Degradation of the Energy Transfer Effectiveness Described in Terms of Currents' Physical Components (CPC)-based Power Theory

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Cost of the electric energy production and delivery
is related to the apparent power

$$S = U \times I$$

For customers the importance has only the energy delivered

$$W = \int_0^{\tau} P\,dt$$

$$S \geq P$$

The power factor $\lambda = \dfrac{P}{S}$

specifies the effectiveness of the electric energy delivery to customer loads

The question: why ?

$$\lambda < 1$$

is of the major importance for the electrical systems economy

What physical phenomena are behind the inequality

$$S \geq P$$

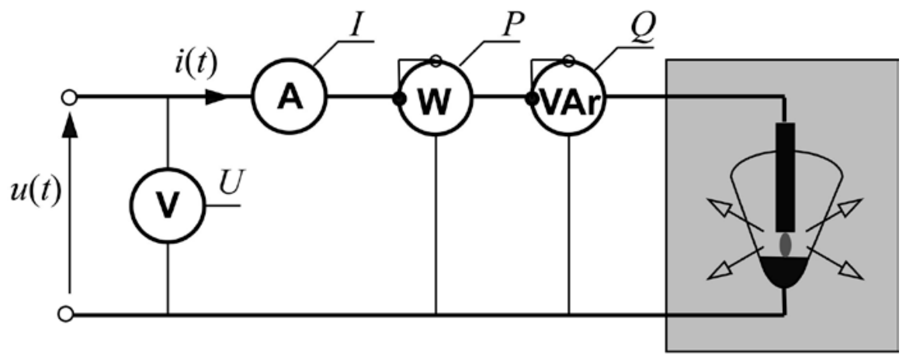
?

By the end of XIX century
it was concluded
that

$$S^2 - P^2 = Q^2$$

where Q denotes the reactive power of the load

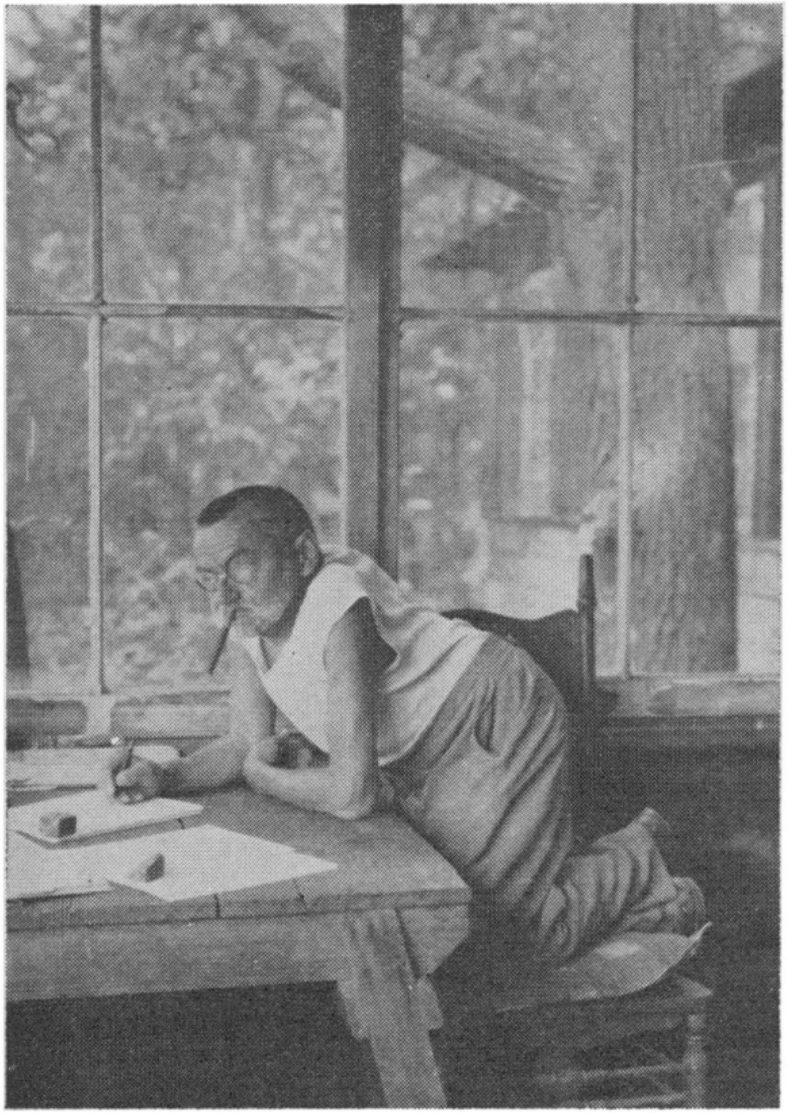
Steinmetz Experiment: 1892



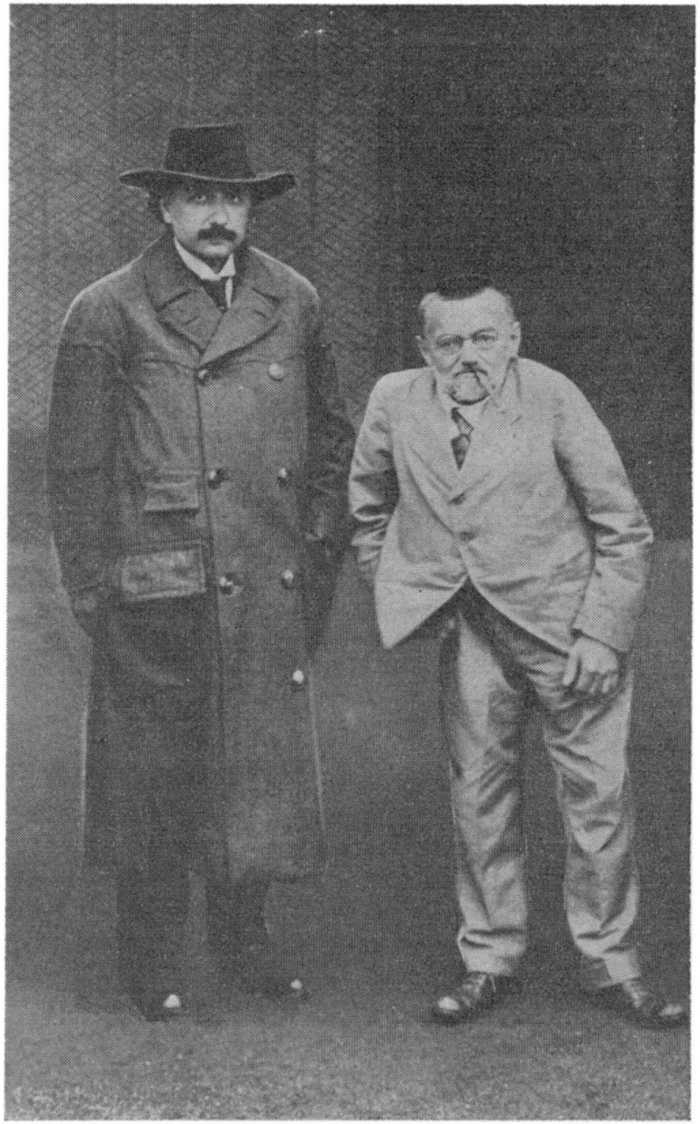
$$P^2 + Q^2 < S^2, \qquad Q = 0$$

Why the apparent power *S* is higher than the active power *P* ?

How the difference between *S* and *P* can be reduced ?



