielectric anode, upon the charged particle density in the gas volume of the gap, the radial and axial electric field distribution, the electronic drift velocity and the time of discharge propagation across the electrode gap. Therefore, the discharge distribute more sparsely. Charges localized on the dielectric surface of an anode were found to induce modification of the axial electric field between the electrodes, strongly reducing its value in the proximity of the anode. While during the incipient formative stages of the discharge at the cathode surface, there occurred relatively moderate differences in the electron and ion charge densities within the gap that were directly attributable to variations in the charge distribution on the anode surface. And this made the positive half cycle signal is much different from the negative half cycle signal. The accumulation of surface charge (particularly in short gaps) can more appreciably influence the discharge characteristics even before the discharge completely traverses the interelectrode distance, because discharge propagation in its subsequent or latter stages of development is controlled by the field created by space and surface charges, in addition to the external applied field. This observed effect on discharge behavior is found to occur because the charge on the dielectric anode surface, remaining from a preceding discharge, decreases the axial component of the applied electric field that may, if sufficiently large, substantially alter the electron and ion charge density within the gap. All these aspects made the distribution displays more random.

On the cavity discharge pattern, a lot of single discharge will be occurring inside the cavity. If the electric field in the gas within a cavity is raised beyond the minimum breakdown field, a discharge (I'D) can take place. After the discharge, the potential level of the cavity will be balanced again. And with the voltage keep rising and reach the breakdown field again, the next discharge will occur. The procedure is with one discharge initiating the following ones, until the changed field distribution inside the cavity makes further development impossible. With the symmetrical shape of the cavity, the PD pulses distribution will also be symmetrically distributed.

4.2.1 Time domain PD signal in Laboratory

To characterize the PD pattern of different types of pure PD, 3 samples shown in Figure 3-5 are tested. The capacitive coupler is a wide band filter and the transmitted 50 Hz and harmonics at the detector clearly obscuring the fast rising PDs are shown in Figure 4-1.

The left figure shows the corona PD at around 15 ms and the magnitude is in the range of 10 mV. The middle figure shows the crowded cavity discharges occurring in both halves of ac cycle with a magnitude of about 20 mV. The right figure shows the surface discharges with a magnitude of 200 mV with spaced time intervals. Hence, denoising and phase referencing are needed for PD identification.

4.2.2 Time domain signal in generating station

On-line PD measurements are done using the layout shown in Figure 3.7. Typical recorded PD signals in 20 ms period at A, C, E and F with 1 M Ω are shown in Figure 4-2. It can be seen that random occurring fast rising PDs appear with periodic 50 Hz charging current and commutation signals of 320 μ s duration due to silicon controlled rectifier (SCR) excitation control at all of the monitored nodes.

Figure 4-2 Simultaneously recorded PD and noise pattern at A, C, E and F

Top - Blue ϕ (G), Mid- Yellow & Red ϕ s (G), Bot - Red ϕ (T)

4.2.3 Frequency domain responses in laboratory

Using the spectrum analyzer, the frequency domain response of the three types of discharge is recorded as shown in Figure 4-3. It can be seen that the PD signal has a wide frequency spread, and spectral energy is mainly spread from 50 Hz to about 100 MHz with the laboratory samples. Out of 100MHz, the signal will damp lower than -60dB.

Figure 4-3 The spectral responses of corona, cavity and surface discharges in laboratory

4.2.4 Frequency domain responses in generating station

The spectrum analyzer is used to evaluate the frequency content of the propagated PD signal and ambient high frequency noises at the monitored nodes. To identify the frequency bandwidth of ambient noise, spectrum analyzer is used at the same nodes of the tested generator when it is not operating. Figure 4-4 (a) shows the measured response with single triggering. The noise floor of the generating station spectrum is around -67 dB. Three significant noise spectrums around 100 MHz, 180 MHz and 195 MHz are noticed and later it is verified to be due to the local transmitting station. Largest 50 Hz signal content is seen in the low frequency range. The spectrum in Figure 4-4 (b) at the same node under operating condition indicates the presence of additional frequency bands around 45 MHz and 250 MHz. This may be due to the commutation noise and PD signals.

(a) offline spectrum by single triggering

(b) online spectrum by single triggering

(c) averaged 20 offline spectra

(d) averaged 20 online spectra

Figure 4-4 The single and averaged spectrums of off and on-line data on generator

Since PD occurrence is a random phenomenon, 20 measurements are made under on and off-line modes to cancel the random noise, and to identify ambient noise and PD spectrum. For example of online measurement, the spectrum data were collected 20 times under same circumstances. And then an average was made on these 20 data. The average one was the final results. The averaged spectrum in Figure 4-4 (c) confirms the existence of 3 interfering frequency bands. The averaged spectrum with on-line data in Figure 4-4 (d) indicates the presence of PD spectrum up to 300 MHz or more. After a few analyses, it is found that the calculated spectrum varied randomly with each data acquisition. The obtained result is used to determine the maximum bandwidth of the measured PD and to identify the noise levels and frequency ranges. It is found that the PD bandwidth from operating generator may be up to 300 MHz.

4.3 Denoising methods

Introduction

From time domain responses in Figure 4-1 and Figure 4-2, it can be seen that noise is the dominant factor in PD measurements. ERA and earlier instruments [66] use elliptical display and various kinds of filters to minimize the effect of 50 Hz signal. In this project, digital techniques are developed to minimize PD signal loss. Apart from denoising the original signal, the types of noises and extracted PDs are identified for characterization. Digital filter like butterworth filter based on fourier transform (FT) is the dominant analytical tool for frequency denoising. However, these filters cannot provide any information on the change of spectrum with time. Also, they may introduce phase shift to the filtered time domain signal. For FT analysis, the signal is stationary, but PD signal is always non-stationary. To overcome this deficiency, wavelet method is developed to match the real PD signals which are not periodic and transient in character. The wavelet analysis is done based on time-frequency windows described in section 2.6.7. To evaluate the quality of denoising, the mother wavelet and decomposition levels are studied.

4.3.1 Wavelet method

In order to remove 50Hz with its harmonics and other low frequency noise, the wavelet packet technique [99] is developed. Daubechies mother wavelet is selected. The wavelet packet transform is an extension of the wavelet transform. It performs the multi-resolution analysis not only for approximation signals but also for detailed signals at each scale, using wavelet packets produced by a chosen compactly supported wavelet. The distinct advantage of using wavelet packet transform over the wavelet transform is that wavelet packet transform permits a library of disjointed wavelet bases, unlike a single wavelet basis utilized in the wavelet transform.

The wavelet packet method is a generalization of wavelet decomposition that offers a richer range of possibilities for signal analysis over the general DWT. In general DWT, a signal is split into an approximation and a detail. The approximation is then itself split into a second-level approximation and detail, and the process is repeated. For an n-level decomposition, there are n+1 possible ways to decompose or encode the signal. While in the wavelet packet

analysis, the details as well as the approximations can be split. This yields more than different ways to encode the signal. For n -level decomposition, there are $2n$ possible ways to decompose or encode the signal. For example, in Figure 4-5, component $(4, 0)$ can be seen as noise, while $(4, 1)$ to $(4, 15)$ can be used to re-construct the signal. But in general DWT, the $(4, 1)$ to $(4, 7)$ will not be available.

The typical method of analysis is shown in Figure 4-5. 4-level wavelet decomposition by the mother wavelet of 'db6' is shown.

Figure 4-5 The decomposition tree of wavelet package with 4 levels

As can be seen at the 4th level, the original signal is decomposed into 16 components from $(4, 0)$ to $(4, 15)$. Following the sequence from left to right, it contains more approximate part at $(4, 0)$ and detail part at $(4, 15)$ as shown in Figure 4-6 for corona data of Figure 4-1 (a). At $(4, 0)$, approximated signal contains the 50Hz with its harmonics and other low frequency noises. While at $(4, 15)$, the detail signal contains the high frequency components connected to PD and other noises. Other decomposed signals at $(4, 1)$ to $(4, 14)$ contain decreasing order of approximated signal and increasing order of detail signal.

Figure 4-6 Decomposed corona signals at (4, 0) and (4, 15)

To extract the PD signal, the decomposed signals can be grouped and PD signal can be reconstructed. As indicated, the (4, 0) is the decomposed noise content. Decomposed signals from (4, 1) to (4, 15) are used to reconstruct the PD signal shown in Figure 4-7.

Figure 4-7 The denoised corona discharge

4.3.2 Choosing a Mother Wavelet

Theoretically, there are various kinds of wavelet functions and each wavelet basis will make the transient analysis efficient and effective when applied to a particular problem. Extracted features vary with different wavelet bases. So it is essential to select some suitable bases in denoising the PD signal. When analyzing signals with wavelet bases [87], symmetrical, orthogonal, vanishing moment, damping characteristic and compatibility are the main

consideration factors. Therefore, the selection of wavelet bases for different problems is based on individual criterion. Based on the extra presence of large wavelet coefficients (WTC) at different detailed levels, wavelets are used to detect discontinuities and breakdown points. The PD signals can be extracted with low level details. The main reason why observing at lower levels is that the wavelets at lower levels are being compressed and have many rapid changing WTCs which contain more important information. Hence, best results can be extracted from these rapidly changing large coefficients.

The criteria taken in my analysis is based on the maximum correlation coefficient between the extracted original single PD and the extracted PD with different wavelets. In addition, the matching of cumulative energy function is also done. In Figure 4-7, at around 14ms the largest PD spikes occur. It should be noted that apart from denoising, the extracted single PD wave shape will be distorted a bit by the selected wavelet. The correlation coefficient between the original largest single PD signal and the denoised single PD is determined. The matching of the extracted PD by different wavelet in relation to original signal in dotted line is shown in Figure 4-8. The computed correlation coefficients are shown in Figure 4-9.

Figure 4-8 Fitting of denoised PD with different wavelets on the original PD

Dotted line: original signal; solid line: Denoised signal

The justification of the mother wavelet is finally based on the similarity of the original signal and the denoised signal, which was described by the correlation value between the two waveforms. As shown in Figure 4-8, correlating fitting result of 'db6' wavelet fits well, therefore, 'db6' is taken as the proper mother wavelet for the wavelet decomposition in the rest of the denoising procedures. The reason to do so is that different mother wavelet has their own character wave and we may choose the most proper one to our signal, that is introduce less distortion.

Figure 4-9 Computed correlation coefficient with different wavelets

Figure 4-10 Fitted denoised signal from different decomposition levels

Dotted line: original signal; solid line: Denoised signal

4.3.3 Effect of decomposition level on fitting

For proper denoising using wavelet decomposition, the level of decomposition is important. If the number of levels is small, the fast and slow decomposed components may not be adequately separated. Also, if the number of decomposition levels is many, the fast and slow components may have been already separated, and computational resources will be wasted. In addition, the slow component may be over separated and it leads to poor fitting.

The justification of the decomposed level is also based on the similarity of the original signal and the denoised signal, which was described by the correlation value between the two waveforms. As shown in Figure 4-11, correlating fitting result of 'level4' is almost reach 1 that means the 2 waveform is almost the same without distortion. Therefore, it can be concluded that at least the decomposition is to be done up to level 4 for my measurements

Figure 4-11 Computed correlation coefficient of extracted PD at different levels

4.3.4 Extracted PD signals from laboratory data

Using the mother wavelet 'db6' and decomposition at level 3, cavity and surface PDs shown in Figure 4-1 (b) and (c) are denoised. Denoised PD distribution is shown in Figure 4-12. The surface PD peak magnitude is significantly more in comparison with cavity PD.

Figure 4-12 The denoised cavity (LHS) and surface (RHS) PD distribution

4.3.5 Extracted PD signals and noise from field on-line data

Figure 4-13 Original data at E and extracted noises at red Φ of 250 MVA generator

Typical data measured from E in Figure 4-2 is taken for denoising. Left of Figure 4-13 shows the original recorded data with the available coupler and connected detector. Using the developed techniques in sections 4.3.3 and 4.3.4, PD is denoised and the extracted noises are shown in the right of Figure 4-13. Top right figure shows the periodic 50 Hz current waveform with 4 largest SCR signals and 2 picked up low SCR signals. The zoomed view at the bottom right figure shows the shape of SCR noise. A simple FFT analysis indicates that the bandwidth of that noise is around 100 kHz.

Further signal processing with this data is done after phase referencing the PD occurrence with respect to 50 Hz charging current waveform shown in Figure 4-13. The denoised PD distribution is shown in figure 4-14. Other digital processing is found to introduce phase errors and this procedure of denoising and phase referencing is followed for all recorded field

Figure 4-14 Denoised PD distribution at E of 250 MVA generator

data. It can be summarized that using the wavelet packet analysis method, the noises such as the 50 Hz and its harmonic peaks in laboratory, SCR noise in field and other picked AC noise in measurement can be decomposed to extract PD without magnitude and time distortion.

4.3.7 Effect of differential field measurement to reduce noise

Since our field set up is the generator connected to step-up transformer using a short-length busbar, it is planned to use a differential measurement to eliminate noise coming from transformer side. With reference to the red phase, simultaneous measurements at E and F are taken. The measured and determined PD distributions are shown in Figure 4-15. Similar distribution is observed at E and F. PD peak magnitude is comparatively more at E terminal. The simple subtraction (E-F) signal does not reduce the number of noise pulses. It is found that PD at E and F occur with time delay yielding more sampling points. Hence, differential method of canceling the noise is not used for further analysis.

Further studies are concentrated on identifying the severity, type and number of developing PDs with various techniques. Wavelet denoising technique is used to detect PD buried in noise. After that, 5 processing techniques are selected for the reasons indicated below: (1)

Phase distribution study, (2) Shape of PD distribution in repetitive 20 ms period, (3) Sequential pulse analysis, (4) Weibull analysis, and (5) Single pulse analysis.

Classical phase distribution study is selected to relate to the reported qualitative pattern on identifying the type of PD and characterize the unknown PD as single or multi-sources PD.

Shape of PD distribution in 20ms period is studied to quantify the shape distribution in 20 ms in terms of quantitative parameters. This can be used to identify/characterize the severity of PD occurrence.

Sequential pulse analysis is taken up to get the range of random scatter associated with each type of discharge. This can be used to characterize the type of developing discharge clusters.

Weibull analysis is used to identify the scale and shape fitting of multi exponential distribution of cumulative number of PD occurrence with the magnitude of PD. This can be used to identify the type of PD as each type has a unique range of scale and shape values.

Single pulse analysis is used to group the types of PD and extract the time and frequency domain characteristics of single PD. This method is useful to identify the number of different PD sources and characterize them with time and frequency domain parameters.

The objectives of different methods are to identify the types of mixed PD sources and characterize the unknown PDs using five different techniques.

4.4 Signal Processing – 1

As pointed out, PD identification is done in various ways as there are not enough experimental field observations to correlate with analysis. Many of the studies are done with laboratory

Figure 4-15 40 superimposed PDs at E and F. Top: E; Mid: F; Bot: (E-F)

data and no standard analyzing factors are established for field interpretation of different PD sources. The main reasons are the diversified usage of PD couplers, sensors and analyzing programs with various conditions. In our signal processing, each one of the factors is taken into account for analysis on laboratory and field data.

4.4.1 Analysis of different PD distribution

Since PD is a random occurring process, different PD distributions of the occurrence of PD in 20 ms period in the form of shape distribution/pattern is made. Using the laboratory samples, the characteristics of pure PD in the form of $q-\phi-n$ described in section 2.6.2 is evaluated.

The data in one cycle interval (20 ms) is divided into 200 phase windows with each window having duration of 0.1 ms. If the duration of window is long, the shape distribution will be lost as discussed in later section 4.11.11. If it is small, interference due to neighboring pulses and fluctuation due to fast changing pulses will be reflected on the distribution.

4.4.2 $qm-\phi$ and $qave-\phi$ distributions on laboratory samples

By picking the maximum peak pulse heights in each window, $qm-\phi$ plot is made as shown in Figure 4-16. Comparing with the Figure 4-7 and Figure 4-12, the distribution is seen much more

Figure 4-16 $qm-\phi$ patterns for the laboratory data

clearly. The results shown in Figure 4-16 is an accumulated outcome of 20 cycles of 20ms sampling. For the analysis of stochastic properties of PD, multi cycles are used to evaluate the distribution of the pulses.

