Diagnosis of High Voltage Insulation Systems

Partial discharge phenomena, detection and analysis

March 2015
Dr Jack Hunter

- Teaching fellow in the EEE group
- Studied EE at ECS for UG and completed PhD under the supervision of Prof. Lewin in 2013
- Broad research area: HV phenomena within dielectric materials
- Concentration on Partial Discharge (PD) within cable systems
- Experimental, field data analysis and applied signal processing
- Heavily involved with activity at TDHVL (Bld. 20)
Lecture scale and content

- 15 lectures delivered by me (3/week)
- Break during week 8 (16/03/2015 to 20/03/2015)
- Coursework deadline for Prof. G. Chen (Bushing)
- Coursework associated with this portion of the course (Computer based – applied signal processing)
- Context of condition monitoring process, Introduction of Partial Discharge (PD) relevant research, details of the coursework
Industrial setting

- UK Power Networks Ltd
- Distribution network (6 and 11 kV)
- 38,000 km (Cables only) Majority 50-60 years old
- Total replacement cost: £4 Billion
- UKPN turnover ~£400m
- Additional economic and social implications of completing this work
- How do we find ourselves in this situation??
Nationalised => Privatised

- Heavy investment during Nationalised period
  - Huge operational/safety margins
  - Heavily over engineered system
  - Low failure rates, highly supply continuity
  - Extremely reliable for its design life (40-50 years)

- Privatisation (1989)
  - Shareholders
  - Interest shifts to life extension, health estimation and condition monitoring
  - Impact on maintenance – Scheduled to dispatchable
Diagnosis of high voltage electrical insulation systems

- Asset manager needs:
  - Reduce maintenance and operation costs
  - Increase availability and reliability
  - Optimise refurbishment plan

- CBM: Condition Based Maintenance
  - Maintenance is carried out on the basis of asset condition
  - Unnecessary actions are avoided (money saved), failure can be prevented (increase availability), old assets can be replaced according to their actual conditions, life extension can be evaluated.
Diagnosis of high voltage electrical insulation systems

An efficient CBM programme can be implemented only through risk assessment.

In fact, to manage and plan proper maintenance actions the hazards of a given status of electrical system must be evaluated.
Failure Risk: defects and ageing
Maintenance effect: TBM – Time based maintenance

Problem: The bath tub curve must be known with extreme precision
Problem: too much or too little maintenance activity

\( h_c \) – Risk critical value

Complete maintenance and/or replacement

Time
Diagnosis and maintenance (Condition based CBM)

Best working conditions for a component or a system – minimum and constant hazard (risk)

Knowledge of the start time of ageing process (3rd part of the bath tub curve)

Condition based (and not time based) maintenance

Efficient diagnostic techniques are required.
The role of Diagnostics

Diagnostics allows the status of the components/apparatus to be assessed

Diagnostics allows failure uncertainty to be reduced

Optimisation of the maintenance procedure – CBM

Maximisation of the system components availability

... but ... only effective Diagnostics!
Diagnosis

Purpose: infer the state of the system prior breakdown by measuring suitable diagnostic properties (markers)

Stop operation when diagnostic property is approaching a given threshold

Threshold should be regarded as a gray zone due to:

- Noise in diagnostic property
- Uncertainty about the limit property conditions

Perfect diagnostic marker: varies linearly with ageing (predictable)

Bad diagnostic markers:

- Too early warning
- Too late warning
- Noisy/non-monotone
Diagnostic properties

Bulk degradation

(oxidation, polymer chain scission, micro-cavities formation and enlargement, water treeing etc)

Measurements of bulk properties i.e. tanδ and space charge, plarisation etc

Local degradation

(Defects such as protrusions, cavities)

Measurements of localise phenomena (present in weak points) i.e. partial discharges
Partial Discharge Theory
Partial Discharge (PD) phenomena

• Definitions of partial discharge:
  – “Electrical discharges that do not completely bridge the electrodes are called partial discharges.” – Kreuger [1]
  – “Localised electrical discharge that only partially bridges the insulation between conductors and which can or can not occur adjacent to a conductor” - IEC60270 [2]

• High frequency discharge phenomena
  – Electrical, acoustic, optical, thermal, chemical

Different types of PD

- Corona
- Surface discharge
- Void discharge
- Floating discharge
- Streamers in liquid
Consequence of PD

- Degradation or erosion of the insulation – symptom and cause
  - Repeated PD events

- In solids
  - Non reversible damage
  - Electrical treeing
  - Breakdown and failure

- In liquids and gases
  - Self healing effect

- Damage to the electrode itself

- Key ability is to link the evolution in signals to the insulation state
Electrical tree within a model system

Experiment setup
Sample prep.
Time period
Observation
Avoid breakdown
Chemical analysis
Electrical analysis
The motivation to detect and study