Charles Proteus Steinmetz

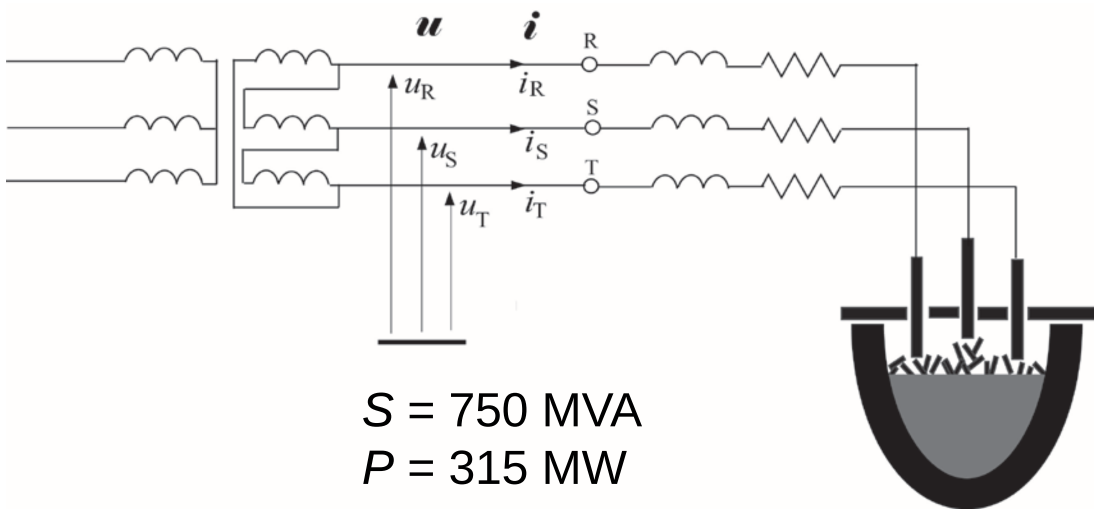


Einstein and Steinmetz.

In Einstain's company…

Present day “Steinmetz Experiment” with line currents up to

625 kA



S = 750 MVA
P = 315 MW

Current not only distorted, but also asymmetrical and random
Power factor: $\lambda \sim 0.42$

Annual bill for energy
~ 500 Million $

Why the apparent power S is higher
than the active power P ?

How the difference between S and P
can be reduced ?

These apparently simle questions
have occurred
to be ones of the most difficult questions of electrical engineering
for the whole XX century.

Hundreds of scientists were involved
in the quest for the answer.
Hundreds of papers have been published.

Major disscussion forums:

International Workshop on Reactive Power Definition
and Measurements in Nonsinusoidal Systems,
Bi-annual meetings in Italy,
Chaired by A. Ferrero

International School on Nonsinusoidal Currents and Compensation
(ISNCC)
Bi-annual meetings in Poland
Chaired by L.S. Czarnecki

A number of different answers to the Steinmetz's question have been suggested:

1927: Budeanu: $S^2 - P^2 = Q_B^2 + D^2$ $\qquad Q_B = \sum_{n=1}^{\infty} U_n I_n \sin\varphi_n$

Endorsed by the IEEE Standard Dictionery of Electrical and Electronics Terms in 1992 and German Standards DIN in 1972

1931: Fryze: $S^2 - P^2 = Q_F^2$ $\qquad Q_F = \|u\|\,\|i_{rF}\|$

Endorsed by German Standards DIN in 1972

1971: Shepherd: $S^2 - S_R^2 = Q_S^2$ $\qquad Q_S = \|u\|\,\|i_{rS}\|$

1975: Kusters: $S^2 - P^2 = Q_K^2 + Q_r^2$ $\qquad Q_K = \|u\|\,\|i_{rC}\|$

Endorsed by the International Electrotechnical Commission in 1980

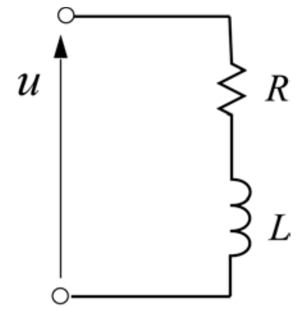
1979: Depenbrock: $S^2 - P^2 = Q_1^2 + V^2 + N^2$ $\qquad Q_1 = U_1 I_1 \sin\varphi_1$

2003: Tenti: $S^2 - P^2 = Q_T^2 + D_T^2$ $\qquad Q_T = \|u\|\,\|i_{rT}\|$

Since the Steinmetz's experiment
in 1892, after 91 years
of Power Theory development for single-phase, LTI loads,
such as

$$u = U_0 + \sqrt{2}\,\mathrm{Re}\sum_{n=1}^{\infty} \boldsymbol{U}_n\, e^{jn\omega_1 t}$$

$$i = G_0 U_0 + \sqrt{2}\,\mathrm{Re}\sum_{n=1}^{\infty} \boldsymbol{Y}_n \boldsymbol{U}_n\, e^{jn\omega_1 t}$$



we have had five different power equations and five different reactive powers

Compensation problem was not solved

The problem was eventually solved
in frame of the
Currents' Physical Components (CPC) – based power theory
by
L.S. Czarnecki in 1984

This, eventually a positive result
was a conclusion
of a specific approach to the power theory development.

Its core is the concept
of

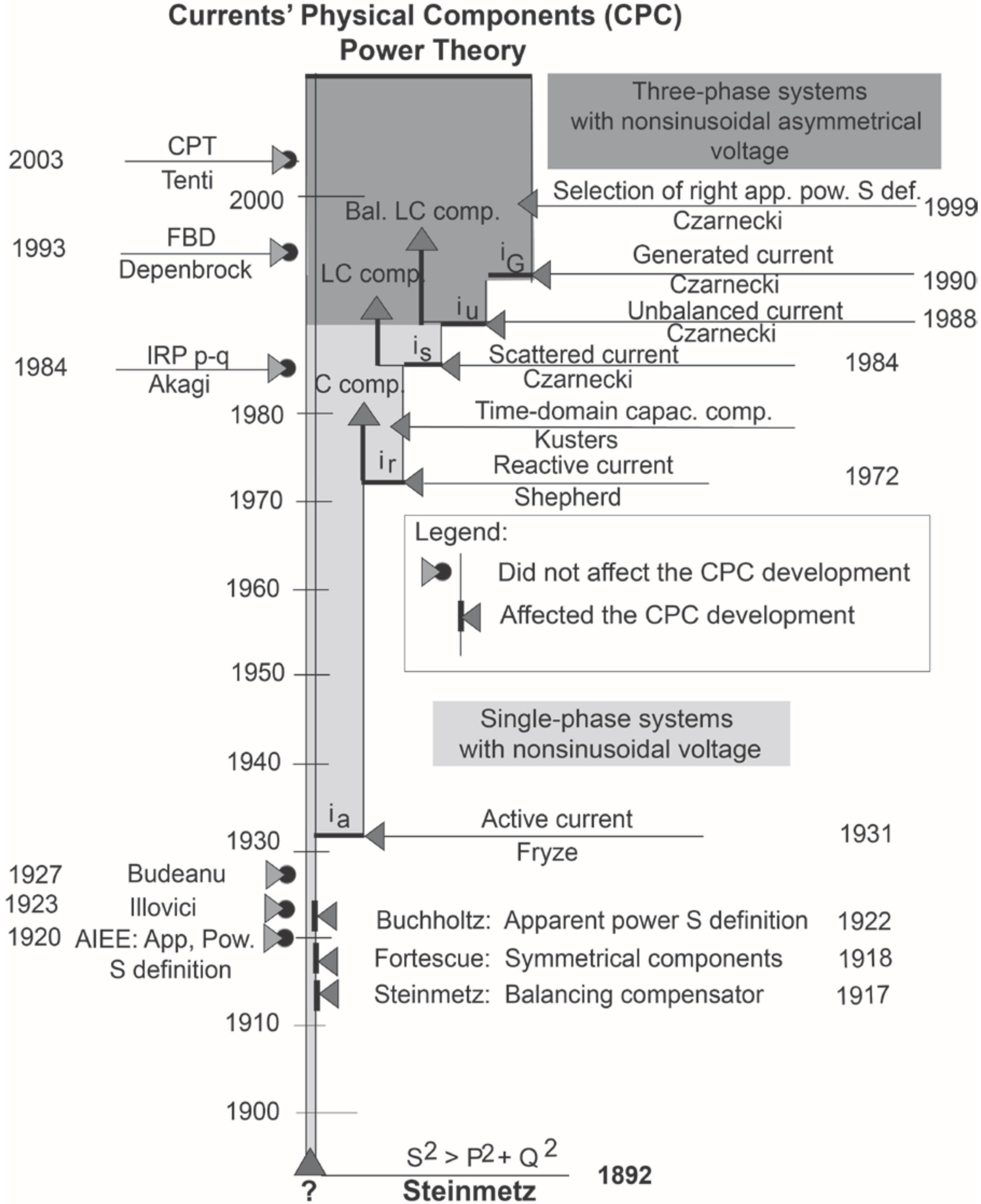
Currents' Physical Components (CPC)

