Research on power cable condition monitoring and assessment

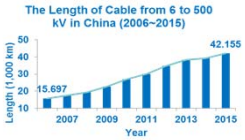
- Why cable condition monitoring
- Failure mode/mechanisms
- GCU research on PD based Condition monitoring techniques
- Prof Zhou speech at 2016 international conference CMD

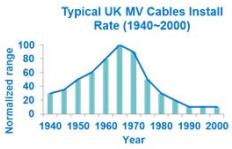
Prof Chengke Zhou
Glasgow Caledonian university

Prof Zhou Research on cable condition monitoring

- Attracted 2 EPSRC funded research projects between 2006 and 2012, joint research partners included Strathclyde Univ., National Grid, IPEC, HVPD, E-On, UK Power Network
- Industrial research funding from EDF Energy, Scottish power and UK Power Network, National Grid, Aggreko
- Developed world leading technologies in condition monitoring data analysis and automated pattern recognition algorithms
- Research papers most highly cited in the world, successful application stories, key member in 2 CIGRE working groups

Why Condition Monitoring





- Increasing use of cables in urban power systems
- Early failures due to manufacturing or installation issues
- Some reaching or expiring the end of design life
- Financial constraints and no sign of imminent failure means condition monitoring and diagnosis can play an important role in extending the cable asset life.

Current Off-line Measurements

Typical Off-line Methods	Disadvantages
Partial Discharge	• Don't reflect in-service conditions • Non-operational Stress • Risk of failure between measurements • Destructive
Insulation Resistance	
Dielectric Loss	
Very Low Frequency Test	
AC And DC Withstanding Voltage Test	
The Damping Oscillatory Wave Test	
…	

Current On-line Monitoring

Typical On-line Measurement Methods	Disadvantages
Partial Discharge	• Initial investment high • Noise interference • Lack of standards or code of practice • Knowledge base for diagnosis not as matured as offline
Sheath Current	
Cable Temperature	
…	

Cable operators --- further research required in condition monitoring and diagnostics techniques!

Need for Rapid Fault Localisation

- Cable failures often happen while in service (2005 CIGRE report)
- Cable failures can take days or longer to locate and repair
- Cable failures led to more than half of customer lost minutes in many urban areas

Failure rates on different types of cables

		XLPE CABLES (AC)			SCOF CABLES (AC)		
A. Failure Rate – Internal Origin Failures		60-275kV	220-500kV	ALL VOLTAGES	60-275kV	220-500kV	ALL VOLTAGES
Cable	Failure rate (fault per 100km/cable)	0.027	0.067	0.030	0.014	0.107	0.041
Joint	Failure rate (fault per 100 comp.)	0.005	0.025	0.005	0.002	0.010	0.004
Termination	Failure rate (fault per 100 comp.)	0.006	0.032	0.007	0.005	0.015	0.009
B. Failure Rate – External Origin Failures		60-275kV	220-500kV	ALL VOLTAGES	60-275kV	220-500kV	ALL VOLTAGES
Cable	Failure rate (fault per 100km/cable)	0.057	0.067	0.058	0.095	0.141	0.108
Joint	Failure rate (fault per 100 comp.)	0.002	0.022	0.003	0.002	0.004	0.002
Termination	Failure rate (fault per 100 comp.)	0.005	0.018	0.006	0.005	0.013	0.010
C. Failure Rate – All Failures		60-275kV	220-500kV	ALL VOLTAGES	60-275kV	220-500kV	ALL VOLTAGES
Cable	Failure rate (fault per 100km/cable)	0.085	0.133	0.088	0.109	0.248	0.149
Joint	Failure rate (fault per 100 comp.)	0.007	0.048	0.008	0.004	0.014	0.006
Termination	Failure rate (fault per 100 comp.)	0.011	0.050	0.013	0.014	0.028	0.019

Objectives of present research

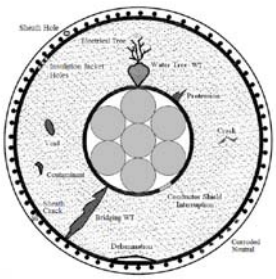
Monitoring roles		Benefit
Warning of incipient failure	→	Avoided/Reduced Plant failure and black-out
Fast location of failure (nature)	→	System self-healing/ timely restoration
Condition assessment /failure prediction	→	Optimal maintenance replacement

Failure/defect causes

- Manufacturing --- imperfection
- Installation ---improper procedure
  ---adverse environment
- Third party damage --- construction work etc
- Operational--- overvoltage/ overcurrent

- Understanding the cause of failures helps to reduce the failure rate.

Types of defects



- Voids
- Contaminations
- Embrittlement
- Protrusions
- Water trees
- Detachments
- Corrosions
- Outersheath damage

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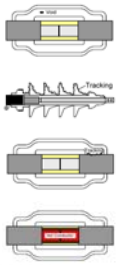
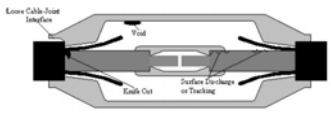
Defect types in accessories

- Voids/contamination
- Surface contaminations/poor design
- Poor joints due to wrong installation
- Poor conductor jointing





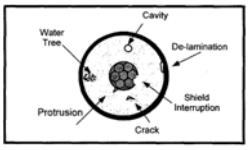
Failure mechanism

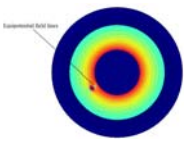
- Partial discharge
- Water tree（Water ingress + electric field）
- Electric tree（Water tree/stress，defects/PD？）
- Aging degradation（drop in insulation resistance）
- Thermal breakdown（Heat generation>heat dissipation）
- Mechanical deformation – resulting in increased electric stress
- Corrision causing short circuit

Understand the mechanism helps with design of condition monitoring techniques

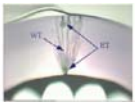
Partial discharge

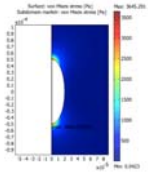
- Partial breakdown of insulation
- 50% plant showed PD before failure
- Reflection of insulation problem, causing further insulation deterioration
- Stress in defect site higher than main insulation





Water tree，electric tree，space charge，local stress





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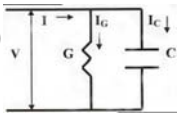
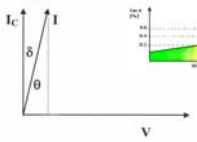
Aging - tanδ increasing- insulation resistance rising