The three used reference PDs are shown in Figure 4-16. Figure 4-16(a) shows the PD occurrence using corona sample shown in Figure 3-5(a). It can be seen that corona discharge occurs in the negative half cycle. The small magnitude pulses do not deviate from each other very much. All the pulses are evenly distributed around the peak of the negative half cycle. It matches with the ionization and pulse current phenomena with negatively charged point electrode. The appearance of trichel pulses [32] matches with the theory and experimental observations. Figure 4-16(b) shows the cavity discharge pattern generated using the sample shown in Figure 3-5(c). The pulses are concentrated around the peak of both half cycles indicating the discharge is likely due to high voltage stress. The magnitude of the pulses near the peak of half wave is much higher than the pulses appearing on either side of the peak. Identical phase patterns are reported for cavity discharges [68] which behave like a capacitively divided voltage induced discharge. The cavity size determines the capacitance and the corresponding PD peak magnitude depends on the capacitance of defect cavity. From the surface discharge pattern shown in Figure 4-16 (c), it can be concluded that the magnitude of surface discharge is more in comparison with other two discharges. Dominant pulses occur in both positive and negative half cycles with wide phase separation between

consecutive pulses. The magnitude of pulses in the negative half cycle is much greater than the pulses appearing in the positive cycle. However, there are more pulses in the positive half cycle. Surface contamination may have uncontrollable weak-link path. Surface PD capacitance will be more yielding high discharge magnitude. It also matches with the reported PD pattern [7]. All the discharges are random events and the statistical occurrence patterns for the last 50 years are used to identify the different types of discharge. Since our observation with the developed PD samples shown in Figure 3-5 matched the reported PD pattern, the knowledge gained from them are used for PD identification in operating PD generators

Also the qave-phase distribution described in section 2.6.2 is determined and the analysis shown in Figure 4-17 shows that the magnitude of corona discharge pulses is much lower than surface discharge pulses. Corona discharges occur in negative half of the voltage cycle only. The discharges are symmetrically distributed around the negative peak. The discharges are regularly spaced and have almost equal magnitude. Cavity discharge shown in Figure 4-17 (middle) shows that the pulses are concentrated at the center of the both half cycles. In every

Figure 4-17 qave- ϕ patterns for laboratory data

half cycle, the pulses are symmetrically distributed around the center peak. From the right of Figure 4-17, the surface discharges also occur in both half cycles. In positive half cycle, the

pulses often appear between 30° to 90° . In the negative half cycle, it appears between 210° to 260° . The magnitude of pulses in the negative half cycle is higher. There is more number of small pulses in the positive half cycle. Hence the mean pulse distribution in positive half cycle is more sparseness due to averaging of low magnitude pulses compared to the similar pattern of $q_m-\phi$. The qualitative features of PD phase distribution are summarized in Table 4-1.

Table 4-1 Qualitative features of PD phase distribution

Features		Corona	Cavity	Surface
Positive Half cycle	Presence of pulse	No	Yes	Yes
	Symmetrical		Yes	No
	Center skewness		Yes	No
Negative Half cycle	Presence of pulse	Yes	Yes	Yes
	Symmetrical	Yes	Yes	No
	Center extrude	No	Yes	No
Symmetrical in both half cycles		No	Yes	No

4.4.3 $q-\phi$ distribution of field data

40 sets of field data in 20 ms after denoising and phase referencing are superimposed on

Figure 4-18 The q - ϕ pattern for field data at A Figure 4-19 The q - ϕ pattern for field data at E

the same phase plane for the observations at A, C, and E of the generator. The PD activity in yellow phase at C is significantly less. PD magnitude is more in blue phase at A as shown in Figure 4-18. Peak magnitude of 5.5 V with $1\text{M}\Omega$ resistor is recorded. The dominant PDs are crowded in the first 3 ms period of both half cycles. The next phase with significant PD activity is at E of red phase as shown in Figure 4-19. Peak PD magnitudes up to 3.5 V are recorded and the dominant PDs occur in the initial 3 ms for both half cycles of ac wave. It is more crowded and the duration is longer in comparison to blue phase. The distribution suggests that developing PD in generator is not corona discharge. To eliminate the role of reflection, $50\ \Omega$ resistor is used. The recorded PD distribution is shown in Figure 4-20. Peak PD magnitude reduces only by 4 times. The distribution follows that of $1\text{M}\Omega$ resistor.

Figure 4-20 The q - ϕ pattern for field data at A and E with 50Ω

4.4.4 q - n distribution on laboratory samples

The maximum charge of the distribution for each type of laboratory discharge is determined and that interval is divided into 100 windows. The number of pulses occurring in that charge window is counted and the corresponding q and n of that window is plotted in Figure 4-21. Figure 4-21(a) on corona discharge and Figure 4-21(c) on surface discharge have more count of discharges. Figure 4-21(a) on corona discharge indicates the presence of PDs with small

Figure 4-21 The q - n pattern for laboratory data

magnitude of high repetition rate. Figure 4-21(b) on cavity discharge shows a distributed pattern without significant dominance in number and in number of pulses is also small in comparison with other two PDs. Surface PD shown in Figure 4-21(c) resembles a centralized distribution with more number of discharges. The figure shows clearly that corona and

surface PDs have more counts of pulse distribution. The pulse height variation in q is 0.035 V for corona, 0.055 V for cavity and 0.37 V for surface respectively. All the discharges have more counts in the low magnitude discharges and fewer counts at the high magnitude discharges.

4.4.5 q - n distribution of field data

The number (n) distribution with pulse magnitude (q) is evaluated in both half cycles for the field data and the distribution for A and E terminals are shown in Figure 4-22. The Figure shows that q - n distribution has maximum number of PDs with q value of 0.34 V at A and q value of 0.38 V at E and then for higher PD amplitudes, it decreases monotonically. Pulse height varies up to 5 V at A while it is up to 3.1 V at E. Comparing with the laboratory data, this pattern suggests the existence of surface discharges.

Figure 4-22 The q - n patterns for field data at A and E

4.4.6 q - Φ - n distribution of field data

A better picture of the distribution of the number of pulses with q and Φ can be seen in Figure 4-23. Left figure shows more than one hump in blue phase suggesting a possible multiple existence of PD sources. The above qualitative analysis on PD distribution in 20ms period suggests the existence of surface discharges in two locations in blue phase and one location in red phase. Further quantitative analysis is under taken with statistical operators.

Figure 4-23 The q - Φ - n pattern of field data at A and E

4.5 Signal Processing - statistical analysis -2

To make quantitative comparison of the PD signals, this second method of signal processing on the shape distribution of PD pulses is investigated by statistical operators like mean (μ), standard deviation (σ), skewness (Sk), cross correlation (cc), kurtosis (Ku) and asymmetry (asym) on positive and negative cycle data. The mathematical details on the operators are described in section 2.6.2. The aim of this signal processing is to extract the quantitative characteristic features from the laboratory data to compare with the field data for PD identification.

4.5.1 μ and σ of the laboratory data

μ and σ of pulse activity indicate the severity of PD activity and its randomness respectively. By taking the q_m - Φ distribution shown in Figure 4-16, it is found that μ of cavity PD in negative half cycle is slightly less than that for positive half cycle. Therefore, both the positive and negative half cycle will have comparable value of the μ and σ . The reason for the symmetric distribution is that the initial conditions of the discharge in both half cycles are almost the same. This is because of the symmetric character of the cavity, and the discharge mechanisms are also the same.

For surface discharge, μ in negative half cycle is much greater than that for positive half cycle as shown in Table 4-2. This is due to change in discharge conditions with polarity. The

electron and ion charge densities in the discharge around the cathode surface are relatively different. The charge density may be directly attributable to variations in the charge distribution on the anode surface. Surface PD in negative half cycle has the greatest σ indicating more randomness.

Corona's σ is least indicating less scatter. In the corona discharge, the probability of availability of initiating electrons is very small in case of point electrodes. The corona discharge inception therefore occurs when the electrons become available, making the discharge intermittent. At higher voltages, the depth of the electric field in the gap increases. Electrons somewhat away from the point, but still in its vicinity can initiate the discharge. Hence the intermittent discharge period increases.

Table 4-2 Variation of μ and σ by taking $q_m-\Phi$ of laboratory data

Qm- Φ (Figure 4-16)		Mean value, μ (V)	Standard deviation, σ (V)
Corona	Negative half cycle	0.0235	0.0054
Cavity	Positive half cycle	0.0258	0.0143
	Negative half cycle	0.0210	0.0139
Surface	Positive half cycle	0.0392	0.0255
	Negative half cycle	0.1596	0.1373

By taking the average pulse distribution in the window as shown in Table 4-3, μ of cavity discharge is least indicating the average effect of cavity discharges with high σ . Corona PD in -negative half cycle and surface PD in positive half cycle comes next in terms of averaged severity. They have least σ indicating less scatter. Surface PD in negative half cycle has maximum μ indicating the dominant PD activity and high σ indicating the randomness. For cavity discharge, the trend in both half cycles is the same whether we take q_m or q_{ave} .

Table 4-3 Variation of μ and σ by taking $q_{ave}-\Phi$ of laboratory data

qave- Φ (Figure 4-17)		Mean value, μ (V)	Standard deviation, σ (V)
Corona	Negative half cycle	0.0135	0.0015

Cavity	Positive half cycle	0.0063	0.0087
	Negative half cycle	0.0060	0.0088
Surface	Positive half cycle	0.0139	0.0017
	Negative half cycle	0.0287	0.0100

μ of corona PD in Table 4-3 negative half cycle using q-n analysis indicates more number of PD pulses and its σ varies a lot indicating wider range of pulse height variation. Cavity has minimum μ in both half cycles. For surface PD, μ in negative half cycle is more with large σ .

Table 4-4 Variation of μ and σ by taking q-n of laboratory data

q-n ()		Mean value (V)	Standard deviation (V)
Corona	-	3.1754	2.3000
Cavity	+	1.3333	0.4830
	-	1.3571	0.9288
Surface	+	1.6667	0.8660
	-	2.4444	1.5899

4.5.2 μ and σ of the field data

After extracting the qmax pulse distribution shown in Figure 4-18 and Figure 4-19, computed μ of qmax- Φ distribution at A and E in 200 windows is shown in Table 4-5. The responses at A and E are almost the same. The σ in E terminal is lower indicating lesser randomness.

Table 4-5 Variation of μ and σ by taking qm- Φ of field data

qm- Φ		Mean value (V)	Standard deviation (V)
A (Figure 4-18)	+	1.1116	0.9554
	-	1.0126	0.8431
E (Figure 4-19)	+	0.9065	0.6047
	-	0.9354	0.5990

By taking the average pulse distribution in 200 windows, computed μ at A and E is shown in Table 4-6. At E terminal, μ in positive half cycle is more with high σ indicating more random PD activity. In the negative half cycle, μ and σ are lower indicating lesser randomness.

Table 4-6 Variation of μ and σ by taking qave- Φ of field data

qave- Φ		Mean value (V)	Standard deviation (V)
A (Figure 4-18)	+	0.7572	0.4521
	-	0.7199	0.3955
E (Figure 4-19)	+	0.6768	0.6927
	-	0.3781	0.3648

Figure 4-23 shows that q-n distribution has maximum number of PDs with q value of 0.34 V at A and q value of 0.38 V at E. Pulse height varies up to 5 V at A while it is only up to 3.1 V at E. Computed μ and σ of PD activity at A and E with q-n distribution is shown in Table 4-7. μ at A is comparatively higher than at E indicating more number of PD pulses at A with a large scatter. Also both at A and E, more activity is noticed in positive half cycle. Table 4-5, Table 4-6 and Table 4-7 suggest that PD at A may be due to cavity discharges since similar activity is observed in both half cycles. Similar conclusion can be made at E but the result in Table 4-6 contradicts the above conclusion as mean value differs in positive and negative half cycle.

Table 4-7 Variation of μ and σ by taking q - n of field data

q-n (Figure 4-23)	Mean value (V)		Standard deviation (V)
A	+	7.2727	8.6357
	-	6.8864	7.3807
E	+	5.4286	5.8274
	-	5.1148	5.3169

4.5.3 Sk of the laboratory data

The PD distribution shown in Figure 4-16 is analyzed and the results are shown in Table 4-8. With qm distribution shown in Figure 4-16, Sk (-) for corona and cavity is around 0.2 indicating the symmetrical distribution. Sk (-) for surface is around 0.67 indicating the asymmetrical distribution to the left.

Table 4-8 Variation of Sk with qm- Φ , qave- Φ and q-n of laboratory data

Type	qm- Φ		qave- Φ		q-n	
	Sk (+)	Sk (-)	Sk (+)	Sk (-)	Sk(+)	Sk (-)
Corona Discharge	-	0.2030	-	0.6547		0.32

Surface Discharge	0.3272	0.6710	0.7360	1.1904	1.3978	2.7010
Cavity Discharge	0.3781	0.2328	0.8888	0.5807	1.3483	0.8289

With $q\text{-}\Phi$ distribution shown in Figure 4-17, S_k (+) and S_k (-) for all PDs lie between 0.58 to 1.19 indicating an asymmetrical distribution to the left. With $q\text{-}n$ distribution shown in, the similar trend of asymmetrical distribution to the left is observed.

4.5.4 Sk of the field data

Similar S_k factors are obtained in both half cycles. The factor varies from 0.56 to 0.79 with $qm\text{-}\Phi$ and $qave\text{-}\Phi$ distribution indicating the tendency of asymmetrical distribution to the left. With $q\text{-}n$ distribution, the factors are in the range of 1.83 to 3.6 indicating A terminal PD distribution is more asymmetrical to the left than E terminal response. Comparing with Table 4-8 laboratory results, PD at A and E may be cavity discharges using $qm\text{-}\Phi$ and $qave\text{-}\Phi$ distribution. It can be surface PDs at A and E if $q\text{-}n$ distribution is taken in.

Table 4-9 Variation of S_k with $qm\text{-}\Phi$, $qave\text{-}\Phi$ and $q\text{-}n$ of field data

Node	$qm\text{-}\Phi$		$qave\text{-}\Phi$		$q\text{-}n$	
	S_k (+)	S_k (-)	S_k (+)	S_k (-)	S_k (+)	S_k (-)
A	0.7413	0.5674	0.7953	0.5818	3.3072	3.6336
E	0.6498	0.6722	0.6456	0.6551	1.9511	1.8309

4.5.5 cc of the laboratory data

For cavity PDs, they are more correlated in both half cycles by taking $qm\text{-}\Phi$ and $qave\text{-}\Phi$ as shown in Table 4-10. Correlation with $q\text{-}n$ is not good in both half cycles indicating different pattern. For surface PD, correlation in $q\text{-}n$ is better in both half cycles.

Table 4-10 Variation of 'cc' with laboratory data

cc	$qm\text{-}\Phi$	$qave\text{-}\Phi$	$q\text{-}n$
Surface Discharge	-0.3527	-0.2684	0.7259
Cavity Discharge	0.5576	0.4849	0.3700

4.5.6 cc of the field data

For A and E responses, better cross-correlation factors are obtained in Table 4-11 with q-n data shown in Figure 4-23. Table 4-10 laboratory qm- Φ , qave- Φ and q-n results suggest that the observed PDs at A may be due to surface discharges. While at E, q-n analysis indicates the field PD may be surface, and qm- Φ and qave- Φ analyses indicate it as cavity.

Table 4-11 Variation of 'cc' of field data

cc	qm- Φ	qave- Φ	q-n
A	0.2842	0.2895	0.8932
E	0.5774	0.6060	0.9340

4.5.7 Ku of the laboratory data

Computed Ku for the laboratory data is tabulated in Table 4-12.

Table 4-12 Variation of Ku of the laboratory data

Type	qm- Φ		qave- Φ		q-n	
	Ku (+)	Ku (-)	Ku(+)	Ku(-)	Ku(+)	Ku(-)
Corona Discharge	-	1.4740	-	1.8851		-0.79
Surface Discharge	-0.9174	-0.3331	-0.2927	1.0869	6.6935	1.2309
Cavity Discharge	-0.6204	-0.8460	0.6163	0.0601	-0.6087	1.1020

For corona PD, Ku varies from 1.474 to 1.885 with qm and qave distribution in Table 4-12. The profile follows very sharp distribution in a narrow phase angle. With q-n distribution, it is flat with Ku of -0.79.

For cavity PD, Ku (-) is 0.06 with qave- Φ . It follows the normal distribution. In the positive half cycle, it tends to be a sharp distribution. With q-n distribution, sharp distribution is seen in the negative half cycle.

For surface PD with q-n, a very sharp distribution is obtained in both half cycles. With qave, very sharp distribution is seen in the negative half cycle.

4.5.8 Ku of the field data

The field data with q-n distribution shows a sharp distribution in both half cycles. It is sharper at A terminal compared to E terminal. Comparing with Table 4-11 qm- Φ and q-n results, it suggests the existence of surface PDs.

Table 4-13 Variation of Ku using field data

Ku	qm- Φ		qave- Φ		q-n	
	Ku (+)	Ku (-)	Ku (+)	Ku (-)	Ku (+)	Ku (-)
A	-0.5708	-0.8647	-0.6069	-0.9402	17.5684	15.0259
E	-0.7781	-0.8379	-0.8030	-0.8171	4.6004	3.4636

4.5.9 Asym of the laboratory data

Table 4-14 shows more positive value with surface discharges in comparison with cavity in all the three distributions. Hence surface discharge is more dominated in the negative half cycle in Figure 4-16 and Figure 4-17 either by using qmax or qave or qn distribution. Cavity discharge is more or less distributed uniformly in both half cycles with low Asym values.

