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D6.12.15 Definition of the monitored quantities
D6.12.16 Definition of analysis and modeling methods for selected quantities

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Contents of the presentation

- Data sources for proactive network monitoring
  - Network information system (NIS)
  - Data from existing measurement devices
  - Data from secondary substation monitors
  - Data from other on-line sensors
  - Data from periodic measurements
- Definition of the monitored quantities
  - This study focuses on the quantities monitored by the secondary substation monitors:
    - Partial discharge (PD), power quality (PQ) and MV/LV disturbance records
    - Utilization of supporting information from NIS
  - Utilization of data from existing measurement devices has been dealt with in e.g. D6.12.1
- Definition of the IED level data analysis methods
- Definition of the central system data analysis methods

Network information system (NIS)

- Existing data
  - Line lengths and line types (e.g. underground cable type)
  - Date or year of installation
  - Location of junctions where line type changes
  - Component manufacturers and models

- What would be useful as well?
  - Manufacturer of underground cables
  - Location of all line junctions
  - Manufacturer, type, installation date and installer of line accessories
    - In underground cables: cable junctions and terminations
    - In overhead lines: insulators

Data from existing measurement devices

- Feeder terminal data (dealt with in D6.12.1):
  - MV disturbance records, potential applications
    - Relay test reporting based on real fault events
    - Monitoring of breaker operation times (mechanical condition)
    - Monitoring of breaker contact condition
  - Breaker CM data (number of operations, magnitude of current)
- AMR meters:
  - voltage levels
  - power supply interruptions

Data from the secondary substation monitors

- The following quantities are planned to be monitored by the secondary substation monitors installed at high priority secondary substations:
  - Medium voltage (MV) side
    - Phase currents I_{mvL1}, I_{mvL2} and I_{mvL3}, sensors: HFCTs
    - Residual current I_0, sensor: power frequency current transformer
  - Low voltage (LV) side
    - Phase voltages U_{lvL1}, U_{lvL2} and U_{lvL3}, sensors: resistive dividers
    - Neutral current I_n , sensor: power frequency current transformer
- The focus of this study will be in analysis of these quantities
- The data is stored in network asset management information system

Data from other condition monitoring devices

- Transformer condition monitoring
  - Dissolved gas analyzer
  - Hot spot temperature measurement

Data from periodic condition monitoring measurements

- Periodic on-line measurements
- Periodic off-line measurements, commissioning measurements
- Thermal imaging
- Ultrasonic mapping
- Potential future data
  - Power quality complaints, periodic power quality measurements

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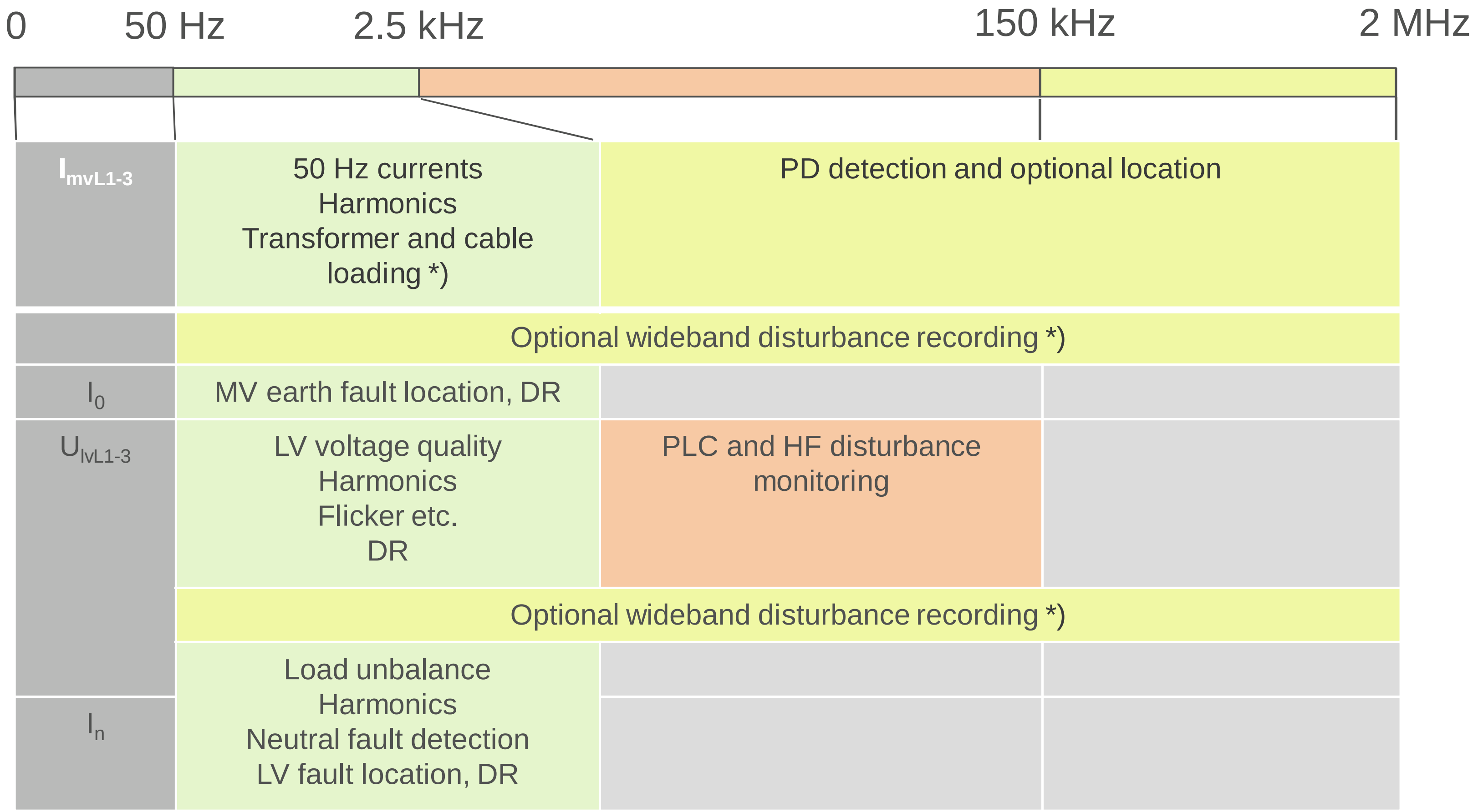
Secondary substation monitoring

