Seminar/Workshop on Controlled Switching

Benefits for Shunt Reactor Applications
WG A3-07

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Introduction

- *Shunt reactor are used to compensate the capacitive reactive power in high voltage systems*
- *They are usually switched very frequently (>700 times/year even several times during the same day)*
- *Important transient currents and overvoltages are produced when they are operated*
- *Conventional solutions: Pre-Insertion Resistors (PIR)*
  Opening Resistors
- *Alternative solution: Controlled Switching System*

Part I: Switching of shunt reactors Basic concepts

Two different situations identified:

- ***Energization***
- ***De-energization***

1. ***Daily operation***
2. ***Chopping current***
3. ***Re-ignitions***

Energization -The effects

1. Closing.

Uncontrolled energization of shunt reactor may provoke high inrush currents (up to 3.5 p.u. have been detected) with high asymmetry and long decay time constant that may:

- Damage the reactor winding and other equipment in the substation

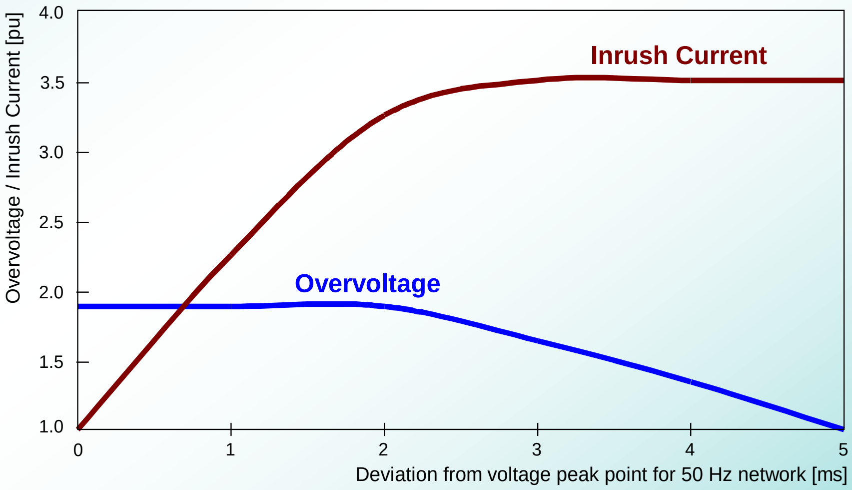
- Malfuntion of protective relays

- Mechanical vibrations and buzzing in reactors have been detected.

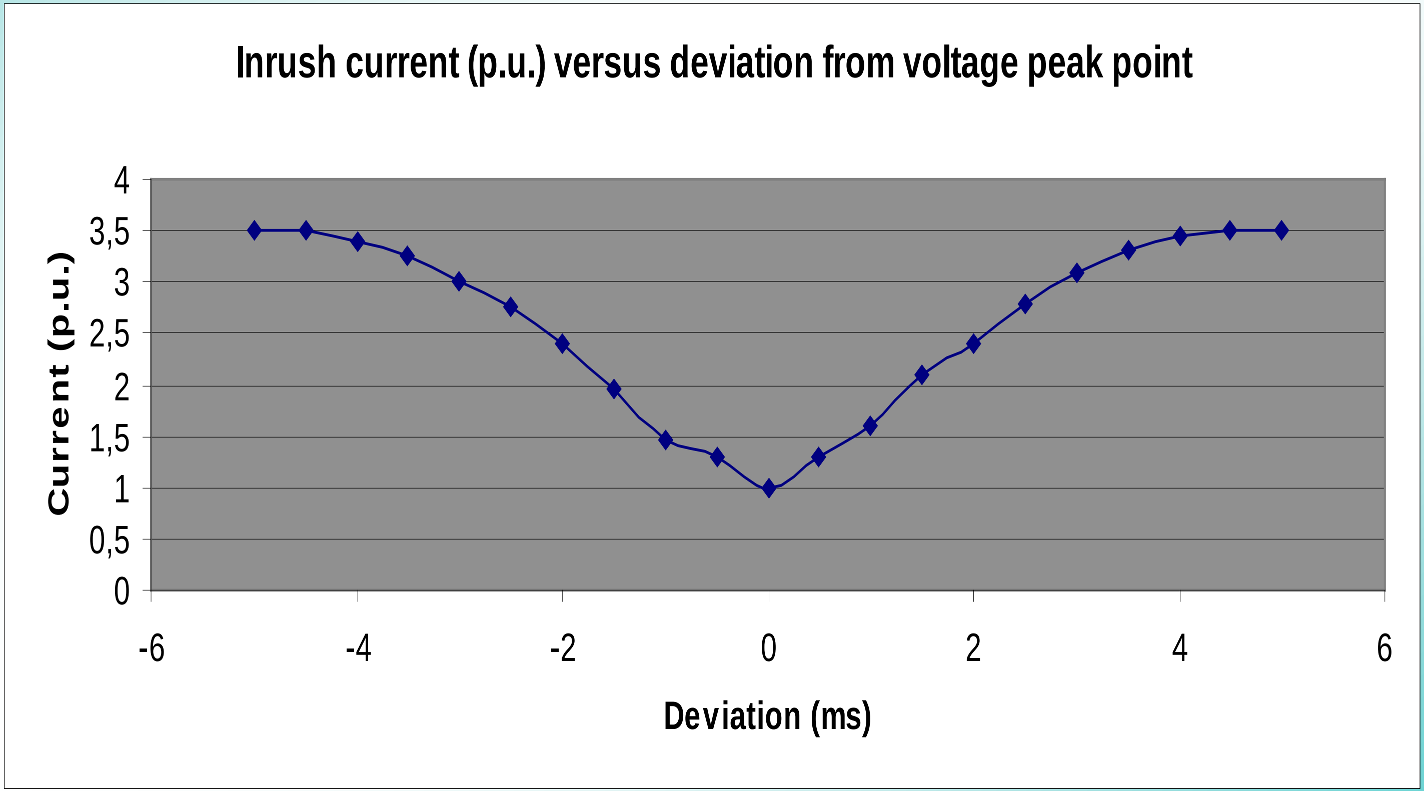
- Develop sympathetic interaction with power transformers located near or in the same substation

Energization

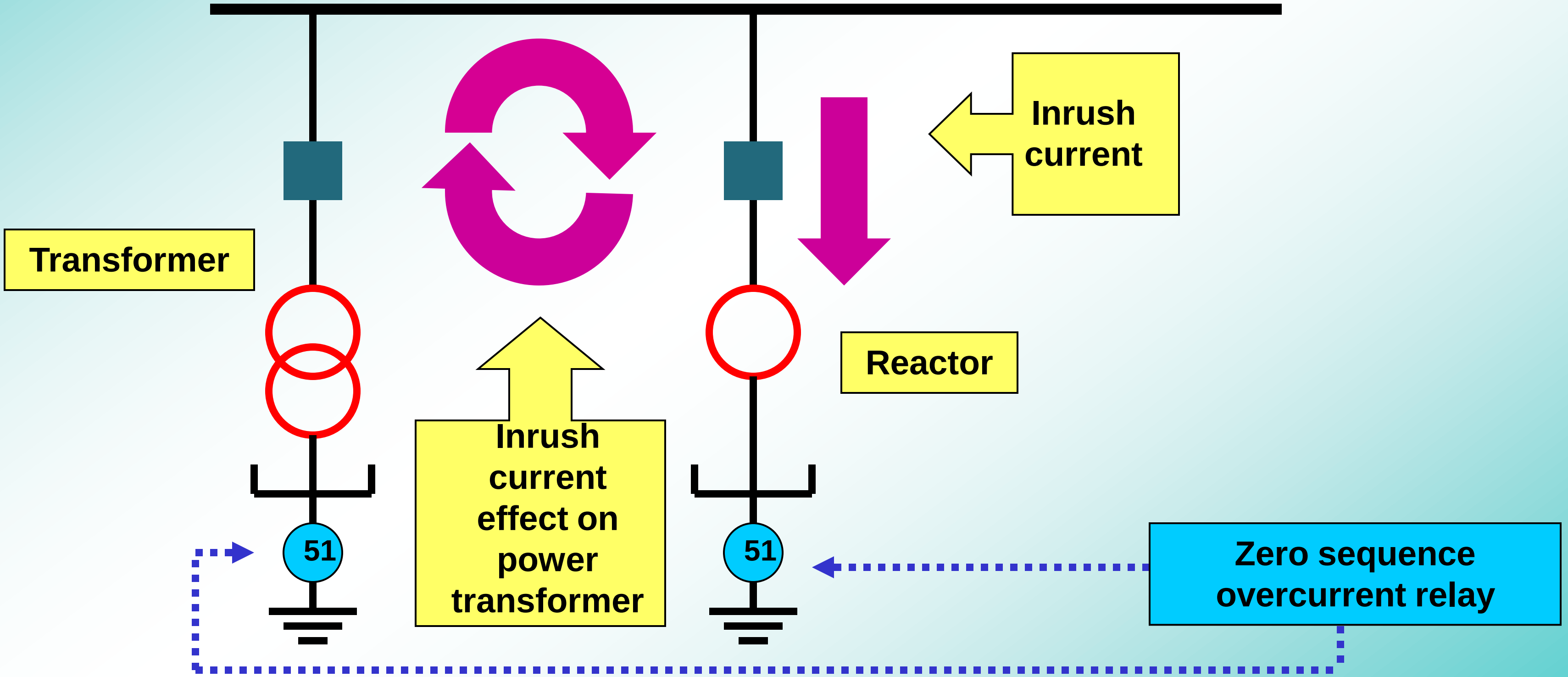
Physical laws that govern the behaviour of the reactors make not possible to achieve suppression of both, inrush current and overvoltage on the reactor simultaneously.