Table 4-14 Variation of Asym of laboratory PD data

Type	qm- Φ	qave- Φ	q-n
Surface Discharge	0.9956	0.8542	0.6818
Cavity Discharge	0.3746	0.2548	0.3231

4.5.10 Asymmetry of the field data

Table 4-15 Variation of Asym of field data

Asym	qm- Φ	qave- Φ	q-n
A	0.9109	0.8978	0.9469
E	0.9690	0.9660	0.9422

Table 4-15 suggests the PD distribution is largest in negative half cycle at A and E. Figure 4-18, Figure 4-19 and Figure 4-23 indicate that PDs in the negative half cycle is distributed over a longer period. It suggests that PD activity may be surface discharge.

From the discussion above, it can be seen that each kind of PD mode has its own character in the set of statistical operators. Hence it is an effective method to extract the discharge character from the large amount of PD data without losing the random distribution features. Therefore it can be used to recognize the character of different partial PD patterns occurring at the field.

Summary of analysis with statistical parameters

In corona discharge, all the statistical parameters describe a flatter pulse distribution in negative half cycle. It was caused by the intermittent nature of the initiating electrons. In surface discharge, the asymmetrical distribution of the positive and negative half cycle is described by different parameters. It was due to the different PD current densities in positive and negative cycles. In cavity discharge, the statistical parameters have similar value during positive and negative half cycles. It was due to the symmetrical discharge conditions inside the dielectric boundaries of cavity.

The operators μ and σ are effective for identification of corona PD, since pulses are more similar in pulse height and σ will be small.

Sk is effective for identification of surface as it has more asymmetry to the left in negative half cycle. Large amplitude pulses in negative cycle contributes more to this asymmetry due to discharge mechanism at metal electrode.

Ku , cc and $Asym$ are effective for identification of cavity. High Ku with $qm-\Phi$ with cavity suggests the existence of very sharp distribution. Due to the use of high order moments, this parameter will be sensitive to noise. Almost equal value in both half cycles shows the symmetry which is the characteristic of cavity PD. High correlation and low asymmetry factors between positive and negative half distribution suggest the presence of cavity PD.

4.5.11 Effect of window sizing

Window sizing is important as discussed in section 4.4.1 to get the proper shape distribution. Again in the three distribution studies, both horizontal and vertical window sizing are studied to understand the effects. The typical data $qm-\Phi$ on corona shown in Figure 4-16 is taken for

illustration. The horizontal axis is divided into 100, 200 and 300 windows with a resolution of 3.6° , 1.8° and 1.2° respectively. The original data points are sampled at $3.6 \times 10^{-3}^\circ$.

Figure 4-24 Effect of horizontal window sizing on corona – $qm-\phi$

The top figure shows a smoothed flat and the change in each window is very sharp as step. The details are lost. The middle figure brings out the detailed profile with a smooth variation between successive windows. The bottom figure is very spiky with too many sharp changes. Hence, 200 windows are taken for the statistical profile analysis. The vertical windowing is also important for studying the profile. For this, typical q-n data shown in Figure 4-23 is taken for analysis. The determined total pulse count is 320. The distribution by taking

Figure 4-25 Effect of vertical window sizing on field data on q-n distribution

30,100 and 300 windows on q values with a window size of 183 mV, 55 mV and 18 mV respectively is shown in Figure 4-26. The original resolution is 1 mV. The top figure shows a maximum count of 80 occurring around q of 0.5 V. This is misleading on two aspects. One is that the shape peak shifted in amplitude value and the other is that the distribution of low magnitude pulses is lost due to wide window width. With 100 windows, the scatter and the peak location are being brought out. With 300 windows, more scatter is observed and some smoothing is to be done. For our analysis, 100 windows are taken to get the profile with initial distribution.

4.6 Signal Processing – 3

The physics of corona, surface and cavity discharges is very interesting. Corona occurs locally with very small capacitance. Surface discharge requires HV to cause discharge due to longer distance between the contaminated islands. Cavity discharge at the initial stage may be occurring in micro-voids. Hence the time interval (Δt) and the difference in pulse magnitude (ΔV) between consecutive PD pulses are used to identify the type of discharges.

Also, this parameter is proportional to the local field change at the discharge site, which is necessary to compensate for the superposed space charge field and thus to retain the inception field after a preceding discharge pulse. The local distribution of space or surface charges, and therefore their field modifying influence, depends significantly on the discharge gap and physical type of insulation defect. Consequently the external voltage difference between consecutive discharge pulses is sensitive to the type of insulation defect causing the PD signals.

4.6.1 (Δt) - (ΔV) distribution of the laboratory data

The original discharge data is taken in. Evaluated distribution of corona discharge is shown in Figure 4-26. As can be seen, most of the pulses are crowded (ΔV) in the range of $1\mu\text{V}$ to 0.01 V and (Δt) in the range of $1\mu\text{s}$ to 100 μs . It occurs only in the negative half cycle.

The difference in successive pulse magnitude and time interval may characterize the type of discharge. At PD inception, the corona discharge occurs when the electrons become available, making the discharge intermittent. At higher voltages, the depth of the electric field

in the gap increases. Electrons in its vicinity can initiate the discharge and hence the interval between successive discharges decreases. Corona occurs around the peak of negative half cycle wave. The voltage changes slowly at the peak and change in PD current will be small. Ionization will be in a very limited volume resulting in similar Δt and ΔV values.

Figure 4-26 (ΔV) - (Δt) distribution for corona discharge

Figure 4-27 (ΔV) - (Δt) distribution for cavity discharge. Top - +ve; Bot - negative

For cavity discharge, it is more or less symmetrically distributed in both half cycles of (ΔV) - (Δt) domain. It appears to be more dominant in the positive half cycle plot of Figure 4-27 (top). The interval between the pulses is longer and more scattered in comparison with corona discharge. A large percentage of pulses lie in (Δt) of 4 ms. In the case of cavity discharge, the volume where the discharge process can start is strictly limited to the small

cavity and it occurs across dielectric surfaces. The ignition conditions of a discharge pulse are also determined by the remaining space charges from previous pulses. The electron avalanches may usually start from different locations of cavity-dielectric. Therefore, the points in Figure 4-27 are distributed widely in both half cycles.

In the case of a surface discharge, electron avalanches may start from different positions on the electrode along the insulator surface. If there are simultaneous active discharge sites, pulses from these sites may occur nearly at the same time causing external time and voltage difference ΔV and $\Delta t \Rightarrow 0$. Negative cycle ΔV is more due to polarity sensitive ionization at metal electrode.

From the above analysis, different kinds of PD has different distribution in $(\Delta V) - (\Delta t)$ pattern. The location and density of points of clusters will change. Also the character is related to the initial discharge condition based on the respective physical mechanism. Therefore, it can be used to recognize different discharge patterns.

Figure 4-28 $(\Delta V) - (\Delta t)$ distribution for surface discharge

4.6.2 $(\Delta t) - (\Delta V)$ distribution of the field data

Similar analysis is extended on the field PD data measured at A and E to identify the type of developing PD. The observed distribution at A with 20 cycles data is shown in Figure 4-29. More dominant PD activity is seen in positive half cycle. They are significantly high in magnitude and are distributed up to (Δt) of 2.5 ms. It is crowded in (ΔV) up to 1.5 V with the

corresponding (Δt) of 1.5 ms in both half cycles. Other minority groups are found to spread in ΔV up to 5 V and Δt up to 2.4 ms. Low magnitude pulse activity is more over the negative half wave. The number of pulses in positive half cycle is 318 while the number in negative half cycle is 301. Almost equal numbers of PD pulses occur symmetrically in both half cycles. Largest pulse magnitudes with long time intervals (Δt) between pulses suggest that the dominant PD sources in blue phase at A may be a surface discharge.

Figure 4-29 (ΔV) - (Δt) and (ΔV) - (Δt) -n distribution for the field data at A

With red phase at E, similar behavior is observed with reduced (ΔV) in the range of 3 V in Figure 4-30. It is symmetrically distributed in both half cycles. The calculated numbers of pulses in positive and negative half cycles are 308 and 316 respectively. The scatter in positive half cycle is more. This type of distribution suggests that the developing PD sources may be cavity discharges. For identifying the number of developing discharges, signal processing using Weibull distribution is carried out.

Figure 4-30 (ΔV) - (Δt) and (ΔV) - (Δt) -n distribution for the field data at E

From the above analysis, different kinds of PD has different character in $(\Delta V) - (\Delta t)$ pattern. The location and density of points of clusters will change. Also the character is related to the initial discharge conditions of the physical mechanism. Therefore, it can be used for recognize different discharge patterns.

4.7 Signal Processing –4

Two parameter weibull distributions are found to fit if there is only one PD source. If there are multi-PD sources, the number of sub populations should be taken into account. S will vary depending on the number of subpopulation as indicated in (4.1).

$$R_{1,2,3}(q) = \sum_{i=1}^s \frac{N_i}{N} e^{\left(\frac{q}{\alpha_i}\right)^{\beta_i}} \quad (4.1)$$

where $S = 2$, $S = 3$, and $S = 4$ for 2, 3 and 4 subpopulations respectively. A non-linear regression method or direct maximum likelihood method is used to estimate the different parameters.

4.7.1 Mixed Weibull Parameter Estimation

Weibull [75] [76] analysis is used to diagnose mixed PD sources. The used software manufacturer of Weibull++ by ReliaSoft Corporation [100] uses a modified Levenberg-Marquardt algorithm (non-linear regression) when performing regression analysis on a mixed Weibull distribution

$$F(q) = \sum_{i=1}^{nw} p_i F_i(q) \quad (4.2)$$

$$= \sum_{i=1}^{nw} p_i \left[1 - \exp \left[- \left(\frac{q}{\alpha_i} \right)^{\beta_i} \right] \right]$$

$$\sum_{i=1}^{nw} p_i = 1$$

In that, α and β are the scale and shape parameters respectively, and q is the height of the detected PD signal [74]. In (4.2), n_w is the number of the fitted subpopulations and $F_i(q)$ is the cumulative weibull distribution of the generic subpopulation and p_i is the weighting factor.

If one type of PD source is present, the Weibull parameters can be calculated by least-square fitting of data to (4.4).

$$\log(-\ln(1-F(q))) = -\beta \log \alpha + \beta \log q \quad (4.4)$$

Pulse magnitude (q) and pulse count (n) plot with one peak shown in Figure 4-23 suggests the existence of one PD source. But cumulative pulse count does not fit two parameter weibull distribution defined by (4.4). The reference [76] suggests in using mixed weibull processing to identify the number of sources. Mixed weibull distribution is an additive combination of several simple weibull functions defined by (4.2).

4.7.2 Mixed weibull fitting on laboratory data

Laboratory data on pulse count shown in Figure 4-21 is used for weibull analysis [100]. Using (4.4), the fitting is made. The cavity discharge q - n distribution is fitted as shown in left figure of Figure 4-31 and the obtained α and β factors are 0.03 V and 3.25 respectively. It matches the results of reference.

Figure 4-31 Weibull distribution of q and cumulative n on cavity and surface PDs

For surface discharge, α increases to 0.14 V and β reduces to 2.

The unit of scale parameter (α) is 'V' and it varies with the type of PD charge quantity. For cavity PD, it is 0.03 and for surface PD, it is 0.14. For corona PD, two scale parameters of 0.018 and 0.024 are determined. Compared to cavity and corona, surface PD is spread with wide voltage scale range. Corona lies in a narrow range indicating more uniformity.

The shape parameter (β) is used as the identifier for different PD pattern [75] [76]. For cavity, it is fitted to 3.25 and for surface, it is 2. Corona PD is found to have high values of β in the range of 7.2 to 38.7. It is found that low magnitude pulses do not follow this modified exponential distribution showing a tail portion. It may be due to different noises in the recording environment.

For corona PD, two populations of corona are observed and the fitted distribution is shown in Figure 4-32.

Figure 4-32 Mixed weibull distribution of q and cumulative n on corona PD

Figure 4-32 clearly shows two distinct PD sources of corona. Mixed weibull distribution defined by (4.2) is used for the calculation. α_1 and α_2 are determined as 0.018 V and 0.024 V with the corresponding slope factors of $\beta_1 = 38.7$ and $\beta_2 = 7.2$ respectively. The weighing factor of first population is 49% while for the second population, it is 51%.

The analysis suggests that the scale factors for corona will be minimum with a large shape parameter. For cavity PD, the scale factor is slightly higher with shape factor in the range of 3. For surface discharge, the scale factor is higher in the range of 0.14 V with a shape factor in the range of 2. Further analysis is extended to field data.

The starting of the discharge is initiated by free electrons generated in the void. Accordingly, the generation rate of electrons is the key item to understand the cavity PD. It is possible to relate the electron generation rate to different PD patterns, since different PD types have different mechanisms to generate free electrons. For example, electrons in a void in a solid dielectric medium may be generated by the superposition of two different phenomena, that is, (i) ionization due to background radiation and (ii) electron entrapping from shallow traps at the void surface.

In summary, for a given PD type, the behavior of the free electron depends on a limited set of quantities. Therefore, there will be relations between the PD pulse amplitude and number. And we can use Weibull distribution to identify these relations.

4.7.3 Mixed weibull fitting on field data

Identification of the number of unknown PD sources and the type of PD is very important. Since yellow phase of PD response is not significant, it is not taken into account. The fitting on q-n distribution of field data indicates that mixed weibull fitting is to be done. The fitted results are shown in Figure 4-33 for blue and red phases. The fitted parameters are tabulated in

Figure 4-33 Mixed weibull distribution of q and cumulative n

Table 4-16 for blue phase which had q activity up to 4.8 V in Figure 4-22. The parameters for red phase are shown in Table 4-17. Three subpopulations are found to fit the cumulative distribution of pulse count of both phases suggesting the existence of three PD sources. p_1 , p_2 and p_3 are the percentage of data belonging to each one of the three sources. The dots in the figure are the determined pulse count distribution in field data. The continuous line represents the fitting by mixed weibull distribution.

Table 4-16 Determined Weibull parameters in blue phase

Subpopulation (p_i)	1	2	3
β_i	6	3.74	2.18
α_i	0.34	0.52	1.04
$p_i\%$	15	37	48

In blue phase, 15% of the counted pulses belong to subpopulation-1. That subpopulation-1 has a scale factor of 0.34 V with a shape factor of 6 suggesting the existence of cavity discharge. 37% of the counted pulses belong to subpopulation-2 with a scale factor of 0.52 V with a shape factor of 3.74. This also suggests that this subpopulation may be cavity discharge. It means that nearly 52% of the total PD counts may be due to 2 minor PD cavity sources. The last group with 48% of the pulse counts is dominant with a scale factor of 1.04 V. The shape factor value of 2.18 suggests the existence of surface discharge. This analysis is extended to red phase. Similar trend with less severity is observed in red ϕ in comparison with blue ϕ .

Table 4-17 Determined Weibull parameters in red phase

Subpopulation (p_i)	1	2	3
β_i	7.8	3.92	2.2
α_i	0.32	0.5	1.17
$p_i\%$	16	44	40

The shape factors β_1 and β_2 are 7.8 and 3.92 respectively for the two subpopulations indicating the presence of two cavity discharges. The corresponding scale factors α_1 and α_2 are 0.32 V and 0.5 V respectively indicating that they may be less dominant PDs. The largest subpopulation with a subpopulation of 40% is found to have a scale factor of 1.17 V with a shape factor of 2.2. This dominant PD source in red phase may be surface discharge.

This type of analysis suggests the existence of 3 PD sources in blue and red phases. Two of the three sources may be due to minor cavity PDs, such as internal PD close to a metallic part, and the largest PD source may be surface PD. The percentage of population varies with each type of three PD sources in blue and red phases.

4.8 Signal processing – 5

In the majority of the PD diagnosis method, the presence of only one PD source being active at a given instant is assumed implicitly. Unfortunately, the situation encountered during practical PD measurement is far different, and most often, more than one source of PD is active simultaneously. A new method is now proposed which may be able to identify the number of PD sources. Every individual pulse will be examined instead of evaluating PD random occurrence distribution in 20 ms. Each of the recorded pulses belonging to the same PD source assumes some definite shape and characteristics. The degree of similarity between pulses can be quantified using cross correlation coefficients.