Data from the secondary substation monitors

- The following quantities are planned to be monitored by the secondary substation monitors (e.g. those designed in SGEM Task 6.3) installed at high priority secondary substations:

Quantity	Frequency range		Monitoring function			Channels used		
MV-side	HF	LF	Primary	Secondary	Tertiary	PD	PQ	DR
I_{mvL1}	x	(x)	PD detection and location	(LF: Disturbance recording, current harmonics, transformer loading, cable loading)		x	(x)	x
I_{mvL2}	x	(x)				x	(x)	x
I_{mvL3}	x	(x)				x	(x)	x
I_0		x	MV fault location, disturbance recording					x
LV side								
U_{lvL1}	(x)	x	LV Voltage quality, harmonics, disturbance recording	PD 50 Hz voltage reference, (HF: PLC/HF interference)	MV phase-to-phase voltages, LV faulty phase detection, fault type assesment	x	x	x
U_{lvL2}	(x)	x				(x)	x	x
U_{lvL3}	(x)	x				(x)	x	x
I_n		x	LV fault location, disturbance recording	Neutral conductor loading, neutral conductor fault			(x)	x
HF: frequency range at least 10 kHz...2 MHz				x: essential				
LF: frequency range at least 50 Hz...2.5 kHz				(x): optional (needed for some additional/secondary function)				

Frequency ranges of monitoring



*) Optional functions (availability depends on sensor characteristics)

DR = disturbance recording

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IED level data analysis

Analysis of MV phase currents

- Source data:
  - 20 ms (one full 50 Hz cycle) 3-phase PD data streams (f_s > 10 MS/s) from the MV HFCT sensors (I_{mvL1}, I_{mvL2} and I_{mvL3})
- Signal processing:
  - Filtering/noise removal
  - Pulse pickup (threshold based)
  - Pulse area (RMS) calculus
- Data analysis:
  - Cumulative phase specific (L1, L2, L3) data aggregation:
    - Trend - daily min/avg/max of largest repeatedly occurring pulse (LROP) calculated according to IEC 60270 of each phase
    - PRPDA (phase resolved partial discharge) pattern (hourly/daily)
    - Optional PD location estimate(s)
  - Alarm generation based on trend (+ later PRPDA pattern and PD location data if available)

Analysis of MV residual current I_0

- Source data:
  - 20 ms (one full 50 Hz cycle) data stream from the I_0 sensor
- Signal processing:
  - Downsampling from f_s > 10 MS/s to f_s = 12.8 kS/s
  - DFT (discrete fourier transform) for harmonic analysis
  - RMS calculus
- Data analysis:
  - Alarm generation if the following I_0 triggering conditions are exceeded:
    - I_0 RMS > trigger level
    - Selected harmonic(s) exceed the related trigger level(s)
  - In case of alarm trigger conditions met:
    - Save disturbance record waveforms of selected channels (I_{mvL1}, I_{mvL2}, I_{mvL3}, I_0, U_{lvL1}, U_{lvL2} and U_{lvL3}, I_n)
  - Automatic earth fault location based on I_0

