Methodology to quantify impact of harmonics

- Problem definition
- Methods, Models, and Tools
- Some examples

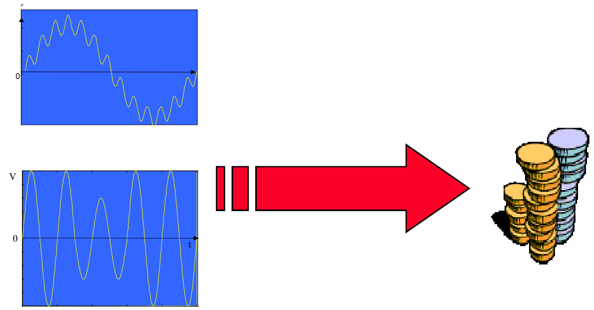
Final Report of JWG C4.107 Chapter 2

Problem definition

- The direct economic value of electric power comes from its conversion into other forms of energy, e.g., thermal energy and mechanical energy.
- A PQ disturbance can not have economic relevance by itself
- The detrimental effects that it causes on the processes where this transformation takes place can have very significant economic consequences.

Problem definition

- The direct economic value of PQ is linked to the effects that PQ disturbances have on equipment and other loads on the system.



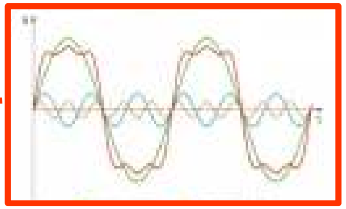
The main question: What is the cost of a given disturbance level in a given scenario?

To answer.....

- Which method?
- Which scenario?
- For how many years?
- Which are the “sensitive” variables?
- Is there general consensus on available methods and tools?

Classifications on methods

- In function of the "users"
  - Models for "Utilities"
  - Models for End use
- In function of the "available data"
  - Direct methods
  - Indirect methods
- In function of the disturbance type
  - Methods for events
  - Methods for variations
- In function of the scenario
  - Deterministic Methods
  - Probabilistic Methods



In function of the “users”

- Models for “Utilities” : Transmission operators / Distributions companies / Authorities
- Models for “End use”: Industrial facility managers / Large commercial plants
- The models can account different items…

For example…

- Same disturbance: excessive 5thharmonic voltages and currents
- Same components: cable lines and transformers
- Same direct effects: excessive losses, premature ageing, mis-operation of devices

- Models for Industrial facility will take into account
  - The costs of the direct effects of the 5th harmonic on the components and on the process where this component is installed
  - Some indirect costs to analyse, measure, understand the phenomena in order to take decision
  - Penalty to pay or to receive for the exceeded limit (PQ contract)
- Models for Distributions companies will further take into account
  - the costs of personnel for responding to PQ issues (call center, responding crew, consultation, resolution)

In function of the “available data”

- Direct methods
- Indirect methods

Direct methods

- The Direct economic analysis methods consider:
  - characteristics of the disturbance (time specific values, global indices, probability of the occurrence)
  - characteristics, of the equipment response to those disturbances (increased losses, reduced lifetime, misoperation)
  - cost of equipment response
  - cost of immunity or mitigation

- Main disadvantage: availability of complete data

Indirect methods

- The Indirect economic analysis methods consider such economic measures as:
  - How much is a customer willing to pay to avoid this event?
  - How much is a customer willing to pay to accept worse PQ?
  - How much did historical events cost?
  - What is the total market size for existing solutions for this problem? ....
- Main disadvantage: availability of complete data

In function of the “scenario”

- Deterministic Methods
  - Adequate when all the items of the analysis, from the operating conditions of the system to the discount rate value, are known without uncertainty.
  - This can be the case of ex post analyses performed on existing systems whose operating conditions are repetitive and well stated.
  - Some real cases can refer to industrial systems.

In function of the “scenario”

- Probabilistic Methods
  - Needed when some of the problem variables are affected by uncertainties.
  - This clearly happens for non-existing systems or also for existing systems where some expansions have to be planned
  - Estimating the costs to face for the future operation of existing systems when both cash flows and operating conditions of the system vary over a range

Let’s go inside

- Direct deterministic methods for harmonics
  - Models
  - Analysis tools
- Probabilistic direct methods for harmonics
  - Models
  - Analysis tools

Models for direct methods in deterministic scenarios for harmonics

- Costs of the effects on the equipments (Economical damage)
- For any equipment the effects are:
  - Increase of losses: losses are superimposed to the losses due to the fundamental
  - Decrease of life: life is reduced in respect to the life in sinusoidal condition
  - Mis operation: the equipment does nor work correctly

General model for increased losses

Single k^{th} electrical component continuously subject to H_{max}

harmonics of voltage or current $G^{h1},...,G^{Hmax}$ in the time interval ΔTi

The loss costs in ΔTi are

$$\left(Dw_k\right)_{\Delta Ti} = K_w P_k\left(G^{h1},....,G^{hmax}\right)\Delta Ti$$

- K_w is the unit cost of electrical energy,
- Pk are losses due to the harmonics on the k^{th} component.

