### Interruptions

### Content

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<th>Topic</th>
<th>Notes</th>
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<td>Introduction to Power Quality</td>
<td>- What is PQ&lt;br&gt;- Economic value&lt;br&gt;- Responsibilities</td>
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<tr>
<td>Session 2</td>
<td>Basic terms and definitions</td>
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<td>PQ standards</td>
<td>- EN 50 160&lt;br&gt;- Other standards&lt;br&gt;- Limit values</td>
</tr>
</tbody>
</table>
| Session 4 | PQ monitoring | - Measurements<br>- PQ analyzers<br>- Data analyses
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| Session 1 | Harmonics – definitions | - Calculations<br>- Non-linear loads<br>- Harmonic sequences |
| Session 2 | Harmonics - design of power factor correction devices | - Resonance points<br>- Filter design |
| Session 3 | Flicker case study | - Calculation of flicker spreading in radial network<br>- Variation of network parameters |
| Session 4 | Other voltage variations | - Unbalance<br>- Voltage transients<br>- Overvoltages |
Terms and definitions

- EN 50160 (IEC)
  - long interruption: longer than 3 minutes
  - short interruption: up to 3 minutes
- IEEE Std. 1159-1995
  - momentary interruption: between 0.5 cycles and 3 seconds
  - sustained interruption: longer than 3 seconds (overlap with temporary interruptions)
  - temporary interruption: between 3 seconds and 1 minute

Terms and definitions

- IEEE Std. 1250-1995
  - instantaneous interruption: between 0.5 and 30 cycles
  - momentary interruption: between 30 cycles and 2 seconds
  - temporary interruption: between 2 seconds and 2 minutes
  - sustained interruption: longer than 2 minutes
- IEEE Std. 859-1987
  - transient outages are restored automatically
  - temporary outages are restored by manual switching
  - permanent outages are restored through repair or replacement

Terms and definitions

- confusion about terminology
  - short interruption – the supply is restored automatically
  - long interruption – the supply is restored manually
- EN 50160 term
  - supply interruption – a condition in which the voltage at the supply terminals is lower than 1% of the declared voltage
Terms and definitions

- reliability indices
  - Energy Not Supplied – ENS
    - \( D_{\text{si}} \) – average load,
    - \( T_i \) – interruption duration in node \( i \)
  - System Average Interruption Frequency Index – SAIFI
    \[ \text{SAIFI} = \frac{\text{Total Numbr of Customer Interruptions}}{\text{Total Numbr of Customers Served}} \]
Terms and definitions

- reliability indices
  - System Average Interruption Duration Index – SAIDI
    \[ \text{SAIDI} = \frac{\sum \text{Customer Interruption Duration}}{\text{Total Number of Customers Served}} \]
  - Momentary Average Interruption Frequency Index – MAIFI
    \[ \text{MAIFI} = \frac{\text{Total Number of Customer Momentary Interruptions}}{\text{Total Number of Customers Served}} \]
EN 50160 definitions

• supply voltage disturbances
  – supply interruption
    • prearranged, when consumers are informed in advance, to allow the execution of scheduled works on the distribution system, the effect can be minimized
    • accidental, caused by permanent or transient faults, mostly related to external events, equipment failures or interference

EN 50160 definitions

• supply interruption
  – prearranged (planned) and accidental (unplanned) interruptions per customer per year

EN 50160 definitions

• supply interruption
  – prearranged (planned) and accidental (unplanned) interruption minutes lost per customer per year
EN 50160 definitions

• supply voltage disturbances
  – accidental interruption
    • unpredictable, largely random events
    • a short interruption (up to 3 minutes) caused by a permanent fault
    • a long interruption (longer than 3 minutes) caused by a transient fault

EN 50160 definitions

• voltage supply-characteristics
  – short interruptions of the supply voltage in LV and MV networks (up to 3 minutes)
    • annual occurrence: from up to a few tens to up to several hundreds
    • approximately 70% of short interruptions may be less than one second
    • in some documents short interruptions are considered as having durations not exceeding 1 minute
    • sometimes control schemes are applied which need operating times of up to three minutes in order to avoid long voltage interruption

EN 50160 definitions

• voltage supply-characteristics
  – long interruptions of the supply voltage in LV and MV networks (longer than 3 minutes)
    • indicative values: less than 10 or up to 50 depending on the area
    • differences in system configurations and structures in various countries
    • indicative values are not given for prearranged interruptions
Long interruptions