Analysis of PQ data

- Source data:
  - 20 ms (one full 50 Hz cycle) 3-phase voltage streams from the LV voltage sensors (U_{lvL1}, U_{lvL2} and U_{lvL3})
- Signal processing:
  - Downsampling from f_s > 10 MS/s to f_s = 12.8 kS/s
  - DFT (discrete fourier transform) for harmonic analysis
  - RMS calculus
  - Aggregation of data for flicker calculus
  - Optional DFT and RMS calculus of the 3…150 kHz voltages (for PLC and high frequency disturbance monitoring)
- Data analysis:
  - Voltage level - 10 minute min/avg/max values from each phase
  - Voltage THD - 10 minute min/avg/max values from each phase
  - Voltage harmonics 2-50 (10 minute min/avg/max values for selected harmonics from each phase)
  - Flicker – Pst- and Plt-values from each phase

Analysis of LV neutral current I_n

- Source data:
  - 20 ms (one full 50 Hz cycle) data stream from the I_n sensor
- Signal processing:
  - Downsampling from f_s > 10 MS/s to f_s = 12.8 kS/s
  - DFT (discrete fourier transform) for harmonic analysis
  - RMS calculus
- Data analysis:
  - Alarm generation if the following I_0 triggering conditions are exceeded:
    - I_0 RMS > trigger level (neutral conductor overloading or earth fault)
    - I_0 THD (total harmonic distortion) or predefined harmonics exceed the trigger level(s)
  - In case of triggering conditions met:
    - Save disturbance record waveforms of selected channels (I_{mvL1}, I_{mvL2}, I_{mvL3}, I_0, U_{lvL1}, U_{lvL2} and U_{lvL3}, I_n), send an alarm
    - Check phase voltages from PQ data, if voltage dip or interruption is detected, start fault recognition and location algorithm (this could also be a central system function)

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Central system data analysis

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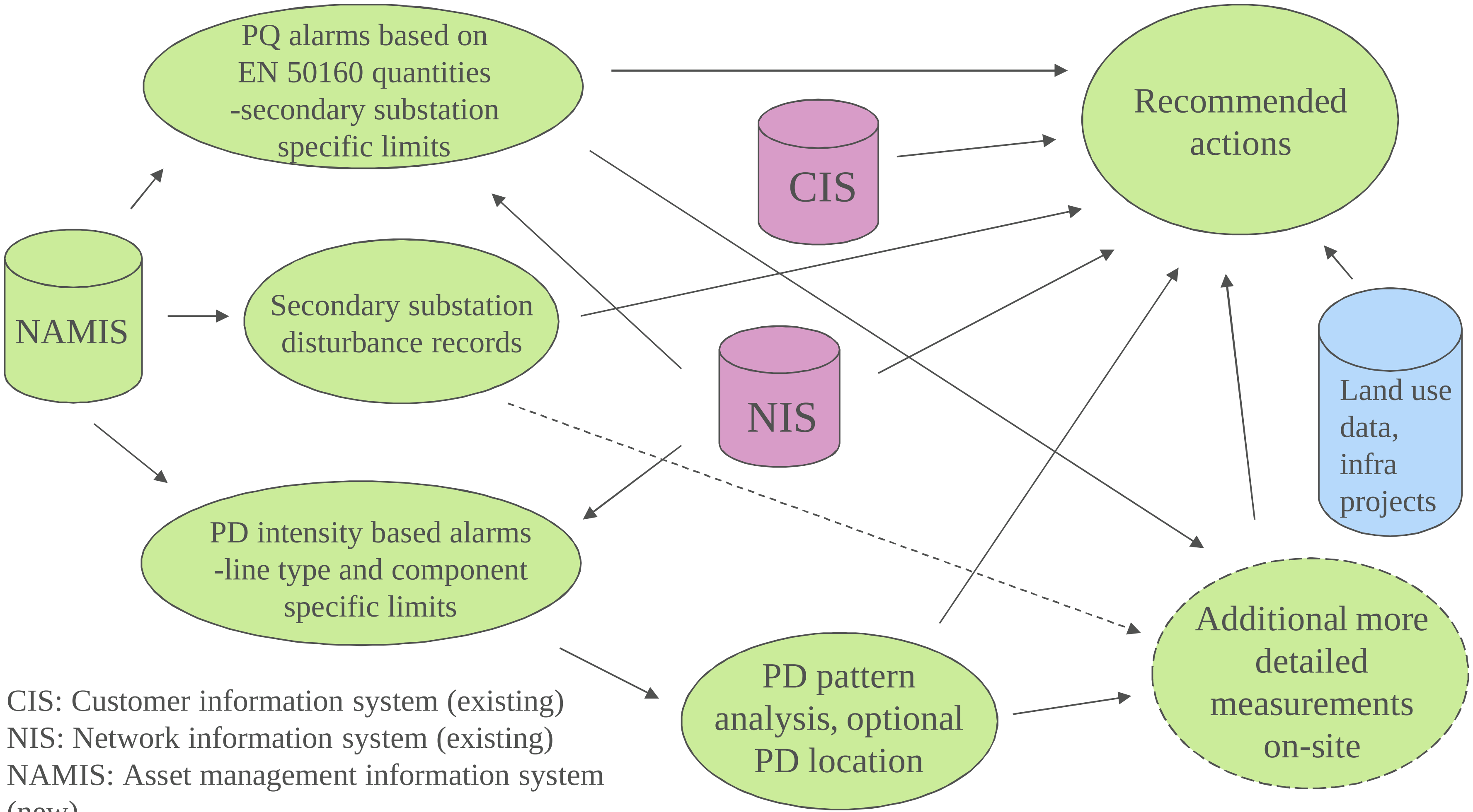
Central system analysis of quantities measured by secondary substation monitor