The loss cost of the component in a generic year n

$$\left(Dw_k\right)_n = \sum_{i=1}^{q}\left(Dw_k\right)_{\Delta Ti}$$

- Sum of the loss costs of all time intervals present in the considered year

General model for increased losses

The loss cost in the year n for the whole system in which m components operate

$$(Dw)_n = \sum_{k=1}^{m} (Dw_k)_n$$

- Sum of the loss costs of all time intervals present in the considered year

General model for increased losses

The loss costs of the system components with reference to more years

$$Dw = \sum_{n=1}^{N_T} (Dw)_{n,pw} = \sum_{n=1}^{N_T} \frac{(Dw)_n}{(1+\alpha)^{n-1}}$$

Variation of the unit cost of electric energy in the coming years

$$(K_w)_n = (K_w)_1 (1+\beta)^{n-1}$$

Present-worth value of the costs in every year

$$(Dw)_{n,pw} = \frac{(Dw)_n}{(1+\alpha)^{n-1}}$$

Needed data

- system operating conditions during the study period, e.g., network configurations and typical duration of system states, knowledge of components and equipment in function;
- type, operating conditions, and absorbed power levels of linear and non-linear loads; and
- variation rate of the electric energy unit cost and the discount rate.

Model for computing the additional losses increased losses

$$\left(Dw_k\right)_{\Delta Ti} = K_w \mathbf{P_k}\left(\mathbf{G^{h1}},\ldots,\mathbf{G^{hmax}}\right)\mathbf{\Delta Ti}$$

- Lines
- Transformers
- Capacitors
- Induction motors

Lines (three-conductors cables joule and dielectric losses*)

$$P_{Ca} = 3 \sum_{h=h1}^{hmax} \left(I^h\right)^2 R_{Ca}^h + 3\omega C_{Ca} \sum_{h=h1}^{hmax} h \, tg\delta^h \left(V^h\right)^2$$

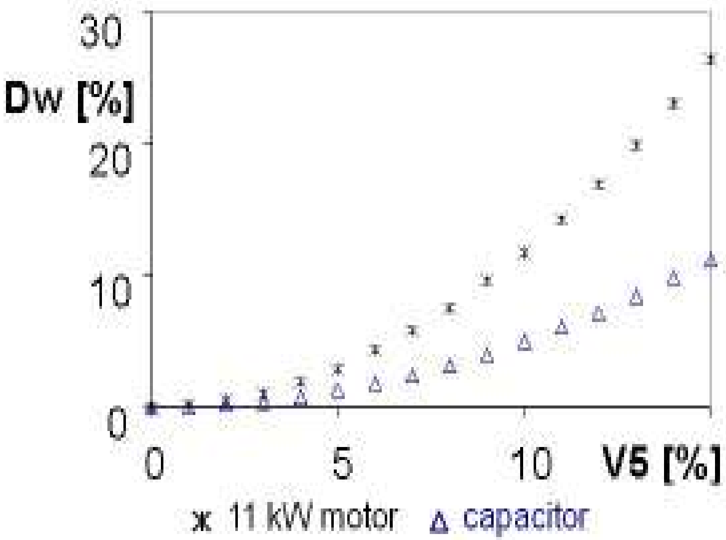
R_{Ca}^h alternating current resistance of one conductor of the cable

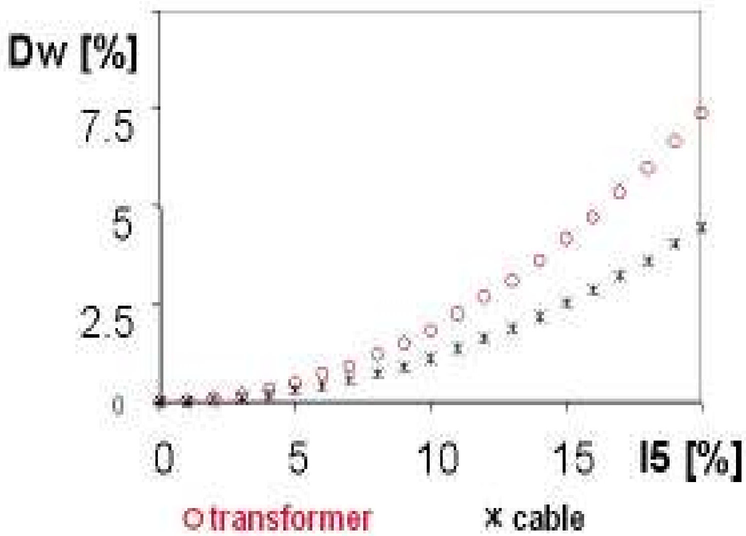
C_{Ca} capacitance per core;

ω angular frequency of system at the fundamental.