According to the CPC concept,
the load current can be decomposed
into

- components associated with distinctive physical phenomena

which are

- mutually orthogonal

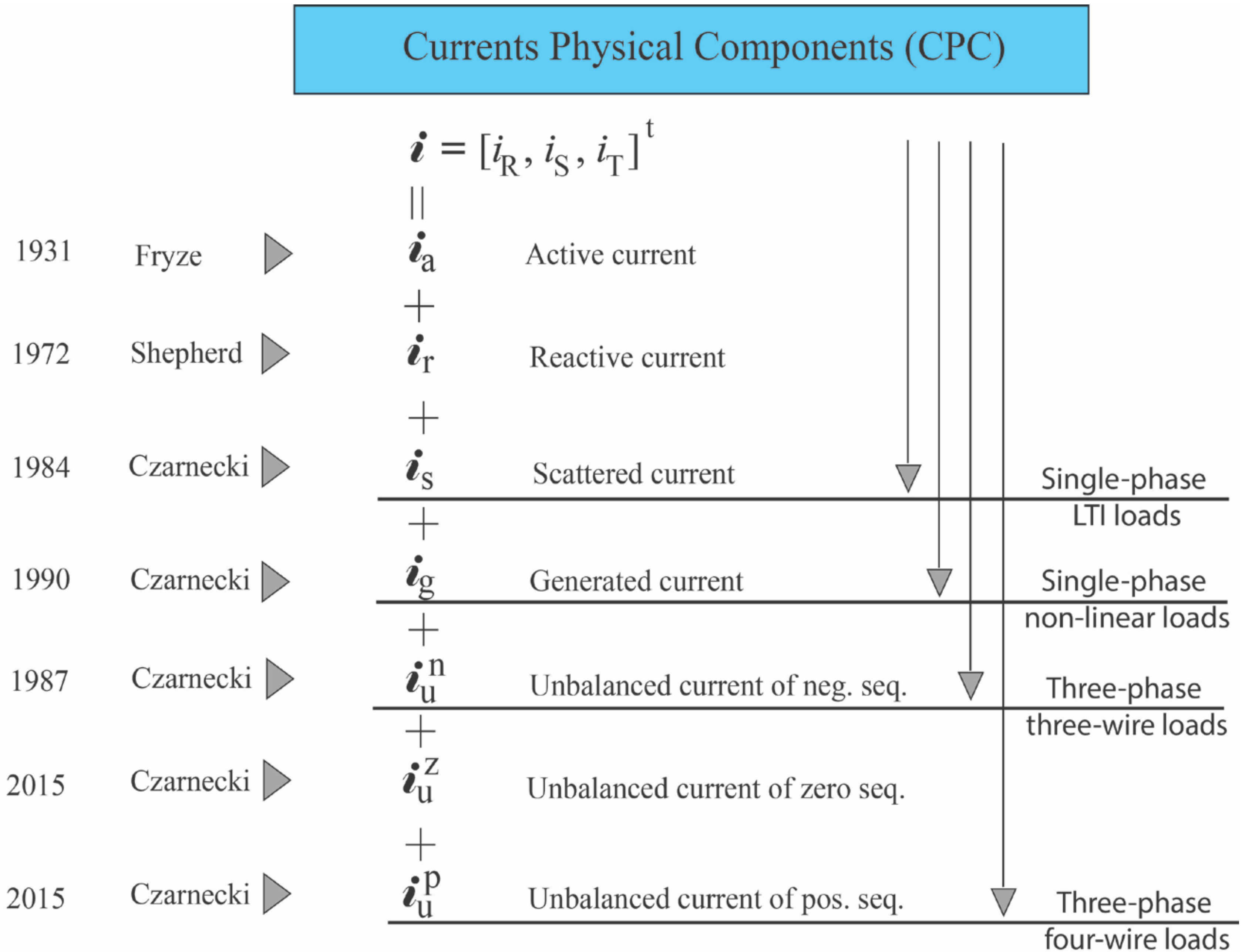


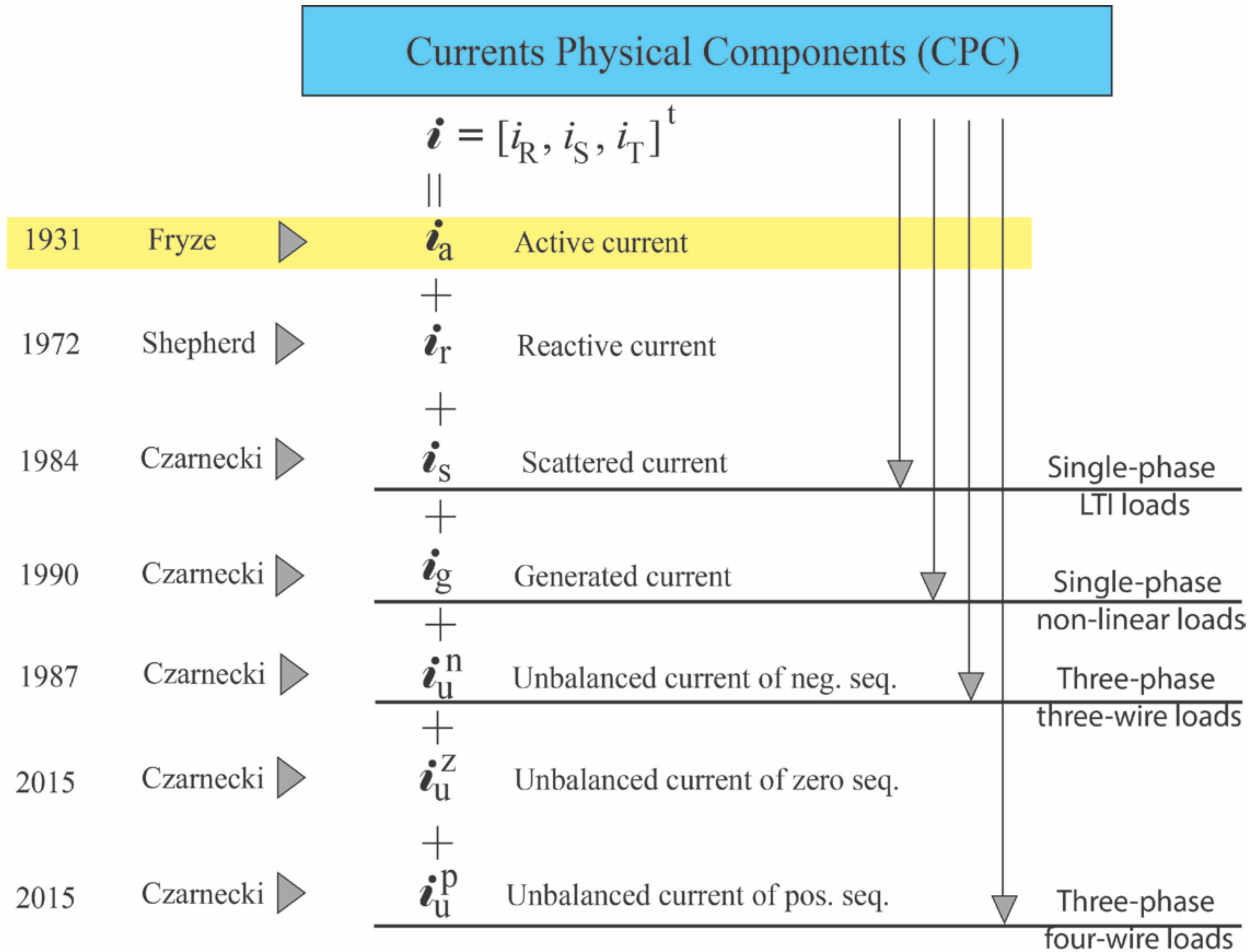
Currents' Physical Components (CPC)
Power Theory
Three-phase systems with nonsinusoidal asymmetrical voltage
2003 CPT Tenti
2000
Bal. LC comp.
Selection of right app. pow. S def. Czarnecki 1999
1993 FBD Depenbrock
LC comp.
i_G
Generated current Czarnecki 1990
i_u
Unbalanced current Czarnecki 1988
i_s
Scattered current Czarnecki 1984
1984 IRP p-q Akagi
C comp.
1980
Time-domain capac. comp. Kusters
i_r
Reactive current Shepherd 1972
1970
Legend:
Did not affect the CPC development
Affected the CPC development
1960
1950
Single-phase systems with nonsinusoidal voltage
1940
i_a
Active current Fryze 1931
1930
1927 Budeanu
1923 Illovici
1920 AIEE: App, Pow. S definition
Buchholtz: Apparent power S definition 1922
Fortescue: Symmetrical components 1918
Steinmetz: Balancing compensator 1917
1910
1900
$S^2 > P^2 + Q^2$
?
Steinmetz 1892