CIS: Customer information system (existing)
NIS: Network information system (existing)
NAMIS: Asset management information system (new)

Functionalities implemented at central system level

- Automatic PD location
- Automatic MV earth fault location based on I_0
- Automatic MV short circuit fault location based on I_{mvL1}, I_{mvL2} and I_{mvL3} (if wideband current measurement from MV side is available)
- Automatic LV fault location based on U_{lvL1}, U_{lvL2}, U_{lvL3} and I_n
- Determination of the recommended actions based on NAMIS, CIS, NIS, land-use and infraprojet data

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Analysis of PD data

- Cables are classified based on the PD level and related data into different failure probability classes
- An example: 7500 km of PILC, EPR and XLPE cables studied by DTE Energy Technologies, Inc.
- Failure probability after 1 year and 2 years after the PD measurement

Level 1: System is free of partial discharge. No action needs to be taken.

Level 2: Small level of PD. In joints and terminations, this level of PD is normal and thus no action needs to be taken. However, in extruded cable, PD retest in two years is recommended.

Level 3: Low probability of failure in 2 years, consider re testing at one year intervals.

Level 4: Medium probability of failure in 2 years, consideration should be given to replacement or other remedial action taken.

Level 5: High probability of failure in 2 years, consideration should be given to replacement.

Classification level	Number of PD sites found	Failure probability after:	
		1 year	2 years
1	*This level means that PDs have not been detected during the measurement*	0 %	0 %
2	400 000	0 %	0 %
3	250 000	0,0028 %	0,0068 %
4	4 000[1]	0,7 %	2,7 %
5	500[2]	14 %	37 %

[1] The calculated failure probability is based on the amount of faults encountered in 1000 sites that had been left in service after measurements
[2] The calculated failure probability is based on the amount of faults encountered in 100 sites that had been left in service after measurements

Reference: N. Ahmed, N. Srinivas, “Experience gained with on-line partial discharge testing in power cable system”, Transmission and Distribution Conference and Exposition, 2001 IEEE/PES, vol.2, pp. 859-864, 2001.

PD alarm generation

- Alarms are generated based on the PD level to initiate more detailed tests or measurements
- Recommendations for actions based on PD trend and more detailed on-line measurements (e.g. PD location, thermal imaging and ultrasonic mapping)