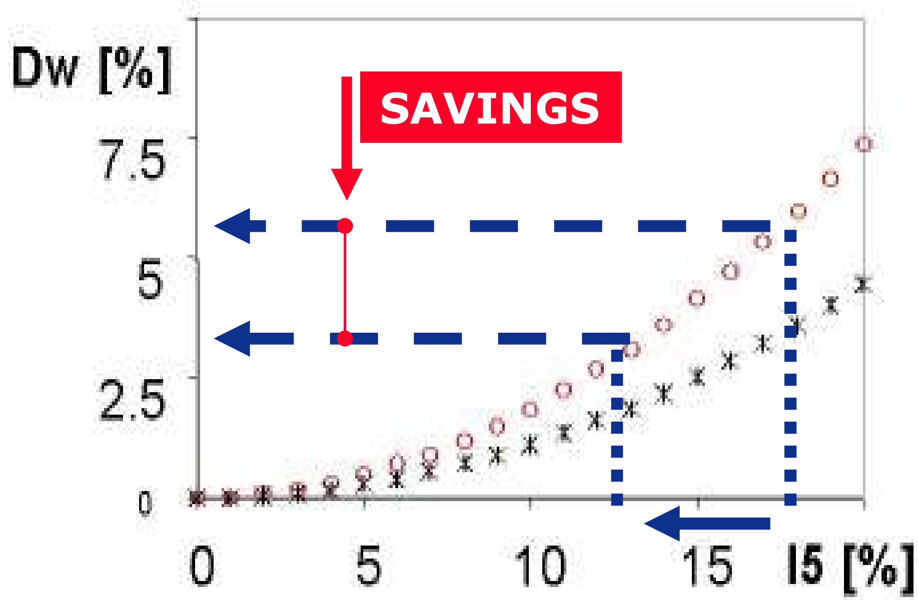
**Other items of losses could be considered*

Some examples/1





Dw increase not linearly with the harmonic pollution and with a law dependent on the type of the component.



These plots give an immediate indication of the amount of costs for component to be met/saved for given increase/decrease of harmonic pollution.

Analysis Tools for using the models

- **Extensive numerical simulation**
  - The harmonics are computed by numerical simulations (typically injection methods)
  - The harmonics are then used to compute Dw and Da

- **Partial numerical simulation**
  - <u>The harmonics are measured</u>
  - The harmonics are then used to compute Dw and DA

Analysis Tools for using the models

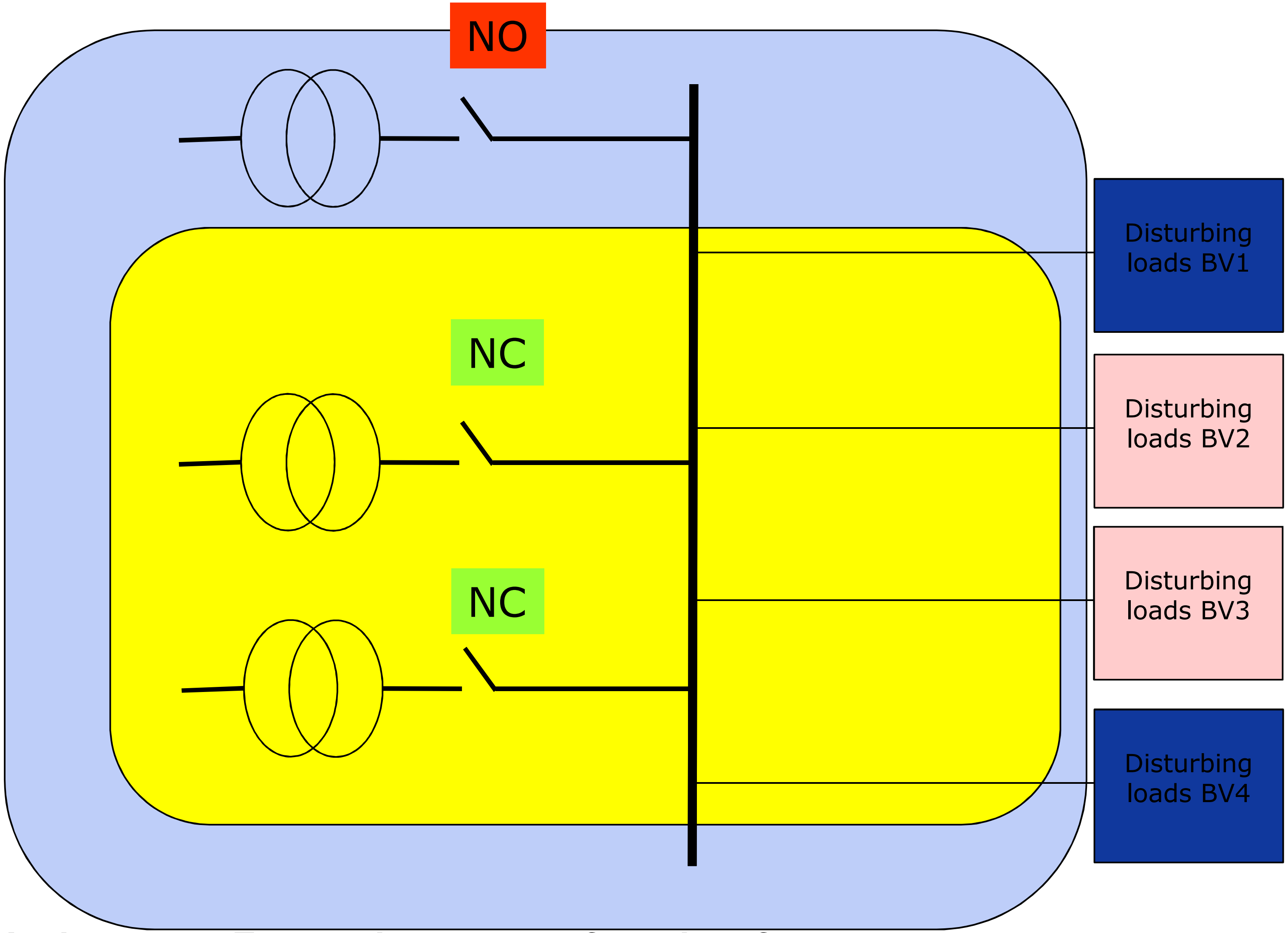
- **Extensive numerical simulation**
  - INPUTS
    - Characteristics and operating conditions of the system
    - Characteristics and operating conditions of linear and non linear loads
    - Variation rate of the price of energy and components
    - Discount rate
    - System models at harmonics
    - Thermal models of components
  - OUTPUT
    - Voltage and current harmonics for each component
    - Additional losses, Reduced life
    - Additional cost Dw and Da