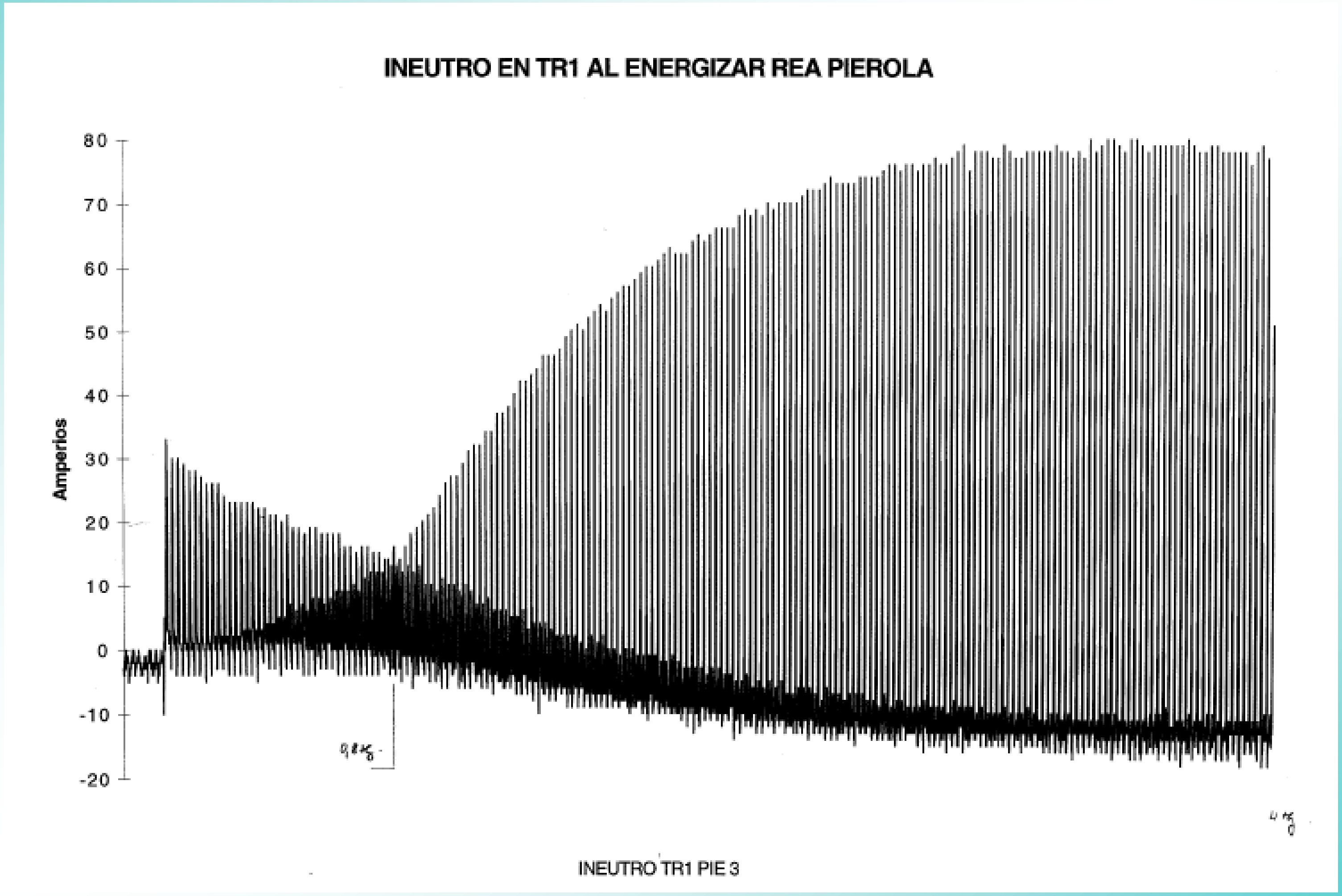


Energization (cont)