- terminology
  - failure
  - outage
  - removal of a primary component from the system
  - forced outage (failure)
  - scheduled outage
  - interruption
  - a customer is no longer supplied with electricity
  - due to outages

Long interruptions

- causes of long interruptions
  - a fault occurs in the power system which leads to an intervention by the power system protection
  - a protection relay intervenes incorrectly, thus causing a component outage
  - operator actions cause a component outage which can also lead to a long interruptions
Long interruptions

- power system reliability
  - number and duration of long interruption are stochastically predicted
  - availability – the probability of being energized
  - unavailability – the probability of not being energized

<table>
<thead>
<tr>
<th>Number of 9s</th>
<th>Reliability [%]</th>
<th>Expected disruptions per year</th>
<th>Acceptable for</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>99.9</td>
<td>9 h</td>
<td>homes</td>
</tr>
<tr>
<td>4</td>
<td>99.99</td>
<td>59 min</td>
<td>factories</td>
</tr>
<tr>
<td>5</td>
<td>99.999</td>
<td>5 min</td>
<td>hospitals, airports</td>
</tr>
<tr>
<td>6</td>
<td>99.9999</td>
<td>32 s</td>
<td>banks</td>
</tr>
<tr>
<td>7</td>
<td>99.99999</td>
<td>80 ms</td>
<td>on-line markets</td>
</tr>
</tbody>
</table>

Long interruptions

- power system reliability
  - the 9s of reliability in power delivery

<table>
<thead>
<tr>
<th>Description</th>
<th>Failure rate [1/yr/100 km]</th>
<th>MTER [hours]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead lines</td>
<td>0.012* 0.002* 0.180*</td>
<td>Low 0.02 0.02 1.0</td>
</tr>
<tr>
<td>Primary lines</td>
<td>0.012* 0.004* 0.008*</td>
<td>Medium 0.02 0.02 0.00</td>
</tr>
<tr>
<td>Secondary &amp; service</td>
<td>0.004* 0.008* 0.016*</td>
<td>High 0.02 0.02 0.00</td>
</tr>
<tr>
<td>Fuse MTR replacement</td>
<td>0.004 0.008 0.016</td>
<td>Low 0.02 0.02 0.00</td>
</tr>
<tr>
<td>Distribution circuits</td>
<td>0.004 0.008 0.016</td>
<td>Medium 0.02 0.02 0.00</td>
</tr>
<tr>
<td>Substation lines</td>
<td>0.004 0.008 0.016</td>
<td>High 0.02 0.02 0.00</td>
</tr>
</tbody>
</table>

* Failure rate per kilometre
Long interruptions

- power system reliability
  - failure rates for underground cables

<table>
<thead>
<tr>
<th>Description</th>
<th>Low (1/365)</th>
<th>Typical (1/365)</th>
<th>High (1/365)</th>
<th>MTR (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Underground cable</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Primary cable</td>
<td>0.002a</td>
<td>0.004a</td>
<td>0.002a</td>
<td>2.5</td>
</tr>
<tr>
<td>Secondary cable</td>
<td>0.002a</td>
<td>0.004a</td>
<td>0.002a</td>
<td>1.5</td>
</tr>
<tr>
<td>Ehto connectors</td>
<td>0.001</td>
<td>0.003</td>
<td>0.001</td>
<td>1.0</td>
</tr>
<tr>
<td>Cable splices and joints</td>
<td>0.04</td>
<td>0.050</td>
<td>0.170</td>
<td>4.1</td>
</tr>
<tr>
<td>Pedestrian crossings</td>
<td>0.001</td>
<td>0.010</td>
<td>0.050</td>
<td>4.6</td>
</tr>
<tr>
<td>Pedestrian switches</td>
<td>0.001</td>
<td>0.003</td>
<td>0.007</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Definition of areas

Europe: Classification

Portugal: Zone A: 1 location with more than 30 thousand customers.
Zone B: 1 location with more than 30 thousand and more than 1 thousand customers.
Zone C: 1 location with less than 1 thousand customers.

Spain: Zone A: 1 location with more than 30 thousand customers.
Zone B: 1 location with more than 1 thousand customers.
Zone C: 1 location with less than 1 thousand customers.

Italy: Zone A: 1 location with more than 30 thousand customers.
Zone B: 1 location with more than 1 thousand customers.
Zone C: 1 location with less than 1 thousand customers.