4.8.1 PD identification using correlation coefficients

If two single pulse shapes can be defined by n sampling points, the correlation between them can be evaluated by (4-5).

$$\rho_{ij} = \frac{\left| \sum_{m=1}^n f_i(m) f_j(m) \right|^2}{\sum_{m=1}^n f_i(m)^2 \sum_{m=1}^n f_j(m)^2} \quad (4-5)$$

where f_i and f_j are two pulses with n sampling points. Clearly ρ_{ij} with a value closer to 1 means that the two pulses have greater similarity. For a pulse sequence P containing N such pulses, it can be readily seen that there will be $N(N-1)/2$ ρ_{ij} . Time sliding is also introduced to get the maximum correlation factor. Based on the evaluation of ρ_{ij} , a computational procedure is now described with the view to classify the pulses into the respective types. The correlation result indicates the similarity of the rest of the pulses to the first pulse. The limit to the closeness is fixed by setting a threshold on the correlation factor. After comparing with the threshold, the pulses which had a greater cross-correlation value than the threshold are grouped as one group similar to the first pulse. The first pulse is removed from the series and the second pulse in the pulse series will be used for the calculation reference. By the same method, the cross-correlation of all the pulses with the new reference will be calculated. After examining them by the threshold, the correlation result can be filled into the matrix with 0 or 1. Inside the matrix, the element C_{ij} represent the correlation result between pulses i and pulse j . The value 1 represents that pulse is highly correlated and can be recognized into one group. On the contrary, the value 0 represents that the pulses are not correlated and could not be recognized into the same group. The next step is to divide all the pulses in the pulse sequence into different groups according to their correlation results in the matrix.

4.8.2 Single pulse analysis of laboratory data

A mixed discharge pattern in 20 ms period with corona and surface discharges was recorded as shown in Figure 4-34(a). It shows the low amplitude corona discharges in the negative half of ac cycle and high amplitude surface discharges in both halves of ac cycle. The base signal is modulated with 50 Hz and its harmonics of energizing high voltage power supply which can be denoised as shown in Figure 4-34(b).

Figure 4-34 Mixed PD pattern in 20 ms due to corona and surface PDs

From the denoised signal, the single pulse wave shape can be extracted at each PD occurrence. Typical single surface and corona wave shape of PDs are shown in Figure 4-35(a) and (b) respectively. The oscillating pulse shown in Figure 4-35 (a) with time duration in the range of $0.3 \mu\text{s}$ is the surface PD and the exponential pulse shown in Figure 4-35 (b) with time duration in the range of $0.15 \mu\text{s}$ is the corona PD

Using (4-5), correlation coefficients are determined for all the pulses shown in Figure 4-34 (a) taking surface PD shown in Figure 4-35(a) as reference, and the results are plotted in Figure 4-36. It can be seen that similar range of correlation coefficients are obtained if the reference surface PD is taken either from positive or negative half cycles. One pulse train distribution is found to have high magnitude lying in a short time window of about 2 ms in the beginning of each half cycle. The coefficients vary from 0.6 to 1. The second coefficient pulse train distribution with uniform magnitude of 0.45 occurring only in negative half cycle appears like dense brush.

Figure 4-35 Wave shapes of (a) single surface PD and (b) single corona PD

Figure 4-36. Variation of correlation coefficient in 20 ms

- * the reference single surface PD pulse is selected from positive half cycle
- o the reference single surface PD pulse is selected from negative half cycle

Figure 4-36 shows the distribution of the number of pulses with the calculated correlation coefficient using surface PD as reference. In the figure, one can see that there is one peak occurs with correlation coefficient around 0.35. It may be corona discharge due to low correlation coefficient with surface PD and the number of occurrences peaked with about 150 pulses. The second smaller peak occurs around 0.7. It may be due to surface discharge due to high correlation coefficient and number of limited pulses.

Figure 4-37 The distribution of number of pulses with correlation coefficient

calculated using surface PD as reference

The same procedure was repeated by taking a single corona PD shown in Figure 4-35(b). By taking this single corona PD as a reference pulse, correlation coefficients were determined for all the pulses shown in Figure 4-34(a). The computed coefficients for corona varied around 0.75 and for surface discharges, it was less than 0.5.

Figure 4-38 (a) shows the extracted pulse distribution with correlation coefficients less than 0.55 determined with corona PD as reference. It is more likely due to the surface discharge with high PD magnitude and clear time separation between successive PDs. Figure 4-38 (b) shows the extracted pulse distribution with correlation coefficients more than 0.55. It is more likely the corona discharge with crowded equal low magnitude PD distribution.

Figure 4-38 Identified PDs distribution from Figure 4-34 (b)

Hence, by setting the threshold correlation coefficient and time indexing, PD groups like surface or corona can be extracted from mixed PD pattern without losing or distorting the amplitude and phase information.

4.8.3 Single pulse analysis of field data

Since the details information of single pulse is needed, the data is collected with higher sampling rate. The random occurring single PD pulses is collected in a time interval of 1.6 ms with 100 thousand sampling points resulting sampling interval of 16 ns. Typical recorded PD signals in a time interval of 1.6 ms is shown in Figure 4-39. To get sufficient number of PDs pulses, 40 sampled intervals are used in calculation.

Figure 4-39 PD distribution in 1.6 ms window and the collected single PDs at A and E

To extract the single PD pulses from the baseline noise, a noise threshold is set. If the data point is higher than the threshold, a certain number of surrounding points will be picked out as the waveform of single pulse. After we put all these extract pulses together closely one by one in sequence, we can see the 3 groups of single pulses for three phases are shown in Figure 4-39. Approximately each single PD has a length of about 256 sampled points.

4.8.4 Identified pulse groups in blue phase with correlation coefficient

43 single PD pulses are extracted. Using (4-5), the similarity in grouped pulses is identified by cross correlating one reference waveform to other single PDs. The calculated result is also a sequence. By setting some threshold, the pulses are grouped. For example: The threshold correlation factor for grouping may be set to 0.8. The cross-correlation value of the first pulse

to itself is 1. If the cross-correlation value of the first pulse to the second pulse is 0.23 and the cross-correlation of the first pulse to 24th pulse is 0.92, the correlation result in the final matrix for the first and 24th pulse will be set to 1. In the matrix, single PDs with 1 value are grouped as one group and removed for further analysis. The procedure is repeated with left-over pulses and the pulses can be classified into different groups.

(a) Dominant 3 PD groups at A

(b) Dominant 2 PD groups at E

Figure 4-40 Grouped 43 single pulses in blue ϕ and 45 pulses in red phase

Analysis in blue phase with 43 PDs results in 3 large groups as shown in Figure 4-40 (a) and the first three identified groups have 19, 12 and 10 PD pulses respectively. The red phase with 45 extracted PDs is found to have 2 large groups as shown in Figure 4-40 (b). Further checks on the classification are made by determining frequency content of the single PD. The analysis connected with blue phase is presented in the next section.

4.8.5 Time and frequency domain characteristics of pulse groups in blue phase

The first 3 groups in Figure 4-40 (a) indicate that the pulse pattern in these respective groups have a better similarity than the others. Therefore further analysis is taken on the pulses in these large three groups. Other groups contain one pulse only indicating rarely appearing pulses at A. The typical time domain response and calculated discrete fourier transform of the corresponding single PD in each group are plotted in Figure 4-41 to understand the time and frequency plane characteristics of those identified groups.

Figure 4-41 Typical time and frequency domain responses of single PD from three large single PD sources in blue phase

In time domain response of Figure 4-41, the magnitude of PD pulse profile is a fast rising one followed by a slow decay in time duration of around $0.8 \mu\text{s}$. It is oscillatory with positive and negative magnitudes. To characterize more, power spectral density of the respective pulse is determined and is shown on the right of Figure 4-41. The spectral distribution clearly shows the distinction between three groups. Since the frequency spectrum analysis yields main features, the analysis is extended by extracting the dominant resonant frequencies of each PD in that group. They are plotted in Figure 4-42 with the selected pulse number of that group. The first group of 19 pulses is found to have 3 clusters with one scattered around 30 MHz (0.3×10^8), the second one around 110 MHz and the third one around 170 MHz respectively. The second group of 13 pulses is also distributed in 3 clusters with one centering around 20 MHz, the second distributed around 60 MHz and the last one distributed around 120 MHz. The third group of 9 pulses is clustered around 2 low frequency ranges. One is crowded near 10 to 30 MHz and the other is distributed around 52 MHz.

Figure 4-42 Dominant frequency content distribution in each identified group

4.9 Summary

Five signal processing methods are used to identify the type and number of developing PD sources on the operating generator. The followed procedure is summarized below.

To get the proper bandwidth for PD detection, the spectrum method was used to identify the frequency bandwidth. After knowing the range of signal bandwidth, the denoising was implemented by the wavelet method. By selecting the proper decomposition level and mother wavelet, the original PD signals were extracted without distortion.

Among the 5 signal processing methods, the classical phase – magnitude distribution analysis was made at first. From the International Standards, the character of the PD can be reviewed by different PD distribution patterns. These patterns fully described the PD amplitude, phase locations and PD numbers with qualitative details. But it was difficult to make a direct quantitative judgment about the number of types of PD patterns in that distribution.

Therefore to quantify the shape distribution, signal processing 2 with statistical operators was used. A set of characteristic parameters was used to extract the shape distribution information from the different patterns analysed using signal processing method 1. For each type of PD defect, they have their own characteristic range of parameters. By comparing all the parameters, a decision was made. cc and asym will be the most characteristic parameters for pattern identification of cavity PD. There were also disadvantages as there were many parameters to compare at the same time.

In signal processing 3 with sequential pulse analysis, only 2 parameters Δt and ΔV were used. They give information related to every type of discharge mechanism. They describe the link between initial discharges affected by the ions left over by former discharge. At present, setting clear internal rules will be difficult to achieve and this may form a field of future research.

To understand overall PD behaviour, the Weibull distribution method described in signal processing 4 was used. With the scale and shape parameters, different PD types can be identified since they have their own characteristic range of values. By fitting with mixed Weibull distribution, multi existing sources can be identified with their pattern and also their percentage.

Further analysis with single PD pulse was made by signal processing 5. The correlation method can distinguish different types of PD waveform. It can group the pulses by its wave shape. After grouping them, the number of types in unknown mixed sources distribution can be determined.

Since PD signal is a kind of random high frequency signal with unlimited number buried in noise. It will be difficult to use just one method for PD identification. Each method has its own advantages and disadvantages. One method cannot cover all the information connected with all types of discharges. Therefore a combination of different analysis and methods can identify the types of developing PD.

Reported five methods identify that the types of developing PD may be cavity and surface discharges in generator winding. The number of such PD sources may be three in blue phase and two in red phase. Further identification on slot, delaminated, cavity near metal etc. will be implemented as a future development of research.

Chapter 5 Modelling

The detected PD responses at the stator winding terminals of generator are sums of exponentially damped sinusoids whose initial time and magnitude are difficult to predict [101]. These responses are always corrupted with electrical noise. Because of these problems to date, there is no successful method developed to precisely identify the type, number and origin of PD. This chapter reports about the propagation modes of PD, the role of different apparatus in distorting PD at the monitoring nodes, the matching of experimental observation with the model results and the possible use of the model in identifying the origin of PD. Extensive studies have been made on the surge transfer in transformer winding [102]-[105]. They are classified as electrostatic voltage component, induced magnetic component, free oscillation and an exponential component controlled by the surge impedances. PD can be assumed to propagate in the same way.

Many researchers model uses transmission line model with RLC parameters [106] [107] to match the observed responses with fabricated laboratory models. Practical researchers have speculated the possible behaviors of generator coils with experimental observations [108][109][110]. The network considered in this study is a generator connected to a transformer through a bus bar. Since the stator winding of the generator uses a finite number of wounded coils and a finite-length bus bar, an analysis may highlight the distortion introduced on the propagated PD. To achieve versatile modeling, simulation tools are needed. It can be by analytical method [111] [112] if it is a simple network or it may be analysed using commercial soft wares like Pspice[113], EMTP [114], Simulink [115] and other programs. With information from literature survey, an investigation is taken up using a simplest model as Power Seraya is interested in identifying the location of developing PDs from the measured observations [112] [116].

The location of PD in the transformer is always based on acoustic method. The acoustic signal is not a direct PD current signal compared to electrical signal. There are some other methods used in locating PD in transformer and cable [117][118]. In the case of cable, these methods are used since the structure of the cable is much simple. The corona probe test,

meggering test and visual inspection of discoloration in off-line mode and the vibration test are also used for location of defects in rotating machinery. But structure of the generator is more complex and non-uniform, compared to the structure of the transformer, therefore this acoustic method is difficult to implement in generator. Buried RTD sensors in slots are used to locate PD by monitoring the radiated signals. As a new attempt, modeling studies are taken up to locate PD from recorded on-line PD data from two locations of the same path of PD. Therefore, the simulate-correlate-match approach is used in this work.

5.1 Introduction

With the limited data relating the location of PD and the signal at the monitored nodes, propagation model studies become an important aspect of PD research area. The purpose of this investigation is to develop a PD propagation model which can match the simultaneously measured PD wave shapes at two nodes and then to identify the origin of the analysed PD. In this study, PD propagation from generator to bus bar and connected step-up transformer is studied.

Transformer is important power equipment which has been studied extensively when it is operating under electrical transient conditions [103] [109]. HV transformers with disc winding have uniform winding structure and large number of turns. Uniform transmission line model with series connected R and L with capacitances to ground and interturns is utilized by many researchers to locate PD in the laboratory [104] [105]. The selected bandwidth of matching is about 1 MHz. Off-line data is used in most of the reported research works. They reproduce the time domain measured responses at one measuring terminal with the simulation results. The software EMTP is used. This approach does not predict PD location satisfactory.

Compared to transformer, a large power generator has parallel connected coils with much fewer but longer turns [109] [110]. Since the coils lie in slots, they will have significant capacitance to grounded slot walls, and negligible series capacitance and mutual inductances to conductors elsewhere. The end connections will have less capacitance to the frame and

more mutual capacitance with other conductors in the overhanging region. Very few published papers reporting PD propagation models are available in the literature [111] [112]. Analytical methods using frequency dependent transients program such as an extension to EMTP are developed to study surge propagation in generator windings [30]. Others discuss the possible models and expected values of the model parameters. Heller [109] and Su [110] recommend a ladder network of Bewley's model on homogeneous winding by taking into account the distributed nature of the series self- and mutually-coupled inductance and resistance, capacitance between turns, and a parallel capacitance to ground and leakage resistance. Many authors recommend the use of frequency-dependent resistance and inductance to model the winding [108] [109] [110]. Multi-conductor transmission line model [58] is assumed to explain the surge propagation and the measured fast and slow components of PD. On the other hand, Gross [67] recommends to model the generator winding in the form of a short transmission line with alternate low and high surge impedances representing the coil sections in slot and overhanging area respectively.

In the present investigation, there are on-line PD couplers at 2 locations as part of an operating power system. The aim is to identify the PD activity and external noise in an operating power network. From the PD occurrence distribution in the phase angle plot, it is possible to identify the type of developing PD. External noise originating from transformer and other disturbances are identified because the simultaneous recorded time domain signals had delay at the start. From section 4.14.3, it is analysed that the Fourier analysis of single PDs will have multi resonance peaks up to a bandwidth of 30 MHz. In an attempt to locate PD in a connected network of generator, bus bar and step-up transformer, a simulation study is carried out. No similar work was reported in the literature.

The dominant and frequently occurring single PD pulse is chosen for detail simulation study. Using circuit models of the network and a simple optimization method, an attempt is made to match the simulation results with the single-pulse PD data simultaneously measured at the two ends of a bus-bar. As the simultaneously occurring PD peak signals in other phases are significantly smaller, cross-coupling effect is not considered in this work. The effect of finite

sections of distributed network in causing multi-resonance peaks in a connected network is also studied.

5.1.1 Method

Since the stator winding uses limited form-wound coils and the coil alternated in slot and overhanging sections, a short transmission line model with alternate surge impedances is used to represent the generator. The model consists of several finite sections of ladder networks which result in characteristic resonance peaks at the simultaneously measured terminals. The phase bus-bar of 25m in length is air-insulated in an earthed aluminum conduit. It is also represented by finite sections of short transmission lines. The lumped model is used for the terminating step-up HV transformer as no analysis of PD location in the sections of transformer winding is intended. Simulated PD is injected at various locations and the time domain signals at the 2 nodes are matched by varying the various distributed parameters to optimize the fitting profile at both nodes and to match the characteristic resonance peaks. The role of PD wave shape in prediction is also explored.

5.2 Modeling

Generated exponential PD impulses may be distorted as they travel through the stator winding, bus bar and then to the transformer. Also PD can propagate in different paths and modes. Since no systematic study has been carried out on the role of different paths and modes, this study is concentrated on one serial path and transmission line mode of propagation as the simultaneously recorded PD shows the attenuation and time delay. The developed model for generator, bus bar and step-up transformer is analysed before connecting them together in series for PD prediction.