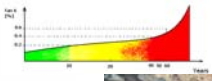
$C = 2\pi k e_o \ln(di/dc)$

$G = 2\pi f C \tan\delta$

tan δ –dielectric loss







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Typical failure example

- Cable joint – moisture caused breakdown
- Wrong connection of cable sheath in HV cable circuits
- Theft of earthing conductor

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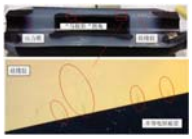
Joint failure – moisture – surface discharge

- Poor jointing led to moisture ingress
- Thermal cycling exacerbate the problem
- Surface discharge due to reduction in dielectric strength。
- Surface discharge – tracking – final breakdown。



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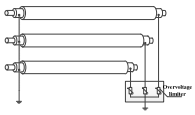
Floating earth – theft of earthing conductor

- Cable sheath at zero potentially in ideal situation.
- When earthing become ineffective, cable sheath is at a potential which too high for the outersheath – breakdown happens.



$$V_{ht} = V_p \frac{C_1}{C_1 + C_2}$$

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Practice with commercial products for cable condition monitoring

- **Infrared thermal imaging**---local heating
- **Pressure test – 1.7-2.0U_o test** --- pass/no pass
- **Time domain reflectometry（TDR）**---location of fault, by using reflection of impulse current associated with fault
- **Partial discharge** --- local defect and insulation quality
- **Very Low frequency dielectric loss/insulation resistance/Damping oscillatory wave test –** off-line test of PD and dielectric loss

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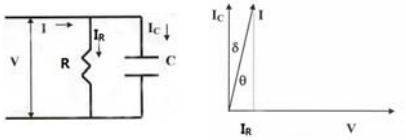
Very low frequency dielectric loss test



$$\tan\delta = \frac{1}{\omega RC}$$

- At work frequency of 50Hz，resistivity is very high, $10^{14}\Omega\bullet m$，$R>>1/\omega C$，*tanδ* is very small
- With considerations of on-site measurement noise， measurement of *tanδ* under 50Hz is extremely difficult。
- Under very low frequency of 0.1Hz, capacity of power supply required is greatly reduced, and tanδ significantly increased, because of lower Ic

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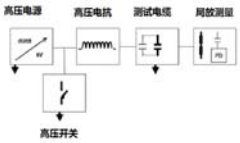
Damping oscillatory wave test（DAC）



- HV supply + HV inductor + cable capacitance --- generates damping oscillatory wave，the wave can cause PD where there exists local defects
- It can be applied the same way as DC pressure test
- Simple，light weight，easy to operate，low capacity, suitable for long lines

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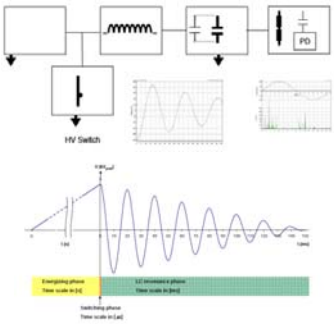
Damping oscillatory wave test（DAC）



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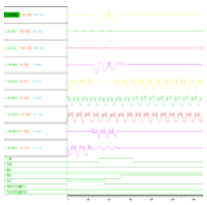
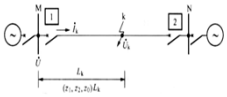
Fault location based on signals from protection and SCADA system

- Calculate the impedance from the voltage an current wave, and then estimate the fault location
- Problems: low accuracy, cannot apply to complicated circuit

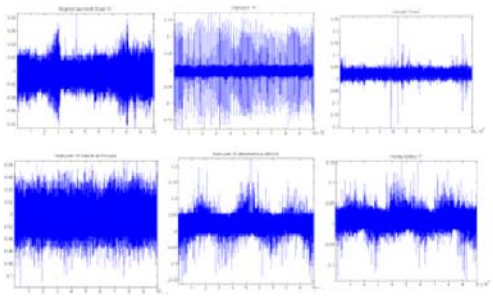




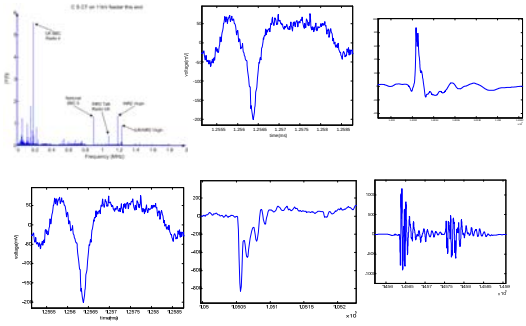
Prof Zhou Research on Cable PD Measurement

- **Background:**
  - **GCU research on the topic addressed the following.**
    - **PD detection - automated denoising**
    - **PD - autonomous pattern recognition**
    - **PD - Source localisation**
  - **These are independent processes, all associated with challenges.**

Challenge 1：Strong Background Noise

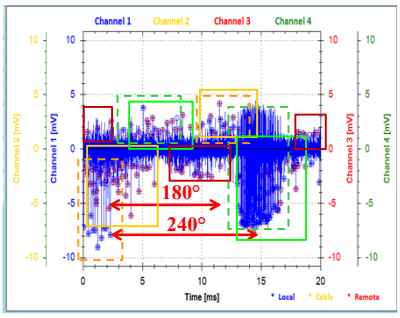


Pulse Shaped Signals from Various Sources



Challenge 2: Phase resolved pattern recognition

– Lack of voltage reference
- Multiple PD sources



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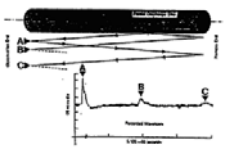
Challenge 3: Localisation of PD Source

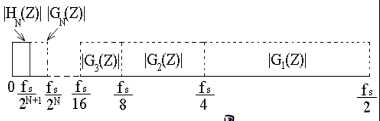


When carrying our off-line measurements, localisation can be made by taking advantage of pulse reflections.

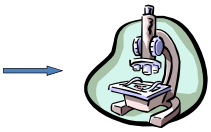
However, when a cable circuit is in service, there is little pulse reflection.