CPC
of three-phase Harmonics Generating Loads (HGL)
supplied by a four-wire line
with nonsinusoidal and asymmetrical voltages:

$$\boldsymbol{i}(t) = \boldsymbol{i}_{\mathrm{a}}(t) + \boldsymbol{i}_{\mathrm{r}}(t) + \boldsymbol{i}_{\mathrm{s}}(t) + \boldsymbol{i}_{\mathrm{u}}^{\mathrm{n}}(t) + \boldsymbol{i}_{\mathrm{u}}^{\mathrm{p}}(t) + \boldsymbol{i}_{\mathrm{u}}^{\mathrm{z}}(t) + \boldsymbol{i}_{\mathrm{G}}(t)$$

These currents are associated
with distinctive physical phenomena in the load


Currents Physical Components (CPC)
$\boldsymbol{i} = [i_R, i_S, i_T]^t$
1931 Fryze $\boldsymbol{i}_a$ Active current
1972 Shepherd $\boldsymbol{i}_r$ Reactive current
1984 Czarnecki $\boldsymbol{i}_s$ Scattered current
1990 Czarnecki $\boldsymbol{i}_g$ Generated current
1987 Czarnecki $\boldsymbol{i}_u^n$ Unbalanced current of neg. seq.
2015 Czarnecki $\boldsymbol{i}_u^z$ Unbalanced current of zero seq.
2015 Czarnecki $\boldsymbol{i}_u^p$ Unbalanced current of pos. seq.
Single-phase LTI loads
Single-phase non-linear loads
Three-phase three-wire loads
Three-phase four-wire loads



The active current is associated
with the phenomenon

Currents Physical Components (CPC)

$$\boldsymbol{i} = [i_R, i_S, i_T]^t$$

$$||$$

1931	Fryze	$\boldsymbol{i}_a$	Active current
		$+$	
1972	Shepherd	$\boldsymbol{i}_r$	Reactive current
		$+$	
1984	Czarnecki	$\boldsymbol{i}_s$	Scattered current
		$+$	
1990	Czarnecki	$\boldsymbol{i}_g$	Generated current
		$+$	
1987	Czarnecki	$\boldsymbol{i}_u^n$	Unbalanced current of neg. seq.
		$+$	
2015	Czarnecki	$\boldsymbol{i}_u^z$	Unbalanced current of zero seq.
		$+$	
2015	Czarnecki	$\boldsymbol{i}_u^p$	Unbalanced current of pos. seq.