5.2.1 Modeling of generator

For the purpose of analyzing surge propagation, coils with similar structure are repeated in the ladder network of a generator [119]. Each coil is represented with surge impedances Z_1 and Z_2 as shown in Figure 5-1. For generators of this type, typically there are 21 such

coils[103]. $Z1$ represents the section of coil buried in the slot and $Z2$ represents the overhanging section of coil. $Z1$ and $Z2$ are modeled with 8 elements. R_s represents the series resistance of the generator coil of unit length. L_{s1} represents the self-inductance of per unit length of the coil in the slot and L_{s2} represents the self-inductance per unit length of the coil in the overhanging area. The parallel resistances R_{p1} and R_{p2} represent the insulation of the coil in the slot and overhanging sections respectively with reference to ground. C_{p1} represents the capacitance of the portion of coil remaining in the slot. C_{p2} represents the capacitance of the portion of the overhanging coil

Hence with multitrans, the above circuit can be duplicated into N sections as shown in Figure 5-2 and the behavior of model is studied. The parameters for the equivalent circuit for PD propagation can be determined by the best-fit between the simulations and the field measurements. For fast transients, induced eddy currents prevent the immediate penetration of flux into the stator iron and into adjacent turns. In that case L_{s1} and R_s have to be modeled as non-linear elements. This point will be studied in a section 5.3.5.

Figure 5-1 Model of a single turn of generator coil

Figure 5-2 Model of stator winding of a 3 ϕ generator

5.2.2 Modeling of bus bar

Each phase of the generator output terminal is connected to the LV winding of the HV transformer through a 25-m air insulated copper bus-bar, kept in a grounded aluminum cylinder. The bus bar is modeled as a short transmission line without coupling between phases and with limited number of sections as shown in Figure 5-3. Permanently installed HV couplers, C_m , of 80 pF at the generator and transformer ends of bus bar are used for the simultaneous PD recording using R_m . The value of the measuring resistance, R_m is 1 M Ω . This is the layout of the bus bar model.

Figure 5-3 Model of an air-insulated bus bar

5.2.3 Modeling of step-up transformer

The transformer is modeled by a lumped-parameter model as the PD propagation within the transformer is not studied. As the concern is about the PD propagation until it enters the

transformer, the role of its termination at bus bar is studied. Therefore, the transformer is represented by the LC model shown in Figure 5-4 [31].

Figure 5-4 Model of the step-up transformer

5.3 Analysis of the ladder network

The behavior of finite sections of a ladder network is analyzed in predicting the possible distortion introduced on the propagated PD in terms of resonance. Since the data related to the apparatus is not available, a simple analysis is undertaken to understand the role of parameter values using the limited sections of ladder network and the reported parameters [58]. The analysis is made by determining the transfer function of the ladder network shown in Figure 5-5. By following the circuit theory, the driving point impedances are determined by lumping each section at a time. Even though the analysis can be done on any number of sections (N), the typical calculation is done by taking N=5, as shown in Figure 5-5.

Figure 5-5 Five sections of ladder network model

The series impedance of L_s and R_s is represented as Z_1 in the ladder network. The parallel impedance of C_p and R_p is represented as Z_2 . For a complex structure such as a generator, alternate impedance configuration shown in Figure 5-1 is used. In subsequent sections, driving point impedances are lumped as impedances Z_3 , Z_4 , Z_5 and Z_6 respectively and the computational steps are shown in (5-1).

$$Z_3 = (Z_2 * (Z_1 + Z_2)) / (Z_2 + Z_2 + Z_1)$$

$$Z_4 = (Z_2 * (Z_1 + Z_3)) / (Z_3 + Z_2 + Z_1)$$

$$Z_5 = Z_2 * (Z_1 + Z_4) / (Z_4 + Z_2 + Z_1)$$

$$Z_6 = Z_2 * (Z_1 + Z_5) / (Z_5 + Z_2 + Z_1) \quad (2-11)$$

Using these defined impedances from Z_1 to Z_6 , the transfer function $G(s) = V_o/V_i$ of the ladder network can be defined as

$$G(s) = \frac{Z_6}{(Z_1 + Z_6)} \times \frac{Z_5}{(Z_1 + Z_5)} \times \frac{Z_4}{(Z_1 + Z_4)} \times \frac{Z_3}{(Z_1 + Z_3)} \times \frac{Z_2}{(Z_1 + Z_2)} \quad (2-12)$$

After substituting the parameters, $G(s)$ can be rewritten in the form as (5-3) where $z_1, z_2, \dots, z_m$ are the zeros and $p_1, p_2, \dots, p_m$ are the poles of transfer function. For (5-3), $m = 2 \times N = 10$.

$$G(s) = \frac{(s - z_1)(s - z_2) \dots (s - z_{m-1})(s - z_m)}{(s - p_1)(s - p_2) \dots (s - p_{m-1})(s - p_m)} \quad (2-13)$$

Using Matlab functions, the transfer function of the network shown in Figure 5-5 can be evaluated to understand the role played by the various circuit parameters and to optimize the number of finite sections needed to model the required output response.

5.3.1 Effect of 'N' on network response characteristics

Typical parameter values for 15 to 250 MVA generators are as follows: total series resistance, $m \times R_s$ varies from 3 to 250 m Ω , total series inductance, $m \times L_s$ varies from 230 to 320 μ H and total parallel capacitance, $m \times C_p$ varies from 0.27 μ F to 0.52 μ F [58], [108] [114]. Greenwood [108] uses lumped parameters for generator as inductance value of 540 μ H and capacitance value of 0.38 μ F; for transformer as inductance value of 2.5 mH and

capacitance value of 3000 pF; and for busbar as distributed parameter values of 2.3 $\mu\text{H}/\text{m}$ and 4.8 pF/m respectively. With frequency, the measured stator winding resistance increases to 800 Ω at 20 kHz and inductance decreases to a few μH above 10 kHz [108]. The values used for the parameters of the network shown in Figure 5-5 are as follows: $m \times R_s = 0.25\Omega$, $m \times L_s = 0.3 \text{ mH}$, $R_p / m = 100 \text{ M}\Omega$, and $m \times C_p = 0.3 \mu\text{F}$. In this study, $m = 10$ to limit the processing time.

Typical predicted responses with 3 and 11 sections predicted using (5-3) are shown in Figure 5-6. It shows the resonance peak amplification and the number of peaks increases with the number of sections. The computed surge impedance, $Z = \sqrt{L_s/C_p}$ with 3 sections is 31 Ω and the velocity of propagation, $v = \sqrt{1/L_s C_p}$ is $3 \times 10^5 \text{ m/s}$. With 11 sections, surge impedance remains the same but the velocity of propagation increases to $1.2 \times 10^6 \text{ m/s}$. Increased propagation speed with 11 sections results in higher bandwidth. Beyond 350 kHz, the output voltage decays rather quickly, indicating attenuation at the high frequency range. In our results [112] and as shown in Figure 5-7, a maximum of 5 large resonance peaks is observed in the single pulse frequency response. Using the trend of the observed response in Figure 5-6 and the measured observation, it is decided that five sections are used for further analysis in an attempt to gain a better understanding of the role played by R_s , L_s , R_p and C_p of the ladder network.

Figure 5-6 Effect of N on G(s)

5.3.2 Effects of R_s , R_p , L_s and C_p on $G(s)$

The role played by R_s , R_p , L_s and C_p on the output responses is analyzed by changing one parameter at a time in all the 5 sections. Figure 5-7 shows the typical variation of 5 peaks by varying R_s from 0.6 m Ω /section to 10 Ω /section. The peak value reduces significantly and the attenuation occurs in the lower frequency range as R_s increases. When parallel resistive parameter (R_p) is varied from 10 M Ω to 10,000 M Ω , no significant change in response is noticed.

Figure 5-7 Effect of R_s on resonance peaks

A change in the series inductance value from 0.2 μ H/section to 12 μ H/section increases the peak magnitudes but the attenuation occurs in the lower frequency range as shown in Figure 5-8. The surge impedance increases and the velocity of propagation decreases as L_s increases. Similar trend in frequency response is observed with variation in C_p . When the value of C_p is reduced from 0.1 μ F/section to 0.068 nF/section, the resonance peak moves to a higher frequency range. The surge impedance increases significantly.

Figure 5-8 Effect of L_s on resonance peaks

5.3.3 Effect of Z on $G(s)$

Gross [67] reports that the conductor bar in the slot will have significant self inductance and capacitance to ground. He models the surge impedance of the turns in the slots in the range of 10 to 20 Ω and estimates the propagation velocity to be about $0.2 \times 10^8 \text{ ms}^{-1}$. With the bar leaving the slot, the overhang conductor will have less capacitance to the frame. In which case, Gross assumes the surge impedance in that section to be greater than 100 Ω . He predicts that the propagation velocity in the overhang area will be in the range of $2 \times 10^8 \text{ ms}^{-1}$. Increased propagation velocity with increase in Z indicates the dominant role of C_p .

In the present study, both L_s and C_p are changed to obtain different surge impedances. The conductor in the slot is represented by a surge impedance value of 10 Ω while that of the overhanging conductor is 664 Ω . The corresponding propagation velocity increases from $9 \times 10^5 \text{ ms}^{-1}$ to $2 \times 10^8 \text{ ms}^{-1}$. Increased propagation velocity results in high frequency resonance peaks as shown in Figure 5-9.

Figure 5-9 Effect of Z on resonance peaks

5.3.4 Effect of termination

Figure 5-10 Effect of inductance termination on resonance peaks

The effect of resistive and inductive terminations is studied by considering one element at a time. When the measured terminal is terminated with a resistor having the network characteristic surge impedance value of 31.6Ω , no resonance peaks is observed. When the termination is an inductor of $90\mu\text{H}$, 6 peaks and one trough are observed as in Figure 5-10. Four high frequency peaks retain their responses and the low frequency peaks move to high frequency range. The lowest resonance frequency response is amplified 1200 times.

5.3.5 Effect of non-linearity in R_s and L_s

When a high-frequency PD pulse propagates in a conductor, the skin effect due to induced eddy currents [103] causes more current to flow near to the outer surface of the wire instead of towards the center. Eddy current prevents the penetration of flux into the stator iron and into the adjacent turns. This effect causes an increase in the resistance and a decrease in the inductance, thus making the parameters frequency dependent. Following Heller's experimental observation [109], the non-linear effects on R_s and L_s are modeled by (5-4) and (5-5). The simulation is extended to study the effects of series non-linear elements.

$$R_s = R * (2 * \pi * f * a)^{0.7} \quad (2-14)$$

$$L_s = \frac{L}{1 + (b * (2 * \pi * f)^{0.5})} \quad (2-15)$$

where a and b are constants.

From the study, it is noted that R_s increases from $100\text{ m}\Omega$ at 50 Hz to $114\text{ }\Omega$ at 1 MHz using (5-4). At the same time, L_s decreases from $21\text{ }\mu\text{H}$ to $0.2\text{ }\mu\text{H}$ for a frequency change from 50 Hz to 1 MHz as per (5-5). The cutoff frequency in the ladder network response shifts to a higher frequency range (Refer Figure 5-8) and the peak of resonance reduces with the increase in frequency (Refer Figure 5-7) due to non-linearity.

5.3.6 Effect of alternate Z_1 and Z_2

The effect of alternate Z_1 and Z_2 as shown in Figure 5-1 is studied with 5 sections of $Z_1=500\text{ }\Omega$ and $Z_2 = 31\text{ }\Omega$ connected in series. The resulting frequency response curve (shown as solid line in figure 5-11) contains ten double overlapping peaks of amplification and 10 troughs of attenuation over the frequency range from 5 MHz to 75 MHz . Note that the peaks of the frequency response lay in the middle of the ladder network responses which have the same and uniform surge impedances of either $500\text{ }\Omega$ or 31Ω . In summary, it is found that increased number of peaks and troughs will occur due to the alternate parameter variations such as those seen in generator winding.

The main findings of the above analysis on finite ladder network can be summarized as follows: the number of resonance peaks increases with the number of identical sections. Increased series resistance attenuates the resonance peaks significantly. Increased series reactance and/or parallel capacitance reduces the bandwidth of resonance peaks. Increased surge impedance with large parallel capacitance variation increases the bandwidth of resonance peaks. With alternate low and high surge impedances such as that existing in a generator coil, the number of resonance peaks will increase in the form of overlapping, and the trough will be introduced.

Figure 5-11 Effect of 10 sections of bar with alternate $Z_1=500 \Omega$ and $Z_2 = 31 \Omega$ on resonance peaks

5.4 Simulation

The starting parameters of the generator for modelling were selected from the reference books and papers [107][109][58][114][109][108] according to their power ratings. But with the same rating, there may be small variation of these parameters for generators of different manufacturers. Their size and structure will also vary with each type of model. With that limitation, fine tuning was taken up to estimate the real value of parameter of the tested generator since it was not known besides in predicting the possible location of PD.

The fine tuning of the parameters was implemented by allowing a variation of less than 10% of the reported values. The methodology is described below. For the voltage and MVA rating of the desired generator, the reported literature parameters are identified. Then a proper distributed model based on the number of coils and overhang area is designed. A tentative signal processing using simulink is carried to get the output at two terminals for the injected PD at different location of winding length. Sensitivity analysis at the two measuring nodes is made by changing different parameters. Using that information, a match on the magnitude and time delay of the simultaneously recorded single PDs in time domain at two terminals is made. This will identify the possible winding length where PD is originated. Then fine tuning is carried out in two steps. In the first step, parameters and waveshape of injected PD are varied to get the maximum correlated time domain output at two nodes. Then

second fine tuning is taken up to match the characteristic resonance peaks of frequency domain responses at two nodes. In all the above steps, the range of variation of the parameters is restricted. The obtained parameter values after all these steps are the values more close to the real model representation of generator.

In an attempt to reproduce the PD data observed on the generator, bus bar and transformer network, a more powerful simulation tool is needed to predict the network responses in time and frequency domains. Simulink [94] is found to be a suitable scientific tool to simulate the required type of PD and has the flexibility of allowing the building up of a very complex network. It is possible to make a precise time domain simulation of the propagation of the PD through the desired combination of apparatus model. PD can be injected at the desired location. The responses can be predicted at the desired multi-locations. The validity of Simulink is tested in predicting the resonance peaks derived using (5-3). Responses shown in Figure 5-6 to Figure 5-11 can be predicted. For the injected PD signal with rise time of 2 ns and fall time of 15 ns, similar experimental resonance peaks are obtained.

Using Simulink layout, the tested power network is modeled as shown in Figure 5-12 by serially connecting each apparatus model [111] [120]. The initial parameter values are taken from [108] [114] [119] [120]. The exponential PD signal is injected at any one of ten sections in the generator model. The output responses are recorded at the bus-bar terminals denoted as C and D in Figure 5-12.

5.4.1 Matching the responses at C and D

The time domain measured responses at C and D terminals are correlated with the corresponding simulated responses. The parameters of the generator, bus bar and transformer are tuned so that maximum correlation is achieved. After that and using wavelet technique [112], the envelope of single pulse without oscillation is extracted. For the measured and simulated envelope responses, the parameters are again fine tuned to achieve maximum correlation. In this study, maximum correlation factors of 0.94 and 0.72 are obtained for C terminal and D terminal responses respectively. Matched absolute time domain envelope profiles are shown in Figure 5-13. For the original responses with oscillation shown in Figure

5-14 and Figure 5-15, the correlation factors at C and D are 0.31 and 0.39 respectively. It is due to improper matching of the time delay on peaks.

Figure 5-12 Simulink layout for PD simulation study

Figure 5-13 Extracted low frequency profiles at C

Using this method, time domain response duration, peak level and envelope of single PD are matched to the recorded time domain responses at C and D as shown in Figure 5-14 and Figure 5-15. It is noted that in this instance, injected PD from the 8th section of generator simulation model matches the recorded responses at the two nodes most closely.

In Figure 5-14, the first and largest peak of the measured PD is 0.53 V, and the main peak of the simulated PD is 0.47 V. The pulse duration of the measured data is 1.26 μ s, as compared to that from simulation of 1.24 μ s. More decaying peaks are observed at C. The peak

magnitude decreases and the pulse duration increases as the measuring location moves away from the origin of the PD. At D, the dominant peak of the measured PD is 0.22 V, and the matched maximum peak of the simulated PD is 0.22 V in Figure 5-15. The pulse duration of the measured data at D is 1.68 μ s as compared to the simulated PD of 1.66 μ s. The delay between the starting times of the two pulses captured at C and D is estimated to be 10 ns. The time difference in the occurrence of the peaks of the two pulses is 400 ns.