To address challenge 1: Wavelet Transform based PD Denoising

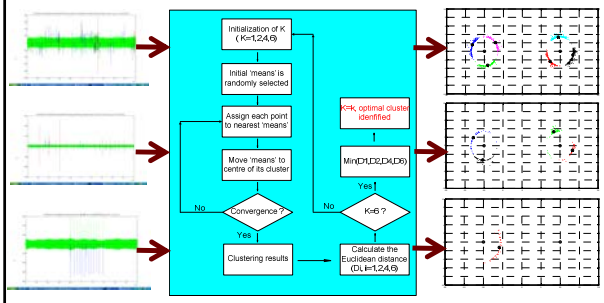
Very Noisy Signal



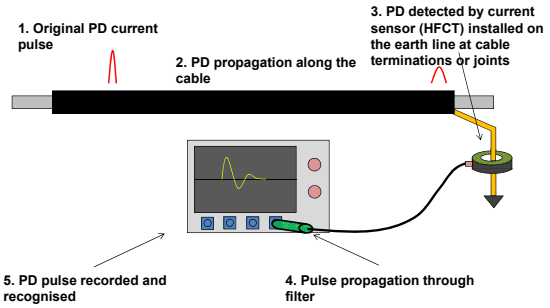
'Clean' Signal



To address challenge 2: K-Means – Autonomous Pattern Recognition

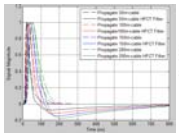


To address challenge 3: PD On-line Monitoring System – Calibration /Localisation

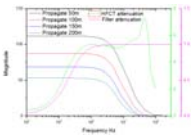


Pulse Propagation in Cable and PD Monitoring System

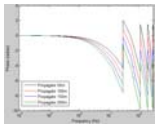
- Established relationship between pulse shape with distance of pulse propagation



(a) output pulses



(b) frequency spectrum change with propagation distance



(c) phase spectrum change with propagation distance

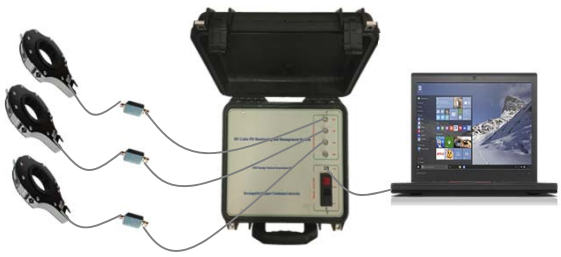
Portable PD Monitoring System Developed at GCU

- High sampling rate, 100MS/s
- High resolution, 12 bits
- Fully automated data analysis
  - Denoising
  - Pattern recognition
  - Criticality analysis
  - Trending analysis

- Technology is unavailable in market place!

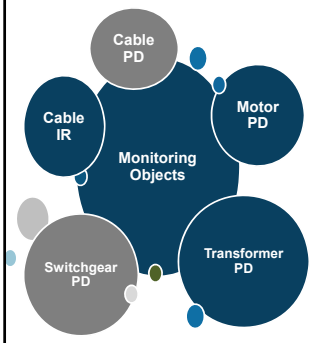
System Configuration

HFCTs Filters DAQ Box X260 Laptop



This PD condition monitoring system was developed at GCU. It includes HFCTs, Filters, DAQ Box and a Laptop installed with Win7.

System Configuration



Underpinning Techniques

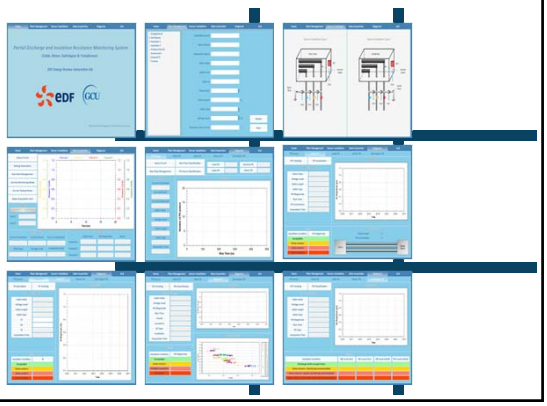
De-noising | PD Identification

Cable PD Localization | PD Trending

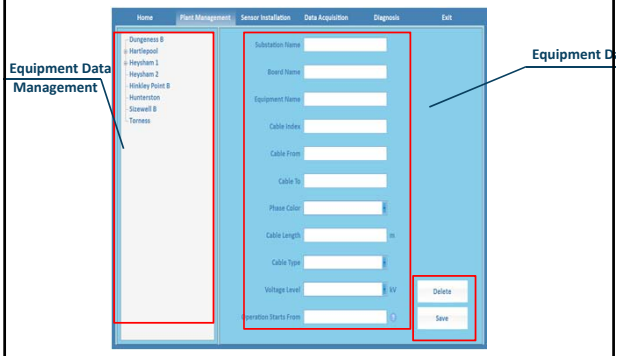
Motor PD Pattern Recognition | Criticality Check

XML Information Management

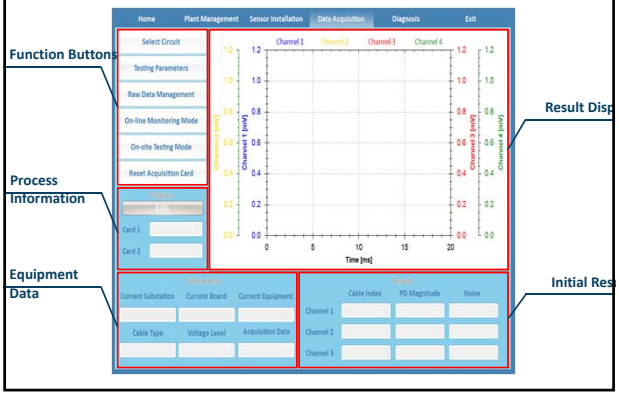
Graphic User Interface (GUI)