Analysis Tools for using the models

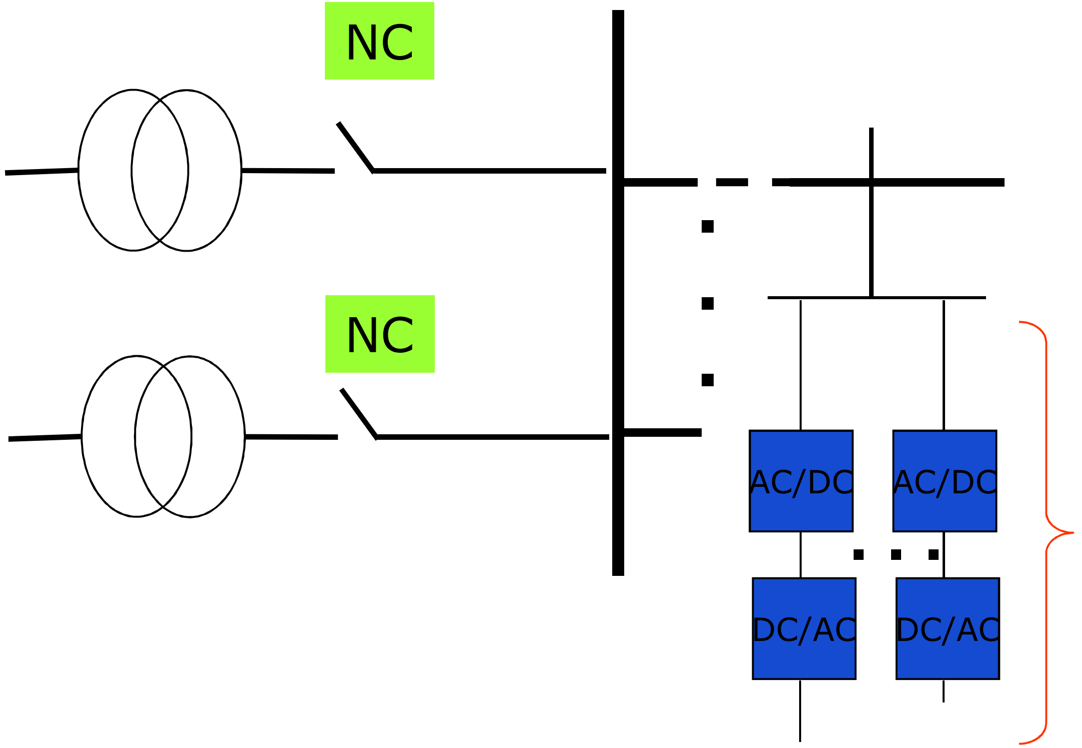
- **Partial numerical simulation**
  - INPUTS
    - Characteristics and operating conditions of the system
    - Characteristics and operating conditions of linear and non linear loads
    - Measured voltage and current harmonics for each component
    - Variation rate of the price of energy and components
    - Discount rate
    - Thermal models of components
  - OUTPUT
    - Additional losses, Reduced life
    - Additional cost Dw and Da