Excluding exceptional events

- definition of exceptional events
Long interruptions

- reliability indices – SAIFI
  - geographical classification

- reliability indices – SAIDI
  - geographical classification

- reliability indices – SAIFI
  - voltage level classification
Long interruptions

- reliability indices – SAIDI
  - voltage level classification

Short interruptions

- automatic restoration
- reclosing of a circuit breaker
- switching to a healthy supply
- automatic transfer switches in industrial networks

Short interruptions

- reliability indices – MAIFI
  - European countries
Improving reliability

- methods
  - reducing the number of short-circuit faults
  - reducing the fault clearing time
  - changing the system such that the short-circuit faults result in less severe events at the equipment terminals or at the customer interface
  - connecting mitigation equipment between the sensitive equipment and the supply

Consequences of inadequate power quality

Content
PQ costs examples

- sensitivity of different industries to voltage dips expressed in estimated dips cost per industry

![Graph showing different types of industries and their costs due to voltage dips.](image)

PQ costs examples

- voltage dips cost per event

<table>
<thead>
<tr>
<th>Industry</th>
<th>Duration</th>
<th>Cost/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK steel works</td>
<td>30% for 3.5 cycles</td>
<td>£250k</td>
</tr>
<tr>
<td>US glass plant</td>
<td>Less than 1 second</td>
<td>$200k</td>
</tr>
<tr>
<td>US computer centre</td>
<td>2 seconds</td>
<td>$600k</td>
</tr>
<tr>
<td>US car plant</td>
<td>Annual exposure</td>
<td>$10M</td>
</tr>
<tr>
<td>South Africa</td>
<td>Annual exposure</td>
<td>$3B</td>
</tr>
</tbody>
</table>

PQ costs examples

- financial losses caused by voltage dips

<table>
<thead>
<tr>
<th>Industry</th>
<th>Typical financial loss per event</th>
</tr>
</thead>
</table>
| Semiconductor
production | 3,000,000                        |
| Financial testing    | 6,000,000 per hour               |
| Computer centre      | 700,000                          |
| Telecommunications   | 30,000 per minute                |
| Steel works          | 350,000                          |
| Glass industry       | 250,000                          |
LPQI - PQ survey

• Leonardo Power Quality Initiative – LPQI
  – PQ survey
    • the survey interviews and web based submission were conducted over a 2-year period in 8 European countries
    • 62 complete and 6 partial interviews were carried out
    • these sectors represent some 38% of the EU-27 total of turnover
    • the main purpose of this project was to estimate costs of wastage generated by inadequate power quality for those sectors within the EU-27 for which electrical power is critical
    • PQ costs are reported in the categories of interruptions and voltage quality

LPQI - PQ survey

• Leonardo Power Quality Initiative – LPQI
  – PQ survey
    • all these cost were specified on an annual basis, either reported as such or pro-rated where frequency was less than once pa
    • also hypothetical costs that would be the potential losses and risk avoided by power systems that had been immunized against the PQ disturbances were under review
    • the subsequent regression analysis was performed to estimate PQ cost across those sectors with "annual turnover" as a key model indicator

LPQI - PQ survey

• PQ survey
  – number of interviews by sectors and countries
LPQI - PQ survey

- PQ survey
  - PQ consequences
  - blame

LPQI - PQ survey

- PQ survey
  - PQ problem sources
LPQI - PQ survey

- PQ survey
  - PQ cost summary by the type of PQ disturbance

LPQI - PQ survey

- PQ survey
  - PQ cost summary by the type of costs
  - labor cost
    - Work in Progress – WIP
      - labor and material inevitably lost
      - labor needed to make up lost production
      - sales or services such as overtime pay, extra shifts
  - equipment costs
    - including damage, shortened effective lifetime, premature component wear-out, need for additional maintenance or repair and for the purchase or rental of backup equipment
    - other costs like additional fines, penalties, personnel injury related costs, including additional compensation or increased insurance rates
  - other costs
    - savings from unused materials, unpaid wages and mainly unconsumed energy

LPQI - PQ survey

- PQ survey – type of costs
  - process slow down when the production process could not reach its nominal efficiency covering equipment restarts, resets, repeating operations, time needed for additional adjustments to and manifestation of equipment including losses in value of products running out of specification and/or value of insufficient quality of products as a consequence of a particular PQ disturbance
  - equipment costs including damage, shortened effective lifetime, premature component wear-out, need for additional maintenance or repair and for the purchase or rental of backup equipment
  - other costs like additional fines, penalties, personnel injury related costs, including additional compensation or increased insurance rates
  - savings from unused materials, unpaid wages and mainly unconsumed energy
LPQI - PQ cost summary