- Relevance is key – are these techniques transferrable?
- PD detection is a non-destructive test technique
  - Detection for assessment of service life
  - Fault detection for repair or service
  - Assessment of design / type testing – used in commissioning
  - Impact of test setup on results – power supply, noise and temperature
- Challenges to researchers
  - Quantify, classify and locate PD activities
  - Field on-line PD measurement (noise)
  - Data mining techniques to optimise the use of memory
Void discharge

![Diagram of a high voltage system](image)

![Graph showing voltage changes over time](image)

- $u_c$ (without discharge)
- $u_c$ (with discharge)

Parameters:
- $u_{CB}$
- $u_r$
- $u_s$
- $u_p$

Time (ms):
- 10
- 20
Equivalent circuit of void discharge
Partial Discharge Detection
PD detection methods

- Electrical
  - Inductive, capacitive, Non-conventional, bandwidth impact

- Acoustic

- Optical
  - Used for GIS

- Thermal – practicality of this within different assets

- Chemical – available in Transformers, high sensitivity required, spectroscopy
Conventional PD measurement

- Standardised laboratory based test, circuit diagram
- IEC270 (1968 and 1981)
- Capacitive sensor – limited practical application – why?
- Bandwidth: 350 ±150 kHz (Narrow) Why this bandwidth?
- Calibration, apparent charge value, capacitance of sample
- Noise background, sensitivity, filtering, three-phase system
PD detector (analogue)
PD detector (digital)
Blocking capacitor (+ input unit) and PD simulator (Calibration)
Modern equivalent

Omicron Mtronix MPD 600 PD measurement system
Conventional PD analysis plot
Generally the magnitude of the capacitances will always be controlled by the inequality

\[ C_a \gg C_c \gg C_b \]
When S is closed, $i(t)$ releases a charge $\delta q_c = C_c \delta V_c$ from $C_c$. Comparing charges within the system before and after this discharge, the voltage drop across the terminals $\delta V_a$ can be easily computed.

$$\delta V_a = \frac{C_b}{C_a + C_b} \delta V_c$$

Note: $\delta V_a$ contains no information about $\delta q_c$ but proportional to $(C_b \delta V_c)$, a quantity called “apparent charge” vaguely related to $\delta q_c$.

$\delta V_a$ is a quantity which could be measured. $\delta V_c$ is in a range of $10^2$ to $10^3$V, but $C_b/C_a$ will be very small ($\leq 10^{-3}$) $\Rightarrow$ $\delta V_a/V_a$ is well below $10^{-3}$. 
Non-conventional techniques

- **Electrical**
  - Current transducer/transformers (CTs)
  - Capacitive couplers
  - Antenna
  - UHF – data processing and storage implications

- **Acoustic**
  - Microphones
  - AE sensors

- **Chemical**
  - Dissolved gas analysis (DGA)

- **Optical**
  - Photo-multiplier tube

Practical experiment example
Thermal calibration experiment

- Thermocouples
Straight lead joint construction
Medium Voltage distribution cable

- Paper Insulated Lead covered Cable (PILC).

- Commissioned in the 40s and 50s to distribute power around London.

- Expected lifespan of around 40-50 years.

- Dense, inter-connected distribution network of aging cables.
Cable construction

• 185 mm² Copper conductor
• Three-phase power transfer
• Oil impregnated paper design with Steel wire armour (SWA)
• 65°C rated conductor temperature
• 11 kV Rated Voltage
Joint selection

- Fault located
- Cable isolated
- Permit of work ascertained
- Cable spiked
- Joint selection completed
- Cable section cut and replacement section positioned
- Cable sections “butted up”
Cable preparation

- Section of outer PVC over sheath removed.
- Stiff wire used to bind Steel wire armour.
- Remaining PVC removed.
- Steel wire armour removed to reveal layer of Bitumen impregnated Hessian.
Cable preparation

- Hessian layer unwrapped.
- Armour bent outwards.
- Gas burner used to remove layer of Bitumen impregnated Hessian to the level of the bend in armour.
- Lead cleaned using warm rag and roughed up using stiff wire brush.
- Armour bent back into place.
Cable preparation

- Wire armour bound and “Plumbers metal” (Tin and Lead) applied to cable using burner to bond Lead and armour layers.

- Heat oil baths and Bitumen to ensure thorough impregnation of tapes and low viscosity of Bitumen respectively.

- Beat Lead sheath into correct shape and cut lengthways.
Cable preparation

- Remove Lead and semi-conducting carbon layer.
- Fillers removed.
- Separate and clean phases.
- Apply cotton tapes that have been soaked in G-38 mineral oil. (To protect phase insulation during the sweating process).
Cable preparation

- Position phases to ensure appropriate spacing and limit phase crossing.
- Remove paper insulation to reveal conductor for each phase.
- Heat Tin/Aluminium mixture to molten state.
Sweating

• Connect appropriate phases together using a ferrule.