A real case of partial numerical simulation

4 lines supplying huge numbers of linear and non linear loads



4 lines supplying huge numbers of linear and non linear loads

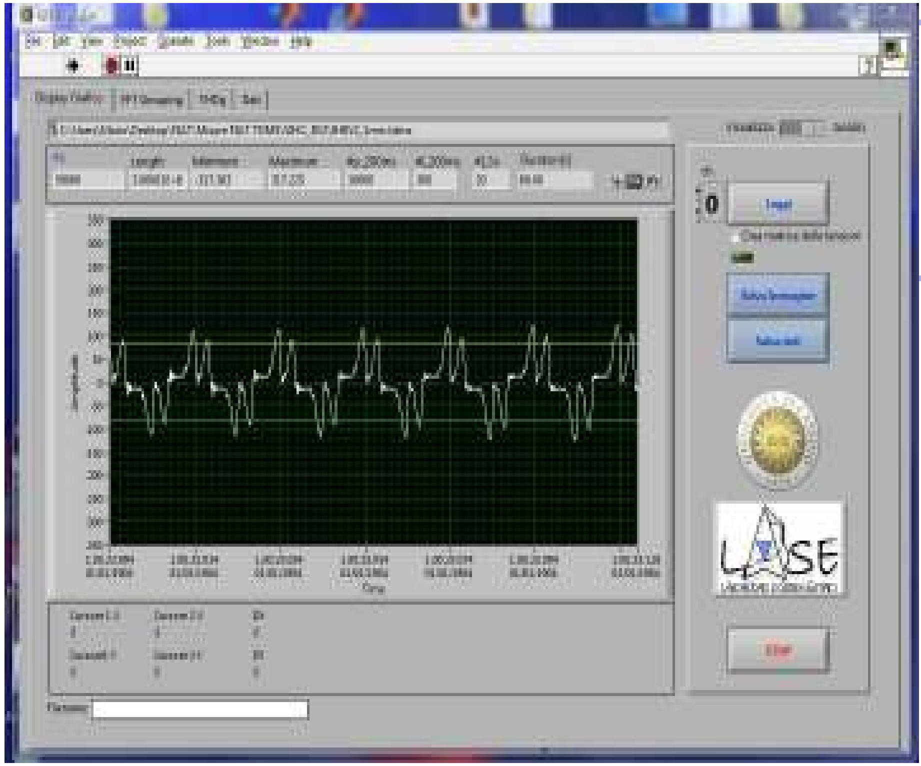


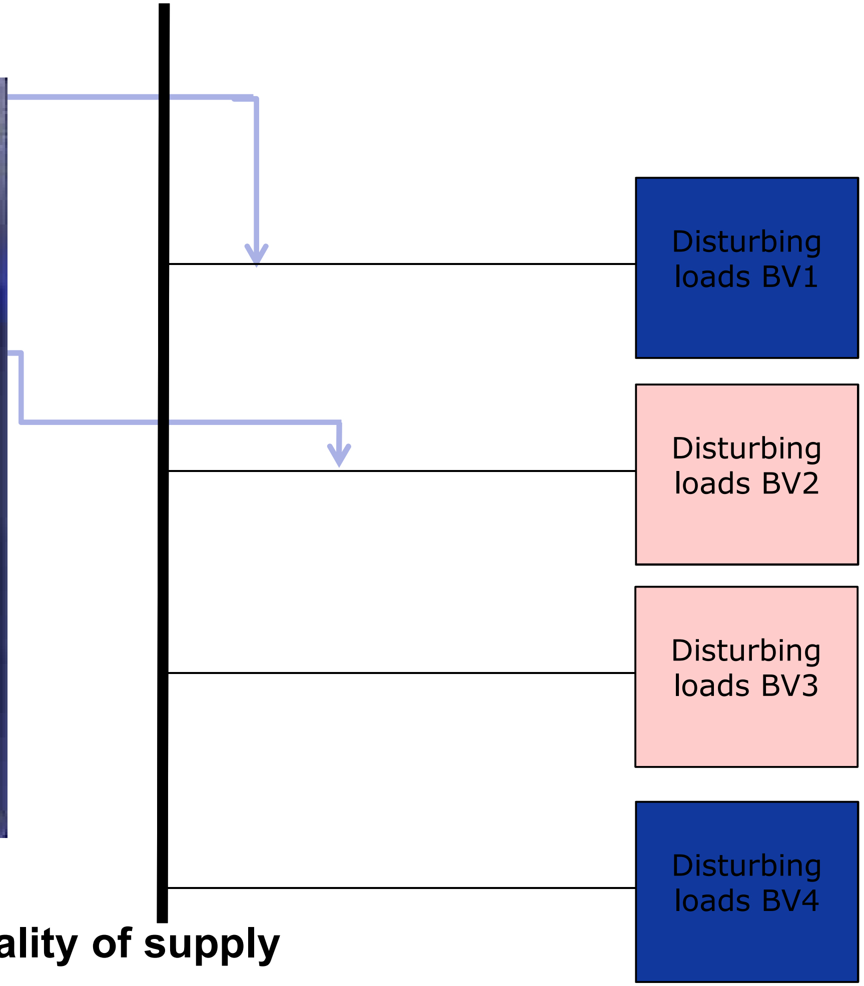
695 robots
(~ 8-10 drives each)