<table>
<thead>
<tr>
<th>Causes of PQ</th>
<th>Description</th>
<th>Cost</th>
<th>Mitigation</th>
<th>Critical cases: % cost savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage dips</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Interruptions</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Harmonics</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

LPQI - PQ survey

- Leonardo Power Quality Initiative – LPQI
  - PQ survey - conclusions
    - Industry wastes a huge amount of resource unnecessarily
    - The nature of the main causes of poor power quality illustrates that better design and greater investment into these systems would eradicate most of these losses
    - Measurement and diagnostics are significantly low for industrial sectors for which electrical power is so important
    - Industry [and others] would appear to be in denial about the levels of waste incurred

Slovenian survey

- LPQI questionnaire
- PQ survey (number of interviews by sectors)

<table>
<thead>
<tr>
<th>Investigated organizations</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food and kindred products</td>
<td>4</td>
</tr>
<tr>
<td>Pulp and paper</td>
<td>3</td>
</tr>
<tr>
<td>Printing and publishing</td>
<td>3</td>
</tr>
<tr>
<td>Plastic and rubber</td>
<td>2</td>
</tr>
<tr>
<td>Metalurgy</td>
<td>2</td>
</tr>
<tr>
<td>Automotive</td>
<td>2</td>
</tr>
<tr>
<td>Cement</td>
<td>1</td>
</tr>
<tr>
<td>Transport</td>
<td>1</td>
</tr>
<tr>
<td>White goods</td>
<td>1</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>1</td>
</tr>
<tr>
<td>Oil or petroleum refining</td>
<td>1</td>
</tr>
<tr>
<td>Textiles</td>
<td>1</td>
</tr>
<tr>
<td>Insurance, broker &amp; services</td>
<td>1</td>
</tr>
<tr>
<td>Chemicals</td>
<td>1</td>
</tr>
<tr>
<td>Not</td>
<td>24</td>
</tr>
</tbody>
</table>
Slovenian survey

• PQ survey
  – reported consequences of experienced PQ events

Slovenian survey

• PQ survey
  – annual costs related to category of organizations with annual consumption of 1 to 5 GWh (8 organizations)

Slovenian survey

• PQ survey
  – annual costs related to category of organizations with annual consumption of 5 to 25 GWh (6 organizations)
Slovenian survey

- PQ survey
  - annual costs related to category of organizations with annual consumption of more than 25 GWh (10 organizations)

Italian survey

- PQ survey
  - number and structure of interviews

<table>
<thead>
<tr>
<th>Variables</th>
<th>Domestic</th>
<th>Business</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of interviews</td>
<td>1100</td>
<td>1500</td>
</tr>
<tr>
<td>Size of the company</td>
<td>Small</td>
<td>Medium</td>
</tr>
<tr>
<td>Geographic area</td>
<td>North</td>
<td>Central</td>
</tr>
<tr>
<td>Size of locality</td>
<td>Metropolitan</td>
<td>Small</td>
</tr>
</tbody>
</table>

- interruption costs
  - direct costs
  - economic damage due to a hypothetical interruption scenario
Italian survey

- PQ survey
  - interruption costs
  - the quantification two key variables
    - willingness to pay (WTP), expressed as the price which the consumer would be willing to pay another company ready to take over with a reserve service in the event of supply interruptions on the part of the main supplier
    - willingness to accept (WTA) expressed as the amount that would be considered satisfactory if the company supplying electricity should decide to discount payment of the supply each time an interruption occurs
  - WTP and WTA act as tools by which to verify the consistency of gathered information
  - from an economic point of view these two aspects express the same concept of valuation of damage due to the interruption

Italian survey

- PQ survey
  - normalization
    - direct costs, WTA and WTP are normalized on Energy Not Supplied (ENS)
    - ENS, in kWh, indicates the quantity of energy that would on average have been consumed if the supply had not been interrupted in a given scenario for a given duration

| Table 2 - Normalized direct costs, €/kWh (1 min. interruptions, €/W) |
|-----------------|-----------------|-----------------|
|                  | Household | Business |
| 3 months         | 6.62      | 55.16   |
| 1 hour           | 25.24     | 157.98  |
| 2 hours          | 31.41     | 185.79  |
| 4 hours          | 15.72     | 97.38   |
| 6 hours          | 9.68      | 48.91   |