Further analysis shown in Figure 5-16 and Figure 5-17 are made in the frequency domain to evaluate the predicted resonant frequencies and its power spectral density values. With the

Figure 5-14 Results of measured (dotted) and Simulink (solid) time domain responses of single PD at C

response observed at C, the three large peaks are observed at 16.1 MHz, 18.8 MHz and 8.3 MHz. The corresponding two of the three peaks obtained from simulation occur at 16.8 MHz and 18.1 MHz respectively. The power spectral densities (PSD) of the corresponding measured peaks are 0.031, 0.016 and 0.009, while that of the simulated PD are 0.03 and 0.014. From the analysis on the measurements carried out at D, there are three large peaks occurring at 5.4 MHz, 16.6 MHz and 27.6 MHz with the PSD of 0.012, 0.003 and 0.003. The simulated resonance signal occurs at close to the same frequencies with magnitudes of 0.012,

Figure 5-15 Results of measured (dotted) and Simulink (solid) time domain responses of single PD at D

0.002 and 0.003. Hence, the simulation results appear to agree reasonably well with the measured data.

This method of analysis can be readily extended for other types of network models taking various modes of PD propagation to make a better match between the measured and simulation results. The advantage of simulation with such an extended network apparatus is the prediction of other observed phenomenon, such as the effects due to other forms of PD waveform or of PD location as will be shown in section 5.4.2.

Figure 5-16 Results from measured (dotted) and Simulink (solid) frequency domain responses of single PD at C

Figure 5-17 Results from measured (dotted) and Simulink (solid):
Frequency domain responses of single PD at D

5.4.2 Predicted responses due to origin/location of PD

The PD can occur at any location within the stressed area. In the time domain response, it is seen that there is a time delay in the range of 5 to 80 ns between the responses measured at C and D. In the simulation studies also, identical range of delay is observed thus indicating the dominant propagation mode as traveling waves. The determined delay increases as the distance between the measuring node and the PD occurrence location increases. In figure 5-18, the predicted frequency domain responses at C for the possible occurrence of PD at sections 2, 4, 6, 8 and 10 of generator model and at E of bus bar are shown by solid lines. Among these responses, PD injected from the 8th section of generator model matches most closely with the measured PD frequency response shown by dotted lines. For other sections of winding, the peak amplitude both in time and frequency domains differs significantly from the measured PD. Figure 5-18 (e) indicates that PD from the nearest monitoring node will result in low PSD with some distributed minor peaks. This may be due to the limited number of reflecting nodes and the PSD content of injected PD. If the injected PD is from E, high frequency resonance peaks occur at 16.8 MHz, 20.5 MHz, 23.9 MHz and 26.1 MHz with corresponding amplitudes of 0.003, 0.006, 0.005 and 0.005 in Figure 5-18 (f). They are due to reflections at E and F. The shift in resonance peaks and its low PSD can be used to identify PDs from the nearest monitoring nodes. In general, the characteristic resonance frequencies of the network and multimode propagation paths through which the wave travels determine

the shape of the peak.

Figure 5-18 Predicted frequency responses due to the injected PD from various sections of generator winding at C

Observed at D, Figure 5-15 shows a close match in the time domain response. In the frequency domain, a match with the measured PD (dotted lines in Figure 5-19 (d)) is obtained when simulated PD is injected from the 8th section of generator model. For PD injected from other sections, the magnitude of resonance peaks differs and the bandwidth of peaks varies. For the injected PD at E, PSD in Figure 5-19 (f) is low with minor resonance peaks. PD injected from section 10 of generator model results in resonance peaks at D in Figure 5-19 (e). Low PSD with wider bandwidth peaks indicates the nearest monitoring node.

Figure 5-19 Predicted frequency responses due to the injected PD from various sections of generator winding at D

5.4.3 Predicted responses due to PD wave shape

Simulation studies are extended to assess the effects of PD voltage magnitude and the shape of PD on the responses. PD is generated using (5-6).

$$u = U_{\max} \left(e^{-\frac{t}{\tau_1}} - e^{-\frac{t}{\tau_2}} \right) \quad (2-16)$$

where τ_1 = coefficient for wave front; τ_2 = coefficient for wave tail and $U_{\max}$ = voltage.

Table 5-1 lists the typical cases simulated and figure 5-20 shows the responses at terminal C.

Table 5-1 Simulated PD waves

	Case 1	Case 2	Case 3
PD front time (ns)	2	50	2
PD tail time (ns)	15	500	15
Apparent Voltage (V)	3.5	3.5	7

Case 1 is that of a 2/15 ns exponential PD used to fit responses shown in Figure 5-14 and Figure 5-15. In Case 2, both the front and tail times are increased. No significant change in high frequency response at 16.8 MHz is noticed. The low frequency range PSD peak increases significantly as the injected signal carries significant low frequency content. In Case 3, the effect of voltage peak magnitude of PD on the responses is evaluated. By comparing the results of Cases 1 and 3 shown in Figure 5-20, the PSD peak is observed to increase by 6.7 times when PD peak magnitude is increased of 2 times.

Figure 5-20 Predicted frequency responses due to the injected PD shapes

From the above study, it can be concluded that

- 1) Simulink can be used to develop network propagation path of PD that occurred in generator winding. In the simultaneously measured and simulated data at 2 nodes, the matching criteria may be the time domain low frequency envelope without oscillation and the frequency domain characteristic resonance frequencies.
- 2) This study indicates that the dominant mode of propagation is the traveling waves. It takes up to 80 ns for a single PD pulse to travel between the two monitored nodes spaced at 25 m in the busbar. The signal is attenuated as it travels away from PD origin.
- 3) The model in Figure 5-18 (e) and Figure 5-19 (f) predicts that the nearest monitoring node may have the PSD distribution of injected PD with minor peaks due to reflection. As the monitoring node moves away, the propagation path length, reflection and resonance characteristics determine the shape and resonance peaks. Possible length of PD occurrence can be predicted by the model using simultaneously measured responses at 2 nodes. Most of PD signal will be dissipated in the generator winding.
- 4) Exponential PD with slow rise and long tail may give rise low frequency resonance response at the monitoring nodes. The output PSD is not linear with the peak of injected PD voltage.

5.5 Conclusion

Models for generator, transformer and bus bar are proposed. Since generator uses a finite number of long coils, the length of bus bar is only 25 m and there is a finite time delay in PD at the two observed nodes of the bus bar, a transmission line model is used in simulation for

modeling the generator and the bus bar. Analysis of ladder network using derived network transfer function and SIMULINK predicts the generation of multi single as well as inter-modulated resonance peaks as shown in Figure 5-11. It is shown in Figure 5-12 that this type of analysis can be extended to connected power network consisting of a 250 MVA generator, bus-bar and unit step-up transformer in predicting the distortion introduced on PD from origin to monitoring node. Measured and fitted single PD at C and D in time and frequency domains shown in Figure 5-14 to Figure 5-17 suggest that the resonance frequencies are generated due to reflection at the mismatching nodes and resonance in the propagation path.

PD peak magnitude is found to decrease due to the resistive attenuation and reflection along the propagation path. At C, the time domain peak signal in Figure 5-14 is 0.53 V with duration of 1.26 μ s. While at D, the peak in Figure 5-15 reduces to 0.22 V with increased time duration of 1.68 μ s. There is 10 ns time delay at the start of PDs, and 340 ns time delay in peak PD occurrences at C and D suggesting the dominant transmission line mode of propagation.

The PD propagation path from origin to C and D introduces the characteristic resonance frequencies. At C in Figure 5-16, the observed frequencies with largest PSD are 8.3 MHz, 16.1 MHz and 18.8 MHz. While at D in Figure 5-17, PSD decreases and the observed largest frequency is 5.4 MHz.

It is also shown in Figure 5-18 (d) and Figure 5-19 (d) that the measured PDs may have been generated at 80% of the length of generator winding from neutral. Analysis with the developed model indicates that PD from the nearest monitoring node will have short duration and sharp rising pulse in the time domain, and low PSD in the frequency domain as shown in Figure 5-18 (e) and Figure 5-19 (f). As the monitoring node moves away from PD origin, resonance peaks of significant magnitude, which give the character information of the network, will be introduced in frequency domain as shown in Figure 5-18 (f) and Figure 5-19 (e).

Further analysis on the results of Figure 5-20 indicates that the low frequency component

will be introduced if the initiating PD contains significant low frequency component.

This method of analysis offers the possibility of evaluating other forms of parallel dynamic modes of PD propagation such as that of a combination of transmission lines model with capacitive and magnetic coupling at various junctions.

Chapter 6 Conclusions and Recommendations

An experienced research and theoretical analysis carried out during the past 3 years of Ph.D program in the laboratory and power generating station to characterization the PD pulses recorded on an operating 250 MVA rated power generator is reported in this thesis. Before starting the work, a literature survey is carried out to learn the developed PD methods over the last 40 years and a summary indicating the types of observed PDs in generator, current measuring and analyzing methods is presented in Chapter . The study indicates that the recorded PD signatures are a function of PD coupler, PD sensor, the type of tested apparatus, the bandwidth and sampling rate of recording devices and the final identification of the type of PF may depend on the analyzing methods. No literature is available to identify the number of developing PD sources and the possible location of them in an operating generator. The identified PF defects in generator are termed as delaminated slot discharge, poor lap at turn, ground wall discharges, exposed conductor, micro-cracks, bonding and contamination discharges. In general, they fall into three major classes of PDs widely known as corona, cavity and surface discharges and their sub-classes. Due to limited facility and time, attempts are made to classify PDs based on major classes of PD and the study may be easily extended to others if essential features connected to defined defects are known.

With that in mind, laboratory test facilities and PD data collection are made as described in Chapter 3. The setting like sampling rate, detector resistance, duration and number of sampling for the data acquisition system are optimized for the PD pulse distribution analysis in 20 ms period and single PD analysis. Three samples are fabricated to generate pure corona, cavity and surface discharges and a PD coupler of HV capacitor with short length cable is used for interfacing. For mixed discharges, coil removed from a generator is used in the laboratory. For field test, an operating 250 MVA/16kV generator connected to step-up transformer through a short-length bus bar is used at a power generating station. 6 PD couplers are available for interfacing. Both on

and off-line measurements were carried out. To avoid error in data collection, the measurement procedure was automated with PC and a 1 GHz bandwidth 4 channel oscilloscope with a newly developed controlling Labview based software. Extensive analyzing software routines were developed using Matlab with its toolboxes. This procedure enables me to standardize the data collection modes for laboratory and field data comparison and to minimize the error due to various interfacing hardware on the random occurring PS signals with different noises.

Having collected PD data, denoising and analyzing techniques reported in Chapter 4 were developed to identify the severity of PD activity, the type of PS and the number of developing PD sources in Laboratory and field recordings. The recorded time and frequency domain signals contained various types of dominant noises. New wavelet packet transform using Daubechies mother wavelet is developed to extract single PS and PD distribution without noises in 20 ms period and without amplitude and phase distortion. 50 Hz phase referencing signal is also obtained without any phase distortion. The existing types of noise can be separated in the time plane. Having satisfied with denoising technique, research is focused on extracting the features of pure PD in the laboratory and using those features to identify the developing PDs in operating generator.

Five signal processing methods were used to identify the severity and type of PD. The first two signal processing methods were based on classical pulse distribution studies and the other three signal processing methods were developed by me. Signal processing – 1 is based on PD occurrence distribution in 20 ms period using PD magnitude (q), number of PDs (n) and the phase which is used for more than 50 years as a qualitative analysis. The distribution pattern can vary depending on vertical and horizontal window sizes, number of sampled data and calculation based on maximum or average signals in that window size. This method of interpretation is good for the identification of corona discharge. To analyze the severity, the trending using the same method may be used with q - n distribution. Main qualitative features are extracted using this method. This analysis suggests that the generator PD may not be corona discharge.

Signal processing -2 used the mean, standard deviation, skewness, cross-correlation factor, kurtosis and asymmetry factors to quantify the distribution of PD. All these analysis can be carried out with q , Φ and n distributions. Here, maximum- q , average- q and n distributions are analyzed.

Mean factor indicates the severity of PD and standard deviation shows the randomness. Surface PD is found to be more severe with q - Φ distribution but corona PD is found to be severe with n - V distribution. Standard deviation reduces with averaged data analysis. Analysis on field data from Table 4-4, Table 4-5 and Table 4-6 suggest that PD at A may be cavity discharges since similar activity is observed in both half cycles. Similar conclusion may be made at E but the results in Table 4-5 contradicts the above conclusion as mean value differs in positive and negative half cycles.

Skewness describes the asymmetry of the distribution with respect to normal distribution. With q_m , corona and cavity are found to have symmetrical distribution and surface is distributed asymmetrically to the left. With the other two analyses, all PDs distribution is found to have asymmetrical distribution to the left. With field data, a terminal PD distribution is more asymmetrical to the left than E terminal response. Comparing Table 4-7 laboratory results, PDs at A and E may be cavity discharges using q_m - Φ and q_{ave} - Φ distributions and they can be surface PDs if q - n distribution is taken in.

Cross-correlation describes the PD distribution similarity in positive and negative half cycles. For cavity PDs, they are more correlated with q_m - Φ and q_{ave} - Φ distribution. For surface PD, they are more correlated with q - n distribution. Table 4-9 laboratory q_m - Φ , q_{ave} - Φ and q - n distributions suggest that the observed PDs at A may be due to surface discharges. While at E, q - n analysis indicates the PD may be due to surface and q - Φ analysis indicates as cavity PD.

Kurtosis represents the sharpness of the distribution. For corona, $qm-\Phi$ and $qave-\Phi$ have sharp distributions and $q-n$ distribution is flat. For cavity with $qave-\Phi$ distribution, it is sharp in positive half cycle and it follows normal distribution in negative half cycle. With $q-n$ distribution, sharp distribution is observed in negative half cycle. For surface PD, $qave-\Phi$ distribution is sharp in negative half cycle and $q-n$ distribution is sharp in both half cycles. Table 4-10 with $qm-\Phi$ and $qave-\Phi$ laboratory distribution is compared with field data and it suggests the experience of surface PDs. The distribution is sharper at A terminal compared to E terminal.

Asymmetry distribution is very clear in the case of surface discharge. In all the distributions, the dominance in negative half cycle is noticed. Cavity discharge is uniformly distributed in both half cycles. Field data asymmetry distribution suggests that PD activity at A and E will be surface discharges.

Hence statistical operators can be used to identify the severity and type of discharges very closely. This analysis suggests that PD activity at A is more severe than at E. The type of PD may be cavity or surface or a combination of them.

Signal Processing – 3 is based on the time (Δt) and magnitude difference (ΔV) between consecutive PD pulses. Laboratory studies with corona discharge suggests that ΔV in the range of $1\mu V$ to $0.01 V$ with Δt distribution of $1\mu s$ to $100\mu s$ since the discharge is going to be a small volume of highly stressed area in air. It occurs only in negative half cycle. For cavity discharge, the distribution is more or less symmetrically distributed in both half cycles. Comparatively the distribution is more in the positive half cycle. The interval between the pulses is longer in comparison with corona discharge but ΔV range is same as corona. When cavity discharge starts, the volume of cavity will be small and time to charge up will be more due to insulation and it will be random due to charge distribution on the walls. For surface discharge, the length of contamination may significantly longer and need a higher charge to build the voltage for discharge. Hence ΔV is found to be significantly more

with longer Δt to charge up. The time is significantly more due to the path of charging is along the insulation surface. Comparing with data on generator, significantly high ΔV with Δt distributed to 2.5 ms is noticed. It suggests that the dominant PD source in blue phase may be surface discharge. Almost equal pulse number in both cycles with crowding at small ΔV and Δt suggest the possible existence of minor cavity discharge also. Symmetrical distribution in both half cycles in red phase suggests that PD source may be cavity discharges.

Signal processing - 4 is developed as the extension of normal distribution with shape and scale factors to match the practical randomly occurring events. Cumulative n distribution using q-n data is used for identification. PDs from cavity and surface discharges fitted two parameter distributions satisfactorily. The fitted factors α and P for cavity PD are 0.03 V and 3.25 respectively. While the corresponding factors for surface PD are 0.14 V and 2 respectively. Scale factor for cavity is much lower. For corona PD, two types of corona are observed with almost equal number and the fitted α_1 and α_2 are 0.018V and 0.024V respectively. The shape factors β_1 and β_2 are high with the fitted values of 38.7 and 7.2 respectively. After extracting the main features, the analysis is used on the field data. It is found that 3 sub populations can fit for field data at blue and red phases. In blue phase, 15% of the counted pulses belong to subpopulation-1 with $\alpha_1=0.34$ V and $\beta_1=6$ suggesting cavity discharge. While 37% of the population belong to subpopulation-2 with $\alpha_2=0.52$ V and $\beta_2=3.74$ suggesting that this is also cavity discharge. The last subpopulation-3 with 48% of the pulse counts is found to fit with $\alpha_3=1.04$ V and $\beta_3=2.18$ indicating that it may be a surface discharge. It suggests the existence of 3 PD sources in blue phase with 2 cavity discharges and 1 surface discharge. While similar analysis at red phase suggests the subpopulation ratio will be as 16%, 44% and 40% with lower scale factors indicating lesser severity. Red phase also contains 3 PD sources with 2 minor cavity discharges and one dominant surface discharge.