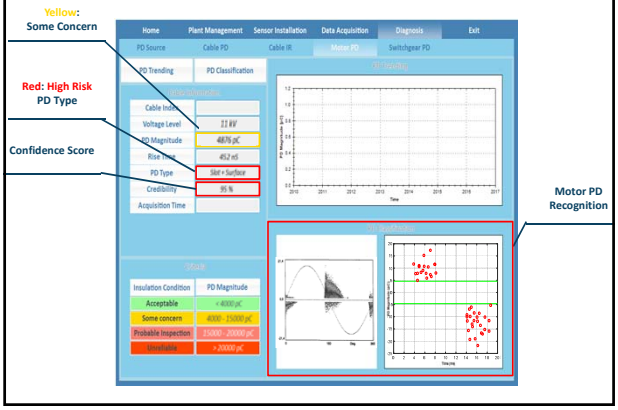
Information Management



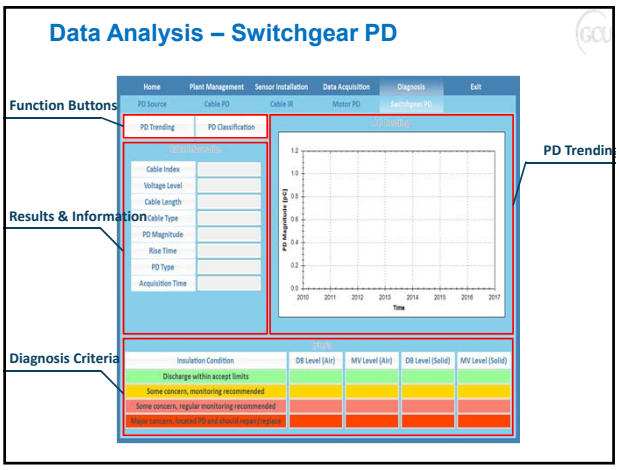
Data Acquisition



Motor PD Recognition and Confidence Score



Data Analysis – Switchgear PD



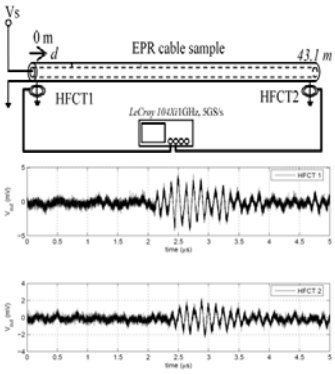
On-site Testing Experience with EDF Energy

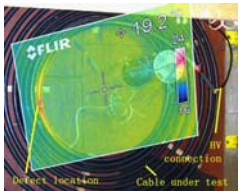
The software de-noising and pattern recognition have been applied to on-site monitoring data from Hunterston, Torness, Hartlepool, Sizewell, Heysham and Hinkley.

- Capable of more detailed analysis and diagnosis than existing commercial products.

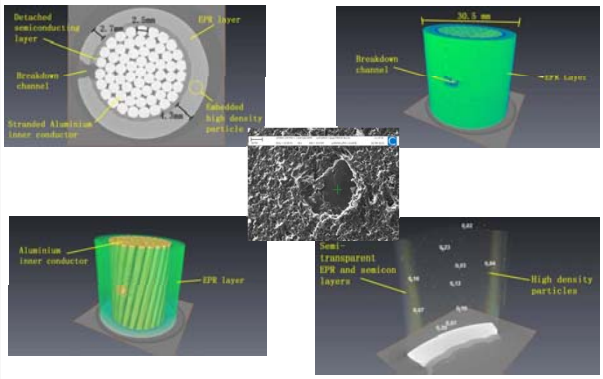
EDF Energy Nuclear Stations in UK

Post Fault Analysis – Torness, 2012



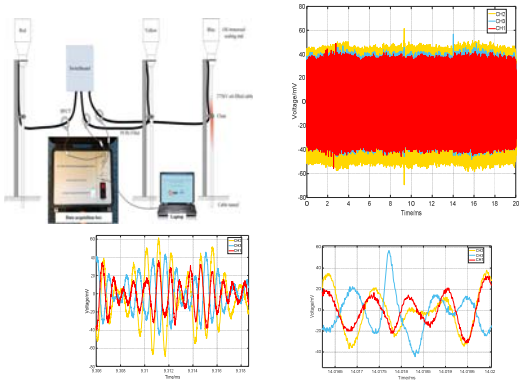


Post Fault Analysis

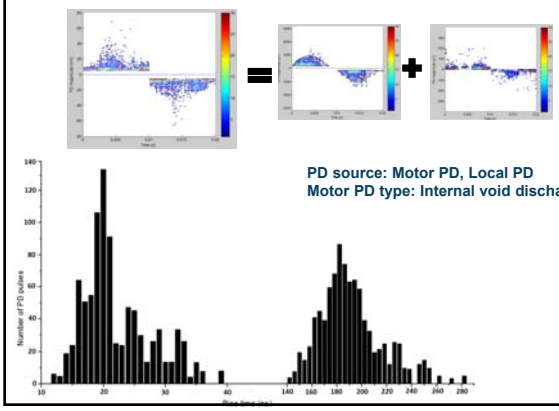


275kV OF Cable PD Test, Jan 2018

- PD activities ruled out – it is important not to give false alarm!!!



PD Monitoring Result in May 2015



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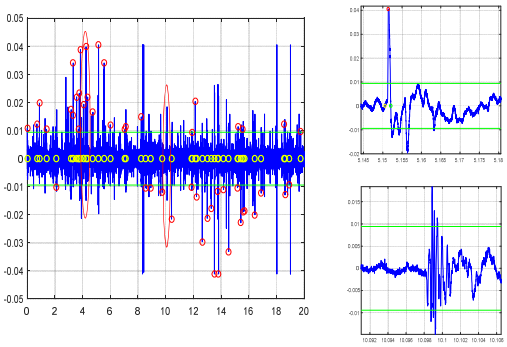
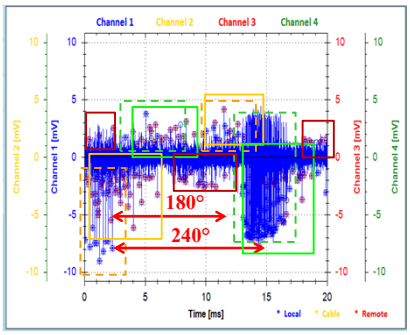
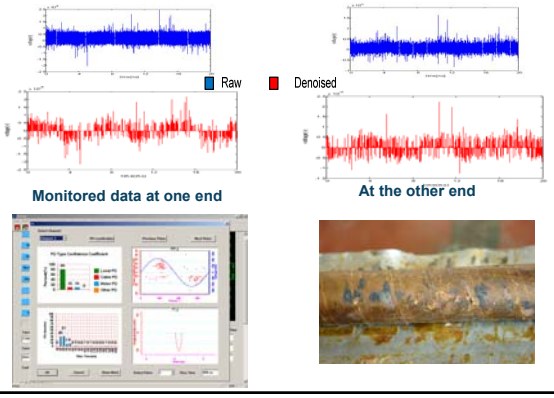
De-noising Technology – removing pulse shaped noise and identification of PD in presence of high level of noise