Power Quality, Ljubljana, 2013/14

Italian survey

- PQ survey
  - WTA and WPT normalized values

| Table 3 - Household, WTA and WTP normalized values, €/kWh (1 min. interruptions, €/W) |
|-----------------|-----------------|-----------------|
|                  | Household | Business |
| 3 months         | 5.40      | 50.32   |
| 1 hour           | 17.02     | 103.32  |
| 2 hours          | 13.02     | 78.40   |
| 4 hours          | 9.69      | 49.51   |

| Table 4 - Business, WTA and WTP normalized values, €/kWh (1 min. interruptions, €/W) |
|-----------------|-----------------|-----------------|
|                  | Household | Business |
| 3 months         | 10.20     | 102.02  |
| 1 hour           | 17.02     | 103.32  |
| 2 hours          | 13.02     | 78.40   |
| 4 hours          | 9.69      | 49.51   |

| Table 5 - Normalized values, €/kWh (1 min. interruptions, €/W) |
|-----------------|-----------------|-----------------|
|                  | Household | Business |
| 3 months         | 6.62      | 55.16   |
| 1 hour           | 25.24     | 157.98  |
| 2 hours          | 31.41     | 185.79  |
| 4 hours          | 15.72     | 97.38   |
| 6 hours          | 9.68      | 48.91   |

Power Quality, Ljubljana, 2013/14
Costs of ENS – Slovenia

- costs of ENS in Slovenia for 2006
  - 83 interviews
  - determination of ENS
  - cost of ENS in Slovenia equals 4.28 €/kWh

<table>
<thead>
<tr>
<th>Year</th>
<th>ENS (€/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td></td>
</tr>
<tr>
<td>Households</td>
<td>1.07</td>
</tr>
<tr>
<td>Industry</td>
<td>4.43</td>
</tr>
<tr>
<td>Other</td>
<td>1.32</td>
</tr>
<tr>
<td>Total</td>
<td>6.82</td>
</tr>
</tbody>
</table>

Costs of ENS – Europe

- overview of costs of interruptions in Europe
  - the differences between countries and between customer groups

Modern compensation devices
Content

<table>
<thead>
<tr>
<th>Session 1</th>
<th>1st day</th>
<th>2nd day</th>
<th>3rd day</th>
<th>4th day</th>
<th>5th day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction to Power Quality</td>
<td>Session 1: Introduction to Power Quality</td>
<td>Session 2: Basic terms and definitions</td>
<td>Session 3: PQ standards</td>
<td>Session 4: PQ monitoring</td>
<td>Session 5: Modern Compensation Devices</td>
</tr>
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<td></td>
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<td>Session 4: PQ monitoring</td>
<td>Session 5: Modern Compensation Devices</td>
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</tr>
</tbody>
</table>

Modern Compensation Devices

- network reconfiguring devices
  - Solid State Current Limiter – SSCL
  - Solid State Breaker – SSB
  - Solid State Transfer Switch – SSTS

- thyristor controlled reactive elements
  - Thyristor Controlled Reactor – TCR
  - Thyristor Switched Capacitor – TSC
  - Static Var Compensator – SVC
  - Thyristor Controlled Series Compensator – TCSC

Modern Compensation Devices

- active compensators
  - Voltage Sourced Converter – VSC
  - Static Compensator – StatCom
  - parallel active filter (Distribution Static Compensator – DStatCom)
  - Dynamic Voltage Restorer – DVR (series active filter)
  - hybrid active filter (different configurations)
  - Unified Power Quality Conditioner - UPQC
Network reconfiguring devices

- Solid State Current Limiter – SSCL
  - in series with a feeder
  - solid-state switches are opened when a fault is detected
  - current limiting inductor

- Solid State Breaker – SSB
  - similar topology as SSCL
  - limiting inductor is connected in series with an opposite-poled thyristor pair (blocked after a few cycles of faulted current)

- Hybrid Breaker
  - combination of mechanical and solid-state breaker
  - conventional circuit breaker has lower conducting losses (normal operating conditions)
Network reconfiguring devices

- Solid State Transfer Switch – SSTS
  - transfer of power to the alternate feeder

Thyristor controlled reactive elements

- Thyristor Controlled Reactor – TCR
  - 12-pulse connection
Thyristor controlled reactive elements