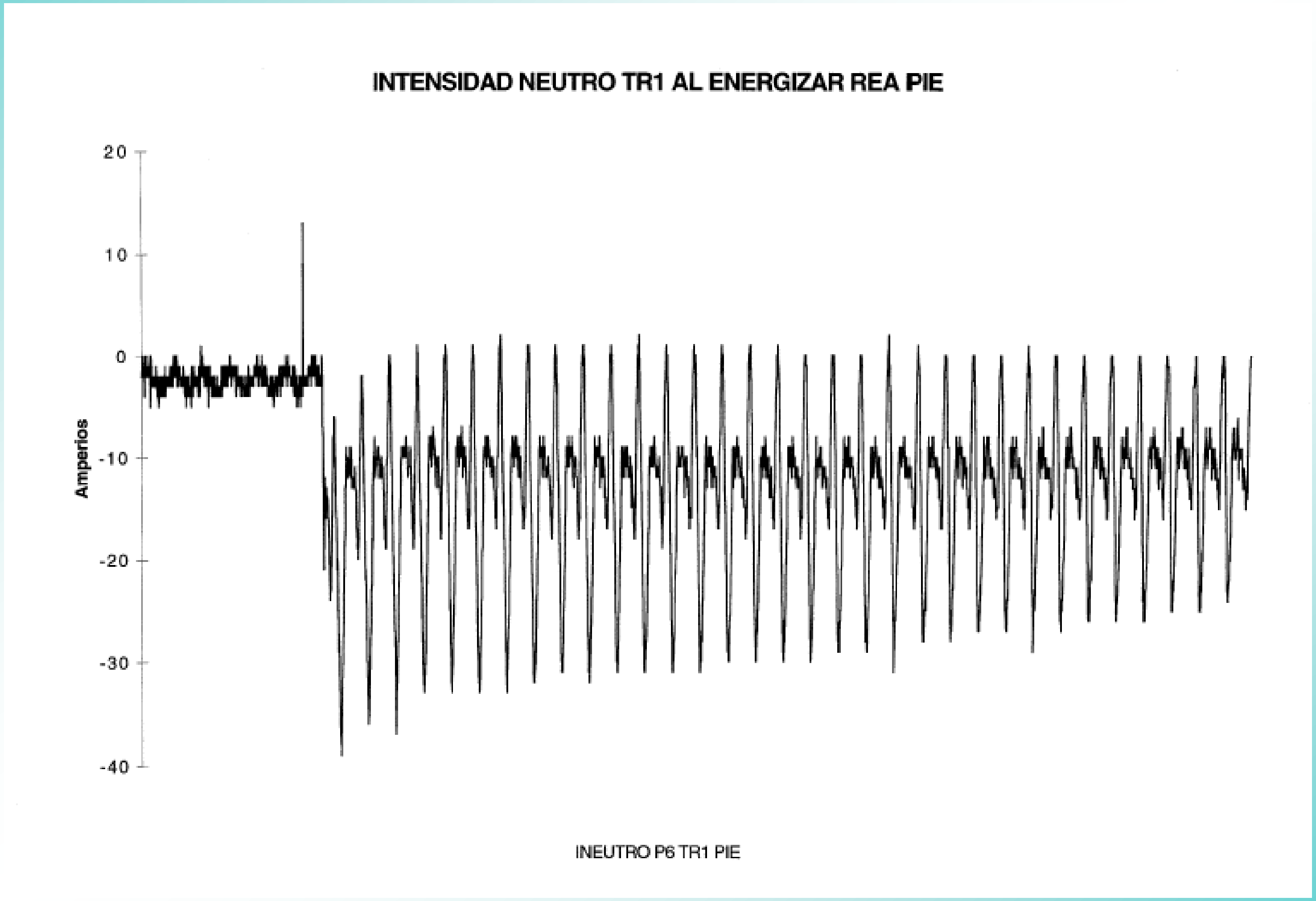


Sympathetic interaction with power transformers

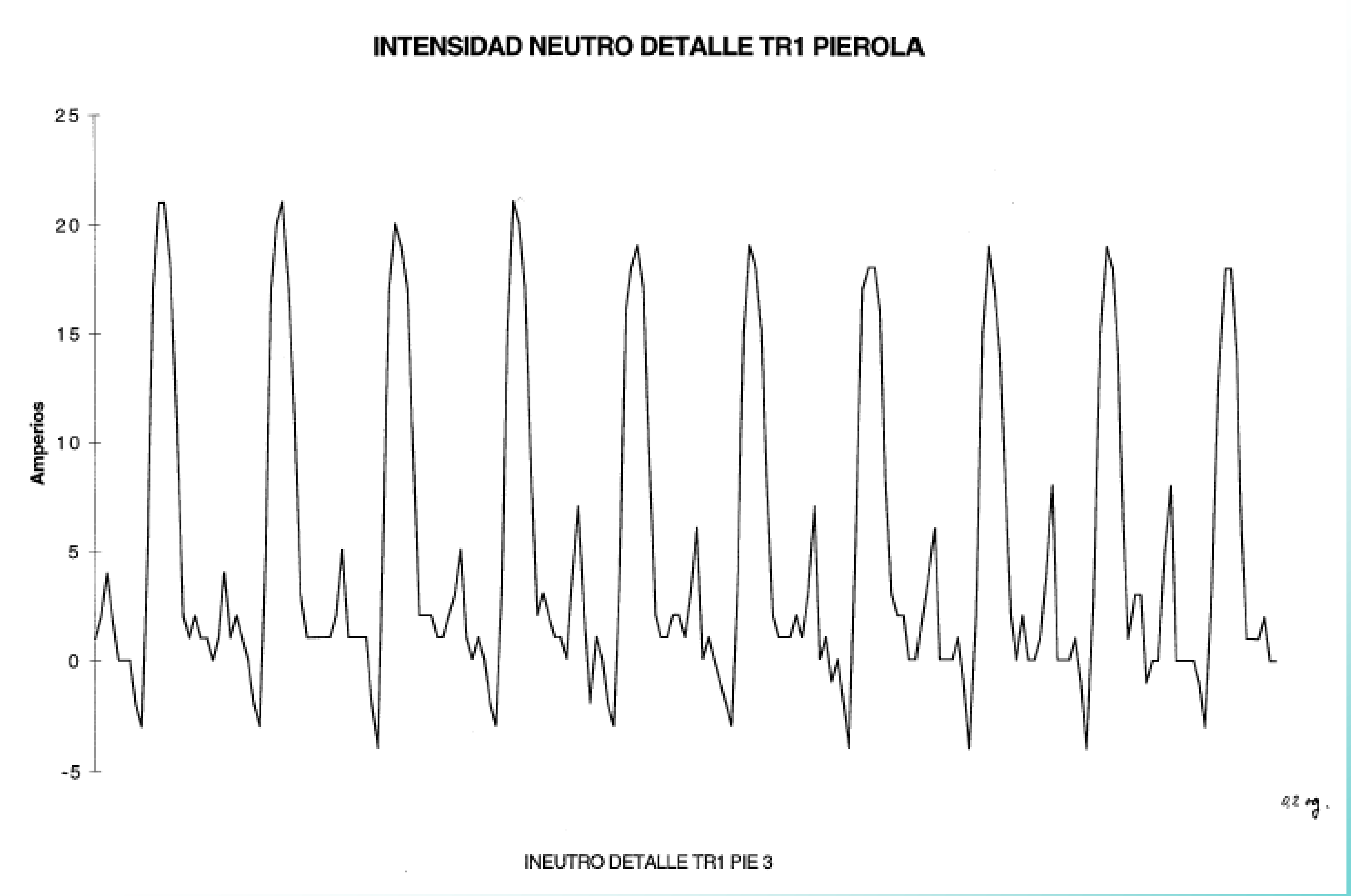


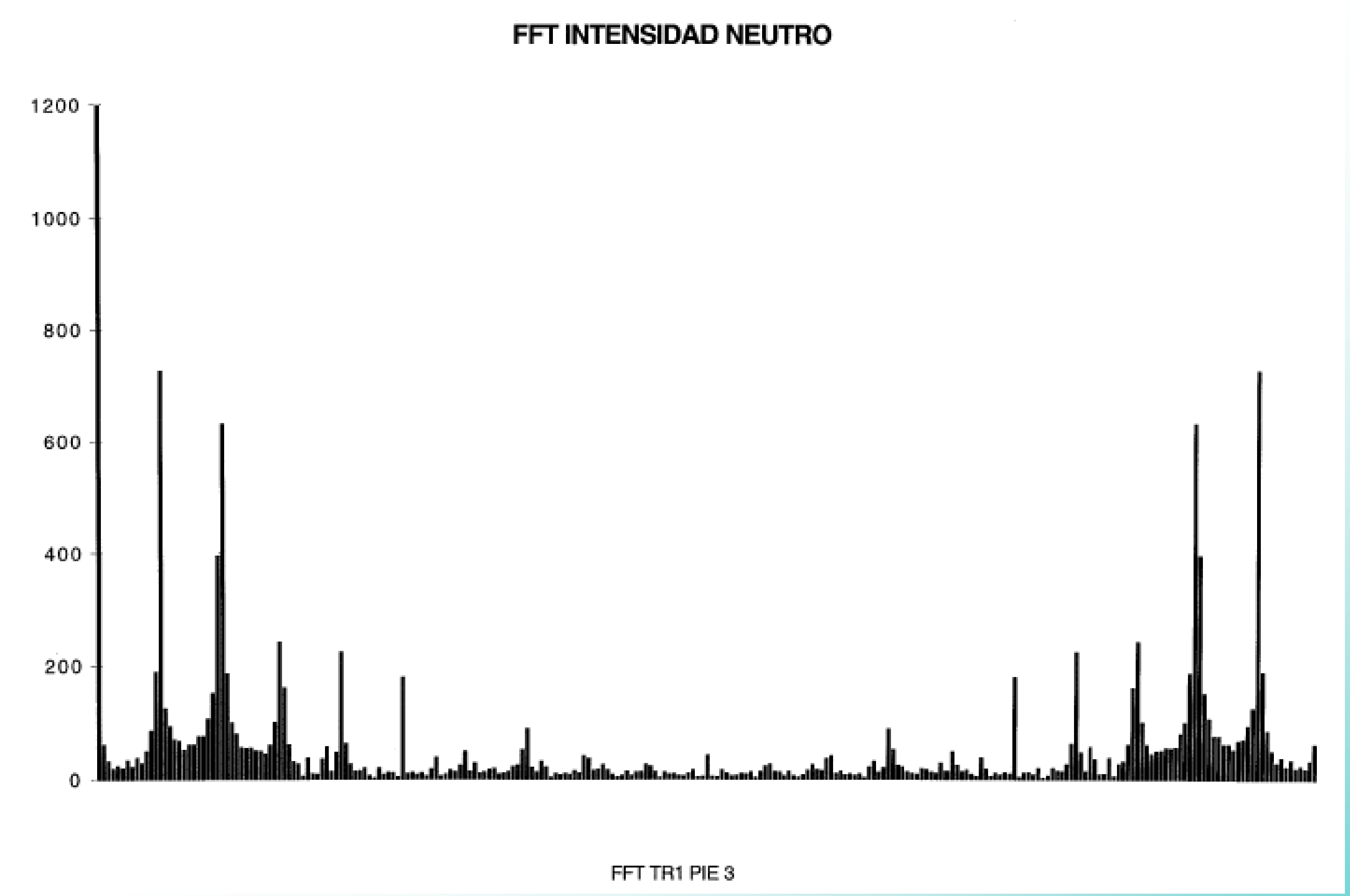

INEUTRO EN TR1 AL ENERGIZAR REA PIEROLA
80
70
60
50
40
30
20
10
0
-10
-20
Amperios
INEUTRO TR1 PIE 3


INTENSIDAD DE NEUTRO TR1 AL ENERGIZARREA PIE
20
10
0
-10
-20
-30
-40
AMPERIOS (A)
INEUTRO P5 TR1 PIE


INTENSIDAD NEUTRO TR1 AL ENERGIZAR REA PIE
20
10
0
-10
-20
-30
-40
Amperios
INEUTRO P6 TR1 PIE

Benefits for Shunt Reactors Applications




FFT INTENSIDAD NEUTRO
1200
1000
800
600
400
200
0
FFT TR1 PIE 3

De-energization-The effects

2. De-energization.

Chopping overvoltages are generated due to the current being chopped by the circuit breaker before the natural zero current of the load current.

Re-ignition occurs when the arcing time is so short that the distance between the contacts is too small to withstand the recovery voltage after arc extinction.

De-energization - The effects

Case 1- No current chopping and no re-ignition

- **Type of stress = <u>Switching surge</u> type of waveshape**

$$f_{transient} = \frac{1}{2\pi\sqrt{LC_L}}$$

Case 1- No current chopping and no re-ignition (continued)

Typical frequencies: 1 to 40kHz (oil-immersed reactor)
>100 kHz (dry-type shunt reactor)

Transient voltage amplitude (grounded neutral)

$$Upeak = \sqrt{2} \times \frac{Un}{\sqrt{3}}$$

Case 2- Current chopping and no re-ignition

Since the circuit-breaker is not ideal, current may be interrupted before its natural zero (characteristic which is circuit breaker dependent)

Chopping number (λ) = ich/√Ct

Ich= Chopping current
Ct= Total capacitance seen by circuit breaker (stray capacitance on shunt reactor + parallel capacitance across the circuit breaker)