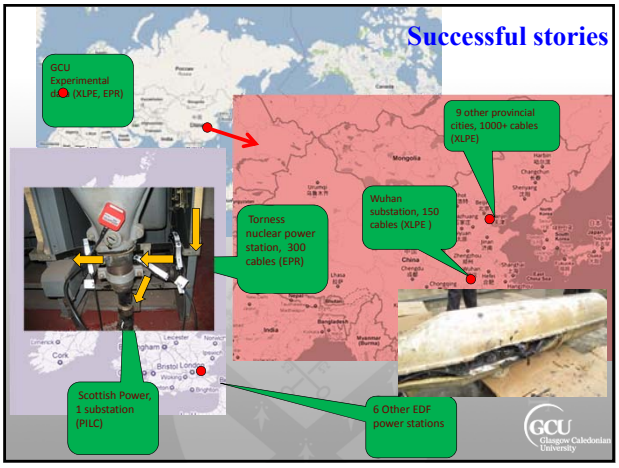
PD Test and Diagnosis Results - PD activities from switchgear and cables



Successful Application Example – London



Successful stories



Relevant publications

•X.Song, **C.Zhou**, D.M.Hepburn, M.Michel: "Second Generation Wavelet Transform in PD Measurement Denoising". IEEE Transactions on Dielectrics and Electrical Insulation. December 2007, Vol. 14, No.6.
•**C. Zhou**, X. Zhou, M. Michel, B. Stewart, A. Nesbitt, D. Hepburn, D. Guo, 'Comparison of Digital Filter, Matched Filter and Wavelet Transform in PD Detection', International Council on Large Electric Systems (CIGRE), Aug. Session 2006
•X. Zhou, **C. Zhou**, I.J.Kemp: "An improved methodology for application of Wavelet Transform to PD measurement denoising", IEEE Transaction on Electrical Insulation and Dielectrics". Vol.12, No. 3, June, 2005
•X. Ma, **C. Zhou**, I. J. Kemp: "Interpretation of Wavelet Analysis and Its Application in Partial Discharge Detection", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 19, No. 3, June 2002
•X. Ma, **C. Zhou** and I.J. Kemp: "Automated Wavelet Selection and Thresholding for PD Detection", IEEE Insulation Magazine, Vol. 18, No. 2, March/April, 2002.

Relevant publications

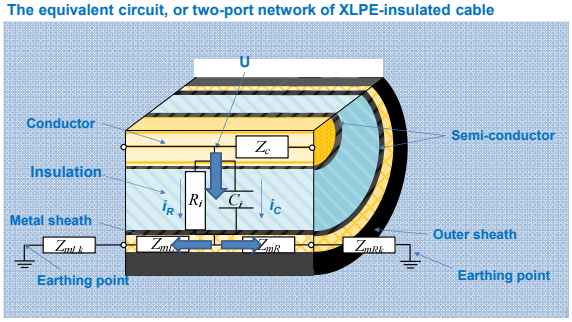
- X. Peng, C. Zhou, D.M. Hepburn, M. Judd and W.H. Siew: "Application of K-Means Method to pattern Recognition in On-line Cable PD Monitoring", IEEE Transactions on Dielectrics and Electrical Insulation, June 2013, Vol. 20, No.3
- J. Reid, C. Zhou and D. M. Hepburn, M. D. Judd and W. H. Siew: "Fault Location and Diagnosis in Medium Voltage Shielded Power Cable: A Case Study", IEEE Transactions on Dielectrics and Electrical Insulation, March, 2013 , Vo. 20, No.2
- Bojie Sheng, Chengke Zhou, Donald M Hepburn, Xiang Dong: A Novel Localisation Method in On-line Cable PD Monitoring Based on the Transfer |function and Pulse Risetime, IEEE Transactions on Dielectrics and Electrical Insulation, August2015
- Bojie Sheng, Chengke Zhou, Donald M Hepburn, Xiang Dong: Partial Discharge Pulse Propagation in Power Cable and Partial Discharge Monitoring System, IEEE Transactions on Dielectrics and Electrical Insulation, June 2014
- Bojie Sheng, Chengke Zhou, Donald M Hepburn, Xiang Dong: Partial Discharge Localisation in 3-ph Crossed Cable Systems, IEEE Transactions on Dielectrics and Electrical Insulation, Oct 2014

Plenary talk to International Conference on Condition Monitoring and Diagnostics

- Dielectric Loss Monitoring
- Cable Sheath Fault Monitoring and Diagnosis
- Rapid Cable Fault Localisation
- Conclusions

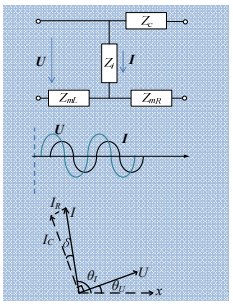
Leakage current

The equivalent circuit, or two-port network of XLPE-insulated cable



Challenge in DL monitoring

-- reference voltage unavailable



Theoretical calculation:

$$\delta = \frac{\pi}{2} - (\theta_I - \theta_U)$$

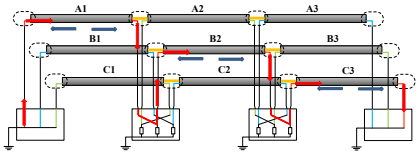
When considering the practical condition:

$$\begin{aligned}\delta_m &= \pi/2 - (\theta_{Im} - \theta_{Um}) \\ &= \pi/2 - (\theta_{I0} + \gamma_I) + (\theta_{U0} + \gamma_U) \\ &= (\pi/2 - (\theta_{I0} - \theta_{U0})) + (\gamma_U - \gamma_I) \\ &= \delta_0 + (\gamma_U - \gamma_I)\end{aligned}$$

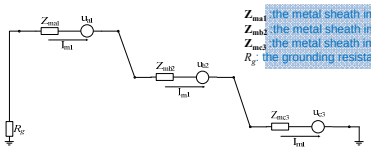
γ_U is the error in voltage measurement
γ_I is the error in current measurement

Voltage varies along a cable circuit, acquiring voltage signal is difficult

Challenge -- presence of circulating current

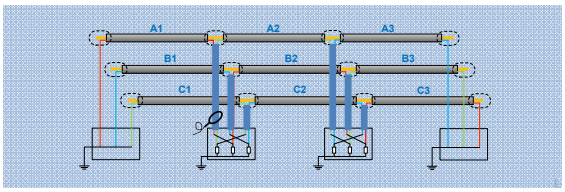


$$\mathbf{I}_{m1} = \frac{\mathbf{u}_{a1} + \mathbf{u}_{b2} + \mathbf{u}_{c3}}{\mathbf{Z}_{ma1} + \mathbf{Z}_{mb2} + \mathbf{Z}_{mc3} + R_g}$$



$\mathbf{Z}_{ma1}$: the metal sheath impedance in section A1
$\mathbf{Z}_{mb2}$: the metal sheath impedance in section B2
$\mathbf{Z}_{mc3}$: the metal sheath impedance in section C3
R_g: the grounding resistance

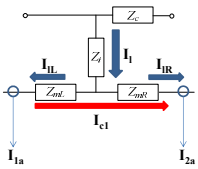
Challenge -- Co-axial cables used for cross bonding



- In order to avoid moisture ingress and for the ease of installation, industrial practise is to use co-axial cable for cross-bonding.
- Each current sensor detects the sheath current from 2 different loops, e.g. Loop1 and Loop3 as shown above.