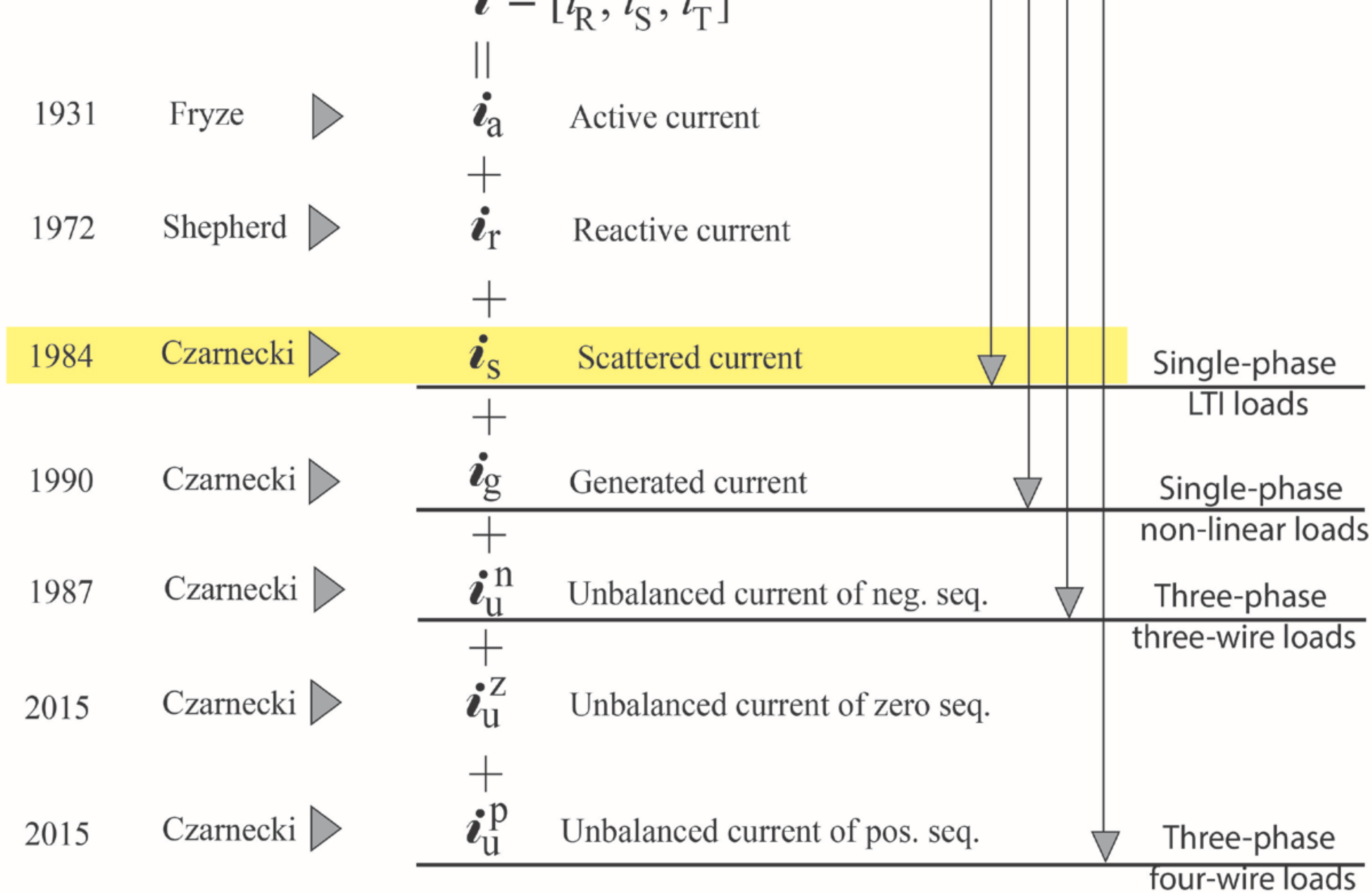
Single-phase LTI loads

Single-phase non-linear loads

Three-phase three-wire loads

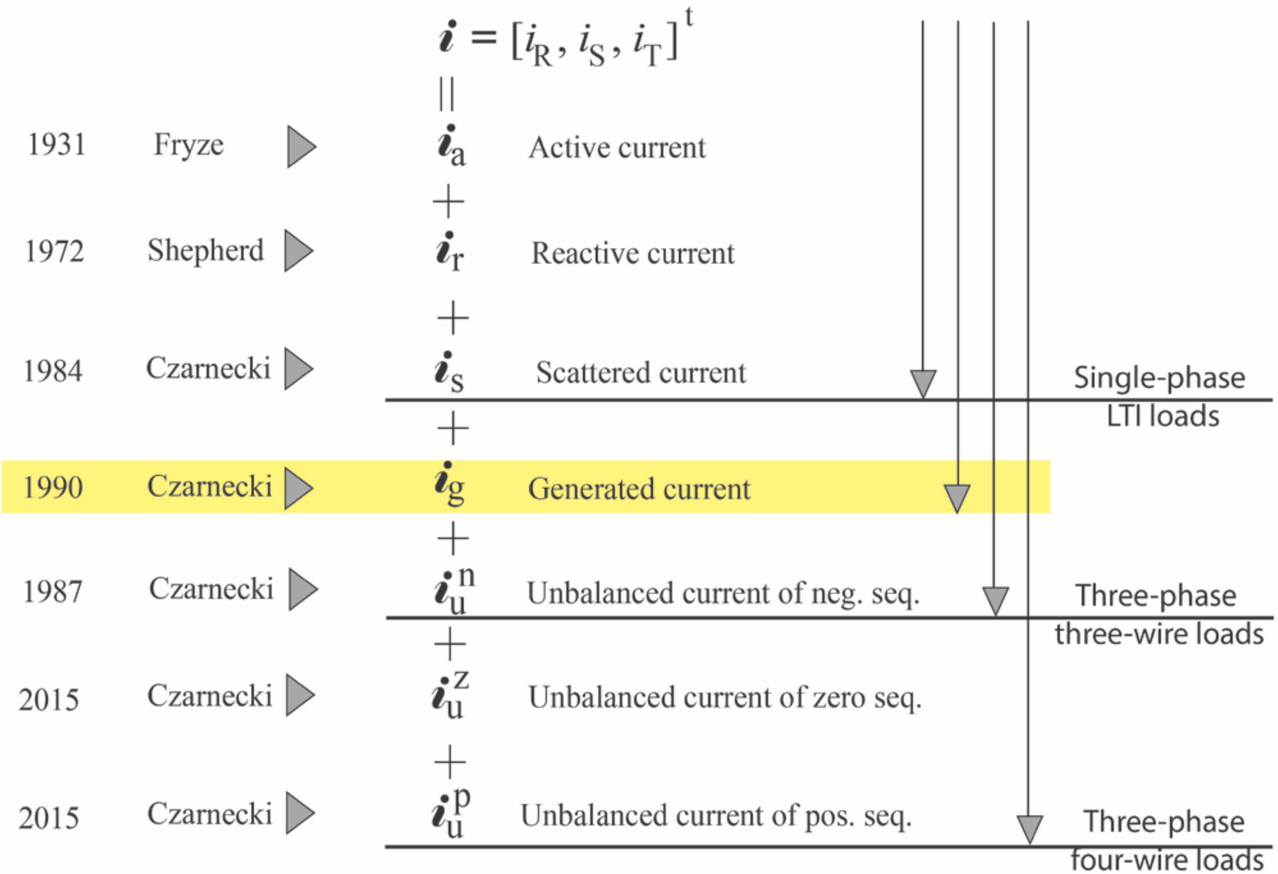
Three-phase four-wire loads

The reactive current is associated
with the phenomenon
of the phase-shift between voltage and current harmonics



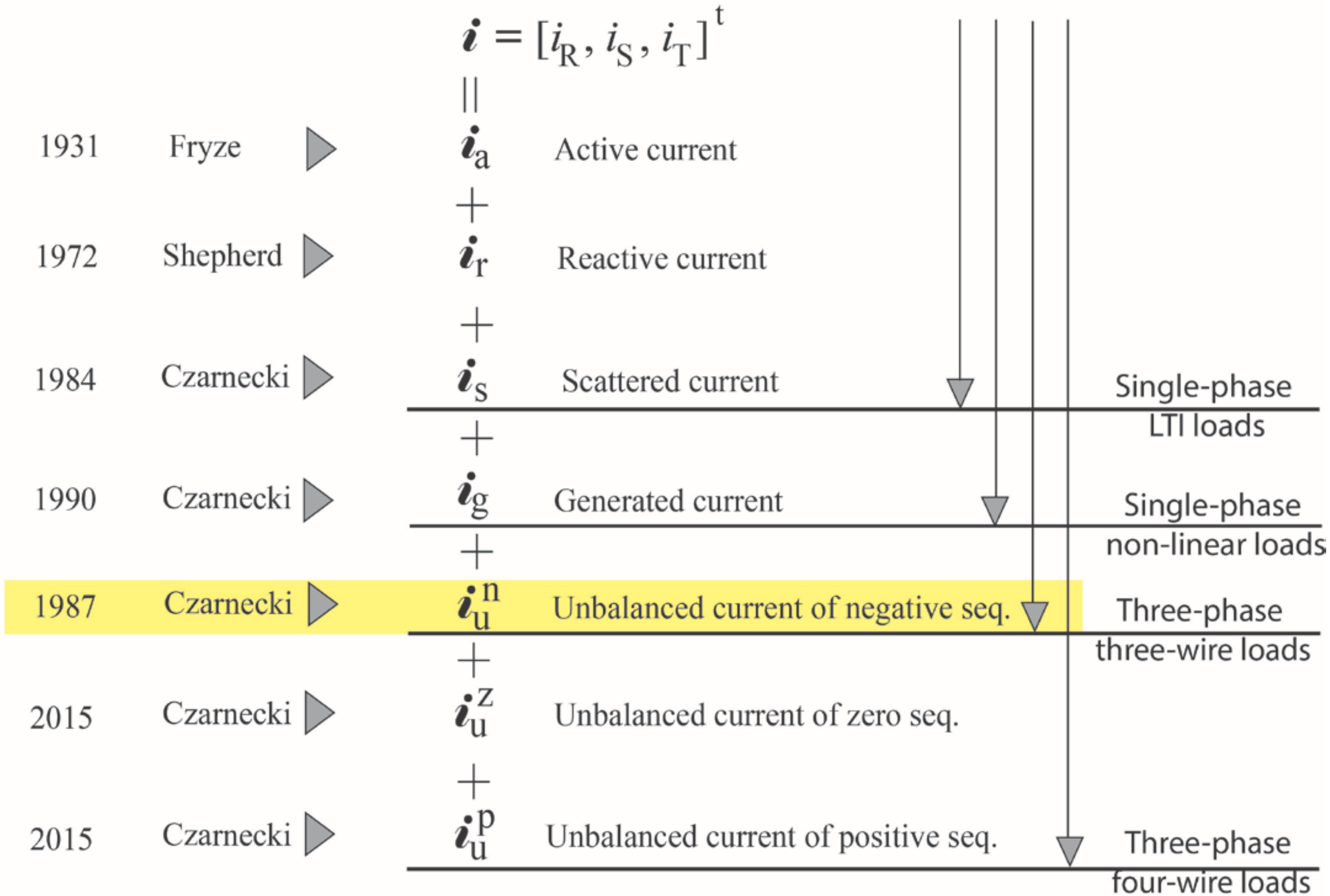
The scattered current is associated
with the phenomenon
of the change of the load conductance with harmonic order

Currents Physical Components (CPC)