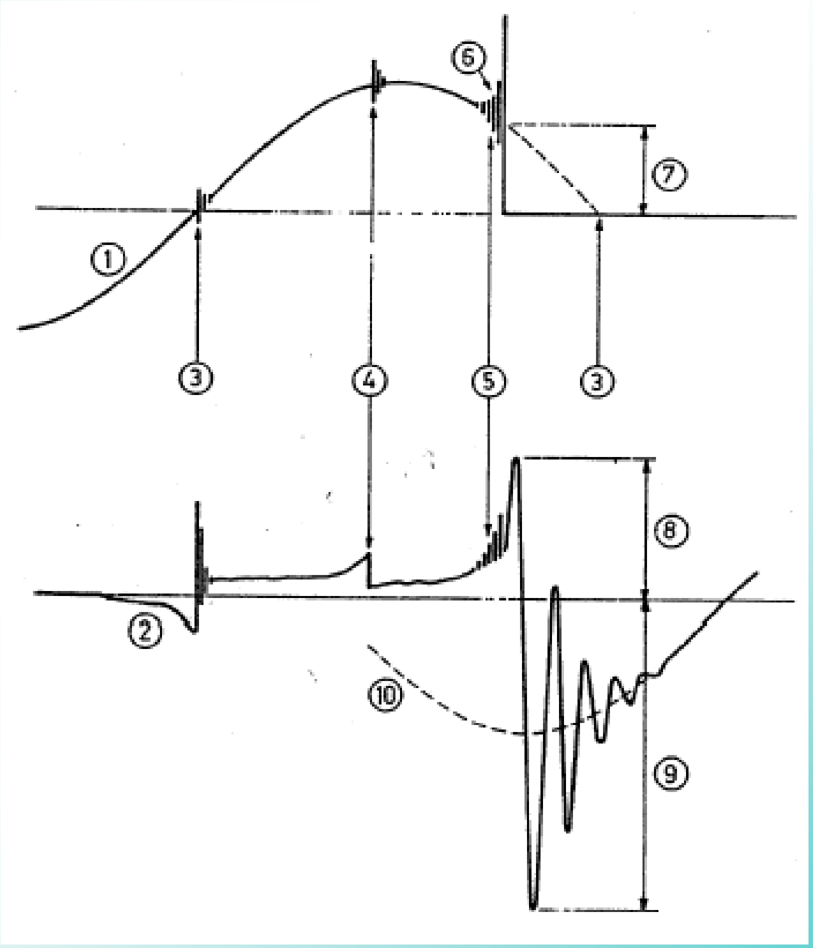
Case 2- Current chopping and no re-ignition (cont)

Typical chopping number

- **Air-blast circuit-breakers: 15-25× 100000**
- **SF_6 circuit-breakers: 4-17× 100000**
- **Oil circuit-breakers: 7-10× 100000**

Figure 2.2.1 Definitions

1 current through circuit–breaker
2 voltage across circuit–breaker (u_s)
3 natural power frequency current zero
4 example of arc instability not leading to current chopping
5 example of arc instability leading to true current chopping
6 instability oscillation
7 chopping current (i_{ch})
8 suppression peak
9 recovery peak
10 supply voltage



Case 2- Current chopping and no re-ignition (cont)

Current chopping effect = Overvoltage since the trapped energy in the reactor at the moment of current chopping is transferred to the parallel capacitance

$$\tfrac{1}{2} \times L \times (i_{chopping})^2 = \tfrac{1}{2} \times C_T \times (\Delta V)^2$$

Case 2- Current chopping and no re-ignition (cont)

For a given shunt reactor (L fixed), the overvoltage depends on the chopped current magnitude

$$\Delta V = ich \times \sqrt{(L/Ct)}$$

The amplitude of chopped current depend on the arcing time (proportional) and

$$\Delta V \approx \text{Arcing time}$$

Case 2- Current chopping and no re-ignition (cont)

Type of stress = Switching surge type of wave shape

$$f_{transient} = \frac{1}{2\pi\sqrt{LC_L}}$$

Case 2- Current chopping and no re-ignition (cont)

Typical frequencies:

1 to 40kHz (oil-immersed reactor)

>100 kHz (dry-type shunt reactor)

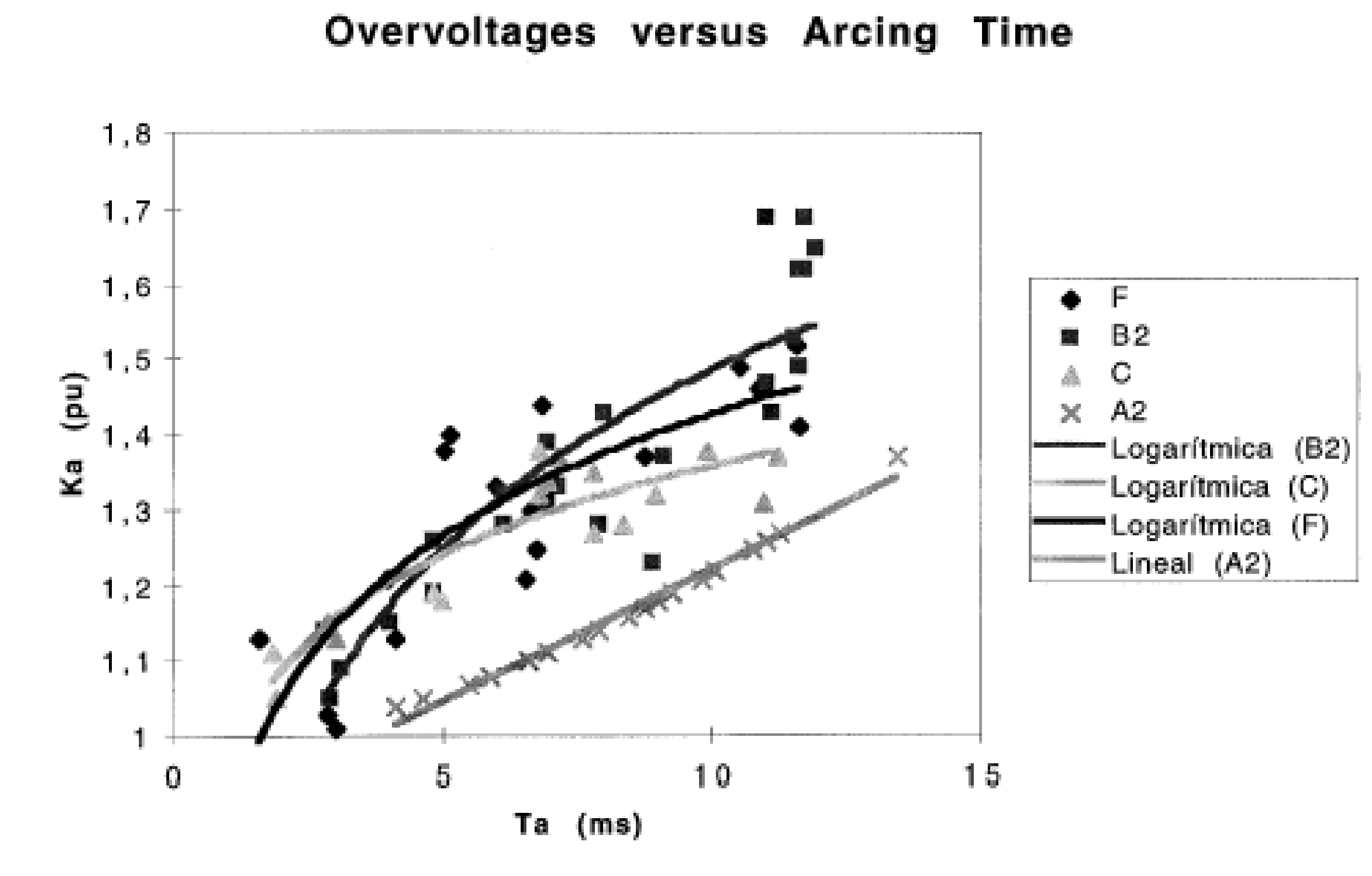
Transient voltage amplitude (grounded neutral)

$$U_{peak} = k_a \times \sqrt{2} \times (U_n/\sqrt{3})$$

ka = chopping overvoltage factor

$$k_a = \sqrt{1 + \frac{3 \times N \times \lambda^2{}_{\max}}{2 \times \omega \times Q}}$$

Overvoltage depend on the chopping number, number of breaking units and the rated power reactor


Overvoltages versus Arcing Time
1,8
1,7
1,6
1,5
1,4
1,3
1,2
1,1
1
Ka (pu)
0
5
10
15
Ta (ms)
F
B2
C
A2
Logarítmica (B2)
Logarítmica (C)
Logarítmica (F)
Lineal (A2)

an approximation which leads to $\kappa_r = \kappa$ in eq. (4.3.7) and Figure 4.3.2.

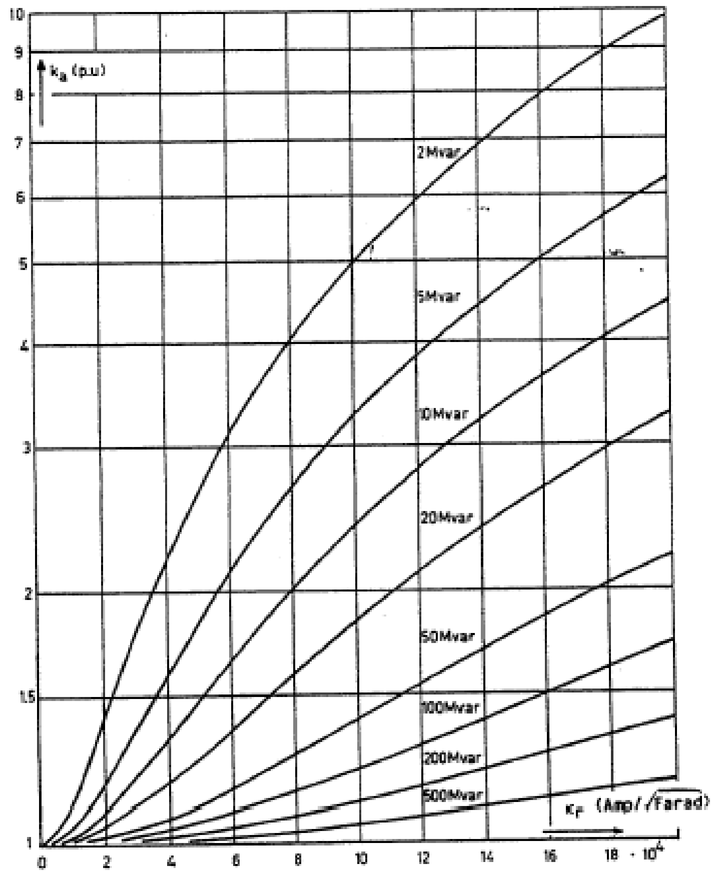


FIGURE 4.3.2 Overvoltage factors k_a vs the reduced chopping number κ_r for a number of inductive power magnitudes. Power frequency is 50 Hz