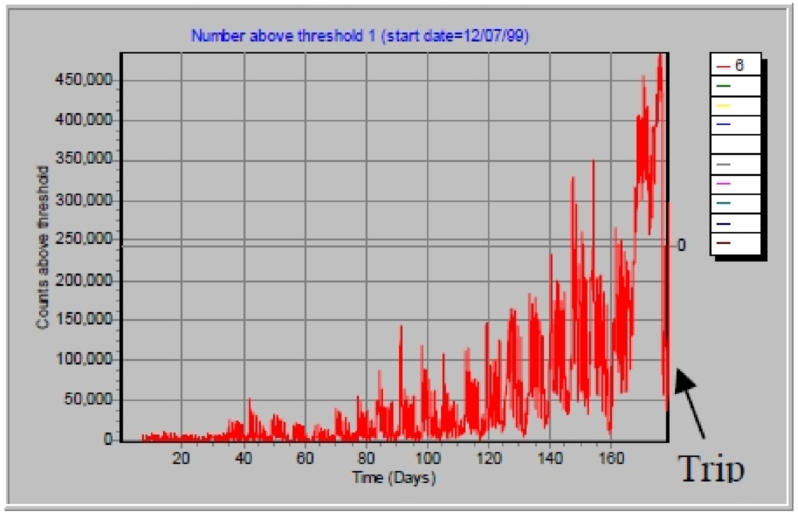

Fig 7 PD activity before circuit trip

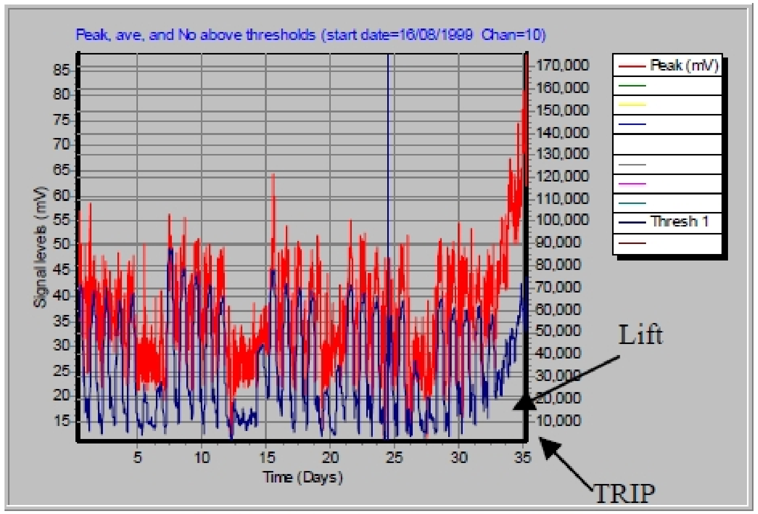

Fig 8 PD behaviour prior to failure

Recommended actions based on PD data

- Additional more detailed measurements
  - On-line or off-line PD measurement and location
  - Thermal imaging, ultrasonic detection
  - Shield integrity and tan-delta measurement
- Changes in network operation:
  - stress relief of the defected cable, e.g. load reduction through network reconfigurations (if applicable)
  - preparation of alternative power supply arrangements
- Maintenance scheduling:
  - repair ASAP
  - repair later in conjunction with other off-line maintenance or construction
- Input for network planning, for example:
  - planning and scheduling of transformer replacement
  - planning and scheduling of cable replacement
  - input also e.g. from PQ analysis and land use planning

Recommended actions based on PQ data

- Additional more detailed measurements
  - Measurement of short circuit current
  - At least one week PQ measurement using IEC 61000-4-30 class A measuring device
- Changes in network operation:
  - network reconfigurations (if applicable)
- Maintenance scheduling:
  - repair ASAP
  - repair later in conjunction with other off-line maintenance or construction
- Input for network planning:
  - planning and scheduling of transformer replacement
  - planning and scheduling of cable replacement (input needed also e.g. from PQ analysis and land use planning)

Recommended actions based on disturbance records

- Changes in network operation:
  - network reconfigurations to isolate the faulted line section
- Additional more detailed measurements
  - Fault location in the faulted line section using cable fault locator, impulse generator and acoustic pinpointer
- Maintenance scheduling (based on e.g. high neutral current and/or harmonic levels) and customer contacts:
  - load balancing
  - harmonic filtering/management
- Input for network planning (mainly based on high neutral current and/or harmonic levels):
  - planning and scheduling of transformer upgrading
  - planning and scheduling of cable upgrading (input needed also e.g. from PQ analysis and land use planning)

References:

- O. Vuorinen, Using process data in condition based maintenance, MSc thesis, 2011.
- H. Kuisti, J. Altonen, Intermittent earth faults challenge conventional protection schemes, 15th International Conference on Electricity Distribution (CIRED), Nice, Italy 1999.
- V. Jokela, Sähköasemadatan laajamittainen analysointi, Diplomityö, 2014. (in Finnish)
- N. Ahmed, N. Srinivas, “Experience gained with on-line partial discharge testing in power cable system”, Transmission and Distribution Conference and Exposition, 2001 IEEE/PES, vol.2, pp. 859-864, 2001.