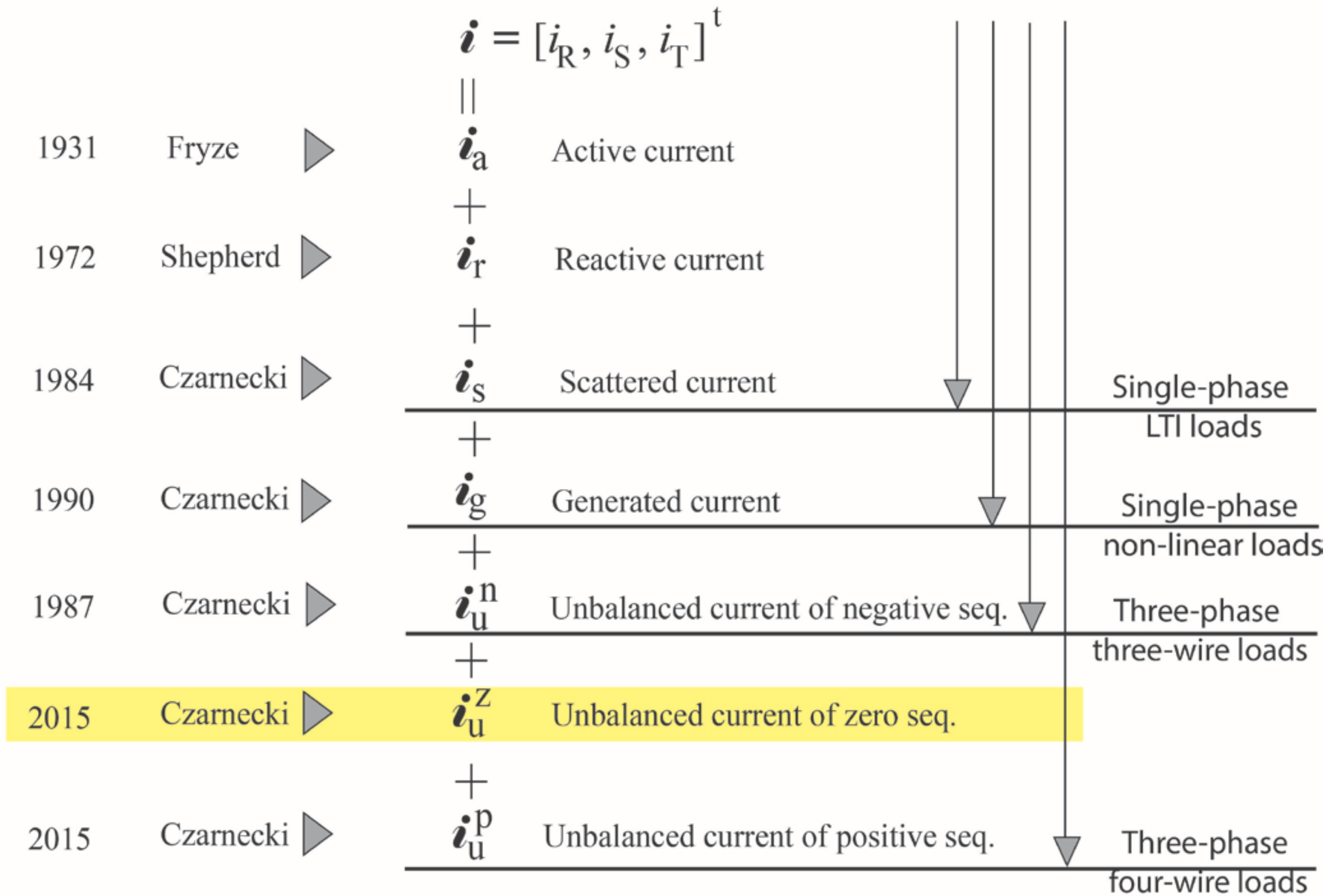
The generated current is associated
with the phenomenon
of reversed direction of energy flow due to current harmonics
generated in the load

Currents Physical Components (CPC)



The unbalanced current of negative sequence is associated
with a phenomenon
of generation of negative sequence current by the load imbalance

Currents Physical Components (CPC)



The unbalanced current of zero sequence is associated
with a phenomenon
of generation of zero sequence current by the load imbalance

Currents Physical Components (CPC)

$$\boldsymbol{i} = [i_R, i_S, i_T]^t$$

$$\|$$

1931	Fryze	$\boldsymbol{i}_a$	Active current
		$+$	
1972	Shepherd	$\boldsymbol{i}_r$	Reactive current
		$+$	
1984	Czarnecki	$\boldsymbol{i}_s$	Scattered current
		$+$	
1990	Czarnecki	$\boldsymbol{i}_g$	Generated current
		$+$	
1987	Czarnecki	$\boldsymbol{i}_u^n$	Unbalanced current of negative seq.
		$+$	
2015	Czarnecki	$\boldsymbol{i}_u^z$	Unbalanced current of zero seq.
		$+$	
2015	Czarnecki	$\boldsymbol{i}_u^p$	Unbalanced current of positive seq.

Single-phase LTI loads

Single-phase non-linear loads

Three-phase three-wire loads

Three-phase four-wire loads

The unbalanced current of positive sequence is associated with a phenomenon of generation of a positive sequence current by the load imbalance

CPC
of three-phase Harmonics Generating Loads (HGL)
supplied by a four-wire line
with nonsinusoidal and asymmetrical voltages:

$$\boldsymbol{i}(t) = \boldsymbol{i}_{\mathrm{a}}(t) + \boldsymbol{i}_{\mathrm{r}}(t) + \boldsymbol{i}_{\mathrm{s}}(t) + \boldsymbol{i}_{\mathrm{u}}^{\mathrm{n}}(t) + \boldsymbol{i}_{\mathrm{u}}^{\mathrm{p}}(t) + \boldsymbol{i}_{\mathrm{u}}^{\mathrm{z}}(t) + \boldsymbol{i}_{\mathrm{G}}(t)$$

These currents are associated
with distinctive physical phenomena in the load

All of them
are mutually orthogonal
so that their three-phase RMS value
satisfy the relationship

$$||\boldsymbol{i}||^2 = ||\boldsymbol{i}_{\mathrm{a}}||^2 + ||\boldsymbol{i}_{\mathrm{r}}||^2 + ||\boldsymbol{i}_{\mathrm{s}}||^2 + ||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{n}}||^2 + ||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{p}}||^2 + ||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{z}}||^2 + ||\boldsymbol{i}_{\mathrm{G}}||^2$$

The effectiveness of the energy transfer
from supply source to a load

$$\lambda = \frac{P}{S} = \frac{||\boldsymbol{i}_{\mathrm{a}}||}{\sqrt{||\boldsymbol{i}_{\mathrm{a}}||^2 + ||\boldsymbol{i}_{\mathrm{s}}||^2 + ||\boldsymbol{i}_{\mathrm{r}}||^2 + ||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{p}}||^2 + ||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{n}}||^2 + ||\boldsymbol{i}_{\mathrm{u}}^{\mathrm{z}}||^2 + ||\boldsymbol{i}_{\mathrm{G}}||^2}}$$

In the CPC-based Power Theory
each current component
that degrades the effectiveness of the energy transfer
is associated
with a distinctive physical phenomenon in the load

It is not enough to specify reasons
for the energy transfer effectiveness degradation

Power Theory should provide fundamentals
for compensation
of the harmful components of the supply currents

The CPC – based Power Theory
satisfies this expectation

It creates fundamentals for design and control
of reactive compensators
&
switching compensators

Ilustration
of improvement of energy transfer effectiveness
by a reactive balancing compensator

CPC-based reactive compensator design

Compensator of zero sequence unbalanced current

$$T_{\mathrm{R}} = -2\,\mathrm{Im}\boldsymbol{Y}_{\mathrm{n}}^{\mathrm{z}} - B_{\mathrm{e}} = -\,0.289\ \ \mathrm{S}$$

$$T_{\mathrm{S}} = -\sqrt{3}\,\mathrm{Re}\boldsymbol{Y}_{\mathrm{n}}^{\mathrm{z}} + \mathrm{Im}\boldsymbol{Y}_{\mathrm{n}}^{\mathrm{z}} - B_{\mathrm{e}} = 0.289\ \ \mathrm{S}$$

$$T_{\mathrm{T}} = \sqrt{3}\,\mathrm{Re}\boldsymbol{Y}_{\mathrm{n}}^{\mathrm{z}} + \mathrm{Im}\boldsymbol{Y}_{\mathrm{n}}^{\mathrm{z}} - B_{\mathrm{e}} = 0.50\ \ \mathrm{S}.$$