Signal processing - 5 is based on single pulse analysis and the developed technique is quite novel based on the details of single PD wave shape. It is first tested in the

laboratory with a combination of corona and surface models. The estimated correlation coefficients enable identifying corona and surface PDs separately from the mixed PD distribution. For field data, the PD single pulses are extracted at a high sampling rate and after grouping, the analysis indicates that the blue phase may have 3 large groups of PD pulses in the extracted family of 43 single PDs while the red phase may have 2 large groups of PDs in the family of 45 single PDs. Detailed analysis on their time and frequency domain features indicates that the differences are distinct. In time domain, the profile for each group is unique with a fast rising front and slow decaying tail oscillatory waveform with duration around 0.8 μ s. It is more quantified in frequency domain analysis. Typical analysis with blue phase indicates that the first group of 19 pulses is found to have 3 clusters with one scattered around 30 MHz, the second one around 110 MHz and the third one around 170 MHz respectively. The second group of 13 pulses is also distributed in 3 clusters with one centering around 20 MHz, the second distributed around 60 MHz and the last one distributed around 120 MHz. The third group of 9 pulses is clustered around 2 low frequency ranges. One is crowded near 10 to 30 MHz and the other is distributed around 52 MHz.

After the identification of the type and possible number of PD sources, Power Seraya is interested in knowing the possible location of these discharges in their operating power network with the limited monitoring nodes and couplers. As a research problem, it is planned to model the PD propagation path from its source to the monitoring nodes and match the simultaneously observed PD time and frequency domain signals at the 2 nodes to identify the origin. No published work is available on the approach or method. Since the monitored nodes are located at the two ends of a bus bar, modeling of the generator, bus bar and step-up transformer are needed. In this study, a simple transmission line model of different layouts for each apparatus is used and the details are presented in Chapter 5. The study indicates that Simulink can be effectively used to develop network propagation path of PD. The matching criteria may be the time domain low frequency envelope without oscillation and the frequency domain characteristic resonance frequencies at 2 measured nodes. The study predicts

that the dominant mode of propagation is the traveling waves and the signal is attenuated as it travels away from PD origin. Most of the signal will be dissipated in the generator winding. The shape of PD at the monitoring node will depend on the resonance characteristics of the propagation path and reflection at connected nodes with different surge impedances. The analysis predicts that the analyzed PD may have been generated at 80% of the length of generator winding from its neutral.

To conclude, it can be said that the developed signal processing methods can be easily applied to characterize the randomly occurring PD pulses in any field power apparatus. The severity of PD in any phase, the types and number of developing PD sources can be predicted without any prior knowledge of PD in an operating apparatus with this on-line non-intrusive technique. The possible location of PD source can be estimated if PD data with sufficient sampling points from 2 or more locations in an operating network is available.

The knowledge gathered and newly developed techniques have established a base to undertake future research work on PD. Possible areas are: -

- Analysis with other distribution can be carried out besides q-n distribution.
- Partial discharge models derived from laboratory tests can be extended to include more realistic defects with single coil and mixed discharges. For pattern analysis, more combinations of the models need to be studied. Physical model of pure discharges can also be studied.
- The PD propagation model may be studied with non-linear parameters and evaluated with other propagation paths incorporating magnetic and capacitive couplings from multiconductors and cross-coupling from other phases.

REFERENCES

- [1] Stone G. C., Sedding H, Experience with the partial discharge testing of operating motors and generators, Proc. Of the 4th Intel. Conference on Properties and Application of Dielectric Materials, Brisbane Australia, pp.566-569, July 3-8. 1994.
- [2] Paul Gill, Electrical power equipment maintenance and testing, Published by M.Dekker, New York, 1988 (a book).
- [3] Kheirmand, A., Leijon, M., Gubanski S.M., Advances in online monitoring and localization of partial discharges in large rotating machines, IEEE Transactions on Energy Conversion, Volume: 19, Issue: 99, pp.53-59, March 2004.
- [4] Paoletti G.J., Golubev A., Partial discharge theory and technologies related to medium-voltage electrical equipment, IEEE Transactions on Industry Applications, Volume: 37, Issue: 1, pp.90 – 103, Jan.-Feb. 2001.
- [5] Boggs S.A., Partial discharge. II. Detection sensitivity, IEEE Electrical Insulation Magazine, Volume: 6, Issue: 5, pp.35 – 42, Sept.-Oct. 1990.
- [6] Van Breen H.J., Golski E., Smit J.J., Verhaart H.F.A., Leeuw W.de Krieg-Wezellenburg M., Standardization of on-line VHF PD measurements on turbo generators, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9, Issue: 1, pp.140 – 149, Feb. 2002.
- [7] Chang C., Su Q., Partial discharge distribution pattern analysis using combined statistical parameters, IEEE Power Engineering Society Winter Meeting, 2000, Volume: 1, pp.691 – 696, Jan. 2000.
- [8] Stone G.C., Campbell S.R., Discussion of Field experiences on the measurement of partial discharges on rotating equipment, IEEE Transaction on Energy Conversion, Volume: 16, Issue: 4, pp.380 –381, Dec. 2001.
- [9] Okubo H., Hayakawa N., Matsushita A., The relationship between partial discharge current pulse waveforms and physical mechanisms, IEEE Electrical Insulation Magazine, Volume: 18, Issue: 3, pp.38 -45, May-June 2002.
- [10] Ficker T., Electron avalanches. II. Fractal morphology of partial microdischarge spots on dielectric barriers, IEEE Transactions on Electrical Insulation, Volume: 10, Issue: 4, pp.700 – 707, Aug. 2003.

- [11] Satish L., Zaengl W. S., Artificial neural networks for recognition of 3-D partial discharge patterns, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 1, Issue:2, pp.265-275,1994.
- [12] Cachin C., Wiesmann H. J., PD Recognition with knowledge-based preprocessing and neural networks, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 2, Issue: 4, pp.578-589, Aug. 1995.
- [13] Na L., Ming Y., Xiaolong C., Changrong Q., Study on identification of electrical aging of epoxy laminate by fuzzy mathematics, Proc. Of the 6th International Conference on Properties and Applications of Dielectric Materials, Volume: 1 , pp.521 -524 , 2000.
- [14] Lalitha E. M., Satish L., Wavelet analysis for classification of multi-source PD patterns, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 7, Issue.1, pp.40-47, 2000.
- [15] Bozzo R., Guastavino F., PD detection and localization by means of acoustic measurements on hydrogenerator stator bars, IEEE Transactions on Dielectrics and Electrical Insulation , Volume: 2 , Issue: 4, pp.660 - 666, Aug. 1995.
- [16] IEEE Standard 1434-2000, Trial-Use Guide to the measurement of partial discharges in rotating machinery, April, 2000.
- [17] Gulski E., Kieuger F. H., Computer-aided recognition of discharge sources, IEEE Transactions on Dielectrics and Electrical Insulation, Volume 27. Issue: 1, pp.82-92, Feb, 1992.
- [18] McAllister I.W., Electric fields and electrical insulation, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9 Issue: 5, pp.672 -696, Oct. 2002.
- [19] Mcallister I.W., Johansson, Partial discharges and bulk dielectric field enhancement, Annual Report on Electrical Insulation and Dielectric Phenomena, ,Volume: 2, pp.457 -460, 15-18 Oct. 2000.
- [20] Hudon C., Bartnikas R., Surface and gas phase reactions arising with epoxy exposed to partial discharges, Annual Report on Conference on Electrical Insulation and Dielectric Phenomena, pp.725 – 734, 18-21 Oct. 1992.
- [21] Stone G.C., Advancements during the past quarter century in on-line monitoring of motor and generator winding insulation, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9, pp.746 -751, Issue: 5 , Oct. 2002.

- [22] Zhenyuan W., Deheng Z., Fuqi L., Yilu L., Kexiong T., PD monitor system for power generators, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 5 Issue: 6, pp.850 -856, Dec. 1998.
- [23] Lloyd B.A., Campbell S.R., Stone G.C., Continuous on-line partial discharge monitoring of generator stator windings, IEEE Transactions on Energy Conversion, Volume: 14, Issue: 4, pp.1131 -1138, Dec. 1999.
- [24] Li H.M., Fouracre R.A., Crichton B.H., Some consideration for obtaining the low frequency response of dielectrics from absorption current measurements, Annual Report on IEEE Electrical Insulation and Dielectric Phenomena, pp.238 -243, Oct. 1994.
- [25] Rux L., Grzybowski S., Evaluation of delaminated high-voltage rotating machine stator winding groundwall insulation, Conference Record of IEEE International Symposium on Electrical Insulation, pp.520 – 523, Apr. 2000.
- [26] Fruth B., Niemeyer L., The importance of statistical characteristics of partial discharge data, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 27 Issue: 1, pp.60 - 69, Feb. 1992.
- [27] Robles E., Solis A., Collado, J., Modeling of stress relief materials used in HV rotating machines, Conference Record of IEEE International Symposium on Electrical Insulation, pp.375 -378, 3-6 June 1990.
- [28] Novak, J.P., Bartnikas R., Effect of dielectric surfaces on the nature of partial discharges, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 7 Issue: 1, pp.146 -151, Feb. 2000.
- [29] Gupta B.K., Use of AC and DC hipot tests to assess condition of stator insulation, Electrical Electronics Insulation Conference, pp.605-608 Sept. 1995.
- [30] Foulon N., Lucas J.P., Barre G., Mailfert R., Enon J., Investigation of the failure mechanism of insulation subjected to repetitive fast voltage surges, Electrical Insulation Conference, pp.401 – 406, Sept. 1997.
- [31] Stone G.C., Recent important changes in IEEE motor and generator winding insulation diagnostic testing standards, Record of Petroleum and Chemical Industry Conference, pp.101-110, Sept. 2003.
- [32] Timperley J.E., Improvements in corona probe testing of modern hydroelectric generators, Electrical Electronics Insulation Conference, pp.300 – 304, Sept. 1989.

-
-
- [33] IEEE standard 43-2000, IEEE recommended practice for testing insulation resistance of rotating machinery, Electric Machinery Committee, March 2000.
- [34] Hee-Gon K., Hee-Soo K., Yong-Kwan P., A study on the analysis of degradation mechanism for generator stator windings, 5th International Conference on Properties and Applications of Dielectric Materials, Volume: 2 , pp.985 – 989, May 1997.
- [35] Lesaint O., Gournay P., Initiation and propagation thresholds of positive prebreakdown phenomena in hydrocarbon liquids, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 1 , Issue: 4, pp.702 – 708, Aug. 1994.
- [36] Fruth B.A., Gross, D.W., Modeling of streamer discharges between insulating and conducting surfaces, 5th International IEEE Conference on Conduction and Breakdown in Solid Dielectrics, pp.350 – 355, Jul. 1995.
- [37] Ficker T., Electron avalanches I. Statistics of partial micro discharges in their pre-streamer stage, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 10, Issue: 4, pp.689 – 699, Aug. 2003.
- [38] Lesaint O., Gournay P., Initiation and propagation thresholds of positive prebreakdown phenomena in hydrocarbon liquids, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 1 , Issue: 4 , pp.702 – 708, Aug. 1994.
- [39] Hodowanec M.M., Bezesky D.M., Field motor testing: limiting risk, IEEE Transactions on Industry Applications Magazine, Volume: 5, Issue: 3, pp.38 - 48, May-Jun. 1999.
- [40] Stone G.C., Lyles J.F., Braun J.M., Kaul C.L., A thermal cycling type test for generator stator winding insulation, IEEE Transactions on Energy Conversion, Volume: 6 Issue: 4, pp.707 -713, Dec. 1991.
- [41] Kanegami M., Okamoto T., Noda T., Hashimoto K., Takimoto K., Kondoh S., Partial discharge monitoring system with use of resistance temperature detector laid in stator coil slot of hydro power generator, International Symposium on Electrical Insulating Materials, pp.657 -660, Nov. 2001.
- [42] Zondervan J.P., Gulski E., Smit J.J., Fundamental aspects of PD patterns of on-line measurements on turbo generators, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 7, Issue: 1, pp.59 –70, Feb. 2000.

-
-
- [43] Chrzan K., Andino J.M., Electrical strength of air containing ozone and nitric oxides produced by intensive partial discharges, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 8, Issue: 4, pp.607 – 611, Aug. 2001.
- [44] Brown A.J., Condition monitoring of HV electrical rotating plant-on-line partial discharge techniques, IEE Colloquium on Understanding your Condition Monitoring, pp.1/1 - 1/3 , Apr. 1999.
- [45] Zondervan J.P., Gulski E., Smit J.J., Krieg-Wezellenburg, M.G., Comparison of on-line and off-line PD analysis on stator insulation of turbo generators, Conference Record of the IEEE International Symposium on Electrical Insulation, Volume: 1, pp.270 - 273, June 1998.
- [46] Emery F.T., Partial discharge activity in high voltage stator coils, Conference Record of IEEE International Symposium on Electrical Insulation, pp.318 - 321, June 1994.
- [47] MacAlpine J.M.K., Zhang C.H., Using a commercial partial discharge detector to investigate ac corona in air, Annual Report. On the Conference on Electrical Insulation and Dielectric Phenomena, pp.420 – 423, Oct. 2001.
- [48] Zahra F., Nema R.S., Partial discharge corona pulses in air and air-solid interface, IEEE Canadian Conference on Electrical and Computer Engineering, Volume: 1, pp.169 – 172, May 1997.
- [49] Bish N.B., Howson P.A., Howlett R.J., Condition diagnostics of a physical breakdown mechanism in high voltage dielectrics utilising `AI evaluation techniques, Fourth International Conference on Knowledge-Based Intelligent Engineering Systems and Allied Technologies, Volume: 2, pp.644 - 650, Aug. 2000.
- [50] Ma X., Zhou C., Kemp I.J., Interpretation of wavelet analysis and its application in partial discharge detection, IEEE Transactions Dielectrics and Electrical Insulation, Volume: 9, Issue: 3, pp.446 -457, June 2002.
- [51] Vudhichamnong R., Thongphuak T., Thaweesub W., Tuntikanokporn E., Tongchim N., Sangkasaad, S., Design and construction of a PC-based partial discharge analyzer using FPGA, IEEE Proceedings on TENCON, Volume: 2, pp.609 -614, Sept. 2000.
- [52] Zhu H., Green V., Sasic M., Halliburton S., Increased sensitivity of capacitive couplers for in-service PD measurement in rotating machines, IEEE Transactions on Energy Conversion, Volume: 14, Issue: 4, pp.1184 - 1192, Dec. 1999.

- [53] Moore, P.J., Portugues I., Glover I.A., A nonintrusive partial discharge measurement system based on RF technology, Power Engineering Society General Meeting, Volume: 2, pp.628-633, July 2003.
- [54] de A Olivieri M.M., Mannheimer W.A., Ripper-Neto A.P., On the use of acoustic signals for detection and location of partial discharges in power transformers, Conference Record of the IEEE International Symposium on Electrical Insulation, pp.259 – 262, April 2000.
- [55] Tian Y., Lewin P.L., Pommerenke D., Wilkinson J.S.; Sutton S.J., Partial discharge on-line monitoring for HV cable systems using electro-optic modulators, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 11, Issue: 5, pp.861-869, Oct. 2004.
- [56] Macia-Sanahuja C., Lamela-Rivera H., Wavelet analysis of partial discharges acoustic waves obtained using an optical fibre interferometric sensor for transformer applications, IEEE International Symposium on Industrial Electronics, Volume: 2, pp.1071 – 1076, June 2003.
- [57] Su Q., James R.E., Blackburn T.R., Tychsen R., Simpson J., On-line calibration pulse injection through high frequency current transformers for partial discharge locations, Conference Record of the IEEE International Symposium on Electrical Insulation, pp.367 – 370, June 1992.
- [58] Keerthipala W.W.L. and McLaren P.G., A multiconductor transmission line model for surge propagation studies in large a.c. machine windings, in Proc. IEEE Symp. on Circuits and Systems, Volume: 2, pp.629-632, 1991.
- [59] Mallikarjunappa K., Ratra M.C., On-line monitoring of partial discharges in power capacitors using high frequency current transformer technique, Proc. Of the 3rd International Conference on Properties and Applications of Dielectric Materials, pp.749 – 751, July 1991.
- [60] Schichler U., Borsi H., Gockenbach E., Problems and new solutions for partial discharge measurement on high voltage cables under noisy conditions, Conference Record of the IEEE International Symposium Electrical Insulation, pp.66 – 69, June 1994.
- [61] Brown A.J., Condition monitoring of HV electrical rotating plant-on-line partial discharge techniques, IEE Colloquium on Understanding your Condition Monitoring, pp.1/1 - 1/3, April 1999.