- Thyristor Switched Capacitor – TSC

- Static Var Compensator – SVC
  - TCR
  - TSC
  - tuned filters
  - fixed capacitors
  - different configurations

- U-I characteristic
  - voltage dependent reactive current
Thyristor controlled reactive elements

- Thyristor Controlled Series Compensator – TCSC
  - series line compensation
  - parallel connection of fixed capacitor and TCR (variable capacitance)

Active compensators

- Voltage Sourced Converter – VSC
  - 6-pulse configuration
  - IGBTs or GTOs with anti-parallel diodes
  - gate turn-off capability

Active compensators

- Voltage Sourced Converter – VSC
  - one leg of a three-phase converter
  - Pulse Width Modulation - PWM
Active compensators

• Voltage Sourced Converter – VSC
  – 2 Voltage Sourced Converters in a 12-pulse connection

Active compensators

• Voltage Sourced Converter – VSC
  – three-level Voltage Sourced Converter
  – harmonics cancellation

Active compensators

• Voltage Sourced Converter – VSC
  – four-wire Voltage Sourced Converter
  – LV applications
Active compensators

- **Statc Compensator – StatCom**
  - shunt connected VSC
  - voltage-independent source of reactive current
  - reactive power
  - voltage control
  - flicker

- **parallel active filter**
  - the same configuration as StatCom
  - Distribution Static Compensator - DStatCom
  - different control algorithms
  - compensation of load current
  - current harmonics
  - current unbalances

---

Active compensators

- **Statc Compensator – StatCom**
  - comparison between StatCom and SVC
  - simulation of voltage sag compensation – motor starting

---

Active compensators
Active compensators

- parallel active filter
  - simulation of compensation of an unbalanced and non-linear load
    - case 1

Active compensators

- parallel active filter
  - simulation of compensation of an unbalanced and non-linear load
    - case 2

Active compensators

- Dynamic Voltage Restorer – DVR
  - series active filter
  - voltage sags and harmonics compensation
Active compensators

- Dynamic Voltage Restorer – DVR
  - simulation of voltage sag compensation

- hybrid active filter 1
  - parallel connection of an active and passive filter
  - less expensive solution
  - active filter is smaller

- hybrid active filter 2
  - series active filter and parallel passive filter
Active compensators

• hybrid active filter 2
  – series active filter and parallel passive filter
  – LV simulation case

Active compensators

• hybrid active filter 2
  – series active filter and parallel passive filter
  – simulation results

Active compensators

• hybrid active filter 3
  – series connection of active filter and passive compensator of reactive power
  – active filter blocks harmonics (resonances)
  – active filter is very small
Active compensators

- Hybrid active filter 3
  - series connection of active filter and passive compensator of reactive power
  - simulation of reactive power compensation
  - resonance with only passive compensator

Active compensators

- Unified Power Quality Conditioner - UPQC
  - series and parallel VSC
  - common dc link

Active compensators

- Active compensation (expensive!)
  - general application
Conclusions

Content

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<td>PQ monitoring</td>
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<td>• energy evaluation methodology</td>
<td>• harmonics - definitions</td>
<td>• PQ monitoring measurements, equipment, software and data analysis</td>
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<td>• economic value</td>
<td>• characterize the system power quality performance</td>
<td>• harmonic calculations</td>
<td>• PQ monitoring measurements, equipment, software and data analysis</td>
</tr>
<tr>
<td>• responsibilities</td>
<td>• estimate the costs associated with the power quality variations</td>
<td>• harmonic sources</td>
<td>• PQ monitoring measurements, equipment, software and data analysis</td>
</tr>
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<td>• economic value,</td>
<td>• characterize the solution alternatives in terms of</td>
<td>• harmonic sequences</td>
<td>• PQ monitoring measurements, equipment, software and data analysis</td>
</tr>
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<td>• responsibility,</td>
<td>costs and effectiveness</td>
<td>• harmonic mitigation</td>
<td>• PQ monitoring measurements, equipment, software and data analysis</td>
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<td>• how to achieve</td>
<td>• perform the comparative economic analysis</td>
<td>• harmonic mitigation strategies</td>
<td>• PQ monitoring measurements, equipment, software and data analysis</td>
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</table>

Economic evaluation

- economic evaluation methodology
  - characterize the system power quality performance
  - estimate the costs associated with the power quality variations
  - characterize the solution alternatives in terms of costs and effectiveness
  - perform the comparative economic analysis
Economic evaluation