• Apply molten Tin/Aluminium mixture to the ferrule using ladles to bond phases together.

• Wipe away excess material and smooth conductor surface using sandpaper.
Joint construction

• Remove cotton paper.

• Apply extra layers of oil impregnated crepe paper to each phase to build up insulation thickness.

• Insert roll of tape between ferrules and wrap paper around the entire arrangement.
Joint construction

• Surround phases with the lead sheath.

• “Plumb” in the sheath to the joint to seal it.

• Cut lead, pour in liquid Bitumen, allow to cool and fully seal the lead joint.
Partial Discharge research overview
Classical PD research topics

- Physics of generation and propagation
- Data acquisition development
- Identification/discrimination
- Relating captured signals to physical changes at the defect site
- Identifying trends in activity
- Predicting future activity under a range of operating conditions
Partial Discharge Analysis
Parameters to describe a PD

- IEC 60270
  - Inception voltage $U_i$
  - Extinction voltage $U_e$
  - Apparent charge $q$
  - Phase occurrence $\phi$
  - Pulse repetition rate
  - Discharge power
  - etc
Techniques to visually represent PD data

- Phase resolved PD (PRPD) : $\varphi$-q-n
Techniques to represent PD type

Pulse Sequence Analysis (PSA)
Techniques to represent PD type

- Pulse Sequence Analysis (PSA)
PD source classification

- Importance of classification
  - Different effects on insulation
  - Multiple PD sources

- Assignment
Assignment Two – PD Classification

- Introduction
- PD classification - examples
- Task
- PD data from “blind” tests
- Assessment
Introduction

• PD can lead to materials degradation but its severity depends on PD types and locations.

• For asset management, it is important to identify and classify PD types.

• Various techniques have been developed to analyse PD characteristics.

• Two techniques are to be employed to analyse PD and identify PD sources.
  - Phase resolved PD analysis
  - Pulse sequential PD analysis
Schematic diagram of PD event

(a) Before PD, (b) During PD and (c) After PD
Phase Resolved PD analysis

- PRPDA has been used for a long time and is the simplest tool for PD analysis.

- PRPD patterns can be represented by phase and discharge magnitude distribution or phase and number of discharges – 2d representation

- If the above two representations are combined it forms a 3d representation, termed as $\phi - q - n$.

- PD sources can be identified through $\phi - q - n$ diagram.

- New features based on PRPDA can be obtained with the aid of statistical tools.
Pulse Sequential Analysis (PSA)

- PSA has been developed to analyse the sequence of each PD event.
- It evaluates the changes in voltage and time difference between two consecutive discharge distributions.
- The technique differs from phase resolved PD by considering the effect of charge deposited during PD.
- Through analysing the sequence of discharge, local defects can be characterised more precisely.
- Single and multiple discharge sites can be distinguished.
Examples - PRPDA

2d diagram of PD in a void
Examples - PRPDA

3d diagram of PD in a void ($\varphi - q - n$)
Examples - PRPDA

2d diagram of PD due to corona
Examples - PRPDA

3d diagram of PD due to corona (φ – q – n)
Examples - PRPDA

2d diagram of PD at surface
Examples - PRPDA

3d diagram of PD at surface ($\varphi - q - n$)
dt diagram of PD in a void
dU diagram of PD in a void
Examples - PSA

dU/dt diagram of PD in a void
Examples - PSA

dt diagram of PD due to corona
Examples - PSA

dU diagram of PD due to corona
Examples - PSA

dU/dt diagram of PD due to corona
dt diagram of PD at surface
Examples - PSA

dU diagram of PD at surface
Examples - PSA

dU/dt diagram of PD at surface
Task

• The Class will be split into Pairs (Teams)

• Each Team will be assigned a different PD classification technique.

• Extensive research and understanding of the technique.

  (i) Phase Resolved PD Analysis

  (ii) Pulse Sequential Analysis (PSA)

• Each Team will be required to write a simple programme to read real PD data (supplied) and analyse the data.
Task

- The data was obtained from different sources.

- The supplied data will be clearly labelled. If your program runs correctly, this will allow you to identify features of PD of your assigned analytical technique.

- Each Team has 10 minutes to present their work (ideally 5 minutes for each student). The presentation should include:
  - Theory and various aspects of the technique.
  - Flow diagram of the program
  - Illustration of working program
Blind Test

• To further demonstrate the effectiveness of your approach, a set of data from a “unknown” source will be given to each Team for classification.

• You need to use your program to identify the features and classify the source based on your program output.
Assessment

• No written report!

• Please send your slides and your program after your presentation (g.chen@soton.ac.uk).

• Marks will be awarded on the basis of
  - Team presentation
  - Knowledge of PD and the technique used for classification
  - Effectiveness and efficiency of your program