Conclusions for chopping current case:

1. **Worst case of overvoltage must be evaluated for a specific reactor and circuit breaker using the longest arcing time without re-ignition**

2. **Chopping number must be obtained from the test results using linear regression**

Case 3- Re-ignition

If during the oscillation of the voltage across the inductive load after current interruption, the momentary withstand voltage of the circuit-breaker is exceeded, the circuit breaker re-ignites

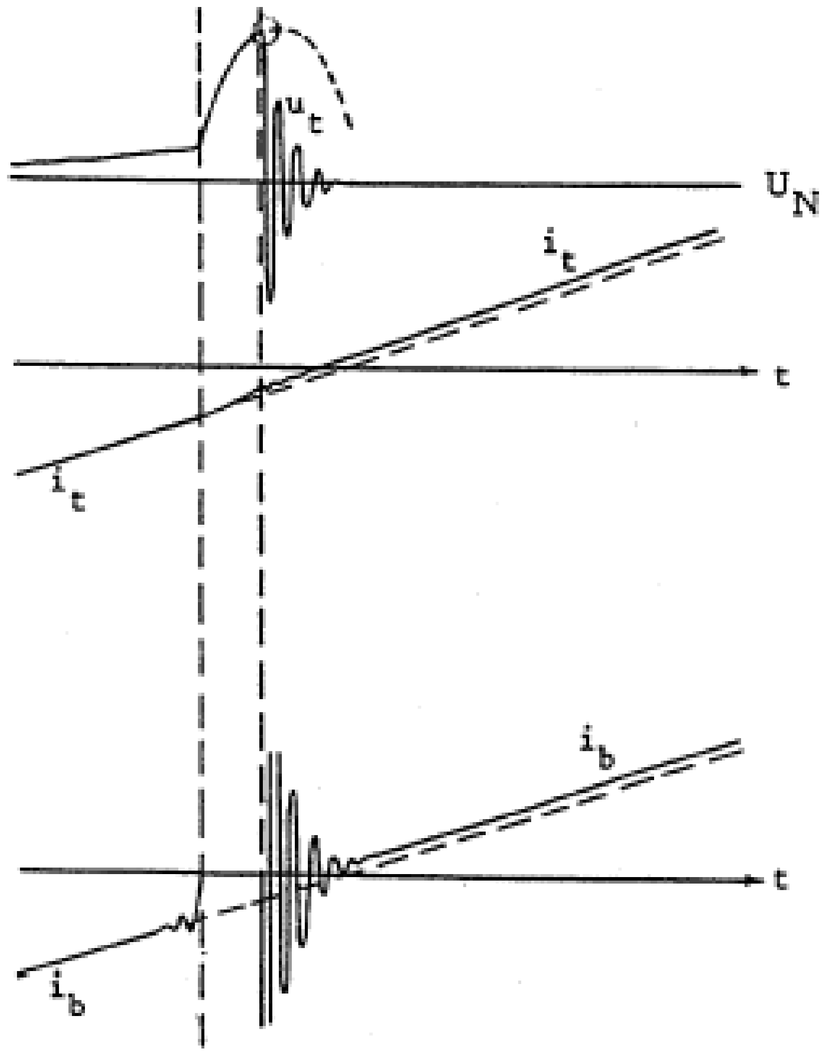


FIGURE 2.5.4 Reignition suppression peak leading to current loop.

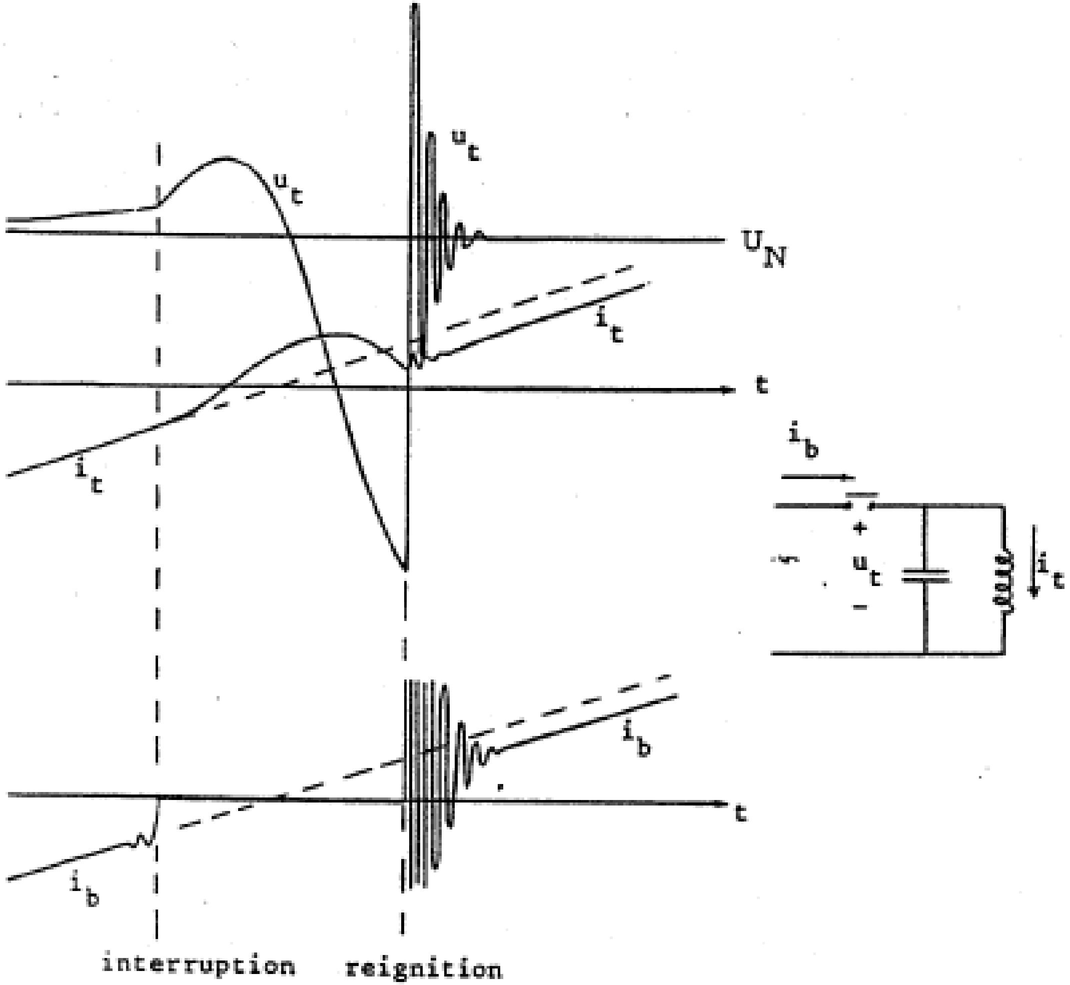


FIGURE 2.5.3 Reignition near recovery peak leading to new current loop.

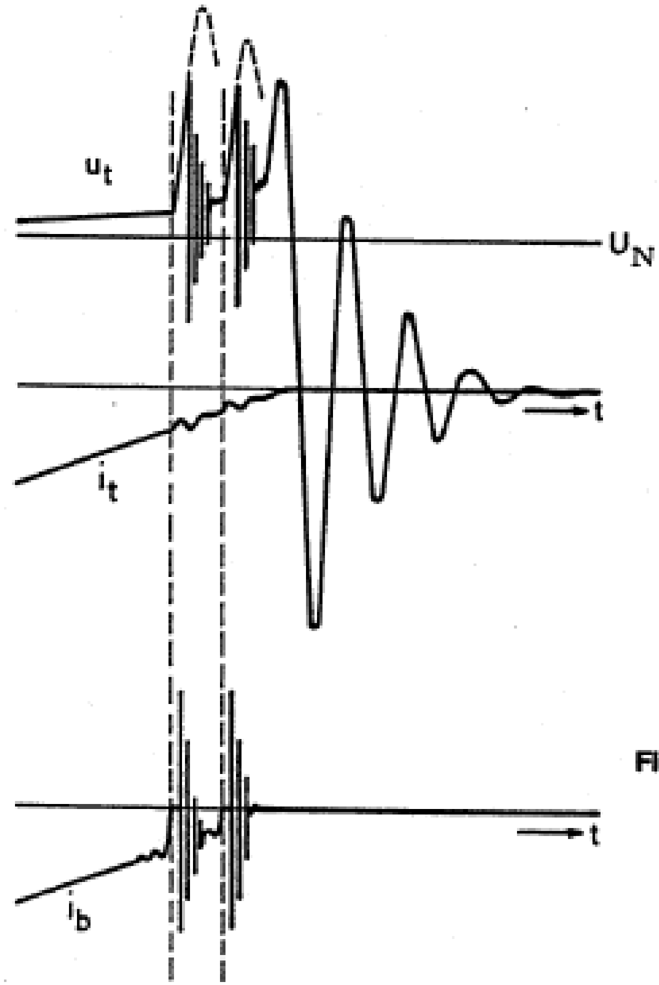


FIGURE 2.5.5 Reignitions before suppression peak not leading to new current flow.