- Economic evaluation methodology

- System power quality performance
  - Annual expected number of voltage sags
  - Annual expected number of interruptions
  - Estimation of other disturbances
  - PQ technical issues

- Costs for power quality variations
  - Costs associated with different disturbances
  - Weighting factors representing the relative impact of different disturbances
  - Summation of weighted costs – equivalent interruptions
  - PQ techno-economic issues

- Cost and effectiveness for solution alternatives
  1. Equipment specification changes
  2. Sub-panel level equipment protection
  3. Site-wide protection
  4. Grid solutions
Economic evaluation

- cost and effectiveness for solution alternatives
  - LPQI PQ survey - PQ solutions

Economic evaluation

- cost and effectiveness for solution alternatives
  - costs of power quality mitigation equipment
Economic evaluation

- cost and effectiveness for solution alternatives
  - costs of mitigation techniques - 1

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Initial cost (k€)</th>
<th>Operating cost (k€)</th>
<th>% of initial costs per year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cables</td>
<td>1000k€</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>IACS</td>
<td>1000k€</td>
<td>1</td>
<td>1%</td>
</tr>
<tr>
<td>Tie-up devices</td>
<td>200k€</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Traction power line 1</td>
<td>50k€</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>UPS</td>
<td>500k€</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Regulator</td>
<td>50k€</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Traction power line 2</td>
<td>200k€</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>UPS</td>
<td>400k€</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Regulator</td>
<td>50k€</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Traction power line 3</td>
<td>100k€</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>UPS</td>
<td>150k€</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Regulator</td>
<td>50k€</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Traction power line 4</td>
<td>50k€</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>UPS</td>
<td>50k€</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Regulator</td>
<td>50k€</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Traction power line 5</td>
<td>50k€</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>UPS</td>
<td>50k€</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Regulator</td>
<td>50k€</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

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Economic evaluation

- cost and effectiveness for solution alternatives
  - costs of mitigation techniques - 2

<table>
<thead>
<tr>
<th>Mitigation equipment</th>
<th>Typical load (kW)</th>
<th>Operating and maintenance costs (% of initial costs per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>100kVA-200kVA</td>
<td>15</td>
</tr>
<tr>
<td>UPS</td>
<td>1000kVA-1500kVA</td>
<td>10</td>
</tr>
<tr>
<td>Bankside UPS</td>
<td>1000kVA</td>
<td>5</td>
</tr>
<tr>
<td>Station switch</td>
<td>2000kVA</td>
<td>5</td>
</tr>
<tr>
<td>Line conditioner</td>
<td>2000kVA</td>
<td>10</td>
</tr>
<tr>
<td>Water outage control</td>
<td>1000kVA</td>
<td>5</td>
</tr>
<tr>
<td>Emergency generator</td>
<td>1000kVA</td>
<td>5</td>
</tr>
<tr>
<td>Load boundary device</td>
<td>400kVA</td>
<td>10</td>
</tr>
<tr>
<td>Switch capacity (10 sec)</td>
<td>1500kVA</td>
<td>5</td>
</tr>
<tr>
<td>Fuel cells</td>
<td>1500kVA</td>
<td>5</td>
</tr>
</tbody>
</table>

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Economic evaluation

- cost and effectiveness for solution alternatives
  - UPS example - the table below compares the relative cost per kW, relative to power requirement, for a distributed system with that for a centralized system

<table>
<thead>
<tr>
<th>Power (kVA)</th>
<th>Centralized UPS</th>
<th>Distributed (UPS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>110%</td>
<td>100%</td>
</tr>
<tr>
<td>30</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>60</td>
<td>21%</td>
<td>20%</td>
</tr>
<tr>
<td>100</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>150</td>
<td>10%</td>
<td>10%</td>
</tr>
</tbody>
</table>

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Economic evaluation

- comparative economic analysis
  - Net Present Value (NPV)
    \[ NPV = \sum_{t=0}^{n} \frac{CF_t}{(1+r)^t} - C_0 \]
    - \( CF_t \): cash flow at time \( t \)
    - \( C_0 \): initial investment
    - \( r \): discount rate
    - \( n \): number of years
    - \( t \): lifetime of investment

- Internal Rate of Return (IRR)
  \[ 0 = \sum_{t=0}^{n} \frac{CF_t}{(1+R)^t} - C_0 \]
  - \( R \): internal rate of discount (IRR)
  - \( CF_t \): cash flow at time \( t \)
  - \( C_0 \): initial investment
  - \( n \): lifetime of investment