Loop1: A1-B2-C3
Loop2: B1-C2-A3
Loop3: C1-A2-B3

Leakage Current Separation



$$I_{m1} = \frac{u_{a1} + u_{b2} + u_{c3}}{Z_{ma1} + Z_{mb2} + Z_{mc3} + R_g}$$

$$I_l = I_{IL} + I_{IR} = (I_{IL} - I_{c1}) - (-I_{IR} - I_{c1}) = I_{1a} - I_{2a}$$

Within the same sheath loop, circulating current is the same at different point of CT sensors, leakage current is different, making possible to detect leakage current.

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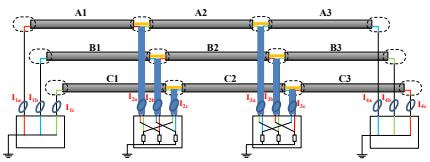
Leakage Current Separation results



The deduced leakage current	Vector difference of leakage current	Expression by the detected currents
I_{1BA}	$I_{1BA}=I_{B1}-I_{A1}$	$I_{1BA}=I_{1b}-I_{2b}-I_{1a}$
I_{1CB}	$I_{1CB}=I_{C1}-I_{B1}$	$I_{1CB}=I_{1c}-I_{2c}-I_{1b}$
I_{1AC}	$I_{1AC}=I_{A1}-I_{C1}$	$I_{1AC}=I_{1a}-I_{2a}-I_{1c}$
I_{2BA}	$I_{2BA}=I_{B2}-I_{A2}$	$I_{2BA}=I_{2a}-I_{3b}$
I_{2CB}	$I_{2CB}=I_{C2}-I_{B2}$	$I_{2CB}=I_{2b}-I_{3c}$
I_{2AC}	$I_{2AC}=I_{A2}-I_{C2}$	$I_{2AC}=I_{2c}-I_{3a}$
I_{3BA}	$I_{3BA}=I_{B3}-I_{A3}$	$I_{3BA}=I_{3a}-I_{4b}+I_{4a}$
I_{3CB}	$I_{3CB}=I_{C3}-I_{B3}$	$I_{3CB}=I_{3b}-I_{4c}+I_{4b}$
I_{3AC}	$I_{3AC}=I_{A3}-I_{C3}$	$I_{3AC}=I_{3c}-I_{4a}+I_{4c}$

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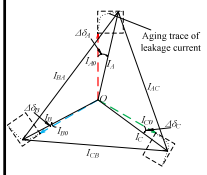
Criteria of assessment



	Diagnosis on relative state of aging	
$\delta_C \le \delta_B \le \delta_A$ $\delta_B \le \delta_C \le \delta_A$	$I_{AC} \le I_{CB} \le I_{BA}$	Phase A is highest
$\delta_C \le \delta_A \le \delta_B$ $\delta_A \le \delta_C \le \delta_B$	$I_{BA} \le I_{AC} \le I_{CB}$	Phase B is highest
$\delta_A \le \delta_B \le \delta_C$ $\delta_B \le \delta_A \le \delta_C$	$I_{CB} \le I_{BA} \le I_{AC}$	Phase C is highest
$\delta_A \le \delta_C \le \delta_B$ $\delta_C \le \delta_B \le \delta_C$	$I_{BA} \le I_{CB} \le I_{AC}$	Phase A is lowest
$\delta_B \le \delta_C \le \delta_A$ $\delta_B \le \delta_A \le \delta_C$	$I_{CB} \le I_{AC} \le I_{BA}$	Phase B is lowest
$\delta_C \le \delta_A \le \delta_B$ $\delta_C \le \delta_B \le \delta_A$	$I_{AC} \le I_{BA} \le I_{CB}$	Phase C is lowest

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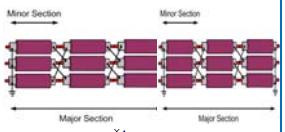
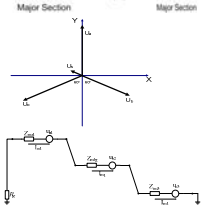
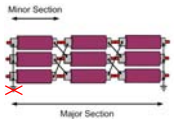
Third party damage, environmental and installation issues -- causing abnormal sheath current

Circulating current is the result of unbalance among the induced voltages in three phases





Circulating current changes drastically when faults developed in outer-sheath or joints



Theft of earthing conductor

flooded link box

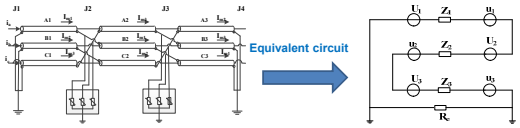
Selected Sheath Faults for Study

Selected sheath fault scenario has been studied and contrasted against normal operating conditions, before criteria is developed for fault diagnosis

	Selected Sheath Fault	
1	Open-circuit fault in sheath loop1 (A1-C2-B3)	Stolen earthing conductor
2	Open-circuit fault in sheath loop2 (B1-A2-C3)	
3	Open-circuit fault in sheath loop3 (C1-B2-A3)	
4	Short-circuit fault due to flooding in link box J1	Cable tunnel flooding
5	Short-circuit fault due to flooding in link box J2	
6	Short-circuit fault due to flooding in link boxes J1 and J2	
7	Sheath Insulation breakdown in joint JA1	
8	Sheath Insulation breakdown in joint JB1	
9	Sheath Insulation breakdown in joint JC1	
10	Sheath Insulation breakdown in joint JA2	
11	Sheath Insulation breakdown in joint JB2	
12	Sheath Insulation breakdown in joint JC2	