Case 3. Re-ignition (continued)

Type of stress = Fast transient type of waveshape

$$f_{transient} = \frac{1}{2\pi} \times \sqrt{\frac{C_L + C_S}{L_B \times C_L \times C_S}}$$

Typical frequencies: 50kHz to 1MHz (depend on the stray capacitance of the shunt reactor and the length of the circuit between the source and the reactor)

Case 3. Re-ignition (continued)

kp= (1+β) (1+ka) -assuming Cs very large-

kp; **re-ignition overvoltage magnitude in p.u. to ground**

β; **damping factor of the re-ignition transient**

ka; **suppression peak overvoltage caused by current chopping**

Overvoltages may be very harmful for the reactor but they are not the worst case.

The most dangerous case is dv/dt produced during the re-ignition since the reactor may not be protected by the surge arrestors.

Summary

•**Switching surge type of waveshape**. Not dangerous

•**Switching surge type of waveshape and overvoltage** proportional to current chopped and to the arcing time. The transient can be severe depending the of cb chopping characteristic and shunt reactor value

•**Fast transient type of waveshape**- **overvoltage to earth- dv/dt**. It can be very dangerous for the reactor.

Part II. Controlled switching

How does it work?

Ensures contact parting with respect to current wave such that interruption occurs in the subsequent current zero.

Controlled switching. Energization strategies

- **Energization at peak voltage**

  Advantages (I)

  - *The inrush current is practically supressed and hence the misoperation of protective relays is eliminated too (neutral overcurrent).*
  - *Inrush current can develop sympathetic interaction with neighbouring power transformers causing misoperation of protective relays and prolonged temporary harmonic voltages with a degradation in the quality of electricity supply. These effects are eliminated.*

Controlled switching. Energization strategies

- **Energization at peak voltage (cont)**

  Advantages (II)

  - *Mechanical vibrations and buzzing in reactor have been reported during uncontrolled energization. The effect can be eliminated and so stress in the reactor is reduced. Maintenance works can be reduced.*
  - *Vibrations occurred in the generators of hydro power generation stations situated close to substation with reactors are eliminated.*
  - *Power quality of system is increased*

Controlled switching. Energization strategies

- **Energization at peak voltage (cont)**

  Drawbacks

  - *Energization at peak voltage stresses the reactor insulation with a steep voltage front caused by the breakdown of the contact gap when the current starts to flow.*

Controlled switching. Energization strategies

- **Energization at zero voltage**

Advantages

- *Energization at zero voltage eliminates the steep voltage front caused by the breakdown of the contact gap when the current starts to flow.*

Drawbacks

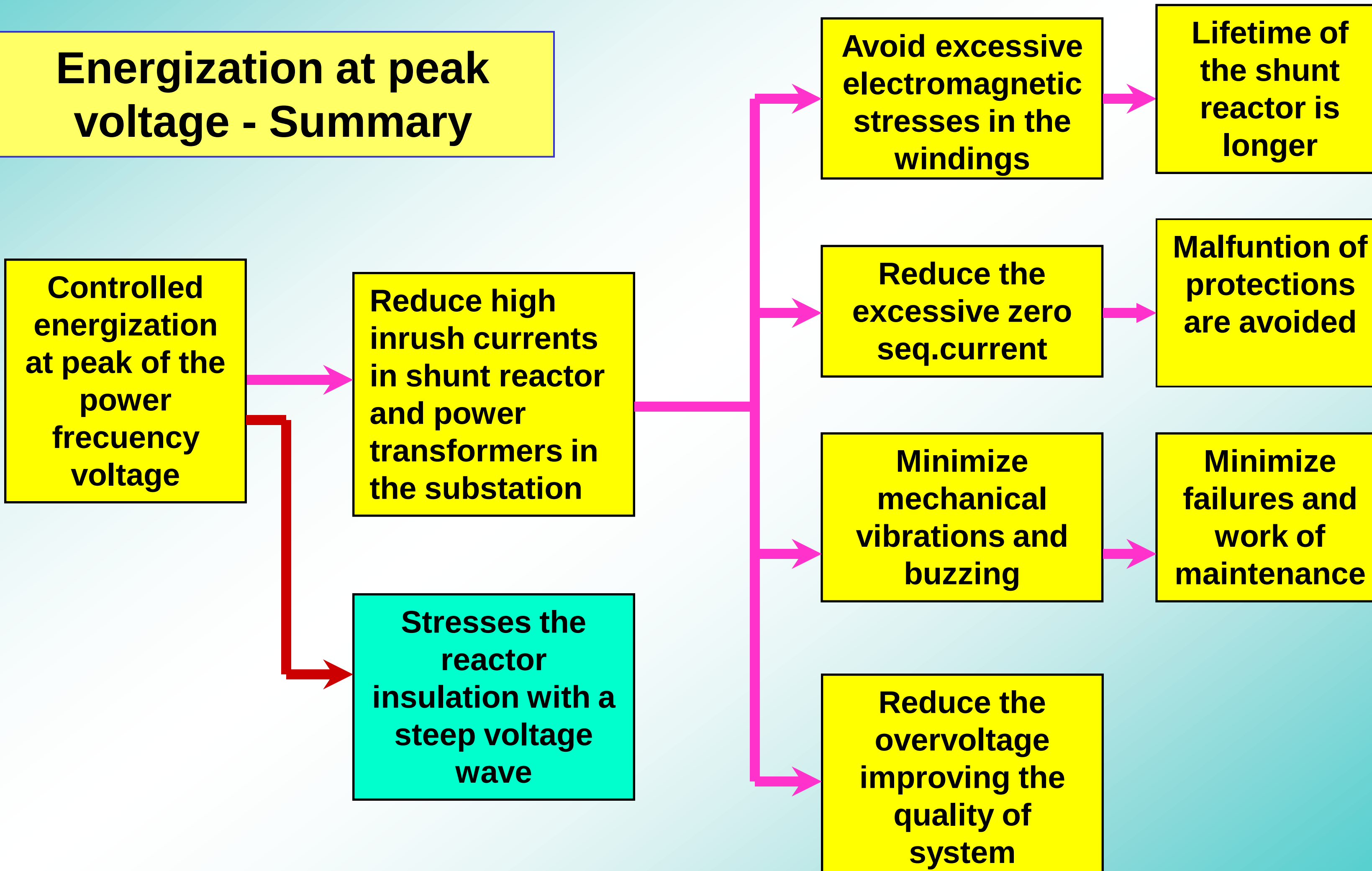
- *This way of energization may cause excessive electromagnetic stresses in the winding because a high energization current in the reactor is generated.*
- *Activation of zero sequence protective relays is produced due to saturation effects*

Controlled switching. Energization strategies

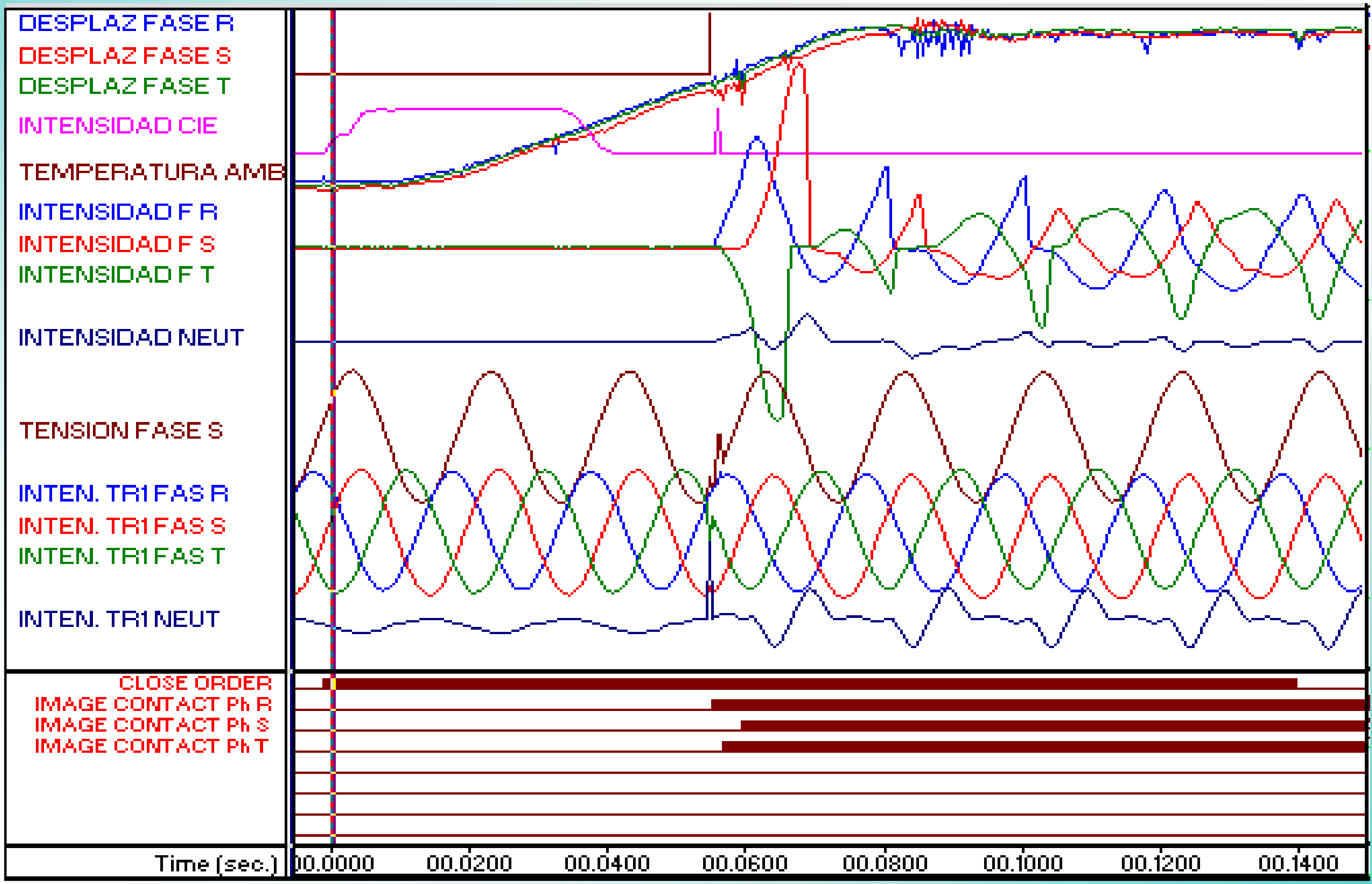
- ***Point on wave energization recommended***

  Since it's not possible to eliminate both inrush current and transient stresses simultaneously, a compromise solution must be adopted according the rules and experience of users and equipment manufacturers.