NPV is a measure of how much value is created or added today by undertaking an investment. It is the difference between the investment’s market value and its cost. For independent projects, an investment should be accepted if the net present value is positive and rejected if it is negative. For mutually exclusive projects, the project with the largest positive NPV should be selected.
Economic evaluation

• comparative economic analysis
  – Internal Rate of Return (IRR)
    – the internal rate of return is the discount rate that makes the NPV of a project equal to zero
    – set NPV equal to zero and solve for interest rate - the interest rate that yields an NPV of zero is the IRR
    – an investment is acceptable if the IRR exceeds the required rate of return - it should be rejected otherwise

Payback Time (PBT)

\[ PBT = \frac{\text{net investment}}{\text{net annual return}} \]

- benefits annual from subtracted expenses annual ...
- return annual net on installation...
- investment net months

- payback is the length of time it takes to recover the initial investment
- assume cash flows are received uniformly throughout the year - calculate the number of years it will take for the future cash flows to match the initial cash outflow
- an investment is acceptable if its calculated payback period is less than some pre-specified number of years
Economic evaluation

- comparative economic analysis
  - example of an analysis for sag and interruption mitigation
  - cost of capital discount rate equals to 10%
  - assumed lifetime is 10 years

<table>
<thead>
<tr>
<th>Mitigation scheme</th>
<th>Present worth factor</th>
<th>NPP (€)</th>
<th>IRR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example 1</td>
<td>1.7</td>
<td>125,096.7</td>
<td>7.78</td>
</tr>
<tr>
<td>Example 2</td>
<td>0.12</td>
<td>100,262.0</td>
<td>26.17</td>
</tr>
<tr>
<td>Example 3</td>
<td>0.51</td>
<td>38,038.4</td>
<td>6.21</td>
</tr>
<tr>
<td>Example 4</td>
<td>0.72</td>
<td>45,062.4</td>
<td>5.07</td>
</tr>
</tbody>
</table>

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Economic evaluation

- comparative economic analysis
  - example of an analysis for replacement of overhead lines with cables
  - considered
    - maintenance
    - reliability
    - losses

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Economic evaluation

- comparative economic analysis
  - example of an analysis for replacement of overhead lines with cables

<table>
<thead>
<tr>
<th>Line section</th>
<th>FRE (km)</th>
<th>BRR (for 10) (%)</th>
<th>NPP (40 years) (€)</th>
<th>x = 0%</th>
<th>x = 4.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>11</td>
<td>6.7</td>
<td>279,531</td>
<td>58,953</td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>29</td>
<td>1.7</td>
<td>139,842</td>
<td>-120,735</td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>47</td>
<td>-0.8</td>
<td>20,228</td>
<td>-116,052</td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>16</td>
<td>5.9</td>
<td>245,593</td>
<td>48,375</td>
<td></td>
</tr>
<tr>
<td>e</td>
<td>36</td>
<td>-1.2</td>
<td>79,664</td>
<td>-25,826</td>
<td></td>
</tr>
<tr>
<td>f</td>
<td>34</td>
<td>1</td>
<td>87,077</td>
<td>-174,100</td>
<td></td>
</tr>
<tr>
<td>g</td>
<td>52</td>
<td>2.2</td>
<td>186,553</td>
<td>-82,395</td>
<td></td>
</tr>
<tr>
<td>h</td>
<td>73</td>
<td>-2.6</td>
<td>25,767</td>
<td>-42,269</td>
<td></td>
</tr>
</tbody>
</table>

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Economic evaluation

- comparative economic analysis
  - example of an analysis for replacement of overhead lines with cables
  - NPV

Conclusions

- importance of power quality knowledge
  - performance and interpretation of PQ measurements
  - detailed analysis of disturbances
    - analysis of disturbing loads
    - determination of emission levels
    - disturbance spreading in the network
  - better negotiating position for concluding the power supply contracts
Conclusions

• importance of power quality knowledge
  – planning and purchasing new equipment and connecting new customers
    • large power electronics devices – THD
    • large motor drives – voltage dips
    • large arc furnaces – flicker
    • connection of passive power factor correction devices
      – resonance
    • specification of other compensation devices
    • …

Conclusions

• importance of power quality knowledge
  – solving conflicts between suppliers and customers
  – evaluating costs due to poor PQ
  – determining economically optimal mitigation techniques
  – …
  – …