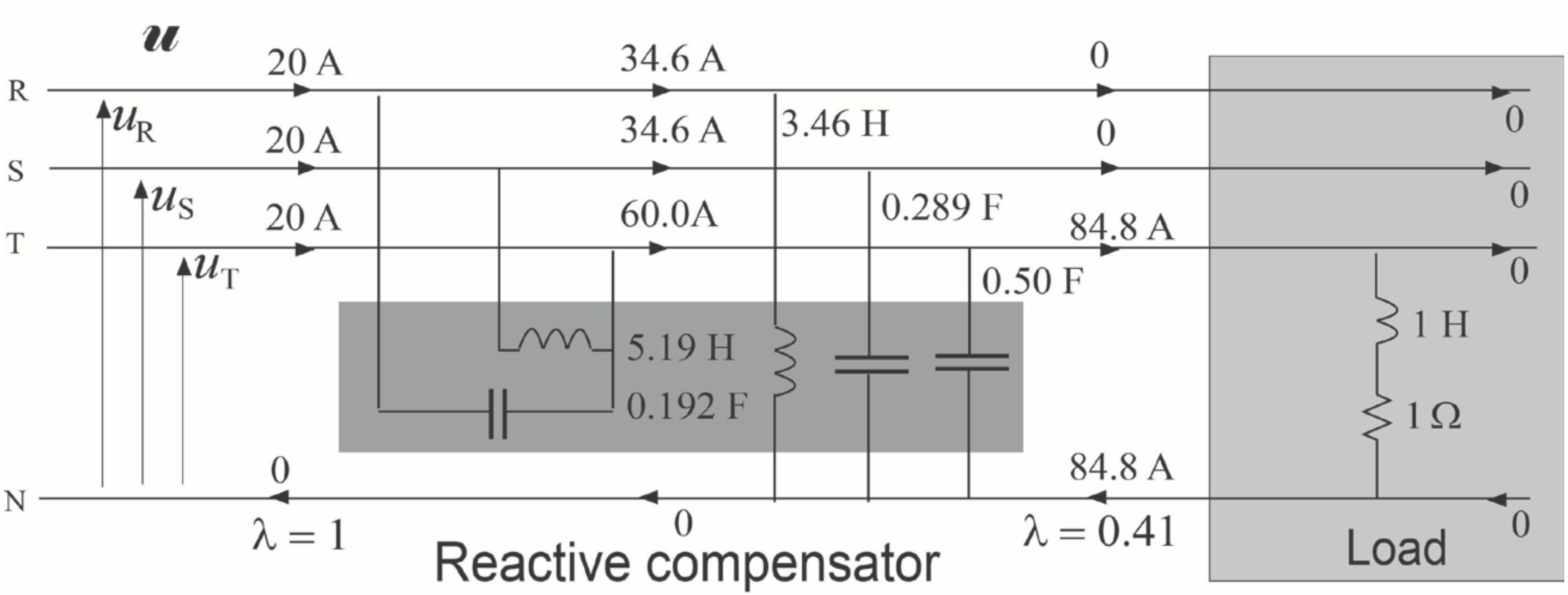
$$\boldsymbol{Y}_{\mathrm{u}}^{\prime\mathrm{n}} = \boldsymbol{Y}_{\mathrm{u}}^{\mathrm{z}*} + \boldsymbol{Y}_{\mathrm{u}}^{\mathrm{n}} = (0.061 + j\,0.228)^* - 0.228 - j\,0.061 = -0.167 - j\,0.289\ \ \mathrm{S}$$

Compensator of negative sequence unbalanced current

$$T_{\mathrm{RS}} = (\sqrt{3}\,\mathrm{Re}\boldsymbol{Y}_{\mathrm{u}}^{\prime\mathrm{n}} - \mathrm{Im}\boldsymbol{Y}_{\mathrm{u}}^{\prime\mathrm{n}})/3 = 0$$

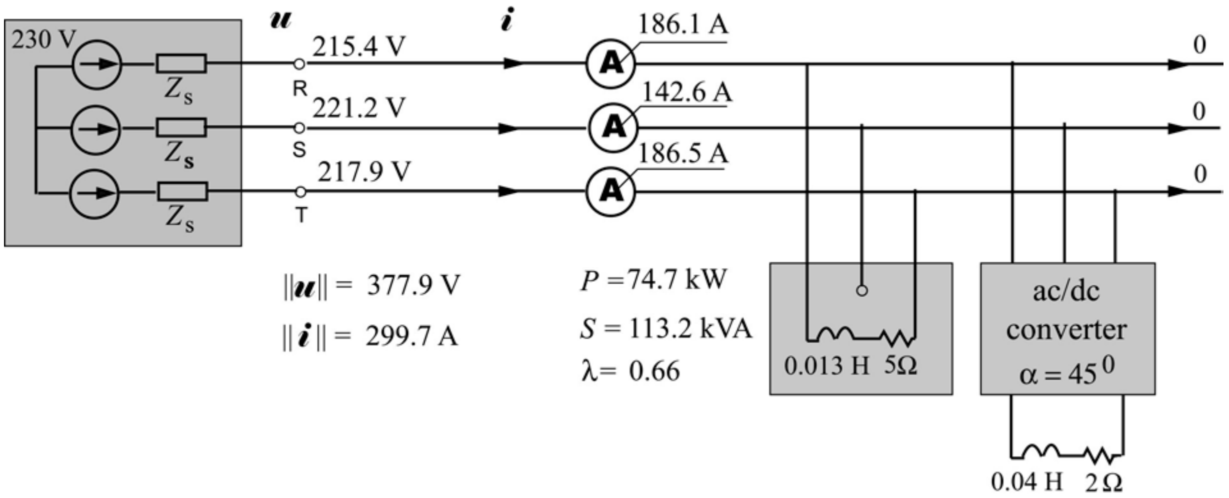
$$T_{\mathrm{ST}} = (2\,\mathrm{Im}\boldsymbol{Y}_{\mathrm{u}}^{\prime\mathrm{n}})/3 = -0.192\ \mathrm{S}$$

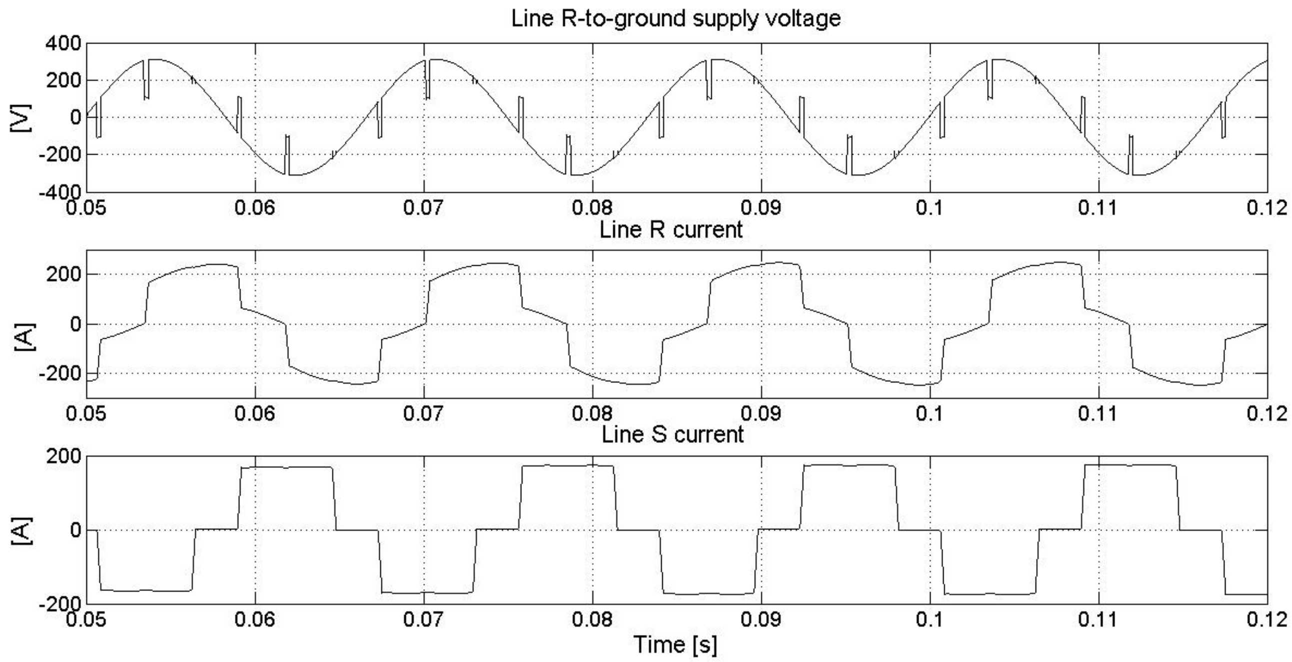
$$T_{\mathrm{TR}} = (-\sqrt{3}\,\mathrm{Re}\boldsymbol{Y}_{\mathrm{u}}^{\prime\mathrm{n}} - \mathrm{Im}\boldsymbol{Y}_{\mathrm{u}}^{\prime\mathrm{n}})/3 = 0.192\ \mathrm{S}.$$