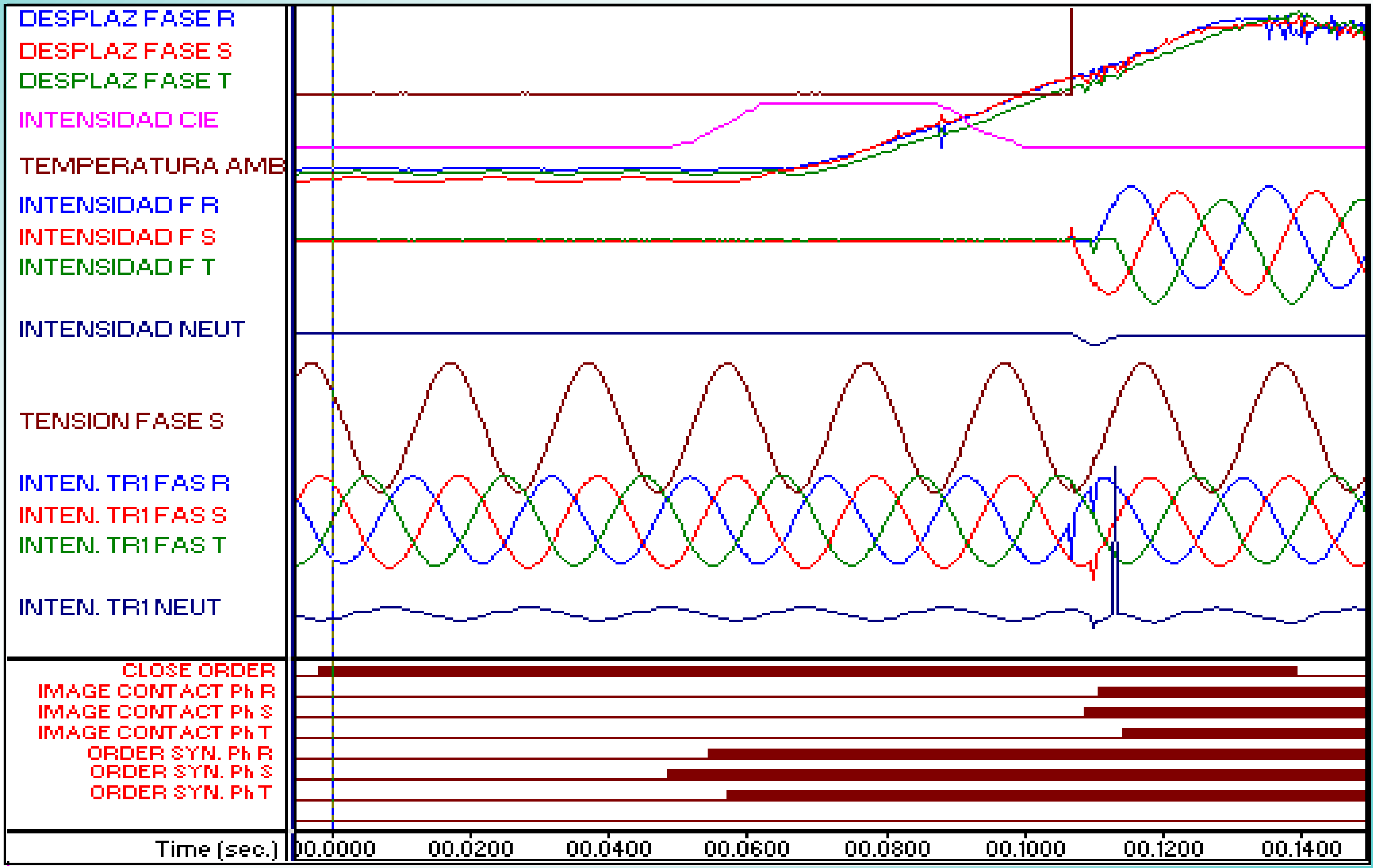
Energization at peak voltage - Summary



RANDOM CLOSING



CONTROLLED CLOSING



Controlled switching. De-energization strategies

- *Open the circuit breaker at the designed point on wave in order to use the optimum arcing time limiting with this the effects of stresses at circuit breaker and other components and reducing the transients in the system (overvoltage and reducing the probability of re-ignitions).*

Controlled switching. De-energization strategies

- **De-energization**

  Advantages (I) - Reactor

  - *Probability of re-ignitions is reduced since the instant of contact opening in the circuit breaker is controlled using the optimum arcing time.*
  - *Travelling waves into the reactor and the stress on its insulation are reduced since the probability of re-ignitions is lower and transients are reduced.Lifetime of the reactor is longer and maintenance work is reduced.*
  - *Overvoltages are limited, and so it possible to increase the margin of protection offered by surge arresters.*

Controlled switching. De-energization strategies

- **De-energization (cont)**

  Advantages (II) - Circuit Breaker

  - *Since the re-ignitions are reduced, electrical wear in the cb is practically eliminated, depending exclusively on factors of influence on the mechanical wear. Risk of explosion of cb and damages on other equipment are practically eliminated.*
  - *Period between maintenance works at cb is extended*
  - *Degree of complexity in maintenance work is reduced and so the cost associated is lower.*