Modeling of sheath current

-- inductive current



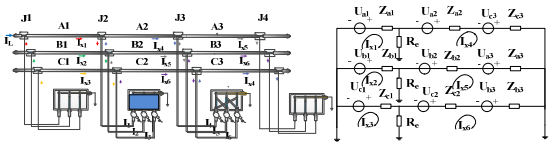
$$U_{A1} = -j\omega[L_{s11}\cdot(i_a + I_{m1}) + M_{ab}\cdot(i_b + I_{m2}) + M_{ac}\cdot(i_c + I_{m3})]\cdot d_1$$

$$U_{B2} = -j\omega[M_{ba}\cdot(i_a + I_{m3}) + L_{s22}\cdot(i_b + I_{m1}) + M_{bc}\cdot(i_c + I_{m2})]\cdot d_2$$

$$U_{C3} = -j\omega[M_{ca}\cdot(i_a + I_{m2}) + M_{cb}\cdot(i_b + I_{m3}) + L_{s33}\cdot(i_c + I_{m1})]\cdot d_3$$

$$I_{m1} = \frac{(U_{A1} + U_{B2} + U_{C3})}{R_s\cdot(d_1 + d_2 + d_3) + j\omega(L_a\cdot d_1 + L_b\cdot d_2 + L_c\cdot d_3) + R_e}$$

Short Circuit in Link Box due to Flooding

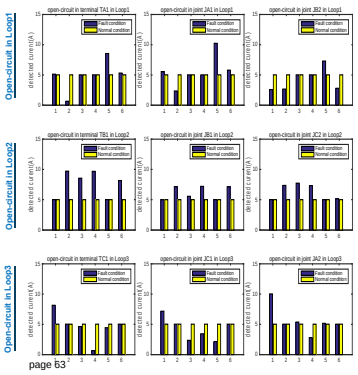


$$I_1 = I_{x1} + I_{x4} \qquad I_4 = I_{x4} + I_{x5}$$
$$I_2 = I_{x2} + I_{x5} \qquad I_5 = I_{x5} + I_{x6}$$
$$I_3 = I_{x3} + I_{x6} \qquad I_6 = I_{x6} + I_{x4}$$

Simulations are carried out for each fault scenario.

E.g., when a cable link box becomes damaged, the conductors in the box could be immersed in water.

Diagnosis of Sheath Faults



Open-circuit Sheath Faults

Open-circuit loop	Fault type determination	Judgment based on detected currents
Loop1 (A1-B2-C3)	$Max(I_j)/I_n<3$	$(I_{2a}, I_{2b}, I_{2c}, I_{3a}, I_{3b}, I_{3c})$ = (1,1,0,0,1,1)
Loop2 (B1-C2-A3)	$Max(I_j)/I_n<3$	$(I_{2a}, I_{2b}, I_{2c}, I_{3a}, I_{3b}, I_{3c})$ = (0,1,1,1,0,1)
Loop3 (C1-A2-B3)	$Max(I_j)/I_n<3$	$(I_{2a}, I_{2b}, I_{2c}, I_{3a}, I_{3b}, I_{3c})$ = (1,0,1,1,1,0)

"1": There is relative change in comparison with that in normal condition ($|I_j-I_n|>1A$);
"0": There is no obvious change in comparison with that in normal condition ($|I_j-I_n|\leq 1A$).

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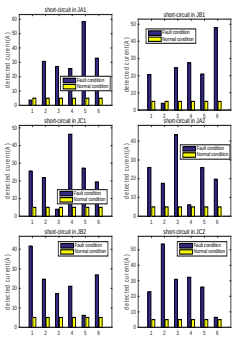
Diagnosis of Sheath Faults



Short-circuited Sheath Faults in Joints

Short-circuit due to breakdown in joints	Fault type determination	Judgment based on detected currents
Breakdown in JA1	$Min(I_i)/I_n \approx 1$ $Max(I_i)/I_n > 8$	$(I_{2a1}, I_{2b1}, I_{2c1}, I_{3a1}, I_{3b1}, I_{3c1})$ $=(1, 2, 2, 2, 3, 2)$
Breakdown in JB1	$Min(I_i)/I_n \approx 1$ $Max(I_i)/I_n > 8$	$(I_{2a1}, I_{2b1}, I_{2c1}, I_{3a1}, I_{3b1}, I_{3c1})$ $=(2, 1, 2, 2, 2, 3)$
Breakdown in JC1	$Min(I_i)/I_n \approx 1$ $Max(I_i)/I_n > 8$	$(I_{2a1}, I_{2b1}, I_{2c1}, I_{3a1}, I_{3b1}, I_{3c1})$ $=(2, 2, 1, 3, 2, 2)$
Breakdown in JA2	$Min(I_i)/I_n \approx 1$ $Max(I_i)/I_n > 8$	$(I_{2a1}, I_{2b1}, I_{2c1}, I_{3a1}, I_{3b1}, I_{3c1})$ $=(2, 2, 3, 1, 2, 2)$
Breakdown in JB2	$Min(I_i)/I_n \approx 1$ $Max(I_i)/I_n > 8$	$(I_{2a1}, I_{2b1}, I_{2c1}, I_{3a1}, I_{3b1}, I_{3c1})$ $=(3, 2, 2, 2, 1, 2)$
Breakdown in JC2	$Min(I_i)/I_n \approx 1$ $Max(I_i)/I_n > 8$	$(I_{2a1}, I_{2b1}, I_{2c1}, I_{3a1}, I_{3b1}, I_{3c1})$ $=(2, 3, 2, 2, 2, 1)$

"3": Highest among three detected currents ($Max(I_i)$)
"2": Significant change detected currents ($7 > I_i/I_n > 2$)
"1": Little change in comparison with that in normal condition but not significant ($I_i/I_n \approx 1$);

State-of-the-art: cable fault localisation

- When a cable failure happens, system protection trips off the whole circuit within 0.1 second
- Current fault localisation system, usually located at one end of a circuit and based on wave travelling or fault impedance.
- The current technology does not provide information detailed enough for maintenance engineer to act, due to poor sampling rate (100KS/s) and resolution (8bits) of DAQ -- inaccuracy of CT (saturation) and determining the arrival of travelling wave)
- It often takes days for a cable fault, especially for the case of long circuit, and/or high impedance fault, to be located.