- [62] Stone G.C., Advancements during the past quarter century in on-line monitoring of motor and generator winding insulation, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9- 5, pp.746 –751, Oct. 2002.
- [63] Stone G.C., Kuffel J., Digital recording techniques for electrical insulation measurements, IEEE Electrical Insulation Magazine, Volume: 5, Issue: 3, pp.9 -17, May 1989.
- [64] Cavallini A., Contin A., Montanari G.C., Puletti F., Advanced PD inference in On-Field Measurements. Part I: Noise Rejection, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 10-2, pp.216-224, April. 2003.
- [65] Itoh K., Kaneda Y., Kitamura S., Kimura K., Nishimura A., Tanaka T., Tokura H., Okada I., New noise rejection techniques on pulse-by-pulse basis for on-line partial discharge measurement of turbine generators, IEEE Transactions on Energy Conversion, Volume: 11, Issue: 3 , pp.585 – 594, Sept. 1996.
- [66] Ma X., Zhou C., Kemp I.J., Novel computer-based processing system for partial discharge detection and diagnosis, Proc. Of the 21st IEEE Conference on Instrumentation and Measurement Technology, Volume: 1, pp.684 – 688, May 2004.
- [67] Gross D.W., Partial discharge measurement and monitoring on rotating machines, Proc. of the IEEE International Symposium on Electrical Insulation., pp.570-574, 2002.
- [68] Sletbak J., The influence of cavity shape and sample geometry on partial discharge behavior, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 3, Issue: 1, pp.126 - 130, Feb. 1996.
- [69] Gulski E., Kreuger F.H., Computer-aided recognition of discharge sources, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 27, Issue:1, pp.82-92,1992,
- [70] Krivda A., Birtwhistle D., Recognition of multiple partial discharge patterns, Eleventh International Symposium on High Voltage Engineering, Volume: 5, pp.17 -20, 1999.
- [71] Culbert I.M., Dhirani H., Gupta B.K., On-line measurement of partial discharges on large motors in a generating station , Electrical Insulation Conference and Electrical Manufacturing & Coil Winding Conference, pp.537 – 540, Oct. 2001.
- [72] Nakao K., Kondo T., Suzuoki Y., Mizutani T., ϕ -q-n patterns and current shapes of partial discharges in void, Proc. Of the International Symposium on Electrical Insulating Materials, pp.665 -668, 27-30 Sept. 1998.

-
-
- [73] Candela, R., Mirelli G., Schifani R., PD recognition by means of statistical and fractal parameters and a neural network, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 7, Issue: 1, pp.87 –94, Feb. 2000.
- [74] Byers J. L., Weibull analysis techniques on a desktop computer, Journal of Gas Turbine and Aeroengine Congress and Exposition, pp. 6-9, June 1988.
- [75] Contin A., Montanari G.C., Ferraro C., PD source recognition by Weibull processing of pulse height distributions, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 7, pp.48 – 58, Feb. 2000.
- [76] Contin A., Gulski E., Cacciari M., Montanari G.C., Applications of the Weibull function to partial discharge data coming from different sources typologies, Conference on Electrical Insulation and Dielectric Phenomena, pp.335 – 338, Oct. 1995.
- [77] Boczar T., Identification of a specific type of PD from acoustic emission frequency spectra, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 8 Issue: 4, pp.598 –606, Aug. 2001.
- [78] Ariastina W. G., Blackburn T. R., Characteristics of partial discharges in oil impregnated insulation using different test voltage frequencies, Proc. Of 6th International Conf. on Properties and Applications of Dielectric Materials, Volume:1, pp. 487-492, June 2000.
- [79] Montanari G. C., Contin A., Cavallini A., Random sampling and data processing for PD pulse height and shape analysis, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 7, Issue:1, pp.30-39, 2000.
- [80] Mazroua A. A., Bartnikas R., Salama M.M.A., Discrimination between PD pulse shapes using different neural network paradigms, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 1, Issue:6, pp.1119-1131, 1994.
- [81] Oki I., Haida T., Wakabayashi S., Tsuge R., Sakakibara T., Murase H., Development of partial discharge monitoring technique using a neural network in a gas insulated substation, IEEE Transactions on Power Systems, Volume: 12, Issue: 2, pp.1014 –1021, May 1997.
- [82] Kranz H. G., Fundamentals in Computer Aided PD Processing, PD Pattern Recognition and Automated Diagnosis in GIS, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 7, Issue: 1, pp.12-20, 2000.

- [83] Tao Hong, Fang M.T.C., Detection and classification of partial discharge using a feature decomposition-based modular neural network, IEEE Transactions on Instrumentation and Measurement, Volume: 50, Issue: 5, pp.1349 –1354, Oct. 2001.
- [84] Salama M.M.A., Bartnikas R., Fuzzy logic applied to PD pattern classification, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 7 Issue: 1, pp.118 –123, Feb. 2000.
- [85] Contin A., Cavallini A., Montanari G.C., Pasini G., Puletti F., Digital detection and fuzzy classification of partial discharge signals, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 9, pp.335 – 348, June 2002.
- [86] Rezinkina M.M., Rezinkin O.L., Experimental research of the correlation between partial discharges in polyethylene insulation and fractal characteristics of causing them treeing, Proc. Of IEEE 7th International Conference on Solid Dielectrics pp.404 - 407, 2001.
- [87] Ma, X., Zhou, C., Kemp, I.J., Wavelets for the analysis and compression of partial discharge data, Conference on Electrical Insulation and Dielectric Phenomena, pp.329 –334, 2001.
- [88] Kawada M., Tungkanawanich A., Kawasaki, Z.I., Matsu-Ura, K, Detection of wide-band E-M signals emitted from partial discharge occurring in GIS using wavelet transform, IEEE Transactions on Power Delivery, Volume: 15 Issue: 2, pp.467 –471, April 2000.
- [89] Katori T., Yamazaki D., Ehara Y., Kishida H., Ito, T., Influence of residual charge on treeing degradation with single pulse analysis, Conference on Electrical Insulation and Dielectric Phenomena, pp.967 – 970 Oct. 2002.
- [90] Fothergill J.C., Dissado L.A., Sweeney, P.J.J., A discharge-avalanche theory for the propagation of electrical trees. A physical basis for their voltage dependence, IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 1, Issue: 3, pp.474 – 486, June 1994.
- [91] TDS7000 Series Digital Phosphor Oscilloscopes Instruction Manual, Tektronix, Inc. USA, 2002.
- [92] Spectrum Analyzer 8595E User Manual, Hewlett Packard, Inc, USA, 2001.
- [93] Labview Measurements Manual, National Instruments Corporate Headquarters, April, 2003.
- [94] Toolbox User's Guide with Matlab, the Math Work, Inc, USA.

-
-
- [95] Nikonov V., Bartnikas R., Wertheimer M.R., The influence of dielectric surface charge distribution upon the partial discharge behavior in short air gaps, IEEE Transactions on Plasma Science,, Volume: 29 , Issue: 6, pp.866 – 874, Dec. 2001.
- [96] da Silva G.C., Filho V.S., Robert R., Study of continuous and pulsed X-ray induced partial discharge statistical behaviour in epoxy samples, The 7th International Conference on Properties and Applications of Dielectric Materials, Volume: 3, pp.831 – 834, June 2003.
- [97] Malec D., Lebey T. Effects of the voltage waveform on partial discharges activity in a vented sample (HDPE), Conference on Electrical Insulation and Dielectric Phenomena, Volume: 2, pp.657 – 660, Oct. 2000.
- [98] Hozumi N., Michiue H., Nagae H., Muramoto Y., Nagao, M., Time-lag measurement of void discharges for the clarification of the factor for partial discharge pattern, Annual Report of the Conference on Electrical Insulation and Dielectric Phenomena, Volume: 2 , pp.717 -720, 2000.
- [99] Ma X., Zhou C., Kemp I.J., Investigation into the use of wavelet theory for partial discharge pulse extraction in electrically noisy environments, Eighth International Conference on Dielectric Materials, Measurements and Applications, pp.123 -126, 2000.
- [100]ReliaSoft Corporation, [Fwww.reliasoft.com](http://www.reliasoft.com).
- [101]Borneburg D, Prediction of field radiation due to partial discharges at HV insulators by measurement of apparent charge or RIV, Eleventh International Symposium on High Voltage Engineering, Volume: 4 , pp.265 – 268, 23-27 Aug. 1999.
- [102]Wang Z.D., Zhu D. H., Simulation on propagation of partial discharge pulses in transformer windings, The International Symposium on EI materials, pp.643-646, 1998.
- [103]Wang Z.D., Crossley P.A., Cornick K.J. Zhu D.H., An algorithm for partial discharge location in distribution power transformers, IEEE Power Engineering Society Winter meeting, pp.2217-2222, 2000.
- [104]Akbari A., Werle P., Borsi H., and Gockenbach E., Transfer function-based partial discharge localization in power transformers: a feasibility study, IEEE Electrical Insulation Magazine, Volume: 18-5, pp.22 -32, 2002.
- [105]Ishikawa Y., Yamada T., Nakazawa H., and Hiratsuka M., The study of the oscillatory lightning surge in transformers and the calculation method of its frequency, Power Engineering Society Winter Meeting, Volume: 3, pp.2171 – 2175, Jan. 2000.

- [106]Imagawa H., Emoto K., Murase H., Koyama, H., Tsuge R., Maruyama, S., Sakakibara T., PD signal propagation characteristics in GIS and its location system by frequency components comparison, IEEE Transactions on Power Delivery, Volume: 16 Issue: 4, pp.564 -570, Oct. 2001.
- [107]Patsch R., Berton F. Benzerouk D., PD-Source identification and characterization on the basis of pulse shape analysis, IEEE Conference on Electrical Insulation and Dielectric Phenomena, pp.728-731, 2002.
- [108]Allan Greenwood, Electrical transients in power systems, John Wiley & Sons, Inc., U.S.A., pp.322-380, 1991.
- [109]Heller B. Veverka A., Surge phenomena in electrical machines, London Iliffe books Ltd., pp.306-387, 1968.
- [110]Su Q., Analysis of partial discharge pulse propagation along generator stator windings, IEEE Power Engineering Society Winter Meeting., Volume.1, pp.269-272, 2000.
- [111]Zhu H. and Kemp I. J., Pulse propagation in rotating machines and its relationship to partial discharge measurements, IEEE International. Symposium on EI, pp.411-414, 1992.
- [112]Birlasekaran S., Identification of the type of partial discharges in an operating 16kV/250 MVA Generator, IEEE Conference on Electrical Insulation and Dielectric Phenomena, USA, pp.559-562, 2003.
- [113]EMA Design Automation, Inc., SIMULATION: PSPICE A/D,USA, 2003.
- [114]Brandwajn V. Liu Y., Electromagnetic Transients Program Version 2.0: Revised Application Guide, USA, Nov. 1991.
- [115]Matlab version 6.5 and toolboxes, The Math Works Inc., USA, 2003.
- [116]Kai G, Kexiong T, Fuqi L, Wensheng G, Feature extraction and pattern recognition of multi-source PD signals, The International Symposium on Electrical Insulating Materials, pp.119 – 122, Nov. 2001.
- [117]de A. Olivieri M.M., Mannheimer W.A., Ripper-Neto A.P., On the use of acoustic signals for detection and location of partial discharges in power transformers, Conference Record of the 2000 IEEE International Symposium on Electrical Insulation, pp.259 – 262, April 2000.

- [118] Gross D.W., Herbig J.G., Partial discharge fault location and diagnosis on HV power cables, Conference on Electrical Insulation and Dielectric Phenomena, Volume: 2, pp.630 - 633, 15-18 Oct. 2000.
- [119] Dick E.P., Gupta B.K., Porter J.W. Greenwood A., Practical design of generator surge protection, IEEE Transactions on Power Delivery, Volume: 6-2, pp.736-743, April 1991.
- [120] Dick E.P., Cheung R.W., Porter J.W., Generator models for over voltage simulations, IEEE Transactions on Power Delivery, Volume: 6-2, pp.728-735, April 1991.
- [121] IEC 60076-3- Power Transformers – Part 3: Insulation levels, dielectric tests and external clearances in air, IEC,2000.
- [122] IEEE Std C57.127-2000, IEEE Trial-Use Guide for the detection of Acoustic Emissions from Partial Discharges in Oil-immersed Power Transformers, IEEE,2000.
- [123] IEC 60270, High-Voltage test techniques- Partial Discharge measurements, IEC 2000-12.
- [124] IEEE Std C57.124-1991, IEEE Recommended Practice for the detection and measurement of partial discharge in dry-type transformers, IEEE,1991.
- [125] M. Wang, A. J. Vandermaar, and K. D. Srivastava, “Review of condition assessment of power transformers in service”, IEEE Electrical Insulation Magazine, November/December 2002, Vol. 18, No.6, pp. 12-25.

APPENDICES

APPENDIX A

Figure 1 LV Terminals of the 6 couplers of

Figure 2 Tested 250MVA Power Generator

APPENDIX B

(a)

(b)

Figure 3 Display and Control panels for (a) spectrum analyzer (b) oscilloscope

Necessary Lab view software routines were developed to control the GPIB controlled instruments and to acquire the data with proper settings. The display and control panel for the control of the spectrum analyzer and oscilloscope is shown in Figure 3. All the measurement is executed automatically. The collected data were stored and then analyzed using developed Mat lab software.

VITA

Yu Ming was born in P. R. China, in 1973. He received his B. Eng. degree in Electrical Engineering from Xi'an Jiaotong University, China, in 1996 and his M. Eng. degree Electrical Engineering from Graduate School of Xi'an Jiaotong University, China, in 1999.

He worked as a lecturer in the School of Electrical Engineering in the Xi'an Jiaotong University from 1999 to 2001. His research areas include Online Condition Monitoring, Partial Discharge Measurements and Identification, High-voltage Test and Insulation Material Analysis.

Research related to this thesis has resulted in the following publications:

- [1] Yu Ming, Birlasekaran S., and Choi S.S., Simulation of Partial Discharge Propagation In Power Network, *IEEE Transactions on Energy Conversion* (accepted for publication).
- [2] Yu Ming, Birlasekaran S., Identification of the Type of Partial Discharge in Mixed-source Discharges by Correlation Method, *Letter of IEEE Transactions on Energy Conversion*(under review).
- [3] Yu Ming and Birlasekaran S., Identification of the type of partial discharges in an operating power network, *IEEE Transactions on Dielectric and Electrical Insulation* (under review).
- [4] Yu Ming, Birlasekaran S., Characterization of partial discharge signals using wavelet and statistical techniques, 2002. Conference Record of the 2002 IEEE International Symposium on Electrical Insulation, pp.9 – 13, 7-10 April 2002
- [5] Yu Ming, Birlasekaran S., Characterization of partial discharge signals from operating 300MVA generator, The AUPEC2002, Monash University Clayton, Victoria, 3800, AUSTRALIA

Publications not related to this research project

- [6] Yu Ming, Xu Yang, Liu Na, Jia Xin, Cao Xiaolong, Qiu Changrong, Recognition of partial discharge patterns in motors using neural network, 2000. The 6th international Conference on Properties and Applications of Dielectric Materials, Volume: 2 , pp.770 – 772, 21-26 June 2000
- [7] Liu Na, Yu Ming, Cao Xiaolong and Qiu Changrong, Study on identification of electrical aging of epoxy laminate by fuzzy mathematics, Properties and Applications of Dielectric Materials, 2000. The 6th International Conference on , Volume: 1 , pp.521 – 524, 21-26 June 2000
- [8] Yu Ming, Xu Yang, Can Xiaolong and Qiu Changrong, Measurement of flash discharge in explosion-proof motors, High Voltage Engineering, 1999. Eleventh International Symposium on (Conf. Publ. Issue: 467) , Volume: 5 , 23-27 Aug. 1999 pp.176 - 179 Volume: 5 ISH1999, London
- [9] Yu Ming, Xu Yang, Can Xiaolong and Qiu Changrong, Automated Recognition System of Partial Discharge Source in Cable Using Centrum Score, Journal of Xian Jiaotong University, Aug,1998
- [10] Xu Yang and Yu Ming, Comparison Between Optic and Electrical Methods for Partial Discharge, IEEE Conference 6th International Conference on Properties and Application of Dielectric Materials, 2000
- [11] Jia Xin and Yu Ming, Calculation of currents rating of single-core cables taking into accord the circulating currents in the sheaths of the cables, High voltage engineering, 2000