Controlled switching. De-energization strategies

- **De-energization (cont)**

  Advantages (III) - System

  - *Avoid nuisance relay tripping*
  - *Increase of power quality*

Controlled switching. De-energization strategies

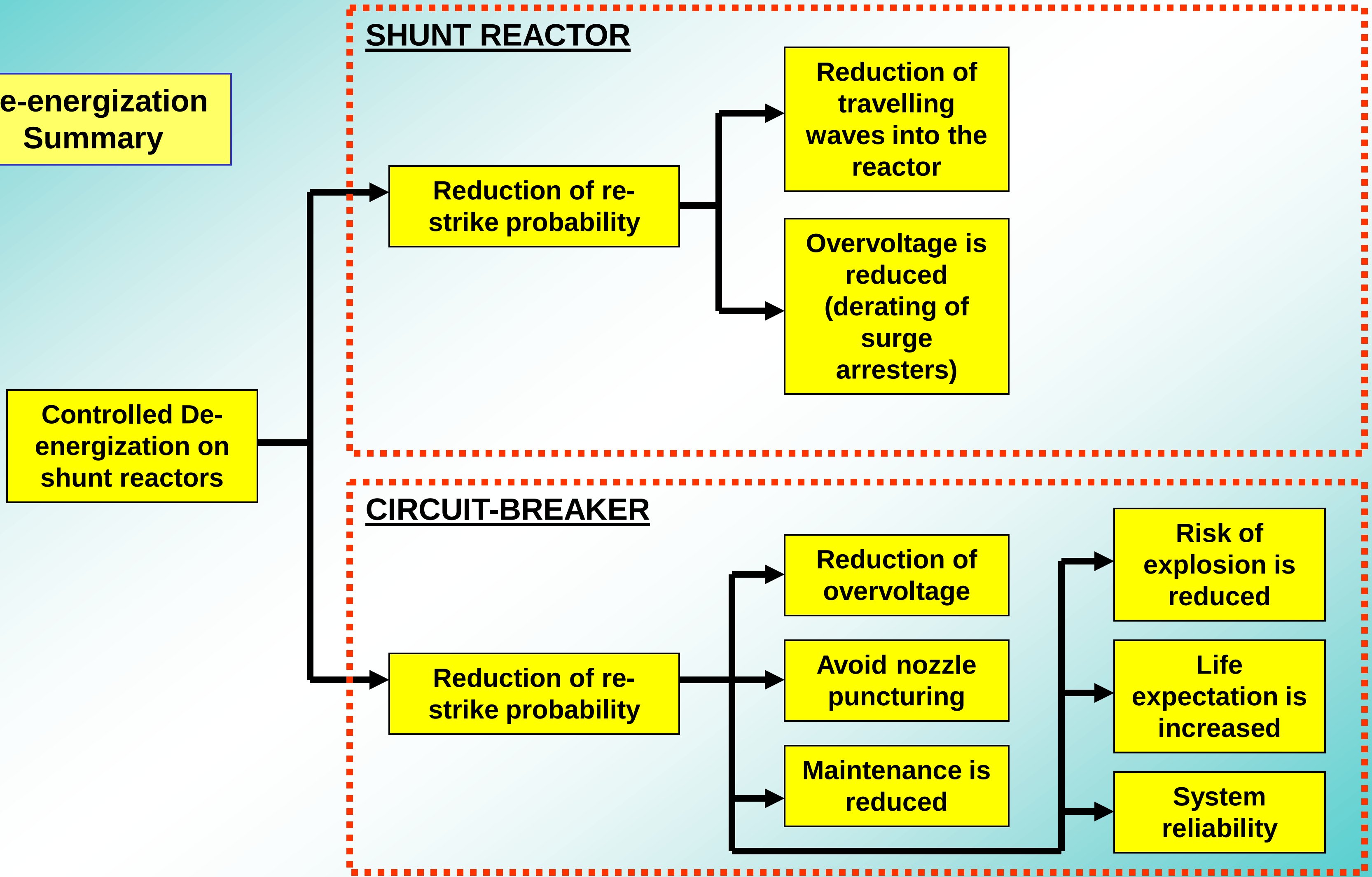
- **De-energization (cont)**

  Drawbacks

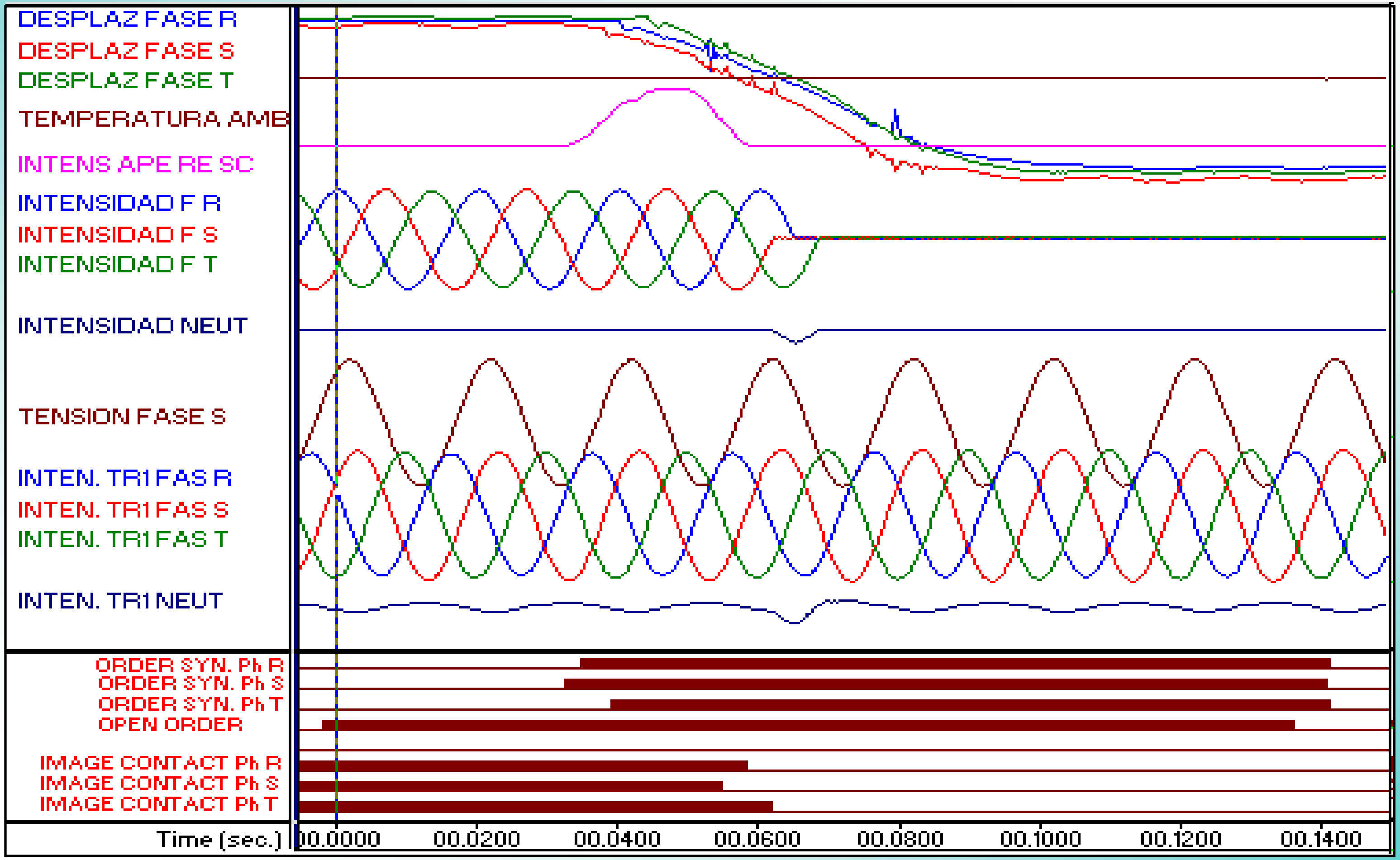
  - *Malfuntion of the controller could be very serious because the worst situation could be repetitive*
  - *Circuit-breaker requires to have independent-poles and strict requirement must be fulfilled (scatter, stable times, etc..)*

Benefits for Shunt Reactors Applications

De-energization Summary



CONTROLLED OPENING



Basic requirements for CSS

- **Circuit-breaker**
  - **Suitable Rate of Decrease of Dielectric Strength (RDDS)**
  - **Required accuracy of switching times (<±1,5ms)**
  - **Stable switching times**
- **Controller**
  - **Accuracy in commands processed**
  - **Compensation of variable parameters (temperature, drive energy, control voltage, etc..)**

Basic requirements for CSS (cont)

- **Laboratory**
  - **Test must be carried out to verify the optimum adaptation between circuit-breaker, controller and shunt reactor.**
- **Field**
  - **Intensive field test must be carried out to verify the optimum adaptation between circuit-breaker, controller and shunt reactor.**

Fig 1. Nozzles of a SF6 circuit breaker after 1500 operations with uncontrolled opening switching

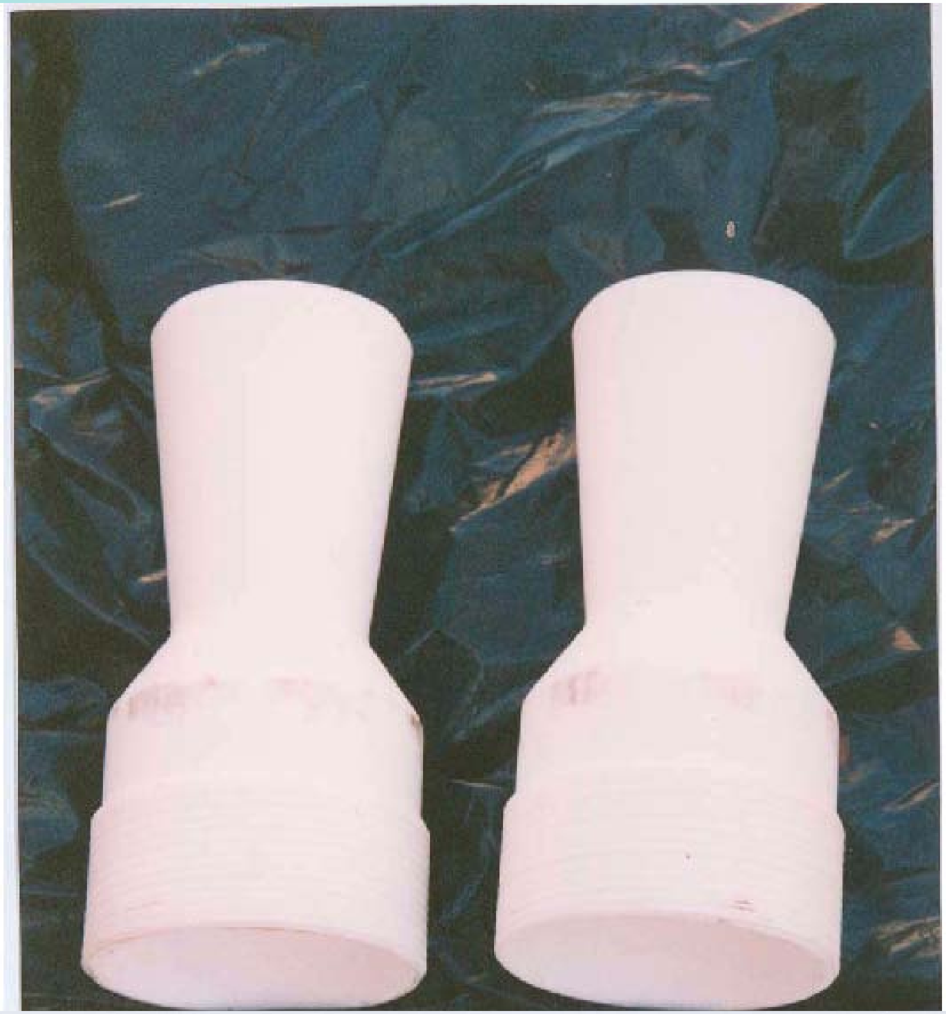


Fig 2. Same nozzles than Fig.1 after 650 operations with controlled opening switching

Fig. 3. Nozzles with puncturing effect after 1500 operations with uncontrolled opening switching

Fig 4. New nozzles were installed in circuit breaker of Fig.3 and after 650 operations were de-assembled. These were the effects.

¡¡THANK YOU VERY MUCH FOR YOUR ATTENTION¡¡