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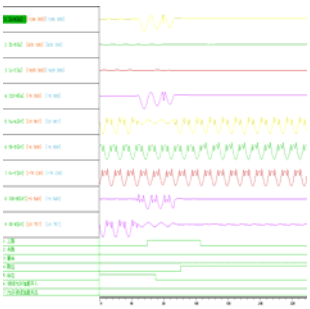
Example : 110 kV Fault current waveform, recorded by distance protection system



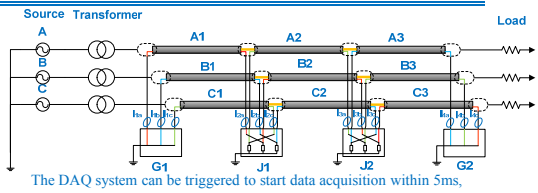
$$Z_m = Z_k = z_1 L_k = (r_1 + jx_1) L_k$$

At the present, the fault location is approximated by estimating the impedance to the fault point.

Problems:

- Inaccuracy in impedance calculation
  - Lack of knowledge in cable length

Proposed system and simulation on a 1.5km, 110kV cable system



The DAQ system can be triggered to start data acquisition within 5ms, whilst it takes 60–100ms for the system protection to clear the fault

	Parameter	Outer radius/mm
1	Centre conductor (Copper)	17.0
2	Inner semi-conductor (Nylon belt)	18.4
3	Main insulation (Ultra-clean XLPE)	34.4
4	Outer semi-conductor (Super-smooth semi-conductive shielding material)	39.4
5	Metal sheath (aluminum)	43.9
6	Outer sheath (PVC)	48.6

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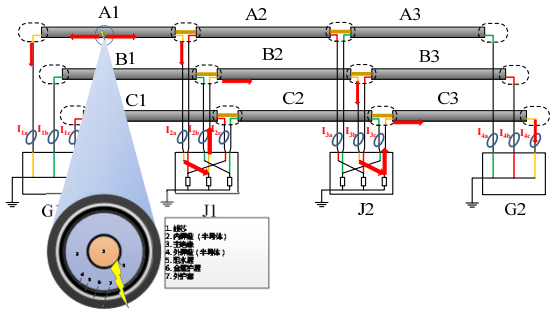
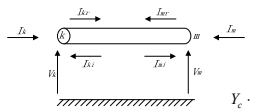
Flow of fault current during a short-circuit fault



Equivalent circuit for short circuit fault analysis



$$\left.\begin{aligned} Y_c \cdot V_k - I_k &= 2 \cdot H^T \cdot I_{mr} = 2 \cdot I_{ki} \\ Y_c \cdot V_m - I_m &= 2 \cdot H^T \cdot I_{ki} = 2 \cdot I_{mi} \end{aligned}\right\}$$

The transfer function matrix H and admittance matrix Y_c

$$H = e^{-\sqrt{Z \cdot Y} \cdot l} \qquad Y_C = Z^{-1}\sqrt{ZY}$$

The basic formulae describing a transmission line system

$$\frac{d\mathbf{V}}{dx} = -\mathbf{Z} \cdot \mathbf{I} \qquad \frac{d\mathbf{I}}{dx} = -\mathbf{Y} \cdot \mathbf{V}$$

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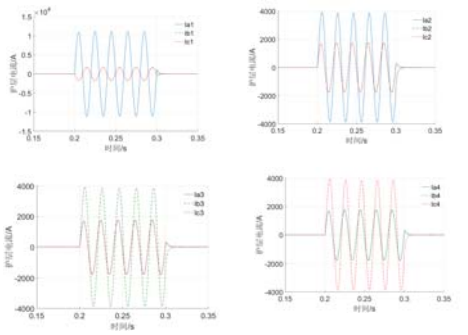
Simulation results – fault in Section A1



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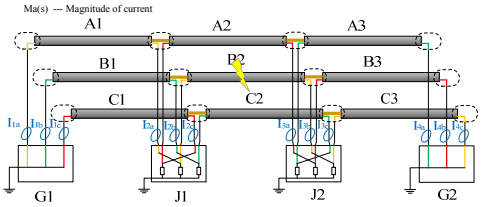
Fault current magnitudes

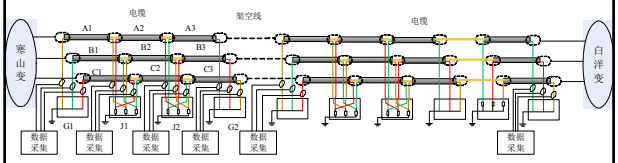
Position of fault	B2
Ma(Ia1)	7294.91
Ma(Ia2)	7296.85
Ma(Ib3)	7308.9
Ma(Ic4)	7312.88

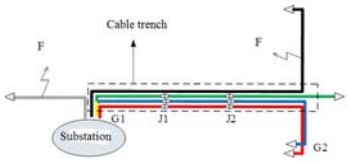
When a fault occurs in the middle sections, it is almost impossible to identify the fault cable section.

Ma(s) --- Magnitude of current



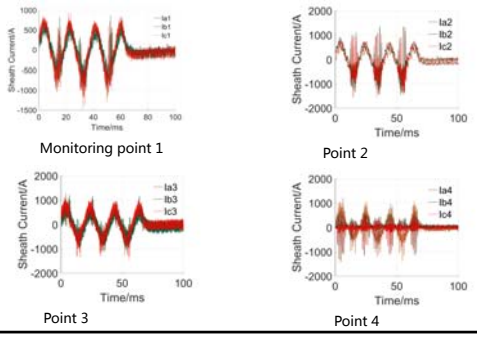
Case study





On the 8th Dec. 2016, the system detected fault in 35kV cables in the same cable trench.

Recorded waveforms in the cable sheath monitoring system



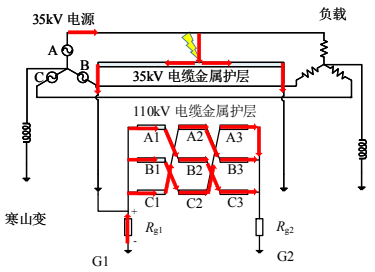
Monitoring point 1

Point 2

Point 3

Point 4

Equivalent circuit



Summary

- Localising fault using phase information is more reliable than using fault current magnitude. When the short circuit fault happens in the middle cable sections, it will be difficult to identify the fault sections if only fault current magnitude is used.
- Accuracy of fault localisation can be improved to under 50 metres, if the induced current in the sheath loop is also considered.
- The system is currently been applied to a metropolitan city in China. Further test results will be reported later.

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THE END

Thanks !

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