360 drives

Annual cost of paid energy ~ 750 k€

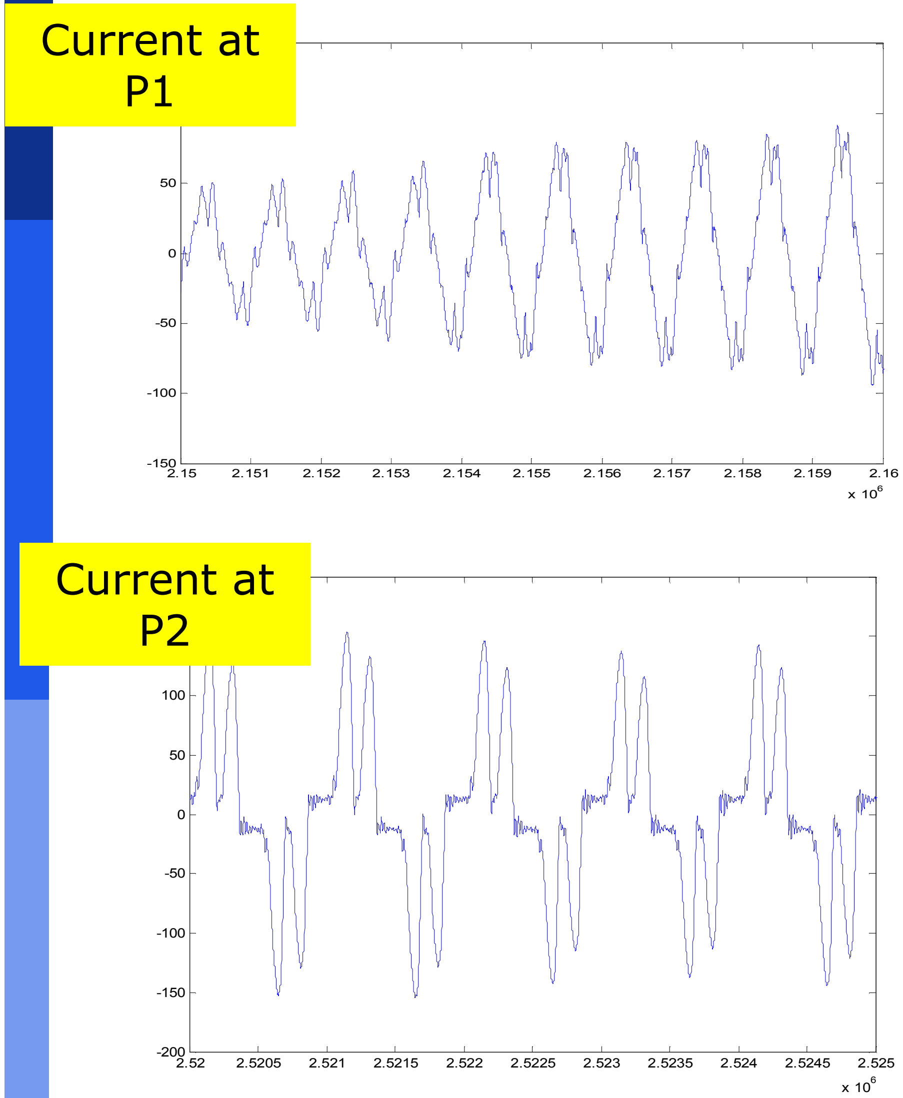
Campaigns of measurements have been conducted to characterize the distortion levels