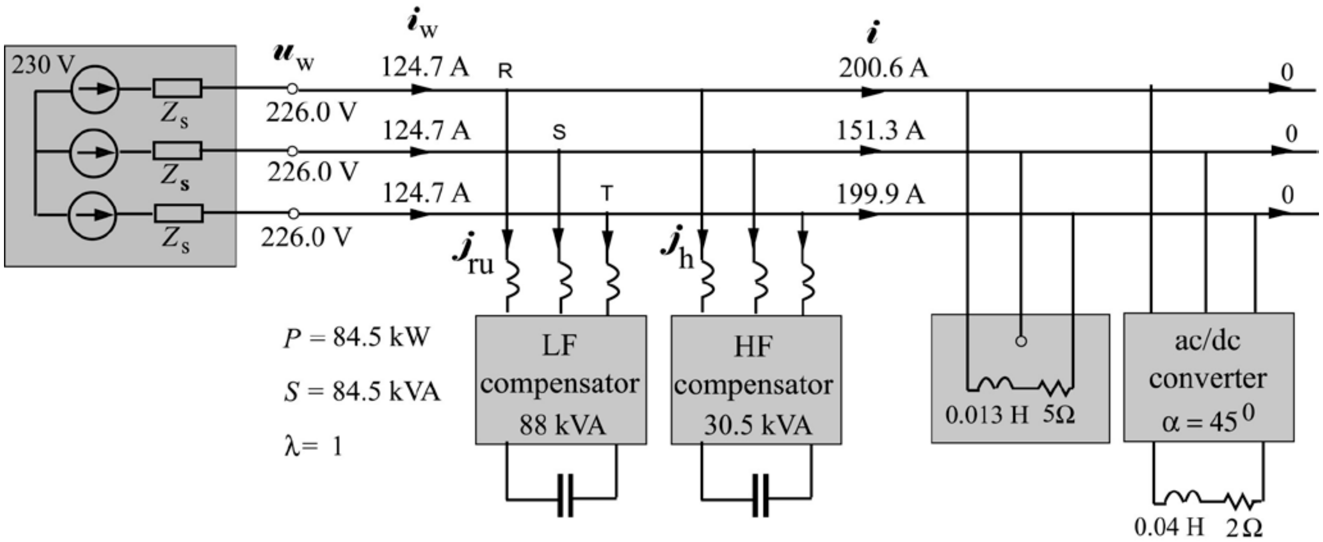
Ilustration
of improvement of energy transfer effectiveness
by a switching compensator

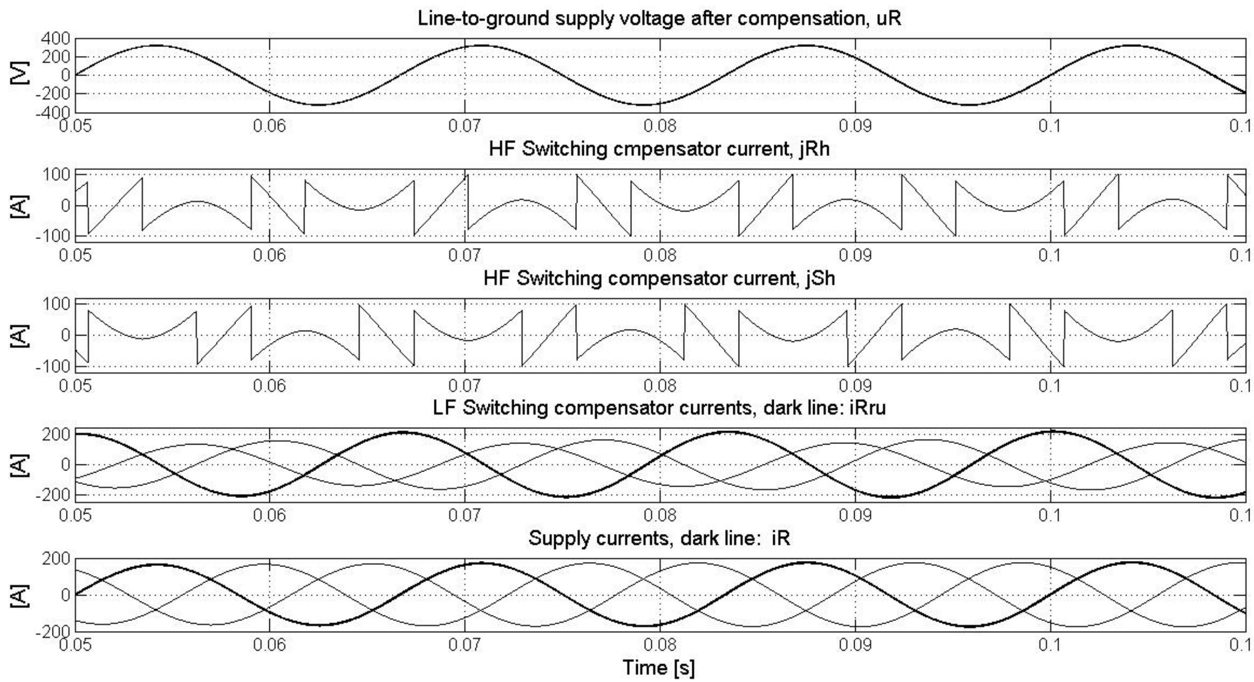
Example of a low quality load

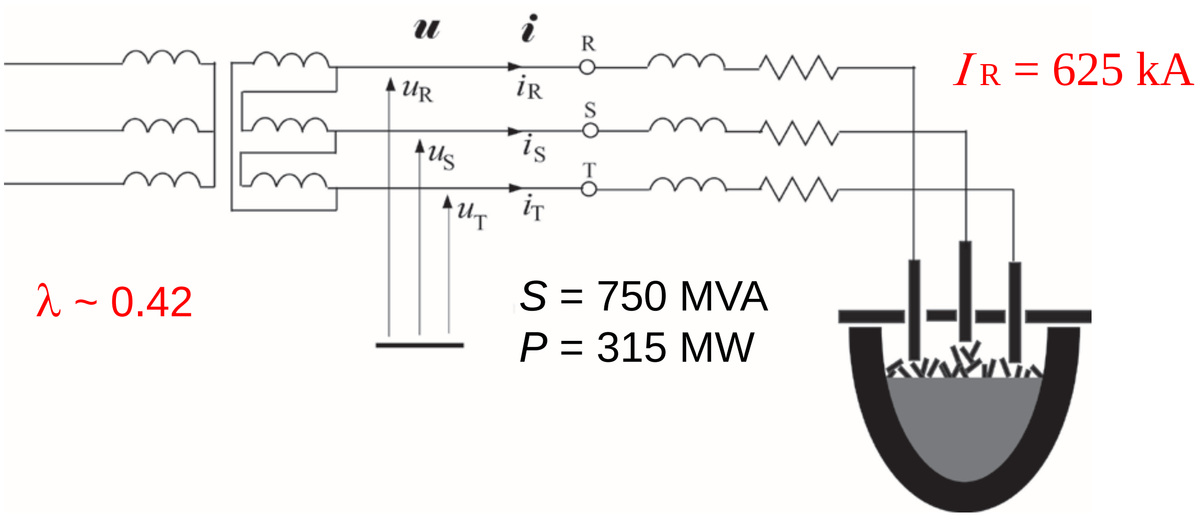




CPC-based switching compensator control







The CPC-based current decomposition of the arc furnace:

$$\boldsymbol{i}(t) = \boldsymbol{i}_{\mathrm{a}}(t) + \boldsymbol{i}_{\mathrm{r}}(t) + \boldsymbol{i}_{\mathrm{u}}^{\mathrm{n}}(t) + \boldsymbol{i}_{\mathrm{G}}(t)$$

$$\lambda = \frac{P}{S} = \frac{\|\boldsymbol{i}_{\mathrm{a}}\|}{\sqrt{\|\boldsymbol{i}_{\mathrm{a}}\|^2 + \|\boldsymbol{i}_{\mathrm{r}}\|^2 + \|\boldsymbol{i}_{\mathrm{u}}^{\mathrm{n}}\|^2 + \|\boldsymbol{i}_{\mathrm{G}}\|^2}}$$

Thanks for your attantion!!