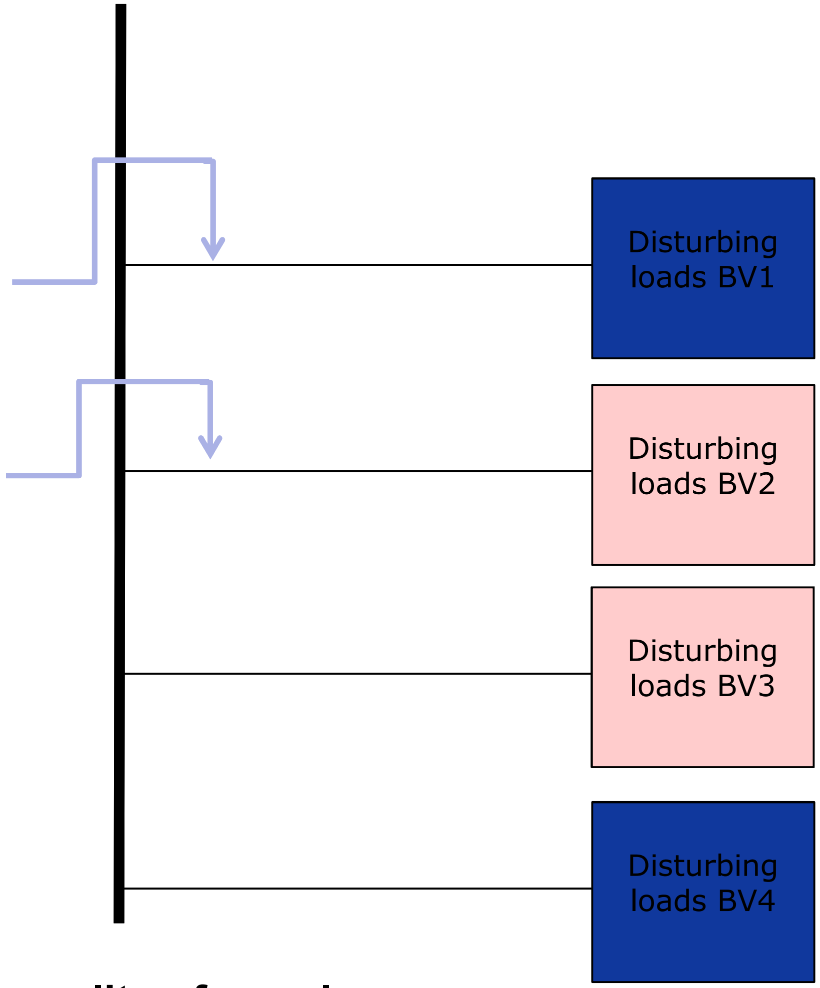




Frankfurt (Germany), 6-9 June 2011

SOME INTERMEDIATE RESULTS/1



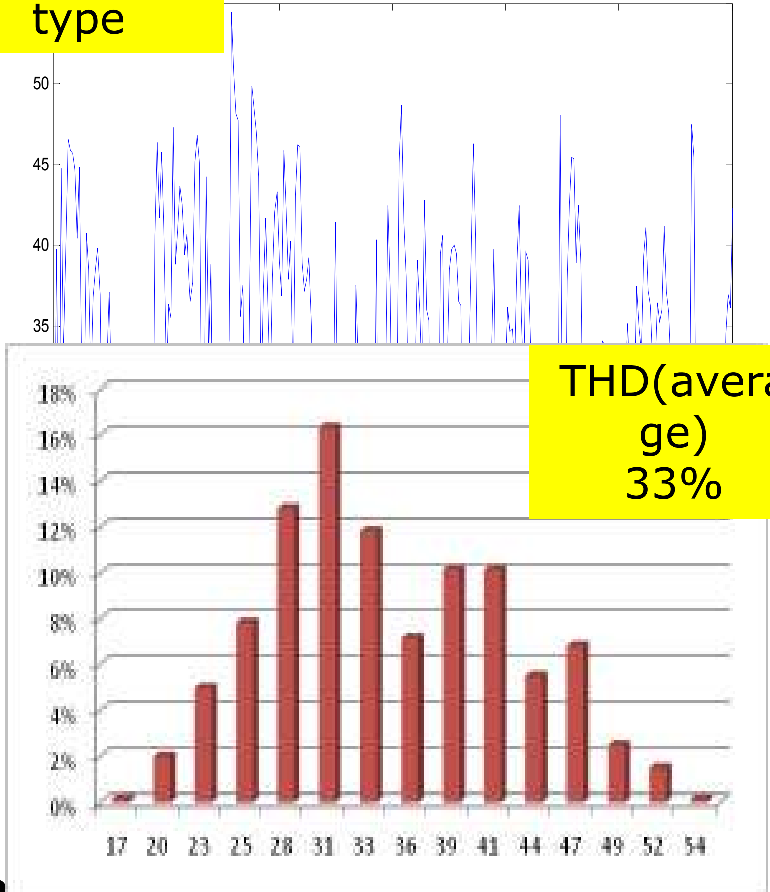


quality of supply

SOME INTERMEDIATE RESULTS/1

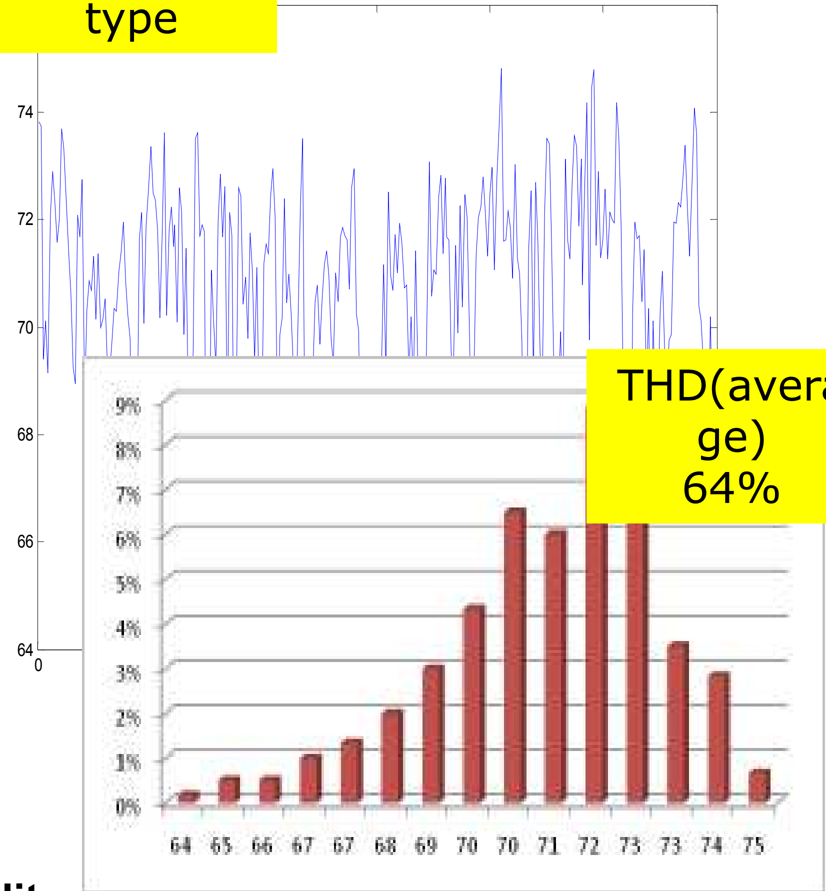
Fourier analysis of current and voltages

THD of P1 type



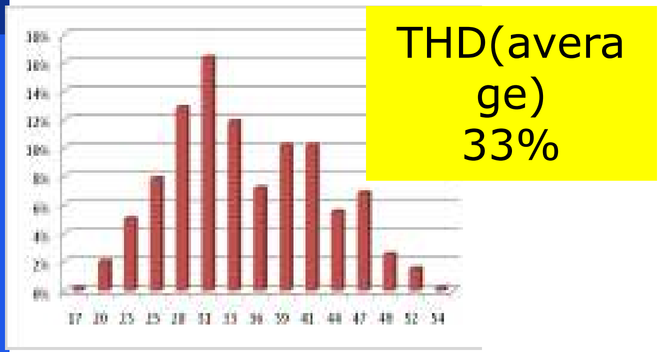
THD(average) 33%

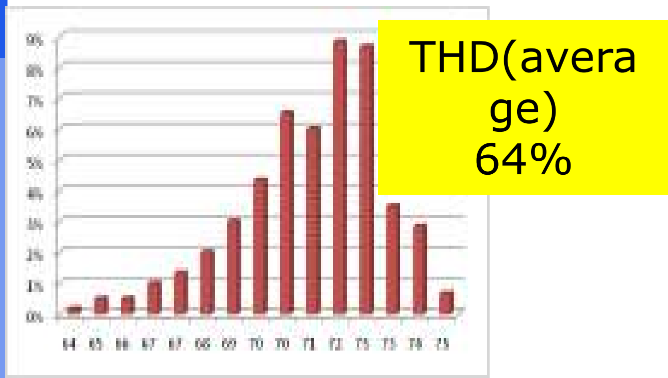
THD of P2 type



THD(average) 64%

COSTS OF ADDITIONAL LOSSES





Even if in presence of high value of current harmonics the economical damage Dw due to additional losses in transformers and lines are negligible….

COSTS OF ADDITIONAL LOSSES ….

The (over) rating of transformers guarantees the negligibility of additional losses

Some data:

Sn=2 MVA - V1/V20= 20/0.53 kV
Vcc= 6.75%
RI^2= 0.54%
No load losses= 0.19%
Winding eddy-current= 1387 W
Ir>>I1tot (I1totmax < 30%)

The lines are not in cables but they are solid conductors without insulation

Conclusions and remarks

- A common frame for estimating the costs due to PQ is mandatory
- For the harmonics methods and tools are available (Final Report of JWG C4.107 Chap.2)
- The most adequate methods ar4e direct methods since harmonics are often not perceived
- The cost of the harmonics can be covered by overrating of the components